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A BREATH OF FRESH AIR: AIR-SCOOPING ELECTRIC PROPULSION IN VERY LOW EARTH ORBIT

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Air-scooping electric propulsion (ASEP) is a game-changing concept that extends the lifetime of very low Earth orbit (VLEO) satellites by providing periodic reboosting to maintain orbital altitudes. The ASEP concept consists of a solar array-powered space vehicle augmented with electric propulsion (EP) while utilizing ambient air as a propellant. First proposed in the 1960s, ASEP has attracted increased interest and research funding during the past decade. ASEP technology is designed to maintain lower orbital altitudes, which could reduce latency for a communication satellite or increase resolution for a remote sensing satellite. Furthermore, an ASEP space vehicle that stores excess gas in its fuel tank can serve as a reusable space tug, reducing the need for high-power chemical boosters that directly insert satellites into their final orbit.

Air-breathing propulsion can only work within a narrow range of operational altitudes, where air molecules exist in sufficient abundance to provide propellant for the thruster but where the density of these molecules does not cause excessive drag on the vehicle. Technical hurdles remain, such as how to optimize the air-scoop design and electric propulsion system. Also, the corrosive VLEO atmosphere poses unique challenges for material durability. Despite these difficulties, both commercial and government researchers are making progress. Although ASEP technology is still immature, it is on the cusp of transitioning between research and development and demonstration phases. This paper describes the technical challenges, innovation leaders, and potential market evolution as satellite operators seek ways to improve performance and endurance.

Air-Scooping Electric Propulsion (ASEP)

If ASEP satellites can overcome technological challenges related to air scoop design and efficient electric propulsion, while enduring the corrosive VLEO atmosphere, they can offer multiple economic and operational advantages, including long endurance missions, high resolution imaging, and potentially reusable space tug applications.

Strengths	Weaknesses
Existing Market Application: Remote Sensing and Communications	
• **Remote sensing** – Higher resolution imaging • **Communications** – Lower latency, improved link budget • **Mission life** – Independent fuel supply, providing potentially longer mission life • **Resiliency** – Can modify orbits • **Sustainability** – Relies upon a renewable fuel source for continuous flight and mission extensibility	• **Tracking challenges** – Need to track fast-moving satellites, tracking antennas are required • **Material longevity** – Potential solar panel degradation over time due to atmospheric effects • **Addressable market** – Uncertainty for planned pLEO constellations
Future Market Application: Space Tug Service Advantages for Satellites	
• **Reduced launch costs** – Less required fuel drives lower mass, thus reducing launch costs • **Maneuverability and life extension advantages** – Offers flexibility and economic advantages to satellite customers • **Debris mitigation** – Tug offers deorbiting service • **Orbital strategies** – Offers replacement to hold orbital slot and orbital repositioning	• **Financial risk** – Unproven economic model • **Uncertain value proposition for space tug services** – If the launch costs decline significantly, or if the trent toward disaggregation (e.g., numerous, inexpensive satellites) abates • **Time requirements** – Space tug refueling process requires significant time

Introduction

In 1961, Felix Berner and Morton Camac, from Avco-Everett Research Laboratory, published “Air Scooping Vehicle,” a paper that described a satellite designed to fly slightly above 160 km while using the atmosphere as a propellant (see Figure 1).[1] Even though this was not the first paper on the subject, it provided a multifaceted review of the problem with a detailed investigation of each required subsystem, a description of the overall system usage, and a discussion of possible economic benefits.[2] A later Air Force study found that:

> the basic A-SCOR [Air Scooping Orbital Rocket] concept is theoretically sound and requires no fundamental scientific breakthroughs… Potential A-SCOR mission applications… would include almost all missions involving Earth… orbiting vehicles. Specifically included in this category would be such missions as the raising of space vehicles from low earth orbits to synchronous altitudes, rendezvous and docking, very low-level reconnaissance and surveillance… and orbital re-supply vehicles….[3]

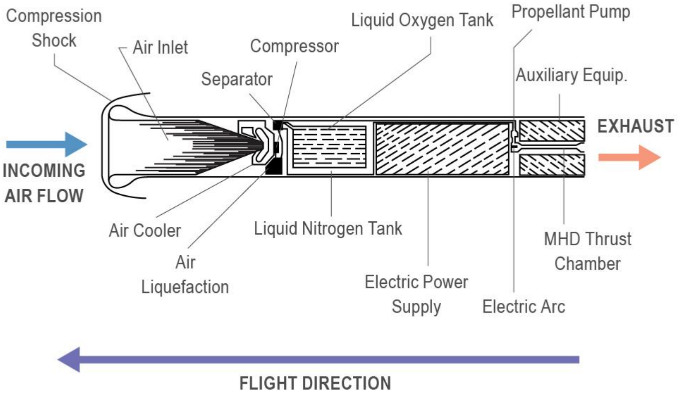

Figure 1: Schematic of an air scooping vehicle.
Source: Adapted from F. Berner and M. Camac, “Air Scooping Vehicle,” Planetary and Space Science, 1961.

In short, an air-scooping satellite in very low Earth orbit (VLEO)[*] has the potential to reduce launch cost, improve mission performance for high-resolution Earth observation (EO) missions, reduce latency for satellite communications, and introduce new space tug servicing capabilities for existing satellites. With the emergence of proliferated LEO (pLEO) communication satellites (such as the OneWeb, SpaceX "Starlink," and Amazon "Kuiper" commercial constellations), it is now a favorable time to consider the advantages and new capabilities that an air-scooping satellite offers.

Background: Technologies and Architecture

Early air-scooping satellite concepts relied on a nuclear reactor to provide power to an electric propulsion (EP) device to compensate for the atmospheric drag produced by the vehicle. However, the idea of an active nuclear reactor continuously flying overhead at a low altitude had the potential to trigger environmental, health, and safety concerns. Even today, a low-flying, nuclear-powered satellite has a slim chance of gaining public acceptance.

As an alternative power source, solar arrays were not sufficiently developed in the 1960s to provide the necessary amount of power. Furthermore, electric propulsion technologies, especially high-efficiency thrusters for space vehicles, were in early development stages during the 1960s, although the first prototypes flew during 1964 in both the United States and Soviet Union. Despite these early technical barriers, today's advances in solar panel and EP technologies offer air-scooping electric propulsion (ASEP) satellites a path to becoming a reality.

Until the 2000s, slow technological progress caused waning interest in air-breathing satellites. By the twenty-first century, however, solar electric propulsion (SEP) gained wide acceptance and accumulated significant flight heritage. While today's flight-demonstrated EP thrusters operate below the 5 kW power level, NASA has recently investigated a 30 kW class mission and even successfully operated a 100 kW Hall thruster in a ground test facility.[4,5] Similarly, solar array technology has steadily improved. While solar cell efficiency has continually increased in the last 50 years, a major improvement in solar array material and construction has led to the development of flexible solar arrays, as demonstrated by the Deployable Space Systems Roll Out Solar Array (ROSA) concept. Flexible solar arrays have now introduced improved power efficiencies, from 60 W/kg to greater than 140 W/kg.[6,7] Both solar array and solar cell performance progress have reignited interest in air-scooping or air-breathing technology and their practical applications for electric propulsion. Multiple government and commercial stakeholders are now investigating ASEP concepts.

Four Critical Enabling Technologies. Air-breathing propulsion can only work in the sliver of altitudes where air molecules exist in sufficient abundance to provide propellant for the thruster but where the density of these molecules does not cause excessive vehicle drag to exceed the thrust produced by the vehicle. Three key technologies play a critical role in enabling the ASEP concept: electric propulsion (EP), solar panels, and an air scoop. In addition to these three key technologies, a fourth technology, a compressor, is needed for enabling the tug concept.

1. **Solar Arrays.** Most modern spacecraft use solar panels to provide onboard electricity. Solar panel technology is rapidly improving. A 2018 NASA industry survey indicates that solar cell efficiency doubled within the last 50 years.[8] Form factor advances, such as the development of the Roll-Out Solar Arrays (ROSAs), further contribute to the increase in available onboard power, although fundamentally it is the power conversion efficiency (watts per unit area) that remains the most critical factor.

   For solar electric propulsion (SEP) vehicles, the power increase may lead to higher thrust levels, enabling shorter trip times while maintaining high exhaust velocity.[9] Efficient solar arrays translate into smaller array areas, which results in reduced drag for an ASEP spacecraft. However, these solar arrays must deal with a challenging VLEO space environment, such as material degradation due to exposure to atomic oxygen and nitrogen at high relative velocity.

2. **Electric Propulsion.** EP relies on accelerating plasma using electromagnetic forces and has the flexibility to

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[*] Very low Earth orbits (VLEO) are defined as orbits with a mean altitude below 450 km.

utilize a wide variety of propellants composed of simple atoms such as oxygen, helium, xenon, or more complex chemicals. Electric energy for the plasma creation and acceleration can come from a variety of sources, such as solar arrays, batteries, or a nuclear reactor. EP can produce very high propellant exhaust velocity, significantly higher than produced by a chemical rocket. Propellant consumption scales inversely with exhaust velocity. Thus, high exhaust velocity allows propellant savings, reduction in the fuel tank size, and lower launch cost. On the other hand, the need to carry a power supply offsets some of these benefits.

While the best chemical rockets can produce exhaust velocity on the order of 4,500 m/s, a modern EP device can typically produce exhaust velocity around 20,000 m/s. A spacecraft in VLEO requires a thruster with an exhaust velocity that exceeds the orbital velocity, around 8,000 m/s, to be able to compensate for the atmospheric drag. Required specific impulse is typically between 1,000 seconds and 3,000 seconds and depends on the operating regime. The thrust produced by an EP device is typically on the order of tens to hundreds of milli-newtons,[†] which is similar to the drag force experienced by the satellite flying at an orbit of around 200 km, as demonstrated by two recent VLEO demonstrations (see Figure 2):

a. European Space Agency's (ESA) Gravity field and steady-state Ocean Circulation Explorer (GOCE) at 255 km.

b. Japan Aerospace Exploration Agency's (JAXA) super low altitude test satellite (SLATS), which flew at altitudes as low as 167 km.

JAXA and ESA's electric propulsion VLEO spacecraft did not include air scoops. Still, both missions demonstrate that electric propulsion can effectively counter atmospheric drag.[10,11]

3. **Air Scoop System.** The purpose of the air scoop is to collect and efficiently compress the atmospheric gas to the densities required for the thruster operation while minimizing drag created in the process. The ASEP air-scoop design needs to consider the specific challenges of less dense or rarefied air at high altitudes. Few research papers have been published on this topic to date.[12,13]

4. **Fuel Tank Compressor.** Although this technology is not critical for a basic VLEO ASEP spacecraft technology, it is a key element for propellant storage for a space tug application. A VLEO ASEP spacecraft operating as a space tug will need to compress air into an onboard fuel tank for consumption during the orbit reposition phase. Air compression from low densities, typical for VLEO, is similar in principle to gas pumping performed for vacuum chambers. This is typically accomplished through a combination of either a cryo or turbo pump as a first stage with a mechanical pump as a second stage. Ground-based pumps are inefficient and heavy and will need to be reengineered for space application.[14,15,16] Very little research on space worthy compressors has been performed to date.

System Architecture. The VLEO environment dictates the overall satellite system architecture. The satellite geometry should be optimized to reduce drag, while providing the maximum possible electrical energy. The thruster performance should be optimized for maximum efficiency for a large range of thrust and specific impulse values. Finally, the air scoop needs to be optimized both for the highest compression ratio and intake efficiency. Most of these optimization requirements present design challenges due to the conflicting needs of the optimization parameters. For example, passive air scoops exhibit an inverse relationship between efficiency and compression ratio.[17]

Orbital Altitudes

Layers of the Earth's Atmosphere. The Earth's atmosphere is "our natural shield against the harsh conditions of space—including everything from meteors and falling satellites to deadly ultraviolet radiation from the sun. It also contains the air we breathe, the weather we experience and helps to regulate planetary

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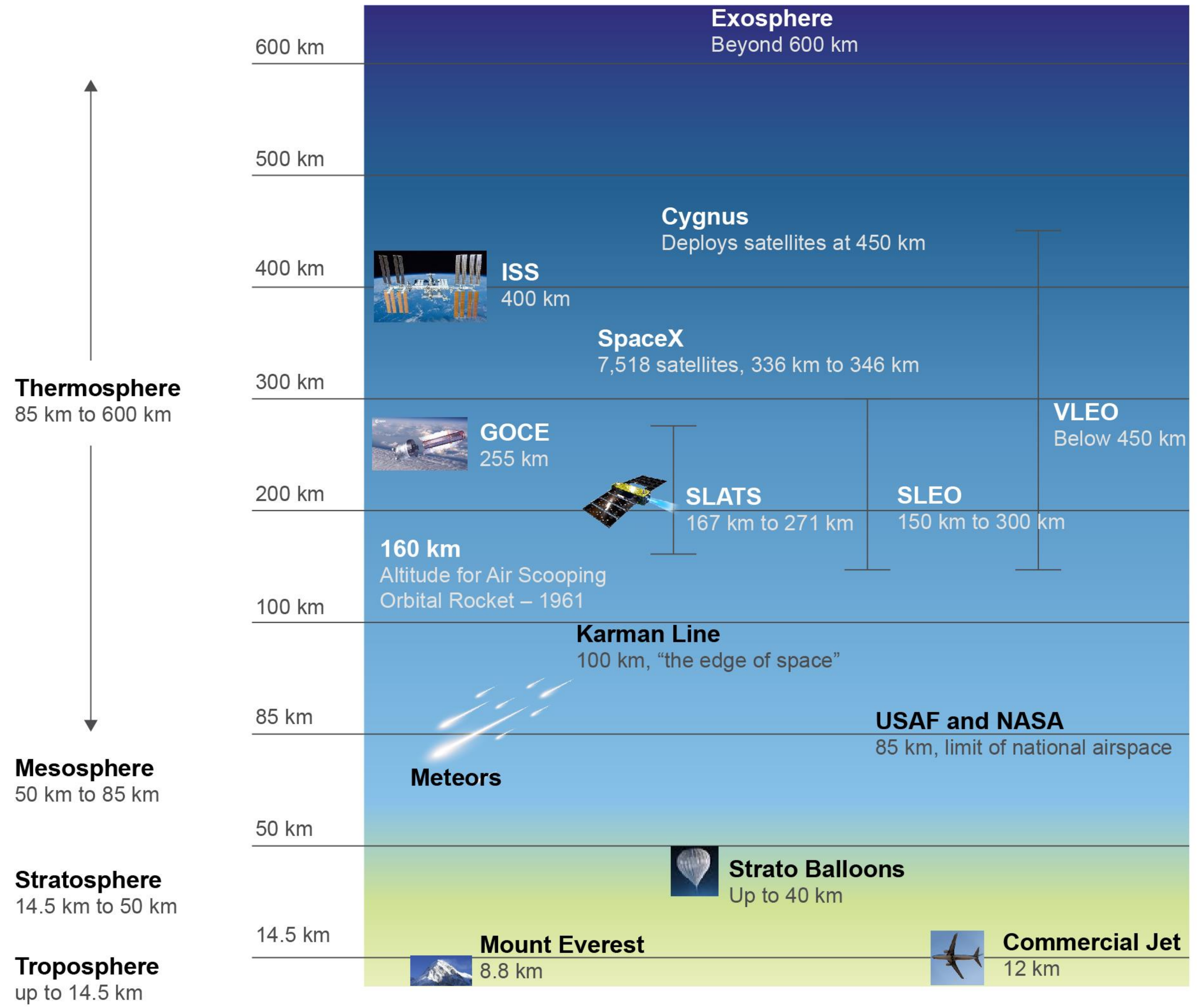
[†] One newton is equal to the force needed to accelerate a mass of one kilogram one meter per second. One milli-newton is equal to 10^{-3} newtons.

temperatures."[18] Earth's atmosphere includes the following layers (also see Figure 2):

- **Troposphere**. Comprised of nitrogen, oxygen, argon, carbon dioxide, small amounts of other gases and variable amounts of water vapor.
- **Stratosphere.** Stratified as a result of absorption of the sun's ultraviolet radiation by the ozone layer, creating warmer layers higher and cooler layers closer to Earth.
- **Mesosphere.** The highest layer of the atmosphere in which the gases are all mixed up rather than being layered by their mass. Meteors entering Earth's atmosphere burn up in the mesosphere.
- **Thermosphere.** Extremely low air density, strongly influenced by temperatures that climb sharply in the lower thermosphere (below 200 km to 300 km altitude), then hold relatively steady with increasing altitude above that height. The thermosphere's density varies with solar weather. Consequently, drag



* below 100 km at 3x background scale to show details.

Figure 2: Layers of Earth's atmosphere.

variations due to solar and space weather cycles present challenges for ASEP VLEO spacecraft seeking to find the "sweet spot" for flight endurance.[19]

The U.S. Air Force and NASA have described the *limits of space* as 85 km. However, the Federation Aeronautique Internationale (FAI), the world governing body for record-breaking flights and air sports, defines the *Karman line*, at 100 km, as the point where airspace terminates and space begins. Regardless, there is no agreed-upon international limit for airspace because outer space does not begin or end at a specific altitude.

Super Low Earth Orbit (SLEO). Typically, VLEO refers to satellites flying at altitudes below 450 km. However, with increasing interest in the lower altitudes of VLEO, the space industry and regulators should consider a new altitude designation. The term *super low Earth orbit* (SLEO) has also been occasionally applied, referring to orbits with a perigee below 300 km.[20] The operational altitude range for ASEP satellites is limited to 150 km to 300 km.

The Inter-Agency Space Debris Coordination Committee (IADC) has issued guidelines for low Earth orbit (LEO) (up to 2000 km) whereby space operators are expected to provide deorbit plans for satellites after they are no longer operational. These guidelines have been incorporated into NASA, ESA, and the International Organization for Standardization (ISO) standard requirements to mitigate space debris. These guidelines are considered prior to issuing launch licenses and access to orbits. An ASEP flying at SLEO altitudes is subjected to significant atmospheric drag and, without orbital maintenance maneuvers, it will naturally deorbit within a matter of days. Unlike geostationary (GEO) satellites, where regulators must consider the long-term consequences of orphan satellites orbiting for a thousand years, the SLEO environment is self-clearing. Therefore, a SLEO designation (between 300 km and 150 km) could potentially enjoy relaxed treatment from a regulatory and risk mitigation perspective.[‡]

VLEO Advantages and Market Drivers

According to ESA, approximately 8,950 satellites have been placed into orbit since 1957, and approximately 5,000 satellites are currently in orbit.[21] These historical numbers are dwarfed by future satellite forecasts. The booming commercial space industry has proposed approximately 20,000 satellites for deployment into non-geostationary orbits, with approximately 13,000 having been approved by the Federal Communications Commission (FCC) thus far.[22] VLEO will become a popular orbit in the future. In March 2017, for instance, SpaceX filed with the FCC for 7,518 satellites in orbits between 336 km and 346 km altitudes.

Key market drivers for VLEO satellites will also drive interest in ASEP VLEO satellites, summarized below. Figure 3 illustrates the various lifecycle maturity phases based on market, technology, or regulatory triggers.

Orbital Endurance and Lower Constellation Maintenance Cost. VLEO satellites typically experience fast orbital decay and require significant propellant for periodic orbital maintenance maneuvers. A proliferated very low Earth orbit (pVLEO) constellation may require a larger initial number of satellites in orbit to provide communication coverage than the existing pLEO constellations. However, an ASEP satellite could have a longer life, because it is not limited by the finite supply of onboard propellant. Therefore, the pVLEO ASEP vehicle replacement rate will be significantly lower, thus reducing the overall cost of the constellation.

Commercial pLEO Communications. Lower orbits enable reduced communication latency. Increasing commercial, civil, and military demands for connectivity to support enterprise and general consumer demand for broadband and Internet of Things is driving commercial space participants to design and deploy pLEO communication constellations. Both factors provide a strong competitive advantage to any company that can fly VLEO ASEP satellites, particularly for those constellations that support latency intolerant applications

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[‡] As a general rule, orbital debris reenters Earth's atmosphere at 200 km, one day; at 300 km, one month; and at 400 km, one year.

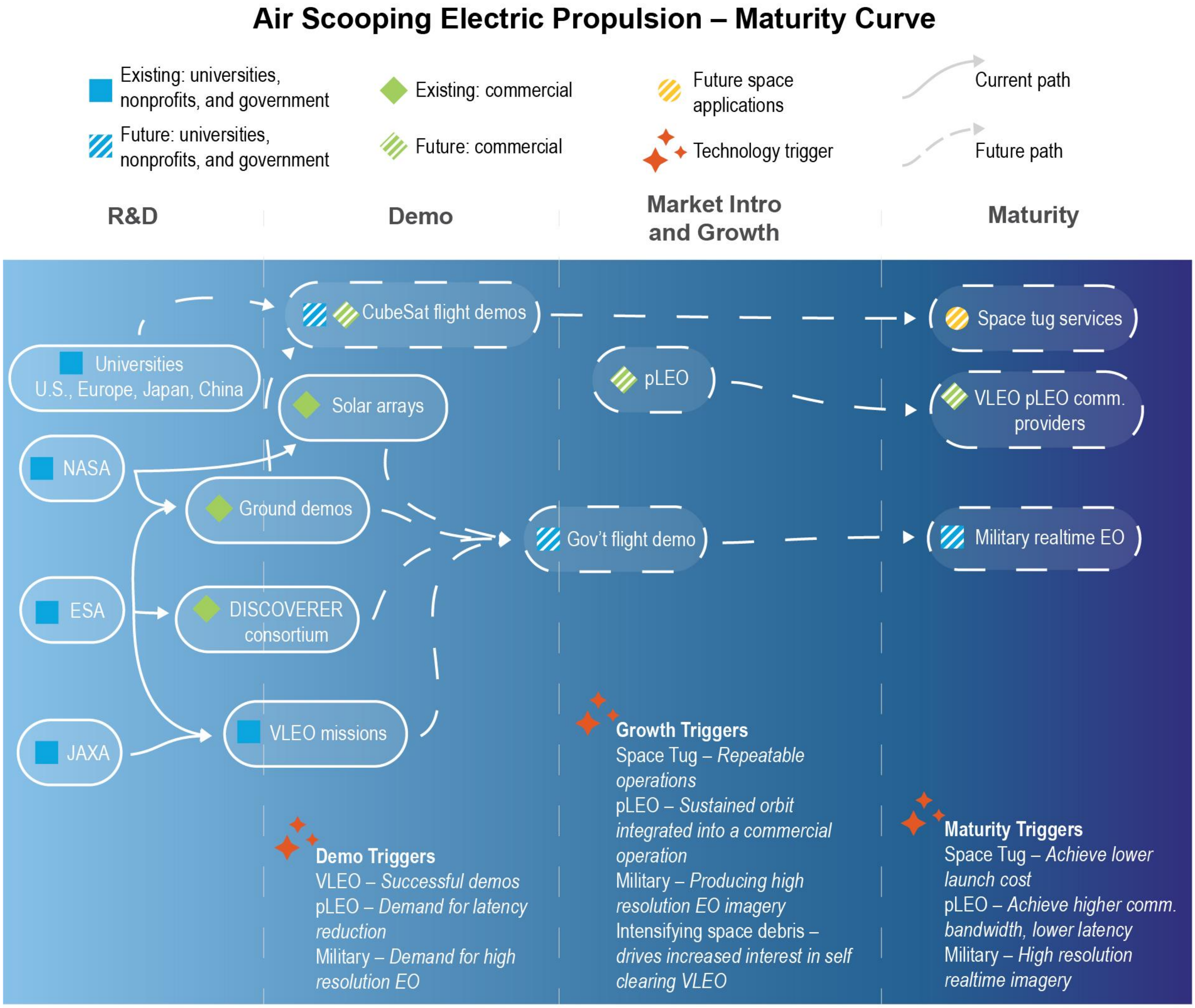

Figure 3: Technology Lifecycle Maturity Curve. *Anticipated ASEP lifecycle including key triggers, which could contribute to market introduction, growth, and maturity. Although ASEP technology is still immature, it is on the cusp of transitioning from R&D to Demo phase.*

such as financial transactions and high-speed trading, autonomous vehicle navigation, multiplayer gaming, and remotely operated robotics that need near realtime capabilities.

The deployment of new satellite constellations, including OneWeb, Starlink, and Project Kuiper, could transform Internet and broadband access markets. These proliferated LEO or pLEO constellations intend to play a key role in closing the digital divide and extending cellular 5G networks to remote and underserved areas. Active strides toward this goal have already been made:

- Starlink (parent company: SpaceX) has over 1,000 operating satellites of more than 4,400 satellites that the FCC approved in 2018.
- OneWeb (Chapter 11 reorganization, British government and Bharti Global) has 110 operating satellites. Plans for the constellation were recently downsized from 47,844 to 6,372 satellites.
- Project Kuiper (parent company: Amazon) has not yet launched any satellites; however, 3,220 are planned for an initial LEO constellation.

Successful commercial pLEO constellations seeking to extend the reach of data and broadband connectivity could stimulate development of the ASEP technology.

High Resolution EO. Lower orbits enable high-resolution imagery and better radiometric performance for spectral sensors and lidar instruments. According to Euroconsult, demand for imagery with resolution better than one meter will grow far more quickly than demand for lower resolution data products. Euroconsult predicts that the market for this very-high-resolution imagery will be worth nearly $1.7 billion by 2027, compared with $938 million in 2017.[23] VLEO satellites fly closer to Earth than higher orbiting LEO, medium Earth orbit (MEO), and GEO satellites, resulting in higher resolution images.

Military Strategic Advantages. ASEP vehicles flying in VLEO offer benefits for the U.S. military, including the ability to outmaneuver and evade bad actors and unintentional space threats. Colonel Eric Felt, director of the Air Force Research Laboratory Space Vehicles Directorate, notes that "it's harder to track satellites in that orbit. First, they zoom overhead so fast. The angular velocity makes it difficult to track a satellite coming over you. Second, the resistance from the atmosphere makes it more difficult to predict where a given satellite is going to be at a certain point. We like that too."[24]

Orbital Debris Mitigation Concerns. Orbital debris stays in orbit longer at higher altitudes. Orbits above 1,000 km can circle Earth for a century or more.[25] As higher orbits become increasingly congested with dead satellites and space junk, VLEO becomes increasingly more appealing to space operators because satellites in this orbit will naturally deorbit at the end of life. Orbits below 650 km, including VLEO orbits, could become more attractive to satellite operators because they might benefit from less restrictive policies and regulations aimed at reducing orbital debris.[§]

Emerging Data Connectivity – LEO Satellite Direct to Cell Phone. Low-flying satellites can help close the radio frequency link budget with unmodified cell phones, in part because shorter distances between receivers and transmitters mitigate path loss.[**] VLEO satellites, flying at relatively higher speeds compared to higher orbits, must also address the Doppler shift. If various technical challenges are addressed on a practical basis, VLEO satellites could help fill gaps in terrestrial cellular coverage and establish an entirely new addressable market for mobile satellite telephony. It is within this market context that ASEP could ensure longer lasting and maneuverable VLEO satellites to support new capabilities and new users.

Research, tests, and demonstrations are currently underway to explore how existing cell phones (with no physical modifications) can connect directly to satellites. LEO satellites traveling at very high speeds, around 7.8 kilometers/second, present unique challenges. According to Charles Miller, CEO of Lynk, "you have to solve two fundamental problems. First, the 'satellite cell tower' needs to provide frequency compensation so that the phone does not see too much doppler shift. Second, we trick the phone into accepting the time delay from an extended-range connection."[26] Satellite connectivity to an unmodified general consumer cell phone could be a significant breakthrough if this service can be rolled out on a commercial basis for both satellite and terrestrial mobile connectivity because ASEP could allow VLEO satellites increased agility and lifetimes at lower altitudes. Lynk (Virginia) and SpaceMobile (Texas) are pursuing direct satellite to cell phone links.

Commercialization of the International Space Station (ISS). In June 2019, NASA announced an effort to encourage greater commercial use of the ISS as part of a long-term vision that sees a gradual transition from the ISS to commercial space stations.[27] The ISS, at an altitude of 400 km, provides a platform for the deployment of satellites in VLEO. In October 2020, Nanoracks LLC successfully installed a four-cubic meter bell-shaped canister, the Bishop Airlock Module, which could be used to deploy satellites into VLEO. As an alternative, Nanoracks has also developed a payload deployer for the Cygnus cargo spacecraft. After it performs a resupply mission, the Cygnus is released from the ISS and raised to

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[§] In February 2019, the FCC proposed and later declined to adopt rules related to satellite orbit debris above 650 km because they believe existing regulations adequately cover debris concerns. Regardless, increased regulatory scrutiny for higher altitude orbits seems inevitable.

[**] Free Space Path Loss where $\mathrm{FSPL\_} = (4\prod d/\lambda)^2$, where d is the distance from transmitter to receiver, and λ is the radio frequency wavelength.

an orbit of 450 km to 500 km (50 km to 100 km higher than ISS), where satellites are deployed before the Cygnus moves into a reentry burn.[28]

Future Space Tug Market. The viability of using a space tug to insert, service, and reposition satellites has been extensively studied in the past. Electric propulsion is pivotal for the feasibility of the space tug concept.[29,30,31] However, the economic viability of a commercial space tug operation has yet to be demonstrated. The ability to refuel using atmospheric gas could be an enabling factor in reducing the overall operational cost and making space tugs economically appealing.

Technology Development and Innovation Leaders

A plethora of companies and institutions are actively designing ASEP concepts (see Table 1). While most technological development is funded and managed by universities, some companies have already successfully demonstrated aspects of the ASEP design. The Busek Co. (Natick, Massachusetts), for instance, demonstrated successful operation of a Hall thruster with CO2 (to simulate the Mars atmosphere) under the NASA Innovative Advanced Concepts (NIAC) grant.[32] Busek's Hall thrusters were also operated with air.[33]

Japan. Japan has assumed an active role in both ASEP development and launch of the VLEO vehicles. Multiple Japanese universities are developing EP devices designed to operate on high-altitude thin atmosphere.[34,35,36] JAXA recently flew super low altitude test satellite (SLATS), equipped with an EP device.[37] The SLATS design is not a fully developed ASEP vehicle since it does not scoop atmospheric air and instead has an onboard fuel tank that feeds xenon to an EP thruster. The satellite's mission was to collect information on the Earth's atmosphere at the operational altitude of 167 km to influence design of future Japanese VLEO missions. China is also working on ASEP concepts, although information on Chinese developments is limited to a few conference publications.[38]

Table 1: Commercial and Government ASEP Innovators

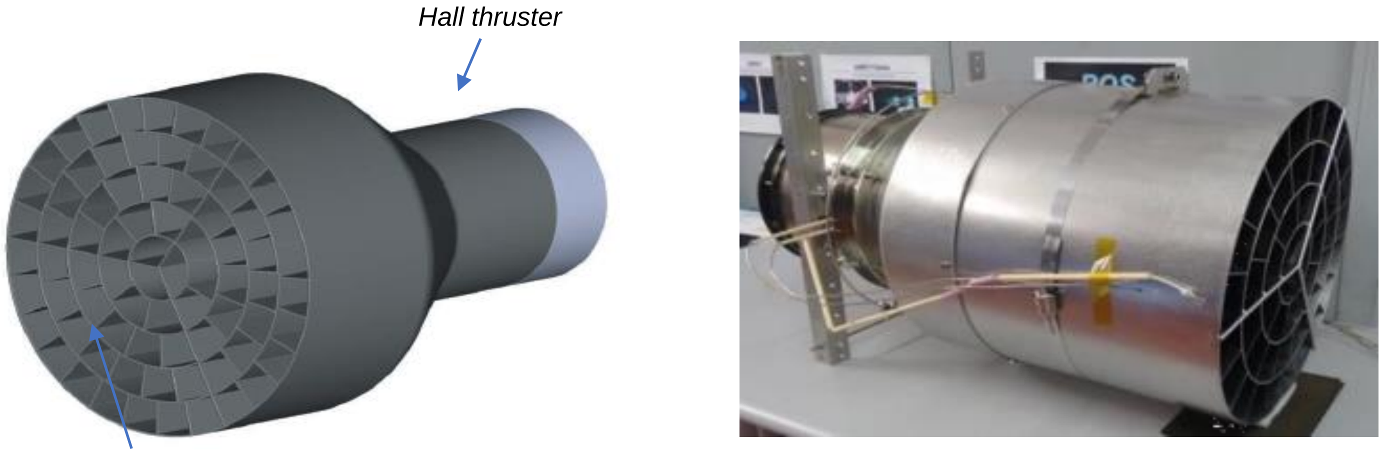
Commercial ASEP Innovators	
Busek (Natick, MA) *Established 1985*	Extensive research into air-breathing thrusters and air-scoop technology. Busek filed a U.S. patent for an air-breathing Hall thruster in VLEO.[††] Busek designed and operated an ASEP prototype in a ground test facility. The effort was focused on redesigning a Hall thruster for air operation.
Sitael S.p.A. (Pisa, Italy)	Designed and tested an ASEP prototype in a ground test facility. Significant effort in designing a scoop prototype with theoretical, modeling, and experimental efforts. Measured system overall performance. While not achieving a break-even condition, the results were encouraging.
Government ASEP Researchers	
DISCOVERER *Nine institutions from six countries*	An international research consortium that aims to revolutionize Earth observation by operating satellites at much lower altitudes than usual using ASEP. Focused on aerodynamic design of spacecraft, material aerodynamics and atomic oxygen resistance, and electric propulsion methods and control methods.
JAXA (Japanese Aerospace Exploration Agency)	SLATS mission to characterize satellite drag at VLEO while using a small atomic oxygen sensor and an optical instrument to take high-resolution satellite images.

[††] Patent US6834492B2 - Busek Co Inc. filed 6-21-2002, patent status is active. Anticipated expiration 6-21-2022. (https://patents.google.com/patent/US6834492B2/en).

Europe. The European Union is leading the most coordinated ASEP development effort, with multiple universities and companies working together with ESA. Significantly, the DISCOVERER Consortium combines various universities and companies with the explicit goal of "radical redesign of Earth observation (EO) satellites for sustained operation at much lower altitudes…by using…atmosphere-breathing electric propulsion for drag-compensation."[39] Furthermore, an ESA-led team consisting of Warsaw University and Italian company Sitael S.p.A. designed and tested on the ground an ASEP system, shown in Figure 4, consisting of an air intake and a Hall thruster.[40] In addition to testing ASEP concepts on the ground, ESA has flown the Gravity field and steady-state Ocean Circulation Explorer (GOCE), a VLEO mission that mapped Earth's gravity field in unprecedented detail.[41] Similar to the Japanese SLATS mission, GOCE did not incorporate an air scoop and instead used onboard xenon as propellant to fly at 255 km.

Growing Commercial Communications Interest. The ground-based ASEP demonstrators and the growing number of VLEO missions are generating increased interest from satellite operators and investors. Additional market triggers that will stimulate investment in ASEP will be driven by successful commercial demonstrations of broadband Internet satellite services in LEO orbit. Round-trip data latency and download speed are two important service metrics for communication satellites. Commercial cable Internet providers deliver broadband services with a 25 ms latency at 120 Mbps, which is sufficient for voice over Internet protocol (VOIP) and other communication services.[42] Fiber optic Internet providers have an even lower latency, around 10 ms. Current satellite providers use geostationary satellites and offer significantly higher latency on the order of 600 ms and lower download speed, around 20 Mbps.[43] An order-of-magnitude reduction in latency can be achieved by pLEO satellites.[44] According to a OneWeb advertisement, 32 ms latency at speeds exceeding 400 Mbps has already been demonstrated with test satellites.[45]

Commercial and military needs for high-resolution EO may also stimulate industry investment in ASEP. A fleet of EO-capable satellites can, for instance, provide live high-resolution coverage of the battlefield or monitoring



Air scoop with honeycomb structure

Air scoop with Hall thruster

Figure 4: Air scoop design integrated with a Hall thruster. Investigated by Barral and Walpot and ground tested by Sitael. The honeycomb structure is designed to capture more air particles by minimizing the backflow to increase pressure and density at the end of the air intake. *Sources: S. Barral, L. Walpot, "Conceptual Design of an Air-Breathing Electric Propulsion System," IEPC-2015-271, 2015. T. Andreussi et al., "Development and experimental validation of a hall effect thruster ram-ep concept," International Space Propulsion Conference, SP2018-00431, 2018.*

of fires. NASA may also be interested in a more ambitious goal: space tugging to remote outposts, such as the moon or the L2 point[‡‡], the target for the James Webb Telescope. An ASEP-enabled space tug could reach high-altitude orbits, such as GEO and further, and come back to VLEO to refill the tank, thus introducing a reusable space tugging capability. A fleet of ASEP space tugs has the potential to disrupt the entire space launch architecture by obviating the need for heavy lift vehicles, except for those satellites that require short station delivery timelines. While the ASEP-enabled space tug mission may not yet be achievable with the current state-of-the-art technology, future technology demonstrations could stimulate significant government and commercial interest.

> ***“The air scoop design must find a way to compress and store the oxygen without overburdening the spacecraft with additional weight which would consequently increase the power needs and thus the fuel and thrust requirements. The complexity of the engineering design will drive weight growth, which will drive structural and size requirements that in turn result in an atmospheric drag profile that necessitates bigger engines. These then further the power and size requirements. Ensuring that the size, weight and power requirements can all close to support a mission will be a challenging engineering feat.”***
>
> ***Greg V. Meholic***
> *Sr. Project Leader*
> *The Aerospace Corporation*

The development of efficient solar arrays is another key element needed for the space tug and other ASEP applications. While current solar arrays may provide sufficient efficiency to enable a VLEO ASEP satellite, more progress is needed for the increased needs of a space tug operation. Furthermore, more efficient solar arrays may open the altitude envelope for the VLEO ASEP satellites, enabling them to operate at a wider orbital range.

Technological Challenges

Greg Meholic, an engineer at The Aerospace Corporation who studies electric propulsion systems, notes that, from a mission and operations perspective, air-breathing satellites “present significant mass flow challenges; for instance, finding the right narrow band in the atmosphere which is sufficiently dense to capture enough oxygen atoms but not overwhelmingly dense as to increase atmospheric drag beyond the spacecraft’s ability to maintain the orbit.” Furthermore, the sweet spot for this atmosphere band is not static because an air-breathing satellite must contend with atmospheric density fluctuations, which depend on seasonality, time of day, and geography.[46]

Multiple technological challenges remain for the development of an ASEP satellite, such as development of an efficient air scoop, design of an efficient air-breathing EP, and material compatibility with the VLEO environment.

- **Air Scoop Design.** Currently the air intake is the least developed subsystem requiring substantial development. While two prototypes have been tested (by Busek and Sitael), further development is needed. Specifically, the demonstrated compression ratios of approximately 125 is at least an order of magnitude smaller than required for a VLEO ASEP satellite. Possible compression ratio improvements could be achieved through geometric design optimization and potentially active compression.

- **Efficient EP System Design.** An optimized design for the VLEO environment remains a technological challenge. Busek and Sitael have demonstrated successful first prototypes, but more development is needed. A robust thruster design is needed to work with a range of composition levels of oxygen and nitrogen, which vary by VLEO altitudes. Further advancements in thruster efficiency may also lead to a larger operation envelope. Finally, designing a thruster to work at lower intake pressures may relax the design requirements on the air scoop.

- **VLEO Environmental Compatibility and Material Durability.** VLEO satellites must endure the unique challenges posed by atomic oxygen (AO) and its reaction with various materials, which could cause degradation. Satellites must be designed with oxygen-

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[‡‡] L2 or the second Lagrange Point, an area where gravity from the sun and Earth balance the orbital motion of the satellite.

resistant materials. NASA, for instance, developed thin film coating to protect solar arrays. The severity of the AO problem may be gauged from the data collected from a recent satellite launched in 2019 by the Japanese Aerospace Exploration Agency (JAXA). The SLATS set a Guinness Book world record by descending from 271.5 km to the record 167.4 km, where it captured high-resolution Earth imagery. SLATS was equipped with an AO monitor and a material degradation monitor (MDM). The first sets of data from the instruments have already been published.[47] According to the available MDM data, no significant material degradation has been measured.[48] This initial data provides a first positive sign that material compatibility and durability challenges may not pose a significant challenge to VLEO satellites, but more work needs to be done to retire this risk.

Conclusion

A future with ASEP VLEO satellites holds promise because current solar array designs are mature enough to produce electricity at sufficient power densities and EP running on high-altitude thin atmosphere has been demonstrated. Still, significant technical challenges remain because no one has yet demonstrated a high-efficiency and high-compression ratio air scoop. While advances with EP and solar array efficiency will mitigate some requirements for the air scoop, government funding combined with commercial "know how" and innovation will be needed to further advance the state of play.

Successful technology demonstrations, supported by both government funding and commercial innovation, may lead to rapid adoption by industry, particularly as LEO satellite operators seek ways to derive value from lower Earth orbits. Satellites that are equipped with an air scoop, propelled by electric propulsion, and powered by solar arrays could offer multiple economic and operational advantages at very low altitudes, including:

- Long endurance missions where the expected satellite lifetime is not limited by the fuel supply.
- High-resolution EO imager or low latency communication missions.
- A solution that will not cause longer-term debris pollution.
- New capabilities, such as reusable satellite tugging and yet-to-be-discovered applications.

Historically, the VLEO orbital regime has been a tough neighborhood for long-term survival. However, *if* ASEP enabled satellites can be successfully demonstrated in VLEO, they could transform lower-altitude orbital slots into prime real estate to support a range of long duration missions.

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