Air-Breathing Electric Propulsion vs. Traditional Electric Propulsion: Earth Observation Mission Analysis

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This paper describes a tradeoff study between a satellite with an ABEP and a traditional (Xenon-based) electric propulsion systems. While comparing two distinct systems and their overall value can be highly mission-specific we constrained our studies to two methododologies: fixing total satellite mass and examining the lifetime at various orbits, and by fixing lifetime to examine mass differences for a system designed to last 5 years at 200 km. With those insights, we moved on to analyziing several mission vignettes, incluidng passive earth obsering, synthetic aperture radar, and a constellation of VLEO vs LEO craft. For Each vignette we looked at the current state of the art in tradtional EP, and compared it to a VLEO ABEP equipped satellite. We found that ABEP equipped VLEO satellites outperfrom traditional EO satellites in size, weight, and power without sacrificing cost and capability. Passive EO say an almost doubling of ground reoslution when compared to MAXARs suite of EO satellites, and SAR ABEP satellites saw an increase of 6x the capability. Constellation parameters, however, saw a decrease in effectiveness due to lower revisit times and decreased access duration to the lower altitude (200km vs 500km). Furthermore, we examine unique space vehicle geometry, specific mission vignettes, actual payloads and use cases with higher fidelity simulation tools.

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Nomenclature

VLEO	= Very Low Earth Orbit
ABEP	= Air Breathing Electric Propulsion
EO	= Earth Observing
L	= Length of The Sythetic Aperature
Res_{AZ}	= Azimuth Resolution
Res_R	= Range Resolution
P_{Rec}	= Power Received by Antenna
P_T	= Transmit Power
P_{Avg}	= Average Power
A_L	= Length of Antenna
A_W	= Width of Antenna
RCS	= Radar Cross-Section
λ	= Wavelength
R	= Range
V	= Orbital Velocity
T_o	= Temperture at Reciever
k	= Boltzmann Constant
F_N	= Reciever Noise
B	= Bandwidth
$NESZ$	= Noise Equivalent Sigma Zero
SQS	= SAR Quaility Score
ϕ	= Incidence Angle (Degrees)
PRF	= Pulse Repition Frequency

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I. Introduction

The availability of cheaper launch services at the beginning of the twenty first century marked rapid development of the space economy. Specifically, two types of services, satellite broadband communication and Earth Observation (EO), are receiving significant investments from both commercial and government sectors. While Geostationary Earth Orbit (GEO) and Medium Earth Orbit (MEO) were historically the first to be commercialized and widely used, Low Earth Orbit (LEO) is increasingly becoming a domain of commercial and military competition. Satellites flying closer to Earth have multiple economic and military advantages. They can provide higher resolution Earth Observation (EO) platforms for optical and electromagnetic surveillance, lower latency communication networks, and agile distributed assets for military purposes.

The emergence of the SpaceX StarLink, Amazon Kuiper, and OneWeb LEO broadband communication constellations highlights one particular business case for low flying satellites. Historically, broadband services were supplied by GEO satellites that suffer from high latency (around 600 ms) due to the electromagnetic wave travel time. This eliminated the possibility of real-time applications, and instead the primary focus of these services was geared to one-way information flow, such as TV or radio broadcasting, where these established constellations generate up to $100B in annual revenue. The new LEO constellations aim to provide communication capabilities with latencies around 20-30 ms, similar to cable internet, enabling two-way live communication, gaming, and financial transactions through satellites. These constellations are being developed to orbit in multiple shells at altitudes between 1,200 km and 450 km.[1]

Very Low Earth Orbit (VLEO) satellites, operating between 100 and 450 km, can further provide improved Earth-facing payload performance, geospatial accuracy, simple End-of-Life disposal, and have reduced space-debris collision risk. However, traditional Earth Observation (EO) and satellite broadband communication services in LEO are typically performed in the altitude range around 500 km, principally due to the challenges of aerodynamic drag and requirements to provide a meaningful orbital lifetime[2,3] while minimizing spacecraft mass and complexity. A cost-effective way of achieving sustained flight in VLEO, below 300 km could lead to major improvements in Earth-facing services. Some groups have focused on developing further improvements to the propellant efficiency of traditional electric propulsion technology to achieve this. Another approach is to develop an Air-Breathing Electric Propulsion (ABEP) system, where propellant efficiency is less concerning because propellant is constantly collected from the atmosphere. This paper outlines the benefits and system level tradeoffs between an ABEP-propelled and a traditional Xenon-propelled satellite in VLEO.

Comparing these two distinct systems and their overall value can be highly mission-specific. One approach is to compare the total launch mass of vehicles that provide equivalent services for the same duration; the other approach is to compare the lifetime of two otherwise equivalent systems. In our studies we approach this comparison from both perspectives by 1) fixing the total satellite mass and examining lifetime, and 2) fixing the expected satellite lifetime to and examining the launch mass difference.

After this study, we examine several mission vignettes to understand how VLEO flight can improve satellite cost with actual payloads and use cases. Specifically, we will examine:

- **Vignette 1:** An optical Earth Observation (EO) satellite in VLEO.
- **Vignette 2:** A Synthetic Aperture Radar (SAR) satellite in VLEO.
- **Vignette 3:** An EO constellation with EO and SAR payloads in VLEO.

For each vignette, a notional design of an ABEP satellite and Xenon satellite were developed and compared. The metrics of system power, mass, revisit rate, physical size, and launch requirements were determined. These metrics, in turn helped to define system complexities, risk and feasibility for each configuration.

In Section II, we compare the lifetime and launch mass of VLEO satellites using traditional and air-breathing electric propulsion. In Section III, we analyze vignette 1 and 2 to demonstrate the value of VLEO flight. In Section IV, we show constellation level considerations for VLEO flight as compared to LEO flight. And in Section V, we discuss these results and the implications for future VLEO developments.

II. Air-Breathing vs. Xenon Satellite Operation in VLEO

If our first study, we analyzed the differences between two systems with equivalent payload and launch mass, one equipped with a traditional Xenon tank and another with our ABEP system. We assumed

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these satellites would require approximately 100kg of mass for the non-propulsion related subsystems and payloads. By fixing the mass of the Xenon equipped satellite to be equiavlanet to the ABEP one, we essentially determined the propellant mass that a Xenon-satellite could resonably be fueled with, and then determine it's maximum life (as compared with the 'unlimited' lifetime of an ABEP system). This calculation was done by first assuming the performance capabilities of a Xenon-based and Air-Breathing base propulsion system (as shown in Table 1). And the sizing for the ABEP systems were derived from power and momentum equations to ensure that the system could indefinitely sustain orbit.[4] The total mass of both the ABEP satellite and the Xenon satellite are calculated self-consistently, taking into account the solar panel mass required, propulsion system mass required, batteries, and propellant tank sizing, and the Xenon satellite was allowed to bring an amount of propellant such that its launch mass was equivalent to the ABEP satellite's launch mass. Finally, the lifetime calculation for the Xenon satellite was performed for varying alittudes by assuming the propellant supply was used to offset drag due to an orbit averaged density calculated at each altitude from NRL's MSISE00 model.

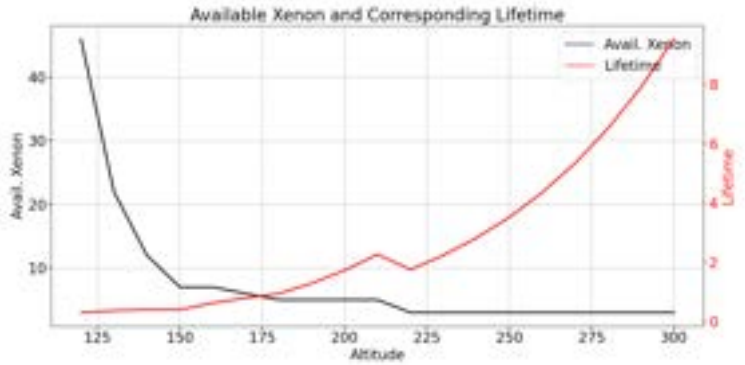


Figure 1: Lifetime and xenon mass requirement for a satellite with Xenon-based propulsion as a function of orbital altitude. The satellite mass was fixed to the mass of an equivalent ABEP system.

Figure 1 shows propellant requirement and lifetime for a satellite with conventional (Xenon) electric propulsion at various orbital altitudes. The mass of the satellite was fixed to match an equivalent satellite with an ABEP propulsion system. Xenon mass and propulsion system sizing can grow rapidly below 200 km, leading to significant design considerations to SWaP.

Subsystem	Mass (kg)	Power (W)	Area (m^2)
Batteries	2	-	-
Solar Array	6	-	3
Thruster	-	153	-
Propellant Tank (Xenon Sat)	3	-	-
ABEP Scoop	5	100	
Xenon Gas	5	-	-
Rest of SV	100	100	0.0628
Total	113	221	0.0628

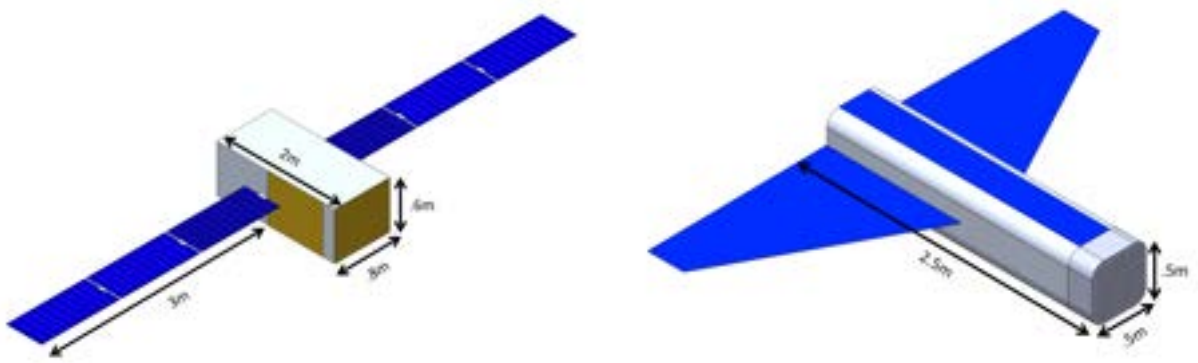
Table 1: MEL/PEL for an equivalent Xenon satellite at 200km altitude (1.75 year lifetime). A 5 year Xenon satellite would need to carry an extra 10kg of Xenon gas to survive

Assuming ABEP lifetimes of between 5-10 years, this study shows that an ABEP equipped system would outperform traditional forms of EP at VLEO altitudes (100-300km), but that they would have little benefit above this altitude range. For similarly sized Xenon and ABEP satellites, Xenon will need to carry signficantly more propellant (and therefore weight signficantly more at launch) to get to a comparable

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lifetime of 5 years. While the power requirements and therefore EPS mass requirements for both ABEP and Xenon systems grow rapidly below 200km, the propellant mass requirements for a Xenon-based system grows signficantly at these low altitudes in order to get any reasonable satellite lifetime.

Our first comparison was of two satellites with equivalent mass; we can also examine ABEP vs Xenon EP by comparing hypothetical spacecraft with equivalent mission life. Many commercial companies are currently looking to develop cheap satellites that can produce 10 cm resolution imagery at large scale. We investigated an two theoreticaly satellites equipped with ABEP and Xenon EP designed to provide this level of resolution from 200 km. To do this, we selected the L3 Harris SpaceView 50 payload for both a traditional Xenon powered and ABEP powered craft. Finally, we sized the Xenon EP craft to have sufficient propellant to reach a 5-year lifetime, which is the minimum projected life for an ABEP system.



(a) VLEO Xenon Equipped Satellite

(b) VLEO ABEP Equipped Satellite

Figure 2: Comparison between two designs for a VLEO earth observation mission, one for Xenon (a) and one for ABEP (b)

Figures 2a and 2b illustrates the geometry differences between the traditional Xenon powered satellite and the ABEP equipped craft. The Xenon powered satellite consists of a 2m long main body where a majority of the volume (about half) is taken up by a significantly large propellant tank. In this satellite the Xenon tank to holds 100 kg of propellant that is required to maintain an 200km orbit. This contributes signficantly to its larger cross-sectional area. The ABEP satellite is optimized for its drag area with the solar panels pushed more aft to provide a stable and power positive platform. Both satellites contain all required subsystems to perform the mission and the L3 Harris payload to provide the 10 cm resolution. Due to the size of the Xenon tank, the minimum drag area for the standard satellite is .5 m while the ABEP craft cross-section is only .18 m. The ABEP cross-section is primarily driven by the amount of scoops required and the payload configuration. Additionally, the ABEP craft will require a larger solar array area to compensate for the lower efficient of running a plasma thruster on atmosphere.

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Parameter	Xenon	ABEP
Volume (m^3)	.63	.4
Weight (kg)	379	203
Power (W)	600	800
Battery (Whr)	200	400
Launch Fuel (kg)	100	N/A
Drag CS (m^2)	0.5	0.18
Lifetime (Years)	5	10
Launch Cost ($M)	$1.1	$.6
Total Cost ($M)	$37	$21

Table 2: Size, weight, power, and cost of the Xenon and ABEP 10cm resolution EO satellites. ABEP is capable of lasting twice as long with signigcantly less cost.

Table 2 below summarizes the differences between the systems. The Xenon system is signficantly more massive thant the ABEP, but requires less power. This contrasts with the ABEP system, which is less massive and more power hungry. Another important note is that the ABEP system is smaller in terms of volume and cross-section, while maintaining its capability. For this analysis we leveraged cost models from *Space Mission Engineering: The New SMAD*, a common space mission analysis reference and tool. To calculate the total costs of the hypothetical systems, SMAD has several cost models that approximate the costs from the subsytem masses. Each model uses the masses and system level requirements to project total costs and complexity of the the larger system of systems. The most common models are the Small Satellite Cost Model (SSCM) and the Unmanned Spacecraft Cost Model (USCM), often paired with the NASA Instrument Cost Model (NICM) for complex or exquisite payloads. The SSCM was used in this comparison. As we can see from the Table, the ABEP craft is cheaper to build and launch while being better suited for the VLEO environment.

III. Comparison of Payloads in VLEO vs LEO

With established altitude range where ABEP has benefits over a conventional propulsion technology, we now investigate the payload benefits for flying in VLEO versus LEO. By performing parametric analysis of ABEP equipped VLEO EO platforms we answer two key questions:

- What are the advantages (sensitivity, resolution, noise-equivalent temperature difference, EO noise irradiance, modulation transfer function etc.) for lowering a satellite orbit for optical and SAR payloads?
- What is the primary size, weight, cost, power, and complexity considerations for a VLEO satellite compared to a traditional LEO satellite?

To answer these questions, we developed a simulation tool that can conduct orbital and system analysis to calculate instantaneous and orbit-averaged power and attitude. The simulation tool can also perform system sizing. The following analysis uses this tool for comparing the ABEP and a traditional Xenon propulsion systems.

Finally, we used SME SMAD's SSCM and USCM cost modeling algorithims[5] to calculate the approximate costs of our ABEP systems, and then compared these to published values or calculated values of the current state-of-the-art systems for each vignette.

A. Vignette 1: Passive earth observation ABEP equipped satellite in VLEO

For passive optical systems, low-cost panchromatic and multispectral optical imaging platforms will benefit from lower altitude flight as the spatial resolution and SNR can be improved or smaller diameter optical

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apertures utilized, thus reducing mass and integration requirements. These improvements, however, come at the cost of lower observation swaths.

To understand these tradeoffs, we investigated an ABEP equipped satellite flying in VLEO at 200 km and carrying a 0.4 m aperture optical payload capable of 30 cm ground resolution. We compared this satellite concept to the existing state of the art for LEO EO spacecraft. In this case, MAXAR's WorldView-4[6] and WorldView Legion satellites[7] . Both these systems have an advertised 30 cm resolution, at their respective altitudes as governed by Equation (1).

$$Res_{GND} = Range * (\lambda / D) \tag{1}$$

Parameter	WorldView-4	WorldView Legion 1-6	ABEP
Orbit (km)	600	450	200
Aperture (m)	1.1	1	0.4
Volume (m^3)	10	5	.125
Weight (kg)	2600	750	110
Power (W)	3100	2000	800
Lifetime (Years)	12	10	10
Launch	Dedicated Atlas V	Dedicated F9	ESPA Class
Cost per Satellite ($M)	$435	$108	$4.3

Table 3: Direct comparison between MAXAR's systems and Viridian's ABEP system.

Table 3 illustrates the MAXAR systems, and their direct comparison to an ABEP system. Cost calculations were made by referencing availbe size, weight and power information for each system, then inputting those into SMADs SSCM and UCSM[5] cost modling algorithims. Launch costs were approximated for all, and the Legion satellites where broken up into a single satellite cost. If there were published values for cost, those were used instead.[6,7] From this table, we see that an ABEP system has a significantly smaller volume due to the smaller telescope requirements, and therefore it is cheaper to build and launch while maintaining the exact same resolution capability. However there is some obvious trade offs, such as the lower altitude and its VLEO environment and coverage issues, in addition to the complexities of ABEP propulsion. To achieve similar coverage, the VLEO satellite would likely require 9x the number of satellites compared to WorldView-4 at 600km, and 5x the number of satellites compared to Legion at 450km. We will explore more precisely how many more satellites will be needed when operating from VLEO in our constellation level analysis in Section IV. However, for the calculations in Table 3, we have assumed the ABEP constellation is of 30 satellites, compared to WorldView Leigion's 6 satellite constellation.

From this study, it is clear that ABEP equipped satellites can be significantly more appealing than the state of the art LEO EO satellites. That appeal is due to a significantly cheaper price but also because of the robustness of the constellation to a single-satellite failure. However, in addition to the need to create viable ABEP systems to achieve these benefits, we also need to understand the differences in CONOPs for an ABEP satellite constellation, as these may ultimately influence the systems size, weight and power.

B. Vignette 2: Active earth observation satellite in VLEO

While optical and other passive payloads can see signficant improvements by flying in VLEO, active payloads can potentially see even larger improvements from lower flight. We investigated active RF payloads with a similar methodology to the passive EO analysis above. Synthetic Aperture Radar (SAR) requires unique considerations that are going to be determined by the system power tradeoffs at VLEO and LEO.

There are a few different imaging modes for SAR platforms. Viridian considered two such modes, strip-map and spotlight. The below figure illustrates broadly what strip-map imaging modes look like.

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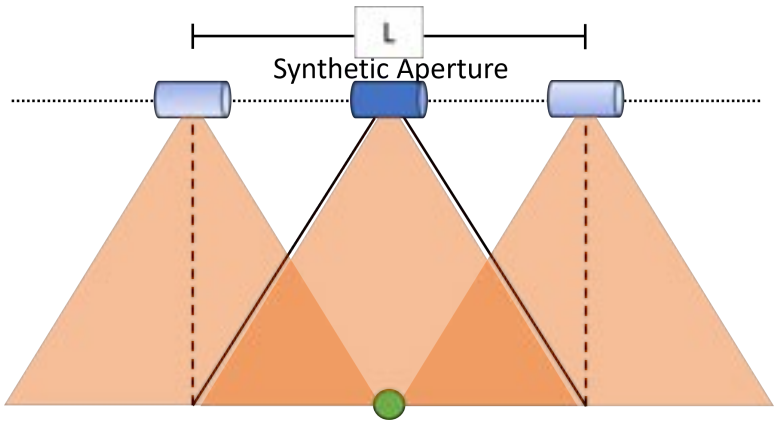


Figure 3: Stripmap modes on SAR radars illuminate a swath of ground via a staccato of choerent microwave pulses, the antennta measures the echos as it passes in typical broadside configuration.

From the above figure, Strip-map mode pulses are sent out at a constant rate, usually broadside to the flight direction. Wider beams are produced by smaller antennas mean longer apertures and better azimuth resolution.

Spotlight from SAR varies the boresight in the azimuth direction to illuminate a fixed ground location. This increases the synthetic aperture length and offers excellent azimuth resolution, at the cost of ground coverage. Some current commercial SARs can illuminate a spot for 10 seconds, given a velocity of 7.5km/s, this yields an aperture of 75km. The figure below shows what Spotlight modes typically look like.

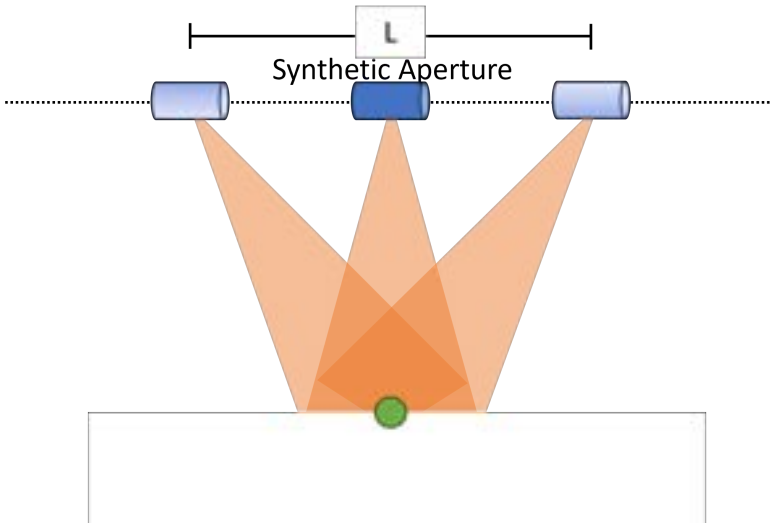


Figure 4: Spotlight modes illuminate a single point with microwave pulses. The longer you can stare at an object, the higher resolution the image is.

SAR azimuth resolution is based off the wavelength of the waves and the change (delta) of the integration angle while the ground location is being imaged. Resolution improves when the wavelength is small, and the angle is large as seen in Equation (2). Range Resolution is based off the chirped pulse bandwidth, and is entirely based off on how much bandwidth we impart to said pulses as seen in Equation (3).

$$Res_{AZ} = \lambda/(2 * \delta\theta) \tag{2}$$

$$Res_R = c/(2 * B) \tag{3}$$

Note both resoluations are agnostic to the distance (range) to the target. However, range impacts other aspects of SAR design such as signal strength. As range increases, there is a loss of power in the pulse as

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it travels from the antenna to the ground and back to its source. At this point weak signals must compete with noise. Overcoming weak signals impacts design considerations such as antenna size, pulse repetition frequency, resolution, radar band, and swath width.

Two equations govern the received power and noise considerations in SAR systems.

$$P_{Rec} = [P_T A_L^2 A_W^2 RCS / 4\pi\lambda^2 R^4] \tag{4}$$

$$NESZ = [8\pi\lambda R^3 V (kT_o F_N) / P_{Avg} A_L^2 A_W^2 Res_r] \tag{5}$$

NESZ indicates how weak the reflection of a resolution cell can be before its signal equals the noise magnitude. To ensure low NESZ values, we would like a combination of short wavelength, short range, more power, and large antenna. Higher bandwidth signals increase the noise floor and increase the NESZ value. Improvements to range resolution must be balanced by improvements to other parameters. NESZ is levied as an engineering requirement on SAR systems. For common space-borne X-Band, it is usually required to be -20dB or lower. Clearly for spacecraft, the best choices are increased power, larger antennas, high-quality transceivers, and lower orbits. Typically, the best arrangement is to image broadside between 30 to 50 degrees incidence angle

The SAR Quality Score (SQS) Equation is another key performance paramater, and it is based off the mathematical foundation established by Claude Shannon.[8] Shannon realized that the maximum speed of information that can be transmitted via some channel is dependent on bandwidth, strength, and noise in the system. He called this channel capacity. We can apply this to SAR by replacing bandwidth with our azimuth and range resolution figures, getting the information into units of bits per square meter. SQS is the core single-value statement of operational SAR image quality.[8]

SAR design requires more compromises than passive EO systems; it is not possible to construct a one-size-fits-all approach to SAR payload design and CONOPs. These considerations forced us to make more design trade-offs when trying to compare similar performing systems. Table 4 lists sensor and illumination parameters and shows what is needed to improve the quality parameters on the top row.

- e.g., a short antenna improves strip-map resolution, but longer ones improve signal power and noise.
- e.g., High PRF minimizes ambiguities and increases average signal power, but low PRF allows for wider swaths

Parameter	Azimuth Resolution	Range Resolution	Azimuth Ambiguities	Range Ambiguities	Swath Width	Signal Power	NESZ
Antenna Length	Short	-	-	-	-	Long	Long
Antenna Width	-	-	-	-	Narrow	Wide	Wide
Incidence Angle	-	Shallow	-	Steep	Shallow	Steep	-
Wavelength	Short	-	-	-	Long	Short	Short
Pulse Length	-	-	-	Short	-	Long	Long
Pulse Frequency	-	-	High	Low	Low	High	-
Range Bandwidth	-	High	-	-	-	-	High

Table 4: Tradeoffs between a desired effect, and what parameter optimizes that effect. For example, if you want to maximize Azimuth Resolution, you would want a short antenna and a shorter wavelength.

SAR platforms seem well suited to operate in VLEO as they use rectangular and elongated antennas that need to be oriented in the along-track direction. This is ideal for VLEO, as this type of configurations already exhibits low drag (due to their low cross-section area). Therefore, adapting SAR platforms to operate in VLEO may be simpler overall than adapting platforms with optical instruments (which have elongated optical systems that need to be pointed towards nadir). The SAR antenna is one of the design drivers of SAR platforms and its minimum area is driven by the constraints imposed by the minimum and maximum pulse repetition frequency to produce desired results. When all the other parameters are maintained constant (operating frequency and signal incidence angle), lowering the operational altitude directly reduces the minimum antenna area that complies with the pulse repetition frequency constraints. The power requirements and cross track resolution can also be improved if the operational altitude is lowered. If the antenna

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dimensions are maintained constant, the power required to achieve a certain cross track resolution can be lowered, or if the power is maintained, the resolution can be increased. Also, if the power and resolution are maintained constant, the antenna area can be reduced. Having a smaller antenna and a lower power requirement can lead to smaller, lighter and hence lower cost platforms. While VLEO flight can generate many of these improvements for SAR, it faces two key challenges: increased drag (even with favorable antenna configurations) and reduction of the communication windows. Therefore, drag compensating propulsion may be required, as well as extra ground stations.

From these basic principles and derived figures of merit, we can build out our comparison. To that end, we studied the ESA's Sentinel-1 for a capability comparison for the state of the art.[9] Sentinel-1 is a C-Band SAR platform, flying in a 700km sun-synchrnous orbit that weighs about 2300kg, including 130kg of propellant. Sentinel-1's peak power is 4.3kW, paired with a NESZ of -22db. These SWaP metrics will be important for comparison to our eventual ABEP design.

Sentinel-1 also operates in four different modes, but we will focus on Strip-Map Scan for simplicity of the previously discussed principles. In Strip Mode, the radar covers a ground swath of 80 kilometers providing imagery at a ground range resolution of 5 meters and an azimuth resolution of 5 meters. The radar operates at incidence angles of 20 to 47 degrees, with 25 minutes per orbit of operation generating 90 Gbytes of data per orbit.

Our ABEP system and mission requirements for a VLEO SAR platform will be derived assuming a 250 km sun-synchrnous orbit. Our system will also be designed to have identical Strip-Map resolution to Sentinel-1, 5m in ground and azimuth resolution, and as close as possible to 80km swath size, and we will assume a similar C-band antenna configuration. Finally, in order to conform to VLEO geometry constrainsts, the scoop face must always be RAM facing. The below equations are also used to help bound our design.

$$SQS = (1/Res_{AZ})(1/Res_{GR})log_2(1 + 1/N) \tag{6}$$

$$Min_{Width} = \lambda R/(Swath * cos(\phi)) \tag{7}$$

$$Min_{Area} = ((4V\lambda R)/c)tan(\phi) \tag{8}$$

$$[(2V)/AntennaLength] < PRF < [c/(2 * Swath * cos\phi)] \tag{9}$$

Figure 5 shows an ABEP design to operate a C-Band SAR antenna in VLEO. This concept vehicle has a total mass of 430kg, with 5 square meters of solar array. The C-Band antenna is 4 meters in length and .5 meters wide, and it approximatlye 30% of the vehicle mass.

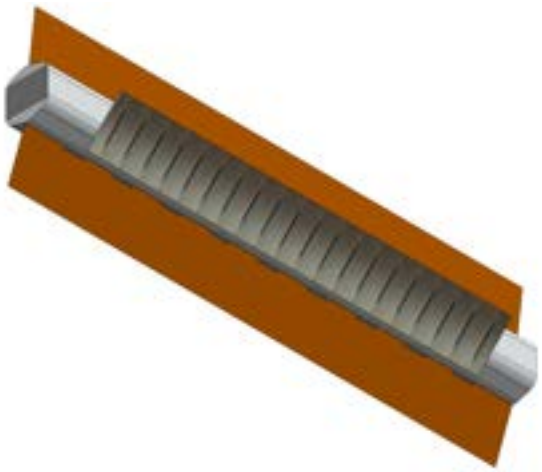


Figure 5: Isometric view of an ABEP SAR concept, note the C-Band antenna at a 45 degree off angle with solar cells pointing opposite to ensure power generation.

Based on our concept ABEP SAR vehicle, Table 5 summarizes the difference betwwen Sentinel-1 and the ABEP design. We see that ABEP requires less total mass and volume, due to a smaller antenna, and

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it requires less orbit average power due to being able to close the SAR system with 4-5x less peak power required to operate the payload. However, as compared to Sentinel-1, the ABEP satellite loses swath width, due to being lower in altitude and having more stringent pulse frequency requirements. Finally, as shown from the SMAD cost model,[5] ABEP costs significantly less than Sentiniel-1 as a function of the lower mass and power requirements, all for the same capability.

Parameter	ABEP	Sentinel-1
Total Mass (kg)	430	2300
Orbit Average Power (W)	450	1700
Antenna Length (m)	4	12
Antenna Width (m)	.5	1
Swath (km)	40	80
Altitude (km)	250	700
Cost (M)	100	375

Table 5: Size, weight, power and cost comparison between ABEP SAR and Sentinel-1. ABEP outperforms and is significantly cheaper for equisite imaging capabiltites.

For performance comparison, Table 6 compares derived figures of merit. The ABEP satellite reaches the recommended NESZ of -22dB, however, Sentinel-1 performs better than recommended. This is primarily because the average power to the antenna in ABEP is much lower. If the ABEP satellite were to supply similar power it could achieve a similar NESZ. However, the ABEP satellite reaches a $\tilde{3}$x better SAR Quality Score, driven primarily by the improved azimuth resolution for both the spotlight and stripmap modes. Unlike the optical comparison in Vignette 1, we only compared the cost of single SAR platforms in this study. However, the coverage the change in coverage statistics will be explored for both optical and SAR in Section IV below.

Parameter	ABEP Stripmap	Sentinel Stripmap	ABEP Spotlight	Sentinel Spotlight
Min. Antenna Width (m)	0.66	0.93	0.66	0.93
Min. Antenna Area (m^2)	1.94	5.25	1.94	5.25
Designed Area (m^2)	2	12.3	2	12.3
Peak Power (W)	1000	4000	1000	4000
Azimuth Resolution (m)	2	6.15	0.12	0.35
Range Resolution (m)	1.50	1.50	1.50	1.50
NESZ (dB)	-24.42	-33.46	-24.42	-33.46
SQS (b/m^2)	1.63	0.54	26.94	9.56

Table 6: Performance comparison of ABEP and Sentinel-1, between different image modes. ABEP outperforms due to being in VLEO. ABEPS SNR is 10dB better and gives 3x-4x better image quailty, with smaller more power effeicent antennas.

IV. VLEO Constellation Coverage Analysis

This study aimed to assess the coverage performance of constellation architectures operating in VLEO. The primary objective was to determine the feasibility of constellation configurations by evaluating the trade space between the number of spacecraft, constellation planes, revisit rates, and coverage achieved by comparing constellation operations at 500 km vs 200 km.

The study was performed using the Mission Unified Space Engine (MUSE) platform developed by Con-

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tinuum Space Systems (Continuum). MUSE is a novel, cloud-based, interactive and collaborative design tool suite that provides high-fidelity simulations for the preliminary design, optimization analysis, deployment and operations of arbitrarily large constellations of satellites around the Earth or any other planetary body in our solar system. MUSE provides spacecraft performance analysis throughout the entire mission development and lifecycle. MUSE is focused on the challenges that are associated with large constellations of spacecraft.

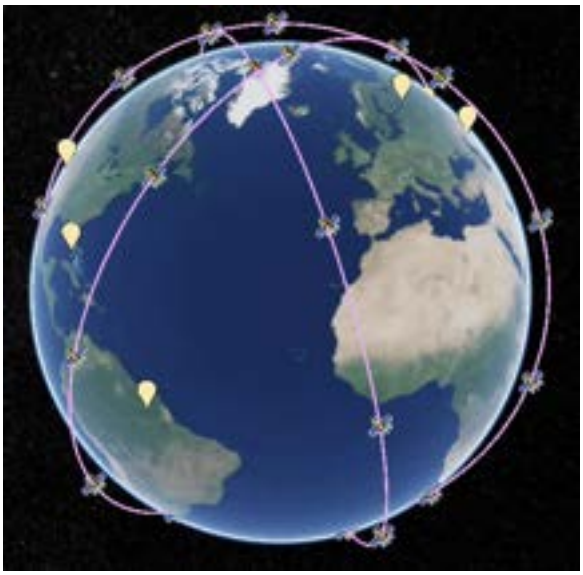


Figure 6: Rendering of the constellation, a clear Walker-Delta pattern can be observed with the desired targets identifed.

The tool is coded with a high-performance technical language and also leverages NASA tools such as SPICE and GMAT. MUSE's scope encompasses all mission phases from orbital deployment to end-of-life deorbit, including trajectory and maneuver design capabilities for these specific phases. Throughout the life of the space assets, all spacecraft activities from power generation, data collection, data transfer are modeled, designed, and optimized to high levels of fidelity. MUSE's trade analysis capabilities were utilized in the study to generate, record and output the desired statistics along with comparative graphics for conducting assessments.

The constellation was modeled as a Walker Delta configuration with J2 perturbations, and the spacecraft attitude was constrained to fixed nadir pointing. A trade space was set up by varying the number of spacecraft, planes, orbital altitude range, and inclinations. The study considered a variety of orbit inclinations for comparison including 55° and Sun Synchronous orbits (SSO).

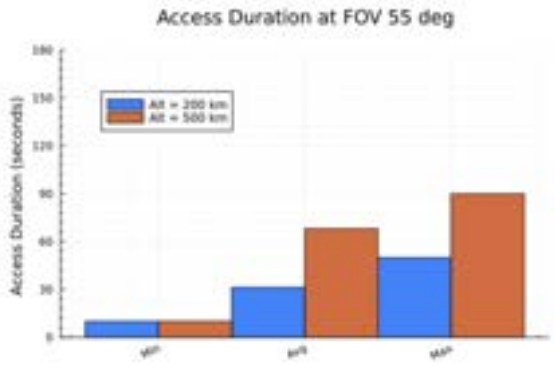


Figure 7: Access times of the two constellations with a 55 degree FOV. The higher altitude had more access time.

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For coverage statsitics, we analyzed a series of 12 'targets' scatterd non-uniformly around the globe. The areas they covered ranged from common space centers and launch centers around the world, including the United States, China, and Russia. A coverage trade analysis was then performed to obtain the revisit rates and coverage statistics for each configuration and determine the most feasible altitude and configuration combinations to achieve complete coverage of the desired targets. The trade study was performed for both LEO at 500 km and VLEO at 200 km to highlight the impact on coverage performance in VLEO. This trade space was assessed by considering two different observational payloads with different fields of view (FOV). It was observed that a trade-off between altitude and sensor would be necessary to meet coverage requirements in VLEO by using a sensor with larger FOV to overcome limitations of coverage in VLEO.

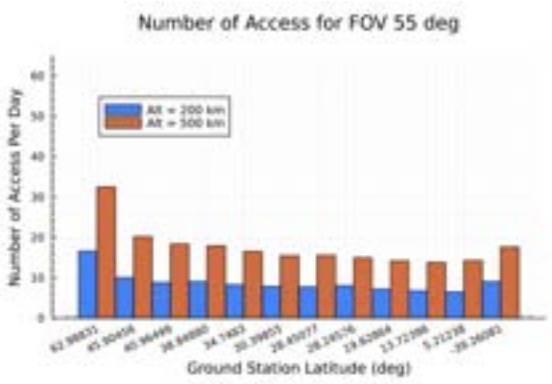


Figure 8: Number of accesses of the two constellations with a 55 degree FOV. The higher altitude had more access across the board.

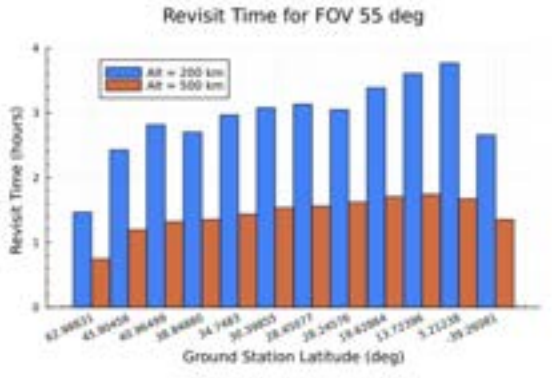


Figure 9: Revisit times of the two constellations with a 55 degree FOV. The lower altitude had more longer revisit times.

When comparing the 200km orbit to the 500km orbit, the 200km constellation got 50% less coverage when flying the same number of satellites. Therefore, while VLEO might have cheaper satellites (as show in previous sections) would also need more satellites to get similar coverage. The exact total cost of the similar constellations is then hard to calculate. However, we have assumed in the optical analysis in Section III that the total coverage loss (and required additional satellites) scales inversely with altitude squared. But a VLEO constellation still has advantages, such as more robustness since it's more distributed, enables higher data rates, lower latency communication. It was also established that a separate constellation optimization study will likely be warranted to determine an optimal VLEO configuration for each specific mission configuration. The findings emphasize the importance of considering the trade space between constellation parameters, orbital altitude, and sensor characteristics when designing constellations for VLEO operations.

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V. Conclusion

Many groups have explored Air Breathing Electric Propulsion concepts as a way to achieve unlimited propellant operations in VLEO. In this study, we demonstrated that ABEP systems can be superior to traditional xenon satellites at LEO in terms of the payload performance and cost. This is primarily due to the fact that and ABEP system can take advantage of sustained flight at lower altitudes.

In our vignette on optical passive payloads, we showed that a much smaller satellite could achieve similar capabilities by flying in VLEO with an ABEP system. In our vignette on active SAR payloads, we showed that a 4x improvement in SNR for the spotlight and stripmap modes can likely be achieved by flying in VLEO. This means that we can use less SWaP hungry equipment to get similar capability, or use the same payloads to achieve significantly better capability.

In our constellation-level study, a coverage trade analysis was then performed to obtain the revisit rates and coverage statistics for each configuration and determine the most feasible altitude and configuration combinations to achieve complete coverage of the desired targets. A follow-on study compared the performance of the same configuration in LEO at 500 km, highlighting the impact on coverage performance in VLEO. A new trade space was assessed by considering two different observational payloads with different fields of view (FOV) for the follow-on study. It was observed that a trade-off between altitude and sensor would be necessary to meet coverage requirements in VLEO by using a sensor with larger FOV to overcome limitations of coverage in VLEO. Our findings emphasized the importance of considering the trade space between constellation parameters, orbital altitude, and sensor characteristics when designing constellations for VLEO operations.

Acknowledgments

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