Building a Global Launch Network: Extending the Reach of Dedicated Small Satellite Launch Using New, Data-Driven Spaceport Assessment Tools

John Fuller, Ren Liao, Kirit Patel, Sirisha Bandla, Monica Jan
Virgin Orbit
4022 E Conant Street, Long Beach, CA 90808, United States
info@virginorbit.com

Wade McElroy, Mandy Vaughn
VOX Space
840 Apollo St, Suite 100, El Segundo, CA 90245, United States
info@voxspace.com

ABSTRACT

The proliferation and sustained growth of small satellite architecture solutions, once an uncertain aspect of tomorrow's space industry, are now largely perceived as a firm reality. Recent trends continue to show an increasing fraction of launch industry revenue being captured by small and dedicated launch vehicles, such as Virgin Orbit's LauncherOne. Concurrently, another indicator of small satellite proliferation are recent announcements of increased rideshare opportunities by large launch vehicle operators. As numerous dedicated and rideshare launches emerge as solutions for small satellite customers, understanding the relative advantages and performance of these vehicles will be crucial to satisfy not only single launch, but broader architectural mission needs.

Virgin Orbit and VOX Space have presented how a responsive air-launched architecture with multiple hosting spaceports and modularized systems at each can be leveraged to launch entire constellations within days. We have since continued to grow our spaceport network to support domestic and international mission planners that desire a launch vehicle that isn't constrained to a permanent fixed site or departure corridor. Building upon that work, new analytical methods to analyze and communicate the advantages of air-launch from spaceports around the globe have been devised. Specifically we will quantitatively show how commercial and national security missions, especially in an era that require hybrid architectures, are improved with a geographically flexible and distributed launch capability. Tens of thousands of launches from unique sites are simulated to support various mission types. The result is an explicit evaluation of how the flexibility, ease-of-access, and unconstrained orbital inclination ranges of a global launch network can support hybrid system needs in ways that no other comparable launch system can, dedicated or otherwise.

INTRODUCTION

The state-of-the-art in the space industry has advanced incredibly in the past decade. Achievements once thought to be impossible are now commonplace, such as the autonomous Entry, Descent, and Landing (ED&L) of the Mars Curiosity rover or the open sea barge-landings and subsequent refurbishment of boost stages of the Falcon 9 launch vehicle. World-changing LEO satellite constellations of thousands of satellites are commonly conceived with viable manufacturing and launch infrastructure to support them. Satellite servicing spacecraft have been successfully devised and implemented to interface with older spacecraft in geostationary orbit to extend their service lifetimes[1]. However simultaneously and in many ways, the industry has not changed. Missions still rely on launch vehicle technology first conceived over half a century ago, and originate from the same launch ranges from the Cold War era. They fly along fixed range safety corridors and regulatory environments devised in decades past, and have perhaps seen even more constraints due to growth in population densities as well as air, sea, and space traffic since that time. Mission timelines are measured in years from contract signing to launch, rather than months.

Virgin Orbit is working to change these last stubborn aspects of launching payloads to space. Recent trends suggest that an increasing fraction of launch industry revenue is being captured by less expensive and innovative launch vehicles,[2,3] such as Virgin Orbit's LauncherOne. As dedicated launchers continue to emerge as solutions for small satellites, understanding the relative performance capabilities of these vehicles will be crucial to industry development. Released LauncherOne studies have shown how a responsive air-launched architecture with multiple hosting spaceports and modularized systems at each can be leveraged to launch entire constellations within days[4]. Subsequently and following extensive dialogue with customer and spaceport communities around the globe, it was deemed advantageous to further and decisively quantify the advantages of air-launch. Communicating the LauncherOne value proposition for all mission stakeholders became the driving force behind creation of a high-fidelity spaceport assessment tool suite.

The most important feature of any dedicated launch vehicle is the ability to provide a specific orbital injection required by a customer on their terms and schedule. Any features that add flexibility to this scenario further aid the value of dedicated launch, and starkly highlight the drawbacks of rideshare arrangements on bigger vehicles. With this in mind, numerically illustrating the capability of LauncherOne to reach more orbits with a greater degree of availability than any other launch system is the mission statement of this tool suite. The suite introduced here is used to quickly establish the viability of safe and flexible operations of the LauncherOne system at any spaceport around the world by way of:

1. Parametric evaluation of tens of thousands of air-launch trajectories to a wide swath of orbital inclinations as a function of aircraft range
2. Characterization of safe range safety corridors using high-fidelity population overflight results and casualty expectation methodologies based on FAA evaluation methodologies
3. Preliminary telemetry coverage analysis with respect to ranked release sites and corridors

The tool capabilities will be detailed, followed by briefings of analyses at six spaceports: Mojave Air & Spaceport, Andersen Air Force Base (AFB) in Guam, the Launch and Landing Facility at Kennedy Space Center (KSC), Spaceport Cornwall in the U.K., Oita Airport in Japan, and Alcântara Launch Center in Brazil. The results detail the extent of LauncherOne orbital access and window availability achievable for each of the sites and are compared against those of fixed-site counterparts. The conclusion is that air-launch definitively and reliably increases the inclination and launch availability of any region considered. Inclination access is increased by simply expanding the catalog of available launch solutions that avoid downrange population overflight. Launch assurance is increased due to the ability to select one of many launch sites to avoid unanticipated launch restrictions such as weather, space conjunction avoidance, or air/maritime traffic infringement. Further, twice-daily departure azimuths to both the north and south injections are a possibility with air-launch, as opposed to once-daily opportunities that generally characterize a fixed launch site.

This paper outlines Virgin Orbit's role in furthering the ongoing small satellite revolution, with particular emphasis on the role of orbital access and launch availability as critical metrics by which launch vehicle performance can be assessed. Here a distributed launch architecture with multiple geographic launch sites and modularized systems at each is proposed as a candidate launch system that can be used to reach inclination ranges and availability that far surpass existing envelopes. The extensive internal toolset developed for determining the tangible value of air-launch to satellite system planners will be described, alongside the results it produces. The resulting advantages offered by a mobile, air-launched small satellite launch vehicle as opposed to a ground-launched vehicle from fixed site are numerically identified. We conclude by discussing how these assessments can serve as the foundation for future work in dedicated small launch strategies.

STATE OF THE SMALLSAT INDUSTRY

The rise of the small satellites have excited investors around the world by creating a new space startup race with unprecedented amount of private capital invested in the last decade. In 2019, 135 startup space ventures received investment, a 34% increase over 2018, the previous record. In total, start-up space ventures attracted $5.7 billion in financing of all types during 2019, shattering the $3.5 billion record set the previous year[5]. The crowded landscape of this new space ecosystem created a necessity for new entrants to establish differentiation through technological advancement, disruptive cost models, or unique space mission designs.

Broadly speaking, the benefits of smallsats have driven interest in agile spacecraft that are often leveraged as part of distributed missions including multiple spacecraft or as technology demonstration missions that support rapid maturation of space-based instruments[6]. As necessity for differentiated smallsat mission architectures grows, the needs for agile and responsive launch systems capable to reach unique orbits are similarly increasing. There is widespread acknowledgement of the bottleneck in small satellite launch opportunities,[3,7] and in some cases, even if launch slots are available, launch systems may not provide tailored smallsat mission support. For unique orbits, it is extremely challenging to find rideshare opportunities. Simply put, there are an insufficient number of dedicated launch opportunities for unique space missions and this limitation is restricting technical and financial growth in both sectors.[6]

Looking ahead, 2020 is shaping up as an important year to continue the maturation of the space start-up ecosystem. Investors look to see continued progress in deploying constellations and new technologies from high profile start-ups. The U.S. Government (USG) continues to be an important source of revenue for startup space companies, as seen through efforts like the Air Force Space Pitch Day to support non-traditional contractors supporting government needs. At a larger scale, transition to distributed proliferated architectures can be found in the growing support of programs like DARPA Blackjack and the Space Development Agency (SDA) mission layers approach. International governments are recognizing the importance to be part of this global space race to maintain competitive advantage in developing skilled labor force, technological advancements, and sovereign defense capabilities for their nations. Indications are that this trend, which accelerated in 2019, will continue in 2020 and beyond.

Space investment growth in the last decade suggests that both smallsats and launch capabilities have been critical to overall space industry development. Beginning in 2012, the prevalence of small satellites rose dramatically. Some 1,300 smallsat missions were launched between 2012 and 2018, and approximately half of these spacecraft were designed to provide commercial services.[8] The small satellite launch industry has similarly expanded in recent years, and the small satellite launch rate has risen by 250% since 2016.[8] Both private investors and governments realized that a localized end-to-end space value chain provides the best opportunities to capture value for their stakeholders through financial returns, job creation, academia-industry alignment, workforce development, and defense capability.

Changing Paradigm of Launch Sites

Given the high barrier to entry on new launch vehicle development both in time and capital, a new spaceport race has formed in recent years. Countries without domestic launch capability are setting up spaceports working with launch partners to complete their local space value chain and to maintain their competitive position in this new space race. Spaceports are now viewed as important regional economic development activity as well as a key component of national defense strategy.

Historically, the vast majority of launch service providers have leveraged ground-based launch systems [9] which require substantial infrastructure investment, both in terms of the permanent ground support equipment that is constructed at each launch location and with respect to the policy elements that must be in place to license and support active launch sites. Considered as a launch manifesting optimization problem, the location of the launch site serves as a constraint on the set of orbits that can be reached. Performance of the launch vehicle, in that sense, can be seen as an emergent property of the system that includes the launch site and launch vehicle pairing. Therefore, a launch system capable of fully transporting their launch site to any location has more control over the location variable and the emergent performance, offering a greater set of possible orbits for the same launch vehicle.

The changing needs of space missions, demanding more flexible launch schedules and unique orbits, provide an excellent opportunity to demonstrate and assess the advantage of air-launched systems. As launch supply rise to meet demand in the coming years, smallsat customers may shift their focus from finding available launches to looking for a smoother launch process. By launching from a domestic spaceport, satellite and mission providers can expect simpler logistics in transportation and cross border regulatory process that results in cost saving in their total mission cost.

Launch sites which can be more geographically dispersed offer opportunities for non-traditional launch sites and access to more azimuths.[10] Virgin Orbit's broader strategic architecture includes key regional spaceport hubs positioned around the U.S. and world that will provide not only regional launch access (e.g. Mojave, Guam, Florida) and international spaceport access (e.g. Oita Spaceport in Japan and Spaceport Cornwall in the United Kingdom) but also help implement the infrastructure required for resilient launch capabilities. In addition, Virgin Orbit and its government focused subsidiary VOX Space are working closely with the USG to accommodate air-launch from allied spaceports around the world. Launch diversity and responsiveness, particularly via air-launch systems, will enhance USG and allied partners' abilities to meet increasingly urgent operational needs. Launch site diversity also enhances assured access by providing alternative means should traditional fixed US launch sites be jeopardized. Ultimately a global network of spaceports will provide the operational capabilities to accommodate a resilient responsive launch competency.

TERMINOLOGY AND SCOPE

Terminology

The following common terminology is used in the setup, analysis, and discussion of results for the spaceport feasibility analyses. Definitions are provided here for clarity and consistency.

- **Spaceport –** a geographic site capable and permitted in hosting one or more launch systems and their ground support systems
- **Air-Launch –** a mode of launch involving a carrier aircraft and a launch vehicle to be released for launch to orbit, generally within the region of a host spaceport and over nearby bodies of water
- **Responsive Launch –** a descriptor for a mode of orbital launch that can react quickly and positively to changing payload, customer, or situational constraints, whether predictable or not

Scope and System Overview

A multi-faceted and capable spaceport analysis tool suite will be introduced in this paper in order to illustrate the flexibility and responsiveness of the air-launch approach using a mobile, modular infrastructure. The LauncherOne air-launch architecture forms the basis of this analysis.[11] This study is about capabilities as they can potentially be, and is not intended to be definitive that the system is the best to support all possible mission approaches.

The LauncherOne system developed by Virgin Orbit is an air-launched platform, consisting of three primary segments: the launch vehicle, its 747 carrier aircraft, and the mobile ground support segment. The launch vehicle is a two-stage LOX/RP-1 liquid propulsion rocket, powered by the Stage 1 engine, Newton 3 with 73,500 lbf vacuum thrust and Newton 4, a 5,000 lbf Stage 2 engine. The carrier aircraft, named “Cosmic Girl”, is a modified 747-400 that will carry the launch vehicle under its left wing between the fuselage and inboard engine, as shown in Fig. 1. The ground support segment consists of a set of mobile equipment to load propellants on the launch vehicle, mobile payload trailer for launch site satellite servicing, ground stations to gather and distribute telemetry, and a launch control center to monitor the launch operations. Launching from an aircraft with a mobile ground segment minimizes constraints associated with ground launch systems. This unique feature enables the most flexible and responsive solution and the fastest ramp up for spaceport operations, with ground assets such as those in Fig. 2 are able to follow the carrier aircraft to any launch site in the world.

Figure 1: LauncherOne and Cosmic Girl, Virgin Orbit’s small satellite launch platform.

Figure 2: LauncherOne’s rapid-response mobile ground support trailers are globally transportable.

Operations begin with the receiving and mating of Cosmic Girl, LauncherOne, and the encapsulated payload, using GSE trailers. First, the payload fairing is mated to LauncherOne by backing the rocket trailer up to the payload trailer, a mobile cleanroom. In contingency scenarios, the mate configuration can also be leveraged to de-mate the fairing while LauncherOne is on the aircraft wing as well. After payload mate is complete, the LauncherOne rocket is then mated to the carrier aircraft and GSE is connected to facilitate final checkouts. Preflight operations begin with RP-1 loading, bottle pressurization, and liquid oxygen and cold gas loading. When the loading is complete, GSE will be disconnected, and Cosmic Girl will taxi and take off to the release point for launch.

SPACEPORT ACCESS ANALYSIS TOOL SUITE

Tool Suite Introduction

The modular nature of the LauncherOne architecture means that the hardware discussed may be cost-effectively duplicated as much as needed, and distributed internationally to compatible spaceports around the world. The utility of this system predicated the need to rapidly assess the mission possibilities that air-launch can bring to any spaceport around the globe. Consequently, Virgin Orbit has created a comprehensive tool suite that achieves this goal. The primary technical areas requiring detailed study when considering a candidate spaceport for air-launch include:

- Trajectory Analysis & Orbital Access Review
- Population Overflight Casualty Expectation
- Telemetry Coverage
- Aircraft Range and CONOPS Requirements
- Spaceport Infrastructure Analysis

This paper will cover the above aspects of the tool suite, but will focus most heavily on the first three bullets. Orbital inclination access is primarily driven by azimuth corridors of departure in direct vicinity of a spaceport, which is greatly expanded via air-launch. These three analyses are conveniently covered in what is called the Drop Site Selection tool.

Drop Site Selection (DSS) Tool

The Drop Site Selection (DSS) tool is a collection of MATLAB-based parametric simulation and post-processing algorithms, which are used to generate and assess hundreds of thousands of potential LauncherOne trajectories in the vicinity of any candidate spaceport around the world. Simulated via 3DoF trajectory optimization in the Program to Optimize Simulated Trajectories (POST3D), these trajectories are then evaluated for their downrange population overflight, casualty expectation corridors, and telemetry coverage. Analyses can be executed on a desktop PC with multiple processors, or via Amazon Web Server (AWS) instances with parallel processing enabled for fastest completion time.

A case study for a particular spaceport of interest begins with the specification of release site “sectors” within range of the takeoff runway. These sectors are defined by both minimum and maximum drop ranges and azimuths relative to the spaceport, as well as a desired resolution of release site gridpoints to populate within the sector. An example sector design is shown in Fig. 3 for Spaceport Cornwall in the United Kingdom. In this particular case, thirteen sectors were specified in 200 nmi increments of range, with a resolution of approximately 20x20 nmi. The tool automatically discretizes the sectors by this resolution to maintain equidistant release sites regardless of their range from the host spaceport using an established geometric discretization method.[12] Release sites determined to be over land with nearby populations are automatically disregarded from the discretization, as indicated in the figure.

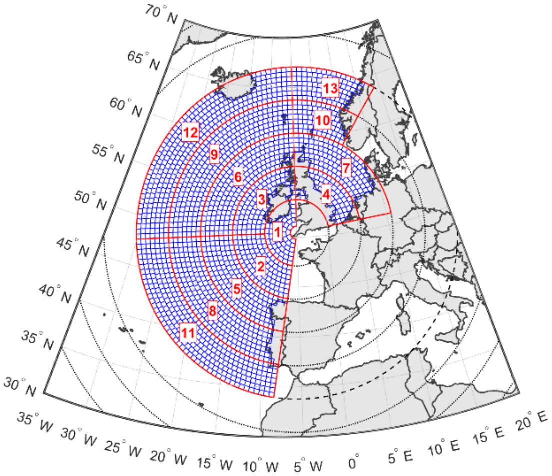


Figure 3: The Drop Site Selection tool uniformly discretizes user-specified sectors into equidistant release sites in the vicinity of Cornwall, UK.

Following site discretization, trajectories are configured and simulated from each to applicable orbital inclinations at both northern and southern departure azimuths from each launch site. Any orbital target is possible, however for the purposes of this discussion, a baseline circular orbit 500 km in altitude is used. Consequently, for M discretized release sites and N potential trajectories, up to 2*M*N trajectories are designed and evaluated. Candidate trajectories where release latitude exceeds the accessible inclination are disregarded, as are those that originate over land with resident populations.

Once a nominal, optimized trajectory is simulated for each release site, a separate subroutine to calculate overflight casualty expectation is initiated. Casualty expectation (E_c) is the estimated probability that a person within an overflown population can be impacted by the debris of a launch anomaly. Virgin Orbit utilizes a substantive and high-fidelity set of tools to calculate this overflight risk, pursuant to FAA regulations defined in Title 14, Parts 417 and 420. A brief overview of this calculation as relevant to the DSS toolset will be provided, where more detail of the methodology can be found in the FAA regulations.[13,14]

Provided each trajectory's downrange instantaneous impact trace, a corresponding E_c risk corridor is generated based on simulated malfunction turn results from 6-DoF Monte Carlo results. These anomalous cases simulate a hard-turn of the LauncherOne thrust vector control system, followed by vehicle break-up. Collection of the malfunction turn data and statistical assessment of the debris impacts as a function of downrange distance and mission timing permits definition of 3σ impact probability boundaries that vary as a function of the launch vehicle's turn capability at any given point during powered flight. Figure 4 provides an example overview of such Monte Carlo data as assessed for a 61° inclination mission from Mojave, CA with a trajectory that skirts the Baja peninsula. Here, nominal flight is indicated in blue, immediately followed by a simulated malfunction turn that transpires during the red phase. The malfunction turn then transitions into a debris phase in green after reaching threshold conditions such as aerodynamic break-up, maximum structural G loads, or minimum G loads and loss of propellant head. A debris break-up model with additional explosive ΔV is applied, paired with a detailed debris catalog with variable ballistic coefficients that affect reentry characteristics, based on various studies such as the Columbia accident[15]. The subsequent 3σ debris corridor limits are indicated in yellow.

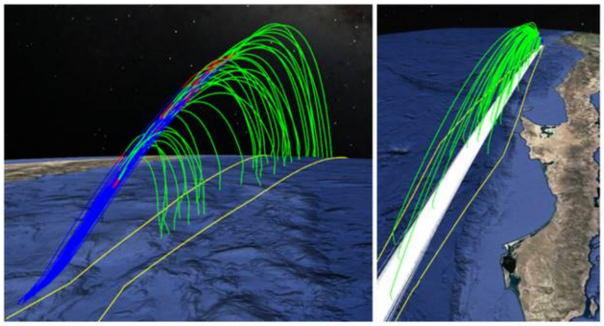


Figure 4: Monte Carlo 6-DoF malfunction turn simulations define downrange debris corridors, enabling high-fidelity end-to-end E_c estimation.

These impact boundaries are assigned to each trajectory simulation in the DSS mission scenario, and the downrange populations within these corridors are assumed to be susceptible to flight debris in the event of a launch anomaly. The E_c methodology prescribed in FAA electronic CFR Part 420 is then applied using the overflown population density in this corridor, as defined by NASA's socioeconomic data and applications center (SEDAC) gridded population of the world.[16] The trajectory is rejected if either $E_c > 1e\text{-}4$ or if the 3σ vacuum impact ellipses of a nominal Stage 1 or fairing reentry contains population. A direct product of DSS is a clear geographic depiction of where is the best location to release a LauncherOne vehicle based on casualty expectation risks. Figure 5 shows such plots for a theoretical launch to 40° inclination along a southern launch azimuth from Mojave, Guam, or Japan.

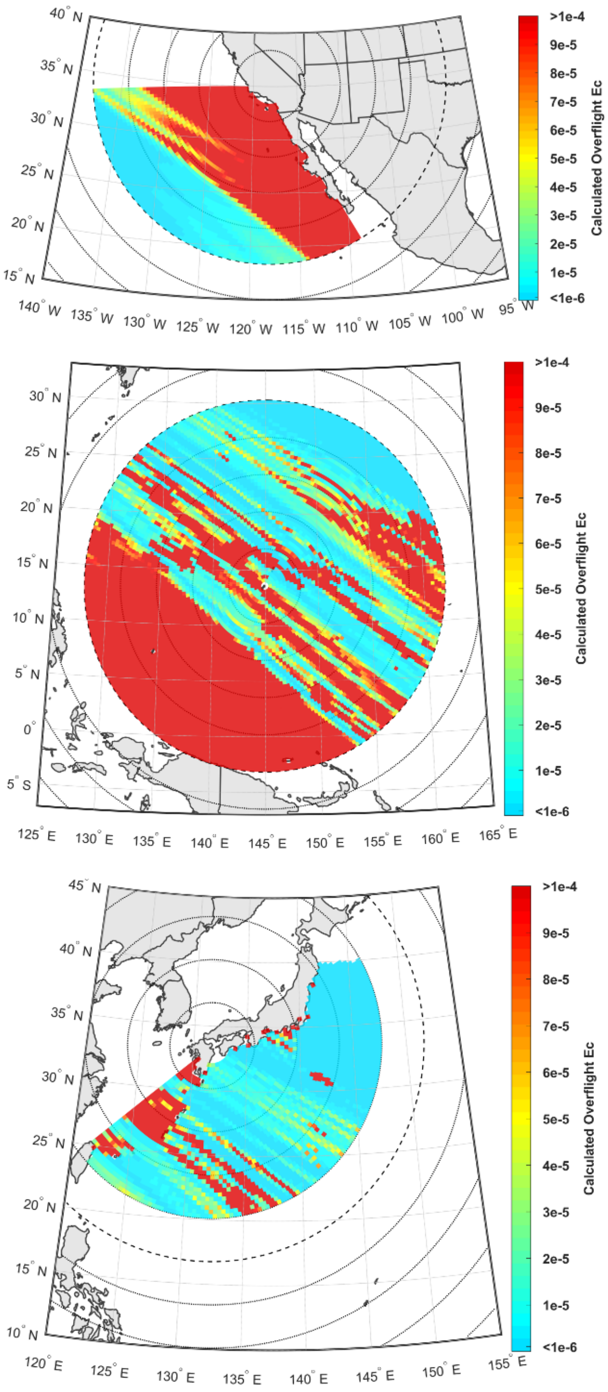


Figure 5: Casualty Expectation for launches to 40° inclination from Mojave, Guam, and Japan indicate the possibilities of access enabled by air-launch.

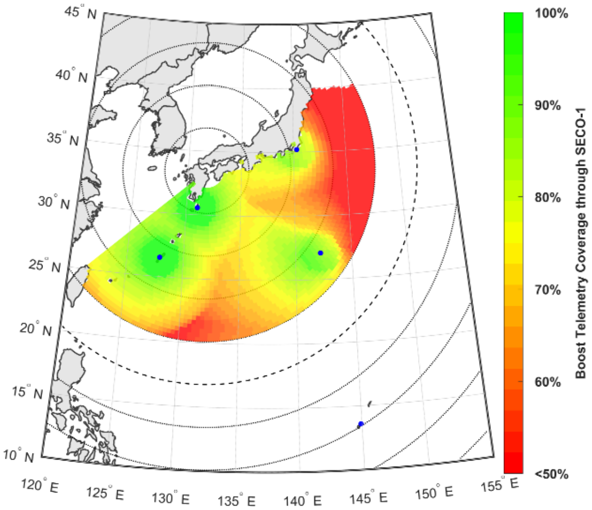


Figure 6: Cumulative telemetry coverage example for launch to 40° inclination in the vicinity of Oita, Japan informs selection of an optimal release site.

In addition to casualty expectation, telemetry coverage of each trajectory can be individually assessed and post-processed to ascertain suitability for captive-carry operations before release, during Stage 1 boost, Stage 2 insertion, and separation events. This is achieved by specifying telemetry asset coordinates and performance parameters. Coverage can then be evaluated per trajectory as part of a detailed link margin analysis, or a simple declination minimum threshold for preliminary purposes. Figure 6 shows such an example for a notional 40° mission from Oita spaceport in Japan, where Virgin Orbit is establishing launch operations. Such analyses of fixed telemetry assets are also valuable alongside prior E_c calculation, because they indicate where modular, mobile dish assets could be positioned to ensure larger availability of release sites and coverage. Otherwise, this component of the analysis is useful for indication of when other telemetry options like space-based or mobile assets are required.

Finally, after all trajectories have been evaluated and post-processed for the casualty expectation and telemetry coverage results discussed, valuable summary data is generated to help define mission criteria achievable in scenarios involving single or multiple spaceports. A definitive conclusion is characterization of total inclination access with respect to the regions considered. Relative launch availability is also implicitly defined by indicating quantity of drop sites with viable daily access to each inclination. Finally, by grouping together sites with low casualty expectation risk vs. launch azimuth, regions near the spaceport with the highest degree of access and telemetry coverage can be pursued for mission planning.

Two analogous examples of this type of drop site selection data are shown in Fig. 7 as part of a launch analysis for notional LauncherOne operations from the spaceport in Alcântara, Brazil. Here, the azimuth access map on the left identifies zones that can access unique combinations of azimuths while also depicting zones with the lowest (orange) and highest (cyan) degree of safe launch corridors. The fan plot on the right goes further to depict the shortest distance between the spaceport and the launch site required to safely access a particular inclination. This plot also estimates the approximate inclination available to a launch vehicle fixed at the spaceport, assuming no trajectory dog-legs.

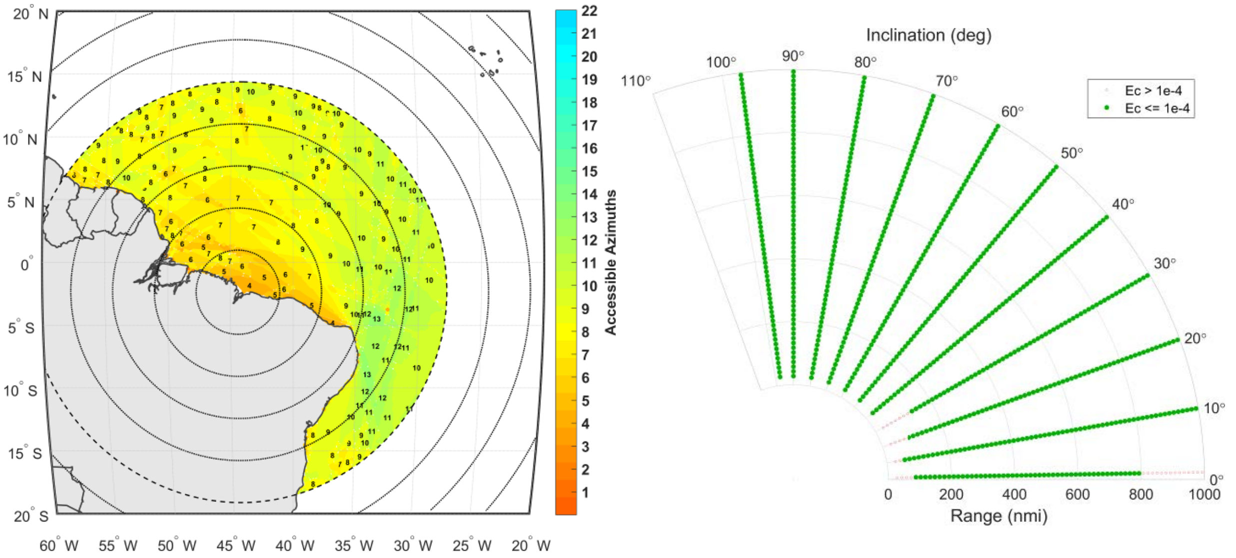
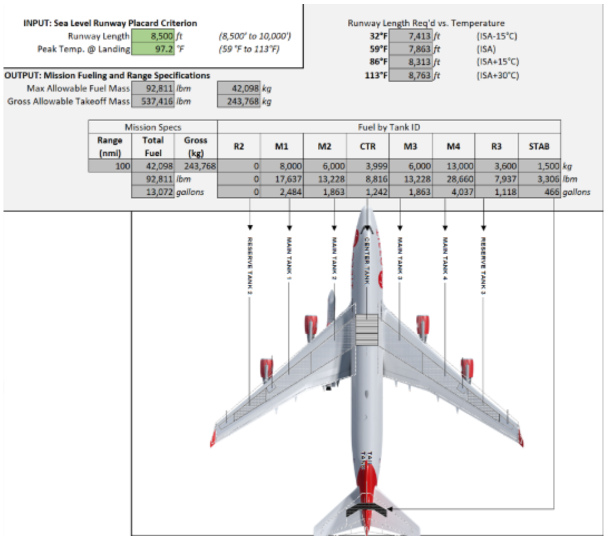


Figure 7: Site azimuth access map and inclination fan plot for a notional launch origination from Alcântara, Brazil highlight regions with substantial azimuth access and their low aircraft range requirements.

Simultaneously within this DSS post-processing, other output files are generated for passage into other planning tools within the spaceport suitability analysis. Suitable spaceports have requirements such as runways capable of 747 landing weights, allowance for safe LauncherOne operational footprints, and low population overflight nearby. Other functionalities to inform these items primarily include automated spreadsheets with pivot and sorting capability, as well as visual aids that can be manipulated in Google Earth via keyhole markup language. Another functionality of the model-based tools are passage of carrier aircraft range requirements to a runway length assessment analysis, returning actionable data on LauncherOne mission capabilities vs. specific environmental and infrastructure characteristics of the hosting spaceport. Figures 8 and 9 show some overviews of these tool components. This diverse composition of output ensures efficient transmission and consumption of feasibility data across mission, spaceport, and customer stakeholders.

Detailed summaries of the output discussed above will now be shared for various established and notionally compatible spaceports around the world.



INPUT: Sea Level Runway Placard Criterion

Runway Length	8,500	ft	(8,500' to 10,000')
Peak Temp. @ Landing	97.2	°F	(59 °F to 113°F)

Runway Length Req'd vs. Temperature

32°F	7,413	ft	(ISA-15°C)
59°F	7,863	ft	(ISA)
86°F	8,313	ft	(ISA+15°C)
113°F	8,763	ft	(ISA+30°C)

OUTPUT: Mission Fueling and Range Specifications

Max Allowable Fuel Mass	92,811	lbm	42,098	kg
Gross Allowable Takeoff Mass	537,416	lbm	243,768	kg

Mission Specs			Fuel by Tank ID								
Range (nmi)	Total Fuel	Gross (kg)	R2	M1	M2	CTR	M3	M4	R3	STAB	
100	42,098	243,768	0	8,000	6,000	3,999	6,000	13,000	3,600	1,500	kg
	92,811 lbm		0	17,637	13,228	8,816	13,228	28,660	7,937	3,306	lbm
	13,072 gallons		0	2,484	1,863	1,242	1,863	4,037	1,118	466	gallons

Figure 9: Aircraft operations and runway length assessment tools accept input data from DSS post-processing.

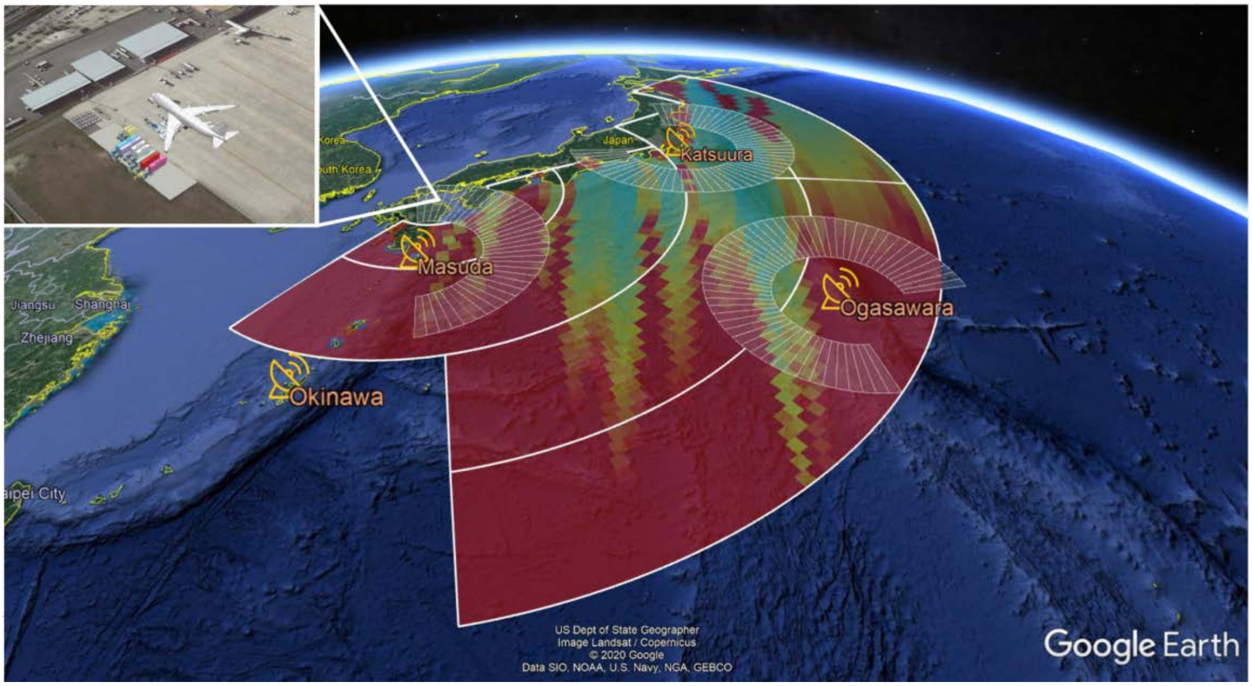


Figure 8: Analysis results and access insight data are compiled Google Earth keyhole markup files to easily convey information to mission stakeholders, as indicated in this SSO mission overview from Oita, Japan.

ANALYSIS RESULTS

Mojave Air and Spaceport Air-Launch Analysis

As the initial spaceport of the LauncherOne system, the feasibility of Mojave Air and Spaceport for west coast, high-inclination launches was understood well before the inception of these tools. This made it an excellent candidate for validating their foundational approach, but also to gain insight into the potential for reaching inclinations lower than those generally assumed possible for west coast based launches. A region over the Pacific Ocean up to 1,000 nmi in range from Mojave was discretized into five sectors of 20x20 nmi candidate release sites as shown in Fig. 10. Launches to inclinations as low as 40° were assessed, which corresponds to the E_c heatmap shown previously in Fig. 5. Only southern departure azimuths were considered, resulting in 18,138 simulated and evaluated trajectories.

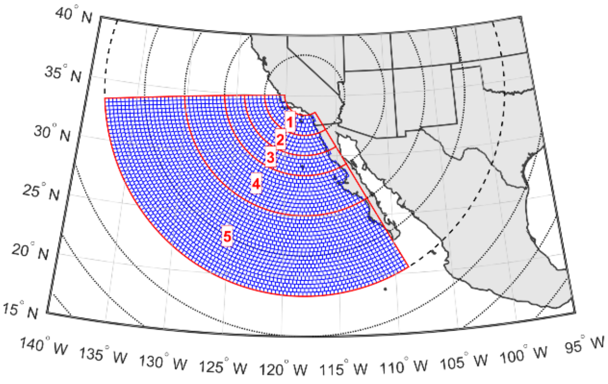


Figure 10: Five launch sectors in close proximity to Mojave Air and Spaceport are discretized into 2,592 potential LauncherOne release sites.

An inclination access summary plot for Mojave is shown alongside an azimuth access map in Fig. 11, assuming adherence to $E_c \leq$ 1e-4. The summary plot bars are shaded with respect to the aircraft range required to meet that inclination. The larger the dark region of the bar, the higher the density of sites within close proximity (≤100 nmi) of the spaceport.

In addition to naturally high polar and sun-synchronous access, the results indicate a healthy degree of inclination access down to 40° from Mojave, even when assuming modest aircraft range at less than half the maximum of 1,000 nmi assumed in this analysis. This is due to the ability to displace trajectories that would normally overfly dense populations in South America further to the west. Similarly, inclinations as low as 60° can be achieved within ~150 nmi range or less. While not explicitly assessed in this analysis, it is anticipated that inclinations 30° and below may eventually be achievable near the extent of 1,000 nmi aircraft range. This capability will be examined in future work. These results conclusively indicate that air-launch can enable a U.S. west coast launch site to reach inclinations substantially lower than ground-launched counterparts, and without costly dog-leg maneuvers.

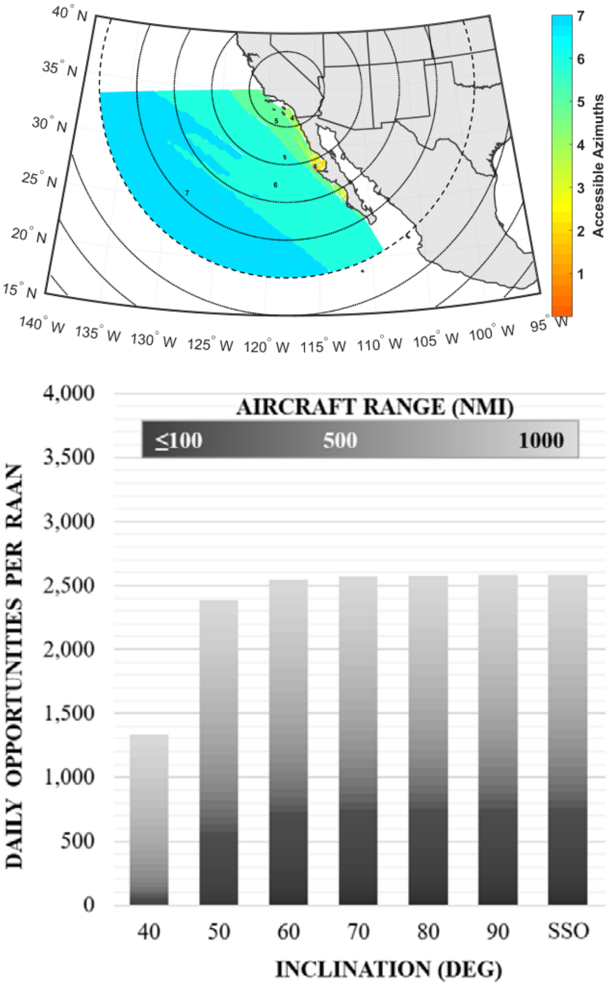


Figure 11: Air-launch is shown to extend inclination access to 40° and potentially lower when considering release sites as low as 450 nmi from Mojave.

Another aspect of Mojave spaceport feasibility examined includes the telemetry coverage, where fixed sites along the western coast of the U.S., Baja, and within Antarctica were considered. An ideal degree of telemetry coverage is assessed for the balance of inclinations, although space-based telemetry may be considered to expand coverage to missions originating or dwelling at further ranges from Mojave.

Guam Air-Launch Analysis

Guam, using either Andersen Air Force Base or A.B. Won Pat International Airport, is Virgin Orbit's default choice to host launches to low-inclination orbits. A large region over the Pacific Ocean up to 1,000 nmi in range from Guam was discretized into ten sectors of 20x20 nmi candidate release sites as shown in Fig. 12. Launches to inclinations as low as 0° were assessed. Both northern and southern departure azimuths were considered due to the low degree of nearby overflown populations, resulting in 144,523 simulated and evaluated trajectories.

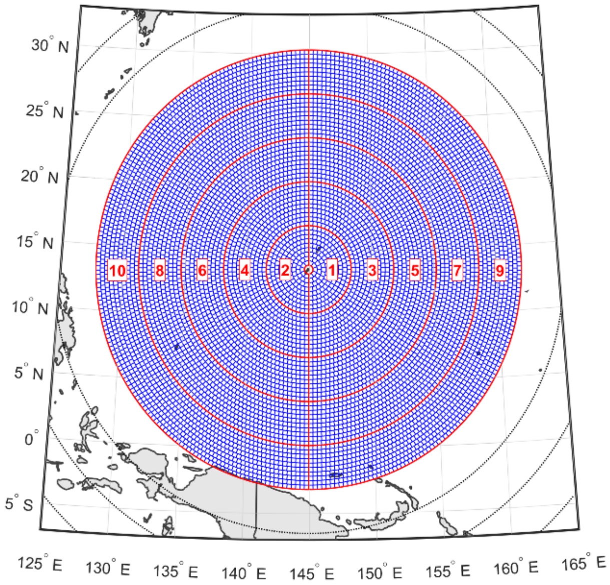


Figure 12: Ten launch sectors in close proximity to Andersen AFB, Guam are discretized into 7,894 potential LauncherOne release sites.

An inclination access summary plot for Guam is shown alongside an azimuth access map in Fig. 13, assuming adherence to $E_c \leq$ 1e-4. The summary plot bars are shaded with respect to the aircraft range required to meet that inclination. The larger the dark region of the bar, the higher the density of sites within close proximity (≤100 nmi) of the spaceport.

Remote islands like Guam are ideal hosts for air-launch because of the access, responsiveness, and flexibility they offer such a modular system. This aspect is proven here with results indicating full inclination access between 0° and SSO, and with a substantial amount of daily opportunities per orbital RAAN. All inclinations 10° and above are readily accessible via modest aircraft ranges between 100-200 nmi from Guam.

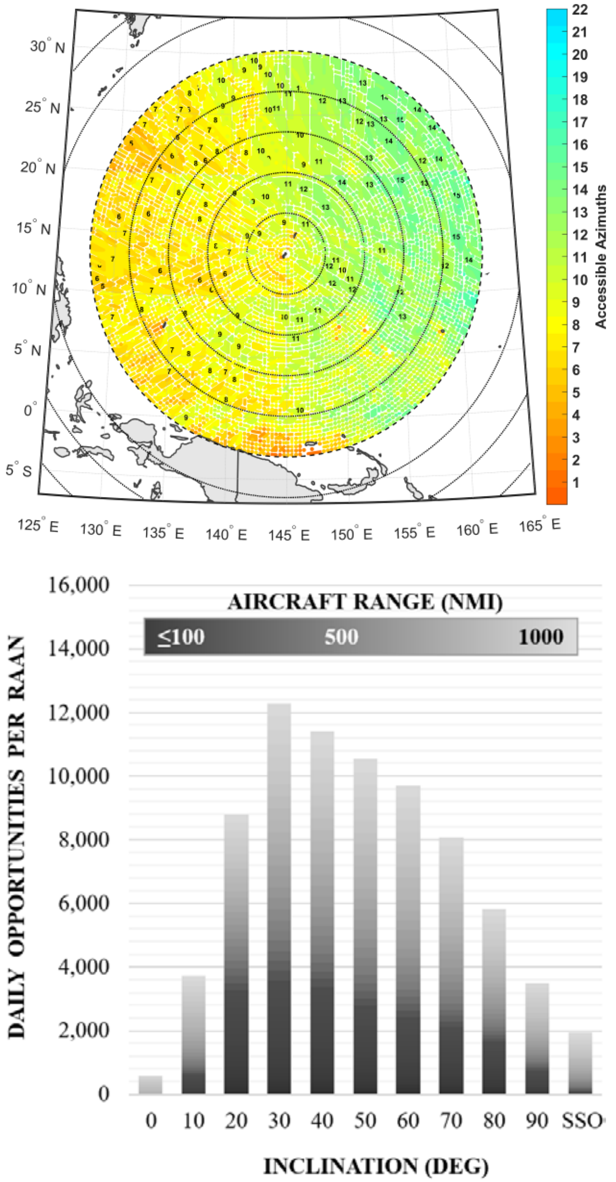


Figure 13: Air-launch is shown to permit complete inclination access between 0° and SSO from Guam with thousands of daily launch opportunities per orbital RAAN.

Guam missions are fairly well-situated in terms of telemetry, where Japanese and Australian fixed sites were considered in addition to remote sites on various Pacific islands. An ideal degree of telemetry coverage is assessed for the balance of inclinations, although space-based telemetry may be considered to expand coverage to missions originating at further ranges from Guam to further expand availability.

Kennedy Space Center, Florida Air-Launch Analysis

The Launch and Landing Facility (LLF) at Kennedy Space Center (KSC) is an ideal, existing spaceport location that is well-suited for air-launch operations. A region over the Atlantic Ocean and Caribbean Sea up to 1,000 nmi in range from KSC was discretized into ten sectors of 20x20 nmi candidate release sites as shown in Fig. 14. Launches to inclinations as low as 20° were assessed. Both northern and southern departure azimuths were considered, resulting in 52,191 simulated and evaluated trajectories.

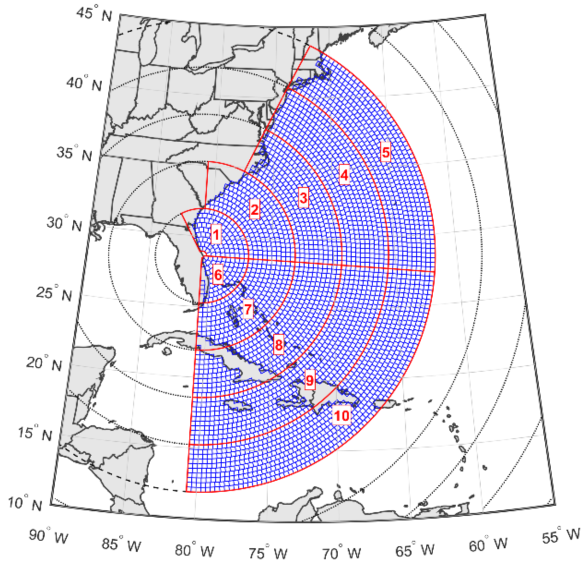


Figure 14: Ten launch sectors in close proximity to Kennedy Space Center are discretized into 3,335 potential LauncherOne release sites.

An inclination access summary plot for KSC is shown alongside an azimuth access map in Fig. 15, assuming adherence to $E_c \leq$ 1e-4. The summary plot bars are shaded with respect to the aircraft range required to meet that inclination. The larger the dark region of the bar, the higher the density of sites within close proximity (≤100 nmi) of the spaceport.

In addition to the anticipated mid-inclination access expected from KSC the results indicate a healthy degree of possibilities down to 20° and as high as 80°. While there is a high degree of access, no single release site near KSC can singularly access all inclinations considered due to the densely populated regions downrange in Europe, Africa, and the Americas. Higher polar inclinations are anticipated to be possible if trajectory dog-legging or other special accommodations are made beyond the assumptions used in this analysis. Increased aircraft range slightly beyond 1,000 nmi has also been indicated to permit sun-synchronous orbit access. Inclinations as low as 20° can be achieved within ~650 nmi range.

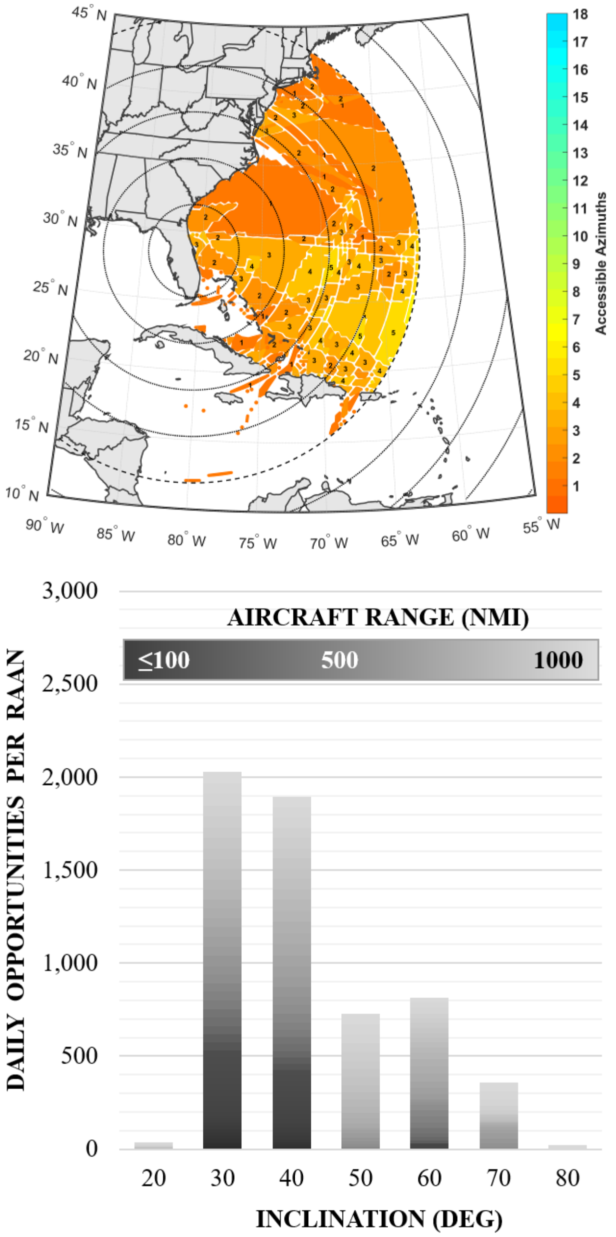


Figure 15: Air-launch is shown to extend KSC inclination access between 20° and 80° without special trajectory dog-legging accommodations.

Telemetry coverage is most optimal for trajectories that originate in the vicinity of KSC, Wallops, and Bermuda and subsequently fly in the vicinity of Brazil or Ascension Island. An ideal degree of telemetry coverage is assessed for the balance of inclinations, although space-based telemetry could be considered to expand coverage to missions originating or dwelling at further ranges from KSC. Mobile assets positioned in the Caribbean or Virgin Islands are also a possibility.

Spaceport Cornwall, UK Air-Launch Analysis

Virgin Orbit is currently partnered with Spaceport Cornwall in the UK to establish high-inclination launch capabilities from mainland Britain. A region over the Atlantic Ocean, North and Norwegian Seas up to 1,000 nmi in range from Cornwall was discretized into thirteen sectors of 30x30 nmi candidate release sites as shown in Fig. 16. Launches to inclinations as low as 65° were assessed. Lower inclinations would predicate overflight of dense populations in Europe, Africa, and the Middle East, and were therefore avoided. Both northern and southern departure azimuths were considered, resulting in 22,859 simulated and evaluated trajectories.

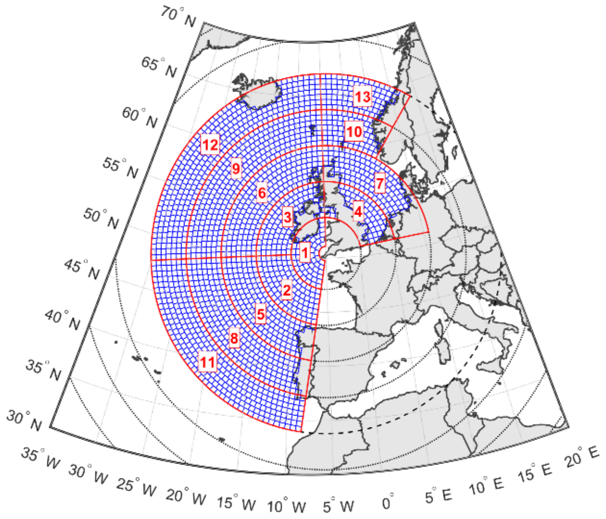


Figure 16: Thirteen launch sectors in close proximity to the UK are discretized into 1,911 potential LauncherOne release sites.

An inclination access summary plot for Spaceport Cornwall is shown alongside an azimuth access map in Fig. 17, assuming adherence to $E_c \leq 1e\text{-}4$. The summary plot bars are shaded with respect to the aircraft range required to meet that inclination. The larger the dark region of the bar, the higher the density of sites within close proximity (≤300 nmi) of the spaceport.

As domestic launch from the UK is a revived concept since the Black Arrow program in the early 1970's, there is little existing research into what orbital inclinations are possible. However with these results, there is indication that air-launch enables access to inclinations between 70° and sun-synchronous orbit. Lower inclinations are anticipated to be possible if trajectory dog-legging or other special accommodations are made beyond the assumptions used in this analysis. Inclinations as low as 75° can be achieved within 300 nmi range, while 70° can be achieved within 850 nmi.

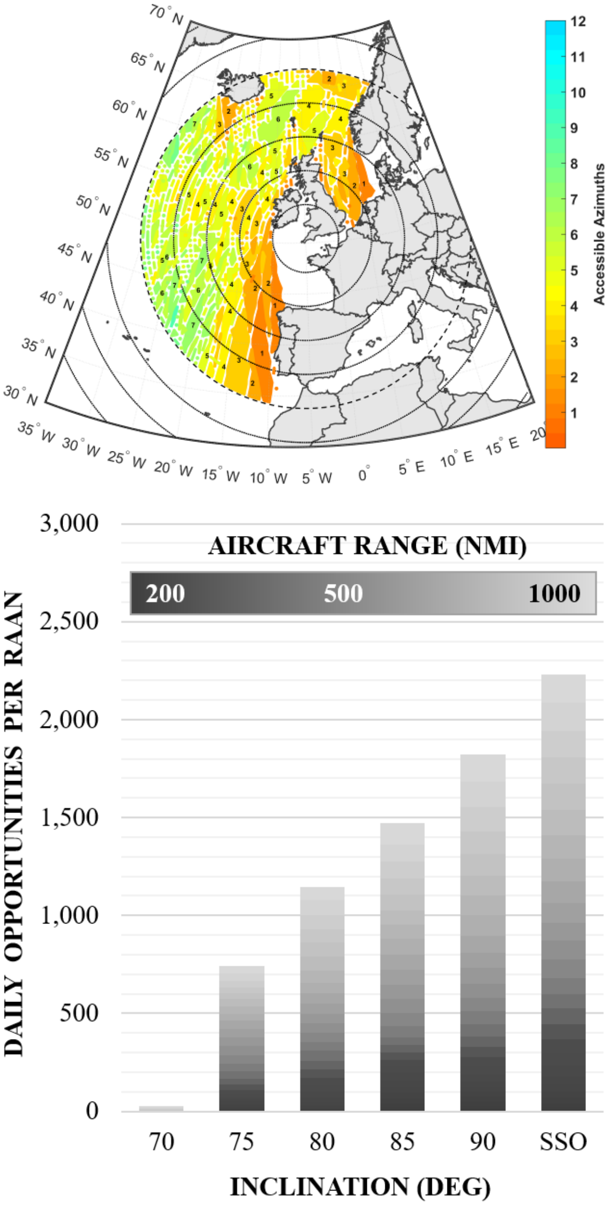


Figure 17: Air-launch is shown to enable UK inclination access between 70° and SSO.

Fixed telemetry coverage is most optimal for trajectories that fly in the vicinity of Andøya as well as Svalbard, Santa Maria, and Gran Canaria islands. Space-based telemetry could be considered to expand coverage to missions originating or dwelling at further ranges from Cornwall, particularly during the early phases of the mission. Mobile assets positioned overlooking the North Sea, or within Ireland or Iceland can further expand coverage for nearby trajectories.

Spaceport Japan (Oita) Air-Launch Analysis

Virgin Orbit is currently working with Oita Airport to establish air-launch capabilities from mainland Japan.[17] A region over the Pacific Ocean, North and Norwegian Seas up to 800 nmi in range from Oita was discretized into eight sectors of 20x20 nmi candidate release sites as shown in Fig. 18. Launches to inclinations as low as 25° were assessed. Both northern and southern departure azimuths were considered, resulting in 37,230 simulated and evaluated trajectories.

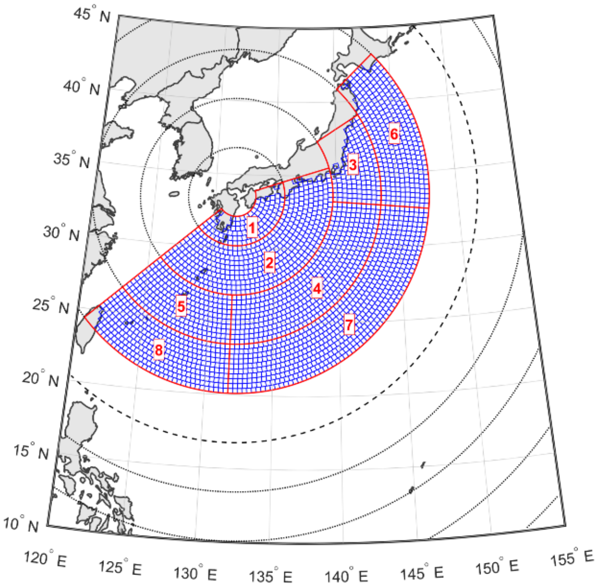


Figure 18: Eight launch sectors in close proximity to Japan are discretized into 2,405 potential LauncherOne release sites.

An inclination access summary plot for Spaceport Oita is shown alongside an azimuth access map in Fig. 19, assuming adherence to $E_c \leq 1e\text{-}4$. The summary plot bars are shaded with respect to the aircraft range required to meet that inclination. The larger the dark region of the bar, the higher the density of sites within close proximity (≤100 nmi) of the spaceport.

Similar to KSC and concerning ground-launched vehicles, Japan inclination access tends to reside in the mid-inclination range. It is found that air-launch enables sweeping access to inclinations between 25° and sun-synchronous orbit. Lower inclinations 20° and below are anticipated to be achievable, as cases where the aircraft range reaches 1,000 nmi still require inclusion to the analysis. Inclinations as low as 25° can be achieved within 500 nmi range. Sun-synchronous launches from Japan are normally complicated by dense populations to the south, but enabled by air-launch within just 250 nmi of carrier aircraft range from Oita.

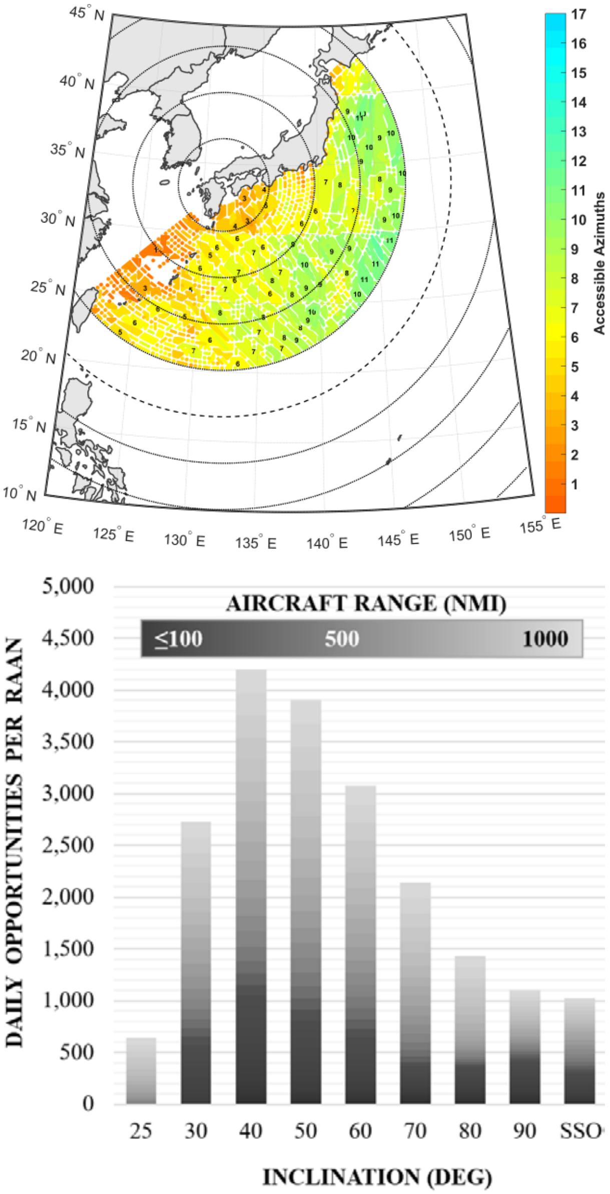


Figure 19: Air-launch is shown to expand domestic Japanese inclination access between 25° and SSO.

An ideal degree of telemetry coverage is assessed for the balance of inclinations shown, being most optimal for trajectories that fly in the vicinity of existing JAXA telemetry facilities as well as over Guam. Space-based telemetry could be considered to expand coverage to missions originating or dwelling at further ranges from Japanese assets. Mobile assets are likely unnecessary, but could be positioned overlooking the Northeast reaches of the region, permitting expanded polar and sun-synchronous missions to northern azimuths.

Alcântara, Brazil Air-Launch Analysis

The Alcântara Launch Center in Brazil is an interesting case study of the potential of air-launch. A region over the Atlantic Ocean up to 1,000 nmi in range from Alcântara was discretized into eleven sectors of 15x15 nmi candidate release sites as shown in Fig. 20. Launches to inclinations between 0° and SSO were assessed. Both northern and southern departure azimuths were considered, resulting in 144,932 simulated and evaluated trajectories.

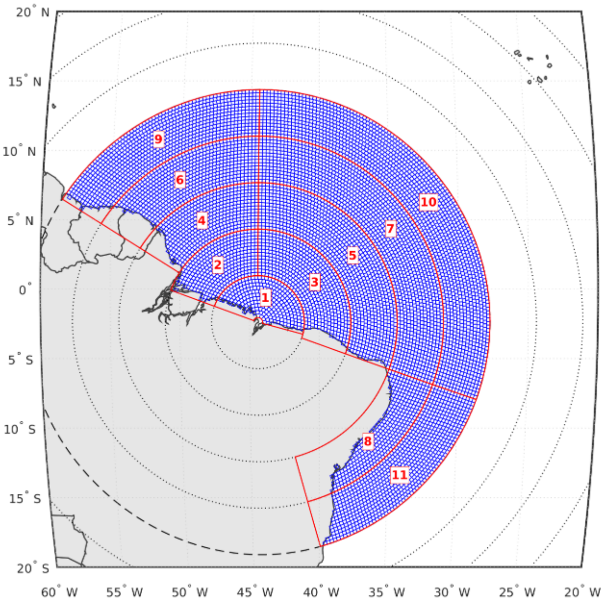


Figure 20: Eleven launch sectors in close proximity to Brazil are discretized into 7,358 potential LauncherOne release sites.

An inclination access summary plot for Alcântara Launch Center is shown alongside an azimuth access map in Fig. 21, assuming adherence to $E_c \leq$ 1e-4. The summary plot bars are shaded with respect to the aircraft range required to meet that inclination. The larger the dark region of the bar, the higher the density of sites within close proximity (≤100 nmi) of the spaceport.

Alcântara is unique in that it is one of few launch sites in the world that is both nearly equatorial and also part of a continent, similar to Kourou in French Guiana. As a result, air-launch enables substantial inclination access for the site. Every inclination between 0° and SSO is accessible with modest aircraft range to release sites near the spaceport. Scenarios like this are generally only witnessed for remote island spaceports like Guam, which can be more complex due to logistical matters in shipping support hardware, payloads, and commodities to an island. Alcântara is one of the only continental launch sites in the world that can potentially access every orbital inclination when enabled by air-launch. Proximity to the equator also ensures maximum payload performance for any mission attempted here.

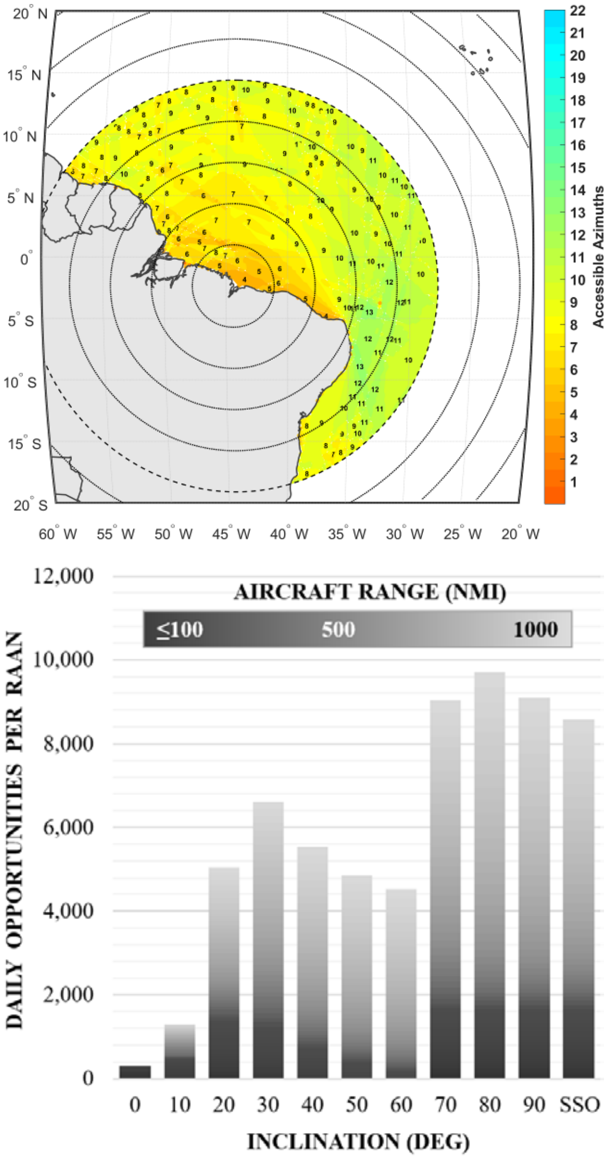


Figure 21: Air-launch is shown to permit domestic Brazilian access to all orbital inclinations.

An ideal degree of telemetry coverage is assessed for the balance of inclinations, with fixed telemetry coverage that is most optimal for trajectories that originate in the vicinity of existing northern Brazilian telemetry facilities and that also fly over facilities in Bermuda, Gran Canaria, Ascension, or Antarctica. Space-based telemetry could be considered to expand coverage to missions originating or overflying further ranges.

Air-Launch Analysis Results Summary

The Virgin Orbit spaceport access analysis tool suite has been instrumental in defining what possibilities air-launch can enable from virtually any location in the world. Here, the analysis results for six spaceports have been reported, and an overview of their results is shown below in Table 1 and Figure 22.

Air-launching vehicles has long been understood to increase the viable range of inclination access but has not been thoroughly proven via quantitative means. This novel toolset settles this issue. In the case of established U.S. ranges, the results indicate that inclination access is expanded on both the minimum and maximum bounds. Launch campaigns originating from Mojave Air & Spaceport show viability to reach inclinations as low as 40° with mild aircraft range requirements, opening west coast access to inclinations historically only available to east coast sites. Campaigns originating from the Launch and Landing Facility at KSC show viability to reach inclinations approximately ±20° beyond the established minima and maxima of range safety corridors for conventional fixed-site ground launchers. The same advantage applies for "blackout" inclinations within the azimuth sweeps, where these Drop Site Selection results indicate that simple repositioning of the air-launched vehicle release site can avoid downrange populations normally unavoidable by conventional vehicle trajectories.

Table 1: Increased air-launch inclination access is proven for each hosting spaceport

Spaceport	Air-Launch Inclinations	Conventional Inclinations
Mojave Air & Spaceport	40° - SSO+	56° - SSO+ *†
Guam	0° - SSO	N/A
Florida	20° - 80°	39° - 57°
Cornwall, UK	70° - SSO	N/A
Japan	25° - SSO	30° - SSO†
Alcântara, Brazil	0° - SSO	0°-20°, 70°-SSO†

**VAFB allowable azimuth range used as reference*

†Includes blackout inclinations and implied dog-legging

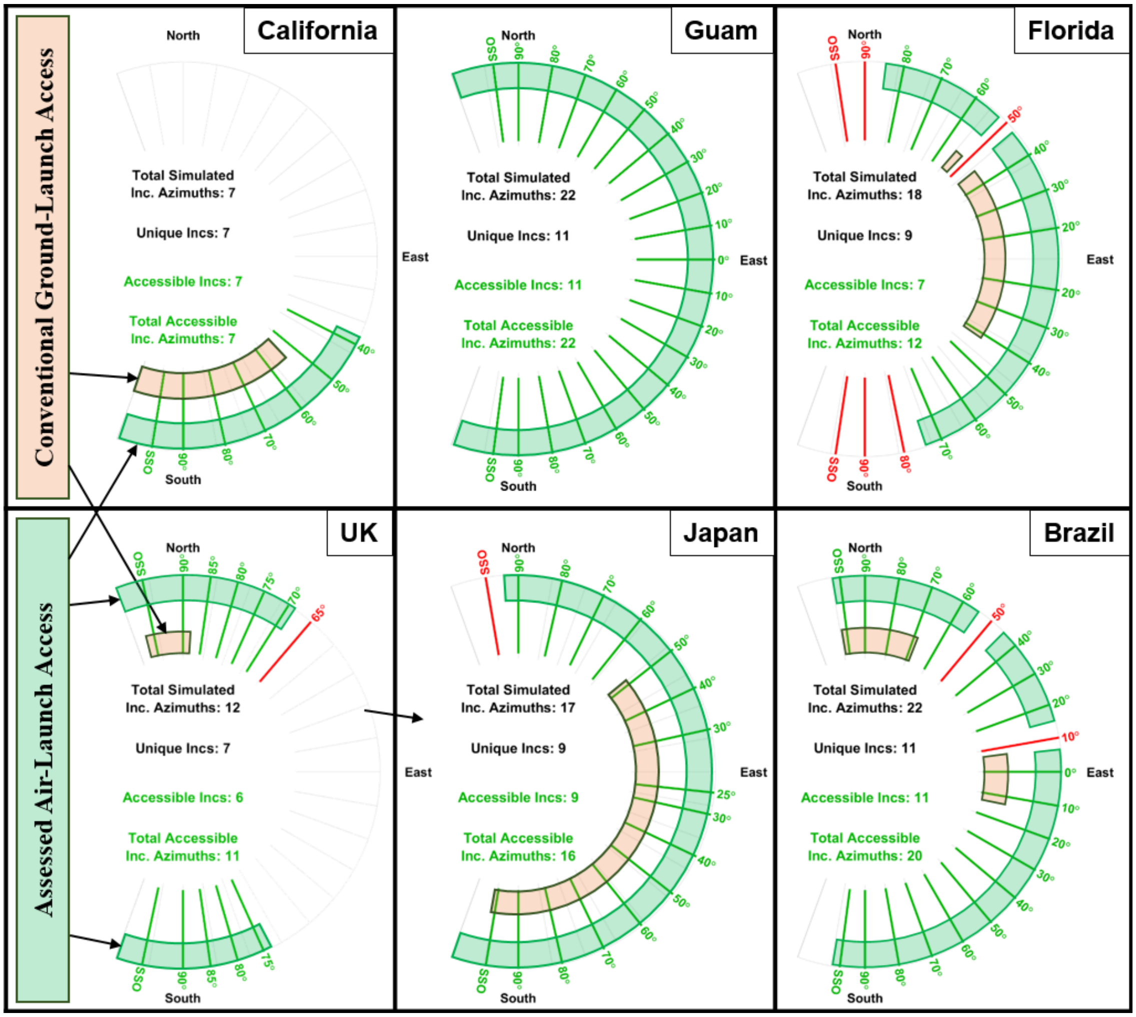


Figure 22: Site inclination access enabled by air-launch azimuth (green) indicates expanded availability compared to counterpart ground-launch vehicle envelopes (orange).

Beyond established launch ranges, the results highlight what potential exists for geographic locations that haven't sustainably hosted orbital launch vehicles and their pads. In the cases of Guam and Spaceport Cornwall, an impressive amount of orbital access is indicated. With mild aircraft range requirements, launches from Guam are shown to safely reach effectively all useful orbital inclinations. Launches hosted from Spaceport Cornwall are shown to reach most high inclinations of interest, at 70° through SSO.

The ability of air-launch to diversify and improve launch access for established international launch ranges is indicated by the results for Japan and Brazil. Both of these ranges already permit ground-launched vehicles to reach a wide envelope of inclinations, but with inclination blackouts or trajectory dog-legging required. Small launch vehicles can be heavily penalized by dog-legging maneuvers compared to larger counterparts that have fuel to spare. The added benefit of originating air-launched trajectories just a short distance from the host spaceport in either case has been shown to greatly enhance the available access.

Aside from explicit orbital inclination access, expanded launch availability is also implicitly addressed via these results. The bar charts from each of the spaceport access analyses indicate a multitude of release sites that adhere to mission and casualty expectation requirements, meaning that flexibility in choosing one of many trajectories to avoid weather, on-orbit collision avoidance (COLA), or other infringing aircraft or maritime traffic is possible. Choosing between northern and southern departure azimuths that expand beyond the possible corridors of a ground launcher is also enabled, as shown in Fig. 22. In many cases, this means two daily launch opportunities per orbit as opposed to one.

The post-processing analytics of the tools allow the mission planner not only to uniquely cater launch access for the customer, but to simultaneously optimize overarching launch campaign design for Virgin Orbit and its hosting spaceport stakeholders. One such example is the ability to assess and rank singular release sites for their viability to launch several different types of missions. A few examples of this are indicated by the detailed azimuth access maps shown in Fig. 23. Here, specific zones with larger than average ranges of inclination access are identified in the vicinity of Cornwall, Brazil, and Japan. These results are a detailed extension of the access colormaps discussed previously, each showing only one selected family of accessible azimuths at a particular "zone". Hundreds of release zones within range of the spaceport have a similar range of access and are reported separately.

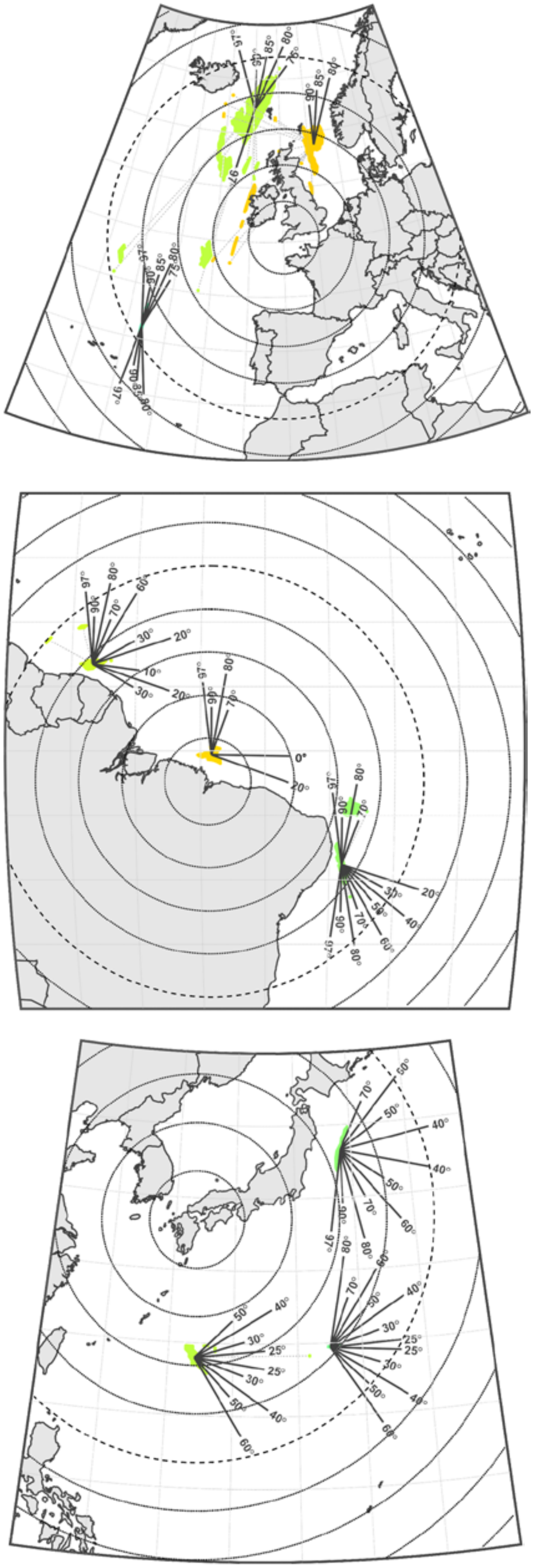


Figure 23: Air-Launch access "zones" are identified and catalogued for use in larger, overarching mission strategies for a particular spaceport.

In all cases, the ability to parametrically assess the optimal release site for unique mission scenarios proves particularly robust when faced with the growing and diverse demands of the small satellite industry. Mission stakeholders find the capability useful when assessing multiple degrees of freedom in tailoring a dedicated launch profile to the customer. This directly translates to greater flexibility in orbital injection requirements, mission pricing, launch windows, and/or payload performance.

IMPLICATIONS

In addition to air-launch benefit of added ΔV provided by the increased altitude and velocity at release, the mobility and mission flexibility earned by the carrier aircraft itself is also quantifiable. Proving and communicating this aspect is a complex undertaking, but is precisely what is attempted with this tool suite.

With these spaceport analysis tools, Virgin Orbit seeks to make readily communicable the value proposition that is the flexible air-launch system. The benefits of such granular quantification of access to the mission planner and customers reviewing the feasibility data are fivefold:

1. Explicit dictation of inclination access ranges, based on proven, high-fidelity trajectory & casualty expectation analysis with clear definition of access as a function of host spaceport selected
2. Launch availability expansion via backup or alternative launch release sites, as well as azimuths (northern vs. southern) to reduce day-of-launch restrictions such as COLA, weather issues, or other scenarios normally ending in a mission scrub
3. Established benefit in access and mission confidence enabled by air-launch with modest range capabilities when compared to a fixed-site launch vehicle at the same spaceport
4. Substantially increased insight into other mission planning aspects such as telemetry asset down-selection, iterative launch opportunity analysis, customer mission profile design, etc.
5. Ability to fully minimize risks to overflown populations and traffic routes while permitting reduced costs normally associated with extreme reliability requirements

These implications are particularly important in the evolving small satellite industry. As small satellites become more common and easily mass-produced around the globe, freeing up orbital access will reduce the bottlenecks commonly associated with delays in the launch segment. Additionally, as small satellites are integrated into larger hybrid architectures the ability to tailor their orbits and launch sites will be increasingly critical. Replication of a modular launch system like LauncherOne among the investigated spaceports would further open access to orbit. Commercial business case aspects like minimal time-to-market may increasingly dominate the launch decision space.

Advances in the smallsat manufacturing industry and increased availability of small, dedicated launch will cause the design of constellation architectures to evolve altogether. The ability to fly more low-cost satellites more often while concurrently improving on the next design iteration feeds the narrative where smaller dedicated manifests are favored over high-quantity smallsat manifests on larger payload class vehicles. The above are all factors that will only increase the need for dedicated small launch vehicles that are simultaneously flexible and responsive.

Government mission planners and architects benefit from added launch site availability. The 2018 National Defense Strategy recognizes space as a war-fighting domain and with increasing threats to commercial and military uses of space, the presences of a distributed launch capability helps to detour bad actors through a network that provides assured global space access. Fixed launch site infrastructure is innately vulnerable and predictable. A robust and resilient launch capability provides a strategic advantage to the U.S. and allied mission planners to create the space effects needed to keep all orbital systems healthy and protected. The introduction of multiple launch sites changes the launch calculous, and favors those with the capability of increased options. Fundamentally all existing space missions are strengthened with distributed launch, with the added benefit of opening new mission plans that would otherwise be constrained by limitations in launch time and location with a fixed site.

Policy Discussion

The Commercial Space Launch Act (CSLA) of 1984 assigned the duties of overseeing and coordinating commercial launches, issuing of licenses and permits, and promotion of safety standards to the Secretary of the Department of Transportation (DoT)[18]. The Commercial Space Transportation office (AST) within the Federal Aviation Administration (FAA) was then established to:

- Regulate the U.S. commercial space transportation industry, ensure compliance with international obligations of the United States, and protect the public health and safety, in addition to the safety of property, of the United States;

- Encourage, facilitate, and promote commercial space launches and reentries by the private sector; and
- Facilitate the growth of the U.S. space transportation infrastructure.

Commercial space regulations are located in Chapter III, Parts 400 to 460, of Title 14 Code of Federal Regulations and implement statutory requirements established by the CSLA. These regulations are now undergoing a revision to effectively regulate public safety for the variety of launch vehicles on the market today such as air-launched vehicles and those that are range independent[19].

As industry aims to increase orbital access to customers, and as customer aim to decrease their timeline to orbit – more and more sites across the globe are becoming candidates as a launch site. However, the U.S. currently is one of the few countries that has a robust launch regime in place for commercial companies. In addition, if a U.S. launch company launched outside the United States, it is still required to obtain a license through the DoT[20]. This means, a U.S. company has to obtain a license to launch from the U.S., as well as any regulatory authority required from the country of launch. This can easily become burdensome with many requirements, leading to duplicative work which can deter commercial companies from pursuing business outside the U.S.

However, this "dual licensing" framework is necessary for safety and liability. Unlike the civil system of liability where liability from negligence that applies under ordinary civil law typically results in a person being held liable only for damage caused by his or her deliberate acts or negligence - states have the responsibility to ensure public safety and protection of the environment. The state is responsible for non-fault compensation in full to other states, and of course, non-fault liability toward its own nationals, and thus must establish a system of compensation for those affected by any accidents or mishaps that may occur. Which is why, it is critical to establish clear provisions covering commercial launch activities for safety of the uninvolved public as well as clear liability provisions for protection of property.

New Zealand is currently conducting routine launches of commercial U.S. launch vehicles[21]. Other countries have established or started developing commercial launch framework to allow both domestic and foreign companies to conduct launches in their country. For example, Japan established a framework for private space launch through the Japan Space Activities Act of 2016, the Australia updated regulations that were put in place in 1998[22], and the United Kingdom have publically stated they are working on new launch regulations for the private sector.

If foreign governments and spaceport operators work with the U.S. government to develop a system that allows for licenses to be transferrable to an extent, create requirements that can be substantially satisfied with a current FAA launch license, or streamline multi-country licensing processes, safety can be preserved without slowing down the pace of innovation of business. This includes:

- Adopting a performance-based licensing regime
- Allowing for multiple and international site approval as a part of their domestic launch license
- Streamlining "dual use" licensing for commercial launch companies

Future Work

The air-launch access toolset and associated spaceport analysis results have already returned great value in helping to plan, assess, and communicate the mission scenarios possible from any airport capable of hosting the modular LauncherOne system. There remains tremendous potential in terms of additional capabilities that will be a focus during future work:

- Ongoing identification and validation of additional candidate spaceports and inclination access ranges
- Increased resolution of existing results, in the form of more considered inclinations and launch sites
- Improvement of ties to rapid mission planning tools to streamline iterative mission design activities

As Virgin Orbit expands its global launch footprint via existing and new spaceport partnerships, new mission-unique launch campaign scenarios will be developed and executed as well.

CONCLUSIONS

Air-launch architectures have been proposed as a flexible solution to responsive launch needs, but have only recently begun to exhibit quantifiable characteristics decisively indicating this to be the case.[4,10] While working to bring such a launch system into operation, Virgin Orbit is simultaneously developing extensive mission planning tools to transparently communicate the benefits of air-launch. The tools described in this paper are the latest product of this effort.

A high-fidelity suite of analysis tools that establish the access potential of a modularized, global network of mobile support assets based on the LauncherOne vehicle has been presented with direct implications on the responsiveness and flexibility of air-launch. Founded on a vision of global host spaceports and utilizing Virgin Orbit's mobile ground support infrastructure, air-launch is shown to definitively increase inclination access when compared to counterpart ground-launched vehicles. In some cases, virtually any inclination may be accessed with only modest carrier aircraft range. Increased launch availability is also guaranteed given the widely tailorable drop site allowing avoidance of abort-worthy constraints like weather and traffic, plus the ability to access both northern and southern launch azimuths. Interplanetary launch solutions are also greatly enabled by the same degree of azimuth access, where escape velocity declinations are not bound by conventional range safety constraints.

Simulations involving tens of thousands of candidate launch vehicle drop sites and subsequent downrange overflight scenarios form the basis of the assessment results, permitting on-the-fly mission planning of any manner of launch requirements dictated by a particular mission. Spaceport stakeholders simultaneously find value in the data products so as to assess what degree of launch access can be realized with an air-launched system.

Confidence in any responsive mission scenario is assured by such a concept, given that thousands of origination launch sites can be pre-arranged across a widely varying launch window per orbital plane. Small satellite constellation population, replenishment, and rapid replacement via a responsive launch capable system will provide on-going missions with the critical support necessary for continuity of service. The benefits of such an architecture are wide-ranging and critical for the growth and sustainment of constellation services.

Significant effort still lies ahead in bringing such a responsive launch network to fruition, both on the technical and policy sides. Given the promising state of the smallsat economy and the natural advantages that come with such an offering, the challenges are outweighed by boundless opportunities. Future work in these technical and policy areas has been outlined and will be pursued as Virgin Orbit brings the LauncherOne service into rapid, full-scale production cadence.

The emergence of international spaceports is expected to further ignite small satellite operational launch rate and manifest in the coming decade. Their regional governments should commit to create a sustainable local space ecosystem by committing to a "critical mass" of annual launch rate to support local LEO missions. By formalizing and demonstrating small launch operational concepts, tactics, techniques, and procedures, it provides a path to building the foundation for solving the important operational, legal, and logistical challenges identified to establish a rapid reconstitution and responsive launch capability.

REFERENCES

1. Henry, C. 'Northrop Grumman's MEV-1 servicer docks with Intelsat satellite', *SpaceNews,* 26 February 2020. Available at: https://spacenews.com/northrop-grummans-mev-1-servicer-docks-with-intelsat-satellite/ (Accessed: 19 Mar 2020).
2. Bryce Space and Technology, "2018 State of the Satellite Industry Report," 2018.
3. Bryce Space and Technology, "2019 State of the Satellite Industry Report," 2019.
4. Fuller, J., Foreman, V. L., Bandla, S., Jan, M., McElroy, W., & Vaughn, M., "Modularized air-launch with Virgin Orbit's LauncherOne system: Responsive smallsat constellation construction measured in hours, not months," Small Satellite Conference, Logan, UT 2019.
5. Bryce Space and Technology, "Bryce Start Up Space 2020," 2020.
6. Foreman, V. L. (2018). *Emergence of second-generation low earth orbit satellite constellations: A prospective technical, economic, and policy analysis* (Master's thesis). Massachusetts Institute of Technology. Retrieved May 12, 2019, from https://dspace.mit.edu/handle/1721.1/119297.
7. Space Studies Board, Achieving Science with CubeSats. Washington, D.C.: National Academies Press, 2016.
8. "Smallsats by the Numbers," Bryce Space and Technology, February 2019, p. 4.
9. Isakowitz, S. J., Hopkins Jr, J. P., & Hopkins, J. B. (1999). International Reference Guide to Space Launch Systems, American Institute of Aeronautics and Astronautics. *Inc. Reston, VA.*
10. Frick, W., Guerci, J., & Horais, B. (2004, April). Responsive air launch. In *2nd responsive space conference, Los Angeles, CA.*
11. *LauncherOne Service Guide* (Version 1.2). Virgin Orbit, LLC., July 2019, https://virginorbit.com/wp-content/uploads/2019/09/ServiceGuide_Sept2019.pdf
12. Fuller, J. & Tolson, R. H. (2009). Improved Method for the Estimation of Spacecraft Free-

Molecular Aerodynamic Properties. *Journal of Spacecraft and Rockets*, *46*:5, 938-948.

13. Streamlined Launch and Reentry Licensing Requirements, 14 C.F.R. §417 and §420 (2019) Federal Aviation Administration, U.S. Department of Transportation.
14. Federal Aviation Administration, (2011). *Flight Safety Analysis Handbook*, Version 1.0. U.S. Department of Transportation.
15. Robledo, Luis, "Analysis and Integration of a Debris Model in the Virtual Range Project" (2004). University of Central Florida, Electronic Theses and Dissertations, 2004-2019. 231.
16. Center for International Earth Science Information Network - CIESIN - Columbia University. 2018. Gridded Population of the World, Version 4 (GPWv4): Population Count, Revision 11. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H4JW8BX5. Accessed 15 Sept 2019.
17. Virgin Orbit. (2020, April 2). *Oita Partners with Virgin Orbit to Establish First Horizontal Spaceport in Asia* [Press release]. Retrieved from https://virginorbit.com/oita-partners-with-virgin-orbit-to-establish-first-horizontal-spaceport-in-asia/
18. “General Authority,” 51 U.S.C. § 50903, from the Commercial Space Launch Act of 1984 (PL 98-575) as amended.
19. Streamlined Launch and Reentry Licensing Requirements. Federal Aviation Administration. May 2018. Docket Number: FAA-2019-0229.
20. “Who must obtain a license or permit.” 14 C.F.R. § 413.3. Federal Aviation Administration, U.S. Department of Transportation. Accessed May 31, 2020.
21. Matignon, Louis de Gouyon. “The Space Program of New Zealand.” Space Legal Issues. September 26, 2019.
22. Foust, Jeff. “Australia updates commercial launch regulations.” SpaceNews. September 4, 2019.