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LauncherOne Now in Orbit: Dedicated Air-Launch Brings Proven, Responsive Space Access with Historic NASA VCLS Demonstration Mission

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ABSTRACT

The LauncherOne air-launched rocket system, under commercial development by Virgin Orbit since 2015, is now fully flight-qualified. This small, dedicated launch vehicle first reached orbit on January 17th, 2021 as part of the NASA Venture Class Launch Services (VCLS) ELaNa 20 mission, injecting ten small satellites into orbit. This historic mission saw the world's first liquid-propulsion, orbital class air-launched vehicle succeed with incredible performance and accuracy.

Founded upon the capabilities of the Boeing 747-400 carrier aircraft, LauncherOne maintains safe operations using flight controls and an Autonomous Flight Safety System (AFSS) that have been fully internally-developed and certified by the Federal Aviation Administration (FAA) of the United States. This uniquely mobile launch system is designed to bring tailored small satellite launch services to any corner of the globe. This paper details the inaugural NASA VCLS LauncherOne mission. Review of the mission and customer outcome will reveal how some of the most challenging aspects of air-launch have now been achieved by the LauncherOne design.

In successfully overcoming the design challenges of a cryogenic air-launch vehicle, the substantial accompanying rewards can now be realized. We have shown how such a modular launch system can be replicated and disaggregated across many sites, offering flexibility and extreme orbital access for small satellites without a fixed infrastructure or permanent footprint. Accordingly, we have continued to grow our spaceport network to support domestic and international mission planners that benefit from such a capability. The status of these activities and facilities will be discussed.

Following extensive qualification testing, the NASA VCLS mission success, and all of the associated cryogenic loading and vehicle preparation operations successfully completed from an austere runway apron, LauncherOne's air-launch approach is now proven to be foundationally responsive. Virgin Orbit and the dedicated, flight-proven LauncherOne system are now uniquely positioned to both serve and grow the global small satellite market from spaceports around the world.

INTRODUCTION

The LauncherOne system began as a twinkle in the eye of Sir Richard Branson, the founder of the Virgin Group and a long-time force in the New Space movement. Sir Branson recognized the oncoming rise of small satellites in a changing space ecosystem, and leveraged the resources and expertise of Virgin Galactic to formulate a solution. By 2015, earnest development of the system began and proceeded alongside the creation of a dedicated company to deliver it, Virgin Orbit. Its system, LauncherOne, would become the world's first liquid-propulsion and air-launched rocket—combining low-cost cryogenic rocket technologies and their heritage with state-of-the-art manufacturing and flight operations—while making Virgin Orbit a leader in global, responsive launch. LauncherOne was conceived to fundamentally differ from traditional launch service providers that use fixed infrastructure and pads. Its carrier aircraft, fully mobile ground support infrastructure, and proprietary AFSS allow for the launch of small satellites from nearly anywhere, when provided a runway long enough to accommodate a 747. The result is a flexible system that can safely reach any orbit from a customer's own backyard if they so prefer.

Developing such a capability required Virgin Orbit to overcome substantial obstacles. The known technical challenges of the design, integration, test, and flight of a liquid cryogenic launch vehicle were magnified by the constant attention to the safety needed to do so from a crewed aircraft, at high altitude with an energetic release, and from anywhere in the world.

LauncherOne's first-of-its-kind AFSS was fully internally-developed and certified by the Federal Aviation Administration (FAA), with added attention to accommodate compliance to foreign regulatory bodies. Additionally, progress to establish the framework to manufacture, test, and deploy up to 24 rockets per year to a global network of spaceports was prioritized before a launch was attempted. Virgin Orbit built and initialized a high-rate rocket production factory in Long Beach, California (CA) and is now actively implementing spaceport operations in Mojave, CA; Cornwall, United Kingdom (U.K.); Oita, Japan; and Alcântara, Brazil. The LauncherOne factory as well as the operational progress and capabilities at each of these new spaceports will be detailed further here.

The NASA Venture Class Launch Services (VCLS) ELaNa 20 mission was awarded[1] to Virgin Orbit (then part of Virgin Galactic) by the NASA Launch Services Program (LSP) in October of 2015 near the inception of the LauncherOne program. "LSP is attempting to foster commercial launch services dedicated to transporting smaller payloads into orbit as an alternative to the rideshare approach and to promote the continued development of the U.S. commercial space transportation industry," said Jim Norman, then-director of Launch Services, adding, "VCLS is intended to help open the door for future dedicated opportunities to launch CubeSats and other small satellites and science missions." Following an extensive development and test program of the LauncherOne system, 10 CubeSat payloads[2] were delivered into orbit on January 17th, 2021 as part of the VCLS ELaNa 20 mission.

The successful deployment of all payloads and verification of their final orbital parameters confirmed that the mission met or exceeded all customer requirements. As a result, LauncherOne is now fully flight-qualified with every system and subsystem having achieved a NASA Technology Readiness Level (TRL) of nine. This paper will detail the capabilities of the LauncherOne system, the success of the NASA VCLS launch demonstration mission, the status of Virgin Orbit's manufacturing and operational infrastructure, and the growing LauncherOne international spaceport network.

LAUNCHERONE SYSTEM OVERVIEW

The LauncherOne system developed by Virgin Orbit is an air-launched platform, consisting of three primary segments: the launch vehicle, its 747-400 carrier aircraft, and the Mobile Ground Support Equipment (MGSE) segment. The launch vehicle is a two-stage LOX/RP-1 liquid propulsion rocket, powered by the Stage 1 engine, Newton 3 with 75,000 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 carries 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, a mobile payload trailer that maintains an ISO-8 environment for the Encapsulated Payload Assembly outside the Payload Processing Facility (PPF), 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 MGSE shown in Fig. 2 that follow the carrier aircraft to any launch site in the world.

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

Operations begin with the receiving and mating of Cosmic Girl, LauncherOne, and the encapsulated payload, using MGSE trailers. First, the rocket is mated to the carrier aircraft. Then the payload fairing is mated to the rest of the rocket by backing the payload trailer, a mobile cleanroom, to the rocket under the wing. 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, MGSE 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, the MGSE will be disconnected, and Cosmic Girl will taxi and take off to the release point for launch.

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

NASA VCLS ELANA 20 MISSION SUCCESS

The NASA ELaNa 20 mission, targeted for a launch to 500 km circular orbit with an inclination of 60.7° was comprised of ten CubeSat payloads, most of which from universities:

- PolarCube - University of Colorado at Boulder
- MiTEE - University of Michigan, Ann Arbor
- CACTUS-1 - Capitol Technology University, Laurel, MD
- Q-PACE - University of Central Florida, Orlando
- TechEdSat-7 – NASA's Ames Research Center, Silicon Valley, CA
- RadFXSat-2 - Vanderbilt University, Nashville, TN
- EXOCUBE-2 - California Polytechnic University, San Luis Obispo
- CAPE-3 - University of Louisiana at Lafayette, LA
- PICS (2x) - Brigham Young University, Provo, UT

Virgin Orbit hosted the customer payload teams[3] at its Long Beach headquarters and payload processing facility in late 2020, shown in Fig. 3. Payload operations progressed smoothly, where the CubeSats were loaded into their dispensers on the LauncherOne Integrated Payload Stack (IPS) shown in Fig. 4. The IPS includes eight Xtenti railed CubeSat dispensers and one Planetary Systems Corporation (PSC) tabbed dispenser mounted on top of a payload adapter plate.

The IPS was then encapsulated within the LauncherOne fairing, and transported to Mojave Air and Spaceport within Virgin Orbit's mobile payload processing trailer shown in Fig. 2. The encapsulated fairing was later mated to the LauncherOne rocket at the normally vacant hammerhead apron by the southeast end of the Mojave runway. More information about LauncherOne payload accommodations, environments, and integration timeline can be found in the Payload User's Guide[4].

Figure 3: Customer and VO teams process VCLS CubeSat payloads at the Long Beach facility.

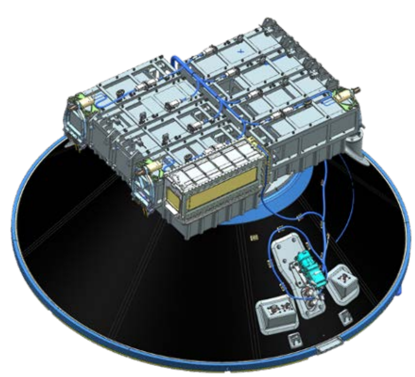

Figure 4: The VCLS Integrated Payload Stack.

Day-of-launch operations commenced in the early morning darkness of January 17th, 2021 where RP-1 kerosene, liquid oxygen, and pressurant gases were loaded into the LauncherOne vehicle. Launch operations proceeded smoothly with no significant issues or stoppages, due to extensive qualification campaigns previously imposed on the MGSE during LauncherOne development. Following completion of all loading activities, Autonomous Flight Safety System (AFSS) initialization, and site safing activities, the pilot and launch engineering teams boarded the Cosmic Girl aircraft at 10:20 AM local time, completing their pre-launch checklists in time for rollout and a 10:50 AM takeoff shown in Fig. 5.

Figure 5: LauncherOne Mojave launch operations proceeded nominally for the NASA VCLS mission.

VCLS Flight and Launch Operations

Following takeoff, Cosmic Girl ascended to a cruise altitude of 32,000 feet and proceeded into a racetrack loop off the coast of California near San Nicolas Island. Pre-launch checklists were conducted, which involved flying through the planned release point to confirm telemetry locks with ground stations in Mojave and Long Beach alongside final checks of system health, AFSS response modes, weather, and Collision On Launch Assessment (COLA) allowance. The aircraft then proceeded once around the racetrack loop, reached the release point again, and performed a controlled pitch-up and release maneuver at 11:38 AM local time. It is important to note that while the VCLS mission had no formal RAAN or launch window time requirement, vehicle release was achieved within 20 minutes of the time predicted prior to the start of launch operations. Having accurately predicted the release point on the first customer's mission bodes well for future refinement and streamlining of the LauncherOne responsive launch operations.

A trajectory overview for the VCLS mission is provided in Fig. 6. Following release and a stable descent away from the carrier aircraft, the Newton 3 main engine ignited and LauncherOne proceeded into a controlled pitch-up maneuver called a gamma turn, shown in Fig. 1. The intent of this maneuver is to continue to turn the flight path angle of the trajectory higher, eventually directing it towards space. LauncherOne is the first orbital air-launched vehicle conceived to perform this maneuver without the aid of a wing, and instead achieves substantial turning performance via gimbaling of the Newton 3 engine. Roll control during the ascent phase is managed via actuation of a gas generator exhaust nozzle as well as roll tabs on the Stage 1 fins. After passage through maximum dynamic pressure, completion of the gamma

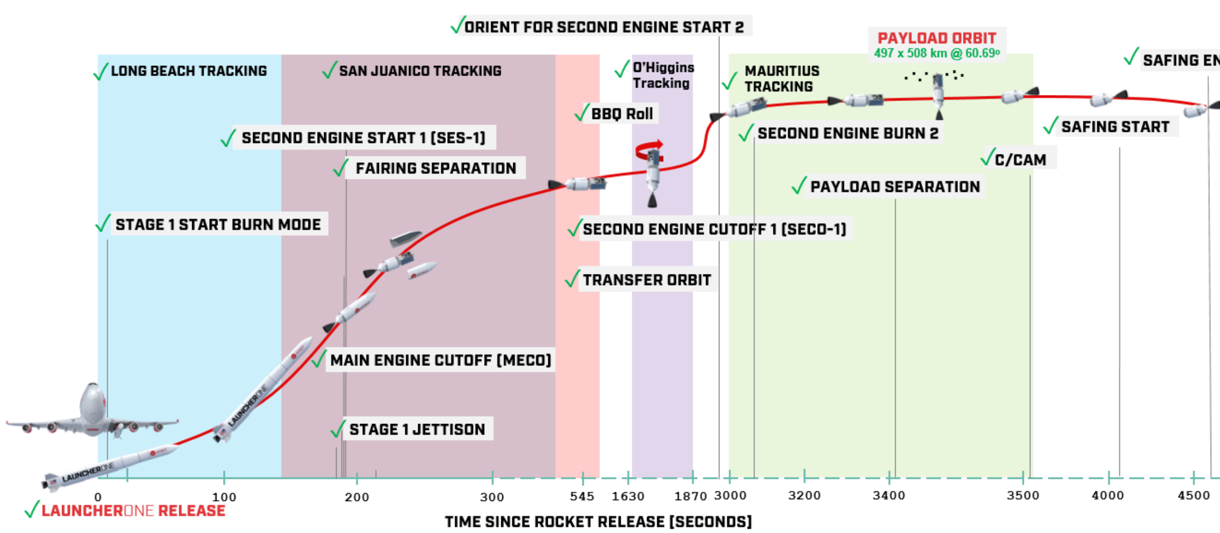

Figure 6: All major trajectory events of the VCLS LauncherOne Demonstration Mission were achieved.

turn, and consumption of all Stage 1 propellants, the Newton 3 engine cut-off nominally occurred at T+190 seconds. Stage 1 separation then followed with no recontact, confirmed by onboard camera footage as shown in Fig. 7.

The Stage 2 Newton 4 ignition then proceeded nominally, followed shortly after by fairing separation. As with the Stage 1 separation event, telemetry and camera footage indicate that the fairing separation progressed smoothly and with no recontact with the Stage 2 vehicle or payloads. The Stage 2 burn then proceeded for approximately 5.5 minutes, followed by engine cut-off and safing upon injection to a 187 x 518 km Hohmann transfer orbit. The vehicle then initiated a BBQ roll for thermal management while coasting southward, west of South America and over Antarctica, prior to reaching apogee in the vicinity of Mauritius approximately 42 minutes later. The Newton 4 engine then restarted, followed by a brief but nominal circularization burn only five seconds long. The final achieved orbit prior to payload deployment was 497 x 508 km with an inclination of 60.69°.

Figure 7: Camera footage and vehicle telemetry data confirmed a clean, nominal separation of the LauncherOne first stage.

The payload deployment sequence began at T+3127 sec, when all ten payloads were successfully injected into orbit. The deployment occurred over Mauritius in the darkness of Earth's shadow, where obtaining footage of the deployed satellites was not possible. Successful deployment was instead confirmed by way of vehicle telemetry, independently verified CubeSat Two-Line Elements (TLEs), as well as by working closely with the customer payload teams to establish contact with their payloads. Finally, the mission closed with the performance of a Collision & Contamination Avoidance Maneuver (CCAM) followed by passivation of the stage commodities and batteries. Detailed post-flight analyses have been conducted using all available forms of data and telemetry. All NASA objectives and requirements as well as internal mission requirements self-imposed by Virgin Orbit were confirmed to have been met, declaring the VCLS ELaNa 20 mission a complete success.

Figure 8: Camera footage of the VCLS Integrated Payload Stack (IPS) prior to deployment.

SCALING FOR GLOBALLY RESPONSIVE LAUNCH OPERATIONS

Since inception of the LauncherOne program, Virgin Orbit has purpose-built its workforce, facilities, infrastructure, and spaceport network to support high-rate production and global launch activity. A strategic focus on building out all required supporting facets of this responsive launch capability meant a longer and more capital-intensive development program that extended far beyond development of an air-launch vehicle or carrier aircraft alone. The NASA VCLS mission success marked a significant milestone in flight-qualifying the LauncherOne system; however this is just the first of many steps in carrying its responsive and flexible qualities to spaceports anywhere around the world. A brief overview and status of Virgin Orbit's support structure and global launch activities will be discussed here.

The LauncherOne Factory of the Future

The engine of Virgin Orbit's LauncherOne responsive launch capability is its factory headquarters in the city of Long Beach, California. This vertically-integrated rocket production facility, the first of its kind in Long Beach, is configured to produce up to 24 LauncherOne rockets per year using state-of-the-art manufacturing processes. Scaling to a high-rate production capability was a program requirement long before LauncherOne became flight-qualified, meaning the facility is already equipped and staffed to meet rapid launch cadence. Up to six rockets have been maintained in the production flow at once, with plans to increase further given the recent VCLS mission success. The facility is shown in Fig. 9.

Additive manufacturing (AM) is a centerpiece of LauncherOne's high-rate production scheme, where specifically costly or long-lead vehicle components are identified for production by AM processes. Virgin Orbit first implemented AM in 2015 with the procurement of DMG Mori's inaugural LASERTEC 4300, a Directed Energy Deposition (DED) laser additive and subtractive machining system shown in Fig. 9. More recently, Virgin Orbit has partnered closely with DMG Mori to

Figure 9: Virgin Orbit's state-of-the-art Long Beach production facility and staff is equipped to support rapid and reliable shipment of LauncherOne vehicles for launch from any spaceport in its global network.

bring a LASERTEC 6600 into service – a first-of-its-kind machine shown in Fig. 10 capable of both AM and 5-axis subtractive machining of complex parts on two independent spindles within a massive workspace volume. Its tool spindle is equipped with both the AM head and AM nozzle, allowing it to carry out metal powder injection and laser irradiation simultaneously. The result is an order of magnitude reduction in the lead time for producing Newton thrust chambers and other complex, multi-material propulsion subcomponents. Strategic implementation of AM processes within the LauncherOne production flow has allowed propulsion componentry lead times to match those of the existing lean carbon composite production timelines.

Figure 10: Virgin Orbit's LASERTEC 6600 by DMG Mori revolutionizes the AM production of complex LauncherOne parts.

Other innovations to revolutionize rocket production lead times include a new A-series composite milling machine provided by Multiax America of Grand Rapids, MI and shown in Fig. 11. Virgin Orbit worked closely with Multiax to derive and construct a customized platform, involving a closed cell CNC 9-axis machining center for composites that is compact, enclosed, with a moving bridge design, engineered to perform extremely accurate, 3D drilling and trimming operations.

Figure 11: Virgin Orbit's A-series composite milling machine by Multiax America turbocharges an already-lean composites manufacturing process.

These features are just a few examples of the many innovative facets of Virgin Orbit's Long Beach facility. Numerous production process improvements have been implemented since inception of the LauncherOne program, and for all steps of the production flow. State-of-the-art automated techniques have not only improved manufacturing portions, but also streamlined internal quality assurance, inspection, and test procedures. As new LauncherOne-ready spaceports are brought into operation, rocket production demand is anticipated to potentially outstrip the capabilities of the Long Beach facility, predicating new advancements and capitalization for which Virgin Orbit has also planned in its strategic roadmap. More detail on the status of the global spaceport network in development will be discussed in the next section.

The First Truly Global Launch Network

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 by 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[5] 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, small satellite 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[6-8]. 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, Spaceport Cornwall in the United Kingdom, and Alcântara Space Center in Brazil) 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 U.S. and allied governments such as the U.K. and Netherlands to accommodate responsive air-launch from spaceports around the world. Responsive launch, particularly via mobile air-launch systems, will enable U.S. Government and allied partners to rapidly demonstrate new payload technologies, quickly deploy new space-enabled services over areas of interest, and most importantly, reconstitute tactical and strategic space assets that have been purposely or accidentally neutralized. Launch site diversity, which is most cost-effectively achieved with air-launch systems, also enable assured access by providing alternative means should traditional fixed U.S. launch sites be jeopardized by a natural disaster, launch failure on the pad, or threatened by an adversary. Ultimately a global network of spaceports will provide the operational capabilities to accommodate a resilient responsive launch competency. The current status and anticipated capabilities of many of these spaceports will be detailed here.

Western United States: Mojave Air & Space Port

Mojave Air & Space Port is Virgin Orbit's inaugural launch operations headquarters. The spaceport has a long history in the development of new and innovative aerospace technologies, with LauncherOne becoming the latest developmental system to successfully enter operations from its runway. The NASA VCLS mission was executed from a vacant apron at the southeast corner of the main runway, depicted in Fig. 12 below. The rapid deployment and execution of a full launch operation using the LauncherOne MGSE described was a milestone qualification event, now proven by the VCLS mission. Current commercial mission ConOps require deployment within three days prior to launch, with development underway to reduce this timeline further to just 24 hours.

Western launch sites near Mojave generally offer access to polar orbital inclinations and higher. Virgin Orbit has conducted detailed analyses on LauncherOne access. Previously publicized studies[7] had indicated that inclinations as low as 40° were accessible via release sites approximately 400 nmi from the coast of California. New progress in studying the peak performance of LauncherOne access has now confirmed potential for access to these same orbits and lower, much closer and within the same approximate release range as the VCLS mission with both acceptable margins in casualty expectation risk as well as sufficient telemetry coverage by existing assets.

Figure 12: NASA VCLS LauncherOne operations transform a vacant Mojave runway apron.

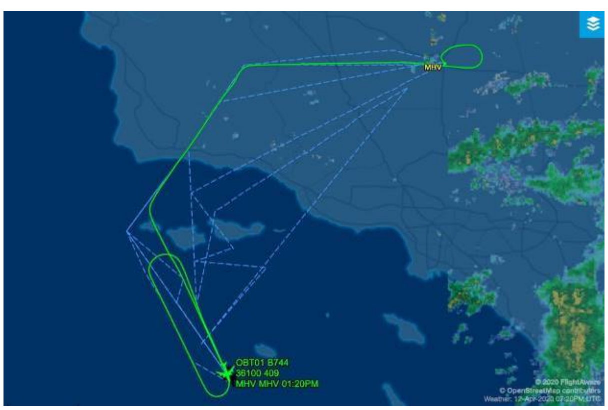

Figure 13: LauncherOne VCLS mission operations racetrack in the vicinity of San Nicolas Island.

Access to inclinations lower than most of those conceived from a west coast launch site are enabled not just by air-launch, but also by the ability to "dog-leg" the LauncherOne trajectory seeking to substantially reduce overflight risks to downrange populations beneath its path. Assessment of a 45° inclined LEO injection utilizing a dog-legged trajectory along the coast of the Baja peninsula originating from a release site in the vicinity of the successful VCLS mission has confirmed viable access to mid-inclination orbits, when exercising LauncherOne from Mojave Air & Space Port. Orbits of this inclination have generally only been considered achievable via east coast launch sites like those at Florida, bringing a new perspective regarding the orbital access afforded by air-launch. For commercial small satellite customers this would mean low-cost, dedicated access to orbital inclinations between 30° and sun-synchronous (SSO) from a singular spaceport in Mojave.

United Kingdom: Spaceport Cornwall

Virgin Orbit has made exciting progress in establishing launch operations from the U.K. mainland at Spaceport Cornwall, having been selected in 2019 to become LauncherOne's first of many international launch sites. Leveraging a deep partnership with spaceport authorities, the engineering and production teams have collaborated to produce a streamlined launch ConOps that leverages the local British space industry to enable domestic small satellite launch from the runway at Newquay with minimal interference to existing commercial airline operations. Substantial progress in the development of the LauncherOne Transportable Ground Operations System[9] (TGOS) has been made resulting in the selection of local manufacturer AVS, to build this critical portion of infrastructure[10]. Building upon the MGSE approach developed for launch operations in Mojave, TGOS represents an evolutionary approach that allows Virgin Orbit to conduct expeditionary responsive launch operations from its growing network of international spaceports. Leveraging local British industry to participate in building this domestic capability not only grows the regional space ecosystem, but expands local industry's ability to engage in the global space marketplace.

Figure 14: LauncherOne U.K. operations at Spaceport Cornwall are foundationally designed to dovetail with ongoing commercial airline operations.

The approach here is inherent to the Virgin customer-centric focus much like the Virgin Launchpad incubator and education program, which provides mentorship to startup space companies and connects them with global incubator and investor networks. Programs like TGOS and Virgin Launchpad are designed to create and accelerate an industrial and scientific cluster to provide a boost to the industry, in partnership with research and development initiatives driven by the British government as well as local universities and research institutions to harness and transform skilled resources for the nation.

Alongside the progress on the spaceport operations site and mobile infrastructure, Virgin Orbit has also seen promise in new mission analysis work highlighting the orbital access afforded by air-launch from Cornwall. Previous work[7] showed an ability to reach inclinations as low as 70° using air-launch release sites within range of the U.K. mainland. At the time of that analysis, access to lower inclinations was impeded by hazard assessments for downrange flight corridors over populated areas in Europe and Africa. Following the success of the VCLS flight, updates to the LauncherOne casualty expectation model and spaceport feasibility access tools previously published[7] have indicated new potential in reaching orbital inclinations down to 40°. An inclination access "fan plot" specifically for orbits between 35° and 60°, as well as a release site selection map are shown in Fig. 15.

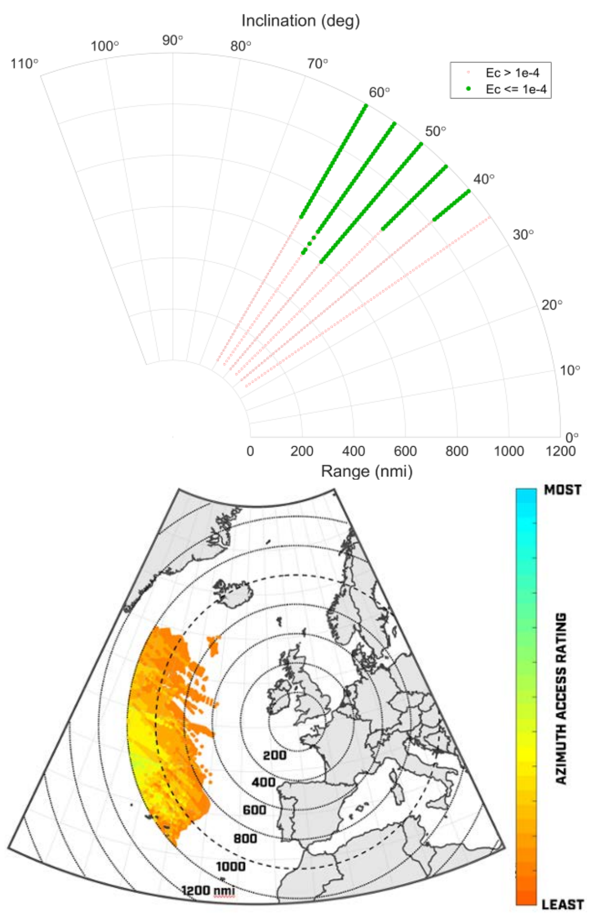

Figure 15: New LauncherOne mission analyses from west of Spaceport Cornwall indicate eventual access to mid-range inclinations from 40° to 60°.

Favorable access to most of these orbits is found to the southwest of Cornwall, at release sites ranging between 800 and 1,200 nmi from the spaceport. Access to inclinations between 50° and 60° are possible at sites just beyond 600 nmi. Many viable sites are located in the vicinity of the Azores, meaning potentially favorable telemetry coverage by either existing island sites or new transportable ground assets also under review.

These results are particularly promising in that they indicate a large degree of orbital access long considered unsafe or impossible from a mainland U.K. spaceport. Now that LauncherOne and its mobile ground support infrastructure ConOps are flight-proven, an eventual high cadence of the launch for nearby British and Eurozone payload customers to a wide range of orbital targets from Cornwall is within reach. For more information on previous analyses used to confirm U.K. access to inclinations higher than 60°, including polar and sun-synchronous, please see Ref. 7.

Various LauncherOne mission design activities are moving forward in the U.K. such as the Royal Airforce (RAF) project Artemis[11], with Surrey Satellite Technology Ltd., Airbus, Raytheon, the U.S. government, and launch provider Virgin Orbit as partners. The RAF has also seconded Flight Lieutenant Mathew "Stanny" Stannard, who has been integral to flight operations and airspace regulatory framework design, and will co-pilot the first LauncherOne mission from Spaceport Cornwall, establishing a blueprint for how Virgin Orbit is working with U.S. allies to help them train and equip a sovereign responsive launch capability.

The international importance and gravity that a responsive sovereign launch capability will carry within the coming decades cannot be understated. Britain and Spaceport Cornwall's inaugural role in its development are critical. Accordingly, Virgin Orbit was honored to present LauncherOne on-site to the allied world leaders arriving at the 2021 G7 conference in Cornwall.

Figure 16: LauncherOne on display for allied world leaders attending the G7 conference in Cornwall.

Japan: Spaceport Oita

In April 2020, Virgin Orbit announced a collaboration with ANA Holdings and Oita Prefecture of Japan to establish the first horizontal spaceport in Asia. Using an existing seaside runway at Oita Airport, LauncherOne operations there will bring Japan added domestic orbital access to a wide range of inclinations. Since that time and much like the progress made in operational work at Spaceport Cornwall, teams across Virgin Orbit and the Oita Prefecture government have collaborated to arrive at a streamlined ConOps design for the safe execution of LauncherOne mission campaigns.

Evolved modular ground support equipment will be implemented for responsive launch operations on the Oita commercial apron. Launch operations designers have also confirmed that a compact LauncherOne operational footprint is safely feasible with minimal disturbance to ongoing commercial airport operations. In addition to launch operation planning and build up, FAA is working closely with Japan regulators on streamlining international spaceport collaboration and launch licensing process. Virgin Orbit is collaborating with ANA Holdings and the Space Port Japan Association to bring not only on-demand responsive launch solutions to Asia, but a new space innovation model through programs such as the Virgin Launchpad and a future regional space innovation center.

Beyond the progress in launch operations design, equally exciting work is underway on assessing the LauncherOne release site and orbital access corridors feasible from Spaceport Oita. Previous studies[7] have already indicated a healthy degree of orbital inclination access from Oita, between 25° and SSO. Additionally, LauncherOne's ability to release at many sites in the vicinity of Japan enables many JAXA telemetry coverage solutions and greatly increases the amount of daily launch opportunities to all of those inclinations, especially to mid-inclination targets. Such conclusions were sought early on to establish the responsive and flexible launch options inherent to LauncherOne.

Recent work has now focused on designing mission-specific trajectories to many of the inclinations in that range, and to confine them to common release regions in order to streamline the regulatory processes necessary for each mission. Two promising release site regions have been identified as shown in Fig. 17: one in the vicinity of Okinawa for mid-inclination access, and one south of Chiba prefecture for inclinations 60° and higher. These regions are convenient not only because of their low, approximately equidistant range from Spaceport Oita but also because of the favorability in coverage by existing JAXA telemetry assets for the trajectories assessed. Previous work[7] did indicate substantial quantities of feasible release sites closer to Spaceport Oita as well, but these new collections have been derived in an effort to further "commonize" the solutions into similar mission ConOps when extreme flexibility is not necessarily needed by the customer.

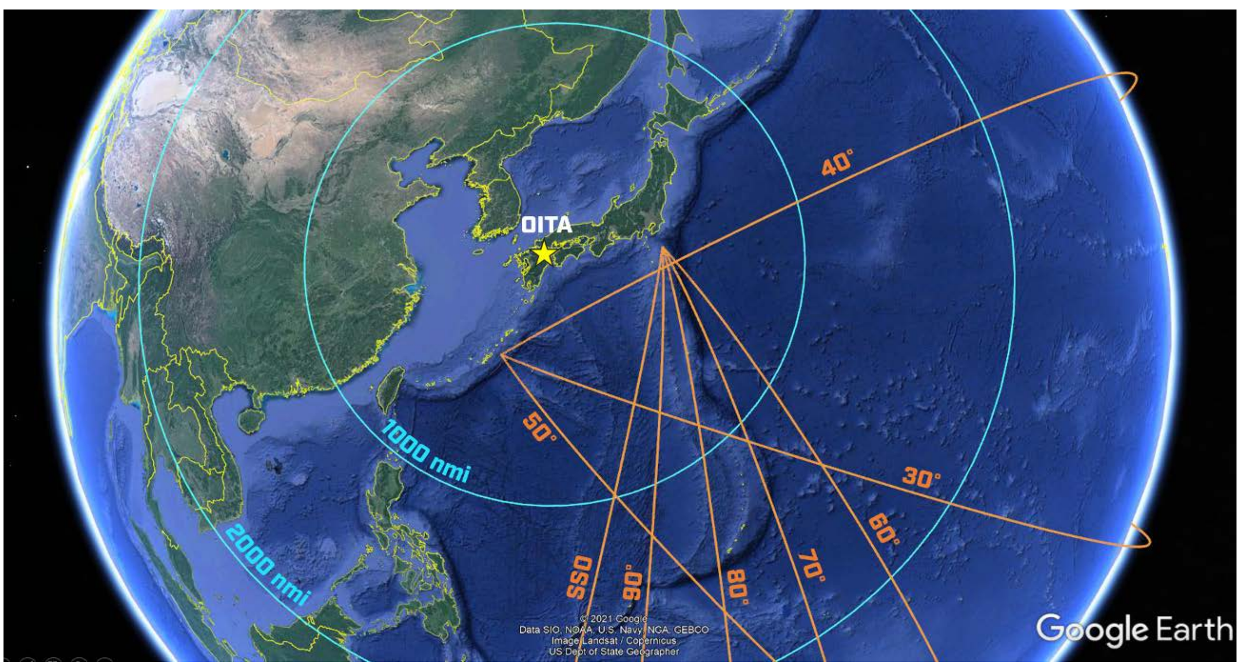

Figure 17: Detailed trajectory analyses in the vicinity of Spaceport Oita have identified two convenient regions for the origination of many LauncherOne mission inclinations with favorable telemetry coverage.

Brazil: Alcântara Space Center

Alcântara Space Center of Brazil is the newest addition to Virgin Orbit's global network of potential LauncherOne-ready spaceports. A deep and growing interest by the Brazilian government to jumpstart their local aerospace sector recently coalesced with the passage of a Technology Safeguards Agreement (TSA) with the United States Government[12]. Following ratification, Brazil and the U.S. could now review and permit U.S.-based launch operators like Virgin Orbit for operations at the existing Alcântara Space Center near the equator. The Brazilian Space Agency and Brazilian Air Force then issued a public call for proposals from operators, after which Virgin Orbit was honored to be selected[13] to formally enter into negotiations for potential LauncherOne operations in Brazil. The nationally-publicized selection ceremony pictured in Fig. 18 occurred on April 28th, 2021 in the capital city of Brasilia and was attended by President Bolsonaro alongside several ministers and officials within the Brazilian government.

Figure 18: Virgin Orbit's selection for potential LauncherOne operations at Alcântara.

The Alcântara Space Center represents a tremendous resource for Brazil and its growing aerospace sector. Situated near the equator, the facility is already geographically ideal for peak launch performance. It has accommodating and predictable weather patterns, and low nearby population and traffic densities that reduce launch risks. And perhaps most importantly, Alcântara possesses a high degree of capable and accommodating infrastructure that can support temporary or long-term mobile launch operations, reducing the "setup cost" barrier to entry. These and other important factors drove Virgin Orbit's decision to pursue partnering with Brazil toward potential LauncherOne operations at the facility.

When paired with air-launch, a continental launch site on the equator like Alcântara represents a 'wild card' for orbital access. Stated another way: there are virtually no LauncherOne small satellite missions that cannot be accommodated by the site. Previous studies[7] by Virgin Orbit indicated substantial access to all orbital inclinations as indicated in Fig. 19, and many with twice daily launch opportunities given the ability to launch at both northern and southern departure azimuths. This is a powerful conclusion when pursuing a flexible and responsive launch approach, with call-up times targeting 24 hours or less; this also provides planners for missions to cis-lunar space and beyond with expanded access to optimal launch windows, maximizing their launch flexibility. No orbit is out of reach when pairing the mobile qualities of LauncherOne with the superior geographics and logistical support potential at a site like Alcântara.

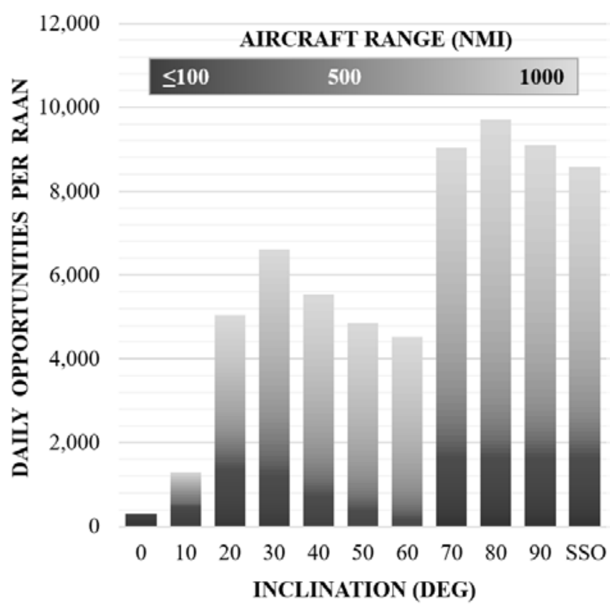

Figure 19: Air-launch is shown to permit domestic Brazilian access to all orbital inclinations[7].

Provided the possibilities above and the honor of Virgin Orbit's selection by Brazil for consideration, engineering teams are now working to develop detailed ConOps and logistics to facilitate potential LauncherOne missions from Alcântara. As with the other spaceports discussed in this paper, progress is underway to determine the potential of an evolved MGSE shipset that can rapidly deploy in Brazil to support mission campaigns of 2-3 launches at a time. There is confidence that the Center can support near-term LauncherOne operations with minimal modification to the existing facilities due to their inherent compatibility with air-launch and a liquid vehicle of this scale. The operations apron adjacent to the Alcântara airbase runway has already been evaluated for viability to support the launch operations footprint with minimal interference to ongoing base activities, with the layout shown in Fig. 20. This is particularly important because Virgin Orbit seeks to implement operations using only existing space center facilities, with no expansion risks to nearby communities. Its portable qualities make this goal achievable while simultaneously bringing growth potential and jobs to the region.

Regulatory work is now underway to establish compatibility with FAA-regulated launch licenses, with good progress given the excellent collaboration between the FAA, Brazilian, and Virgin Orbit teams. Given the orbital access advantages of Alcântara discussed, there are virtually no barriers to conducting multiple commercial or government missions in rapid succession. This aspect is powerful in both the flexibility to re-arrange manifests with low impact to schedule and cost.

Figure 20: LauncherOne's Alcântara operations can be accommodated by the existing airbase apron, demonstrating the uniquely mobile and expeditionary capabilities of the system.

Pacific Ocean: Guam

The island of Guam is Virgin Orbit's second-announced destination for LauncherOne operations. A U.S. territory within close proximity to the equator, Guam possesses two compatible airbases for launch operations: A.B. Won Pat International Airport and Andersen Air Force Base. Virgin Orbit and its subsidiary VOX Space are collaborating closely with U.S. Government personnel to establish inaugural launch operations from Andersen AFB, with the first LauncherOne mission scheduled there for 2022. LauncherOne operations using a set of MGSE stationed in Guam creates a prime launch location expected to unlock responsive access to any orbital inclination required by a payload, between 0° and SSO[7].

Future Spaceports

Virgin Orbit has now established a flight-proven, responsive launch capability that is pre-dispositioned for launch from compatible spaceports around the world. As indicated in previous work[6,7], the company has invested heavily in the workforce, autonomy, and tools necessary to rapidly assess and qualify new potential spaceports for this compatibility. Alongside the tremendous progress at the publicly announced spaceports discussed, other work is underway to determine the options and value of air-launch operations at other new spaceports as well. The current roster of upcoming LauncherOne-ready spaceports already guarantees access to any orbital inclination, and always with at least two sites being capable for any one mission for redundancy. The establishment of any new horizontal spaceport will simply add to the existing flexibility of the system, offering more launch options to more customers, while growing the local space ecosystems of the regions that choose to do so. Virgin Orbit will continue to release periodic updates regarding ongoing and new spaceport developments.

Furthermore, given LauncherOne's mobility, Virgin Orbit is working with various allies to establish a global spaceport architecture built upon a 'hub and spoke' model. While LauncherOne hubs such as Mojave, Cornwall, and others will service missions in their region and house their own MGSE, LauncherOne ready sites will serve as 'spokes' and serve as pre-analyzed sites capable of supporting quick-call expeditionary launch campaigns. In addition to spurring regional industry space ecosystems, this network will enable government operators to rapidly disperse and disaggregate their launch infrastructure while preserving assured access to space. The establishment of any new horizontal spaceport will simply add to the existing flexibility of the system, offering more launch options to more customers, while growing the local space ecosystems of the regions that choose to do so. Virgin Orbit will continue to release periodic updates regarding ongoing and new spaceport developments.

Air-Launch Fueling a Responsive Space Ecosystem

With the VCLS ELaNa 20 mission success, the LauncherOne system is now flight-proven and positioned to enable launch responsively from austere locations around the world with minimal infrastructure. Virgin Orbit has detailed the responsive qualities of air-launch in the proceedings of the North Atlantic Treaty Organization's (NATO) 2021 Joint Air & Space Power Conference[14]. Horizontal launch operations can be implemented rapidly to bring orbital access to nearly any country from any airport near a coastline with a sufficiently long runway. Typical air-launch operations generally require a concrete apron large enough to accommodate the carrier aircraft that is displaced from heavy traffic or other airport personnel. Most international commercial airports or government airbases can accommodate such a need. LauncherOne is now the foundation of a "Responsive Space" ecosystem.

Responsive Space yields a broad set of strategic benefits that can enhance the activities of payloads in space while enabling added resilience. One unique benefit of Responsive Space is the ability to rapidly deploy a new system. A mobile air-launch system can be deployed from a myriad of existing airports regardless of current system deployment locations and mobilized to rapidly launch a constellation of new satellites. Access to these multiple horizontal launch sites can provide payload customers with the ability to inject the satellite directly into its orbit to minimize the time in between launch and activation of a complete satellite constellation. When coupled with a network of spaceports within different countries, multiple viable pathways to orbit exist and can be quickly activated in any combination. Satellite spares can be stored on the ground rather than on-orbit, allowing further cost savings for payload customers. This unlocks an array of opportunities to enhance space-based missions, particularly focused on national security applications, such as:

- Intelligence, Surveillance, and Reconnaissance: Unexpectedly deploy a new overhead sensing layer to hinder adversarial efforts to conduct operational maneuvers during existing collection gaps
- Communications & Positioning, Navigation, and Timing: Directly inject into a unique orbit (e.g. Magic Orbit) to surge capacity over an area of interest
- Space Domain Awareness: Respond and rapidly deploy into a mission-specific orbital plane to observe a specific target and preserve satellite onboard propellant for required follow-on maneuvers

A tactical benefit for national security customers of a disaggregated LauncherOne system is the ability to provide multiple mission origination locations that can hinder an adversarial response to the deployment of new space capabilities. For example, via loitering or switching among different potential release zones, an air-launch platform provides thousands of daily launch solutions when compared to a fixed-site launch infrastructure. Figure 21 shows how multiple orbital inclinations are accessible via different release points within close proximity of both Alcântara and Oita. Thousands of different origination points with little downrange land overflight can be pre-planned, selected, and executed at will as part of a responsive mission scenario, offering the most flexible and variable orbital launch capability ever conceived. These tactical benefits roll up into a broader strategic impact that expands the space decision-making landscape. Traditionally, space operations have been dictated by the long lead times and the predictability of space activities—operations in space require known sequential dependencies that are defined by physics and orbital mechanics that cannot be disobeyed. LauncherOne transforms this dynamic as it allows for planners add far more situational variables, such as access to orbit from numerous launch sites and a reduced timeline to execute. As former U.S. Assistant Secretary for the Air Force Dr. Will Roper explained[15], this capability is "The satellite equivalent of keeping an ace up your sleeve."

CONCLUSIONS

The NASA VCLS ELaNa 20 mission success was a historical milestone for both Virgin Orbit and for the small satellite industry. LauncherOne entered the history books as the first cryogenic-fueled air-launched rocket to reach orbit, capping off six years of development while immediately transitioning into low-cost launch operations. The obstacles overcome during this time were not confined to the technical complexities of launch vehicle design – but also spanned a broad strategic horizon focused on creating the most mobile, responsive, and powerful launch solution ever conceived:

- A world-class staff skilled in all aspects of vehicle design, qualification, operations, business, and program management was assembled from scratch
- The design, qualification, integration, and successful flight of the LauncherOne vehicle
- A flexible and long-range 747 carrier aircraft was procured and modified for global captive carry and release operations
- The LauncherOne production facility, a factory of the future, was conceived and built to produce LauncherOne vehicles at high rate and low cost
- Several major spaceport initiatives with active work underway to build a truly global launch network

Post-flight analyses have confirmed all objectives of the ELaNa 20 mission were achieved. All payloads were injected to orbits of semimajor axes within ±7.5 km and inclinations within 0.01° of nominal targets. Engineers are now utilizing telemetered flight data and calculated flight margins to further tune and improve future LauncherOne flights with promising progress. An imminent update to the LauncherOne Payload User's Guide[4] is also underway.

Air-launch architectures have long been proposed as a flexible solution to responsive launch needs[6-8], a fact that has now been flight-qualified from a normally vacant runway apron in Mojave. Virgin Orbit now continues to build upon this globally responsive launch solution with the development of extensive mission planning tools to transparently communicate the benefits of air-launch. The products of these tools have been used extensively in the collaborations identified here, at the spaceports across LauncherOne's growing network. New improvements to these tools alongside lessons-learned from the ELaNa 20 mission success have revealed new and exciting conclusions for LauncherOne global operations:

- Confirmation of mid-inclination access, 40° and potentially lower, from release sites in the vicinity of Mojave, CA
- New viability of lower orbital inclination access from Spaceport Cornwall in the U.K., originally presumed limited to only near-polar access
- Consolidation of mission-specific trajectories in the vicinity of Spaceport Oita in Japan into common regions allowing streamlined regulatory approval scenarios
- Refinement of operational feasibility and extreme orbital access afforded by LauncherOne operations based at Alcântara Space Center in Brazil

Confidence in any responsive mission scenario is assured by the LauncherOne system, 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. The emergence of international spaceports is further igniting small satellite operational launch rates and manifests. Their regional governments are committing to create sustainable local space ecosystems as evidenced by recent public announcements and work. Virgin Orbit observed these trends before LauncherOne was conceived, and has developed the system, its supporting production and operational infrastructure, and a truly global spaceport network to match the needs of a thriving small satellite industry.

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