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Modularized air-launch with Virgin Orbit's LauncherOne system: Responsive smallsat constellation construction measured in hours, not months

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ABSTRACT

As small satellites and the constellations they comprise have become increasingly prevalent, there has been greater interest in the value added by agile and responsive launch systems. Responsiveness, defined here as the ability of a launch vehicle to react quickly and positively to changing payload, customer, or situational constraints, is a capability that has largely been enabled by the rise of the smallsat launch industry and introduces a new set of considerations for smallsat mission stakeholders. This work examines the relative advantage of an air-launched small satellite launch vehicle network for rapid deployment of small satellite constellations, using Virgin Orbit's LauncherOne system and three hypothetical constellation architectures.

Using a combinatoric approach to analyze the possible launch manifests for hypothetical constellations, the impacts of geographic launch site positioning and launch vehicle recycle time on constellation injection time and thereby time-to-market for the constellation missions' provided service are examined. It is demonstrated that the air-launched architecture requires a third as many launch platforms at fewer activated spaceports than an equivalently-performing fixed-site launch network, among other advantages. Gaps in the existing policy framework to support responsive launch as well as a plan for future work within this research area are then identified.

INTRODUCTION

The rapid growth of the small satellite industry has recently revived the concept of satellite constellation architectures as highly applicable, practical, and commercially viable pursuits. Extensive prior work has studied the manner in which small satellite technology directly enables the development of constellation mission architectures.[1,2] In many cases, modern constellations leverage ground-breaking manufacturing practices to support the rapid, low-cost production of small spacecraft.[3] In turn, mission designers are pursuing constellation architectures that can include upwards of hundreds of small satellites that will be capable of providing revolutionary insights into terrestrial infrastructure, Earth science, broadband communications, and emergency response, among others. These new constellation systems have already begun to challenge the traditional launch-manifesting paradigm and spurred innovation among launch service providers in the form of new vehicles and novel aggregation strategies.

Recent trends suggest that an increasing fraction of launch industry revenue is being captured by less expensive launch vehicles,[4] such as Virgin Orbit's LauncherOne. As dedicated launchers continue to emerge as solutions for small satellite constellations, understanding the relative performance capabilities of these vehicles will be crucial to industry development. A key emerging question is how dedicated small launch vehicles can bolster the small satellite market through advances in responsive launch strategies. Particularly, as these satellites are rapidly mass-produced, constellation customers will be best served by launch solutions that minimize time-to-market. A virtuous cycle would then allow manufacturers and operators alike to continuously offload costly reliability and risk design margins from their on-orbit assets in favor of rapid constellation construction and replenishment.

Virgin Orbit's LauncherOne system has been developed to provide dedicated, responsive launch opportunities to small satellites and aims to address the diverse and

unique challenges facing today's small satellite industry. LauncherOne leverages the benefits of air-launch and advances in additive and subtractive manufacturing to enable constellation missions to pursue more nuanced deployment strategies and to provide small satellite missions with tailored launch services.

This paper outlines Virgin Orbit's role in furthering the ongoing small satellite revolution, with particular emphasis on the role of responsiveness as a critical metric by which launch vehicle performance can be assessed. Here a responsive launch architecture with multiple geographic launch sites and modularized systems at each is proposed as a candidate launch system that can be used to bring an entire constellation online within timescales measured in hours, not weeks or months. The relative advantages offered by a mobile, air-launched small satellite launch vehicle for such constellations as opposed to a set of ground-launched vehicles from fixed site are identified. Using a hypothetical reference mission as a baseline, we are able to quantify the relationship between the nature of the launch vehicle and the amount of time it takes to bring a full constellation of small satellites online. This work contributes both an initial framework for the parameterization of this question, as well as a demonstration of the increase in value offered to constellation end-users through rapid first-to-market capabilities. We conclude by discussing how this case study can serve as the foundation for future work in rapid constellation replenishment strategies.

STATE OF THE SMALLSAT INDUSTRY

The rise of small satellites has transformed the industry approach to space mission design. Small spacecraft are more capable than ever before, and in many cases can be developed more quickly and cost-effectively than their larger predecessors. 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.[3] As enthusiasm for novel smallsat mission architectures grows, the dynamic needs for agile and responsive launch systems are similarly increasing. There is widespread acknowledgement of the bottleneck in small satellite launch opportunities,[5,6] and in some cases, even if launch slots are available, launch systems may not provide tailored smallsat mission support. Simply put, there are an insufficient number of dedicated launch opportunities for small spacecraft and this limitation is restricting technical and financial growth in both sectors.[3]

Commercial Space Revolution

Many of the recent conversations surrounding "New Space" technology and investment have centered on the notion of a modern day space race. Unlike the geopolitical conflicts governing the "First Space Age" (1957-1990), the "Second Space Age" (1991-Present) has been significantly driven by commercial interests, including renewed investment, innovation and utilization of small satellite technologies.[7] The resultant technical development has been diverse and disruptive, making space-based resources more commonplace as commercial tools and infrastructure elements, but also presents greater capacity for disordered growth. [7] More than 220 new angel- and venture-backed space companies were founded between 2000 and 2018.[8] Furthermore, growth within this time frame has been accelerating. In the early 2000's, an average of four funded space companies were started per year, and in the last six years, that average has increased to 21 new, funded companies per year.[8] Small satellite growth in this timeframe suggests that smallsats 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.[9]

The small satellite launch industry has similarly expanded in recent years, and the small satellite launch rate has risen by 250% since 2016.[9] However, existing launch services address only 52% of the current, total market demand. Small satellites have primarily been manifested as rideshare or secondary payloads on much larger launch vehicles, Smallsat access to space is limited by rideshare and secondary payload capacities on large launch vehicles, and the waiting period for these launch slots can range from six months to two years.[10] Collectively, the impacts of these practices can constrain smallsat mission design and dramatically impact spacecraft storage, processing, and integration strategies. The development of low-cost launch vehicles that offer on-demand access to space for small satellite operators has helped to close this gap, but further development will be needed to promote long term smallsat success.[6] More than 40 small launch vehicles, defined as those which have a payload capacity of less than two tons, are currently under development and set to be operationalized in the next two to four years.[10]

Constellations

A key subset of the current commercial launch demand stems from the implementation of distributed space missions (DSMs) and constellations. The rise of second generation constellation missions has coincided with a 189% increase in the annual non-geosynchronous launch rate since 2010, relative the first generation of constellation development (1997 to 1999).[3] While smallsats are being used for a greater diversity of objectives than ever before, telecommunications and remote sensing missions are finding novel solutions by leveraging constellation architectures and have contributed much of this growth:[3] "In total, more than 30 commercial operators are building small satellite capabilities and large constellations in Low-Earth Orbit (LEO) to offer low-cost imagery and affordable global connectivity solutions." [10] Recurring and continuous launch capabilities will be essential to the success of these systems, and the launch market value associated with establishing and maintaining fully operational pLEO constellations is estimated to exceed $62 billion by 2030.[10]

The global demand for space-based broadband internet is calling particular attention to the needs of telecommunications constellations. By the end of 2019, half of the world's population is expected to be connected to the Internet, leaving the remaining approximately 3.8 billion people disconnected from both social and economic resources in the ever expanding digital world.[11] Many companies are seeking to address this gap through constellations capable of providing global internet access by leveraging networks of hundreds if not thousands of spacecraft. This architecture type, commonly known as a planned commercial proliferated LEO (pLEO) constellation, has been adopted by SpaceX, Amazon, Facebook, Boeing, and OneWeb, among others.[10, 12, 13, 14]

Interest in small satellite remote sensing spacecraft has grown similarly, particularly with the rise of companies like Planet Inc., which has leveraged low cost, highly iterative generations of spacecraft within its Earth imaging constellation to generate vast quantities of data for a wide range of applications. Furthermore, small satellite constellations are likely to offer unique, cost-effective solutions for science missions in the coming decades in a way that has not been technically feasible until now.[6] Existing research has examined how the design of Earth observation constellation designs must take into account these increased capabilities, while trading against the remaining technical limitations and a desire for mission robustness.[15] Continued research in this arena is likely to further bolster Earth science and remote sensing constellation mission success.

Changing Paradigm of Launch

Historically, the vast majority of launch service providers have leveraged ground-based launch systems,[16] 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. Launch sites which can be more geographically dispersed offer opportunities for non-traditional launch sites and access to more azimuths.[17] Virgin Orbit's broader strategic architecture includes key 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. Spaceport Japan and Spaceport Cornwall in the United Kingdom) but also help implement the infrastructure required for resilient launch capabilities. In addition, Virgin Orbit is working closely with the U.S. Government to accommodate air-launch from allied spaceports around the world. This global network of spaceports will provide the operational capabilities to accommodate a resilient responsive launch competency.

The changing needs of small spacecraft and smallsat constellations, demanding more agile and flexible launch schedules, provide an excellent opportunity to demonstrate and assess the long term viability of air-launched systems, such as LauncherOne or Northrop Grumman's Pegasus vehicle. Constellation missions have spurred interest and research in how the overall launch mission strategy can impact constellation performance. Prior work focused on constellation launch manifesting has considered launch strategies for optimal constellation performance, for both homogeneous and heterogeneous constellations, as well as the effect of the manifesting strategy on system reconfigurability.[18, 19, 20] However, there is limited work thus far examining the changes in these strategies when using an air-launched vehicle. Frick et al., have previously examined the role of responsiveness in supporting U.S. government interests, including constellation replenishment or initial constellation block installation. [17]

TERMINOLOGY AND SCOPE

Terminology

The following common terminology is used in the setup, analysis, and discussion of results for the responsive constellation launch analysis. 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; in the case of LauncherOne, a spaceport is specifically an airport with runways capable of accommodating 747 carrier aircraft
- **Air-Launch –** a mode of launch involving a carrier aircraft and a rocket 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 launch that can react quickly and positively to changing payload, customer, or situational constraints, whether predictable or not
- **Constellation Injection Time –** the duration between initiation of first launch and final launch to the planes of a complete constellation

Scope and System Overview

In order to illustrate the flexibility and responsiveness of the air-launch approach using a mobile, modular infrastructure, this paper provides an analysis that examines how such a system can perform to rapidly launch a variety of diverse smallsat constellations. The LauncherOne air-launch architecture forms the basis of this analysis. This study is about capabilities as they can potentially be, and is not intended to be definitive that the system is the best of all possible launch 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 liquid propulsion rocket, powered by the main stage engine, Newton-3, a 73,500 lbf, LOX/RP-1 rocket engine after releasing from the carrier aircraft. After stage separation, the upper stage engine, Newton-4, a 5,000 lbf LOX/RP-1 rocket engine will ignite and carry the satellite(s) into orbit. 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 Figs. 2 and 3 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

Figure 3: Mobile payload trailer assets offer maximum payload processing flexibility

LauncherOne operations consist of the integration of four elements: Cosmic Girl, the carrier aircraft; LauncherOne, the payload launch vehicle; the customer payload; and Ground Support Equipment (GSE). 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 L1 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 then 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 takeoff to the release point for launch.

ANALYSIS AND RESULTS

Responsive Launch Experiment Setup

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. A result of this application would mean that constellations can be launched more rapidly, utilizing both 747 and support hardware shipsets for launch in tandem and in quick succession.

Three constellation launch case studies will be designed and assessed to demonstrate the advantages in responsiveness of a globally distributed air-launched rocket architecture as conceived in Fig. 4. Notionally comprised of three or more launch-capable carrier aircraft, multiple shipsets of mobile ground support equipment, and self-enabled by cargo carrying aircraft capacity, this system can be globally disaggregated to form the basis of a responsive launch architecture. While it is clear that activating several spaceports with one or more launch systems at each means that several unique orbits can be populated quickly, both the actual constellation injection timing and the high degree of launch permutations possible are obscure without further detailed study. The case studies considered will pose varied and unique commercial and government constellations to be launched from some combination of activated spaceports in the fastest manner possible, and in any ConOps combination. The results here demonstrate a small subset of what may be launched responsively in this manner.

Analysis Tool Description

A Matlab-based responsive launch toolset specific to this application was designed based on combinatorics. Combinatorics is a branch of mathematics dealing with the enumeration, combination, and permutation of sets of elements that adhere to certain constraints. In this case, the elements are considered geographic locations (spaceports) with some combination of launch systems that may launch to some number of orbital planes in a constellation. The constraints are that some spaceports may not launch to certain orbits based on inclination, range safety, or launch system recycle restrictions. This type of analysis is necessary because for any given set of activated spaceports each with some quantity of readied air-launch systems, hundreds of thousands of possible launch scenarios might be considered. This is also particularly relevant since the actual flexibility,

Figure 4: A globally distributed, modular air-launch architecture offers distinct benefits when pursuing responsive constellation launch

responsiveness, and/or unpredictable qualities of such a system inherently enable it to meet many of those possible scenarios. Successful implementation thus demonstrates a high degree of launch possibilities for injecting large constellations in less than a day.

This tool suite requires the following inputs:

1. Activated spaceports – geodetic latitude, longitude, and inclination/azimuth restrictions
2. Constellation architecture – orbital plane quantity *N*, and the orbital elements of each plane
3. System recycle time – minimum amount of time between launches that one unique aircraft can achieve

Using the above inputs, the tool will analyze the great circles of the considered constellation and propagate the activated spaceports and their launch zones underneath in inertial space as shown in Fig. 5. The tool assumes that each rocket is fully manifested for each orbital plane, such that specific satellite payload mass and quantity are separated from the responsive launch analysis. Furthermore, the constellation performance is assumed to be independent of order in which the spacecraft are activated. Each of these assumptions simplifies the analysis, and further research into the complexities of the launch manifesting problem constitutes a meaningful venue for future research.

Upon calculating the intersections of these launch zones with the constellation's great circles, combinatorics are then used to consider every potential launch combination that may exist for a given constellation and set of activated spaceports. Launch scenarios which require launch to orbits that exceed the inclination or azimuth limitations for any candidate spaceport are identified and removed from consideration. The resulting output is a set of launch scenarios that each launch *N* rockets to the orbital planes desired, using *N* aircraft or less depending on their locations and specified system recycle time. These scenarios are then ranked in terms of fastest constellation injection time, or by minimizing the number of spaceports or aircraft needed for completion.

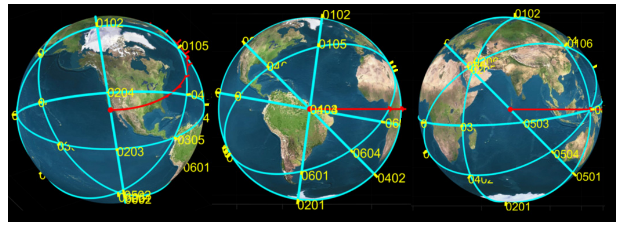


Figure 5: Constellation great circles intersect with inertially-propagated launch site ground tracks, resulting in launch opportunity combinations

Constellation Case Study Definitions

Three constellation cases will be studied in this responsive launch analysis. In these scenarios, each orbital plane would be assumed to accommodate the full payload performance mass of the launch vehicle, so specific quantities of satellites per orbital plane, and by extension for the constellation itself, need not be specified. Hypothetically speaking and in the case of LauncherOne, if these constellations comprised circular LEO orbits, the satellite mass per plane would be approximately 300 to 500 kg depending on inclination. The orbits need not be circular or in LEO however, and are only required to be reachable by the launch vehicle with some deployable payload mass.

The first case study analyzes a common commercial constellation, using six sun-synchronous orbits spaced for relatively even global coverage and generally suited for remote sensing applications. Four commercial spaceport regions capable of handling one or more LauncherOne 747 aircraft are considered: Mojave, Cornwall (UK), the equatorial region of South America, and Japan. Additional spaceports can be considered, however given the already high accessibility to SSO from these four it is not required for the purposes of this study. Table 1 details the parameters of case study #1.

The second case study involves a notionally designed military communications constellation, utilizing six orbits at various inclinations and rights ascension. This constellation is tailored to mimic more frequent revisit times at lower latitudes that are potentially attractive to military users. Five commercial and possibly military spaceport regions each capable of handling one or more

Table 1: Responsive constellation launch case study #1: Commercial remote sensing

Constellation Type	Commercial remote sensing
Orbital Planes (N)	6
Apse Altitudes	Any altitude achievable by launch vehicle
Inclination	Sun-synchronous (all planes)
RAAN	0°, 120°, 240°, 30°, 150°, 270°,
Spaceports	Mojave, South America, UK, and/or Japan (4)
System Recycle Time	4 to 16 hours between launches

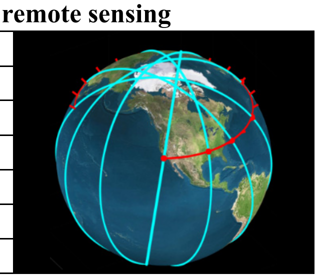
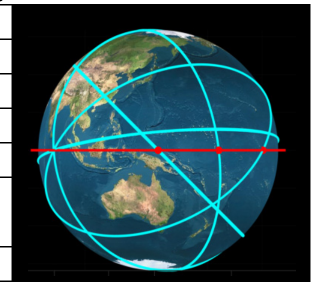


Table 2: Responsive constellation launch case study #2: Resilient military communications

Constellation Type	Military resilient constellations
Orbital Planes (N)	6
Apse Altitudes	Any altitude achievable by launch vehicle
Inclination	97.6°, 97.6°, 10°, 45°, 45°, 10°,
RAAN	0°, 90°, 0°, 0°, 120°, 240°,
Spaceports	Mojave, Guam, South America, Diego Garcia, and/or Ascension (5)
System Recycle Time	4 to 16 hours between launches



LauncherOne 747 aircraft are considered: Mojave, Guam, the equatorial region of South America, Diego Garcia, and Ascension island. Table 2 details the parameters of case study #2.

The third case study considers a newer concept of a disaggregated string of pearls constellation or "A-Train" style launch utilizing five coincident orbits, but with payloads that originate on different launches. This mission architecture could be suited to civil and international emergency response initiatives requiring ultra-fast response and launch paired with disaggregated risk. An example would be a large-scale disaster monitoring response, rapidly tailored to suit highly specific geographic targeting parameters. Four commercial spaceport regions each capable of handling one or more LauncherOne 747 aircraft are considered: Mojave, Guam, the equatorial region of South America, and Cornwall (UK). Table 3 details the parameters of case study #3.

These three diverse case studies are designed to show how an air-launch architecture inherently suited to responsive launch has particular advantages to launch such constellations in less than a day and with disaggregated risks. It can do so from a myriad of different spaceports (normally more of which would be included in these case studies, but are limited by way of computational resources), highlighting a flexibility that cannot be matched by ground launch architectures designed for the same purposes without substantially higher infrastructure investment. The following sections detail the results of the combinatoric analyses on each of the case studies proposed.

ANALYSIS RESULTS

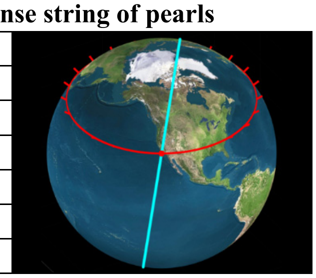
The combinatorics analysis of each case study produced thousands of launch combinations that achieve completion in less than a day, which may be organized and sorted so as to meet a particular combination of spaceports, aircraft count, or constellation injection time. These combinations are reported in Figs. 6-8, which show analysis results from two of the four recycle cases considered: the 4-hour and 12-hour timing.

The first case study involving the commercial sun-synchronous remote sensing constellation produced a diverse field of possible launch scenarios, where 8,964 acceptable launch combinations to the constellation exist. The minimum achievable time for total launch is shown to be 4.3 hours, and would require six 747 carrier aircraft distributed among at least three of the four airbases considered regardless of system recycle time. Given the axisymmetric nature of this constellation, this timing is achievable from several varied combinations of aircraft across the spaceports, highlighting an attractive flexibility in responsive launch despite where carrier aircraft, ground support equipment, and customer payloads happen to actually reside when a launch is needed.

The results also indicate that total constellation launch from a single spaceport in the UK can be achieved within 8.9 hours (or Japan within 10 hours) using just three recyclable carrier aircraft when recycle timing as low as four hours is considered, or with six non-recycled carrier aircraft when higher recycle timing is required. Additionally, 24 such scenarios exist where

Table 3: Responsive constellation launch case study #3: Civil rapid response string of pearls

Constellation Type	Civil rapid response to coincident planes
Orbital Planes (N)	5 coincident planes
Apse Altitudes	Any altitude achievable by launch vehicle
Inclination	Sun-synchronous
RAAN	0° (all planes)
Spaceports	Mojave, South America, UK, and/or Guam (4)
System Recycle Time	4 to 16 hours between launches



any of the spaceports considered can alone support total launch within 11.1 hours or less, using three recyclable carrier aircraft when considering low recycle timing or six non-recycled aircraft otherwise.

In cases of lowest recycle timing, 636 launch scenarios exist where only three carrier aircraft distributed across three spaceports or less can achieve total constellation launch in 12.5 hours or less, and in some cases as little as 8.3 hours. Similar combinations exist when considering higher system recycle time, where up to six non-recyclable carrier aircraft are instead required at the resulting spaceport combinations. The text boxes within Fig. 6 as well as dashed trend lines indicate launch time achievable when considering cases of fastest launch, minimum spaceports activated, or minimum carrier aircraft required.

The second case study of the resilient communication constellation produced 2,759 acceptable launch combinations, notably less than the first case study. This reduction in possibilities is due to the lower inclinations of some orbital planes, leading to access restrictions to spaceports capable of reaching those orbits and azimuths. Selection of an air-launch system in this scenario is identified to be critical for maximizing responsiveness, given the ability to reach a wider degree of inclinations and acceptable range safety envelopes by flying extended distances from the host spaceports. This constellation cannot be launched without access to a launch point near the equator, which is a problem that mobile air-launch platforms can avoid.

A singular minimum achievable time scenario for total launch is shown to be 4 hours, and would require six 747 carrier aircraft distributed as follows and regardless of system recycle time: four aircraft based in Guam, one aircraft in Mojave, and one aircraft at Diego Garcia. Up to 286 scenarios exist where total launch can be achieved in eight hours or less, and would involve between three and six aircraft distributed in various combinations across the five spaceports considered depending on system recycle time.

The results also indicate that total constellation launch from a single spaceport in Guam can be achieved within eight to twelve hours using three recyclable carrier aircraft when recycle timing as low as four hours is considered, or with six non-recycled carrier aircraft when higher recycle timing is required. Only twelve such scenarios exist and only from Guam, as it is the only candidate spaceport from which air-launch can permit all needed azimuths and inclinations of this constellation in less than a day's time. When considering launch campaigns beyond 24 hours, other combinations involving singular spaceports such as Diego Garcia or South America are also possible.

When considering lowest recycle timing, 79 launch scenarios exist where only three carrier aircraft distributed across three spaceports or less can achieve total constellation launch in 15.3 hours or less, and in some cases as little as 8.9 hours excluding the minimum time case already identified prior. Similar combinations exist when considering higher system recycle time, where up to six non-recyclable carrier aircraft would be

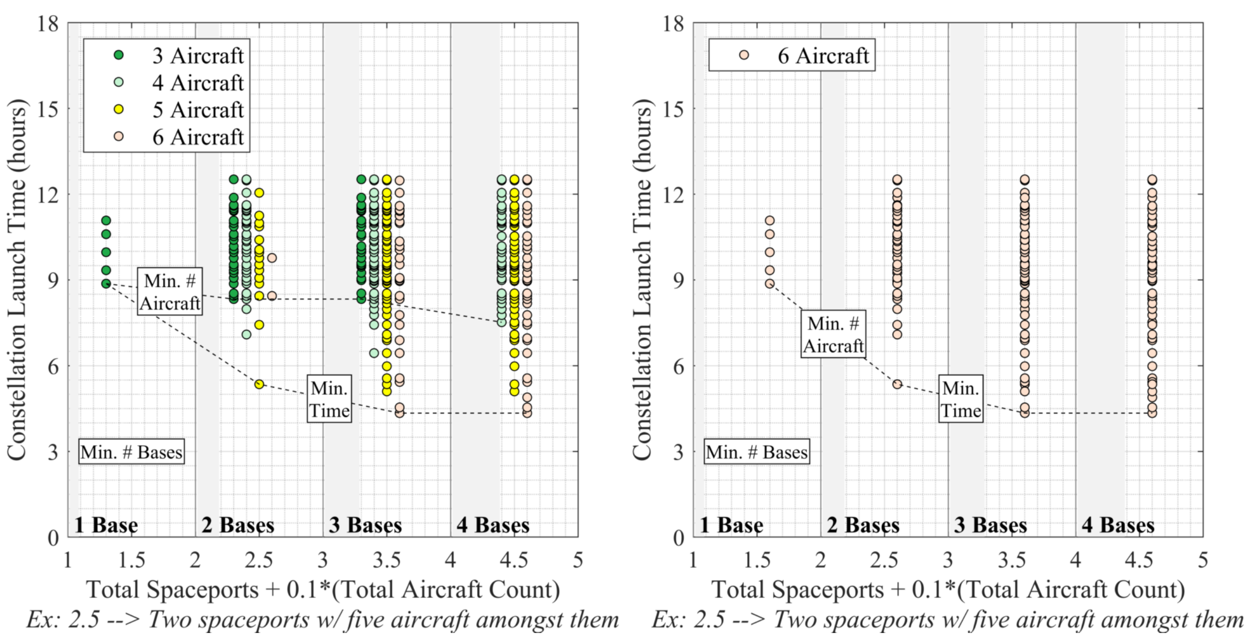


Figure 6: Constellation #1 injection time and architecture specs assuming 4-hr and 12-hr sys. recycle times

required. The text boxes within Fig. 7 as well as dashed trend lines indicate launch time achievable when considering cases of fastest launch, minimum spaceports activated, or minimum carrier aircraft required.

The third and final case study of the civil rapid-response A-train mission produced 2,703 acceptable launch combinations. The count in possibilities is somewhat low, attributed to the fact that only four candidate spaceports were considered for this fully sun-synchronous constellation. There are naturally several combinations possible which allow for simultaneous launch of five rockets from the same spaceport, resulting in a construction time of nearly zero. These cases will be removed from further consideration since they are effectively identical to a single large rocket launch and not the focus of a responsive, disaggregated launch application. Aside from these cases, several scenarios exist which allow launch within an hour when five aircraft, rockets, and their payloads are distributed in various combinations between Guam and South America, or Guam and the UK.

When considering lowest recycle timing, 163 launch scenarios exist where only three carrier aircraft distributed across three spaceports or less can achieve total constellation launch in 24 hours or less, and in some cases as little as 11 hours. Similar combinations exist when considering higher system recycling time, where 52 launch scenarios involving only three recycled carrier aircraft can still achieve launch in less than a day and potentially in as little time as the recycle duration itself. The text boxes within Fig. 8 as well as dashed trend lines indicate launch time achievable when considering cases of fastest launch, minimum spaceports activated, or minimum carrier aircraft required.

While the case studies reviewed here have demonstrated a distinctly rapid launch capability, another particularly important result is how thousands of potential launch combinations can exist for any given constellation scenario even when considering modest quantities of spaceports and carrier aircraft alongside mobile support shipsets. In some customer scenarios, speed of launch is not so important a factor as architecture resilience. In this case, no matter what combination of spaceports are active or what resident carrier aircraft they host, viable pathways to orbit exist and can be activated at a moment's notice. The increased envelope of access afforded by air-launch enables this argument further by enabling sites that may not normally permit the inclinations or azimuths needed for a particular constellation or direct-inject mission. The result is premier orbital access by a small grouping of active spaceports, which can be reconfigured at a moment's notice by way of moving the mobile assets that comprise the entire launch system. This inherent property can also enable international collaborative Earth science or civil response missions where constellation launch campaigns can be readily designed around member governments and their local or preferred spaceports.

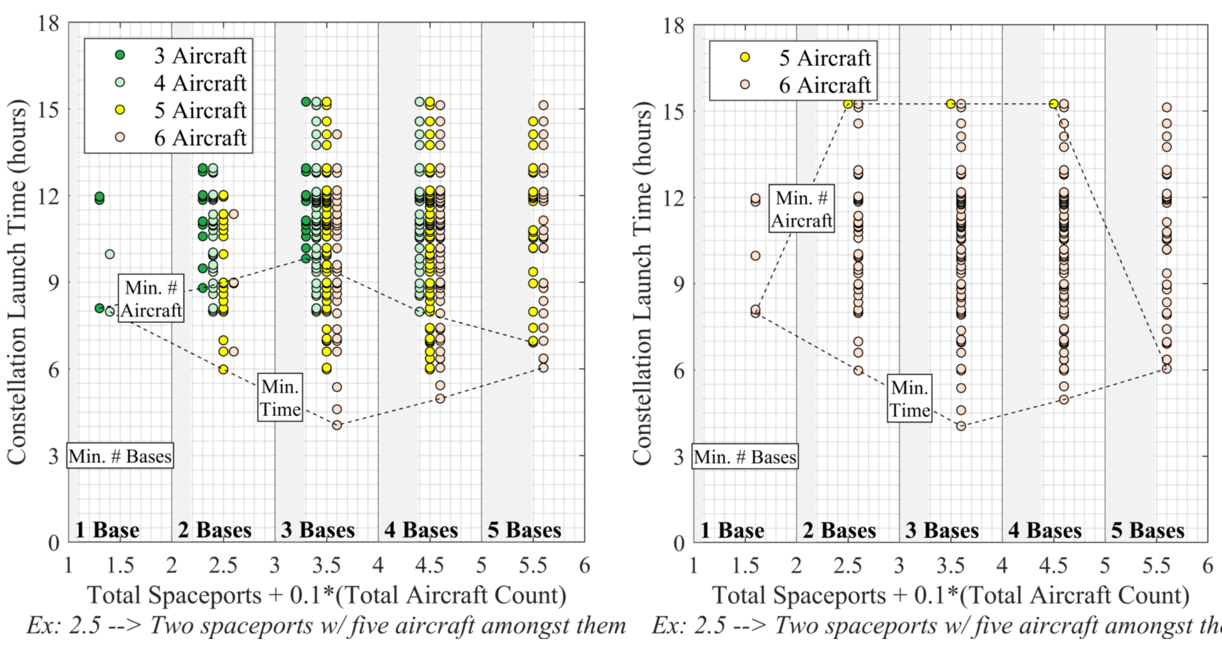


Figure 7: Constellation #2 injection time and architecture specs assuming 4-hr and 12-hr sys. recycle times

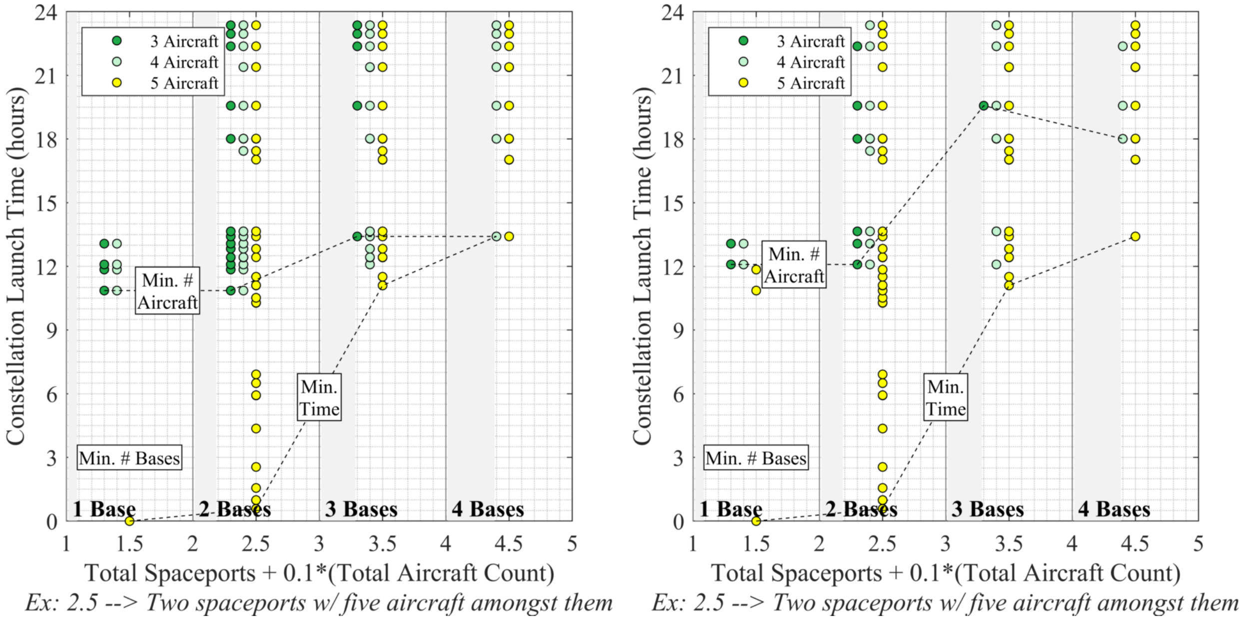


Figure 8: Constellation #3 injection time and architecture specs assuming 4-hr and 12-hr sys. recycle times

A graph summarizing the concentration of launch combinations in terms of counts of activated spaceports and distributed carrier aircraft among them is shown in Fig. 9. The histograms indicate count of launch combinations across all three case studies considered. This provides a visual progression of what air-launch infrastructure strategies align best with system capability in terms of recycle time. When considering an aggressive recycle time of four hours between launches, a highly capable architecture of four carrier aircraft distributed among three varied active spaceports at any given time allows for over 4,000 daily combinations to launch to the three constellations studied. As recycle time is increased, the concentration of maximum combinations approaches solutions involving six carrier aircraft that would not require recycling. In the case of a 12-hour system recycle, architectures with six aircraft distributed across three or four varied spaceports could see over 10,000 daily opportunities to the three constellations considered. While these higher recycle times elicit less cases in which total constellation launch with less than *N* aircraft can be performed within a day, the ability to launch within days still exists. It should also be noted that recycle times as low as four to eight hours will be part of LauncherOne's evolved responsive launch program as envisioned in this paper pending further capability refinement.

Comparison to Fixed-Site Ground Launch

Evaluation of the utility and responsiveness of the air-launched approach afforded by LauncherOne would be incomplete without an adequate comparison to a similar attempt via ground-launched vehicles. Most launch vehicles operating today are launched from fixed sites and infrastructure. A brief analysis will be performed here assuming fixed-site launch to the second case study constellation using a vehicle of equal payload capability so as to compare results to those already presented for distributed air-launch.

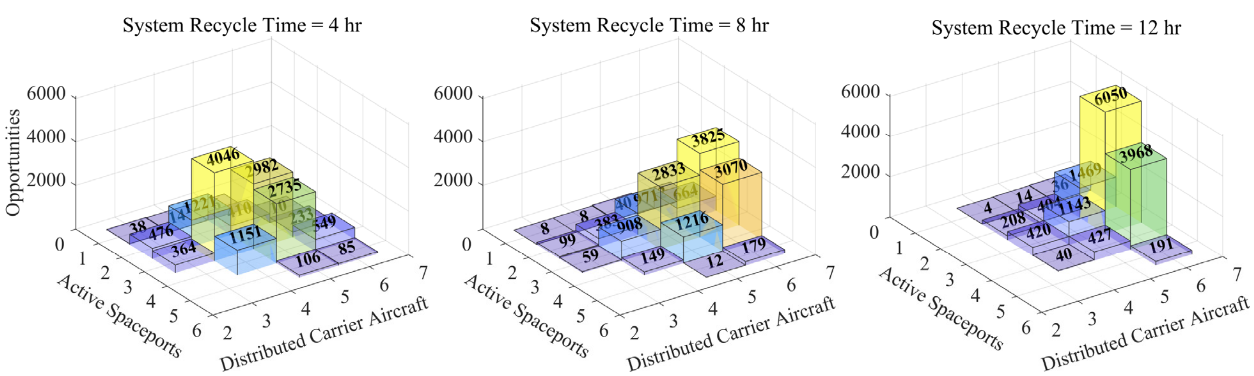


Figure 9: Launch opportunity histograms vs. spaceports, distributed carrier aircraft, and recycle time

The second case study involving orbital planes of various inclination is chosen for this evaluation, since comparison via fully sun-synchronous constellations may not highlight latitude-based availability issues. In order to represent a fixed launch site architecture more realistically, some spaceport locations within case study #2 were replaced with existing known sites. The air-launch candidate spaceports considered were Mojave, Guam, equatorial South America, Diego Garcia, and/or Ascension Island. The fixed ground launch sites considered are instead Kwajalein Atoll, Vandenberg AFB, Cape Canaveral AFS, Wallops Flight Facility, and equatorial South America.

The same responsive launch tool was used to analyze this fixed site case, but with important caveats. Firstly—evaluation of a fixed-site network in this manner means that all five candidate spaceports have fully capable and active launch pads at the ready. Since a ground site cannot be transported at will between geographic regions as an air-launch platform would be, each site must be ready for launch whether needed or not. In addition, ground launchers must adhere to stricter inclination and azimuth restrictions of these sites, as they are not enhanced by an ability to fly for a launch over distant international waters.

Assuming one or more launch pads are ready and active at each of these five sites, 2,864 potential launch combinations are achievable. While comparable to the tally of possible combinations for air-launch, important distinctions to maintain responsiveness remain as indicated below, in Table 4, and in Fig. 10:

- The ground system requires that all five spaceports and their pads are active and ready for launch at all times. Since an air-launch platform counterpart and associated assets can be moved, as little as three spaceports can instead be activated at short notice.
- Once committed by design years in advance and unlike the distributed air-launch assets, infrastructure that comprise the fixed-site system cannot be readily moved between spaceports. In other words, only a fraction of the assessed opportunities can actually be realized, unless all considered spaceports have active pads ready for a responsive launch scenario.
- Due to the above and in order to achieve all combinations, each spaceport must comprise up to six independent fixed launch pads launching in succession, or more than triple the launch platforms as the comparable air-launch network. Table 4 highlights this comparison.
- Significantly more of the comparably performing fixed site scenarios require launch from each of four or five spaceports as opposed to three or less hosting spaceports for the air-launch system, on average
- Even with more activated spaceports and/or pads, a fixed-site launch architecture achieves, on the average, +25% longer constellation injection time as the distributed air-launch case. Reduced day-of-launch availability due to weather/range safety and subsequent mission scrubs will further impede actual constellation injection time as well.
- The fixed-site launch vehicle must be approximately matched in performance scale for the constellation's needs. Overly large vehicles or rideshare situations are not commercially conducive to this application.

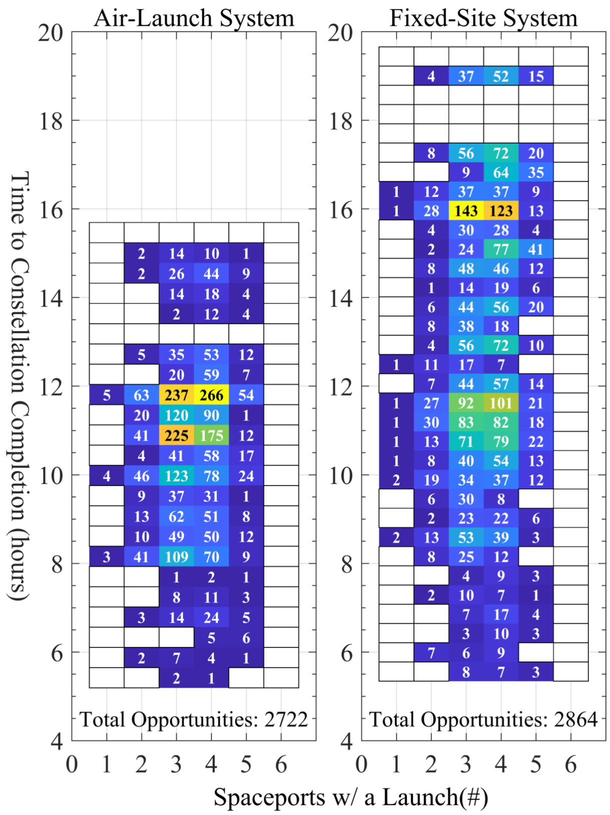


Figure 10: Comparison of launch opportunities between air-launch and fixed site architectures

Table 4: Launch platforms requiring activation

Spaceport	Active Pads Required	
	Minimum	Maximum
Kwajalein	3	6
South America	3	5
Florida	1	3
Wallops	2	3
Vandenberg	1	2
Fixed-Site Total	**10**	**19**
Air-Launch 747 Total	**3**	**6**

It is quantifiably apparent that a fixed-site launch approach is not ideal for responsive constellation injection. Meeting the same responsiveness characteristics requires construction and maintenance of triple the launch platforms: between 10 and 19 ground launch pads as opposed to between 3 and 6 carrier aircraft of the air-launched architecture depending on recycle time assumed. The tremendous resources that must be repeatedly committed in developing dedicated launch sites impede the launch operator's ability to quickly tailor a service around a changing market that demands flexibility. Most ground-launch vehicles operating today do so from no more than two launch sites as a result. By permanently handcuffing these vehicles and their support systems as permanent constituents to particular spaceports, a potential element of responsiveness is forever denied.

A mobile and modular air-launch architecture like LauncherOne stands apart by divorcing expensive and capable ground support assets from permanently fixed locations. In times of conflict, an element of unpredictability in attempting to locate these mobile launch assets aids an argument in resilience as well. All else being equal (development costs of launch assets, ground support systems, and launch vehicles,) it is demonstrated that the ability to quickly and cleanly transport or store all required support infrastructure, vehicles, and payload between several spaceports greatly enables the responsive launch argument.

IMPLICATIONS

A review of the combinatorics analysis results for just three unique smallsat constellations has quantifiably confirmed how a mobile air-launch architecture can form the basis of a responsive launch service. The key implications are:

- Total injection to a constellation of several planes of RAAN in less than a day is not only possible, but achievable by way of several thousands of possible launch combinations per constellation
- An ability to both tailor rocket release site or avoid adverse weather to maximize launch availability extends the responsive launch capability
- The enabling mobile qualities of an air-launch carrier aircraft and its supporting ground assets ensure that, unlike fixed-site launch, engaging any of these thousands of launch combinations is possible regardless of initial spaceport site selection(s)
- A network of fixed ground launch sites and vehicles cannot surpass the response time or flexibility of a mobile launch platform without development of substantially more fixed launch pads and ground support equipment, at great cost

These implications are particularly important in the evolving small satellite industry. As small satellites become more common and easily mass-produced, the idea of shipping and storing larger quantities of flight-ready satellites or ground spares will not be as cost-prohibitive as in decades prior. Commercial business case aspects like minimal time-to-market may increasingly dominate the launch decision space.

It is also conceivable that these 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 and military users would benefit from the added bonus of unpredictability and resilience that are features of a global responsive launch network, creating an effective deterrence.

Policy Discussion

Government can either rapidly facilitate or severely hinder a responsive launch architecture through the structure of regulatory environments, and as a standard-setting customer. 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)[21]. 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. However, since their establishment during an era of fixed-site vertical take-off and landing rockets, little has been done to update the regulations at the pace of industrial innovation. As-written, current regulations cannot effectively license next-gen vehicles such as those that return to their launch pads, or that are launched from an aircraft. The launch regulations as written are prescriptive rather than based on the performance and intent of a launch vehicle – which is not conducive to a responsive launch architecture. For example:

1. The current regulations require deliverables to the FAA at L-60 days, L-30 Days, L-15 Days, and full engagement at L-72 hours. This timeline would be difficult to achieve for a responsive launch – the FAA should consider condensing the timeline based on requirements of the mission and data of similar missions conducted previously.
2. The National Airspace System (NAS) closures are completed at least 30 days prior to launch. The Air Traffic Office (ATO), the entity responsible for the NAS, receives Aircraft Hazard Areas from AST and then is able to determine the impacts to the airspace. Responsive launch might dictate that the approvals needed to operate in the NAS would need to be streamlined, and the timeline could be condensed.
3. Special Use Agreements (SUA) for military zones can take months to get signed. For a responsive launch capability, companies need expedited agreements as well as an ability to bump existing events from the area as they are usually booked well in advance. For example, the SUA at Pt. Mugu is booked at least 6 months in advance.
4. If a specific spaceport/launch site is required to be used, agreements are required 180 days in advance of a launch. The ability to transfer a launch license between pre-determined sites as long as certain requirements are met is needed for quick-turnaround launches.
5. The Commercial Space Operations Center (CSpOC) that performs Collision Avoidance Analysis (COLA) to clear projected flight profiles does not model mobile launch sites in their propagation analysis. Instead, air-launch systems are modeled as fixed launch locations at their drop point. This should be addressed in next-generation Space Situational Awareness and Space Traffic Management analysis systems.

In addition, if a U.S. launch company launched outside the United States, it is still required to obtain a license through the AST. It is recommended that the U.S. government work closely with foreign governments and spaceport site operators to develop a system that allows for licenses to be transferable to an extent, or create requirements that can be substantially satisfied with a current FAA launch license for responsive launch operations that are not location-constrained. Government can facilitate responsive launch by utilizing the solution for their civil and national security needs and set standards for rapid procurement and architectures that can be used by future commercial customers. In addition, the U.S. Government, especially the Department of Defense (DoD) can utilize responsive launch for rapid reconstitution of assets on orbit in case of an adverse event.

DoD's Space Policy points to the need to deter aggression in space by denying benefits of an attack using the three tools of Space Mission Assurance: defensive operations, resilience, and reconstitution. Current DoD plans include efforts focused on two of these three tools, but strategies to achieve reconstitution as the third critical strategy of space mission assurance is absent. While reconstitution can be achieved through the use of larger launch vehicles, their cost, long planning cycles, extended launch campaigns, and limited launch-base locations make them unsuitable to respond to losses in a high threat and quickly changing operational environment. Rapid reconstitution through responsive launch, especially utilizing air launch, not only replaces lost capacity quickly, but also creates operational agility and greater benefit for DoD joint space operations by:

1. Complementing proliferation measures through rapid replacement of smaller, less costly, and non-hardened commercial assets;
2. Increasing diversity and distribution of launch locations during time of war or natural disaster thus complicating adversary efforts to deny replenishment;
3. Enabling a varied set of tactically responsive capabilities that can include unexpected wartime reserve approaches not previously factored into adversary plans;
4. Providing a means for low-cost, rapid iteration, and experimentation of new space capabilities and prototypes.

Future Work

Additional future studies involving application of the responsive air-launch architecture are planned. These studies involve the design of specific ConOps for constellation missions of interest, as well as detailed investigation of the architecture launch systems and

their capabilities necessary to achieve optimal results. Some pertinent future work is listed below:

- Initial design work on evolved mobile ground support architectures, cargo-capable carrier aircraft, and associated logistics that further enhance the speed and flexibility of an overall global air-launch network
- Crew and ground system feasibility work on reduction of launch system recycle time, enabling rapid turnaround and extreme reduction in overall constellation launch time while prioritizing safety
- Enabling automation and artificial intelligence as a means to further increase launch system performance, availability, and reduce turnaround times
- Increased tailorability of the constellation launch opportunity ConOps analysis, including optimized release site coordinate selection for multiple launches from the same spaceport
- Detailed review of regulatory environment and policy implications when implementing a responsive launch system, as briefly reviewed in the previous section

CONCLUSIONS

Air-launch architectures have often been proposed as a solution to responsive launch needs, but rarely present quantifiable results decisively indicating this to be the case. A detailed study on a modularized, global network of mobile air-launch assets based on the LauncherOne vehicle has been presented here with direct implications on the responsiveness and flexibility in achieving total constellation launches within a day or less. Founded on a vision of global host spaceports and utilizing Virgin Orbit's mobile ground support infrastructure, a fleet of just three or more carrier aircraft is shown to capably inject entire constellations within several hours. A combinatoric analysis was performed across three candidate constellations, and indicates that anywhere between approximately 3,000 and 9,000 launch ConOps permutations exist – each readily supportable by the system's ability to reconstitute at alternative spaceports. Factors such as reduced system recycle time further serve to either greatly improve injection time or minimize active spaceports, carrier aircraft, or both. Speed, redundancy, and ability to pivot all define this responsive launch approach.

The same analysis framework indicates that in order for a fixed-site ground launch vehicle and supporting network to achieve comparable responsiveness to the air-launch network, more than triple the launch platforms are necessary. For every spaceport that an air-launched carrier aircraft can visit and later depart, an equivalent ground-launched counterpart must build assets and maintain them indefinitely to respond equivalently. Ground-launch vehicles are also bound by stricter inclination and azimuth limitations than air-launched counterparts. The design and intent of such a ground launch network must be decided and "locked in" several years in advance of responsive launch operations, unlike a mobile air-launch system that may be relocated at will. Consequently, supporting mobile ground assets ensures that, unlike fixed-site launch, engaging any of these thousands of solved launch combinations is possible regardless of initial spaceport site selections.

Indeed, a global spaceport architecture utilizing air-launch for small satellite constellation population, replenishment and rapid replacement via a responsive launch capable system will provide end-users and constituents with the critical support necessary for mission assurance and continuity of service. The benefits of such an architecture are wide-ranging and critical for the growth and sustainment of constellation services. These include:

- Less than 24-hour constellation replacement, ensuring continuity of services
- Mobile launch system provides wide variety of spaceport options, reducing risk and limitations or restrictions on launch locations and trajectories
- Deterrence against bad actors or insurance to counter on-orbit anomalies
- Economic benefits of maintaining ground spares, avoiding on-orbit spare degradation
- Encourages space ecosystem growth and commercial development as schedule risk and service outages are significantly reduced
- Creates the basis of a "Civil Reserve Space Fleet," similar to the "Civil Reserve Air Fleet" capability to provide surge support for national security needs

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 production cadence.

The emergence of international spaceports (i.e. UK, Japan, Brazil, and Portugal), 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, 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.

Assuring a meaningful quantity of guaranteed small satellite launches each year will establish a new “highway to space” core launch acquisition ecosystem and better positions launch providers to support commercial, civil, and defense launch requirements. This sustainable local ecosystem will enable “Launch-as-a-Service” programs that significantly speed up launch acquisition and time-to-orbit to meet the new constellation rapid replenishment needs.

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