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Small Satellite Launch to LEO: a Review of Current and Future Launch Systems

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As minaturisation of ever improving enabling technologies increase the capabilities of small satellites, the issue of commercially affordable access to Earth orbit becomes more significant. Whilst the current practice of multiple manifesting is dominant, the emergence of new small launch vehicles may instigate a transition to the dedicated launch of these small satellites. A brief review of the current range of launch vehicles is presented and available small satellite launch market projections briefly examined. The small launch vehicles currently in development are also outlined and their potential to drive the future small satellite launch market discussed.

Key Words Launch Systems, Small Satellites, Access to Space

Nomenclature

g_0	:	Standard Gravity [m s^{-2}]
h	:	Orbital Height [m]
m	:	Mass [kg]
R	:	Radius [m]
Δv	:	Delta-V [m s^{-1}]
μ	:	Standard Gravitational Parameter [m^3 s^{-2}]
ω	:	Rotational Speed at Equator [m s^{-1}]
ϕ	:	Launch Latitude [°]
β	:	Launch Azimuth [°]

Subscripts

0	:	Initial
E	:	Earth
p	:	Payload

1. Introduction

Since the late 1980s, a divergence in mass of satellites launched in to Earth orbit has appeared. Whilst the mass of satellites has generally increased since the days of the “Space-Race”1), a trend in miniaturisation of small satellites has also appeared2,3). This miniaturisation has been enabled and is driven by the increasing capability of small electronics, materials and sensors4). However, whilst the trend in satellite mass growth has been accompanied by systems large enough to launch them into orbit, the more recent miniaturization in satellites has not yet been echoed by smaller launch vehicles.

Satellites are generally classed by their wet mass, the class definitions evolving over time as the different trends in satellite growth have appeared. At present, the classifications for small satellites (< 1000kg) are shown in Table 1. The term CubeSat, refers to a subset of nanosatellites and picosatellites which conform to the CubeSat specification.

Table 1. Typical small satellite mass classification.

Classification	Mass Range [kg]
Minisatellite	100 - 1000
Microsatellite	10 - 100
Nanosatellite	1 - 10
Picosatellite	0.1 - 1
Femtosatellite	0.001 - 0.1

The CubeSat specification was developed at Stanford University and the California Polytechnic State University, San Luis Obispo in 1999 to facilitate the participation of science and engineering students in academic satellite development programs5). Evolution of the original picosatellite specification of a 10x10x10cm cube with maximum mass of 1kg (a 1U CubeSat) has since resulted in the standardisation of larger 2U and 3U nanosatellites. The early CubeSats were mainly simple demonstration missions, sometimes referred to as BeepSats, constructed and launched by educational institutions due to their low cost and short time scale for development. The follow-on attempts by these institutions however have been more ambitious; involving technology demonstration and qualification, observation of deep space or the Earth, or performing on-orbit scientific experiments6–8). In addition to the reduced development time and platform costs, the cost and availability of access to orbit for nanosatellites and picosatellites has also been somewhat alleviated by the adoption of the CubeSat standard and use of the associated deployment mechanisms (P-POD, T-POD, XPOD etc), certified by launch providers to isolate the satellite from the vehicle and other payloads5).

Table 2. Current small launch vehicles.

Vehicle	Reference Payload [kg]	Reference Altitude [km]	Reference Inclination [deg]	Approx. Cost [USD]	Specific Cost [USD/kg]	Notes/Known Issues	Source(s)
Shtil-1	80	500	79	$2.1M	$26,300	Submarine launch	[26,27]
Shtil-2.1	150	500	79	$4.5M	$30,000	Submarine launch	[26,27]
Shavit (LK-A)	350	420	143	Unknown	-	Commercial status unknown	[26,28]
Shavit-1 (LK-1)	350	700	90	Unknown	-	Commercial status unknown	[26,28]
Pegasus XL	443	200	90	$25M	$45,100		[26,29]
Minotaur I	580	185	28.5	$20M	$34,500	US Government sponsored payloads only. Planned retirement in 2017.	[26,30]
Start-1	632	200	52	$9M	$14,200	Suspended pending launch site expansion	[26]
Athena Ic	700	200	28.5	$20M	$28,600	Reactivated. No launches since retirement in 2001.	[2,31]
Shavit-2 (LK-2)	800	700	90	Unknown	-	Commercial status unknown	[26,28]
Falcon 1e	1000	185	20	$10.9M	$10,900	Discontinued	[32,33]
Taurus (2110)	1000	500	28.5	$35M	$35,000		[2,34]
Kosmos 3M	1500	250	51.6	$12M	$8,000	Discontinued	[26]
Vega	1500	700	90	$35M	$23,300	Early operation	[2,35]
Athena IIc	1540	200	28.5	$30M	$19,500	Reactivated. No launches since retirement in 1999.	[31]
Minotaur IV	1720	184	28.5	$50M	$29,100	US Government sponsored payloads only. Planned retirement in 2017.	[36]
PSLV-CA	2100	200	28.5	$15M	$7,100		[18,26]
Rockot	2140	200	63.2	$20M	$9,300		[14,37]

The increasing successes of launched small satellite missions and university CubeSat programs have captured the interest of commercial and government entities (NASA Educational Launch of Nanosatellites, NRO Colony, The Aerospace Corporation AeroCubes, UK Space Agency UKube). Among the past and future microsatellite and nanosatellite missions, a transition from simple technology demonstration to fully operational satellites for scientific experimentation, Earth observation, and communication appears.

Additionally, an increasing interest in the use of distributed or fractionated small satellite systems has become apparent[9]. Thus far, these missions have typically involved the demonstration of required technologies for use in formation missions or constellations: NASA EDSN (Edison Demonstration of SmallSat Networks), SMDC-One, NRO Colony-1, DARPA F6, ESA PROBA3. However, some microsatellites and nanosatellites have already been launched for use as part of operational constellations (BRITE, AprizeSat/ExactEarth, CINEMA) whilst it has been proposed that microsatellites or nanosatellites could be used to replace or renew existing constellations of larger satellites whilst maintaining or increasing performance for a similar cost. For example, by replacing the 5 satellite RapidEye constellation with 38 nanosatellites of 8kg rather than 150kg a shorter revisit time can be achieved for the same mission costs[10].

Surrey Satellite Technology Ltd (SSTL) has been a continued presence throughout the recent small satellite renaissance. The company was initially involved in the development of more affordable minisatellites and microsatellites through the use of COTS components and innovative design processes first demonstrated by the UoSat family of satellites[1,4,11]. SSTL has since pioneered the use of constellations of small satellites for Earth observation missions through its RapidEye and Disaster Monitoring Constellation (DMC) minisatellite systems, and also forayed into the development of nanosatellites and CubeSats with the launch of SNAP-1 in 2000 and STRaND-1 in 2013[12].

2. Current Launch Opportunities

The low availability of launch opportunities for small satellites is often regarded as the most significant threat to the continued growth of this sector[1,2,13]. As the cost of small satellite development is driven down through use of COTS components, standardised commercially available bus designs, and simplified manufacturing processes, the impact of launch cost becomes increasingly significant compared to the total mission budget.

The current opportunities for launch of small satellites to LEO are distributed between dedicated launch by a small vehicle provider, launch as part of a rideshare agreement or cluster launch, or by piggyback where the satellite is classed as secondary or tertiary payload and utilises excess capacity on a scheduled launch. In each case, a compromise between the cost of the launch, date of launch, and access to the desired orbit is required.

Table 3. Available rideshare and piggyback launch prices.

Launch Vehicle/Provider	Mass/Form	Cost [USD]	Specific Cost [USD/kg]	Source(s)
Lockheed Martin Athena IIc	110 kg	\$12.5M	\$113,600	15)
	3U P-POD	\$300k	\$60,000	
SpaceX Falcon 9	3U P-POD	\$200k-\$325k	\$40,000 - \$65,000	38)
	ESPA Class (180 kg)	\$4M\$-5M	\$22,200 - \$27,800	
Spaceflight Services (Falcon 9, ULA EELV, Antares, PSLV)	1U CubeSat	\$125k	\$125,000	39)
	3U CubeSat	\$325k	\$65,000	
	180kg microsatellite	\$4.95M	\$27,500	
	300kg microsatellite	\$6.95M	\$23,200	

A further complication of the launch market for small satellites is the availability of the suitable small satellite launch vehicles. Of the currently active vehicles with a payload mass of less than 1000kg, few have demonstrated regular and successful commercially available launches.

2.1. Dedicated launch

For payloads in the minisatellite and microsatellite class with a higher budget, a number of launch vehicles are available for dedicated launch. However, the typical specific launch cost of these vehicles is often greater than their medium and intermediate lift counterparts and the payload may not utilise the full capability of the vehicle. The payload operator may therefore not be able to economically justify the use of the launch vehicle14).

The clear advantage of a dedicated launch however, is that the destination orbit of the payload can be selected to best fit the mission and the date of launch can be chosen to coincide with the payload development and mission operation schedule. The added value that can be attributed to dedicated launch however is highly variable and dependant on the mission requirements and the flexibility of the spacecraft bus and subsystems, which in turn has an effect on the cost of development and manufacture of the spacecraft itself.

For nanosatellite and picosatellite systems, in particular those designed and built by educational institutions, the cost of dedicated launch is usually far in excess of that which can be afforded by the system budget. They are therefore generally restricted to rideshare or piggyback launch.

2.2. Rideshare and cluster launch

Rideshare missions are a type of multiple-manifested launch where a number of similarly sized payloads share a single vehicle launched to a mutually agreeable orbit. These missions are typically offered by launch service providers or can be arranged by launch brokers in order to reduce the launch cost of each individual payload. The Dnepr and PSLV vehicles are currently the most commonly used for cluster or rideshare launches with an approximate cost of \$10k/kg2), whilst Athena IIc “RideShare” costs are advertised at \$12.5M USD per 110kg slot (approx \$110k/kg)15).

In the case of Rideshare launches, the total payload capacity of the vehicle can be utilised, reducing the launch cost for each satellite. However, due to the multiple-manifestation of payloads, the launch date is subject to the proposed development schedule of all the payloads and as such can be affected by delays from multiple sources. The destination orbit will be similarly determined by the satellite operators, likely resulting in a non-optimal inclination and/or altitude for all the payloads.

A common use of rideshare missions is the launch of satellite constellations, where multiple satellites of similar form or specification require transportation to the same orbit for deployment (e.g. Orbcomm on Pegasus XL, RapidEye on Dnepr). For these launches, the optimum orbit and launch date can be chosen as the launch has only one effective payload and customer.

2.3. Piggyback launch

A piggyback launch opportunity allows for the launch of a satellite as a secondary payload, utilising excess volume and mass on a commissioned vehicle. The destination orbit and launch schedule is determined by the requirements of the primary payload. As a result, to be launched by piggyback, the payload must either be agnostic to the destination orbit (e.g. some technology demonstration or microgravity and other space-science missions), and be flexible in design to allow for operation in all LEO environments, or be prepared to wait for a suitable piggyback opportunity to become available.

In a piggyback mission the deployment of the primary payload will not be compromised for the secondary payload. This is a risk for secondary payloads which may not be deployed as planned in the event of a launch anomaly. An example of this was the launch of SpaceX CRS-1 mission to the ISS on 7 October 2012. The Orbcomm secondary payload was not inserted into its intended orbit to ensure the delivery of the Dragon capsule primary payload following a first stage engine issue. The Orbcomm satellite was subsequently destroyed on re-entry.

Additionally, the insurance costs for secondary payloads may require additional cover for damage to the primary payload as a result of the secondary payload. If the primary payload is much more valuable than the secondary payload(s), then the cost of this insurance may be prohibitive. These costs can be somewhat mitigated by using certified launch adapters as previously discussed to isolate the secondary payloads from the launch vehicle and primary payload.

The cost of piggyback opportunities has been advertised by some launch vehicle providers and launch service brokers, ranging from $200k-325k for a 3U P-POD to $3M-7M for microsatellite-class payloads. Details of these are given in Table 3. The prices advertised are greater than the specific cost of the launch vehicles themselves but allow these small payloads to achieve orbit at a significantly lower expense than a dedicated launch.

2.4. Current launch vehicles

The specific cost of payload delivered to orbit for the current set of launch vehicles has been shown to decrease as the payload capability of the launch vehicle increases16). However, as the launch vehicles are all designed to achieve different nominal altitudes and inclinations from different launch sites, the actual performance of each vehicle is not considered by the classic comparison. In order to compare the launch vehicles by their performance, the total momentum provided to the payload can be used. This value, the Payload Impulse, is calculated as in Eq. (1) using the payload mass and terms for the orbital velocity, potential energy gained and velocity contribution of the Earth. The value obtained is approximate as factors such as the ascent trajectory and aerodynamic effects have been neglected.

$$m_p(\Delta v_{net}) = m_p\left(\sqrt{\frac{\mu_E}{R_E+h}} - \omega_E \cos\varphi \sin\beta + \sqrt{2g_0 h}\right) \qquad (1)$$

Fig. 1. compares the range of existing small launch vehicles using the payload impulse and specific launch cost. The basic trend shows that as the total useful energy delivered to orbit by the launch vehicle increases, the cost per unit mass of payload decreases.

The reasonably uniform distribution of the data points about the regression line supports the existence of a clear overall trend. However, given the deviation of data points about the regression line and the value $R^2 = 0.519$, the model could not be reliably used to predict the specific cost of an individual launch vehicle given a value of payload impulse.

Both the classic and the adjusted trend demonstrate the effect of launch vehicle scaling on the specific launch costs. As the launch vehicle increases in size to accommodate a bigger payload, the ratio of surface area to volume reduces. The relative drag experienced by the vehicle therefore reduces and the fuel required to combat this drag reduces. As the fuel tanks also increase in volume, the wall thickness is not required to increase linearly, resulting in relatively lighter tanks. Similar scaling effects may be experienced by the engine or other subsystems i.e. the avionics system is unlikely to scale with vehicle size. The structural mass fraction of the vehicle will therefore also decrease with increasing payload capability. The launch vehicle cost will therefore not reduce with payload mass, resulting in greater specific launch costs for smaller vehicles.

If the gross liftoff mass of the launch vehicle is also considered, an expression of the efficiency of the launch vehicle in providing useful energy to the payload can be obtained. This is term, the impulse-mass efficiency of the vehicle is calculated in Eq. (2). Using this metric, vehicles of different sizes can be directly compared to each other with respect to their performance.

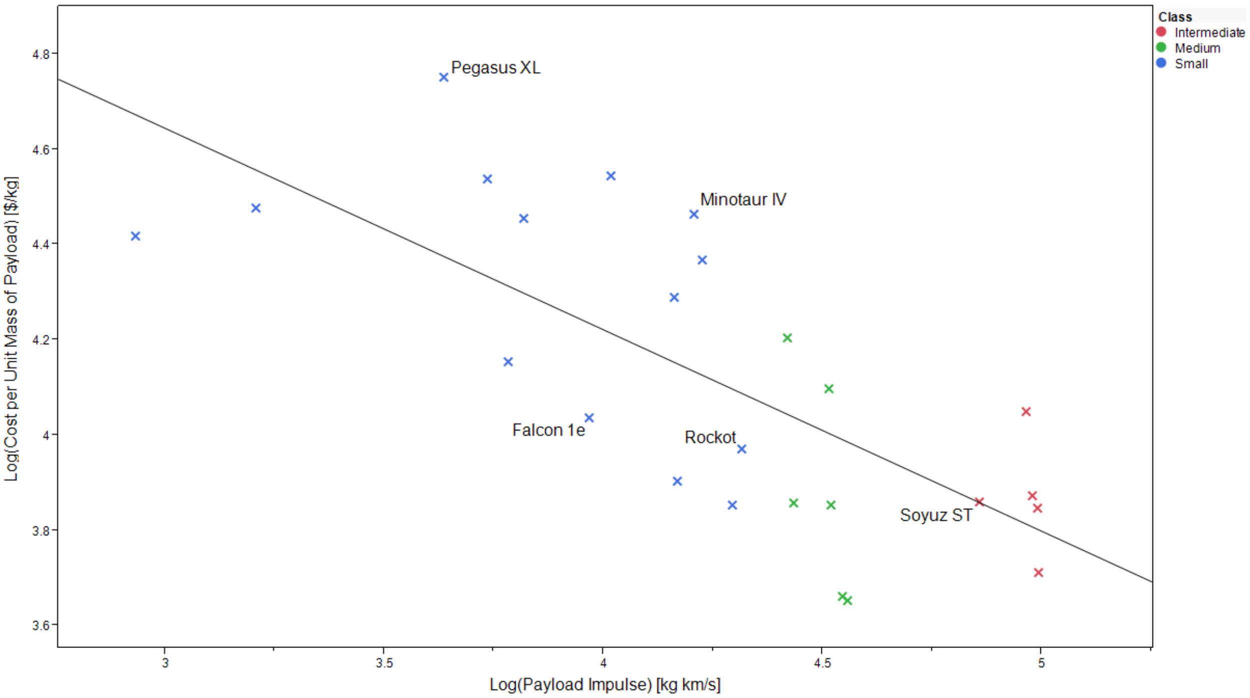

Fig. 1. Payload impulse and specific launch cost (R^2 = 0.519)

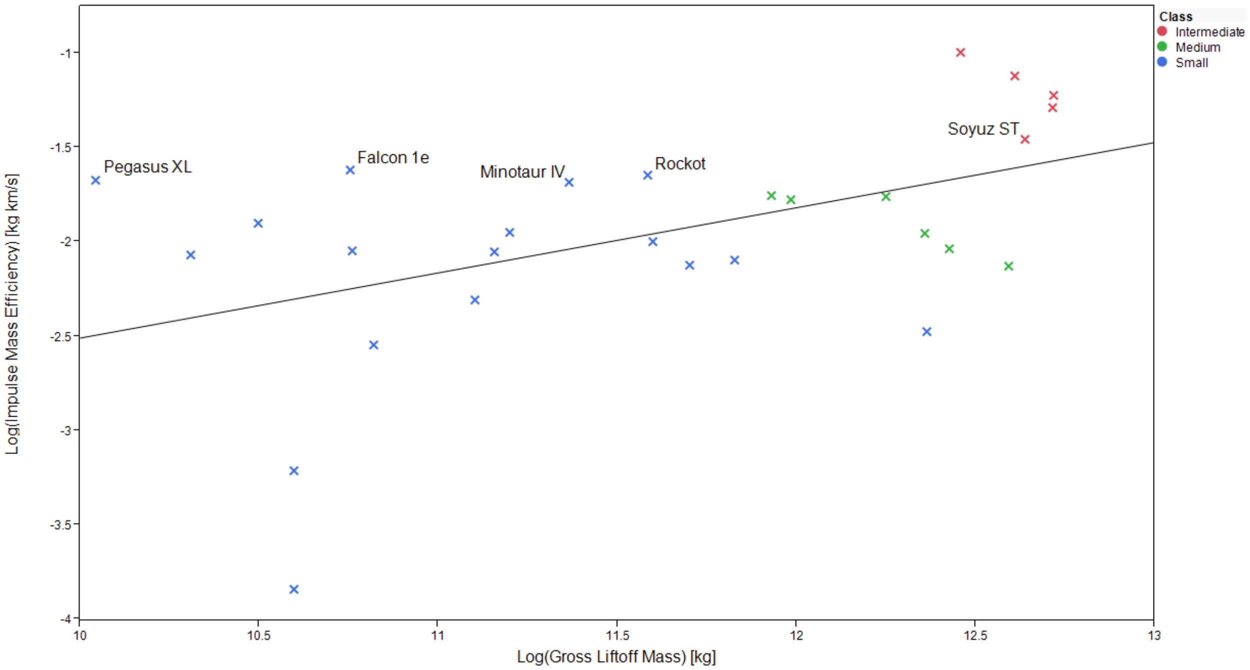

Fig. 2. Gross liftoff mass and impulse mass efficiency ($R^2 = 0.242$)

$$\frac{\text{Payload Impulse}}{\text{Gross Liftoff Mass}} = \frac{m_p(\Delta v_{net})}{m_0} \qquad (2)$$

Fig. 2 shows that the small launch vehicles have a typically lower impulse-mass efficiency than their medium and intermediate counterparts, supporting the effects of launch vehicle scaling discussed previously.

The distribution of data points about the regression line however is not very uniform, with higher deviations below the line, resulting in a less clear trend. This is characterized by the value $R^2 = 0.242$, suggesting that gross liftoff mass is not a reliable predictor of impulse mass efficiency.

Of the small launch vehicles, the Falcon 1e, Rockot, Minotaur IV, and Pegasus XL vehicles demonstrate a high impulse-mass efficiency, greater than the medium-lift vehicles. The Falcon 1e and Rockot achieve this relatively high impulse-mass efficiency by utilizing the increased ISP of liquid fuelled stages. Many of the other small launch vehicles are derived from ICBMs which use solid fuels to enable a rapid launch response but have a typically lower ISP.

The Minotaur IV vehicle achieves a higher impulse-mass efficiency through use of a 4-stage design, reducing the fuel fraction and allowing for a greater overall payload fraction. The Pegasus XL also has 4-stages, the carrier aircraft can be considered as a 0th stage, and is air-launched and benefits from a lighter structure due to lower peak dynamic pressure, optimised nozzle expansion ratios, and lower drag, gravity, and steering losses17). However, these vehicles are more expensive than their 3-stage equivalents and therefore result in high specific launch costs.

Similar to the Falcon 1e, the liquid fuelled Falcon 9, H-IIA, and EELV launch vehicles exhibit high impulse-mass efficiencies. However, the intermediate-class Soyuz ST vehicle is significantly affected by its relatively high liftoff mass due to its older design and heavier structure, resulting in a lower impulse-mass efficiency.

Whilst all the analysed launch vehicle have the capability to transport small satellites to orbit through the use of payload adapters and deployment mechanisms, there are very few which have a suitable cost and payload mass for the dedicated launch of microsatellites or cluster launch of nanosatellites and picosatellites. In this respect a capability gap in the market exists for a commercially available microsatellite or nanosatellite launch vehicle.

3. Launch Vehicle Market

Whilst the forecast of launch demand for larger satellites is a reasonably mature business (Commercial FAA launch demand forecasts have been published annually since 1994), the forecast for launch of small satellites has been generally neglected, a result of their typically low budgets restricting them to either secondary payload opportunities or cluster launches18). However, with the introduction of more capable small satellites able to perform valuable missions, the ability of these satellites to generate demand for launch has increased. As a result, demand forecasts for small satellites are beginning to appear in the market:

- Annual Nano/Microsatellite Launch Demand Assessment (1-50kg) from SpaceWorks Commercial first published in 201119).

- Demand for launch of very small satellites by Suborbital Reusable Vehicles (SRVs) identified by the Tauri Group in 2012[20)].

The SpaceWorks Commerical reports are relatively immature and their forecast methodologies are likely to result in initially poor projections. However, if only the general trend is appreciated at this time it is predicted that the number of nanosatellites and microsatellites requiring launch will grow significantly through to 2020. Similarly, the Tauri Group report predicts that the number of very small satellites (15kg and under) requiring launch will grow from 105 launched between 2002 and 2011 to about 100 per year in 2024.

The FAA predicts that the emergence of a microsatellite capability, if priced competitively could initiate a change in the method of launching microsatellites, nanosatellites, and picosatellites from secondary payload options to dedicated or small cluster launches. With the combined prediction of increasing numbers of small satellites requiring launch, the market for emerging launch vehicles with microsatellite and nanosatellite payloads appears to be positive.

4. Future Launch Vehicles

Launch vehicle manufacturers aiming to address the microsatellite and nanosatellite launch capability gap will be primarily competing with the current secondary payload launch opportunities and the smallest existing launch vehicles. Whilst the unit and specific payload cost of these vehicles will be important in determining their gain of launch market share, the availability, readiness, and reliability of these vehicles will also have a significant effect.

As with all launch vehicles the system reliability is a largely unknown factor, especially throughout its early operation. As a result, many payloads are unwilling to either accept the additional risk or increased insurance costs associated with the first few launch attempts. Initial demonstration missions with subsidised launch opportunities are often performed by the launch provider in order to increase confidence in the vehicle and generate demand for future launches.

A further complication associated with new launch vehicles is the growth of reliability. Vehicles based on existing and mature technologies and design elements should experience a much quicker growth in reliability as only the integration aspects of the system are unknown. However, launchers based on immature technologies and designs will experience slower growth in reliability and may present a greater risk during early flights even if the projected reliability at maturity is higher[21)].

A key issue with the current set of small launch vehicles is their availability for commercial launch. Many of the existing vehicles derived from decommissioned ICBMs are limited in number, restricted to government-sponsored use (typically US), or have issues relating to their life-span, requiring costly maintenance procedures. The availability of launch facilities can also have a significant effect on the availability of the vehicle for launch.

For the majority of emerging vehicles, the issues experienced by converted ICBM launchers should be mitigated. However, problems such as export controls will still impose limits on whether certain satellites can be launched using domestic or foreign capabilities or whether a launch vehicle or technology can be exported and launched from a non-domestic site.

Associated with the availability is the readiness of the launch vehicle. Whilst responsive launch is a high priority goal for military applications (nominal 6-day call-up for ORS mission requirements[22)]), the design compromises for a highly responsive launcher can adversely affect the cost and performance of the vehicle. However, with the trend of shorter development and manufacturing timescales for smaller satellites a more responsive launch capability, on the order of weeks to months rather than years would be valuable.

Flexibility in the vehicle manufacturing process will also be required in order to respond to the demand in the launch market. As the small satellite launch market and the forecasting assessments are immature, the demand for launch will be relatively unknown.

An overview of small launch systems currently in development is presented in Table 4. The majority of vehicles identified are clearly aimed at addressing the very small launch capability gap, having a target payload of less than that of the Pegasus XL (443kg). Additional small launch systems have been announced (Swiss Space Systems, Interorbital Systems Neptune Series, Garvey Space NLV, and Boeing SLV), but are either in the very early stages of development or sufficiently detailed information is not currently available.

Of the new launchers identified, three are to be air-launched systems (GOLauncher2, ALASA, and LauncherOne) and one launched from a suborbital vehicle (Lynx Mk III). The proposed US Army SWORDS (Soldier-Warfighter Operationally Responsive Deployer for Space) is intended to be a highly responsive system, transportable by a C-130 aircraft and vertically launched from a mobile vehicle to maximize versatility[23)]. As the launcher is a US Army tactical capability it is very unlikely that the vehicle will be available for non-DoD payloads.

Initially, the ALASA and SPARK vehicles may also be restricted to the deployment of US Government (and sponsored payloads). The potential for future, global, commercial launches using these vehicles is currently unknown. The commercial status of the other national launchers (VLM-1, VLS-1, Tronador II, Long March 6, and Epsilon) is similarly unknown at this time.

The air-launched systems have potentially greater flexibility than their vertically launched competitors as the use of a suitable carrier aircraft can allow launch from a variety of locations and the ability to reach all orbital inclinations whilst maximizing payload performance. Disruptive weather conditions can also be generally avoided reducing potential delays. Additionally, if the systems are designed to require minimal ground operation for payload integration to the launcher and launcher attachment to the carrier aircraft, the use of multiple launch sites can also aid in decreasing the call-up time for launch and number of launch opportunities[24].

However, as air-launch-to-orbit systems are much less mature than conventional vertically launched vehicles (Pegasus the only representative example), new technologies or subsystems may require additional development and testing. A representative technology roadmap is presented by the ALSET (Air Launch System Enabling Technology) research and development program which identifies capabilities or systems which require development and those which can be extended from existing launch vehicle and commercial technologies[25]. Most significantly, the method and sequence of deployment and aerodynamic stabilization of the launch vehicle at ignition are identified as requiring substantial development and verification. The Virgin Galactic LauncherOne vehicle may be able avoid some of these developmental issues by utilizing the existing systems and technologies developed for the deployment of the SpaceShipTwo suborbital vehicle from the WhiteKnightTwo carrier aircraft.

As the VLM-1, VLS-1, Tronador II, Long March 6, and Epsilon launch vehicles are vertically launched and based on conventional launch vehicle technologies (Demonstrated solid, hypergolic or liquid based propellants) and the SPARK vehicle based on the Strypi sounding rocket, the technologies involved should be relatively mature and the development schedule reduced as a result.

Whilst issues discussed above will all have an effect on the launch rate and commercial competitiveness of the proposed vehicles, the most significant factor in generating demand for launches will be the unit cost for launch. Aside from the basic cost of the launcher itself, the range, ground operations, and launch agency costs contribute to the total launch cost. These costs are typically well understood for conventional vertically launched vehicles and can be derived from existing launchers. However, the additional costs for air launched systems are less certain and can diverge from the conventional launcher cost models.

The Pegasus vehicle demonstrates that the cost of an air launch system can be much higher than the cost of a comparable conventional launcher on a cost per unit mass of payload basis. However, it has been able to generate demand for dedicated launch by having a lower unit cost than other US commercially available launch opportunities. Some of the high cost of the Pegasus system is attributed to the lifecycle costs of the launch assist aircraft[24], whilst the nature of its private finding with very little federal financial

Table 4. Small launch systems currently in development.

Vehicle	Payload [kg]	Nominal Orbit	Cost [USD]	Specific Cost [USD/kg]	Development Status
XCOR Lynx Mk III	12	LEO	$500,000	$41,667	Suborbital launch. First launch planned for 2016.
SWORDS (US Army Nanomissile)	25	750 km, 28.5°	$1,000,000	$40,000	Liquid CH4/LOX propellant. Vertical mobile launch. Test flight in 2014. Operationally responsive – 24h.
Generation Orbit GOLauncher2	25	LEO	-	-	Air launch. First launch planned for 2018.
DARPA ALASA (Airborne Launch Assist Space Access) Program	45.4	LEO	< $1,000,000	< $22,026	Air launch. Unknown development schedule.
VLM-1 (Brazil)	150	300 km	-	-	Solid propellant. Vertical launch. First launch planned for 2015.
Virgin Galactic LauncherOne	225	LEO	< $10,000,000	< $44,444	Air launch. First launch planned for 2015, commercial operations begin in 2016.
Tronador II (Argentina)	250	600 km	-	-	MMH/N202 hypergolic bipropellant. Vertical launch. First launch planned for 2015.
VLS-1 (Brazil)	250	700 km	-	-	Solid propellant. Vertical launch. First launch planned for 2014.
SPARK (University of Hawaii, Sandia, Aerojet)	300	475 km, 45°	$15,000,000	$50,000	Solid propellant. Vertical launch. First launch planned for 2013. Operationally responsive – 6 days.
Long March 6 (China)	1080	700 km	-	-	Kerosene/LOX propellant. Vertical Launch. First launch planned for 2013. Commercially Available¹⁸⁾.
Epsilon (Japan)	1200	375 km	$47,000,000	$39,167	Solid propellant. Vertical Launch. First launch planned for 2013.

support forces the unit cost upwards in order to amortize the development costs over the low launch rate. However, by air launching and avoiding most range-related services (launch site facilities, range safety costs) the DARPA program expects that the cost per unit mass payload can be reduced by up to 25%[24)].

The LauncherOne vehicle will benefit from the investment in launch facilities by Virgin Galactic for their space tourism business (Spaceport America and the planned Spaceport Abu Dhabi). Additionally, as the carrier aircraft should not require modification, costs beyond the development of the launcher should be minimized resulting in a lower total launch cost.

With respect to cost, if eventually offered commercially the vehicles being developed for national space agency or defence launch capabilities will profit from their initial funding from government sources. If the development and manufacturing capital costs have already been paid for and were not funded by private investors then only the marginal costs of the vehicle manufacture, range and facility hire, and safety aspects must be accounted for before profit can be made.

Of the vehicles for which projected launch costs are available, the specific launch costs are within the range of those identified for existing secondary payload launch options, but also include the inherent value of dedicated launch. In addition, the unit cost of launch of the very small vehicles (Lynx Mk III, SWORDS, and ALASA) is significantly lower than the smallest existing launchers (Shtil and Pegasus XL). Assuming that the costs of these vehicles do not escalate too far from these projections, the available data supports the FAA prediction that the emergence of a dedicated microsatellite launch capability would initiate a move from multiple-manifested to dedicated launch of very small satellites.

The aspect of competition in the market should also be noted. Whilst the first competitively priced solution for dedicated launch of small satellites should generate launch demand quite easily, the introduction of further systems to the market should result in a general reduction of cost towards the marginal base cost. This may be additionally driven by price incentive programs for the first flights of new vehicles in order to demonstrate reliability and operational or financial requirements that determine the minimum number of launches per year.

5. Concluding Remarks

As advancements in technology continue to enable more sophisticated and capable small satellites, the demand for commercial launch of these systems to Earth orbit will increase. The successful demonstration of co-operative small satellite systems will also generate interest in the development of commercial constellations, swarms and clusters, establishing a definite market for a small satellite launch capability.

Whilst there are already vehicles in production or service which are capable of launching individual or clusters of small satellites to orbit, their unit costs are either too expensive to be considered viable by the satellite owners or there are issues with availability, resulting in the launch of small satellites as secondary payloads on larger vehicles.

The trends identified show that the specific launch cost should increase with decreasing payload size to a given orbit. However, through system design choices and careful consideration of lifecycle operations, the specific launch costs of new very small launch vehicles should be able to equal their current comparative small launch systems.

The performance of these vehicles should also be greater than their existing equivalents as they have been purposefully designed for the launch of small payloads rather than in many cases converted from ICBMs. Additionally, emerging or improving technologies such as hybrid or liquid fuelled propulsion and air/sub-orbital deployment can be utilized to improve performance.

The very small launch vehicles currently in development span a range of payload capabilities (12-300kg) for launch of very small satellites. However, the availability of many of these systems for global commercial launch is yet to be established, and is likely to be restricted to native launches for the early operation period.

The available specific cost predictions for these vehicles are similar to the existing multiple-manifest options and current small launchers, suggesting that market share can be quite easily attained by the virtue of being an affordable dedicated launch option.

The vehicles which are the first to become openly available for global commercial launch are likely to attract significant demand given the current number of small satellites being launched and the number of microsatellite and nanosatellite payloads and systems at different stages of planning and development.

Whilst the specific cost of launch to Earth orbit will not be reduced by these small launch vehicles, the overall accessibility of Earth orbit to very small payloads will be significantly increased by the greater variety and availability of the systems in development. Primarily, the range of vehicle sizes available for launch of payloads in the picosatellite, nanosatellite, and microsatellite classes has increased whilst the vehicle manufacturers have also moved away from the custom of using decommissioned ICBMs to the design and use of dedicated small launch systems, characterized by the number of air-launched vehicles in development.

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