How to launch small payloads? Evaluation of current and future small payload launch systems

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Abstract: This paper describes a preferable vehicle classification alongside a brief description of key technologies available on the shelf or under development to address the demand of the small payload market. This is followed by a discussion on the investigation of the current market and the future forecast; regarding the delivery of small payloads into orbit.

Keywords: Small Payload Satellite Market, Launch Vehicles

ACRONYMS / ABBREVIATIONS

AD^2	Advanced Development Level
ELI	Elliptical Orbit
ELINT	Electronic Intelligence
ELV	Expendable launch vehicle
FAA	Federal Aviation Authority
GEO	Geostationary Earth Orbit
GSO	Geosynchronous Earth Orbit
GTO	Geostationary Transfer Orbit
IMINT	Imagery Intelligence
ISS	International Space Station
ITAR	International Traffic in Arms Regulations
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MSTO	Multi-Stage to Orbit
MTCR	Missile Technology Control Regime
SSO	Sun Synchronous Orbit
SSTO	Single Stage to Orbit
TRL	Technology Readiness Level
TSTO	Two Stage to Orbit
UN	United Nations

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1 INTRODUCTION

Catalysed by the UK vision to become a key player in the space market, there has been a marked increase in activity from all players – academic, government and industry – in both downstream applications and in providing a full-service access to space. This includes examining the entire chain, from the R&D and manufacturing of future space access vehicles to the operations and ground infrastructure. With the recently introduced Modern Transportation Bill, the avenues have been opened to operate licenced spaceports in the UK. The question is, who is going to use them, and for what?

Starting in 2014 with the first talk of developing commercially viable UK spaceports, the aerospace industry focused its efforts on launching small payloads into polar or near-polar orbits, primarily for Earth Observation.

This paper collects and expands these analyses, looking at the current and predicted market demands for payloads up to 600 kg, from Nano-Satellites and CubeSats, swarms and constellations, to single or small formation small satellites, and to which operational orbits. Based on the predicted satellite demands, a survey and technical assessment will be shown comparing existing launch system designs and assessing key technologies.

The capability to launch small satellites already exists, mainly through rideshare launches on traditional vertical rockets. Orbital ATK Pegasus, one of the few operating systems specifically for small payloads, uses a modified aircraft to air launch a 3-stage solid-fuel rocket with an optional 4th upper stage. These models traditionally use the cost/kg as a metric; it is well known that lower cost/kg of payload comes with having larger vehicles (as the payload has a relatively small mass fraction of the overall vehicle), which for small payloads means the disadvantages of ridesharing, which can add indirect financial costs. The impetus is then to develop engineering innovations which can lower the total launch cost to the manufacturer/operator of a small satellite, improving or adapting known launch approaches to providing a commercially feasible near-term solution.

A classification of launch system types is presented differentiating largely based on stage designs (e.g., powered or non-powered, propulsion type) which accounts for many of the different approaches from horizontal to vertical take-off and landing, and reusability versus expendability. Within this, different concepts currently being proposed are analysed looking at the development stage, time to market, predicted cost and key/critical technologies.

Several these different approaches, especially the more innovative concepts, rely on similar critical technologies, such as novel propulsion systems, thermal protection systems and reusability. Different specific solutions for each of these categories will be examined looking at the Technology Readiness Level (TRL), Advancement Development Level (AD2), and operational characteristics. Propulsion systems examined include rockets that are throttleable and/or restartable, use liquid fuel (LOX-LH, -RP1, hydrogen peroxide) and combined cycle or hybrid propulsion systems. Thermal Protection Systems include ablative materials, Ultra High Temperature Ceramics (UHTCs), and regeneratively cooled systems, while reusability options include horizontal and vertical recovery methods and re-entry options.

Within this paper, Section 2 looks at a broad classification of the configurations for launch vehicles while Section 3 examines the technologies involved and the level of development. Section 4 consists of a market assessment and forecast, followed by a market share analysis.

2 LAUNCH VEHICLE SYSTEM CLASSIFICATIONS

In Figure 1, a tree chart of possible launch vehicles is depicted. The general trend is for a decrease in the cost to orbit per kg of payload with increasing technological sophistication moving from left to right across the following graphic. The launch vehicle technology available today involves an expendable Multiple Stage to Orbit (MSTO) spacecraft that takes off vertically. Some air-dropped launchers are also available today, for example, the Orbital ATK Pegasus (OATK2015).

To drastically decrease the launch cost, the systems must employ reusability. Today, some systems attempt to reuse only the first stage; which are under development and have reached a very high level of maturity, regarding vertical take-off and landing. Other options are also possible, for example by employing air-drop or autonomous horizontal take off. Furthermore, the propulsion efficiency of these systems could be drastically improved by employing an air-breathing engine. Eventually, a full reusable Single Stage to Orbit (SSTO) vehicle could be developed in the next decade (see Figure 1).

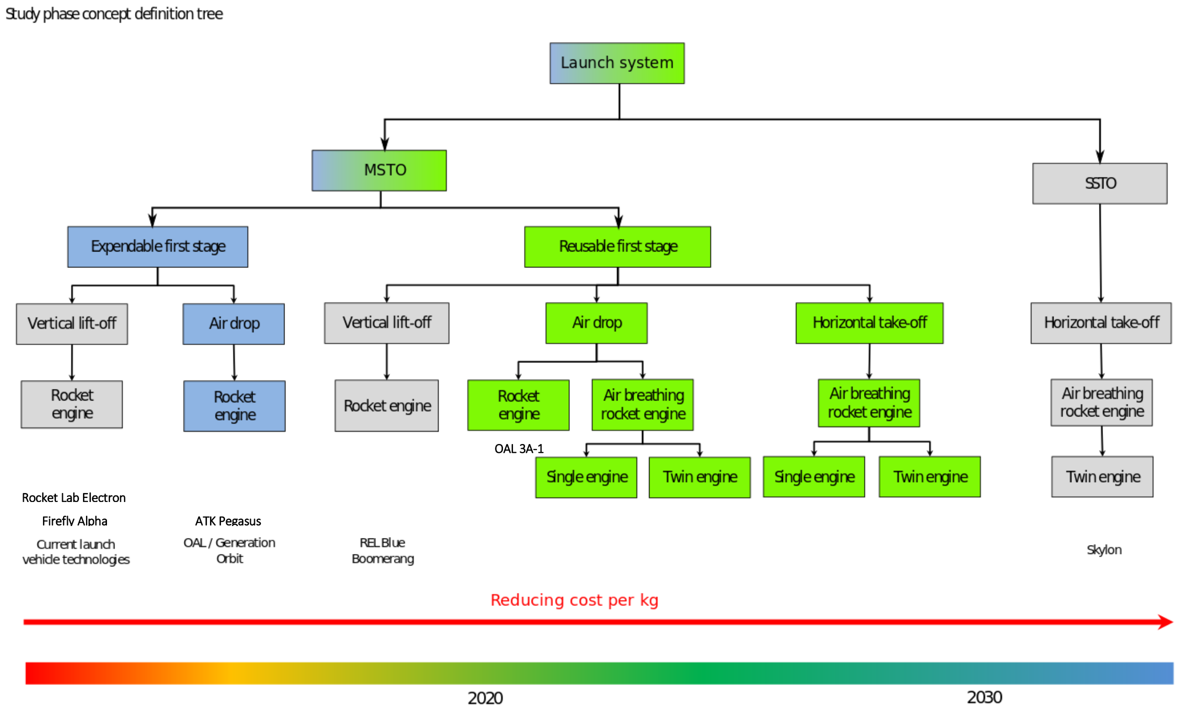

Figure 1 - Vehicle classification definition tree

3 TECHNOLOGY ASSESSMENT AND EVOLUTION

In order to more easily identify the technologies required for space access, five different key technology areas have been identified: air-launch, propulsion, thermal control, reusability and guidance and control. For each of these key areas, a list of available technologies is outlined, together with information about the maturity level and the performances. The maturity level has been measured in terms of TRL, (ESA, 2014). For technologies with a TRL lower than 9, the Advancement level of Difficulty (AD2) (Zhao & Wei, 2014) is also provided to measure the difficulty of the development that is required to reach full maturity.

3.1 Air launch

In this section, all the possible technological solutions for the integration of the launcher with the carrier airframe are analysed. The choice of the integration strategy plays a very important role in the final design of the system; which drastically influences the development costs and time.

The chosen technology will influence the general design of the launcher since it can impose stringent size and operational limits. Moreover, it will also define the carrier separation environment, with immediate consequences on the development challenges.

Up to date, there have been examples of relevant launch systems integrated below the carrier fuselage and below the wing. The Pegasus launcher, for instance, is integrated below the carrier fuselage and has had numerous successful flights (Orbital ATK, 2015). An example of integration under the wing of the carrier is given by the X43-A, (NASA, 2014a).

The main limitation of the integration under the wing is the interference of the wing aerodynamics on the launcher separation dynamics. On the other hand, the integration below the fuselage mitigates this risk, but it imposes strict size limits on the launcher design.

An alternative to the aforementioned two options can be the integration of the launcher above the fuselage of the carrier. This solution would avoid the aerodynamics problems of the wing and the space issue of the under-fuselage option, however, would cause interference with the vertical tail of the carrier aircraft. This solution has not been used in any orbital mission yet, therefore its TRL is quite low.

A further option could consist of the launcher being towed behind its carrier aircraft. Compared with the previous case, with this option, the main problems of the other three configurations are not applicable. However, it must be designed to avoid the wake turbulence of the carrier aircraft, for example using an extremely long tow cable (NASA, 1998). However again, the TRL is quite low. That being said, in both of the last two air launch methods, the AD2 level is relatively low.

3.2 Propulsion

In this section, the available propulsion technologies have been divided based on the used propellants. The main division considered is between solid, liquid and hybrid propellant. However, the liquid propellant option has been further divided into several further propellant options.

Beside conventional rockets, the option for an air-breathing rocket design has also been considered. Among the propulsion technologies considered, only hybrid rockets have not reached full maturity (i.e., TRL 9). While for the hybrid rocket the TRL is already very high, with some documented successful flights; albeit not routinely (e.g. the Virgin Galactic suborbital space vehicle, (BBC, 2013). Specifically, for the air-breathing rocket, the TRL is relatively low. For example; Reaction Engines Limited is developing the Synergetic Air-Breathing Rocket Engine (SABRE) where the first propulsion mode will be an air-breathing rocket. Reaction Engines Limited have successfully completed some component testing. Nonetheless, the development towards a single flight will be complex; since the similarity with other technologies is not applicable to all the design aspects.

Solid Rocket Motors (SRM) have been employed in many varied launch systems. Their main advantage is their simplicity (no pipelines or turbo-pumps), but this comes with the inability to throttle or reignite the motor.

The liquid propellant motors, conversely, are always fully throttleable and re-ignitable at the expense of a larger complexity. Among the liquid propellant rocket motors, the propellant combination with the highest performance in terms of specific impulse is liquid oxygen with liquid hydrogen (LOX-LH2). The main disadvantage of these propellants is a requirement for it to be stored at cryogenic temperatures. Additionally, the hydrogen is very difficult to handle due to its high volatility and very low density even in liquid form.

A common way to mitigate the problems of LOX-LH2 is to substitute the hydrogen with kerosene, leading to LOX-RP1. The kerosene has a fluid density comparable with that of water and is storable at room temperature. However, this advantage comes with a loss of performance in terms of specific impulse.

The LOX-RP1 engine can be made fully storable if liquid oxygen is substituted with hydrogen peroxide (H2O2-RP1). Besides the full storability, this propellant combination is also hypergolic; meaning that the propellants react upon contact and thus an ignition device is not required. The main disadvantage, in this case, is the high reactivity of H2O2 that leads to a series of handling problems.

Other fully storable propellants commonly used today are the monomethyl hydrazine (MMH) nitrogen tetroxide (NTO) and their variations. In this case, the propellants are not only hypergolic but also toxic, leading to very complex and expensive handling procedures, (Sutton & Biblarz, 2010).

3.3 Thermal control

Thermal control is an important design aspect of a launch system; mainly due to the extreme thermal environment the vehicle will experience during the re-entry and ascent.

Widely used for space transportation applications are ablative Thermal Protection Systems (TPS). They are very mass efficient because the ablation phenomenon absorbs an enormous quantity of heat, however, these are not reusable.

Conventional insulators that do not undergo any degradation can be used to provide re-usability, however, conventional materials cannot withstand the severe thermal environment of re-entry from orbit, but they might be enough for suborbital re-entry of first stages.

Today new insulating materials are being developed to provide reusable insulation for re-entry from orbital speed. These materials are called Ultra High Temperature Ceramics (UHTCs) and they have been successfully tested on the Intermediate Experimental Vehicle (IXV) by ESA (ESA, 2014), therefore demonstrating a very high maturity level.

A heat sink structure can be used to absorb the aerothermal heat. This strategy can be very effective if the heat sink is provided by an existing component with large thermal capacity, for instance, the propellant. However, using the propellant is rarely possible, being the tanks empty during the re-entry, so the method becomes very inefficient if a dedicated heat sink must be designed.

All the aforementioned technologies can be considered passive TPS, whereas active or semi-active TPS are those solutions that foresee the usage of a fluid to absorb/transfer the heat in excess.

Regenerative cooled TPS uses the engine propellant as a coolant. Besides the fact that this solution is not applicable to an unpowered re-entry, it has a quite low technical maturity, (Kelly & Blosser, 1994). Other active options include heat pipe cooling; where the heat within the fluid is transferred by means of natural convection and film cooling where a fluid is forced to flow above the protected surface. Even if potentially very attractive in both cases the technology maturity is not very high. Furthermore, the gas feeding system can make these solutions uncompetitive in terms of mass efficiency (Glass, 1998) (Böhrk, 2015).

3.4 Reusability

Reusability could be the key to reducing the cost of future launch systems. Launchers could be fully reusable or partially reusable. However, today most launch systems are expendable, even if an increasing trend toward partial reusability is evident in new launch systems approaching the market. In this section, a list of different strategies to accomplish reusability is presented.

In recent months, SpaceX has been proving the feasibility of recovering the first stage by means of a vertical landing. The same engine used for the ascent is also used to decelerate and execute a soft controlled landing. The disadvantage is that some propellant is needed to for re-entry and there is not much flexibility for the landing site. SpaceX is solving this issue using a robotic oceanic platform to provide a dedicated landing site, along with the resultant additional costs. Despite the flight success, the TRL cannot be considered 9 because until now the recovered stages have not been re-flown yet.

To solve the issue of the landing site flexibility a horizontal landing strategy can be employed. However, the design of the re-entering stage is complicated by the aerodynamic requirements, leading to the addition of fins and wings to the first stage.

The horizontal re-entry can be obtained gliding or using the stage engine to improve the manoeuvrability and the flexibility of the landing site. Even though the space shuttle performed a glided re-entry (NASA, 2014b), the TRL of these technologies is considered equal to 5 or 6 because the mission profile of the space shuttle was completely different than a re-entry of a first stage. However, due to the close similarity with the shuttle the AD2 has been assumed to be very low.

An option to mitigate the aerodynamic requirements of the horizontal re-entry is to recover only the valuable parts of the first stage, namely the engine and not the tanks. This option is being developed by Airbus with the “Adeline”, (Nathan, 2015) concept. The disadvantage of this solution is the additional complication of the separation between the engine and the rest of the stage.

A relatively easy way to accomplish recovery of the first stage would be to use a parachute. Parachute recovery has been used extensively for this purpose, most recently by the Orion program (NASA, 2016). The disadvantage, in this case, is the very poor flexibility of the landing location and the impossibility to perform a soft landing without additional engines or a splashdown. The recovery, therefore, incurs increased costs because of seawater intrusion or adding additional propulsion systems (Blue Origin, 2016).

3.5 Guidance and control

The guidance and control subsystem function is to make sure the launch vehicle follow the required trajectory to deliver the payload into the desired orbit.

The very first rockets had aerodynamic fins to provide stability to the system. The addition of a movable part to each fin can also provide means to control the rocket. However, this solution can only work in presence of the atmosphere or when the dynamic pressure is high enough, therefore it is not applicable (at least not alone) for launchers. The main advantage with respect to other options is that it can work passively, so also in engine off conditions. This is very important for air-launched rockets because it can deliver the required stability and control during the carrier separation phase when the rocket engines are off for safety reasons (see for instance the Pegasus design (Orbital ATK, 2015).

In contrast with passive aerodynamic control surfaces, active control systems can be achieved using the main engine of the vehicle or using additional secondary rocket engines.

In the former option, the nozzle of the main engine is hinged and actuated to attain gimbaled thrust. In the latter additional smaller engines, known as Vernier thrusters are placed at the sides of the main engine to produce the required moments.

Vernier thrusters have the advantage that they are far less complex. However, Vernier thrusters require a lot of additional plumbing which makes them disproportionally heavier than gimbaled thrust. Vernier thrusters are much less common in modern vehicles, but older vehicles, particularly Soyuz (NASA, 2013) still make excellent use of them. The Atlas V is an example of gimballed thrust, made particularly obvious when the asymmetrical SRB's are offset by the slew angle of RD-180 rocket engines (ULA, 2010).

4 HISTORICAL MARKET ANALYSIS AND SMALL PAYLOAD MARKET FORECAST

The market overview was evaluated by starting with an extensive historical database that catalogued every launch and payload between 2012 and 2016; with a strong commercial rationale and a broad intake of data. Existing market analyses and initial research had deemed years prior to 2012 of little or no impact on the small payload market. Multiple methods of segmentation were then implemented to clarify a market shape and direction. This resulted in a robust range of space activity that was collated and segmented from multiple sources; unified under a single database. The variables for each launch and payload were segmented using the following methods:

4.1 Payload Database

Inside the historical database, the payloads were segmented by the following variables:

- The Federal Aviation Authority (FAA) weight classification was used to categorise the thousands of payloads by their individual mass. This segmentation was refined by primarily focusing on the Pico-Mini satellite segments, between 2012 and 2016
- The payload database within the database was organised by the application for which each payload was designed; consisting of Remote Sensing, Development, Communication, Scientific, Cargo/Crew, Meteorology, Navigation and IMINT.
- The payload database was categorised using the altitude, in kilometres, at which each payload operates. The altitude was recorded alongside the apogee and perigee of each payload in conjunction with the orbit types for each payload; such as LEO, MEO, GEO, SSO, GSO, HEO and EXT.
- Each payload in the database contains the inclination at which each payload was delivered to; with respect to degrees from the equator. These recordings were in conjunction with the orbit categories of each payload.
- Every payload in the database is defined by the country of origin and manufacturer.

Table 1. FAA satellite classifications

FAA Classification	Minimum Weight (kg)(2DP)	Maximum Weight (kg) (2DP)
Femto-Satellite	-	<0.09
Pico-Satellite	0.10	1.00
Nano-Satellite	1.01	10.00
Micro-Satellite	11.00	200.00
Mini-Satellite	201.00	600.00
Small Satellite	601.00	1,200.00
Medium Satellite	1,201.00	2,500.00
Intermediate Satellite	2,501.00	4,200.00
Large Satellite	4,201.00	5,400.00
Heavy Satellite	5,401.00	7,000.00
Extra-Heavy Satellite	<7,000.00	

4.2 Launch and Launch Vehicle Database

The historical database contains both a launch database and a launch vehicle database that is used to record all launches and vehicles that were used in the investigated years (2012-2016).

- The mass of each launch vehicle was recorded, as were the different capacities to LEO, SSO and GEO
- Each launch vehicle has a launch price in US dollars (US$).
- Each vehicle is categorised as a horizontal or vertical and small or large launcher.
- Lastly, the launch vehicle database contains the country of origin of the vehicle.
- Each entry in the launch catalogue contained the total mass of the payload(s) in kilogrammes (kg).
- The difference between the maximum capacity to that orbit and the actual total payload results in a record of each launch's overhead.

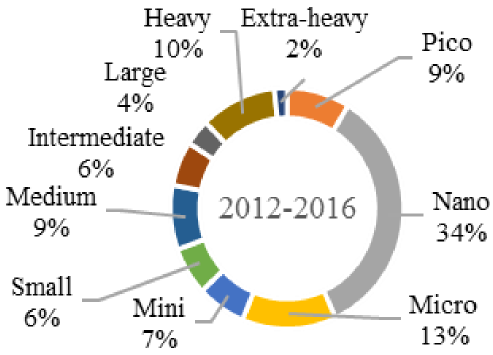

Figure 2 - Historical payload mass breakdown between 2012 and 2016

4.3 Forecast methodology

The methodology for the forecast has been a multi-variable yet subjective analysis on the market forces and strategic factors:

- *Miniaturisation* - The innovation in satellite technologies; which leads to the CubeSat configurations, component miniaturisation, sub-system efficiencies, thermal control architecture, data transfer rates, service life, structural reliability, sensors, power supply and on-board propulsion. This ongoing trend underpins growth in small payload spacecraft development with an increasing focus on higher levels of capability and therefore commercial (as opposed to academic) focus. In turn, this also leads to a trend toward higher LEO altitudes to prolong economic service life.
- *Satellite Applications* - Analysis of emerging new applications and an elaboration into sub-applications to predict the establishment and destination of new satellite constellations and directly inserted payloads; regarding altitude and inclination. This assessment identifies likely growing predominance of earth observation platforms seeking higher altitude launches and sun synchronous orbits as well as the emergence of mega constellations providing space-based global communications and data transmission capabilities.
- *Economic Growth vs Space Sector Growth* - Historical growth in the space sector is founded on underlying global GDP growth. Historical data demonstrates that space sector growth is outstripping global GDP growth and national growth in space industrial economies. Analysis of these differential growth rates provides a baseline for anticipated underlying economic growth in the space sector in the future and is therefore utilised in forecasting future market volumes.
- *Regulatory* – The regulatory environment can dictate, enable or constrain the direction and shape of the market. This environment includes regulations and treaties such as ITAR, MTCR, UN and the United Kingdom Space Act. Increasingly, national space agencies and Governments are defining the regulatory environments, they intend to both promote and control the development of their space sectors. This assessment identifies that large launch capacity development is likely to be tightly confined to existing nations with such capabilities and within existing programs. New launch vehicle development is likely only to be enabled and promoted within the small payload (sub 500kg) capacity sector.
- *Small Payload Launch Capacity* - The introduction of small payload launchers will change how satellite manufacturers will choose a launch system; this is an important area to understand and monitor. Currently, due to the current lack of feasible and available small payload launchers; there is a substantial risk of concentration for small payloads and consequent insurance and finance costs that constrain demand. With the advent of increasing capacity, more financially attractive and lower risk launch opportunities will underpin growth in the small payload sector.
- *ISS and Large Launch Future Direction* - The destination (e.g. ISS) of large primary payloads dictates the destination of the secondary payloads. ISS resupply has been shown to be a dominant force shaping historical small payload launch predominance. However, the potential retirement date for the ISS in 2024 and the increasing focus of large launch to exploration and resource acquisition missions may result in a substantial and inexorable decline in large launch rideshare capacity. This will constrain growth in scenarios where small payload launcher capacity is insufficient to meet demand. It will also result in optimised small payload missions; seeking the specific orbits (inclination and altitude) that their missions require.

A thorough analysis of these market variables was conducted alongside various inputs of research and comparative work from industry experts and satellite manufacturers; which allowed a verification of the contextual research. Using this research, a multivariate forecast model was created to predict the number of payloads that will be launched yearly from 2016 to 2036. Using the contextual research of market forces and industrial factors; the forecast detailed the volume of payloads that fell into each FAA Weight Classification (including Pico-Mini).

Three predictions were generated for the output of this forecast; a Potential volume model created based on assumptions of continuing strong growth with a minimum constraining forces, a Pessimistic model which downplays the emergence of large-scale constellations and relied on conservative ongoing growth rates for small payload demand and between these a baseline model that reflects a balance of growth drivers and constraining effects. This final model was then used as the baseline for the assessment of the launch vehicle configurations developed.

4.4 Market share

Simultaneous to the volume forecast, the market overview included a market share analysis that would give a comprehensive index of existing and upcoming launch systems. This delivered an attractiveness scale to compare vehicle capability and capacity; which gave substance to a prediction on the number of launches for each spacecraft. The vehicle capability and capacity variables considered were of the following:

- The launch system's cost per kilogramme (US$). This scale favours larger launchers as they can take advantage of economies of scale.
- The launch system's total advertised (or estimated) launch cost (US$). This scale favours small launchers as they cost less overall.
- An ITAR rating, which defines how easily the vehicle can access the US satellite market.
- The likelihood of project completion for developing launch systems.
- The reliability and failure rate of a launch system in service.

These factors combined to create an attractiveness index which was then used in conjunction with the following variables to produce a mass launched per vehicle per year. A launch system's payload capacities to LEO, GEO and SSO was used to calculate the total available market per vehicle per year. This used the segmented volume forecast to establish the total mass available. Lastly, for upcoming systems, the launch system's expected year of entry was used while for retiring systems the year of exit was used to

In order to calculate a final market share, upcoming and retiring vehicles required additional data. For upcoming systems, the launch system's expected year of entry was required, while for retiring systems the year of exit was required. This allowed a per year market share with different numbers of vehicles each year.

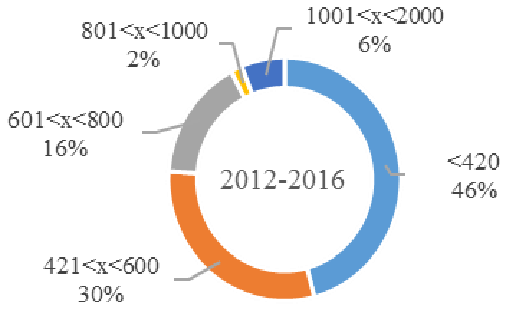

Figure 2 – Historical payload altitude breakdown (values in km)

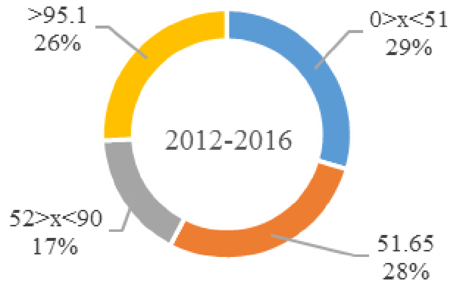

Figure 3 – Historical orbit inclination breakdown (values in degrees)

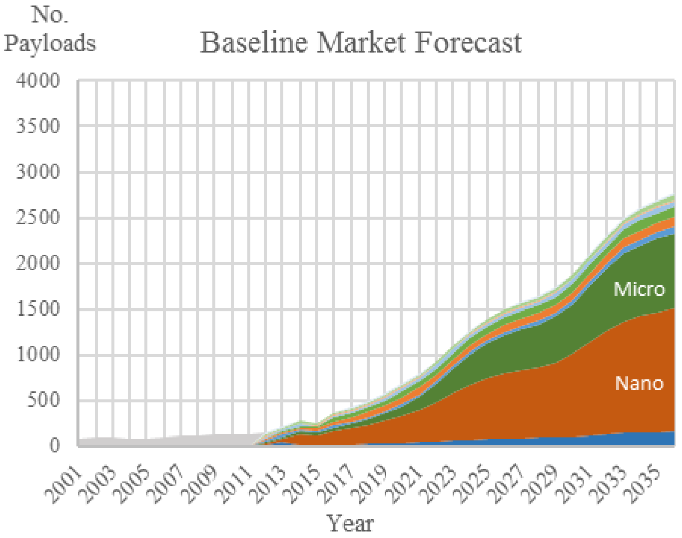

Figure 4 – Future baseline forecast on the volume of payloads per year, segmented by mass

5 MARKET EVALUATION AND DEMAND

5.1 Past and current

From the methods discussed, the small payload market was evaluated in terms of satellites, segmented mainly by mass. The number of payloads were recorded and showed a clear dominance by the Nano (1.01kg-10kg) and Micro-Satellite (11kg-200kg) mass classifications. This was partly driven by the adoption of the CubeSat construction methods (1U, 2U, 3U, etc.) (CubeSat Kit, 2013). These lightweight standards (1kg up to 24kg) (ISIS, 2016) were the answer to deploying miniaturised technologies into space; becoming popular with universities, research agencies and governments. NASA has a role in this progression from the CubeSat Launch Initiative (CLI); allowing a rideshare with primary payloads destined to the ISS, where the station will re-deploy any secondary CubeSat payloads at the station's own orbit (409 km, 51.6°) (Mahoney, 2016). Thus, there was an overall growth in the share of Nano Satellites between 2012 and 2016; shown respectively by year: 9%, 24%, 46%, 42% and 37%. The annual share of Micro-Satellites was as follows: 13%, 8%, 17%, 12% and 7%. The fluctuations of these values were partly caused by the Antares failure in 2014 (Bergin, 2014) and the SpaceX failure in 2015. The year 2016 is still being actively monitored to accommodate various Antares launch delays and the effect of the recent SpaceX launch failure (Foust, 2015b). As of this paper, the payload mass segmentation can be seen in Figure 2. The payload market was then evaluated by plotting the historical altitude and inclinations. This highlighted the popularity certain altitudes and inclinations (Figure 3).

Specifically, 63% of all payloads deployed up to 420km were Nano-Satellites (1.01kg-10kg) and 5% were Micro-Satellites (11kg-200kg). Between 421km and 600km, 38% of all payloads were Nano-Satellites and 22% were Micro-Satellites. With respect to the number of payloads delivered to the altitude segment between 601km and 800km, the market share of the Nano-Satellite and Micro-Satellite were represented as 28% and 40% accordingly. Looking at all payloads taken between 801km and 1000km, Micro-Satellites had a share of 28% and there were no Nano-Satellites at these altitudes. From an altitude of 1001km up to 2000km, there was no Nano-Satellites deployed and only 12% of the payloads at this altitude range were Micro-Satellites. These percentages show that the rideshare programs and the ISS initiatives influence the market by providing a less expensive route for small payloads (Mahoney, 2016). This is clear from the high percentage of Nano-Satellites, which include CubeSats, at altitudes up to 420km.

The next analysed market variable was the inclination of each payload; using the mass segmentation to outline the destination popularity (Figure 4). When considering the mass segmentation, there is a clear dominance in Nano-Satellites (1.01kg-10kg) at an inclination of 51.65°; where the ISS is positioned (Boeing, 2016). Regarding all payloads delivered to this inclination, 74% are Nano-Satellites; this again translates to the popularity of CubeSats that are delivered to the ISS. The next considerable payload mass segment at 51.6° is the Heavy Satellite; which represents 11% of all payloads at the ISS inclinations. This is explained by various cargo modules and crew missions. All other payload segmentations (FAA) do not individually reach higher than 5% of the total number of payloads at the ISS inclination. The second significant concentration of Nano-Satellites can be found in a retrograde, SSO inclination. Considering all payloads at this inclination, 28% are classed as Nano-Satellites. However, the dominant mass segment is the Micro-Satellite (11kg-200kg); which represents 31% of all payloads in a retrograde, SSO inclination. This represents the mixture of Remote Sensing satellites that are used for Earth Observation.

5.2 Future predictions

After considering the small payload market and its strategic factors and forces; there is a growth in the number of payloads per year in the forecasted timeline to 2036 (see Figure 5). For the topic of this paper, the variables discussed include the payload mass segmentation, payload inclination and the payload altitude; to guide the requirements of a future small payload launcher.

2026 (Baseline)

When studying the next ten years, the total number of payloads are forecasted to reach a baseline volume of 1456 in the year 2026. Specifically, within those payloads, approximately 708 are Nano-Satellites (1.01kg-10kg); (213) 30% of the Nano-Satellites are expected to be delivered in an altitude range between 450 km and 650 km, with an inclination between 60° and 90°. Within the same 708 payloads, (142) 20% of Nano-Satellites are expected to be delivered to the same altitude range between 450km and 650km with a retrograde, SSO inclination. This outlines the popular destination of satellites used for Earth Observation and is a clear example of the Planet Labs and Spire constellations (Foust, 2015a).

In the same ten years, the Micro-Satellite (11 kg-200 kg) is expected to grow to 425 payloads in 2026. Approximately (43) 10% of Micro-Satellites are expected to be delivered into an altitude range between 450km and 650km, with an inclination between 60° and 90°. Additionally, 30% (128) Micro-Satellites are delivered at the same inclination range but at an altitude greater than 650 km; which represents mega-constellations such as OneWeb that are destined to an altitude of 1200km at an inclination of 88.2° (Selding, 2014). 20% (85) of Micro-Satellites are also expected to be delivered to an altitude range between 450 km and 650 km with retrograde SSO inclinations. This essentially outlines the Remote Sensing satellites in the Micro-Satellite category.

2036 (Baseline)

When studying years from 2026 to 2036, the total number of payloads are forecasted to increase further; up to a baseline volume of 2716 in the year 2036. Of those payloads, 1354 are estimated to be Nano-Satellites (1.01kg-10kg). 35% (474) of these Nano-Satellites are expected to be delivered into an altitude range between 450 km and 650 km, with an inclination between 60° and 90°. Again, with the same (Nano) payloads, (339) 25% are predicted to be delivered to the same altitude range, between 450 km and 650 km, with a retrograde, SSO inclination.

The Micro-Satellite (11 kg-200 kg) is expected to grow to 822 payloads in 2036; with (124) 15% of Micro-Satellites to be delivered into an altitude range between 450km and 650km, with an inclination between 60° and 90°. At the same inclination, but above 650km, 30% (247) are Micro-Satellites part of the mega-constellations; such as the OneWeb constellation (Airbus DS GmbH, 2015). 20% (165) of Micro-Satellites are also expected to be delivered to the same altitude range between 450km and 650km with an SSO at inclinations greater than 90°. In addition, 25%(≈206) of Micro-Satellites are at the same inclination range but at an altitude greater than 650km.

5.3 Perspective comparison

Three predictions were defined in the volume forecast, driven by measurements of the market forces and industry factors. These resulted in a credible range for the volume of payloads. Specifically, the following graph identifies the range of the small (Pico to Mini) payload market (Figure 6).

Using the volume forecast and market perspectives, there is a clear shift from heavier payloads to smaller payloads, which can be observed from calculating the average mass per payload launched each year. These predictions are driven by upcoming satellite constellations, component miniaturisation, developing applications and the CubeSat configurations. To compose this output, the following graph identifies the three market perspectives that were computed in relation to the average mass of the payloads expected to launch each year. This shows the current trend that a small payload launchers aim to satisfy (Figure 7).

5.4 Market share

Within the market share analysis, the annual number of launches was computed for each existing and upcoming small payload launcher in the years 2016 to 2036. From investigating many of the forces and industrial factors in the market; certain small payload launch systems were removed and determined as unlikely launch systems that will not make it to the market, or expected to be later than announced. Examples of such market factors include the following:

- Old expensive launch systems retiring
- Replacement by newer launch systems
- Expected development delays due to use of low TRL technologies
- Company financial difficulties

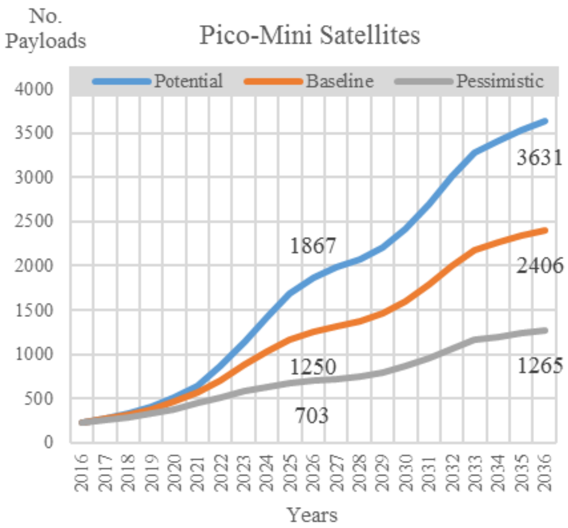

Figure 5 - Three predications of the volume of Pico to Mini Satellites launched between 2016 and 2036

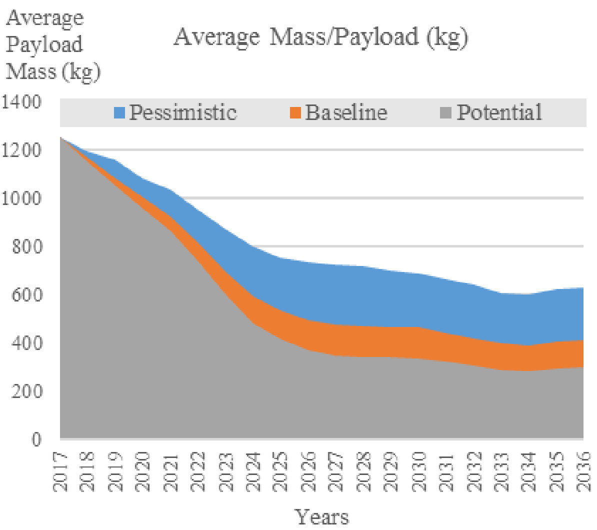

Figure 6 - Average payload mass per year between 2017 and 2036, with perspective segmentation

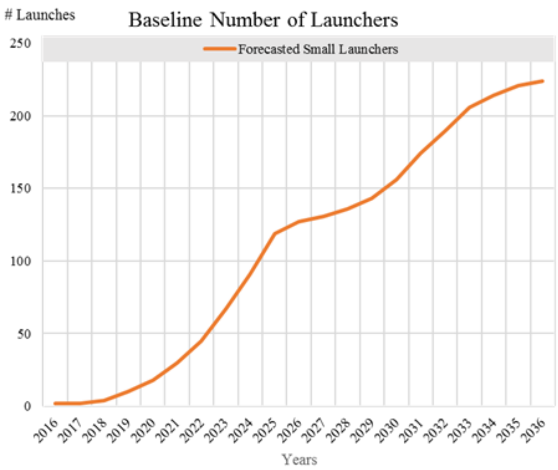

Figure 7 – Baseline forecast of the number of launches by small payload launchers

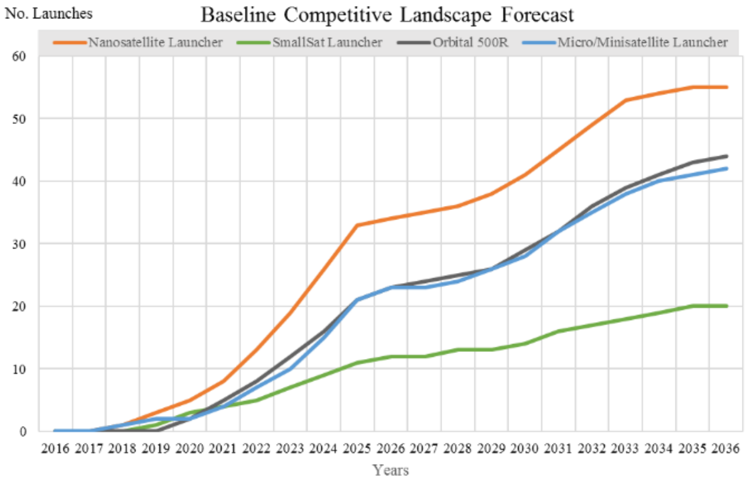

Figure 8 – Baseline forecast of the number of launches per small payload launcher category

This resulted in a market share per vehicle. To ensure integrity, we have analysed the data at a system-specific level, however, for the purposes of publication we have grouped the systems per their market share and launch numbers. As can be seen in the graph below (Figure 8), the forecast number of launches of small payloads is set to increase substantially with the advent of new launch systems. This can be split down into three primary categories; the nanosatellite launchers that only service the smaller CubeSat payloads (1-3U), Mini-satellite launchers (200-500kg) and Small Satellite launchers (up to 1200kg).

As per the graph (Figure 9), the number of launches for each vehicle type will increase rapidly after their introduction date. The smaller vehicles will launch more per year than the heavier launchers. It is important to note that the smaller and medium launchers will see a much greater growth in the number of launchers when compared to the larger launchers. This is in part due to their capacity for more launchers, but also their responsiveness time.

As a result of this, the following nanosatellite launchers could see just upwards of 50 launchers per year, while the micro/mini launchers could reach just above 40 launchers per year. The larger small payload launchers would see approximately 20 launches per year.

6 CONCLUSIONS

In summary, the following factors for the payload were defined and analysed. Firstly, an outline of vehicle classifications was established followed by explanations regarding the process and findings of the technological investigation and market analysis to guide the design of a small payload launcher.

The state of the art of the launch system technology was analysed to identify the main technological trends both at a system level and for specific technological areas. The main trend consisted of moving from fully expendable systems to fully reusable systems has been outlined together with the key technologies that need to be developed to put this plan into practice.

After the technological analysis, the small payload market was investigated along with a prediction of the future volume of payloads. This outlined the popular destinations for small payloads in the future; that can be used to dictate the design requirements and respective technologies to be implemented into a small payload launcher. The small payload market was studied with a methodology that incorporated a historical database combined with an extensive investigation into the market forces and industrial factors that continue to influence the market. This was supplemented by several external industry professionals and previous forecasts that provided composed guidelines for the market forecasted. These comparisons and external sources were combined with a market share analysis; which consisted of an index regarding the competitive attractiveness of current and pending launch systems.

Thus, the small payload market forecast has shown a continued favour towards Nano-Satellites and Micro-Satellites; which translates to a payload mass range of 1.01 kg-200 kg. These mass categories were predicted to be delivered to an altitude between 450 km and 650 km, with an inclination from 60° and beyond 90°. A second popular destination for these satellite categories is at an altitude greater than 650 km with an inclination from 60° and beyond 90°.

Lastly, the market share analysis sees a rapid increase in the number of launches by small payload launchers following the introduction of cheaper launch costs that allow smaller payloads to avoid the drawbacks of rideshare launch. While the large payload launchers still keep some of the small payload market, in particular orbit agnostic payloads, increasingly, satellite operators will take advantage of the ability to pick specific orbits as well as other benefits of being the primary payload.

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