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THE CUBESAT ECOSYSTEM: EXAMINING THE LAUNCH NICHE

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In the last decade, CubeSats have rapidly increased in popularity as a platform for low-cost activity in space by industry, government, academia and the military. This paper discusses the current supporting ecosystem for CubeSat development in the United States, from funding opportunities to ground-station services. It also discusses the opportunities and barriers facing the ecosystem as a whole, with a particular focus on the launch niche; a potential choke point for the entire ecosystem. NASA's CubeSat Launch Initiative is examined as a case study to better understand the CubeSat launch hardware qualification and integration processes.

I. INTRODUCTION

The term "CubeSat" is applied to a class of small satellites that are built in standard sizes measured in 10cm cube units, or U's. A CubeSat standard has been created and updated regularly by the California Polytechnic State University (Cal Poly)[i], although in reality CubeSats often vary from that standard and, therefore, a precise common definition is still lacking. CubeSats have typically been used by universities for training and experimentation since around 1999 when the standard was introduced, but CubeSats have also been used for other purposes including technology development, communications, space science, Earth observation, and intelligence-gathering. Despite their growing use, CubeSats remain generally less capable than the more traditional satellites, especially in regard to hardware reliability, sensor complexity and quality, and operational lifetimes.

CubeSats were of interest for this study because they have a lower barrier to entry into satellite development given their relatively low cost and short development times, characteristics that have the potential to change the way data is collected and analyzed from space. They can also potentially be used to augment more traditional systems for sustained observations, as well as provide opportunities for deep space mission data collection at relatively lower costs. Additionally, CubeSats have been used to raise the Technology Readiness Level (TRL) for future missions by flying technology demonstrations, thereby reducing the risk of flying technology that otherwise would not have been space tested. Finally, CubeSats allow students and early career engineers to have hands-on experience with all phases of a mission that will fly in space.

There are a number of technology factors that have contributed to the increased popularity of CubeSats, including the continued improvement of miniaturized electronics and power systems, though the ecosystem of available services has also been an important factor. These include the availability of standardized parts, launch qualifications, and institutional support (amongst other niches) that create an environment conducive to CubeSat projects regardless of their instrumental value. In this work, we review that last aspect, with an overview of CubeSat support services.

The availability of launch opportunities for CubeSats has been critical to their success, though it may also be a potential choke point for further growth. There is still a limit to the number of affordable rideshare spaces available in the US each year, especially for specific destination orbits. If CubeSats grow in number and utility as expected, then launch availability will need to increase proportionally in volume and specificity. There is evidence that a market is developing rapidly with a number of small and upcoming launch companies acting as brokers, hardware developers, or dedicated small launch vehicle developers; however, since demand for CubeSat launch is limited by the owner/operator's ability to pay, even if a large number of dedicated small launch vehicles were to become available and provided owner/operators the flexibility of dedicated launch (i.e. without having to fly as a secondary payload) a sufficient number of

[1] Currently at the University of Maryland, College Park

paying owner/operators would be necessary to sustain that market.

This paper will explore how this community of heterogeneous actors, including universities, companies, and government agencies, create a launch environment that functions and develops differently than traditional satellite launch.

2. USES AND MOTIVATION FOR CUBESATS

As noted above, the term CubeSat has never formally been defined, though there have been a number of suggested definitions. The reason for establishing a CubeSat standard is to streamline the development and launch processes.[ii] Puig-Suari of California Polytechnic State University and Twiggs of Stanford (amongst others) developed the CubeSat standard in 1999.[iii] Their purpose was to enable the creation of easily launched satellites that could be designed and built by university students for their education. Their most commonly accepted standard dictates dimension and mass constraints, with other factors such as safety requirements dictated primarily by the launch vehicle and CubeSat deployer to be used. Within the broadly defined standard overall design and construction is fairly open and flexible. Satellites conforming to the CubeSat standard tend to be very small in relation to most operational satellites, which can weigh thousands of kilograms. The most common sizes are in the range of 1 to 3 U, or 1.3 to 4 kilograms respectively, though larger sizes produced by using multiple CubeSat units have become more common over time.

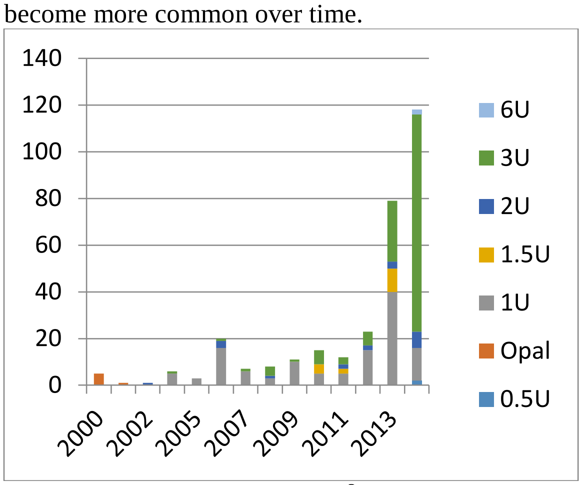

Fig 1: CubeSat Size Over Time.[2]

In addition, the relatively low-cost and mass of CubeSats allows for the launch of several redundant satellites at a time with costs likely comparable to a single larger and less risk-tolerant satellite. Beyond redundancy, identical CubeSats can be used to build relatively inexpensive constellations of satellites for a number of purposes including Earth observations and communications. Such constellations could have the ability to provide relatively inexpensive near continuous, even global, coverage. A further benefit to CubeSats is for training. US government missions today tend to be so large and time consuming that aerospace engineers will typically participate in only a few missions in their lifetime, if at all. In contrast, CubeSats allow for less experienced engineers to gain expertise without high risk to a more costly sustained mission.

The range of application areas for CubeSats includes[iv]:

1. Earth Observations – This includes any Earth-pointing satellite whether for science or commercial purposes.
2. Communications– Provision of communications, broadband, or sensing of AIS ship signals for tracking transportation.
3. Space Science –Science satellite for astronomy or deep space exploration.[v]
4. Position, Navigation, and Timing – Augmentation of systems like GPS1.
5. Space Situational Awareness - Tracking of objects in space using space-based CubeSats.

These are not mutually exclusive groups. For example, US commercial firm Spire plans to provide both communications relay and weather data from their constellation of satellites. In fact CubeSats launched in recent years have been more commonly used for commercial purposes rather than for education, as can be seen in figure 1 (although as the Figure shows, there is only one company – Planet Labs – that currently dominates commercial launches). Additionally, many CubeSats within these application areas can be technology demonstrations. The sections below will provide current and future plans for CubeSats for each purpose area.

[2] Data on the population of existing CubeSats used in this paper were derived from a number of sources, though primarily extended from databases compiled by Swartout (2015) and McDowell (2015). Additional information was collected regarding CubeSat mission nationality (from supplied contractor identities), launch method (e.g. pressurized-cargo launches for deployment from the ISS vs. from external deployers) and participation in the NASA CSLI program.* A total of 365 CubeSats were identified and characterized.

Earth Observations

By lowering the barrier to entry for satellite operators, CubeSats and microsatellites could open opportunities for new entrants into the field of providing and processing Earth observations data. For example, US firm Planet Labs[vi] intends to use near-continuous visible-spectrum coverage to create an on-demand, preprocessed information system for the average non-technical consumer rather than the existing labor-intensive weekly system that is currently focused towards use by scientists.

As an alternative example model, BlackSky is instead trying to provide on-demand satellite access, allowing the customer to purchase time on individual satellites from a large constellation of small satellites.[vii] While not all participants in this trend will necessarily employ CubeSats, (for example, BlackSky is likely to employ slightly larger satellites up to 50kg) they are aligned with the same terrestrial trends for an increased demand for data.

Communications

Spire plans to launch a constellation of Global Positioning System-Radio Occultation (GPS-RO) satellites (radio occultation using signals from space-based Position Navigation and Timing satellites) to both augment weather monitoring capability to fill a perceived gap in US weather forecasting capability while also tracking ships using AIS signals to monitor goods transportation across oceans for commercial interests.[viii]

Two large constellations of communications microsatellites have been proposed. OneWeb, formerly WorldVu, financed by Virgin Group, Qualcomm, and O3b plans to launch 700 satellites by 2019 to provide global Internet coverage.[ix] SpaceX has announced plans to launch 4,000 broadband small satellites each weighing a few hundred kilograms.[x] These two companies are proposing concepts that resemble those of Teledisic and Skybridge that both had similar plans in the 1990's, but which were ultimately unsuccesful. Relevant technology has improved greatly since the 1990s and similar small satellite broadband constellations have been launched to date. O3b, for example, currently has a 12-satellite constellation providing broadband Internet.[xi]

Both OneWeb and Space Exploration Technologies (SpaceX) have secured launches. OneWeb partnered with Arianespace to launch 700 satellites on 21 Soyuz launches. Each launch will carry a cluster of 32 to 36 satellites. The total price for the 21 launches is over $1 billion, costing approximately $1.4 million per satellite or $45 million per Soyuz launch. SpaceX will use their Falcon 9 vehicles for the constellation. Each Falcon 9 launch costs $61.2 million, however SpaceX has not released the planned size of each satellite so a cross-company comparison is not yet available.

Space Science

CubeSats can augment deep space missions and conduct useful space science.[xii] As a demonstration of this, the INSPIRE (Interplanetary NanoSpacecraft Pathfinder In Relevant Environment) mission will fly a pair of CubeSats into deep space to test CubeSat hardware and operations in a deep space environment.[xiii] Mars CubeOne (MarCO) is a mission utilizing two CubeSats that will be included in NASA's next lander mission to mars in 2016[xiv]. These CubeSats will assist the Mars InSight mission lander by relaying real-time data during the lander's entry, descent, and landing, rather than having to wait several hours for data to be sent through the Mars Reconnaissance Orbiter. Both of the deep-space missions described above use two nearly identical CubeSats, in part to reduce the risk of failure should a platform fail at some point in the mission.

Space Situational Awareness

CubeSats could monitor GEO satellites for space situational awareness from a LEO constellation according to Morris[xv] and Snow[xvi]. For example CubeSats with optical sensors could be used to photograph the GEO belt to augment ground-based optical sensors[xvii][xviii].

III. THE U.S. CUBESAT ECOSYTEM

Roughly 70% of the global launch activity in CubeSats is occurring within the United States, as noted in Figure 2.

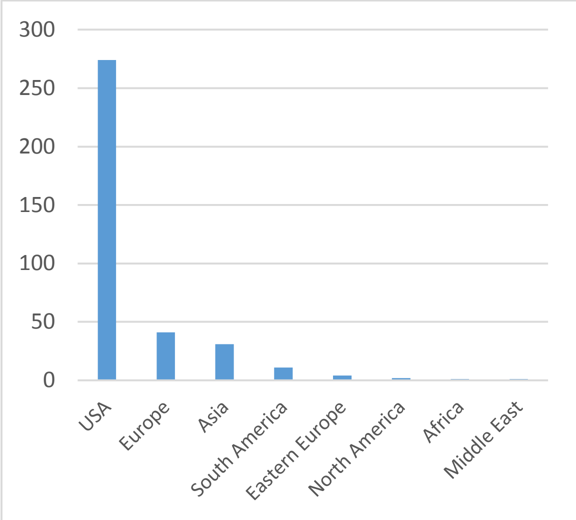

Fig 2: Total CubeSats Launched by Region

Figure 3 below presents a diagram of the different "niches" within the entire CubeSat "ecosystem".

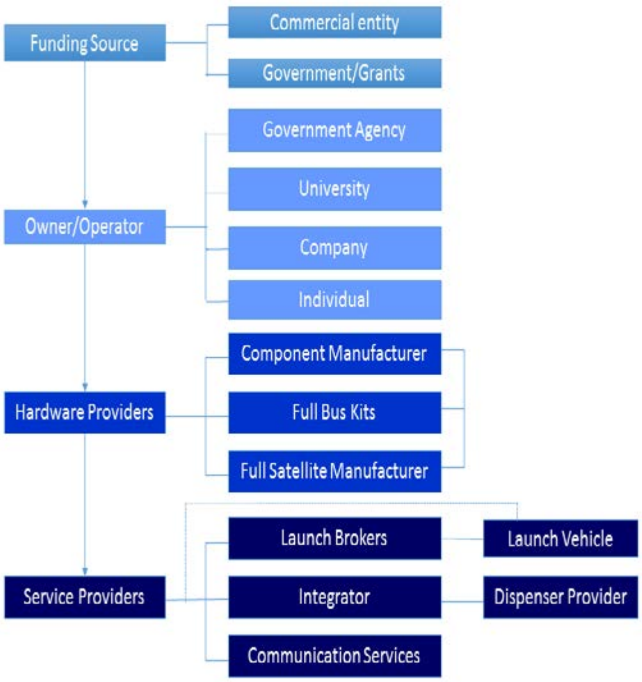

Fig 3: The CubeSat Ecosystem

Any given individual entity may fill multiple niches, but these are the generalized functions that must be performed to support CubeSats. Note that this diagram does not include any actual services that might be provided by CubeSats (see Section 2), only those that support the creation and operation of CubeSats themselves. Starting from the top of the ecosystem, inputs from different niches are shown on the line leading from a CubeSat owner leading to a functioning CubeSat that fulfills the owner's purpose. The niches are not necessarily in temporal order, but instead grouped with similar higher-level niches.

At the highest level, there are four main groups involved: Funding sources that provide the ultimate motivation for the creation of a CubeSat, owner/operators that oversee the complete project, hardware providers that support the actual development of the CubeSat, and service providers that support the launch and operation of the CubeSat, including qualification testing, deployer development, and communications network access. Each of these groups will be expanded upon in the sections below.

In particular, this study notes that limited launch opportunities for CubeSat are a potential choke point for the entire ecosystem, limiting the overall growth potential for CubeSat. While not intended to provide a complete overview of all US activities in CubeSats, the subsections below will provide an overview of current activities and players in the US with examples. The market is rapidly changing with new participants from the government, private sector, and academia. From a policy perspective, government activity related to CubeSats is of particular interest.

Funding Sources

Funding sources can be from commercial ventures such as selling imagery, or from government grants and sponsorships. Currently, a majority of support for CubeSats comes from investment (public, private, and military) rather than through sales to customers external to the ecosystem, such as subscribers to satellite television elsewhere in the satellite industry. Accordingly, that form of support will not be discussed extensively. [xix]

Private investors are also active in CubeSats, notably in the form of venture capital, such as the $80 million provided to Spire[xx] and $183 Million provided to Planet Labs.[xxi] Private investment also extends to elsewhere in the ecosystem, including launch vehicle provider SpaceX.[xxii] Government investment is primarily conducted by NASA and the National Science Foundation.

Owner/Operators

For CubeSats, satellite owners are usually also the operators of the satellite, though this is not necessarily the case. In practice, an operator is anyone who "controls" the satellite while it is in space. An operator can be a government agency, individual, university or company, and in cases where they are not the also the owner of the CubeSat or responsible for managing the entire project, they function as an additional service. Owners do not necessarily build their own satellites; they can purchase fully built satellites from suppliers including Tyvak or Pumpkin. Universities were initially the largest group of CubeSat operators, generally were responsible for final construction, but many stages of operation can now be provided by external service entities. Some specific characteristics of different owner/operators are described below:

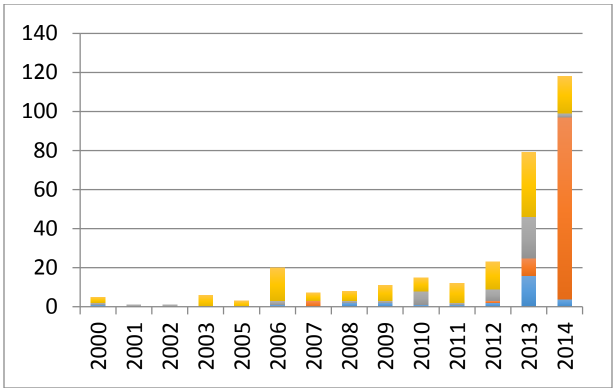

Figure 4: Frequency of CubeSat launches by type. Adapted from Swartwout, M. 2015.[xxiii] Yellow are universities, grey is military, orange is commercial and blue is civil.

Government Owner/Operators

NASA Centers, particularly Ames Research Center and the Goddard Space Flight Center, have been active in CubeSat development directly in addition to sponsoring their development through the Small Business Innovation Research (SBIR) programs and university partnerships. The various CubeSats are being used for Earth observations, deep space explorations (e.g. MarCo), and communications (SCaN Near Earth Network). Additionally, NASA centers have been actively using CubeSats for technology demonstration such as the Advanced Radio and Laser Communications and Formation Flight and Autonomous Docking as well as power generation and propulsion for deep space[xxiv]. In general, NASA has the ability to fill all niches of the CubeSat ecosystem, including but not limited to some aspects of launch and the establishment of dedicated ground stations for CubeSats.

The National Oceanic and Atmospheric Administration (NOAA) satellite and information service (NESDIS) is separately interested in the use of CubeSats to augment weather monitoring through microwave sounding or GPS-Radio Occultation (RO). NOAA has sponsored the Microsized Microwave Atmospheric Satellite (MicroMAS) [xxv] that was built by MIT Lincoln Labs as a proof of concept mission and was launched from the ISS in March 2015, as well as the follow-on Microwave Radiometer Technology Acceleration (MiRaTA)[xxvi].

The Department of Energy (DOE) has two national laboratories that are conducting CubeSat missions: Lawrence Livermore National Laboratory and Los Alamos National Laboratory. Los Alamos launched the Prometheus constellation as a technology development mission to explore the ability of CubeSats to meet Special Operations Forces (SOF) mission needs.[xxvii] The Air Force Research Laboratory also launched TacSat-6 in 2013. Federally Funded Research and Development Centers (FFRDCs) such as NASA's Joint Propulsion Laboratory, MIT Lincoln Labs (LL), and the Aerospace Corporation are also performing research on CubeSats. JPL is focused on planetary science, earth science, astrophysics and heliophysics, as well as general instrument and technology demonstrations.[xxviii] MIT LL develops a variety of CubeSats, perhaps most notably the MicroMAS and MiRaTA missions. Finally, the Aerospace Corporation is also active in the field, having launched several CubeSats for technology development.

Industry Owner/Operators

Planet Labs is the largest CubeSat owner-operator in the world, called out specifically in Figure 5:

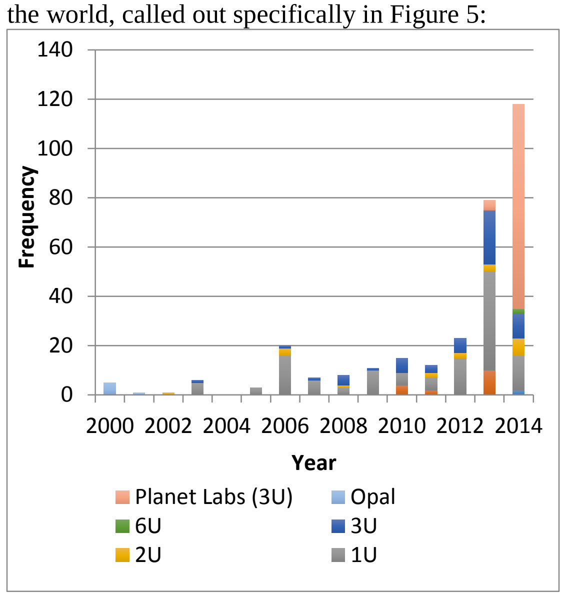

Fig 5: Frequency of CubeSats by Size. Adapted from Swartwout, M. 2015

Other commercial owner/operators include NanoSatisfi (with four CubeSats), Boeing (with two), Planetary Resources (two), the Planetary Society (one), Booz Allen Hamilton (one), and even a group Greek scientists and students in Silicon Valley (one). The vast majority of commercial launches are conducted by Planet Labs alone, meaning that the market is not as extensive as the numerical growth may suggest.

University Owner Operators

Universities represent the largest group of owner operators, comprising half of all CubeSats launched others than those connected with Planet Labs, and almost 60% (n=35) of all US organizations that have launched CubeSats. Universities are often pursuing CubeSats as an educational activity, so much of the design and construction for the CubeSat is performed right on campus. However, with sufficient project funds, universities may take advantage of existing CubeSat components in the open market, and take advantage of launch and other services that may fill large gaps in project team expertise.

Hardware Providers

The private sector has three general types of companies involved in CubeSat development: parts and components (P&C) providers, full bus kit providers, and satellite manufacturers. Many companies can and do act within multiple categories; for example some companies such as Pumpkin, Inc. develop parts and components to sell in addition to full bus kits.[xxix]

Component Manufacturers

Parts and component providers often specialize in specific pieces of the satellite bus such as microcontrollers, memories, communications, and power[xxx], or parts for specialized CubeSats such as star trackers or cold-gas propulsion systems. Many of their components are derived from terrestrial electronics and subcomponents, lowering costs and allowing easier entry by smaller companies that do not have prior experience in the space sector. It is interesting to note that many companies identified as P&C providers are spinoffs of universities, often graduated students who worked on CubeSats while competing their degree. [xxxi] For example, Tyvak Nanosatellite Systems is from Utah University, GOMSpace is from Aalbord University, and 406 Aerospace is from Montana State. This could be attributed to the academic experiences of students with CubeSats leading naturally into leveraging those skills in the open market. Additionally, these companies have often kept close relationships with their universities of origin to allow for knowledge sharing and easy commercialization of academic developments.

An advantage for many P&C providers not always shared by the larger satellite industry is broad compatibility, as a component for one CubeSat can require minimal, if any, customization in order to be used on another CubeSat mission. Rather than developing custom components on contract, many P&C providers can provide list pricing for their products.

Full Bus Kit Providers and Satellite Manufacturers

Adding systems-level capability to P&C providers, satellite manufacturing companies and kit providers design (and in the manufacturer's case, assemble) fully functional satellite buses for external clients that either do not need to retain (or have not yet developed) expertise in house to design and/or build a satellite. Examples include Tyvak[xxxii] and Pumpkin[xxxiii] in the United States, though larger aerospace firms such as Boeing have also demonstrated the capability. Kits have the advantage of ensuring compatibility of all parts provided, and fewer likely system-level problems. This can be more attractive to owner/operators, especially as goals for CubeSat missions expand into purposes beyond training, such as science-based missions, or commercial missions seeking lower risk. The advent of these types of companies have further lowered the barrier to entry into the CubeSat and small satellite market because organizations or governments with significant resources, even without engineering expertise to build a satellite, can instead purchase capability and, if desired, gain expertise to build internal capability.

Service Providers

Service providers offer expertise or infrastructure that is required for the operation of the CubeSat at some point in its lifecycle, but which may not be retained internally by an owner/operator. Many of these providers are concerned with launch, but also include consulting guidance, such as for government certification processes (e.g. registry with the FCC in the United States).

Additionally, some service providers may have unique or expensive infrastructure, such as a network of ground stations or satellites that can provide greater access to an owner/operator's CubeSat as it travels over various points around the world. Communication with CubeSats can be performed by each owner operator with essentially amateur radio equipment.[xxxiv,xxxv] However, for small-scale operators such as a university research group, contact with satellites can be limited to opportune moments of line-of-sight transmission when the satellite is overhead from a single location. Some service providers seek to improve communications, either through access to a network of terrestrial radio stations to communicate with the satellite of interest over a wider region of the Earth's surface, or through radio transmissions to communications satellite networks.

At times these services are bundled together into single companies, for example as in Spaceflight Industries, which has branches in launch brokerage and communications networks, as well as P&C products for CubeSats or CubeSat launch integration.

These groups are usually companies, but may be affiliated with academia (e.g. Tyvak), or internal to the government for US agency missions (e.g. the NASA Launch Services Program). More information on launch-specific services are provided in section 4 below.

IV. THE LAUNCH NICHE

A CubeSat has four options to get into space: obtain a rideshare or "piggyback" onboard a vehicle with an established primary satellite, buy a dedicated small launch vehicle, rideshare with a group of CubeSats on a "cluster launch," or be a hosted payload permanently attached to another satellite. Launch availability is a potential choke point for small payloads such as CubeSats. Obtaining a launch often represents a much larger proportion of the costs of a microsatellite's total budget compared to large missions.[xxxvi]

Hosted payloads are attached to a larger satellite. As a result they tend to be power, size and communication bandwidth constrained because all resources are shared with the hosting satellite. This present work is focused only on free-flying satellites, as they generally have significantly more flexibility and capability than hosted payloads.

Next, cluster launch is when an entire vehicle is filled with small payloads that would normally launch as secondary payloads. The launch is often fully purchased by a launch broker, which will be discussed in detail later in this paper, and spaces are sold to each payload. In 2014 a Russian Dnepr rocket completed a successful cluster launch of 37 satellites, and in late 2015 Spaceflight Services plans to have a cluster launch using their SHERPA system to launch 87 satellites. Spaceflight Services also plans to have yearly cluster launches to LEO and GTO starting in 2017[xxxvii]. These launches can be economically viable, but they will tend to be less frequent and require finding a large number of payloads willing to launch to roughly the same orbit simultaneously.

Finally, dedicated small launch vehicles allow a CubeSat to have full control over launch logistics, but at a premium. They are likely to be the most costly per-kilogram option. These vehicles are of interest to owner/operators when a particular destination orbit is needed that is unavailable with rideshare, or if the CubeSat has an inflexible launch schedule. Dedicated small satellite launch vehicles may be more expensive than rideshare, but they are significantly less expensive than purchasing an entire launch vehicle. For example a Falcon 9 costs $61.2 million compared to proposed dedicated launch vehicles that are proposed to cost as little as 1 million dollars.

The launch sector consists of three main groups: launch vehicle providers who build the rockets that carry CubeSats into space, the launch brokers that arrange for the launch of CubeSats as secondary payloads, launch integrators that ensure their safe integration onto the rocket, and the hardware providers that build deployers and adapters to connect the CubeSat to the rocket body.

Launch Vehicle Providers

The majority of US CubeSats that have been launched since 2010 have ridden on either ISS cargo missions[3] (120 of 236) or US vehicles (98 of the 236 US CubeSats launched)[xxxviii]. The vehicles that have completed resupply missions to the ISS are the Russian Progress, European Automated Transfer Vehicle (ATV), Japanese H-II Transfer Vehicle (HTV), and the American Cygnus and Dragon capsules. The US has used the majority of the excess capacity available internationally to the ISS, 120 out of 131 CubeSat spaces. This may change in time with the advent of more foreign launch brokers such as Japan Manned Space Systems Corporation (JAMSS) aiming to utilize excess capacity on H2-A and H2-B launches to the ISS. Currently most of the excess capacity for the ISS is filled by Nanoracks.

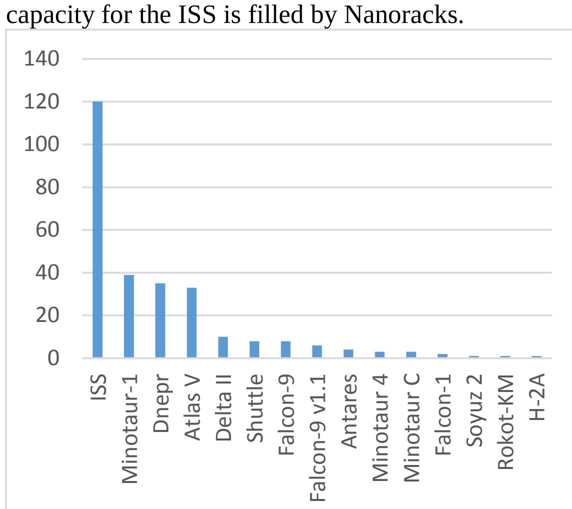

Fig 6: Past CubeSat Launch Vehicles

Only one out of 116 foreign CubeSats have launched on US vehicles since 2010.[xxxix] Launching from the US includes the added complications of handling ITAR restrictions, the generally higher cost of launch, and very stringent safety standards. Despite these added challenges, there are still a

[3] ISS missions are counted as independent from US or non-US vehicles because of their very unique cooperative agreements and standard requirement for payloads to be human rated.

number of rideshare spaces generally available. Many launchers fly with unused excess capacity due to an unwillingness to add risk from secondary payloads; the inclusion of highly classified payloads; or a fear that the secondary payload may drive the schedule.

It is important for CubeSat designers to understand the specific requirements of their launch vehicle. For example prohibitions against pressurized vessels can limit design options in propulsion. Currently CubeSats are generally guessing what vehicle they are most likely to launch on, and designing the mission specifications to meet those requirements. However if a CubeSat is manifested on a launch vehicle with more stringent safety standards than the vehicle for which it was designed, there could be schedule delays or even missed launch opportunities.

Launch vehicle operators may be hesitant to filling excess space with secondary payloads because secondaries might increase the risk of failure for the primary payload and launch vehicle. Secondary payloads also offer little benefit to the launch vehicle because they are viewed as distracting payload integrators from the primary payload. The price for secondary payload spots are low enough to be affordable for the secondary payload, but not high enough for the launch vehicle to make much profit. Despite these issues, a number of operators have shown a willingness to fill excess capacity, and have developed a familiarity with hardware and processes to integrate secondary payloads.

The regular acceptance of rideshares will not be guaranteed without an economic incentive. As such there has been interest in the development of smaller dedicated launch vehicles to deliver small payloads with greater control of the timeline, mission design, and orbit destination, all at an affordable price. The success of these smaller launch vehicles may depend on the overall market demand for precise launch times and orbital parameters from both universities and commercial entities.

Since the beginning of 2015, were at least 19 US small launch vehicle development efforts and 6 foreign ones, all at various stages of development. Appendix 1 provides a list of identified small launch systems. The information gathered in the chart is based on publicly-available information provided by the companies themselves, and has not been verified by the authors. The credibility of these efforts, either from a technical or business standpoint, has also not been evaluated. Note that any small launch company will be driven to make launches affordable, so the low prices quoted should regarded with some skepticism, especially in the absence of actual flight experience.

Figure 7 shows the price per kilogram on a variety of launch vehicles, both large and small. Only 12 of the small launch vehicles, out of 19, provided costing data and one launch vehicle, the Super Strypi or SWORDS, is no longer being pursued. Large vehicles tend to have lower cost per kilogram than the small launch vehicles and have also proven that this cost is sustainable. Only two small vehicles, Pegasus, and Minotaur, have successfully launched a payload into orbit, the rest are still in R&D or development stages. These two vehicles are also the

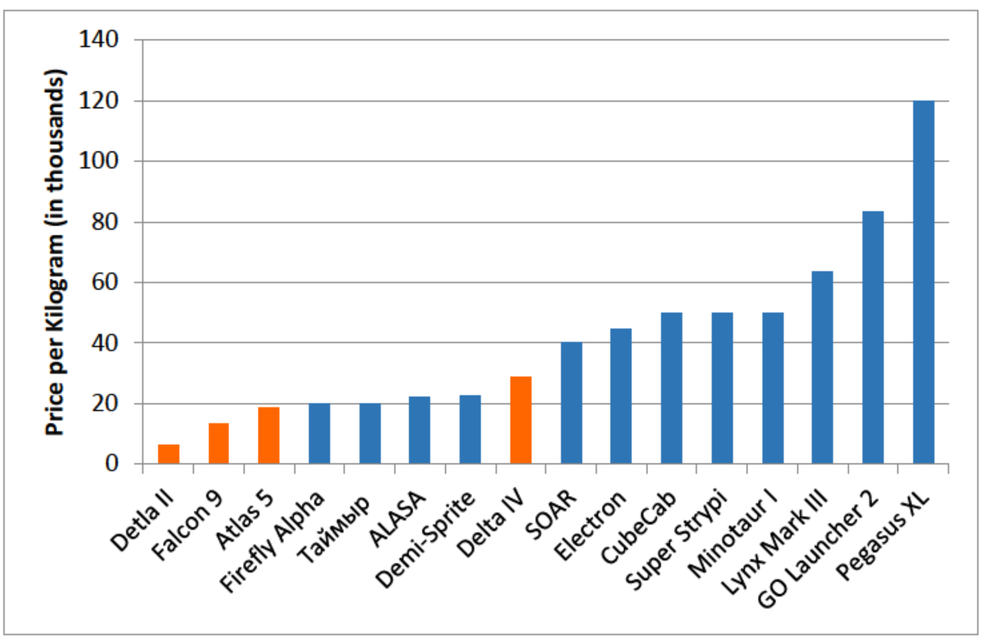

Fig 7: Launch vehicle (Price per kilogram)

most expensive launch vehicles per kilogram. This may be a sign of new small launch vehicle providers underestimating expenses, however, it also provides new entrants into the market a chance to learn from these established government programs.

Launch Brokers and Service Providers

Launch brokers coordinate rideshares between secondary payloads and the rocket or primary payload to fill excess capacity on a launch. They also help negotiate scheduling, integration, safety testing and price negotiations between the launch vehicle and the payloads, acting as a "one stop shop." Brokers have made the rideshare process easier for new entrants into the market and also for the launch vehicle operators. When launch vehicles use brokers to sell excess space, they do not have to add manpower to schedule, integrate, or test any secondary payloads which allows the vehicles to focus on their primary mission. We have identified four US brokers: Tyvak Nanosatellite Systems, Spaceflight Services, Nanoracks, and NASA Launch Services; and, three international brokers: The Group of Astrodynamics for the Use of Space Systems, Adaptive Launch Solution, and Earth2Orbit

Tyvak Nanosatellite Systems is a spin off form Utah State University. Tyvak assembles, integrates, tests and launches picosatellites, nanosatellites and microsatellites. They have successfully launched 17 missions with 6 planned. Tyvak uses the 3U PPod, 6U Tyvak NLAS, NPSCuL, Rail-POD and Grapple-POD on the Atlas V, Falcon 9, Antares, Athena, Kosmotras, and PSLV to suborbital, LEO, GEO, Lunar and Interplanetary destinations[xl]

Spaceflight Services provides rideshares for 3U, 6U, 12U, 50kg, 100kg or 150kg to LEO (including ISS), GTO and GSO. They are the only rideshare provider to publically release a set list of prices. For example, launching a 3U CubeSat to LEO with Spaceflight will cost $295,000 or launching a 150kg satellite to LEO will cost $4.95 million. In addition to set prices, Spaceflight has a public list of available launch manifests. They partner with US, European, Russian and Japanese rides going to the ISS and beyond. The most recent statement from Spaceflight Services claimed that from the beginning of 2015 to 2018, the company had 20 different launches planned, each going to a unique orbit and carrying different quantities and sizes of secondary payloads[xli].

Nanoracks provides suborbital, ISS, and beyond-ISS CubeSat launch services for universities, commercial, non-profit and government payloads. Nanoracks receives excess capacity on launches to the ISS and is also paid by NASA Launch Services through an agreement with the NASA Johnson Space Center, SBIR Phase III, to provide launch integration services for all CubeSat spaces on US launches to the ISS. They are capable of flying CubeSats, 50-100kg, and ESPA class satellites. When launching to the ISS, Nanoracks can use the United States' allotted capacity but they are limited in the number CubeSat releases because Japan only opens their Kibo airlock a few times each year.

NASA Launch Services has two launch initiatives of particular importance that were raised by members of the CubeSat community. These are the CubeSat Launch Initiative (CSLI) and the Educational Launch of Nanosatellites (ELaNa) both run by the NASA Launch Services Program. CSLI provides opportunities for free launches to the ISS for CubeSats. This initiative was created in 2010 with the LST PPOD-1 mission, but the idea predates the Challenger Shuttle accident. The Space Shuttle was originally the only rideshare opportunity for small payloads; however, when the Challenger mission exploded in 1986 and all missions were suspended, small payloads were left without affordable access to space. CSLI and ELaNa are closely aligned, though ELaNa is for educational purposes only while CSLI also provides free rides for nonprofits and NASA centers. In total, CSLI and ELaNa have launched 38 CubeSats. CSLI and the Japanese space agency (JAXA) both get 3U of allocation per launch to the ISS. If Japan doesn't fill the space then CSLI receives the excess.

The Group of Astrodynamics for the Use of Space Systems (G.A.U.S.S. Srl) is an Italian company founded in 2012. They provide launch services for microsats, CubeSats and PocketQube satellites in addition to satellite manufacturing, design and ground support segments. They have launched on Dnepr rockets and plan to launch with Japan to the ISS, where a satellite will be released through the Kibo module, similar to the way Nanoracks operates in the US.

Adaptive Launch Solutions (ALS) provides small payload integration services on Atlas V and Delta IV launch vehicles. ALS has the A-Deck auxiliary payload adaptor for the Atlas V and Delta IV. Payloads from 1-1000kg can be integrated into the A-Deck. ALS is responsible for mission integration, analysis, and testing at AQUILA integration facilities[xlii].

Earth2Orbit (E2O) is an Indian launch broker for Antrix, the commercial arm of the India Space Research Organization (ISRO), filling excess capacity on Indian PSLV flights. E2O has partnered with Firefly Aerospace, an American company, to utilize separation hardware for the payloads.

Deployer and Dispenser Providers

One of the main attractions of CubeSats is their adherence to a standard that can be integrated into a number of different launch configurations. This includes the use of various structures that go by the terms "deployers", "dispensers", "launchers", and "adapters", but all of which are physical hardware that insulate the CubeSat from the launch vehicle. For a given launch vehicle, deployers physically eject CubeSats from the launch vehicle safely. Most deployers will accommodate the general CubeSat specifications while offering different features, interfaces, connections, and designs. These deployers can often be grouped into larger assemblies that can contain and manage the deployment of different numbers of CubeSats. This is used especially for larger vehicles where the additional mass of several CubeSats is inconsequential. These dispensers are mounted to the launch vehicles by standard adapters on the launch vehicles, whether onto existing locations, such as the Atlas V Aft Bulkhead Carrier (ABC), or onto other hardware connections or adapters such as the EELV Secondary Payload Adapter (ESPA) Ring for the Atlas V and Delta IV that is shown in Figure 5. A list of a number of commonly used deployers is provided in Figure 8:

Deployers, dispensers, and adapters are a non-trivial addition of mass relative to the size of the vehicles they are launching, representing a mass-inefficiency against CubeSats in terms of the cost per kilogram metric. But the cost per kilogram metric is often less important to CubeSat manufacturers, for whom launch mass (and thus costs) is already much less than for a traditional satellite operator. However,

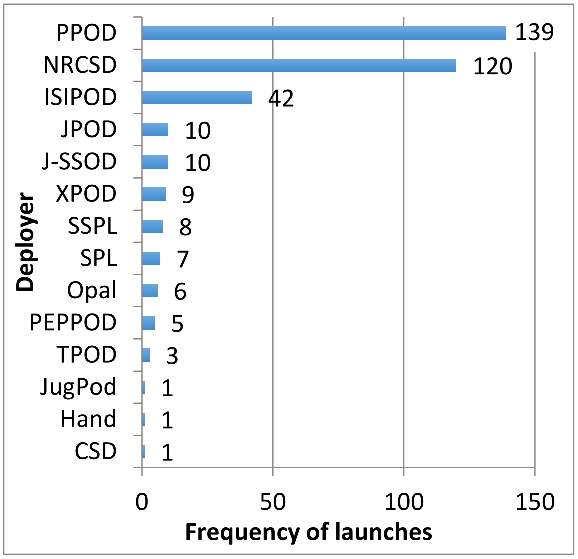

Fig 8: Frequency of CubeSat Launches by Deployer

lower mass is still a metric that launch hardware manufacturers continue to strive for.

Deployers isolate the CubeSat from the launch vehicle – in other words, any CubeSat successfully integrated into a deployer appears identical to the launch vehicle, greatly simplifying the qualification process. Even in cases where a CubeSat developer misses a deadline to integrate onto a flight, a mass simulator can be flown in place of the CubeSat without requiring significant additional qualification.

Deployers also provide CubeSat designers a strong mounting point to the launch vehicle, but since they are separate pieces of hardware they have to be separately qualified for launch vehicles to ensure safety.[4] While this is an additional (and costly) step[xliii], once qualified for a launch vehicle the deployer may be used on subsequent launches at a reduced cost.

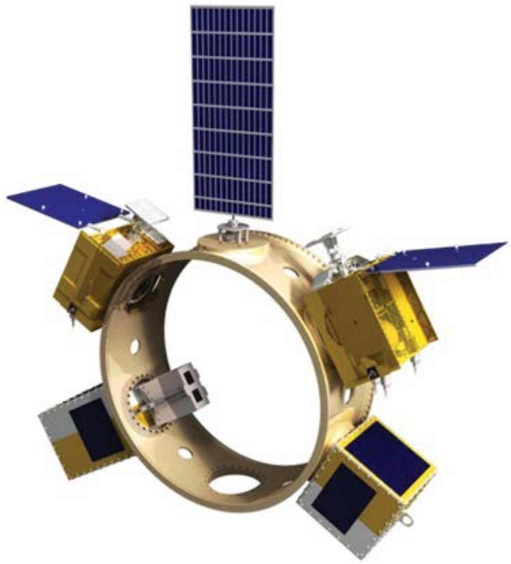

Fig 9: ESPA Grande Ring

A number of deployers have been developed worldwide, though in the United States, a few have seen more common use as noted in figure 6. The PPOD deployer developed by Cal Poly[xliv] which until recently[xlv] was the deployer of choice for NASA and a number of military missions.

Dispensers can be used to provide an additional layer of physical connections (or interfaces) between the launch vehicle and the deployer, usually grouping

[4] Long list of deployer hardware (including upcoming hardware) here: https://www.sprsa.org/sites/default/files/conference-presentation/Rideshare2015_Secondary-Adapters_Tech-Committee_Maly-Rev0.pdf

several deployers together and controlling their deployment (timings, etc.). The exact configurations and standards used vary by launch vehicle, and sometimes the primary payload especially if the primary payload requires a size adaptor of its own that secondary payloads may also use.
Determining appropriate and reliable adaptors is part of the qualification of a launch vehicle for launching CubeSats.
Some examples of current dispensers in development or use include:

- Naval Postgraduate School CubeSat Launcher (NPSCuL): 8 x 3U or 4x6U
- SpaceX surfboard
- Aquila CubeSat Accommodation by Adaptive Launch Solution
- Wafer adapters: 8x3U or 4x6U and can carry "primary" small sat
- Design Net Falcom 1e Rideshare Adapter
- LM Athena Composite P-POD carrier
- TriSept/Moog FANTM-RiDE generic small sat dispenser family

Some examples of current adaptors in development or use include:

a. Moog ESPA SUM
b. SHERPA

V. DEVELOPMENT OF US CUBESAT LAUNCH THROUGH THE LENS OF CSLI

NASA's CubeSat Launch Initiative is expanding launch services to include satellites with masses between 30 and 60kg. Interestingly, in 2014 the NASA ISS Program, NASA Johnson Space Center Engineering, and Department of Defense Space Test Program (DoD STP) collaborated on The Space Station Integrated Kinetic Launcher for Orbital Payload Systems (SSIKLOPS), known as "Cyclops."xlvi Cyclops is a deployment system from the ISS for 10-100kg payloads, significantly larger than the system by CSLI for CubeSats. This system expands ISS deployment to a wider range of satellites. However, it is unclear at this writing whether NASA Launch Services will coordinate the use of Cyclops, or if it will remain separately coordinated by the NASA ISS Program.

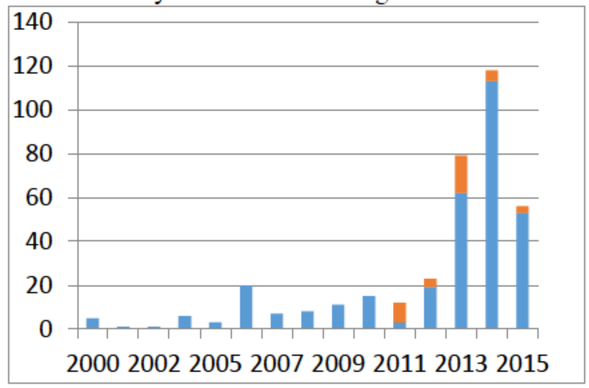

Fig 10: Number of CSLI (Orange) and Non-CSLI flights (Blue) by year

Similarly, NASA Launch Services has released a series of RFPs for venture class, or small satellite launch vehicles The first RFP recipient did not attain enough outside funding. The RFP released in 2015 is for a vehicle capable of launching 30kg of CubeSats.[xlvii]

As mentioned before, NASA Launch Services will also have the ability to launch CubeSats into deep space when and if the Space Launch System (SLS) is active. A single SLS will be able to take 11 6U CubeSats into deep space; this is planned starting in 2018 with BioSentinel, Lunar Flashlight, and NEA Scoutxlviii. The interface agreement was planned to be completed by September 20, 2015 (progress is unknown), payloads delivered to Kennedy Space Center (KSC) by February 1, 2018, and launch date in July 2018. This deep space opportunity is not open for academic or commercial payloads; it is for NASA Centers only at this time. However, the capability is important to note because it shows interest by NASA in furthering the use of CubeSats beyond Earth orbit.

The CubeSats Launch Initiative, and NASA and other US government agencies have used the Cal Poly PPOD deployer most commonly until recently, and have had a hand in the development of new launch vehicle/adapter/dispenser/deployer combinations. In particular, CSLI has been at least partly involved in the initial qualification and use of four vehicles for CubeSats, as seen in Table 1.

Deployer	Launch Vehicle	Overall 1st Use	CSLI 1st Use
NRCSD	ISS	2/11/2014	10/28/2014
PPOD	Atlas V	9/13/2012	9/13/2012
PPOD	Delta II	10/28/2011	10/28/2011
PPOD	Falcon-9 v1.1	4/18/2014	4/18/2014
PPOD	Minotaur C	3/4/2011	3/4/2011
PPOD	Minotaur-1	12/16/2006	11/20/2013

Table 1: List of Initial Qualification and Use of Deployer by Vehicle

Recently, CSLI has been investigating the ability to launch payloads through brokers, which may extend the range of deployers used in the program, taking advantage of other's first-time engineering. However, CSLI has announced interest in small dedicated launch vehicles which may (e.g. Super Strypi) require additional first-time qualification as performed in the past for the Atlas V, Delta II, Falcon 9 v1.1 and Minotaur C.

VI. CONCLUSIONS AND NEXT STEPS

The rapid growth in CubeSat activity leads to a question of whether this is a sustainable trend or simply a bubble. The potential applications for CubeSats appear to be expanding; however most of these uses remain at the R&D stage, and their use as reliable and operational assets is largely unproven. This is also true of the small, dedicated launch vehicles, which will rely on a consistent market of small satellites like CubeSats to be successful.

In this paper, we presented a map of the CubeSat development ecosystem, and observed that the launch component provides a series of challenges for the sector going forward. Flexibility in CubeSat design can be limited by the rideshare system, as this often includes uncertainty in launch vehicle availability. This in turn forces responsibly designed CubeSats to optimize against the strictest set of amalgamated requirements for launch vehicles. An example case is ISS deployment, which precludes pressurized vessels from use on the CubeSat, restricting some propulsion systems and experiments. The use of excess capacity on launch vehicles should also be made more profitable in order to make the launch market sustainable. Launch brokers seek to ease the launch process for vehicle providers and payload, but do not provide certainty that launch vehicles will continue to accept the added risk of secondaries. Finally, dedicated small launch vehicles could help provide options, but though launch companies are abundant with optimistic plans, only two have actually flown successful missions.

With CubeSat growth come a series of challenges: Space debris (potentially including operational CubeSats without propulsion systems) caused by CubeSats in popular orbits, such 480km around the ISS, concerns the space situational awareness community as there is no enforcement of spacecraft orbit lifetimes or a reliable ability to track their orbits accurately. The ability to track a CubeSat is very important because of their common lack of propulsion and their release through cluster launches, which can take days to track all CubeSats. However, this likely represents a technological opportunity that may address the issue: Retroreflectors and RFID tags can help ground-based sensors better track CubeSats while in operation and after its operational lifetime[xlix]. Other debris mitigation techniques that can be used for CubeSats include limits on popular orbits, especially around the ISS and requiring propulsion on high altitude LEO CubeSats to ensure an ability to deorbit.

Next Steps

Tempting though it may be, it is beyond the authors' scope and capabilities to make reliable predictions for the future of CubeSats; however, we would like to note some trend indicators.

On the civil side, a large (though steadying) number of applications for launch continue to be processed through the CSLI program, while maintaining a significant backlog of missions ready to launch from US universities that have successfully applied for support. In addition, this program is reaching out to commercial launch brokers, numerous in-development small launch vehicle providers, and integration service providers in order to broaden the paths available for launch to space. All three of these groups were less prominent or not even available at the start of the program in 2010.

Commercially, large constellations have been planned by credible companies, seeking different markets (Earth observations and communications) with a range of launch options at various stages of development, though the constellations are not wholly reliant on small dedicated launchers. The largest jump in CubeSat missions launched was related to the activities of a single company, whose success or failure may dictate future interest by investors.

CubeSats have until recently been first and foremost an activity carried out by university students as part of their education to provide first-hand experience with design, construction, and launch. The experience over an entire space-sector project is difficult to find otherwise early in a career, but at the same time the development and launch cycles necessary for CubeSat missions are not an insignificant cost. Judging the educational value of CubeSats might be an additional aspect of interest, also taking account of spinoff companies and project leads coming from prior CubeSat projects (e.g. Tyvak).

The CubeSat standard addresses some of the difficulty in launching additional small payloads while mitigating additional risk to primary payloads. Many of the costs and difficulties in obtaining a launch are likely the result of high qualification and integration safety standards, especially in the United States. Additional research into quantifying the risk posed by CubeSat secondary payloads and the costs of their qualification could be helpful in determining if the effort is worthwhile for all parties.

Launch can also impose limits in the design stage of the CubeSat, through the varied launch environments possible, as the launch vehicle is often unknown when designing a CubeSat (such as for CSLI). This uncertainty might lead to incorrect assumptions about the launch environment or overly conservative design. Further research could determine how commonly such uncertainty impacts CubeSat operators during the design phase, or if such factors should be taken into consideration more often, as consistent lessons-learned across missions.

Finally, a future study on CubeSats and their addition to the space debris environment would be of value. A follow-on study may be able to provide clarity on how much debris CubeSats add to the environment, the burden CubeSats provide to the SSA tracking community, and potential mitigation techniques.

Appendix 1

Vehicle Name[l]	**Company**	**Year**	**Mass (Kg)**	**Price**	**Price per kilogram**	**Country**
ALASA Program Vehicle (DARPA)[li]	Boeing	2016	45	$1,000,000	$22,000	US
CubeCab[lii]	CubeCab		1.33	$100,000	$75,000	US
			5	$250,000	$50,000	US
Demi-Sprite[liii]	Microcosm		160	$3,600,000	$22,500	US
Firefly Alpha[liv]	Firefly	2017	400	$8,000,000	$20,000	US
GO Launcher 2[lv]	Generation Orbit	2016	30	$2,500,000	$83,000	US
LauncherOne[lvi]	Virgin Galactic	2016	120/225	$10,000,000		US
Lynx Mark III[lvii]	XCOR Aerospace	2017+	15	$950,000	$63,000	US
M-OV[lviii]	Mishaal Aerospace		363-454	Unknown		US
Nanosat launch vehicle[lix]	Garvey Spacecraft Corporation (NASA SBIR)	2015	20	Unknown		US
NEPTUNE 45[lx]	Interorbital Systems	2011 (failed)	40			US
Pegasus XL[lxi]	Orbital ATK	1990	468	$56,500,000	$120,000	US
Super Strypi[lxii]	University of Hawaii, Aerojet Rocketdyne, Sandia	2015	300	$15,000,000	$50,000	US
Haas 2C[lxiii]	Arca Space Corporation		400	Unknown		US
Minotaur I[lxiv]	Orbital	2000	584	$30,000,000	$50,000	US
Bloostar[lxv]	Zero2Infinity		75	Unknown		Spain
Electron[lxvi]	RocketLab	2015	110	$4,900,000	$44,000	New Zealand
Neutrino I[lxvii]	Open Space Orbital		50	Unknown		Canada
Sagittarius Space Arrow[lxviii]	Celestia Aerospace	2016	4-16 nanosats	Unknown		Spain
SOAR[lxix]	Swiss Space Systems	2017	250	$10,000,000	$40,000	Switzerland
Таймыр [lxx]	Lin Aerospace		9	$180,000	$20,000	Russia

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http://www.academia.edu/7787592/CubeSat_Component_Manufacturers or
http://granasat.ugr.es/index.php/es/documentaciontecnica/documentaciongranasat/satellite-2/cubesat?start=9

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The CubeSat Ecosystem: Examining the Launch Niche

By: Emily Nightingale, Lucas Pratt, Asha Balakrishnan

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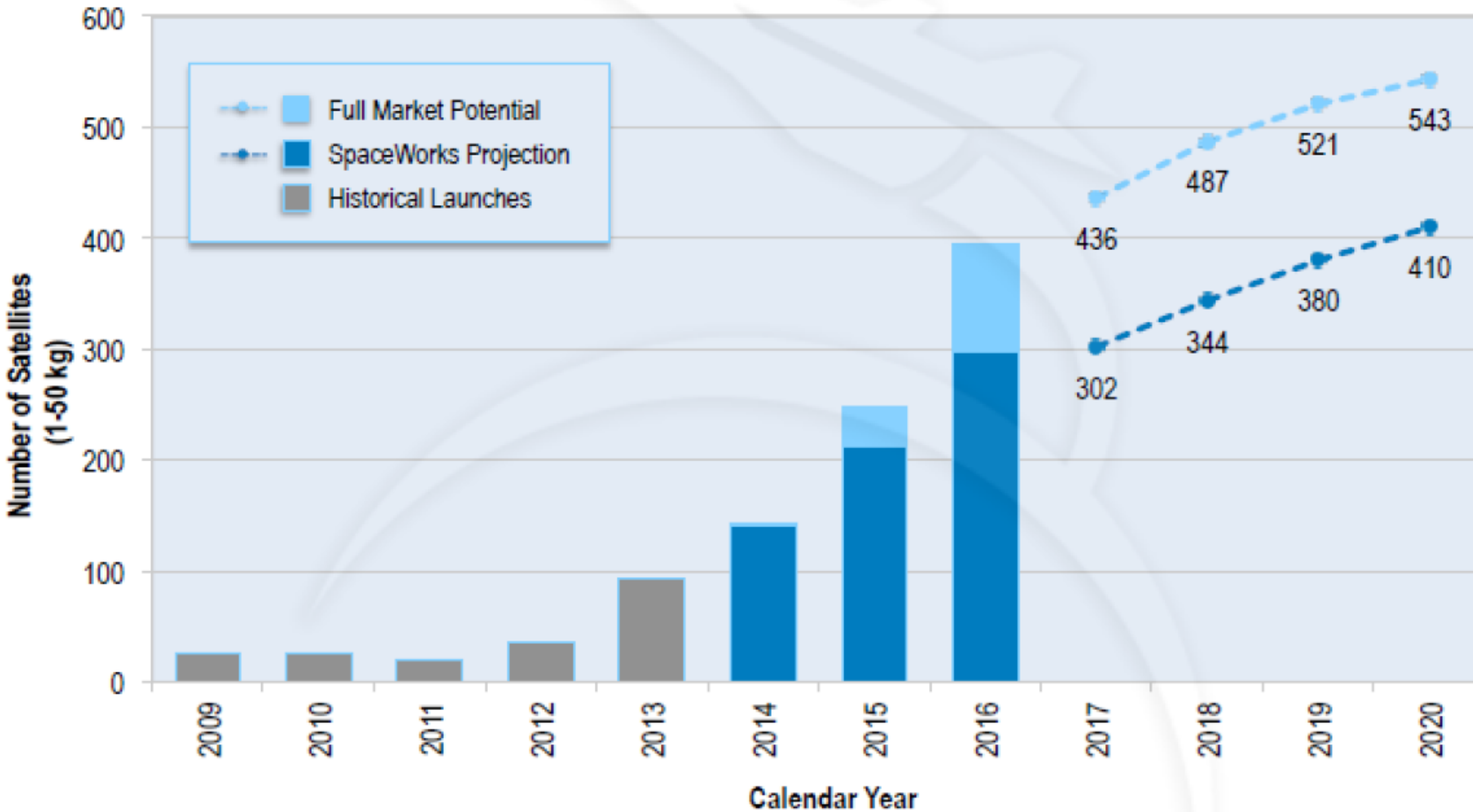
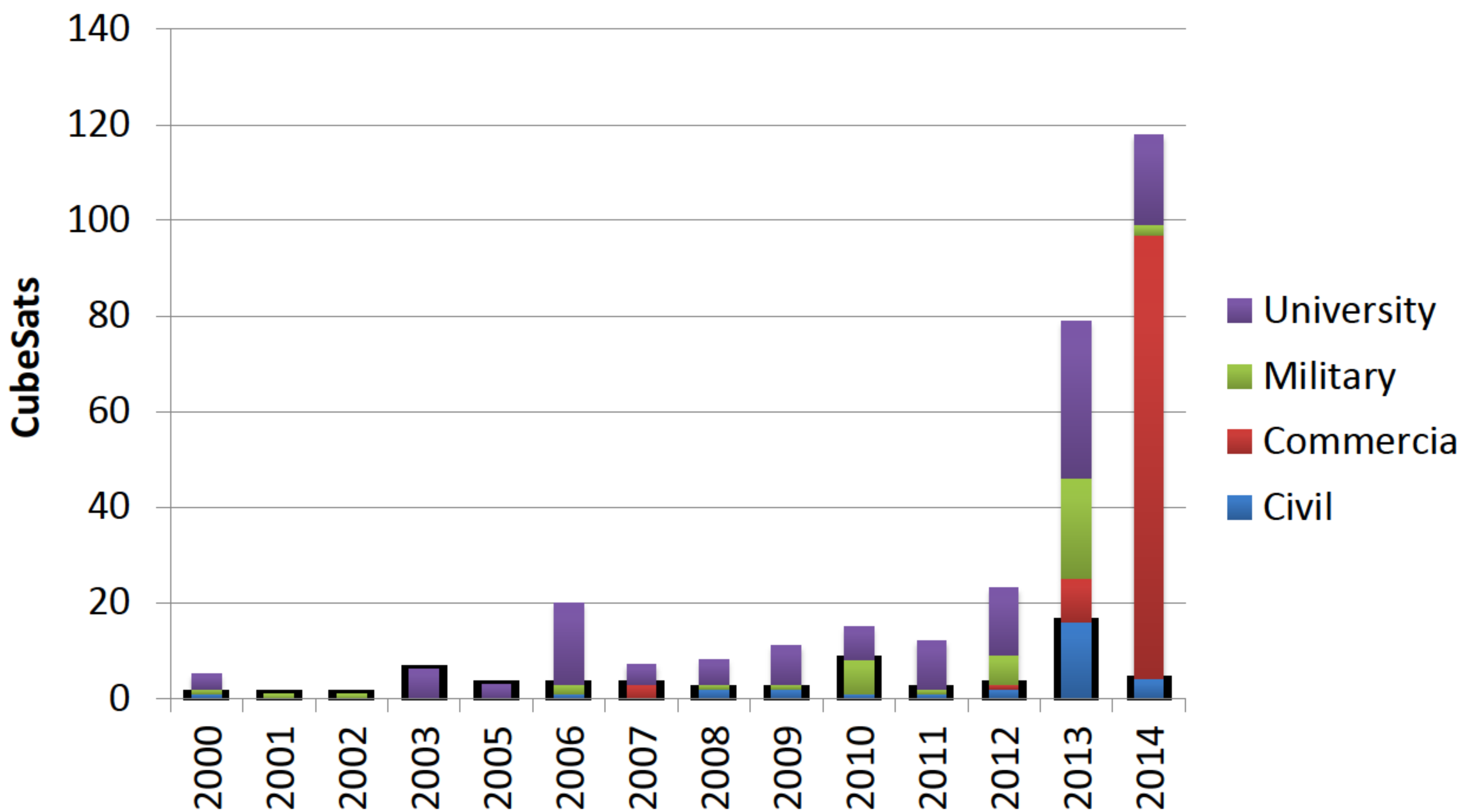
Growing Interest in CubeSats



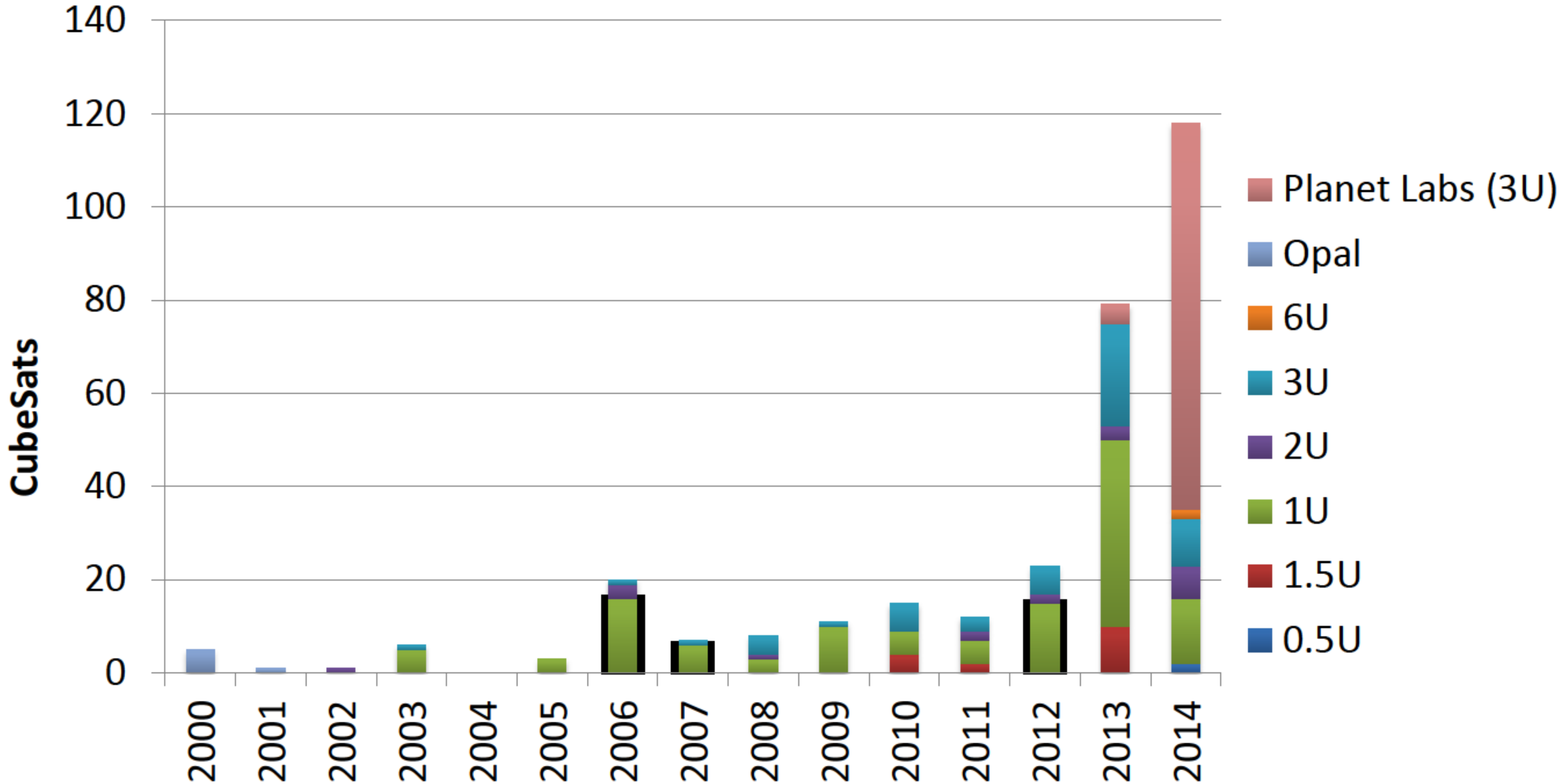
The Full Market Potential dataset is a combination of publically announced launch intentions, market research, and qualitative/quantitative assessments to account for future activities and programs. The SpaceWorks Projection dataset reflects SpaceWorks' expert value judgment on the likely market outcome.

SpaceWorks Enterprises. 2014.

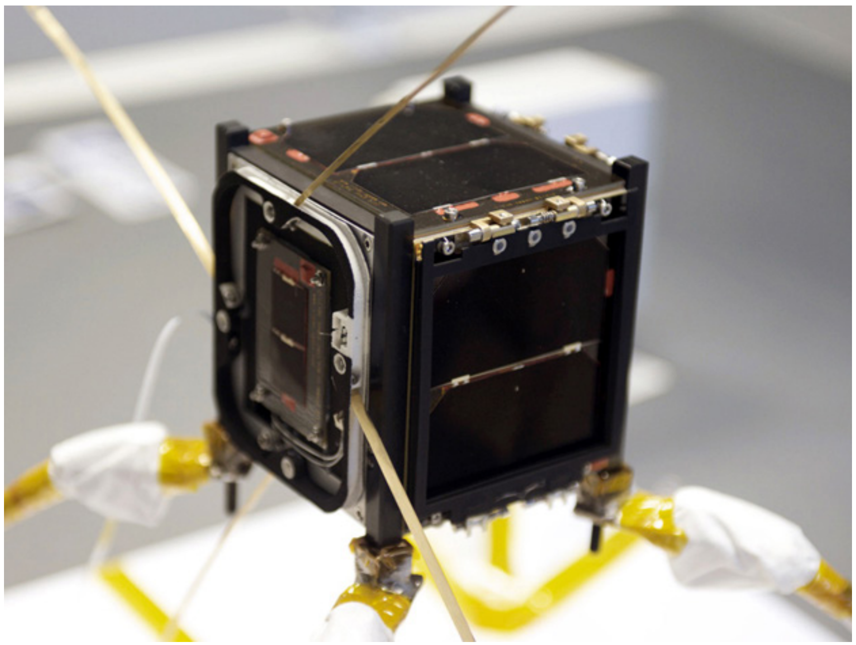
CubeSats are Becoming More Commercial



Trend Towards Larger CubeSats



Interest in CubeSats



Originally intended for education, but has seen increased interest from the S&T community due to:

- short development times
- ability to augment sustained observations
- acceleration of technology development
- greater potential for "commercial off-the-shelf" parts production

Application Areas

- Civil Earth Observations
  - Ex: Planet Labs
- Communications
  - Ex: Spire
- Space Science
  - Ex: MarCO
- Position, Navigation and Timing
- Space Situational Awareness

Potentially Limiting Factors

- Space debris

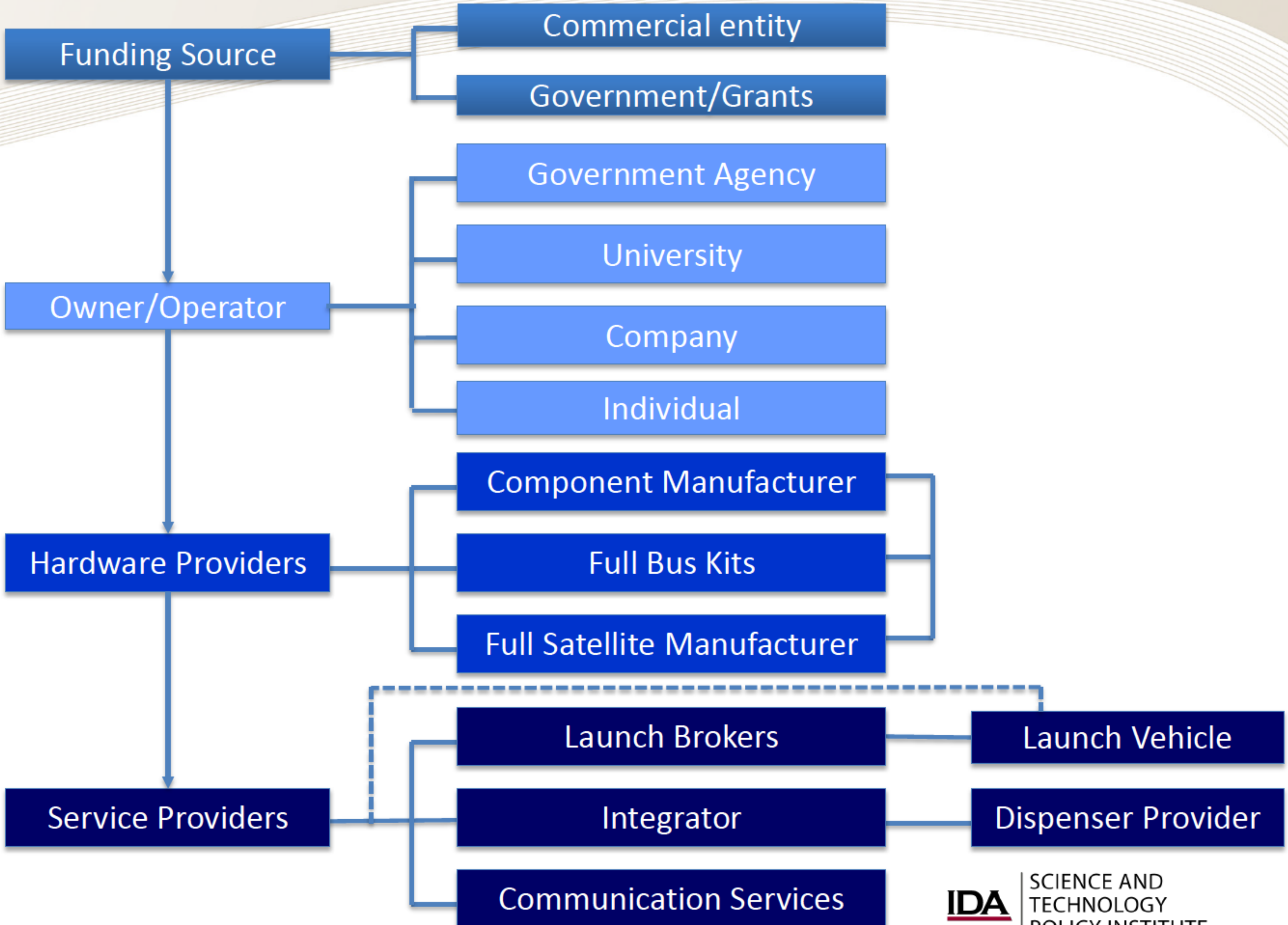
- Spectrum interference

- Launch

CubeSat “Ecosystem” and Launch

- Literature Review
- Interviews
- Analysis of Launch Data
  - Census of launched CubeSats based on data from Swartout and McDowell databases (Swartout, 2015) (McDowell, 2015)
  - Created database of CubeSat launch vehicles

Supporting Ecosystem



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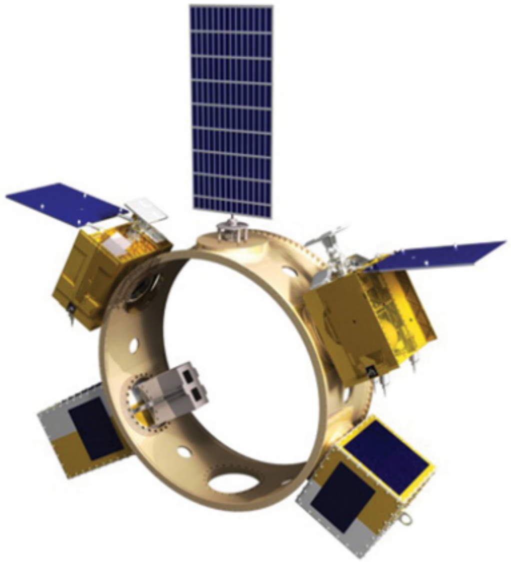
CubeSat Launch Background

- Current options for CubeSat launches
  - Rideshare
  - Dedicated small sat launch vehicle
  - Cluster launch
  - Hosted payload
- Launch comprises larger proportion of total cost for CubeSats than for larger satellites



Source: Magnuson, Stew. 2012.

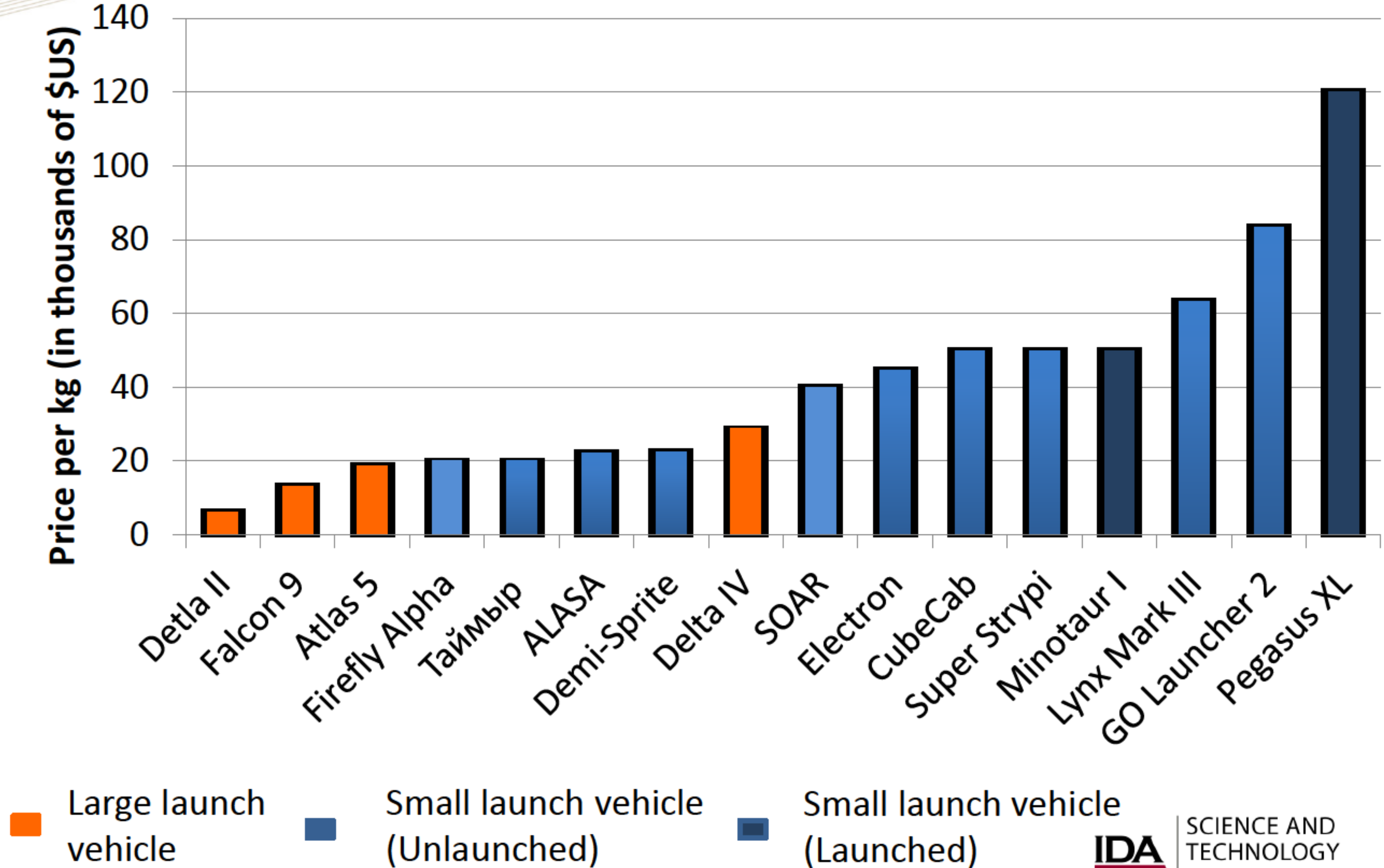
Rideshare

- Rideshare is the most frequent launch type because it is low cost. However, it also has many limitations:
  - Strict design limitation due to “do no harm” requirement for secondary payloads
    - Perceived added risk to primary payload causes many launch vehicles to ride with unfilled excess capacity
  - No control over orbit (not all orbits are available with rideshare)
  - Schedule driven by primary payload

Launch Brokers

- Ease the process for new entrants by acting as a "one stop shop" for launch coordination and integration
- Many launch vehicles are available including cargo to the ISS
  - All ISS launches use a launch broker
    - 70% of US CubeSats fly to the ISS
  - Every launch vehicle has unique safety requirements
    - Ex: No pressurized systems to the ISS

Price per Kilogram by Launch Vehicle



NASA CubeSat launch Initiative (CSLI)

- Part of the Launch Services Program at NASA
- Provides free launch to US government, US universities, FFRDC's, and non-profits
- Launched 24 satellites since 2011 with 92 in progress
  – (~3/4) of USA university missions since 2011
- Has performed Non-Recurring Engineering (NRE) to qualify the PPOD on Atlas V, Delta II, Falcon 9, and Minotaur C
  – Assumed some monetary and time burden to ease the process for industry

Findings

- Rideshare continues to be the most common way for CubeSats to launch, but many in the community are hoping the other options bear fruit
- Dedicated small launch vehicles are still on the horizon and demonstration of the these vehicles at a low price per kg will likely dictate success
- CubeSat owner/operators do not typically know on which vehicle they will launch, must design and adhere to the strictest requirements. This can be seen as limiting, or as an emerging standard for launch qualification.
- CSLI has been essential to university CubeSats in the US

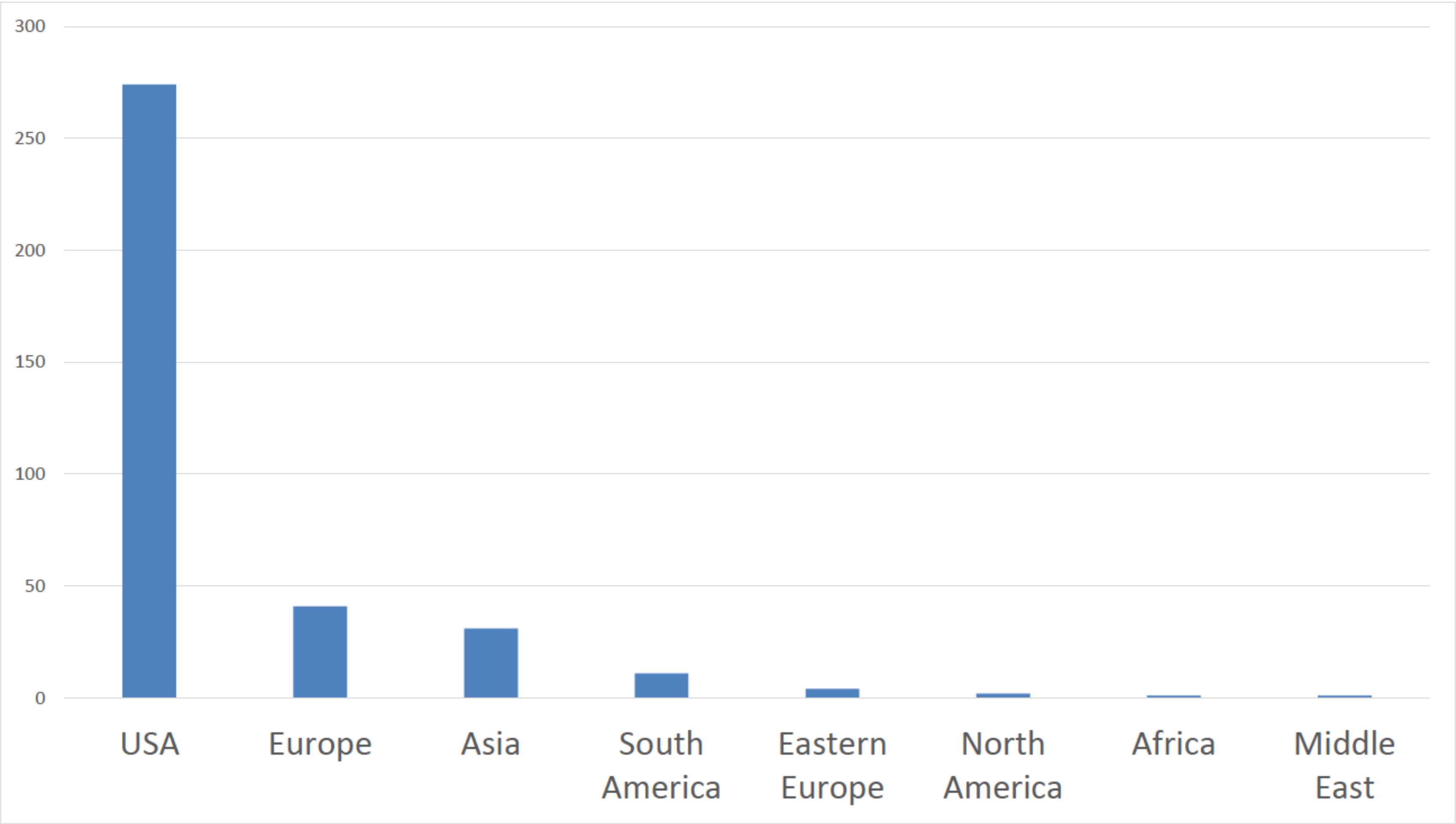
Remaining Questions

- Evaluate educational value of CubeSats, in relation to costs incurred
- Quantify costs for:
  - Flight qualification and integration for CubeSats onto known deployers and launch vehicles
  - NRE of qualifying new deployers and payload locations
- Determine full extent of design limitations imposed by "Do No Harm" standard and variations in launch environment by vehicle
- Conduct an in-depth study on CubeSats' effect on space debris and potential mitigation techniques

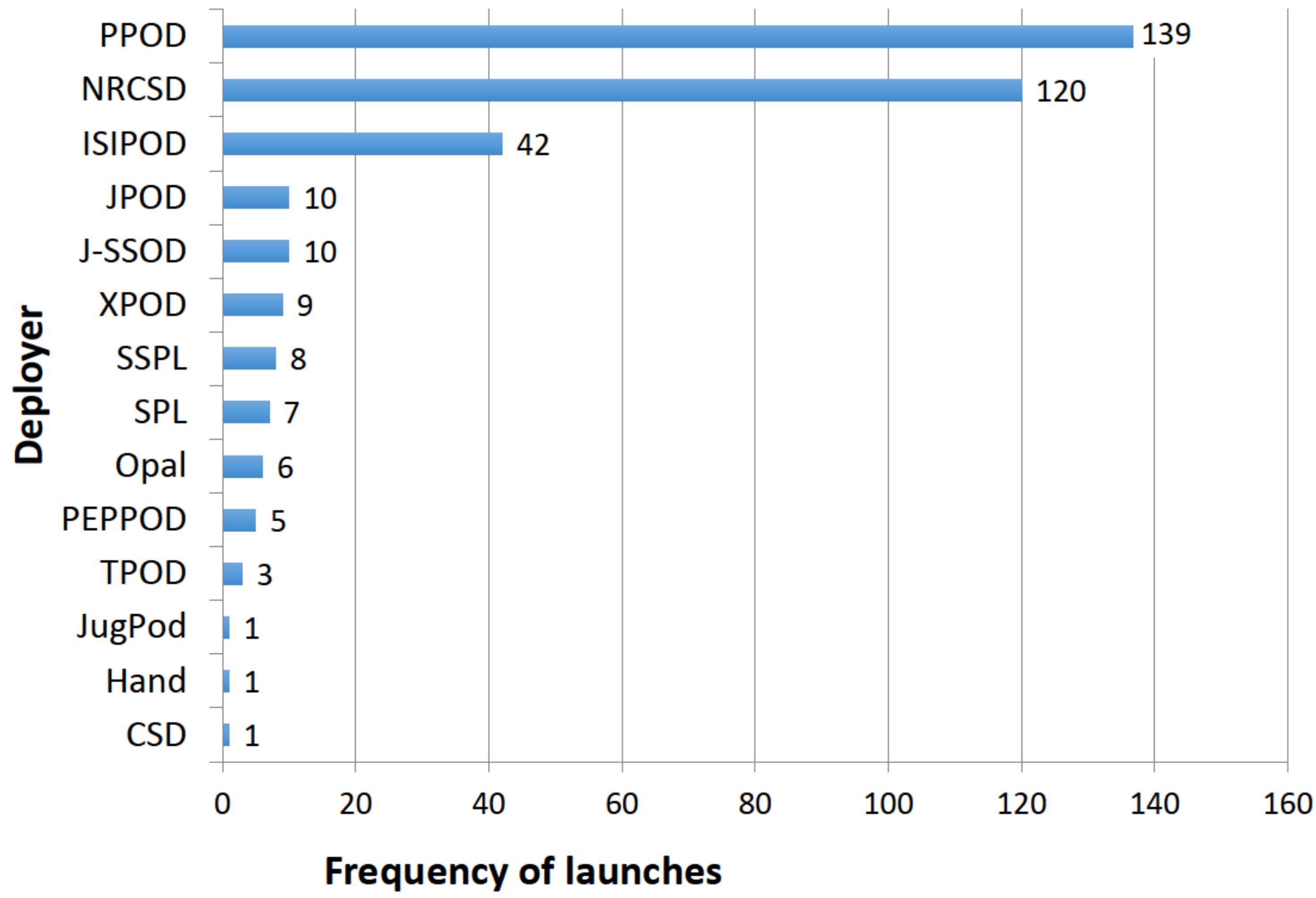
Thank you

BACKUP SLIDES

Launched CubeSat Owners by Region



Common CubeSat Deployers



Vehicle Name	Company	Year	Mass (Kg)	Price	Price per kilogram	Country
ALASA Program Vehicle (DARPA)	Boeing	2016	45	$1,000,000	$22,000	US
CubeCab	CubeCab		1.33	$100,000	$75,000	US
			5	$250,000	$50,000	US
Demi-Sprite	Microcosm		160	$3,600,000	$22,500	US
Firefly Alpha	Firefly	2017	400	$8,000,000	$20,000	US
GO Launcher 2	Generation Orbit	2016	30	$2,500,000	$83,000	US
LauncherOne	Virgin Galactic	2016	120/225	$10,000,000		US
M-OV	Mishaal Aerospace		363-454	Unknown		US
Nanosat launch vehicle	Garvey Spacecraft Corporation (NASA SBIR)	2015	20	Unknown		US
NEPTUNE 45	Interorbital Systems	2011 (no launch)	40			US
Pegasus XL	Orbital ATK	1990	468	$56,500,000	$120,000	US
Super Strypi	University of Hawaii, Aerojet Rocketdyne, Sandia	2015	300	$15,000,000	$50,000	US
Haas 2C	Arca Space Corporation		400	Unknown		US
Minotaur I	Orbital	2000	584	$30,000,000	$50,000	US
Bloostar	Zero2Infinity		75	Unknown		Spain
Electron	RocketLab	2015	110	$4,900,000	$44,000	New Zealand
Neutrino I	Open Space Orbital		50	Unknown		Canada
Sagittarius Space Arrow	Celestia Aerospace	2016	4-16 nanosats	Unknown		Spain
SOAR	Swiss Space Systems	2017	250	$10,000,000	$40,000	Switzerland
Таймыр	Lin Aerospace		9	$180,000	$20,000	Russia

Citations

- Swartout, M. 2015. CubeSat Database. Find at https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database
- McDowell, 2015. Jonathan's Space Report. Find at http://www.planet4589.org/space/jsr/jsr.html

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14. ABSTRACT
This paper and accompanying presentation were prepared for the 66th International Astronautical Congress, held in Jerusalem, Israel, October 12–16, 2015. In the last decade, CubeSats have rapidly increased in popularity as a platform for low-cost activity in space by industry, government, academia, and the military. This paper discusses the current supporting ecosystem for CubeSat development in the United States, from funding opportunities to ground-station services. It also discusses the opportunities and barriers facing the ecosystem as a whole, with a particular focus on the launch niche, which is a potential choke point for the entire ecosystem. NASA's CubeSat Launch Initiative is examined as a case study to better understand the CubeSat launch hardware qualification and integration processes.

15. SUBJECT TERMS
CubeSats, Small Satellite Launch, Launch, NASA CubeSat Launch Initiative (CSLI), Launch Broker, Ecosystem

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