Benchmarking the Small Satellite Industry – Identifying Emerging Trends to Increase Access to Space

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Abstract

Small satellites have the potential to allow rapid and affordable access to space; especially for small satellites or payloads that are used to test or validate new concepts or technologies. But limited launch manifest opportunities can hinder the exploitation of the qualities that make small satellites attractive. This paper outlines the work done to collect information on historical and developmental small satellite missions. Trends from the data and the implication on future small satellite missions are described. These trends and common characteristics are then tied to the limited manifesting opportunities offered to small satellites. Finally, development of future launch capability and how that could impact the small satellite market is addressed. Possessing knowledge gained from a thorough benchmarking effort of the small satellite industry can help improve the ability of gaining manifesting opportunities, thereby increasing access to space.

1 Introduction

Small satellites provide an unmatched capability to allow for more rapid and accessible space experimentation. Technology demonstrations and test beds could be more feasible providing an increased capacity to prove components and systems for space flight reducing risk to larger, more expensive space flight missions.[1] Also, small satellites could tap into unused launch capacity for space access sharing the cost of expensive launch vehicles with numerous programs and customers. But is this symbiotic relationship between larger spacecraft and small secondary payloads being realized? Are small satellites populating the market the way that so many estimates predict they could?

This paper aims to try and capture the small satellite industry trends in four main parts. First, the benchmarking effort for this research collected technical and mission orientated data on almost 200 small satellite missions. A review of this data shows how small satellites are becoming more capable while remaining fairly constant in size. Then this paper goes on to explore the launch opportunities small satellites have and if those launch opportunities are enabling an increased access to space. Throughout this exploration of small satellites, university built small satellites are uniquely highlighted to determine if they are experiencing the same trends as the remainder of the industry. And finally, this paper looks into some of the near and long-term possibilities that could increase access to space for small satellites.

2 Capabilities of Small Satellites

Small satellites are becoming more mainstream. Recent thrusts by NASA and various other government agencies have demonstrated the potential of small satellites and how they could revolutionize space science, experimentation and operational use. This section shows that small satellites are demonstrating increased mission capability and sophistication without increases in mass.

2.1 Data Collection Methodology

The data collected for this paper were gathered from various sources including program websites, recent periodicals, press releases and conference proceedings. The benchmarking search was geared towards collecting information on satellites flown from 1990 until the present that had a mass that was less than 300 kg.

For each spacecraft included, the sponsoring organization, mass, payload mass, physical dimensions, power generation, type of solar array mounting, stabilization technique, orbital parameters, launch vehicle, launch date and mission objectives were collected. Not all information was found for every spacecraft. In this case, only the spacecraft with a particular value would be included in aggregated statistics.

One special case in the data is in regards to constellations of small satellites. There were a few series of small satellite constellations, which could unfairly bias the trends. The Kosmos constellation provided tactical military communications for the Russian military and is comprised of 24 satellites with a mass of 61 kg, and 74 satellites with a mass of 231 kg. Another is the Orbcomm constellation, which consists of 24, 45 kg satellites. GONETS contains 12 satellites with a mass of 231 kg and, finally, Oderacs contained 12 satellites each with a mass of only 5 kg. The physical trends presented in this paper only include 1 spacecraft from each constellation rather than the complete population. This was done in order to capture each different small satellite design. The 74 Kosmos satellites that each had a 231 kg mass would skew the results for the complete population. To counter this trend, a single spacecraft is included in the data in the first year that the constellation was initially placed on station.

2.2 Physical Trends

Part of this benchmarking effort was an attempt to capture typical values for small satellites over time to try and determine if there are any emerging trends. One striking trend is that there isn't one in regards to spacecraft mass. Small satellites have remained roughly similar for the 13 years covered in this research.

Figure 1, below, shows this consistency of average spacecraft mass over the years covered. The average mass over the time of this study was 83.2 kg. This data does not include the multiple spacecraft of the constellations mentioned previously.

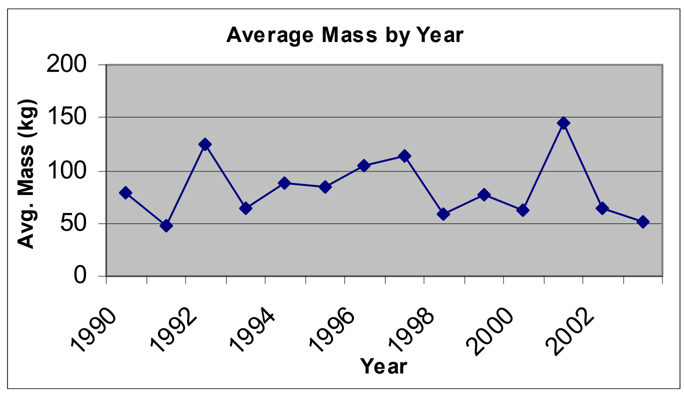

Figure 1: Historical data of average spacecraft mass

To further support that the average mass of small satellites has not drastically changed over the time period of interest, Figure 2 shows the mass of each spacecraft placed on-station in each year. Again, there is no discernable trend from this information with the average remaining around 83 kg.

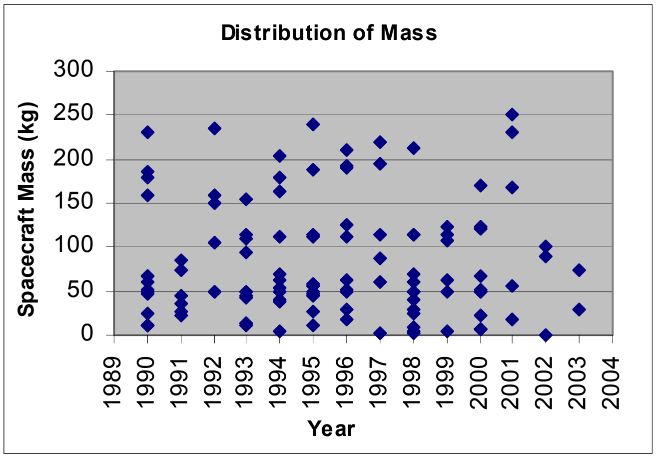

Figure 2: Historical data of mass distribution

Performing an f-test across this distribution yields a probability of 0.62 that the average is not significantly changing from year to year supporting the assertion that there is not an underlying trend of small satellite mass.

A subset of the complete population of particular interest is the university satellite portion. When masses of the university-built satellites were pulled out of the data set, they show the same type of results. There is no discernable trend of an increase or decrease in spacecraft mass. Figure 3 shows the average mass for university built small satellites over the period of 1990-2003. The overall average over this time period was 69.2 kg.

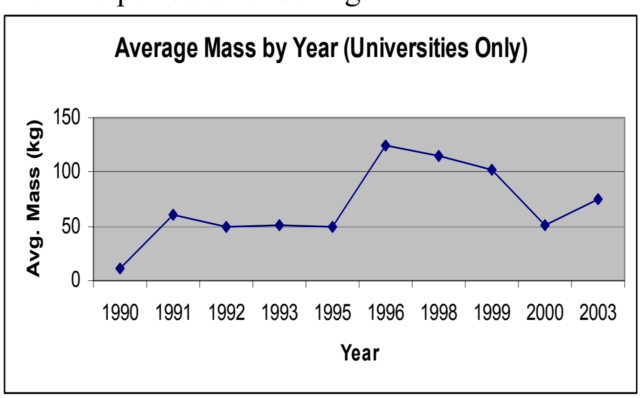

Figure 3: Average mass of university built spacecraft

However, physical properties alone do not capture how small satellites have changed from 1990-2003.

2.3 Capability Trends

One item of interest is that small satellites have increased their mission capability over the same time period in which the average mass exhibited no trend. But this is difficult to show objectively.

One approach that has been used to try and address this problem is the concept of a "complexity index" introduced by Bearden.[2] This idea of a complexity index incorporates multiple attributes of a complex system in order to try to create a basis for comparison. Similar to Bearden's work, this paper utilizes a complexity index based upon technical parameters of various sub-systems of small satellites. However, this research utilizes fewer sub-system details and does not attempt to compare development time or cost information because of the lack of publicly available information required to reach a similar level of fidelity. Nonetheless, the complexity index created for this research can provide a crude estimate of spacecraft complexity.

The complexity index values generated for the small satellites in this research include the launch mass, type of solar array mounting (none, body-mounted or deployed), type of attitude control system (none, gravity gradient, spin or 3-axis stabilized) and the number of major payloads carried. For the launch mass, each spacecraft was assigned a percentage value of where the individual launch mass fell into the complete range of launch masses. For example, the maximum value of launch mass in the data set is 295 kg. So a spacecraft with a launch mass of 68 kg is given a mass percentage of 23% since 68 kg is 23% of the maximum 295 kg. This same approach was used for the number of payloads carried on board as well.

The discrete properties of the type of solar array mounting and attitude control system were handled differently. For these, values were assigned to the different choices and then percentages were calculated in the same manner as for launch mass. Solar array mounting types were assigned values of:

0 = no solar arrays
1 = body-mounted
2 = deployable arrays.

Attitude control system types were classified as:
0 = no ACS or gravity gradient
1 = spin stabilized
2 = 3-axis stabilized.

Percentages for individual spacecraft were then calculated on those assigned values.

After assigning values for each parameter of launch mass, solar array type, ACS type and number of payloads, the complete complexity index is simply the sum of those four percentages.

Complexity index values were calculated for every spacecraft in the complete data set where all of the parameters were known. 71 out of 172 small satellites were included in the complexity index totals since all of the parameters were available. Figure 4, below, shows the results of this work by plotting the complexity index for these spacecraft over time.

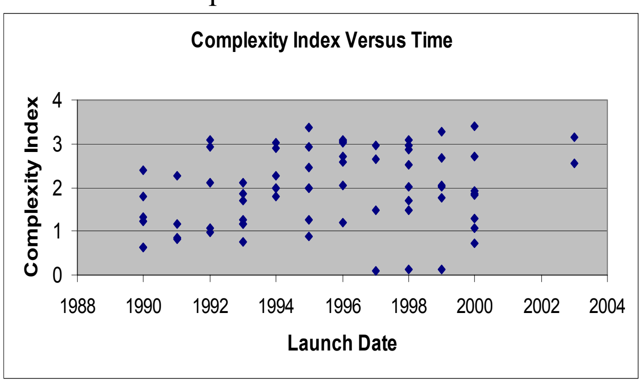

Figure 4: Complexity Index over time

This data shows no discernable trend of a change in complexity index over time. No statistical significance exists across this data set. Figure 5 presents this data in a different manner combining complexity indices for spacecraft launched in given year. Again, while this looks more promising, it results in an R^2 value of only 0.51 indicating a possible correlation between average complexity index and launch year, but not one of statistical significance.

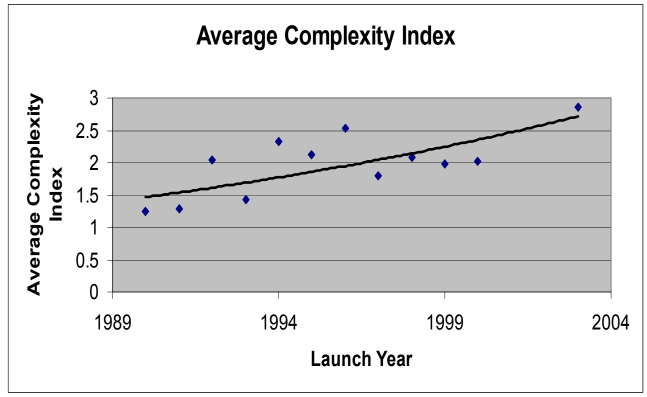

Figure 5: Average complexity index by launch year

These results were not expected. In the course of trying to determine a possible explanation for the lack of a trend in the increase of complexity index, the university subset of the population was evaluated.

The same methodology in determining complexity indices was used for only the university class satellites contained in the data set. Again, the aggregate results did not result in a discernable trend of a changing complexity index over time.

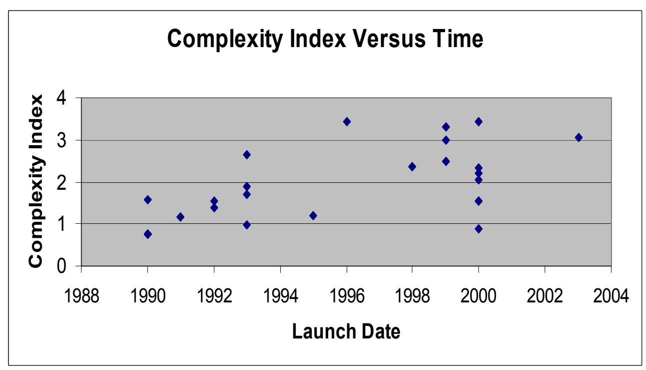

Figure 6: Complexity index over time for University built spacecraft

The average complexity index by launch year for the university built spacecraft is a little more optimistic than the complete data set and gives an R^2 value of 0.61. This corresponds to an f-test result of only a 28% probability that the average from the first half of the data is not significantly different from the average of the second half of the data. More intuitively, there is a 72%

probability that the different in average of the university satellite complexity indices is statistically significant.

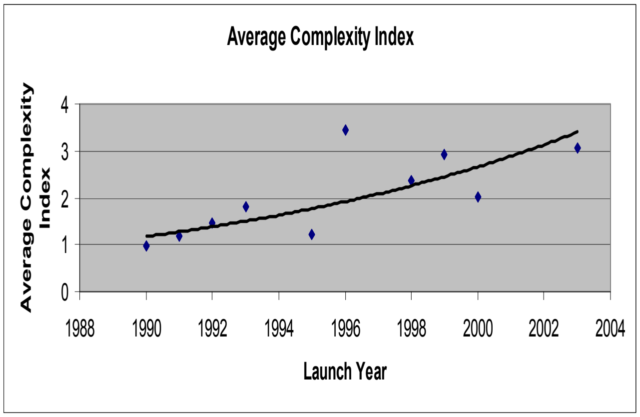

Figure 7: Average complexity index by launch year for university satellites

2.4 Possible Explanations

The results of the university satellite population provide some possible explanations as to why there may not be any obvious trends in the overall data set. One can assume that if the universities have discovered how to improve small satellite capability over time, then the other major parties of the space industry have too. What is possibly skewing the complete result is that there are emerging parties into the complete data set that are not producing highly capable spacecraft. There are small satellites being built by countries that have not previously held major roles in the space industry – Nigeria, Turkey, Korea etc. The capabilities of an emerging space program may not yet match that of the US, Russia and European countries that have been flying small satellites for decades.

It is possible then that the complexity index results are not showing a constant state in small satellite complexity, but rather how many new players there are in the small satellite market.

Another possible explanation of why there is no trend showing increasing capability over time could be in the complexity index itself. Using the number of major payloads or instruments as a performance measure has many problems. In previous research it had been noted that using a performance measure of instrument-months (an even higher fidelity performance measure that what is being used here) did not adequately capture that complexity or capability of the instruments themselves.[3]

No two missions have the same fundamental objectives making it difficult to directly compare one with another. A university built radio communications satellite and AFRL's XSS-10 mission, which demonstrated rapid on orbit activation and autonomous maneuverability around another spacecraft, have dramatically different scopes and resulting information. The makes the use of the number of scientific instruments a difficult comparison. Also, the number of instruments or other prospective measures of complexity may not be true representations for the robustness in which a spacecraft can fulfill its designated mission.

For example, in 1990, most small satellites had only one payload and it was generally store and forward communications. In 2003, GALEX only carried one payload, but it is a ultra-violet space telescope.

There is another piece of evidence that the performance measure of number of payloads is limiting an adequate representative of small satellite capability. Part of the complexity index was comprised of the solar array type and type of attitude control system. Table 1 shows how small satellites changed to favor deployable solar arrays over body mounted, and Table 2 shows the trend to favor 3-axis stabilization over spin or gravity gradient over the time of this study. It can be assumed that a deployable solar array is more complex than a body-mounted one, and that 3-axis stabilization is more complicated than gravity gradient or spin stabilized. And these trends changed while the mass of the spacecraft remained fairly constant.

Table 1: Change in solar array type

1990-1995	1996-2003
80% body-mounted	46% body-mounted
20% deployed	54% deployed

Table 2: Change in Attitude Control System Type

1990-1995	1996-2003
43% no ACS or gravity gradient	17% no ACS or gravity gradient
30% spin stabilized	21% spin stabilized
27% 3-axis stabilized	62% 3-axis stabilized

To further illustrate this increase in capability, brief descriptions of typical small satellites from 1990, 1995 and 2000 are presented. This quick review shows the vast differences in small satellite mission capability and success in a ten-year span.

2.5 Typical Small Satellite Snapshots

In 1990, there were 34 small satellites placed on station. 20 of these 34 were members of the Kosmos tactical communications constellation for the Russian military so only one of these is added into the average mass for the year since the complete constellation would artificially alter the average. These 15 spacecraft have an average mass of 79.4 kg and are generally symmetrical in shape (either cubic or hexagonal) with body-mounted solar arrays.

Of these 15 spacecraft flown in 1990, five spacecraft were dedicated to amateur radio communications and six carried communications experiments to act as technology demonstrations. The remaining four small satellites placed on station in 1990 were US government spacecraft, one in the USA series with no available mission information, one a member of the Kosmos Russian military communications constellation and the other two provided store and forward communication ability for the Department of Defense (Macsat-1 and 2).

1995 saw 11 small satellites be placed on-station. The average mass of this group is 56.9 kg, but this includes the six spacecraft that comprised Oderacs, an Orbital Debris Calibration Sphere that assisted in the calibration of the earth-based radar. Because these were not functional spacecraft, they should not be considered typical spacecraft for the year. Without Oderacs, the average mass of spacecraft in 1995 was 84 kg only slightly larger than the average in 1990.

Missions flown in 1995 include Astrid-1, a Swedish satellite that carried an electron spectrometer, two ultra-violet imagers for auroral observation and conducted magnetospheric research. Another, the Czech Maigon-4 performed solar wind research in conjunction with another spacecraft. Universities sponsored spacecraft that performed experiments in microgravity, aerochemistry and GPS navigation. Commercial work started to be seen as well, with GEMStar-1 placed on-station to provide global electronic messaging services, FAISat carried store and forward communications for users with terminals in the US and OrbComm placed the first two spacecraft of a constellation on-station to provide worldwide 2-way data communications.

There were also 11 small satellites placed on-orbit in 2000 that combined to have an average mass of 61.6 kg. These missions included 6 that were sponsored and primarily facilitated by universities. FalconSat-1, JAWSat and HETE-2 were successful university built spacecraft providing scientific information on spacecraft charging effects, upper atmospheric properties and gamma ray bursts, respectively. There was a university built spacecraft providing hyper spectral imaging and OPAL explored the possibilities for use of "picosats" both in terms of on-orbit deployment and overall functionality. Spacecraft experimented with intersatellite communications and provided demonstrations for the Disaster Monitoring Constellation of small satellites.

So far in 2003, things are even more impressive with the recent success of CHIPSat (75 kg) to measure properties of the interstellar medium, XSS-10 (only 28 kg) which demonstrated rapid activation and maneuverability near a host satellite and GALEX (a heavier spacecraft at 280 kg) which will observe galaxies in ultraviolet light across 10 billion years of cosmic history.

These snapshots help capture the improvements seen in small satellites in the last 13 years. This increase in capability from basic communications experiments to intersatellite maneuvering and high-quality robust science without an increase in mass could be indicative of the fact that small satellites are capitalizing on the miniaturization of electronics and reliable computers. Like computers before them, small satellites seem to be enjoying the trend of increasing performance in comparable size and priced systems allowing for small satellites to become a major player in the space industry.[4]

3 Recent Launch Trends

As part of the benchmarking effort for the small satellite industry, launch trends were explored. Given the increase in capability of small satellites, and the prospects for market growth outlined in the last two sections, it was anticipated to see an upswing in small satellite launch activity. But as the data presented here show, that is unfortunately not the case.

3.1 Small Satellite Launch Data

The data presented here accounts for all spacecraft that were placed on station (whether they were later successfully functioning or not) and those lost in launch failures from 1990 until the present. All spacecraft that comprise constellations are accounted for.

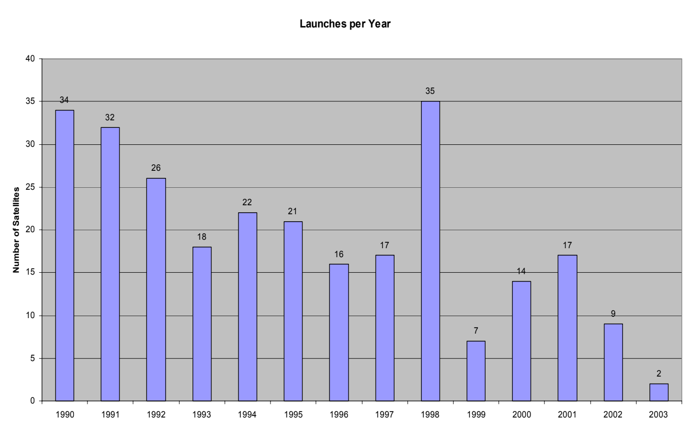

Figure 8: Small Satellites launched from 1990-2003

Figure 9, below, depicts the same data just in a different format to more easily distinguish a possible trend. The linear trend line added to the data has a negative slope with a corresponding R^2 value of 0.56. While this is a poor indication of a correlation that is mainly caused by the single outlier of 35 small satellites placed on-station in 1998. Besides this single point, the data shows a sharp negative trend in launches of small satellites.

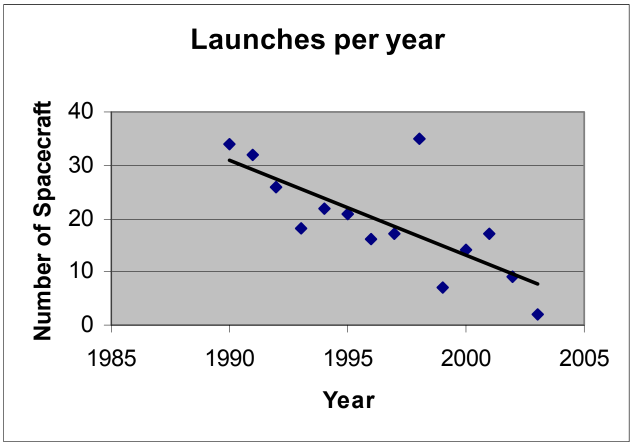

Figure 9: Small Satellite launch trend (all spacecraft)

But this may not be indicative of trends of unique small satellite missions since this included all constellation spacecraft counted individually. The following graph, Figure 10, only includes constellations as 1 spacecraft per launch placed on station rather than the typical range of between 2 and 8. This, like the average physical properties, helps track the number of unique small satellites placed on station rather than these large constellations which may not be representative of the complete data set.

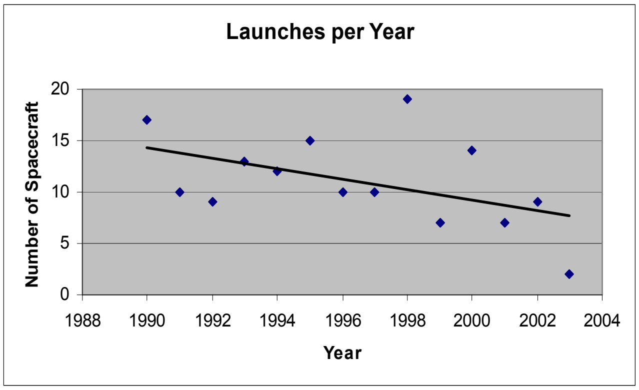

Figure 10: Small Satellite launch trend (constellations only 1 per launch)

In this data set, the trend line has a reduced R^2 value of 0.22. This is more indicative of no trend or correlation in the data and reduces the sharp negative launch trend that could just be the completion of a large constellation.

From this launch data, it seems to be the case that interest in small satellites isn't significantly changing. But this assertion goes against all of the cases presented earlier discussing how there are new parties entering the small satellite market. All of the market prospects seem promising, but the data show a flat, or declining, launch trend.

Launch trends are no different for university built spacecraft. Figure 11 shows the same data for only university spacecraft.

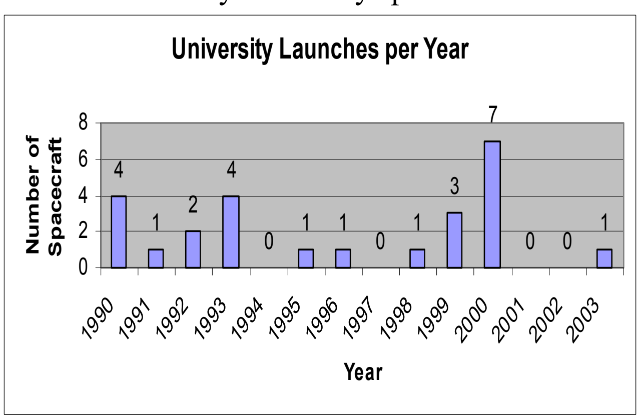

Figure 11: Launch data for university spacecraft

The year 2000 was a particularly busy year for university small satellites, but is not the norm.

3.2 Chicken and Egg Problem

To illustrate the disparity between the potential market share rhetoric and the launch data is the case of the Pegasus small satellite launcher. Over the period studied for this paper, the Pegasus launched more small satellites than any other launch vehicle with 23. But there were no Pegasus launches in 2001, only 1 in 2002 and 4 slated for 2003. Market research has produced figures for the cost of a Pegasus launch to be between \$18-\$22 million, which is a figure that is out of synch with typical small satellite programs. It could be difficult to justify launch costs in that range for a spacecraft that may have only cost \$5 to \$10 million to develop.[5]

Section 2, in part, illustrated that there seems to be interest in small satellites in existing and many emerging markets. It does not seem to be the case that people are losing interest in small satellites, so is it perhaps that launch capabilities are inhibiting the capitalization of those new opportunities? If so, what can be done to help the situation?

It appears that the small satellite industry is in somewhat of a chicken and egg problem whereby small, low-cost programs are becoming difficult to initiate or complete because of the lack of launch capability. But this then creates the case to investors (namely, the government) that there is no need to develop a dedicated launcher for small satellites.

If we assume that there is, in fact, emerging markets that would explode if there was cheaper access to space, would it be worth pursuing? Should the industry even continue to think about small satellites? It seems to be the case that the answer to those questions is, "yes".

There are numerous arguments throughout the industry that it is the lack of launch opportunities that is the hindrance to small satellites, and not the lack of market opportunities. The full potential of small satellites may "be realized only when cheaper ways can be found to launch them."[4]

4 Opportunities for Improvements

There are numerous programs that could alleviate the strain on launch opportunities for small spacecraft. Some near-term solutions include multiple payload adapters for EELV, Ariane V, Minotaur and the Space Shuttle. Also, the Falcon is a new launch vehicle that should be unveiled in the latter part of 2003. Long-term solutions include a jet-powered first stage being developed for a DARPA program, a privately built suborbital space plane, a balloon platform and the Department of Defense's new program "Operationally Responsive Space Lift."

4.1 Near-Term Solutions: MPAs and Falcon

The quickest solution to alleviate the problem of a lack of launch opportunities for small satellites is to efficiently utilize the launch capacity that is already available. Multiple Payload Adapters (MPAs) help use the extra capacity already available in launch vehicles by providing a standard interface for a set of small secondary payloads.

ESPA is the Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter. This is a ring that provides a standard interface for small satellites that fits between the final stage and the primary payload on both the Lockheed Martin Atlas V and Boeing Delta IV rockets. The Air Force pursued the development of ESPA to hold secondary payloads to a set standard similar to primary payloads.

The ESPA is designed to deploy up to 6 radially mounted 181 kg payloads along with a 6800 kg primary payload. ESPA is designed to be nearly transparent to the primary payload and the remainder of the launch vehicle in terms of dynamic responses. To do this, ESPA incorporates Soft-Ride, a spacecraft isolation system that reduces the loads that the payloads experience during the boost environment. Between this and the use of a low-shock separation system that has non-pyrotechnic devices, the presence of secondary payloads or their deployment will not affect the primary payload.[1] The first flight of the ESPA ring is scheduled for March 2006 and will carry 5 payloads.[6]

Another multiple payload adapter has been designed for the Minotaur, the launch vehicle conversion of the Minuteman II ICBM. The Minotaur is derived from the Minuteman II as part of the Air Force's Rocket System Launch Program (RSLP). The MPA for the Minotaur will accommodate 2 to 10 small satellites. Unlike the standard ring configuration of the ESPA, the Minotaur MPA will utilize a building-block approach to allow for custom built configurations that could serve a variety of manifest combinations. This building-block approach could also allow for late manifest changes, if required.[1]

ASAP is a secondary payload adapter for the Ariane V. ASAP will be configurable with the typical configuration carrying 8 small satellites with a mass less than 120 kg each.[7] ASAP carried nine out of twelve of the UoSat small satellites for the University of Surrey enabling Surrey to emerge as a leader in the small satellite industry.

SPORT, the Small Payload Orbit Transfer, is another secondary payload adapter for the Ariane V. This adapter is a rack intended to hold small satellites efficiently in the extra space typically wasted on GTO launches.[4] SPORT will separate from the booster in GTO then lower itself to the desired orbit for the small satellites.[7]

The Space Shuttle is also introducing a few new multiple payload adapters. The Shuttle Hitchhiker Experiment Launch System (SHELS) allows for multiple small satellites to be launched from the shuttle cargo bay.[7] The interface in the cargo bay, along with low-shock separation systems like the *Lightband*, will allow multiple satellites to be deployed from a close proximity. This deployment system will be used for the University Nanosatellite Program which will launch 2 stacks of 3 spacecraft.[1] There is also a pallet ejection system and a canister for all payload ejection system that are in development for the Space Shuttle.[1]

Multiple Payload Adapters are near-term solutions that could provide small satellites with quick launch opportunities. But one problem with MPAs is that the small satellite is typically along for the ride with a larger, primary payload and, therefore, may not end up in the ideal orbit. Or as Elon Musk, CEO of Space Exploration Technologies said, "Taking the bus is okay if you're all going to the same place at the same time."[8] A small satellite program could sacrifice the ideal mission parameters to capitalize on a launch opportunity. A dedicated launch vehicle would be the optimum solution, but there is not an affordable small satellite launch vehicle yet available. The Falcon, in development by Space Exploration Technologies of El Segundo, California, seems to be the most probable dedicated small satellite launcher to be developed in the near future.

Space Exploration Technologies is currently developing a small satellite launcher, the Falcon, with internal funds currently scheduled to make its maiden voyage by the end of 2003 and has lined up two undisclosed customers to date. The Falcon can accommodate payloads weighing up to 250 kg and the partially reusable rocket is targeting a cost of $6 million per flight. A later heavy-lift version of the Falcon will be able to lift up to 1350 kg into low earth orbit. Space Exploration Technologies is not disclosing development expenses, but still aims to keep the costs below $100 million.[5]

4.2 Longer-Term Possibilities

The longer term possibilities presented here, RASCAL, Xerus, a balloon platform, Microcosm's Sprite and the DoD's Operationally Responsive Space lift, all address the achieving affordable and rapid access to space without having to wait for a rideshare launch opportunity. While the multiple payload adapters could be highly efficient use of existing launch capacity, waiting for a rideshare opportunity for small satellites that conduct the vast majority of US missions can be time consuming.[9] Rapid access to space could also be critical if a military satellite system was lost either to a failure or an adversary requiring deployment of an interim capability requiring perhaps several launches in a single day.[9]

The Responsive Access, Small Cargo and Affordable Launch Vehicle (RASCAL) program sponsored by DARPA is looking for a launch capability that utilizes a specially designed aircraft to serve as a reusable first stage for a small satellite launcher. DARPA hopes to use a jet-aircraft to fly out of the atmosphere at a steep angle before releasing a small expendable rocket to carry a payload into LEO. The hope is the RASCAL would demonstrate such a capability that could be a precursor to a system capable of operating out of airfields around the US to launch payloads on short notice. Currently, there are six companies competing to demonstrate a system for RASCAL. Originally, the thought was to utilize existing aircraft for the first stage, but that proving difficult.[10] Designing a new aircraft and the expendable booster within the budget is challenging, but the aircraft is not a combat aircraft simplifying some of the required systems. DARPA's requirements for RASCAL are to design a system that can place a 75 kg payload into orbit for no more than $750,000 per launch and within 24 hours of receiving the payload.[11]

Another idea on the horizon is a suborbital space plane by XCOR. The Xerus is intended to serve three markets: suborbital payloads traditionally flown on sounding rockets, microsatellites for LEO and hops for passengers to the edge of space. The variant to launch small satellites into LEO would use the space plane as a reusable first stage with en expendable second stage attached to the exterior of the plane.[12]

XCOR is making progress in development of the space plane. They successfully test fired a new oxygen and kerosene engine, the XR-4K5, which would serve as the main engine for the Xerus. The XR-4K5 makes use of readily available non-toxic fuels to help reliability and control costs. There is no timeline yet established as to when Xerus will fly.[12]

Another launch possibility being proposed by JP Aerospace of Rancho Cordova, California, is a balloon launched platform. The platform would be carried up to an altitude of 30,300 meters and then launch a small, 2 stage rocket carrying payloads weighing up to 20 kg into LEO. Like the Xerus, the balloon platform would act as a reusable first stage effectively acting as a "miniature launch complex" sitting at altitude. JP Aerospace has teamed up with the CubeSat program at Stanford University as a potential customer to demonstrate the launch vehicle in the future.[9]

A final long term solution that is in work is the product of renewed interest from the Department of Defense in rockets capable of launching various types of military payloads on short notice. The program, dubbed "Operationally Responsive Space Lift" is aimed at fielding a family of small expendable rockets that could be readied for launch in hours or days, rather than current weeks or months. Two platforms being explored under this program are Microcosm's Scorpius family of launch vehicles and the Sprite. The competition will be held in 2004 if the Pentagon receives approval to proceed with the program.[13] Currently, smaller versions of Sprite are in development that will then be scaled up to become a complete launch vehicle.[14]

5 Conclusions

In benchmarking the small satellite market since 1990, data on 172 satellites were collected and analyzed for discernable trends in mass and complexity. What was perhaps a surprising result was that mass has remained fairly constant and using a crude measure of complexity this too has remained fairly constant. The most plausible explanation for this lack of a change in complexity is the entrance into the small satellite market by new players. Qualitatively and by examining how solar arrays and attitude control systems have gravitated towards more complex approaches it has been shown that small satellites are more capable than ever before.

However, despite this demonstration of increased capability, the market, as measured by number of launches, shows some signs of staying flat or declining. This is attributed to the lack of affordable small satellite launch opportunities and hence the reason this conference is focused on the theme of access to space. Yet as summarized in this paper and discussed in other papers for this conference, there are both near-term and longer-term solutions that could improve this launch dilemma. If they are successful, then the true potential of small satellites may be realized.

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Appendix: Small Satellite Data

Data were collected spanning small satellite missions flown from 1990 until the present and those developmental missions that are in production or awaiting a launch opportunity. Missions that are in preliminary design phases were not included.

For each mission, the following information was collected:

- sponsoring organization
- launch mass
- payload mass
- physical dimensions
- power consumption
- power storage
- solar array type
- type of attitude control system
- orbital altitude
- orbit type
- orbital inclination
- launch vehicle
- launch date
- mission objective

Data on 172 missions were collected in total. These missions exclude Cubesats, passive spacecraft (like Starshine), picosats and spacecraft that were deployed from other spacecraft (like OPAL's picosat payloads).

A subset of this complete data set was used for the complexity index work presented in this paper. Spacecraft where all the necessary complexity index factors were known were included in the smaller data set. The complexity index consisted of the launch mass, solar array type, type of attitude control system, launch date (for comparison purposes) and number of major payloads/instruments. 71 spacecraft from the original list had been placed on station from 1990-2003 and contained all of the required parameters.

A further subset of the data was the data used for the university small satellite complexity index work. From the 71 spacecraft that contained all the information for the complexity index, 24 were part of the university class of small satellites.