8th Responsive Space Conference
RS8-2010-5003

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8th Responsive Space Conference
March 8–11, 2010
Los Angeles, CA

AIAA-RS8-2010-5003

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ABSTRACT

A configuration is presented for a low-cost Micro-Satellite Launch Vehicle (MSLV), the Mini-Sprite. This 3-stage configuration exploits Scorpius® technology that is largely developed: all-composite cryogenic tanks; pressure-fed, ablative, LOX/kerosene engines; a High Performance Pressurization System; and a GPS-based, "plug-and-play" avionics system. The Preliminary Design Review has been completed for the larger Sprite, a Small Launch Vehicle (SLV). Indeed, the SR-M suborbital rocket, essentially a "pod" of Sprite, has already been built; it is a larger version of a "pod" of the Mini-Sprite.

Performance estimates show that the Mini-Sprite can deliver payloads well into the micro-satellite payload range of 10 to 100 kg and completely covers the nano-satellite payload range of 1 to 10 kg to modest orbits. The Mini-Sprite delivers about 100 kg to LEO.

The potential market for CubeSats and other SmallSats has been estimated to be as much as 30 to 70 satellites per year. The Scorpius® micro-satellite launch vehicle will provide a cost effective means for delivering these payloads to orbit. The DoD's Space Experiments Review Board (SERB) list alone has dozens of payloads that could be accommodated by micro- or nano-satellites launched on the Mini-Sprite MSLV. This vehicle will demonstrate both the feasibility and utility of launch on-demand, which will have applicability to military tactical, science, technology, and educational missions for commercial, DoD, NASA, and university users.

Recurring price for the launch of the Mini-Sprite vehicle is $3M. Development time is 20 months. Development costs are also very low. The low cost of the vehicle permits a production line and establishment of an inventory of vehicles, if desired.

Assuming progress in lowering the time and cost of range operations, launch from ready inventory of the low-cost Mini-Sprite is achievable in less than 24 hours.

The Mini-Sprite is scalable to small- through medium-lift launch vehicles, Sprite, Liberty, and Exodus, which exhibit the same technologies, design, and responsiveness at a correspondingly low cost.

This paper addresses the capabilities and launch missions of the Mini-Sprite.

KEYWORDS: Micro-Satellite Launch Vehicle, Nano-Launcher, Low Cost Launch

INTRODUCTION

The Scorpius® family of vehicles has been developed over the past 16 years in an attempt to greatly reduce the cost of launch to orbit.[1,2,3,5,6,7,8,9,10,11,12,13,14] The architecture for these vehicles is predicated upon the concept of using simple, pressure-fed systems that are a bit heavier than current systems but much lower in hardware, integration, and operations costs due to avoidance of the use of minimal stages, high performance propulsion (high chamber pressure, hydrogen, turbopumps), and exotic structures (balloon tanks.) See Figure 1.

The 3-stage configuration exploits Scorpius® technology that is largely developed: pressure-fed, ablative, LOX/kerosene engines (Figure 2); all-composite cryogenic tanks (Figure 3); a High Performance Pressurization System; and a GPS-based, "plug-and-play" avionics system with Common Area Network (CAN) bus. The vehicles also utilize a unique "fly out" separation of Stage 2 (on rails and thrusting) from the spent Stage 1, similar to the separation of the liquid booster engines on the Atlas. This parallel staging configuration reduces vehicular length and, coupled with the strong structures required for a pressure-fed system and high engine deflection angles, produces a high tolerance to winds aloft, a common impediment to timely (responsive) launch.

Figure 1. Pressure-fed Scorpius® Vehicle.

As shown in Figure 4, three vehicles have been characterized to date from this scalable architecture: Sprite, Liberty, and Exodus, which deliver 1060, 4200, and 19,700 lbs (481, 1905, and 8936 kg) to LEO, respectively. This paper presents a scaled down Scorpius vehicle, the Mini-Sprite, and its prospective missions that fall within its 220-lb (100-kg) capability. The applicable missions with small spacecraft are drawing renewed attention.

Figure 2. 20K lbf Engine Testing.

Figure 3. 42-in Diameter (Sprite) LOX Tank.

Figure 4. Scorpius® Family of Launch Vehicles.

DESCRIPTION OF MINI-SPRITE

The Mini-Sprite is a scaled down version of the Sprite where propellant capacity, engine thrust level, and, roughly, gross weight are reduced by a factor of 4. Due to the relatively small size of the resulting Mini-Sprite, and the resultant high relative drag losses, payload is reduced by somewhat more than a factor of 4 to 225 lbs (102 kg) Normally, in the manner of scaling the Scorpius® vehicles, the diameter of the "pods" is reduced by the cube root of the (propellant weight) scaling factor of 4, or 1.59. However, given that 25-in diameter composite tanks are a standard production item for our sister corporation, Scorpius Space Launch Company (SSLC), 25-in diameter pods are specified for Mini-Sprite rather than the expected diameter of 26.5 in.

The various general parameters of the Mini-Sprite are listed in Table 1. A schematic of the configuration is illustrated in Figure 5.

Table 1. Mini-Sprite Characteristics.

LEO Payload	**225 lb**
SSO Payload (400 nmi)	138 lb
Payload volume	21 cuft
Launch Price (excluding range costs)	$3,000,000
Price/lb to LEO	$13,333
Overall Height	38.2 ft
Pod Length	26.6 ft
Pod Diameter	25.0 in
Vehicle Diameter	6.7 ft
GLOW	20,100 lb
Empty Weight	2,325 lb
Engine Configuration	
Stage 1	6 x 5K lbf
Stage 2	1 x 5K lbf
Stage 3	1 x .6K lbf
Max Axial g's	5.9
Stage 1	
Thrust, vac	30,000 lbf
Thrust, sl	25,000 lbf
Gross Mass	16,389 lbm
Empty Mass	1,887 lbm
Stage 2	
Thrust	5,562 lbf
Gross Mass	2,733 lbm
Empty Mass	316 lbm
Stage 3	
Thrust	567 lbf
Gross Mass	751 lbm
Empty Mass	122 lbm
Scale (volume or weight)	0.25
Scale, linear, ideal	0.630
Scale, linear, actual	0.595

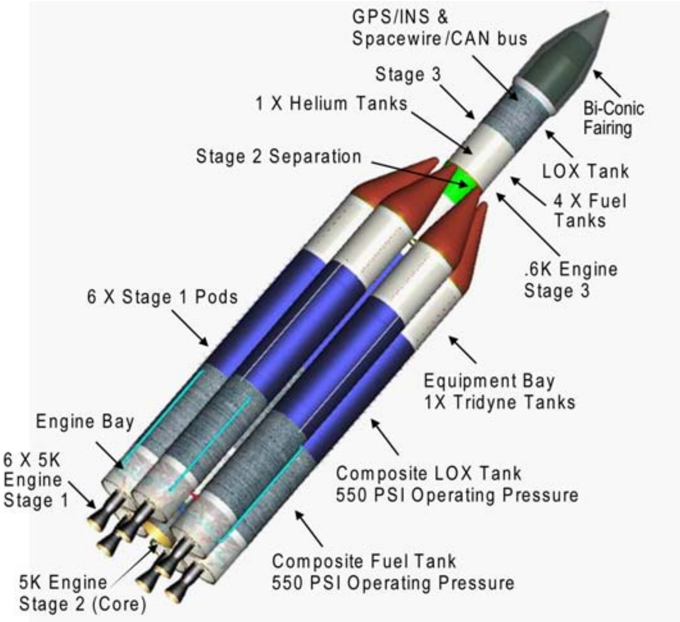

Figure 5. Mini-Sprite Configuration.

A mockup of the Mini-Sprite is shown in Figure 6 where the scale is evident.

Figure 6. Mockup of Mini-Sprite.

Over 35 5K lbf ablative engines have been tested and 3 have flown, one on the SR-S (Figure 7) and two on the SR-XM (Figure 8), a prototype of the 42-in diameter SR-M.

Figure 7. SR-S Launch, January 1999.

Figure 8. SR-XM Launch, March 2001.

As has been mentioned above, cryogenic composite tanks have been successfully flown. The 42-in diameter SR-M suborbital vehicle, essentially a developmental version of a "pod" of the Sprite, has been fabricated with composite tanks as depicted in Figure 9 and is awaiting flight testing.

Figure 9. SR-M, a "Pod" of Sprite.

Several 25-in tanks have been fabricated and a pair were utilized in the flight of CSULB/Garvey Spacecraft Corporation's suborbital rocket as pictured in Figure 10 and supplied by SSLC.

Figure 10. 25-in Composite Tanks on Garvey Rocket.

Microcosm and its sister company, Scorpius Space Launch Company (SSLC), have recently developed a new resin for our composite Pressurmaxx® tanks, Sapphire 77, that perform very well in cryogenic applications, in particular, liquid oxygen. These tanks have been further improved, compared with those utilized in the past, in that metallic bosses have been replaced with composite bosses. Therefore, these tanks are, indeed, all-composite in construction, with no metallic or plastic liners or bosses. The somewhat obvious implication is that the all-composite and integrated nature of the tanks renders them largely immune from problems with differential coefficient of thermal expansion and mechanical movement experienced by composite overwrapped pressure vessels or other tanks that use metallic or plastic components.

Other features of the Mini-Sprite are similar to those of other Scorpius® launch vehicles such as Sprite, for which a Preliminary Design Review has been conducted, and are summarized as follows. A High Performance Pressurization System (HPPS) is implemented to save about half the weight in the tankage of the pressurization system. A Global Positioning System/Inertial Measurement Unit (GPS/IMU)-based "plug-and-play" avionics system, which utilizes the automotive standard Common Area Network (CAN) bus system, has been selected to reduce cost and retain performance compared with past launch vehicles. The high pressure kerosene fuel is exploited as the hydraulic working fluid for the thrust vector control actuators.

Payload performance to various low earth orbits (LEO) is plotted in Figure 11. Performance estimates show that the Mini-Sprite can deliver payloads well into the micro-satellite payload range of 10 to 100 kg and completely covers the nano-satellite payload range of 1 to 10 kg to modest orbits. The Mini-Sprite delivers about 100 kg to LEO.

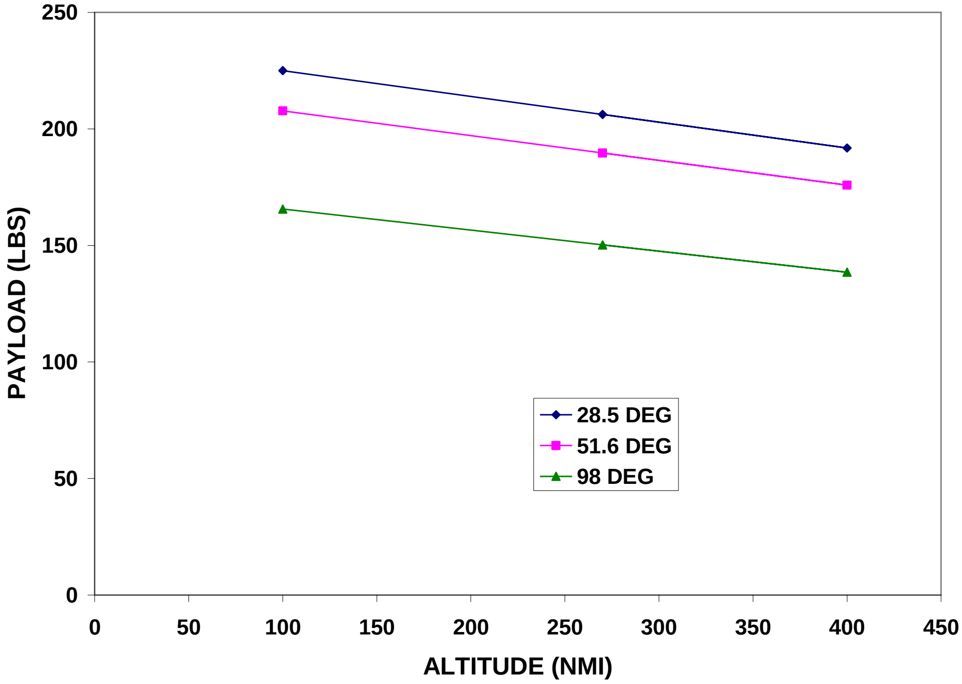

Figure 11. Performance of Mini-Sprite.

Recurring price for the launch of the Mini-Sprite vehicle (excluding range costs) is $3 million by special arrangement and, more generally with no prior arrangement, at $4.5 million. Development time is 20 months. Development costs are also very low. The low cost of the vehicle permits a production line and establishment of an inventory of vehicles, if desired. The cost of the Mini-Sprite is not unlike that of some munitions such tactical missiles.

Mini-Sprite exhibits a responsive launch capability. Assuming progress in lowering the time and cost of range operations, launch from ready inventory of the low-cost Mini-Sprite is achievable in less than 24 hours. It should be emphasized that while the absolute cost for launch of the Mini-Sprite is attractively low compared with other vehicles, its specific cost (cost per pound of payload) is moderate, i.e., comparable to existing vehicles. However, the Mini-Sprite's responsiveness enables consideration of the "opportunity" cost of a responsive mission, mitigating its only average specific cost for many missions.

The Mini-Sprite is scalable to small- through medium-lift launch vehicles, Sprite, Liberty, and Exodus, which exhibit the same technologies, design, and responsiveness at a correspondingly low cost. The first two of these other vehicles are mentioned below in the context of capturing missions of small satellites beyond the payload capability of the Mini-Sprite.

CAPTURE OF THE MICRO-SATELLITE MARKET BY MINI-SPRITE

In order to justify the Mini-Sprite, an examination of the degree to which the Mini-Sprite and other Scorpius® launch vehicles (Sprite and Liberty) capture the market for missions with small satellites has been conducted.

Orbit Cost Function

The first step of the study is the calculation of the Orbit Cost Function (OCF) of the Mini-Sprite vehicle. The OCF is defined as:

OCF = Mass Available in a 100-nmi, 28-5-deg Orbit/ Mass Available in the Mission Orbit

Such a calculation is based on the capabilities of the vehicle shown in Figure 11. In particular, Mini-Sprite can deliver 225 lb (102 km) to 100 NMI (185 km) altitude with a launch due east from Cape Canaveral (orbital inclination of 28.5 deg.) Launch from Cape Canaveral (and Vandenberg Air Force Base for high inclinations) has been assumed everywhere in this study, so that orbits with inclinations smaller than 28.5 deg have not been directly considered.

From the data that originated the curves in Figure 11, a non-linear interpolation equation was derived and the payload capabilities of Mini-Sprite for various altitudes and orbit inclinations were obtained. The baseline mission, i.e., the mission for which OCF = 1, is the due east launch (28.5 deg) to 100 NMI. This OCF was applied to actual missions. The missions for which the inclination is smaller than 28.5 deg were considered to be at 28.5 deg, given the assumed launch from the Cape, and suborbital missions were considered as orbital at the baseline altitude, to provide a more stringent condition for Mini-Sprite. Since all orbits from real missions — both past and planned — have an altitude equal or greater than 100 NMI, the OCF is always equal to or greater than 1, implying that the equivalent mass of the payload is always equal or greater than its actual value.

SERB List

The second step of the study was the analysis of the DoD's Space Experiments Review Board (SERB) priority list, which every year ranks the priorities of space technology demonstration missions. In particular, an assessment was made of the number of missions in the list that can be achieved by Mini-Sprite. In many cases, the SERB list provides the masses of the spacecraft payloads, i.e., the scientific instruments mounted on the spacecraft to accomplish the mission, but it doesn't provide the mass of the spacecraft itself. The assumptions made in the assessment are:

- The mass of the whole spacecraft is approximately double the mass of the payload it carries. In reality, the payload mass usually varies from 30% to 80% of the total mass, but for the purpose of the current study 50% has been considered to be a sufficiently reasonable assumption.
- As mentioned above, launches of Mini-Sprite to orbital inclinations below 28.5 deg were assumed to have a 28.5 deg inclination. This also has been considered to be a reasonable approximation.
- The Orbit Cost Function of Mini-Sprite for each mission has been calculated with respect to the nominal launch (due east, 100 NMI, 28.5 deg inclination).
- The equivalent mass of a spacecraft to the nominal orbit has been calculated as the product of the real spacecraft mass and the OCF of that mission. In this way, it has been possible to effectively compare all spacecraft under the same conditions.
- Suborbital launches have been translated into orbital launches at 100 NMI altitude to provide a more restrictive condition for Mini-Sprite (higher OCF and, therefore, higher payload mass).
- Spacecraft have been considered individually, meaning that one separate launch for each spacecraft has been assumed, while, in reality, many spacecraft (usually the smallest ones) are launched together with others to save costs, often sacrificing the possibility of launch on demand and to a dedicated orbit. Basically, today most small satellites are launched as secondary payloads, except those few that are launched in the form of satellite clusters (e.g., Orbcomm, Iridium). Because of this, small satellites are not permitted to dictate their final orbit, rather, they have to accept the orbit of the main payload. With the Mini-Sprite vehicle, launch of one payload at a time is possible, thus restoring these important features.
- The capabilities of two other vehicles of the Scorpius® family, Sprite and Liberty, have also been considered under the same assumptions, and an estimate of how many missions these two vehicles can accomplish has been made. For this estimate, the equivalent spacecraft weights based on the Mini-Sprite's OCF have been used. Although this is not a completely rigorous comparison, it is still very close to the truth given the similarities, in terms of scalability, of the vehicles of the Scorpius® family.

As stated above, the maximum capability of the Mini-Sprite launcher for the nominal mission (100 NMI, due east at 28.5 deg) is 225 lb (102 kg). The maximum payload capabilities for the Sprite and Liberty launch vehicles are 1060 lb (476 kg) and 4200 lb (1905 kg), respectively.

Based on the available data and on the above assumptions, the results in Figure 12 and Figure 13 have been obtained. The figures show that the total number of SERB missions is 59, and Mini-Sprite can achieve 36 of them (61%), which is a significant amount. Additionally, Sprite and Liberty can accomplish 50 (85%) and 59 (100%) missions, respectively. The results show that the Scorpius vehicles, in particular Mini-Sprite alone, can largely meet the requirements of the DoD technology demonstration missions. Future missions, other than those of the SERB, have not been considered yet, but their assessment is one of the next goals.

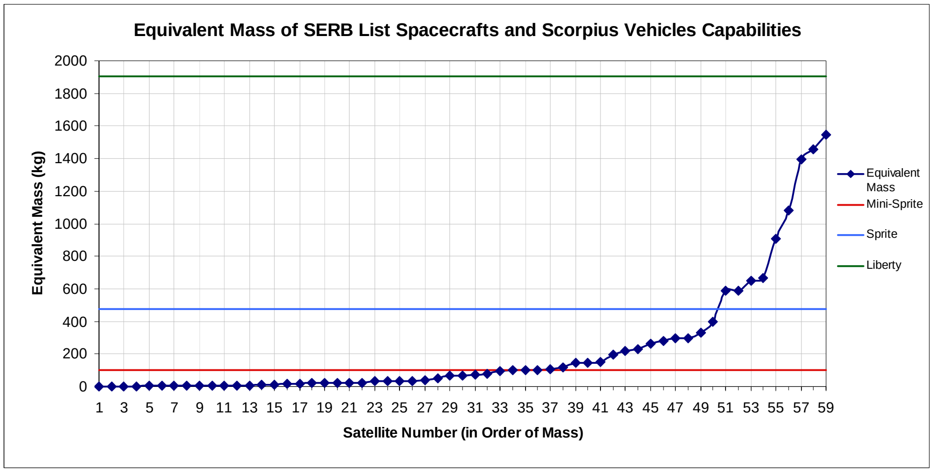

Figure 12. Equivalent Mass of SERB List Spacecraft Based on the Mini-Sprite Orbit Cost Function, and Capabilities of Three Vehicles of the Scorpius® Family: Mini-Sprite, Sprite, and Liberty.

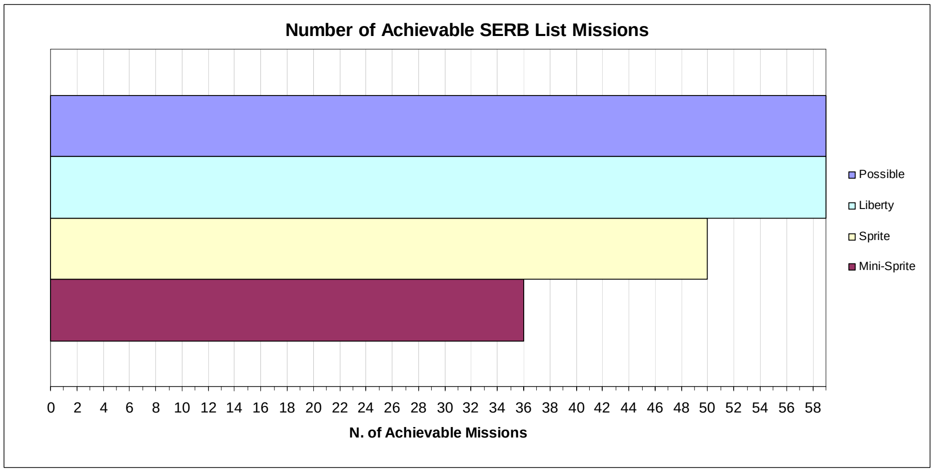

Figure 13. Number of Achievable SERB List Missions by Three Vehicles of the Scorpius® Family: Mini-Sprite, Sprite, and Liberty.

Actual Past Missions

The third part of the study was the analysis of actual past missions, the purpose being to gather information about any trends in the number of small payloads launched in relatively recent years. In particular, all payloads launched in the years 1990, 1995, and 2000 to 2009 have been catalogued and studied, with the expectation to back the argument that small payload launches have remained steady or even increased in the past years, despite the decrease in total number of launches. In the case of the U.S., in particular, this would be an important finding given the longstanding lack of dedicated mini-satellite launchers in this country since the demise of the Scout in 1994.

Most of the data have been gathered from online sources.[15,16,17,18,19] These sources provide the actual mass of the spacecraft, not just of its payload, which makes the process easier and at the same time more accurate. When collecting and sorting the data, the assumptions that have been made (some similar to those applied to the SERB list) are the following:

- Launches to orbit inclinations below 28.5 deg (for example, GEO satellites) were assumed to have a 28.5 deg inclination.
- The Orbit Cost Function of Mini-Sprite has been based on a launch due east to 100 NMI and 28.5 deg inclination (nominal mission).

- The equivalent mass of a spacecraft to the nominal orbit has been calculated as the product of the real spacecraft mass and the OCF of that mission.
- Payloads have been considered individually.
- The capabilities of the Sprite and Liberty vehicles have been considered as well, and they have been compared to the equivalent satellite weights based on the Mini-Sprite's OCF.
- Failed or partially failed launches (like OCO, in 2009) have been included in the study as well, since those missions were "possible," and they would have been realized had the failure not occurred. Therefore, they apply to the study of the Mini-Sprite launch vehicle.
- Human missions have not been included in the study, since those missions do not apply to the Scorpius® family of launch vehicles, because they are not designed for crewed missions. Those missions include, for example, Space Shuttle and Soyuz launches. However, if an unpiloted small payload (for example, Starshine 1, in 1999) was released by the Space Shuttle orbiter or by Soyuz, that payload was considered in the study because it had its own orbital mission and in theory it could have been launched by other vehicles. Similarly, payloads launched from the International Space Station (e.g., Suitsat, in 2006) have been included as well. Finally, space station components brought to LEO (e.g., MPLM modules) have been included since, in principle, they did not need to be carried by a piloted launcher and could just be considered as payloads launched to LEO.
- Interplanetary (heliocentric) missions have almost entirely been excluded from the study. The main reason is the lack of information about the parking orbit around the Earth in which the spacecraft is left before leaving to its destination. Whenever this is provided the mission is considered, but unfortunately this has been the case for only a handful of missions. In the majority of cases in fact, only the heliocentric orbit or the final orbit around the target planet are provided, and those do not apply to the Mini-Sprite's OCF, which has been calculated only for geocentric missions.
- For a few geocentric mission cases (a negligible number), the data about their orbit or the mass of the spacecraft were not found (for example, some classified missions), so those missions were not included. These cases include all the suborbital missions listed in the online databases, which, however, comprise only a very small number.

The total percentage of missions not considered in the study (piloted, interplanetary, and not available) averaged 10% each year, with a minimum of 5.3% in 2000, and a maximum of 13.5% in 2006. These percentages clearly translate into equivalent uncertainties in the final results, which however can still be considered reliable in the context of the goals of the current study.

Figure 14 to Figure 23 show the final results of the study of past missions. In particular, Figure 14 through Figure 19 sort the number of launches that occurred in the past years by mass ranges and show the trends in the existing data. In contrast, Figure 20 to Figure 23 show the results in terms of the capabilities of the Mini-Sprite and of other two vehicles of the Scorpius® family, Sprite and Liberty. The masses of the satellites considered in Figure 14 to Figure 19 are the actual ones. In contrast, Figure 20 through Figure 23 are based on the equivalent masses of the satellites. In general, even numbered figures show the actual number of launches, while odd numbered figures show the results in form of percentages.

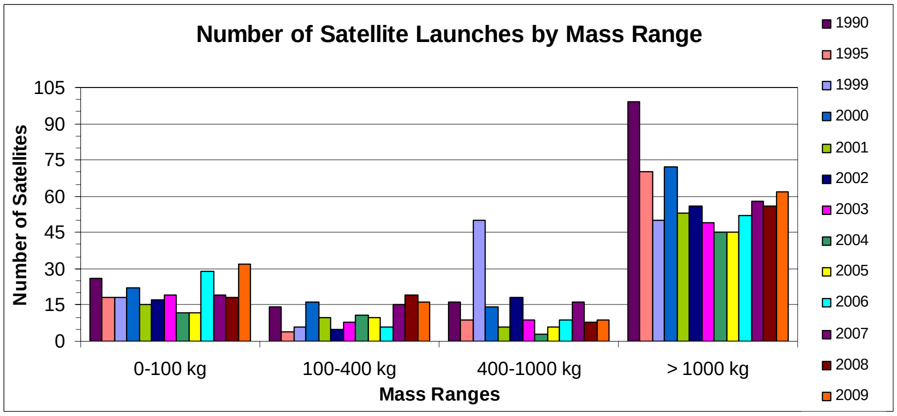

Figure 14. Number of Satellites Launched in the Years 1990, 1995, and 2000 to 2009, Grouped by Mass Range.

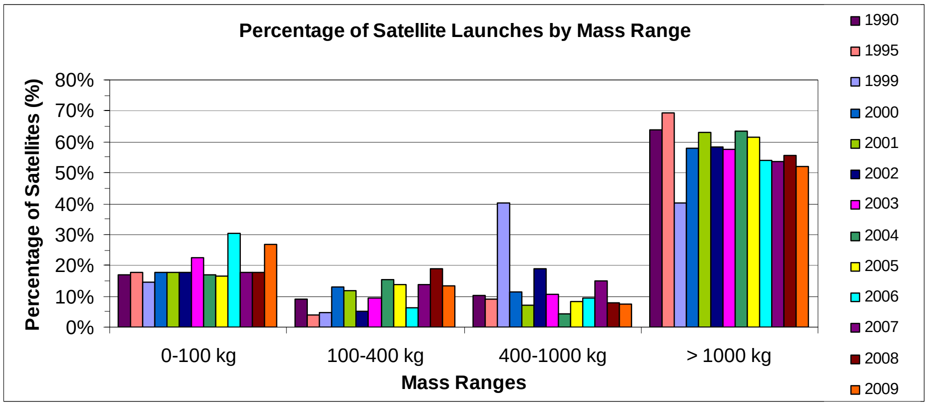

Figure 15. Percentage of Satellites Launched in the Years 1990, 1995, and 2000 to 2009 Grouped by Mass Range.

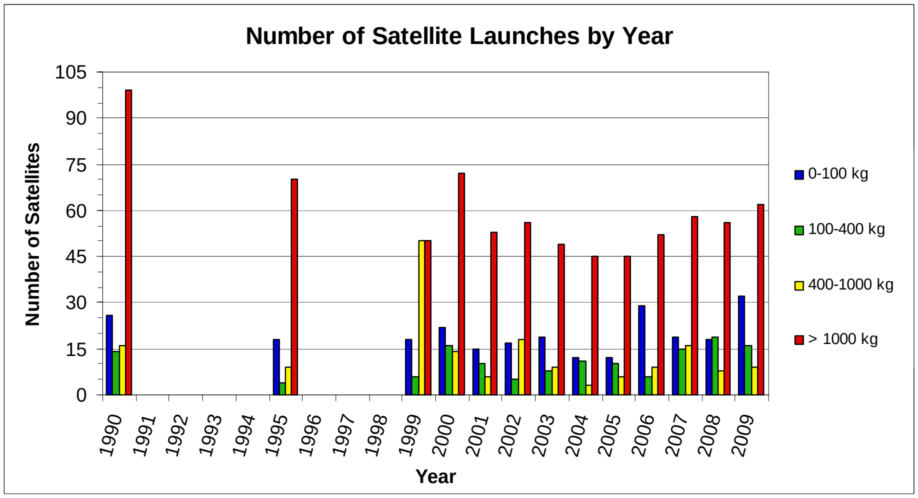

Figure 16. Number of Satellites in Four Different Mass Ranges Grouped by Year.

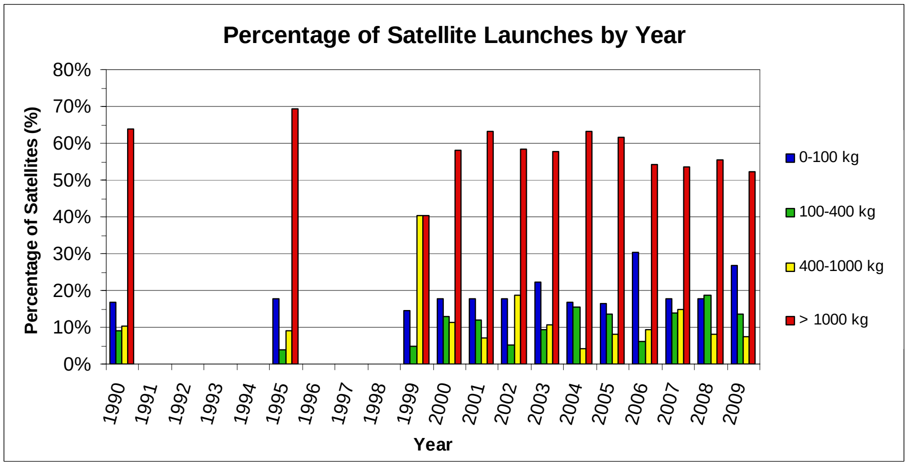

Figure 17. Percentage of Satellites in Four Different Mass Ranges Grouped by Year.

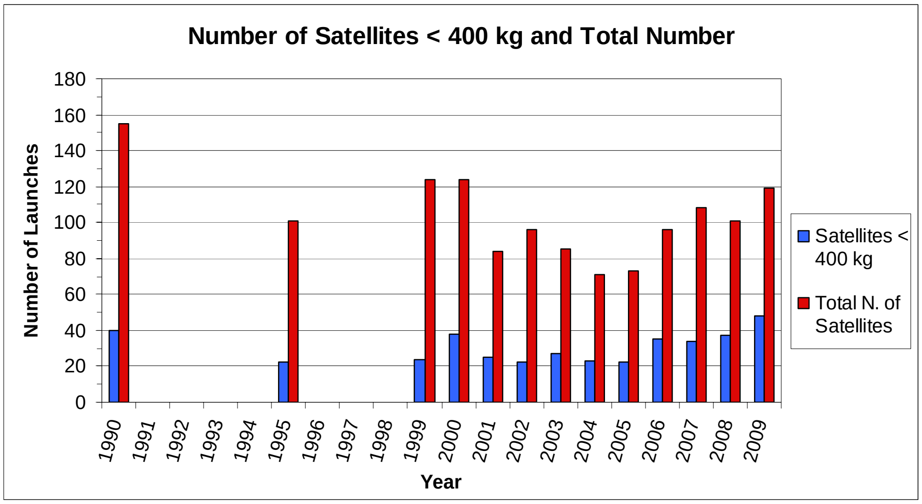

Figure 18. Number of Satellites < 400 kg and Total Number Launched in the Years 1990, 1995, and 2000 to 2009.

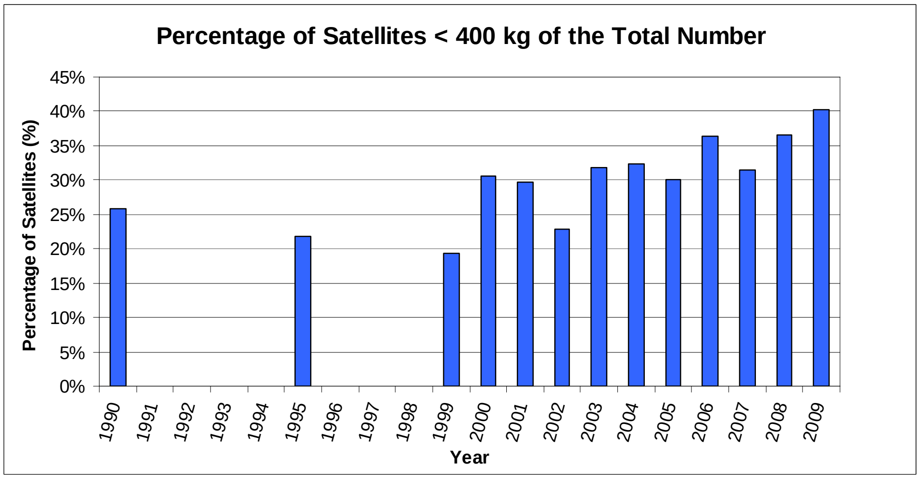

Figure 19. Percentage of Satellites < 400 kg of the Total Number Launched in the Years 1990, 1995, and 2000 to 2009.

More specifically, Figure 14 and Figure 15 show the number and percentage of spacecraft launched in past years grouped in four different mass ranges (in kg): 0–100, 100–400, 400–1000, and >1000. The most obvious result in these figures is that the majority of payloads were in the range >1000 kg, although their percentage has been slowly decreasing. Payloads in the ranges 0–100 and 100–400 seem to have slightly increased in percentage over the years, while the range 400–1000 has remained nearly stable. Figure 16 and Figure 17 show the same data, but grouped by year on the x-axis rather than by mass.

Figure 18 and Figure 19 present the number and percentage of spacecraft with a mass equal to or smaller than 400 kg launched in past years and compare them with the total number of launches in those same years. The cutoff at exactly 400 kg is arbitrary since any small value in the same vicinity would have worked. The real purpose here was to compare the number of light payloads to that of heavy payloads. The plots show that from 1990 to 2009 (leaving out a few missing years) the absolute number of small satellites launched has decreased and then increased a few times, but has remained nearly stable. However, in percentage that number has been constantly increasing, since the total number of launches has constantly decreased (there were at least 155 spacecraft launched in 1990 and less than 80 spacecraft launched in both 2004 and 2005).This percentage passed 40% in 2009.

Figure 20 and Figure 21 show the number and percentage of past missions that can be accomplished by the Mini-Sprite, Sprite, and Liberty launch vehicles.

These are the most important results and they prove the initial thesis of the study: the total number of launches, as shown in Figure 20, has globally decreased in the past years while the number of missions achievable by the three vehicles has nearly remained constant. This produced the important results of Figure 21, according to which the percentage of missions achievable by the three vehicles has been on a slow but continuously increasing trend, reaching a maximum in 2009, and still rising. Figure 22 and Figure 23 are equivalent to Figure 20 and Figure 21; they simply show bars instead of lines for a different visual impact. In conclusion, the growth of the small satellites has occurred in spite of the downfall of the only American mini-satellite launcher, the Scout, in 1994.

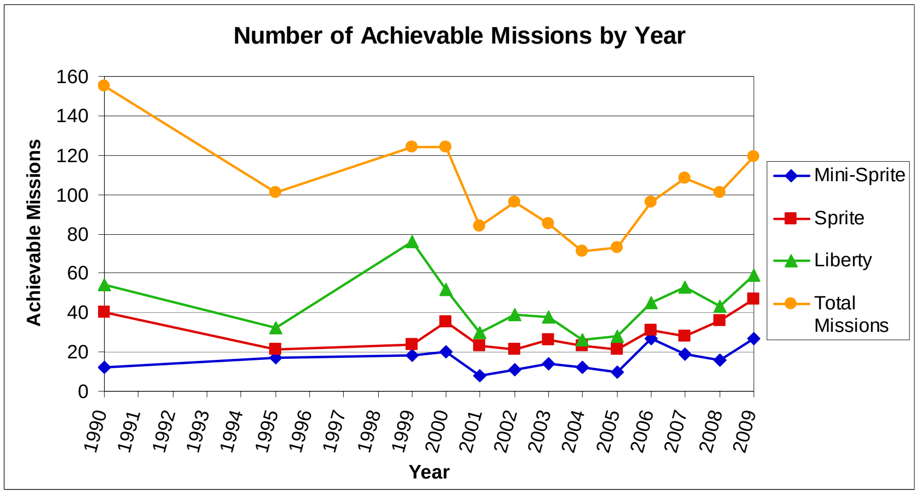

Figure 20. Total Number of Missions and Number of Achievable Missions by Three Vehicles of the Scorpius® Family: Mini-Sprite, Sprite, and Liberty for the Years 1990, 1995, and 2000 to 2009.

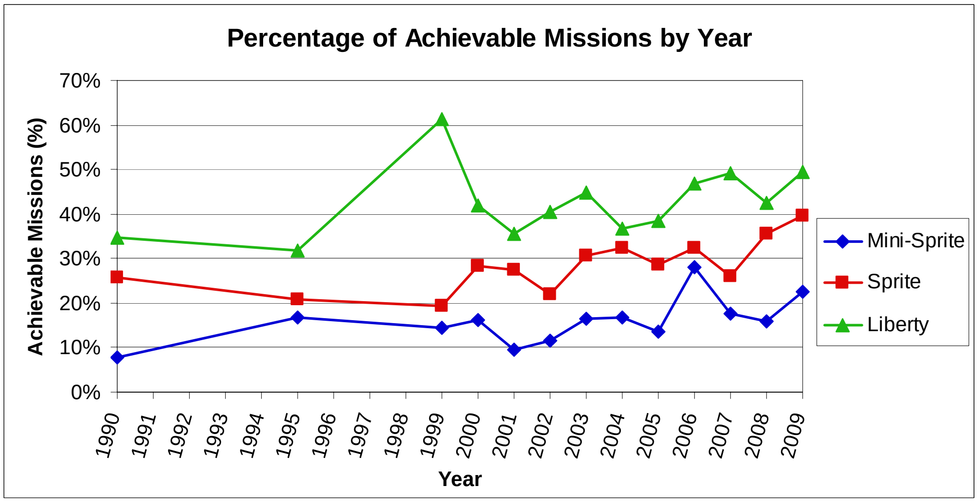

Figure 21. Percentage of Achievable Missions of the Total by Three Vehicles of the Scorpius® Family: Mini-Sprite, Sprite, and Liberty for the Years 1990, 1995, and 2000 to 2009.

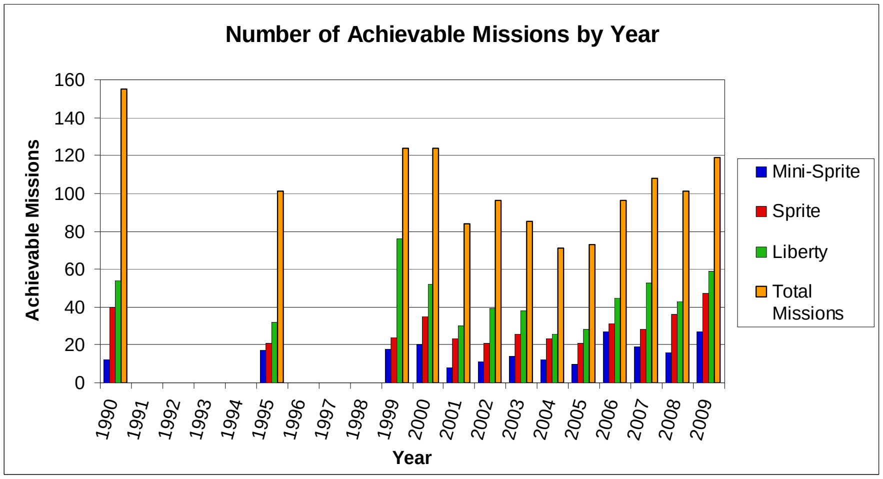

Figure 22. Total Number of Missions and Number of Achievable Missions by Three Vehicles of the Scorpius® Family: Mini-Sprite, Sprite, and Liberty for the Years 1990, 1995, and 2000 to 2009.

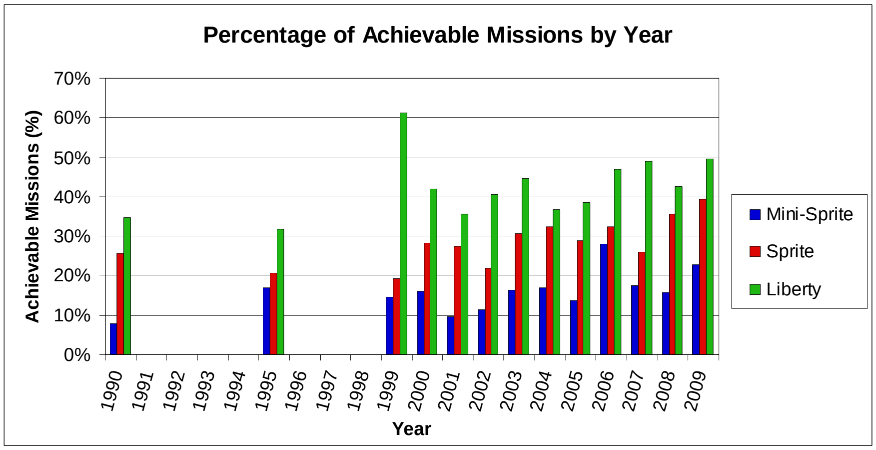

Figure 23. Percentage of Achievable Missions of the Total by Three Vehicles of the Scorpius® Family: Mini-Sprite, Sprite, and Liberty for the Years 1990, 1995, and 2000 to 2009.

As visible in many of these plots, there is a peak in total number of launches in the year 1999, corresponding to a higher number of missions achievable by the Liberty vehicle. This peak is due to the launch of the Globalstar constellation, which comprised 40 spacecraft all having a weight of 450 kg and an equivalent mass of 616 kg.

CONCLUSIONS

1. A low-cost micro-satellite launcher, the Mini-Sprite, has been conceptualized. It exploits the pressure-fed Scorpius® technology and can launch 225 lbs (102 kg) to LEO .
2. Price of the launch of the Mini-Sprite is $3 million (excluding range costs).
3. Mini-Sprite is a responsive launch vehicle.
4. Mini-Sprite is scalable and is the first step to larger vehicles that significantly improve response and lower cost for launch.
5. Mini-Sprite can capture 61% of the SERB missions; Sprite, 85%.
6. Mini-Sprite would have captured about 18% of the actual recent missions; Sprite, 30%.
7. The percentage of missions that are small satellites (<400 kg) is increasing and is now 40%.
8. Currently, the primary user of small satellites is DoD, with the balance of the missions being educational or for NASA
9. There is increased interest in providing tactical capability to the military with small satellites as well as renewed interest in the use of small satellites for earth science and technology validation.

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