AFFORDABLE LAUNCHER FOR SMALL SPACECRAFT MISSIONS*†

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Abstract

Maturation of small, micro-, and nano-satellite technologies is leading to many innovative new space mission applications. A primary obstacle to successful operational transition of these systems is the lack of affordable small launch capability. Due to the extremely high cost of current small launchers, small payloads often have to ride to space as secondary payloads, deferring to the orbital destination and schedule of the primary mission.

This paper will cover the design, technologies, production, and operations characteristics of an all-new generation launch system that will substantially lower the cost of a dedicated small spacecraft launch. A unique combination of low-cost technologies and innovative design and manufacturing approaches enable the *Scorpius*® *Sprite* launcher to deliver up to 700 lbs of payload to low-Earth orbit (100 nmi east) for 20% of the cost of the lowest cost U.S. launch now available.

The *Scorpius*® vehicle architecture employs similar propulsion "pods" for the first and second stages. The first stage uses six of these pods and the second uses a single pod. This means that seven sets of the same hardware are produced for each rocket. This increases quantity while reducing the size and number of part types used to build the vehicle.

Simple pressure-fed engines using LOX and jet fuel propellants power all-three stages of *Sprite*. The technology for these engines is being developed to provide nearly the performance of traditional engines, with far less production cost. Advanced graphite-composite tanks are an enabling technology that allows orbital performance without the cost and complexity of turbomachinery. The paper shows how the high-pressure, graphite-composite cryogenic tank technology is maturing and being flight demonstrated at full-scale. The processes being developed to build these tanks are optimized for very low recurring cost without the need for autoclave curing. Other technologies such as low-cost orbital-capable avionics, low-cost feed and pressurization systems, and others are also presented.

With a low vehicle production cost the need for low operations and range costs gains importance. The simplified operations and range interfaces being developed for *Sprite* to reduce operations complexity will be presented. Finally, the scalability of the *Scorpius*® launch system architecture and technologies to enable larger low-cost launchers will be shown.

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Introduction

New technologies are allowing smaller very capable spacecraft to be deployed. Increasing numbers of pico, nano as well as mini satellites are being constructed. These cover a mass range of 0.5 lbs to 140 lbs for the very small and up to 660 lbs for the mini satellites. Maturation of the small micro, nano and mini satellites lead to many new applications. Listed below are but a few of the science missions in development.

1. Air Force Research Laboratory — TechSat-21 constellation
2. NASA[7] — New Millennium, Magnetosphere constellation (100, 22 lb satellites),Discovery, Midex, Smex, Unex
3. Affordable Little LEO applications for commercial, DoD, and Civil

The primary obstacle to a more robust development of the small satellites is cost of delivery to space. In these and other missions, for which there is a strong desire to develop small payloads, the cost of launch is a strong inhibitor. There have been various attempts to satisfy the need for the affordable missions including those more recently that focus on secondary and ride share alternatives. There are a number of issues that have risen in these attempts.

Secondary and ride share options afford some opportunities, but have many constraints.

- No control over launch time
- No control over orbit selection
- Long wait periods until primary payload is ready
- Cost is not necessarily inexpensive
- Many of the primary payloads producers do not desire the secondaries
- The major launch providers are not interested in the integration and mission support needed for the small payloads

For other than limited science missions, small constellation applications are an even more difficult case.

- Initial deployment may be justified with multi-satellite deployment, but replacement satellites for specific constellation slots are very expensive
- The “mission” cost becomes the driver, and that requires a dedicated Small Launch Vehicle (SLV)
- Total life cycle cost estimates for the constellation have launch as a major cost driver

Why is a small launcher needed? There is a continuing demand to drive down mission cost. Development testing in space is basically nonexistent because of high launch cost. More than ever R&D and space education organizations utilize small micro and nano satellites, individually or in constellations. It is not productive either to launch a $1 million satellite on a $20 million vehicle or to launch if the ride-share costs as much as the satellite.

Launch needs for constellations of small satellites typically call for the initial launch of multiple satellites on a larger launcher to drive down cost. This, of course, can be risky as in Globalstar when 12 satellites were lost during a single launch event. This may work for the initial deployment but will not meet the operational need for replacement satellites due to either single failures or for single constellation replacement units as they age out. This requires timely and specific orbit orientations.

Rapid, low-cost access to space for testing or experimentation can dramatically change the way we do business in space by shortening the schedule and significantly reducing the cost. The small satellite revolution holds substantial promise, but only if we can put them in space quickly and at low cost.

Thus Microcosm is developing *Scorpius*®, an all new generation family of Expendable Launch Vehicles (ELV).

Background

There is significant interest in a low-cost launch vehicle with very small to mini loads (200 lbs to 2,000-lbs to LEO) and a total launch cost below $3 million. These vehicles serve two purposes:

- Test and validate the technology appropriate to larger vehicles
- Serve the mission needs of the Small-Sat community, including
  - University payloads
  - Mini and micro-satellites
  - Micro-gravity experiments
  - On-orbit servicing, refueling, or parts replacement
  - Low-cost missions that need a dedicated launch or a unique orbit
  - Emergency payloads to International Space Station

The *Scorpius*® family of expendable launch vehicles‡ has the objective of reducing near-term launch cost by a factor of 5 to 10 and a potential for greater cost reduction in the future. The program starts with the small sub-orbital vehicles and progresses to the small orbital vehicle to answer the need for the small vehicle market. The *Scorpius*® Program is based on research done over a 15-year period with government development funding beginning with a Phase I Small Business Innovative Research award in 1993.[1–3, 6]

Since that time Microcosm been awarded a total of 18 contracts to accomplish the development to date with funding from BMDO, the Air Force, NASA, and Microcosm internal R&D. The program was initiated by Ed Keith[1] and implements cost reduction strategies identified by John London.[4, 5]

Table 1, shows the price objectives of the various launch vehicles in the *Scorpius*® Program. The fundamental goal of the program has not changed since its inception – to transform launch to orbit from a dramatically high-cost, high-risk activity requiring vehicle procurement months or years in advance, to one more closely resembling normal commercial transportation.

Even with a factor of 10 reduction in cost, space will still be expensive at $800/lb to low-Earth orbit. Nonetheless, we believe that much lower costs, rapid response, and flexible systems oriented toward meeting customer needs will significantly increase the number of missions that will be designed and flown. This, in turn, will further reduce launch costs and significantly aid in opening the space frontier.

The *Scorpius*® program began with the development of several suborbital vehicles. This has two principal purposes. First, the suborbitals serve to validate the launch vehicle technology at much lower cost than is possible with orbital vehicles. This allows far more test flights than would otherwise be done, increases the level of confidence in the technology, and allows the design to mature in response to operational experience.

‡ U.S. Patent No. 5,799,902.

Table 1. ***Scorpius*® Program Objectives**. Dollar values in FY01$.

Vehicle	LEO Payload (100 nmi)	SSO Payload (400 nmi)	Vehicle Price Object	Total Launch Cost	LEO Price/lb to Orbit	SSO Price/lb to Orbit
SR-S Suborbital	200 lb Suborbital		$120K	N/A	N/A	N/A
SR-M Suborbital	2,400 lb Suborbital		$334K	N/A	N/A	N/A
***Sprite* Mini-Lift**	700 lb	330 lb	$1.5M	$1.9M	$2,720	$5,760
***Antares* Intermediate-Lift**	6,500 lb	3,580 lb	$5.2M	$6.4M	$985	$1,790
***Exodus* Medium-Lift**	15,000 lb	8,820 lb	$9.9M	$11.9M	$790	$1,350

Secondly, the suborbitals themselves are commercial products with applications for scientific and microgravity missions as well as low-cost target vehicles. As they become used in this role, they generate initial income, continue to enhance confidence in the vehicle design, provide increasing amounts of test data under diverse conditions, and validate reliability projections (99% reliability requires hundreds of experiences to validate).

Similarly, the objective in launch to orbit begins with the small *Sprite* vehicle, and then progresses to the larger *Antares* and *Exodus* vehicles for which the market is significantly larger. *Sprite* itself will build substantially on the suborbital experience. Thus, the SR-XM suborbital, currently scheduled for launch in early 2001, is in effect the central core of the SR-2 suborbital and *Sprite* Mini-Lift vehicles. The pods of each of these vehicles will be based on the SR-XM but with Microcosm's larger 20,000-lb thrust engines. Therefore, the near-term suborbital experience will be directly applicable to the mini-lift to orbit vehicle, which in turn will establish both the technology and operational procedures to be used in the scaled up *Antares* and *Exodus* vehicles. Figure 1 shows the family of vehicles in *Scorpius*®.

Figure 1. ***Scorpius*® Family Starting with the Suborbitals Up Through a Heavy-Lift.**

The first of the vehicles, the SR-Sa vehicle was successfully launched from White Sands Missile Range in January 1999. Figure 2 shows the vehicle as launched with the 5,000 lb all ablative engine in a traditional 18-inch diameter vehicle. Figure 3 shows the SR-XM during testing in Mojave, California prior to shipment to WSMR for launch. The launch of this vehicle is scheduled for the first quarter of 2001.

Figure 2. ***Scorpius*® SR-S launch from White Sands Missile Range, NM, Jan. 27, 1999.** The vehicle was ready for launch within 8 hours of its arrival at the launch site.

Figure 3. The SR-XM Vehicle during final cold flow and hot fire test site.

These suborbital vehicles are used as technology test-bed flights to validate the subsystem designs and technologies. These same vehicles have application as suborbital products, as well as the incremental steps in creating the *Sprite* Mini-Lift Orbital Vehicles.

Basis of *Sprite* Mini-Lift Vehicle

Key aspects of the *Sprite* Vehicles are the state of the practice technologies, innovative design and design for manufacturing. The *Scorpius*® program is intended to use low-cost technology, simplified vehicle design and low-cost responsive operations. All of the primary subsystems, engines, tanks and avionics are new and the vehicles are from a "clean-sheet" design.

The simple pressure-fed engines use LOX and jet fuel propellants to power all stages of the *Scorpius*® vehicles. The technology for these engines is being developed to provide good performance at substantially reduced cost of traditional expendable engines. *Scorpius*® vehicles give up some per-formance to achieve the cost and reliability objectives of the program. Hot fire testing and production process demonstrations of the engine technology have confirmed the performance originally anticipated, and has continued to improve as the production process as evolved. Figure 4 shows a typical 5,000 lb (vac) engine as flown in the suborbitals.

Figure 4. Typical *Scorpius®* Hardware, 5 K lb. Engine and All composite Fuel Tank.

Advanced graphite-composite tanks, also as shown in Figure 4, is an all-composite fuel tank. This technology allows the use of pressure-fed systems for orbital performance without the cost and complexity of turbo-machinery. The enabling high-pressure graphite-composite cryogenic tank tech-nology is maturing and being flight demonstrated initially with smaller tanks and now at full-scale for the sub-orbital and first orbital vehicle. The processes being developed to build these tanks are optimized for very low recurring cost without the need for autoclave curing. Other technologies such as low-cost orbital-capable avionics, low-cost feed and pressurization systems, are also incorporated in the *Scorpius®* development. The development of the liquid upper stage to be used as the third stage on *Sprite* scales directly to the larger upper stage for the larger *Scorpius®* vehicles, as well as other vehicles including reusable launch vehicles.

The SR-Sa which was launched and the current development and fabrication of the SR-XM yield considerable insight into recurring cost and the ability to scale suborbital to orbital *Scorpius®* vehicles. With a low vehicle production cost the need for lower operations and range costs gains importance. The simplified operations and range interfaces being developed for *Sprite* to reduce operations complexity is being developed based on the launch operations of the sub-orbital vehicles. Further, the scalability of the *Scorpius®* launch system architecture and technologies to enable larger low-cost launchers is another design driver and is incorporated in the system engineering.

Though the next SR-XM vehicle launches will continue to be launched at WSMR, the very energetic SR-2 and *Sprite* vehicles will move to coastal ranges. We anticipate launching the initial DT&E flights from Space Systems International (California Spaceport at Vandenberg AFB), and launch operations processes are currently underway. The objective is to perform the initial DT&E flights in early of 2003.

The *Scorpius®* vehicle architecture employs similar propulsion "pods" for the first and second stages. The first stage uses six of these pods and the second uses a single pod. This means that seven sets of the same hardware are produced for each rocket. This increases quantity while reducing the size and number of part types used to build the vehicle.

The pod configuration of the *Scorpius®* architecture employs multiple, nearly identical pods for all but the final stage. The first two *Sprite* stages include 6 booster pods and a single sustainer pod. Instead of building one large booster and a different smaller sustainer stage, 7 nearly identical pods are built. This halves the number of unique part types and increases the total number of similar parts produced. Production repeatability and reliability are also improved by building enough parts to optimize the production line, without resorting to high cost "aerospace quality" approaches. Likewise reliability is improved since the parts are used multiple times, increasing by almost an order of magnitude their flight experience and associated confidence.

The *Scorpius*® family of vehicles already incorporates the use of GPS/INS for guidance, navigation, and control that is necessary as the launch ranges utilize GPS for range safety. Continued reductions in launch cost are anticipated with range modernization. Further, the *Scorpius*® family of vehicles incorporates a new Thrust Termination System (FTS) which allows for improved ground and flight safety operations.

In addition to the technical progress, substantial business progress has been made as well. The *Scorpius*® Space Launch Company, Inc. (SSLC) has been created with the objective of commercializing the *Scorpius*® low-cost launch products (both suborbital and orbital). SSLC will concentrate on the manufacturing and launch services aspects of low-cost launch. Microcosm will continue to concentrate on R&D and vehicle development.

The *Sprite* Mini-Lift Vehicle

For the *Scorpius*® program, the *Sprite* Mini-Lift vehicle, shown in Figure 5, will address the need for the very small and mini payload markets. *Sprite* has a total vehicle price-to-orbit objective of less than $1.9 million (FY01$) and a performance objective of 700-lb to LEO (due east launch) or 330-lb to a 400 nmi circular, polar orbit. The minimum available payload volume is expected to be comparable to the Scout vehicle large fairing, i.e., 38-inch diameter by 63.25 inches long.

Figure 5. *Scorpius*® *Sprite* Mini-lift Vehicle.

Sprite is designed to accommodate 95% wind levels for the major launch sites with zero visibility, zero ceiling, and moderate precipitation. Launch operations are designed to provide for the potential of launch within 8 to 24 hours after arrival of the payload at the launch site utilizing encapsulated payload-processing methods. The net effect of these design criteria is to provide effectively, "launch-on-demand," in which payloads can be orbited either as needed or as they become available. The intent is to provide a responsive launch service more characteristic of package delivery services than of the current launch environment.

Sprite vehicle height is 48 ft. with a circumferential pod diameter of less than 34 ft. Consequently, the payload area can be accessed as needed with standard commercial equipment. The vehicle itself is designed for complete ground level servicing. The *Sprite* pods and center core will be 42 inches in diameter (as are the SR-XM and SR-M), with an overall vehicle diameter of 11.2 ft., exclusive of the fins.

Figure 6 shows the performance of the *Sprite* Vehicle for different inclinations.

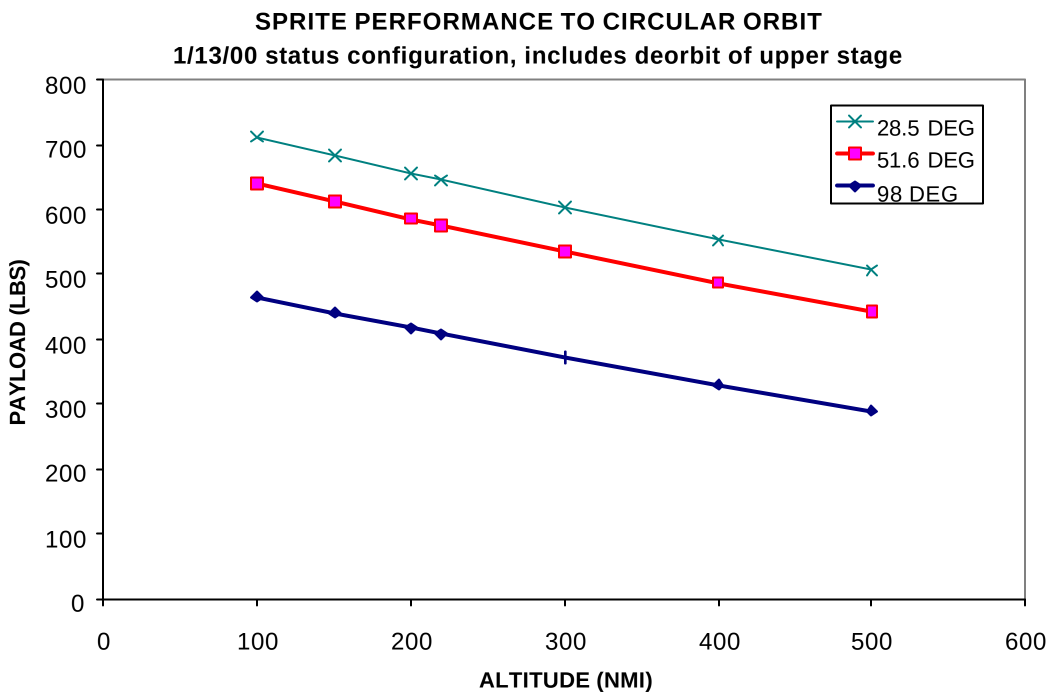

Figure 6. *Sprite* Payload Performance at Various Inclinations.

The vehicles have modest mass fraction, three stages, and robust margins. They are designed to be truly expendable low-cost transportation systems. Further, the *Scorpius*® families of vehicles are designed with scalability as a key design factor.

Cost and Schedule

The use of common pods allows the first and second stages to be manufactured in a production assembly line mode. Further, the significantly reduced parts count of the pressure-fed system allows for significant reduction in touch labor. The price of each vehicle is planned to decrease as production volumes increase.

Specifically, the *Sprite* Mini-Lift Vehicle is projected to have a first DT&E flight in the last quarter of 2003 and first production flight in the last quarter 2004. It has a planned payload capability of 700 lb to low-Earth orbit (due east launch) and added capability as the vehicle matures. For a number of missions easterly launches are desired, and with *Sprite's* low infrastructure cost and simplified operations, easterly range operations and additional polar sites are expected to be available in late 2004.

As *Sprite* transitions into full production, a recurring launch price, with payload delivered on orbit, is projected to be less than $2.5 million initially. Continued improvements in production and proven successful launches are expected to allow prices to be reduced to our objectives at below $1.9 million, and the overall vehicle capability to improve.

The *Scorpius*® propulsion systems utilize ablative engines and composite tanks to reduce mass and cost. The first all-composite LOX compatible tank was successfully flown on a small vehicle in August of 2000. Initial injector tests for the *Sprite* size 20 K lb. (vac) engines were completed in October 2000. As has always been a driving factor within the *Scorpius*® program, improved reliability and reduced cost are the primary objectives. These factors must include not only the vehicle specific items, but also the entire operational aspects.

System development has focused initially on smaller suborbital and the small orbital vehicles, though system engineering level design has been done for vehicles in the medium and heavy class.

Conclusion

There is a growing demand for dedicated launch of small satellites. However, an affordable launch system has not been available, thus this market segment has been slow to grow. The *Sprite* Mini-Lift Vehicle from the *Scorpius*® low-cost launch vehicle program has been designed from the outset to achieve this by manufacturability, ease of operation, and low infrastructure cost. There remains a great deal of engineering development to be done. Nonetheless, based on the *Scorpius*® experience to date, including component development, testing, and the launch of the SR-Sa suborbital vehicle, it has been shown that our cost and operability goals, though challenging, are achievable.

Acknowledgments

It takes a substantial team effort to put together a successful rocket program, ranging from funding and administrative efforts, through innovative design, development, fabrication, integration, and test to the launch campaign itself. A great many people have worked hard to make *Scorpius*® come alive. We could not have progressed this far without their assistance, perseverance, and continuing effort to make the program succeed and drive down cost.

We would like to particularly acknowledge the substantial technical contributions of the Government Program Manager, Ken Hampsten, at the Air Force Research Laboratory Space Vehicle Directorate and the entire staff at the White Sands Missile Range.

Extensive engine testing has been successfully performed at the Rocket Propulsion Test Site at the Energetic Materials Research Test Center (EMRTC) of New Mexico Tech. Tedi Ohanian of the Schafer Corporation has played a key role in development of the engine injectors. Further we would like to acknowledge the substantial effort of Dave Crisalli of Polaris, and the entire Microcosm development team.

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