8th Responsive Space Conference
RS8-2010-5005

Assessment of SmallSat Utility and the Need for Dedicated, Low-Cost, Responsive Small Satellite Launch

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

AIAA-RS8-2010-5005

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ABSTRACT

SmallSats appear to have the potential of significantly decreasing the cost and increasing responsiveness of both military and civil space missions. However, there are 3 major barriers facing the large-scale development and deployment of large numbers of SmallSats:

- There is a very strong need to contain, and most likely reduce, space spending over the next several years, and the military is largely focused on traditional (large and expensive) programs of record.
- There is the perception among some members of the space community that the case for SmallSat utility and the corresponding need for a dedicated, low-cost responsive SmallSat launcher have not been proven.
- There is no current dedicated, responsive (1–2 days), low-cost ($1 million to $7 million) launcher available.

Consequently, Microcosm has undertaken an internally funded study to evaluate, enumerate, and quantify where possible the principal arguments both for and against the development and rapid deployment of SmallSats, SmallSat constellations, and the associated SmallSat launch capability. The overall conclusions are as follows:

Adding SmallSats and one or more dedicated, small, responsive, low-cost launch systems can be used to:

- Create the potential to reduce overall space system costs in the mid-term by billions of dollars
- Reduce risk and fragility and increase overall mission assurance
- Enable missions that are not realistically affordable with traditional systems
- Provide responsive augmentation and replenishment for existing systems
- Make newer, better technology available to the warfighter and the space community in much shorter times
- Be more responsive to world events

A low-cost, responsive small launcher is a mission enabling capability that can complement traditional launch systems, provide greater near-term mission assurance, reduce cost, and significantly improve the utility of space to the modern warfighter and other users of space. The ability to respond to changing world events, the need to avoid creating more orbital debris, and the availability of much better orbits (i.e., better and more frequent coverage than from traditional orbits), require that SmallSats be placed responsively into non-traditional orbit regimes, which, in turn, creates the need for a dedicated launch system for operational SmallSats. While there are civil events that can use responsive missions, it is the military tactical missions that will be primary driver.

SmallSats have clear physical limitations and should not be regarded as a replacement for larger, traditional systems. Nonetheless, the current approach of using almost entirely traditional, large, very expensive spacecraft has led to a space infrastructure that is both too expensive and too fragile. Analogous to the current situation in space, the Air Force could not be successful using only a single type of aircraft, nor could the Navy be successful with only a single type of ship. To create a sustainable, robust, less fragile and more economical Space Force requires a balance of traditional large satellites and smaller, more responsive, much lower cost satellites and launch systems.

KEYWORDS: SmallSat, Small Satellite Launch Vehicle, Mission Utility, Responsive Space

CONTENTS

1. Background

2. Arguments in Favor of SmallSats and a Dedicated, Low-Cost Responsive Small Satellite Launch Capability

2.1 Summary

2.2 High-Value, Low-Cost SmallSat Military Missions

2.3 Orbits

2.4 Cost

2.5 Risk Reduction and Mission Assurance

2.6 Space Debris

2.7 Economically Sustainable Business Model

3. Arguments Against SmallSats and a Dedicated, Low-Cost Small Satellite Launcher

3.1 Summary

3.2 Cost

3.3 Risk

3.4 Utility

3.5 Orbital Debris

3.6 No Validated Need for Responsive Launch

3.7 Magnitude of Cost Savings

4. Limitations of SmallSat Systems

5. Conclusions

5.1 SmallSats vs. LargeSats

5.2 Waiting for RLV

5.3 Conclusions

1. BACKGROUND

SmallSats and CubeSats have made a great deal of technical progress over the last decade and appear to have substantial potential to reduce space mission cost and increase responsiveness. Nonetheless, some within the space community have argued that low-cost SmallSats have unacceptably high risk and that the case for SmallSat utility has not been proven. A similar argument has been made that the need for dedicated, low-cost, responsive small satellite launch has not been proven, **particularly given the need to contain, and most likely reduce, military and civil space spending over the next several years.** Consequently, Microcosm undertook an internally funded study to evaluate, enumerate, and quantify where possible the principal arguments both for and against the development and rapid deployment of SmallSats, SmallSat constellations, and the associated SmallSat launch capability.

2. ARGUMENTS IN FAVOR OF SMALLSATS AND A DEDICATED, LOW-COST, RESPONSIVE SMALL SATELLITE LAUNCH CAPABILITY

2.1 Summary

The principal arguments favoring rapid development and deployment of SmallSats and an associated launch capability are:

1. There are multiple high value, low-cost SmallSat military missions, such as:
   - High value imaging (ORS Sat-1, defined as an "Urgent Need")
   - Hyperspectral Imaging (Artemis payload on TacSat-3 capable of distinguishing otherwise invisible features on the ground)
   - Persistent communications (needed by the Army)
   - Wind lidar (highest utility among >100 missions evaluated in a government study)
2. A Futron study for AFRL identified 13 near-term SmallSat Military Missions with the potential for 30 to 70 satellites launched per year. Example: The DoD SERB list has 62 payloads, of which 57 are < 200 kg and 48 are < 100 kg.
3. SmallSats can enable the potential for moderate-term cost savings of billions of dollars
   - Cost of downstream development funded by near-term savings
   - Rapid turn-around test and experiment missions can be used to significantly drive down the cost of expensive larger missions
4. SmallSats can provide lower risk and greater mission assurance than traditional missions due to the ability to rapidly replenish failed assets
5. SmallSats can be launched into orbits not realistically available to traditional missions that provide better coverage and better performance
6. SmallSats can be launched in response to critical world events to provide supplementary information in times of military or civil emergencies
7. Many high utility SmallSat missions are flown every year (more than 50 in the last 4 years) — primarily on Chinese, Russian, and Indian launchers

Each of the above (other than the last) requires dedicated, low-cost, responsive SmallSat launch, a capability that is either in use or under development by our adversaries. For example, the Soviets launched 29 payloads in 69 days in direct response to the 2.5-month Falklands War in 1982. [Cooper, 1992] China is developing this capability. [Office of the Secretary of Defense, 2007]

Adding SmallSats and one or more dedicated, small, responsive, low-cost launch systems can be used to:

- Create the potential to reduce overall space system costs in the mid-term by billions of dollars, in part by early technical validation of newer, better, and lower cost technologies
- Reduce risk and fragility and increase overall mission assurance
- Enable missions that are not realistically affordable with traditional systems
- Provide responsive augmentation and replenishment for existing systems
- Make newer, better technology available to the warfighter in much shorter times
- Be more responsive to world events

2.2 High-Value, Low-Cost SmallSat Military and Civil Missions

SmallSat missions with high military and civil utility come in 3 broad categories:

- Individual specific missions that have already flown or are in various stages of design
- CubeSats, which are nanosats made up of one or more cubes 10 cm on a side
- General assessments of SmallSat missions that are of interest to specific customers and constitute the potential SmallSat market

For all SmallSat missions, getting a ride to space is the most fundamental difficulty. Experimental and test missions can be done via rideshare or as a secondary payload with a larger primary satellite. On the other hand, operational missions, which should represent the largest number of long-term missions, require a dedicated, on-demand launch system in order to be placed in specific orbits at specific times. Since this capability is not yet available, these represent potential future missions that may or may not come about, depending on the development of an appropriate launcher.

2.2.1 Specific SmallSat Missions

ORSSat-1

ORSSat-1 is the first of the Operationally Responsive Space operational satellites intended for launch in March, 2010. ORSSat-1 was defined as an urgent ISR need by CENTCOM. The spacecraft has a Goodrich payload based on the SYERS payload originally developed for the U2 high-altitude aircraft with a mass of less than 150 kg. [Cox, et al., 2005, 2006] It uses a responsive spacecraft modular bus built by ATK/Swales. [Miller et al., 2009]

ORS Sat-1 (image from Goodrich)

TacSat-3 Hyperspectral Imager

The TacSat-3 SmallSat mission is carrying the Artemis hyperspectral imager payload built by Raytheon. The prototype TacSat-3 mission costs approximately $90 million. However, the total mission cost is expected to be less than $25 million in moderate quantity with a significantly lower cost SmallSat launcher. There is general agreement that the hyperspectral imager has a high-level military utility due to its ability to distinguish a large variety of materials and conditions. [Davis, 2006]

Low-Cost Wind Lidar

A low-cost wind lidar mission was ranked first in importance of more than 100 responsive missions in a 2006 military study of needed responsive missions. The wind lidar has a high level of utility for all the military services. It enhances precision targeting, UAV operations, precision airdrops, and aircraft fuel efficiency. A high altitude NASA wind lidar has an estimated cost of $600 million. However lidar missions are very sensitive to altitude and a low altitude mission greatly reduces cost. A low-altitude wind lidar mission has been defined with an available Raytheon lidar payload and with a total spacecraft mass of 225 kg, 250 W orbit average power, and less than $20 million recurring cost (including low-cost launch). [Wertz et al., 2004a; Emmitt, 2010]

NanoEye

NanoEye is a SmallSat mission being developed by Microcosm for the Army SMDC under a Phase II SBIR just getting underway. NanoEye makes use of an existing ITT 10 inch, diffraction limited, space qualified telescope which weighs 2.95 kg. The total spacecraft has a dry mass of 15 kg and can provide sub-meter resolution at nadir for less than $5 million/ mission, again assuming a low-cost, responsive launch capability.

Fig. 1. Simulated NanoEye image from 175 km.

The NanoEye spacecraft has a total available delta V of approximately 2 km/sec which provides exceptional agility and the ability to raise and lower the orbit to provide high resolution when needed and longer life when the high resolution is not needed. The total spacecraft recurring cost (payload plus bus) is less than $2 million. 3 to 4 satellites can provide 24/7 coverage every 90 minutes for any predefined location on Earth. [Van Allen, 2010]

Supplemental Communications for Less Than $20 Million/Mission

A SmallSat communications constellation has been defined that can provide continuous communications within a theater and also communications back to CONUS with a single intersatellite link. The constellation consists of 3 satellites (6 for full redundancy) in an equatorial circular orbit at an altitude between 15,000 and 20,000 km. Payloads for the system could be provided by a number of contractors. Cost estimates are consistent with current SmallSat communications systems such as the new generation ORBCOMM constellation.

Low-Cost Civil Missions

Nearly all of the military missions defined above have an equivalent non-military counterpart for either science or civil needs. Thus, NanoEye could provide responsive low-cost damage assessment of hurricane, earthquakes, tsunamis or other civil disasters and Supplemental Communications could further improve the capacity to save lives in times of an emergency. NanoEye could also be used as a low-cost planetary explorer, and Artemis payload could provide a wealth of environmental data. These dual use applications can further drive down the cost by allowing multiple copies of a single spacecraft to be built.

It is important to note that much depends on how duel applications are implemented. Traditionally, in the large spacecraft world, using a single spacecraft for multiple applications has dramatically driven up cost and increased schedule, as with NPOESS. There are two ways that this can be avoided in the small satellite world. If they are sufficiently low cost, there is a tendency to use them as is, rather than embark on an expensive process of having a single spacecraft meet multiple, typically contradictory, requirements. The other option is to make minor modifications to an existing design to better meet the needs of different mission, such as using filters to change the spectral band for NanoEye.

2.2.2 CubeSats

CubeSats were first introduced in 1999 as low-cost educational satellites by Jordi Puig-Sauri at CalPoly and Bob Twiggs at Stanford. [Puig-Sauri et al., 2001; Toorian et al., 2005] A "1U" CubeSat is 10 cm × 10 cm × 10 cm and a "3U" CubeSat is 10 cm × 10 cm × 30 cm. These very small satellites are now being used for multiple test and experiment missions, largely because the cost is typically a few $100K/mission. DoD organizations with current CubeSats programs include:

- NRO
- NPS
- Aerospace Corp.
- Army SMDC
- AF SMC/XR
- AFRL

The power of CubeSats to attract substantial interest is illustrated by the example of the Orbiting Carbon Observatory (OCO) mission and CanX-2. On February 24, 2009 the $273 million OCO mission failed when the shroud of the Taurus launch vehicle failed to separate. The *Ottawa Citizen*, later expanded on in the *Montréal Gazette*, reported that "a Canadian microsatellite that does the same job is chugging along happily in orbit — at 1/1000 the cost." This was an exaggeration, but not entirely incorrect either. CanX-2 is a 3U CubeSat built at a total cost of about $1 million (4/1000 of the OCO cost), including $150,000 for launch on an Indian launcher. CanX-2 has a two-year design life, comparable to OCO. The CanX-2 satellite made measurements similar to that of OCO, although certainly not as sophisticated, nor as precise. Nonetheless, it clearly shows the appeal of launching one or possibly many CubeSats to tackle at least some missions. A larger follow-on to CanX-2, called NTS, had a somewhat larger budget and was built in months as a commercial ship tracking mission for COM DEV Ltd. of Canada. [Pranajaya et al., 2009]

The NRO funded 12 CubeSats buses under the Colony I Program and will fund up to 50 more under Colony II. In this case, the NRO is strongly committed to launching only SmallSats that fit within the CubeSat constraints. [Armstrong, 2009]

At a total mission cost in the range of $0.5 to $1 million, CubeSats have the advantage of being extremely inexpensive. Unfortunately they may not be able to achieve many of the near-term, low-cost missions that have high military or civil utility and that can ultimately drive down near-term and moderate-term cost. While CubeSats are low-cost, and can do some missions well, they aren't large enough to do many important, near-term military or civil missions for which larger SmallSats are applicable.

2.2.3 Analysis of Future SmallSat Missions

Futron SmallSat Study

In 2006 Futron Corporation undertook an AFRL-funded study of the market potential for SmallSats and SmallSat constellations. [Foust et al., 2008] The study definition of a "SmallSat" mission was:

- Less than 100 to 200 kg total mass with a payload mass fraction greater than 50%
- 200 W orbit average power (500 W peak)
- 1 to 2 year mission life
- Total spacecraft cost of $5 million to $10 million with low-cost launch options available

The Futron study identified over 30 markets in 4 principal areas:

- Military (the largest market)
- Civil/commercial remote sensing
- Civil/commercial communications
- Other

The 13 military markets identified in the study are:

- Intelligence, surveillance, reconnaissance (ISR)
- Science and technology
- Blue Force tracking
- Meteorology
- Ocean condition monitoring
- Position, navigation, and timing
- Space surveillance and situational awareness
- System augmentation or gap fillers
- Communications
- Missile defense and early warning
- Orbit servicing
- Precision targeting
- Space asset defense

Of the military markets, ISR and science and technology were identified as the largest.

In total, the Futron study defined an overall addressable market of 39 to 76 satellites/year. At an average total cost of $7.5 million per spacecraft, this represents an overall market of $290 million to $570 million per year. Raising the cost to $8 million/ spacecraft, to account for inflation since the time of the study, provides an estimated current market value (payload, spacecraft, and launch, excluding operations) of $312 million to $608 million per year. It is clear from the Futron study that, while specific numbers and missions are uncertain, **the SmallSat market is very robust and could begin to reinvigorate the space business enterprise, if there is dedicated, responsive launch at a cost commensurate with the spacecraft cost.**

Analysis of the SERB List

The current DoD Space Experiment Review Board (SERB) list contains 62 approved and validated payloads or spacecraft needing a ride to orbit. 59 of these provide sufficient information to estimate the Equivalent Mass to the Reference Orbit (EMRO). Payloads on the SERB list were first converted to an estimated spacecraft mass, then the spacecraft mass was converted to an EMRO by multiplying by the Orbit Cost Function* (OCF). Complete spacecraft on the SERB list were simply multiplied by the OCF.

* For a detailed discussion of the Orbit Cost Function, see Wertz [2009], Sec. 12.3.2. The OCF used for this analysis is based on the performance of the various Scorpius® LVs defined above.

The overall mass distribution is shown below.

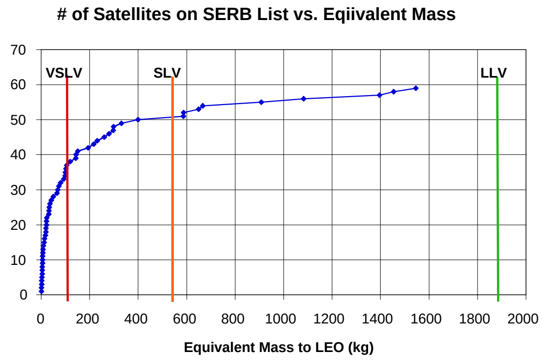

Fig. 2. Satellites in the SERB list sorted by Equivalent Mass to LEO. (Data compiled by Nicola Sarzi-Amade´, Microcosm.)

The results are as follows:

- 36 of the entries could be launched by a Very Small Launch Vehicle (VSLV = 100 kg to a due east orbit)
- 14 additional entries could be launched by a Small Launch Vehicle (SLV = 450 kg to a due east orbit).
- 9 entries are too large (or in too energetic an orbit) to use a small LV and would require a larger Light Launch Vehicle. (LLV = 1800 kg to a due east orbit)

Some of the SERB missions could be launched as piggyback payloads with another mission. Most, however, have specific orbit requirements that would require a dedicated launch.

The general conclusion of this assessment is twofold:

1. There is a minimum of 36 payloads for a VSLV and an additional 14 for a SLV launcher that could be available for near-term manifesting. This represents only DoD experimental missions with no operational military or non-DoD missions included.

2. As a first estimate, approximately 72% of SmallSat missions (i.e., those up to 1000 lbs EMRO) have an EMRO of less than 220 lb (100 kg) and can be launched by a VSLV. 28% require the SLV. For every 100 SmallSat missions there are on the order of 18 larger missions that would require an LLV.

2.3 Orbits

Of course, any satellite can be put into essentially any orbit, but realistically most traditional military satellites will go into traditional orbits intended for global coverage and long mission life, such as high LEO Sun synchronous orbits for observation missions. SmallSats can, and likely will, be put into orbits intended to optimize coverage for specific missions and with potentially shorter lifetimes. Operational SmallSat missions shouldn't be in traditional LEO orbits. [Wertz, 2005]

2.3.1 Why SmallSat Orbits Are Different

The principal problem with orbit design for operational SmallSat missions is that the fundamental mission objectives are different than those which drive traditional mission orbit design. Specifically, traditional space missions are very expensive and have a long on-orbit lifetime. Therefore, the orbits are designed for worldwide coverage because it is not known at the time of launch what area or areas of the world may need coverage, and the area needing coverage is likely to change many times over the life of the mission. Consequently, traditional mission orbit objectives are:

- Global coverage
- Long life
- Use whatever launch vehicle it takes to get there

In contrast, operational SmallSat mission orbit objectives are significantly different:

- Coverage of a specific region, event, or set of events — i.e., localized in both time and space
- Willing to give up long life to get good performance at low cost
- Want low-cost launch commensurate with the satellite cost
- Want to minimize creation and accumulation of orbital debris (discussed in Sec. 2.5 below)

Most operational SmallSat mission orbits fall into one of 2 broad categories. **For SmallSat observation missions, a low altitude, prograde *Repeat Coverage Orbit* [Wertz, 2005] provides better coverage and better resolution with lower collision probability and very rapid debris decay such that orbital debris cannot accumulate. For SmallSat communications missions, circular orbits at 15,000 to 20,000 km altitude and 0 or 90° inclination provides both continuous coverage and one-hop communications with CONUS. These orbits provide better coverage, lower vulnerability to attack, and fewer collision opportunities than highly elliptical orbits (HEOs), which, in the past, have often been considered the best choice for SmallSat communications systems [Wertz, 2007].**

2.3.2 Repeat Coverage Orbits for Observations

For frequent revisit surveillance, a *Repeat Coverage Orbit* (RCO) maximizes coverage for a single region, event, or latitude band. As shown in the figure below, the inclination for the RCO is chosen to be slightly less than the latitude of interest plus half the satellite swath width. This results in the orbit being "tuned" such that a single satellite revisits a predefined location or region for 4 to 6 successive orbits, i.e., every 90 minutes for 6 to 9 hours. The local time of initial coverage is set by the launch time. Precession of the orbit then moves the coverage 15 to 30 minutes earlier each day, depending on the latitude. The use of autonomous onboard orbit control can make the revisit time predictable and controllable, but it can also be changed as needed to confuse the enemy. [Wertz, 2010] With this coverage pattern, 3 or 4 satellites provide coverage every 90 minutes, 24 hours per day, indefinitely. Adding intermediate satellites can provide coverage every 45 minutes or more often if desired. In addition, these moderate inclination prograde orbits reduce the launch energy required such that an RCO orbit typically can result in 30% more mass to orbit than to a traditional Sun synchronous orbit for most launch vehicles. The RCO sacrifices global coverage to focus resources on a particular area of interest.

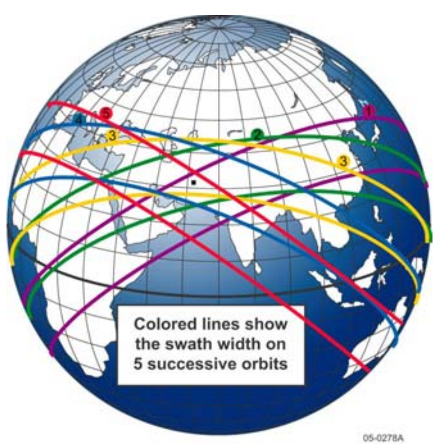

Fig. 3. Repeat Coverage Orbit provides coverage of a particular region or latitude band on 4 to 6 successive orbits.

The chart below shows the coverage vs. latitude for a traditional Sun synchronous orbit (SSO) and the SmallSat oriented RCO. If only daytime passes are included, the SSO coverage would be as shown in the green dashed line, i.e. about one viewing opportunity every other day for most latitudes below about 50 deg. In contrast the RCO provides 4 to 5 orbits of coverage daily over mid-latitudes and much

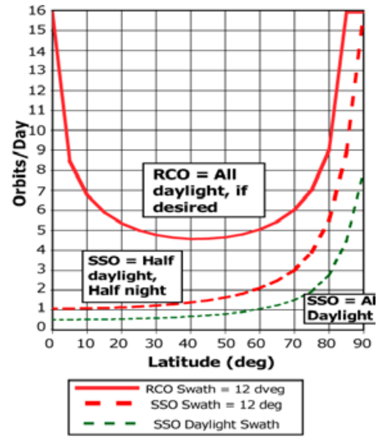

Fig. 4. Single satellite orbits/day of coverage vs. latitude.

higher coverage toward either the equator or the pole. The disadvantage of the RCO is that it requires selecting the orbit to provide coverage of the specific latitude of interest. **The much better mid and low latitude coverage for the RCO comes at the expense of global coverage by adjusting the orbit to the latitude of interest.** (For a more detailed discussion of the RCO, see Wertz [2005].)

2.3.3 Resolution vs. Altitude

Because traditional observation satellites are very expensive, they are normally placed into high-altitude orbits typically in the range of 700 to 900 km in order to provide both a wide swath and long mission life. In contrast, for SmallSat missions we would like to fly in the 200 to 400 km range with sufficient delta V to allow a 1 to 3 year life and substantial maneuvering. This approach provides comparable resolution with a much smaller tele-scope, as shown in the figure below. [Wertz, 2008a]

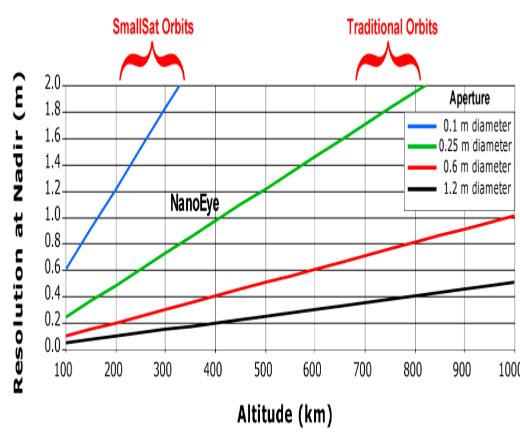

Fig. 5. Resolution vs. Altitude for low altitude SmallSat orbits and higher altitude orbits used for more traditional systems.

Hubble space telescope (2.4 m aperture) initially cost $2.5 billion in FY09$ and, if looking at the Earth, would provide 0.22 m resolution at 800 km altitude. **Essentially the same resolution can be achieved with a 1 m instrument at 300 km or an 0.5 m instrument at 150 to 200 km, but at a cost of millions, rather than billions of dollars per mission.**

Low altitude works very well for systems intended to provide focused coverage over a defined region, rather than needing to provide coverage of the entire world. This ability is substantially enhanced by using a *reduced drag spacecraft* — an approach defined by Microcosm that reduces satellite drag by a factor of 5 to 10 and, therefore, allows spacecraft to fly for extended periods of time in the 150 to 200 km regime. [Wertz, et. al, 2006] In addition *agile spacecraft,* with substantial on-board delta V (studied extensively by Col. Robert Newberry, then at Air Force SMC), can adjust the altitude and coverage parameters as needed to optimize resolution, coverage, lifetime, and maneuvering to confuse the enemy. This high level of agility is much more easily achieved on a lightweight SmallSat than with a more traditional very heavy spacecraft. NanoEye, for example, is intended to provide approximately 2 km/sec of delta V, a much higher level of agility than would be possible with a traditional large and heavy system. **Low altitude, focused coverage can provide high-resolution at very low cost.**

2.4 Cost

Although launch is not the largest cost element for most space missions, dedicated, low-cost, responsive small launch can save millions of dollars in the near term and lead to large savings (i.e., billions of dollars) in the moderate term. In this section we will look at launch as the driver of mission cost, Dr. Pete Rustan's vision for the future of space, and a baseline estimate of the cost savings available due to low-cost launch.

2.4.1 Launch as a Driver of Mission Cost

Launch is typically not the most expensive element for a large space mission. (This is not true for many SmallSat missions, that are typically built for $1 million–$10 million; and there is no dedicated launcher available for less than $10 million.) This has led some observers to conclude that reducing launch cost is relatively unimportant in terms of reducing overall mission cost.

Nonetheless, launch drives the mission cost. It doesn't make sense to launch a $5 million satellite on a $25 million launch vehicle. So long as a dedicated launch costs $25 million or more, the mission (payload, spacecraft bus, launch, and initial operations) will typically cost $75 million to $100 million or more, because it doesn't make economic sense for them to be much cheaper.

Similarly, mission responsiveness is driven by both the cost and responsiveness of launch systems. The Soviets/Russians have had systems in inventory and launch-on-demand (within hours) for over 30 years. As stated previously, the Soviets launched 29 payloads in 69 days in direct response to the 1982 Falklands War that was sufficiently far south that there was relatively little coverage from traditional observation satellites. [Cooper, 1992] But for most US missions, $50 million to $100 million satellites are too expensive to build to inventory, and this is typically not done.

Weather, particularly winds aloft, is among the most common causes of launch delays. This further increases cost by requiring a "standing army" of launch operations personnel. Again, the Soviets/ Russians have had all weather launch capability for decades, such that this is not a major concern for them.

Satellites with high utility costing $5 million to $10 million can have a strong, positive, near-term impact on the ability of space to support the modern war fighter. But **operational** systems in this price range cannot come about unless there is a dedicated, responsive launch at comparable cost. While launch itself is not the highest cost element, the high cost and long timelines of current launch systems prevent us from creating low-cost, truly responsive missions.

The problem of high cost is made increasingly worse by the ***Space Spiral*** shown below of ever-increasing costs and fewer missions. Higher costs lead to longer schedules and fewer missions, which leads to a demand for higher reliability, which, in turn, continues to increase the cost, stretch out the timeline, and lead to even fewer missions.

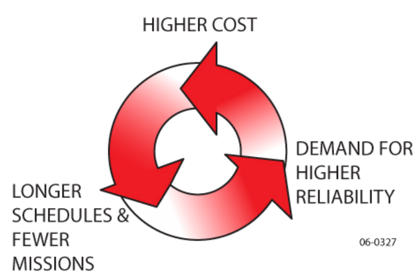

Fig. 6. The Space Spiral of increasing cost and fewer missions with longer schedules.

If we can truly reverse the Space Spiral, the cost reduction potential is very large. Therefore, the role of low-cost SmallSats is not just to do useful work at reduced cost, but also to help us turn around this spiral and, in turn, reduce the cost of larger missions as well. Low-cost SmallSats can be used to validate the technologies, methods, and processes that will help reduce large satellite cost. In addition, the ability to rapidly replace at least some of the essential capability of large satellites can reduce the demand for higher reliability and begin the process of reversing the space spiral. (It is important to note that the reliability of SmallSats has traditionally been comparable to or higher than that of larger satellites, as one might expect from the simpler designs, lower parts counts, and larger margins. As discussed in Sec. 2.5, SmallSats can actually lower the risk and increase mission assurance relative to traditional approaches. It is more the perception of risk that causes the problem.)

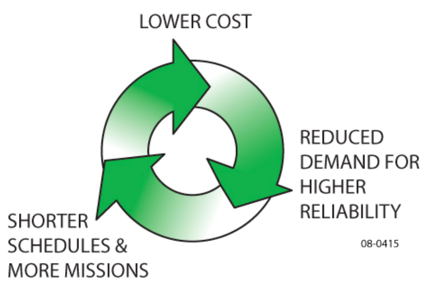

Fig. 7. SmallSats and a commensurate small, responsive, low-cost launch capability can begin the process of reversing the Space Spiral.

The problem of high cost is significantly exacerbated by the current economic downturn and the need to reduce government spending in essentially all areas. The traditional response to reduced budgets is to protect as much as possible the large, remarkably expensive programs, and kill off most or all small, innovative, R&D programs or alternative approaches on the grounds that they are simply unaffordable. This is done for very good reasons — i.e., because the expensive programs were very hard to get started in the first place and are critically important to the warfighter and the intelligence community. Nonetheless, this is the technological equivalent of eating our own seed corn. If we do not innovate, we will cease to be a world leader in space and will have lost one of our major technological advantages over our adversaries.

It is very difficult to reverse the Space Spiral, but it is possible. The key is in first reducing launch costs because they are the major driver of mission cost, particularly for small systems. If SmallSat launch costs are reduced, it then makes sense to build and fly lower cost spacecraft and a larger number of lower-cost missions with newer technologies, both to achieve critical mission objectives and to test lower-cost or more capable technologies for larger missions. There is a real and immediate need to reduce costs. The technology is in place to do this within the SmallSat community. There is, of course, some risk associated with any new program. However, the cost and schedule risk associated with SmallSat programs is relatively very small simply because the cost and time associated with the programs is small. On the other hand, the risk of continuing with business as usual is very large, as will be discussed in Sec. 2.5.

2.4.2 Dr. Pete Rustan's Vision for the Future of Space

At the third Responsive Space Conference in April 2005, Dr. Pete Rustan, then the head of Advanced Systems and Technology for the NRO, provided his vision for the future of responsive space [Rustan, 2005]. Rustan argued that the objective of responsive space should not be just to reduce schedule and cost for niche tactical missions, but to change the present mindset about the way the government and space industry build satellites. We need to apply the best technologies, streamlined management practices, and a new culture to the entire space industry. In his view, this should include DoD, the intelligence community, NASA, and the civil space communities and should apply to satellites (both the payload and bus), launchers, ground systems, and the concept of operations. His goal was to use advanced technology with streamlined processes to affect the entire industry.

Fig. 8. Dr. Pete Rustan's vision for the future of Responsive Space. [Rustan, 2005]

Rustan saw this as a set of needed strategy changes:

- From requirements driven to technology driven
- From risk-averse to risk management

- From process driven management practices to streamlined management processes
- From layers of review to skunk works operation
- From budget constraints to budget flexibility

In summary, Rustan stated that the present emphasis on mission assurance is essential, but is having a negative impact on the industry. This emphasis is being misconstrued to increase cost and schedule instead of using streamlined procedures and risk management. In his view the advocates of responsive space should expand their view to assist in the transformation of the space industry. If we do not transform we will cease to be a leader as a spacefaring nation.

2.4.3 Using Low-Cost, Small Launchers to Lower Mission Cost and Improve Mission Assurance

At the present time, the United States is faced with a classic "chicken and egg" problem. Our current system is both too expensive and too fragile, but is critical to warfighter support and intelligence gathering and, therefore, cannot be changed — because the system is fragile and **any** risk to an operational system is too much.

The only realistic solution is to attack the problem promptly, but indirectly. We need to start with low-cost, rapid-to-deploy small space systems. This would include spacecraft that are either already developed or that can be developed in the very near-term at low cost, such as Artemis, supplemental communications, ORSSat-1, or NanoEye. While test missions are possible in the current launch environment, operational systems for these satellites require low-cost, dedicated, responsive launch, which is not yet underway.

The second step is to use near-term cost savings to fund growth in multiple areas. Scalable small launchers serve as subscale demonstrators for creating larger launchers that can save far more. Relevant small military missions can serve as less-capable backups to traditional systems and add capability, such as hyperspectral imagery, not yet available in older traditional systems. This quickly reduces the highest system-level fragility in terms of data available to the warfighter. It also demonstrates the practical utility of new types of data and guides future growth. Overall this process provides a responsive system for introducing new technology as it becomes available in the short term. Low-cost, responsive science and technology missions can test on-orbit the technologies to be introduced on larger missions more quickly, at lower cost, and with greater assurance than traditional testing. This continues the process of "unwinding the Space Spiral" and also allows us to take maximum advantage of our technology superiority over the current enemy.

By implementing Rustan's vision to both complement and reduce the cost of more traditional systems, we can reduce mission cost and fragility and increase robustness, mission assurance, and data available to the warfighter.

Microcosm has created an economic model of the potential cost savings of low-cost small launch based on **current** US launch rates.* [Microcosm, 2008]

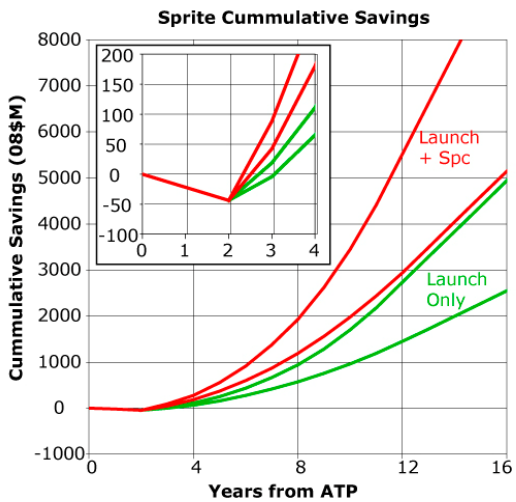

Fig. 9. Projected Cumulative Savings from the development of low-cost Very Small and Small launch systems, i.e., up to 1000 lbs to LEO. [Microcosm, 2008]

The green curves represent savings just in launch costs. The red curve represents savings in launch cost plus spacecraft cost on the assumption that reducing the cost of launch allows lower-cost technologies to be used in the spacecraft. (This is comparable to what has allowed CubeSats to be much lower cost than traditional spacecraft.) The curves do not include any savings from shifting more operational work to smaller systems, although this would certainly occur if smaller launch becomes available at much lower cost. The savings in the plot above are based on implementing only Very Small Launch Vehicles (VSLV) and Small Launch Vehicles (SLV),

* For a discussion of reusable vs. expendable launch costs, see Wertz [2000]. For a discussion of the cost impact of launch-on-demand, see Wertz [2004b].

i.e. up to 1000 pounds to low Earth orbit. The plot below shows the projected cost savings if lower-cost launch systems are developed through medium launch, i.e., up to 20,000 pounds to low Earth orbit. The projected savings can, of course, be applied to budget reduction or doing more for the warfighter or both.

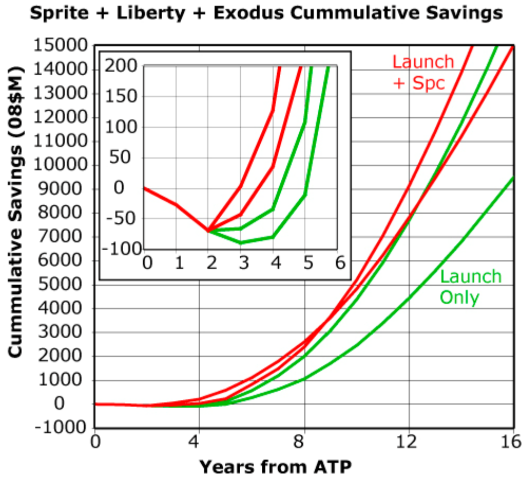

Fig. 10. Projected Cumulative Savings from the development of low-cost launch systems up to medium lift, i.e., 20,000 lbs to LEO. [Microcosm, 2008]

2.5 Risk Reduction and Mission Assurance

Making appropriate use of SmallSats can both greatly reduce cost, as discussed above, **and** provide lower risk with better overall mission assurance.

2.5.1 Achieving 100% Mission Assurance

Traditional "mission assurance" focuses on the spacecraft and launch system to ensure that they will always work, but the real mission assurance is whether the data is available when the user needs it, and having a high quality spacecraft is not sufficient. Specifically, potential system failures from multiple sources can be reduced, but **not** eliminated:

- Launch failures, such as OCO or Columbia
- System failures, such as USA 193
- Collisions, such as Iridium 33/Cosmos 2251, which left thousands of **untrackable** debris particles that significantly increase this risk in the future
- Enemy attack, such as the Chinese ASAT threat

In addition, data can become unavailable (equivalent to a system failure), due to schedule overruns or high cost:

- Extended delays, such as NPOESS
- Program cancellation due to cost, such as T-Sat

The solution to this is to provide systems that are sufficiently low-cost and responsive to allow options in the event that something does go wrong. **There is no failure-free space system — reduced risk and high mission assurance come from system robustness — i.e., having sufficient back-ups and options available to ensure mission success even when failures do occur.**

An analogy is having a group of allied forces dependent for their security on preventing an enemy attack across a bridge over a gorge. One airplane is sufficient to knock out the bridge, but, unless it's impossible to do otherwise, we would never send just one airplane. It isn't that we don't have faith in modern aircraft or that they aren't built with high reliability. It's that in the real world, things go wrong. If we need that bridge to be taken out, we send 3 aircraft. The same is true of space resources. We need options and back-up to have a genuinely robust system.

Nonetheless, culture is very hard to change, and the current space culture wants to guarantee that each individual spacecraft will succeed, rather than allow options or back-ups to current, very expensive space assets. In the terminology of Joe Rouge, director of the NSSO, this has resulted in a system that is both too expensive and inherently fragile.

2.5.2 Cost vs. Reliability

There is often a presumption that what you "buy" with a high cost space systems is a greater level of reliability, but this may or may not be true. There is no quantitative data available on the reliability of low-cost vs. high-cost spacecraft. However, anecdotal evidence suggests that small, low-cost spacecraft may be equally or more reliable than larger, more complex spacecraft.

For SmallSats, we would expect a decrease in reliability corresponding to lower quality parts, fewer, lower-cost procedures, lack of redundancy, and more willingness to accept risk. On the other hand, we would expect an increase in reliability for SmallSats vs. traditional larger satellites due to fewer parts, simpler designs, larger margins, less emphasis on an optimized design, a shorter build and test schedule, and a higher level of personal responsibility. [Wertz, 2008a] For example, on a SmallSat there may be only one person responsible for building the power system. If that system fails, everyone knows whose fault it was. This means that the power system engineer who designed, built, integrated, and tested the entire power system for that spacecraft has as their very first goal that the power system will not fail.

Historically, small spacecraft have excellent reliability records. Many SmallSats from the 1980's are still operating on orbit, although quite a few have re-entered. APL, NRL, and SSTL (University of Surrey) all have excellent success records.

The experience base is small, but the ability to recover from on-orbit failures seems to be comparable for both large and small spacecraft. For example, Galileo (a large interplanetary spacecraft) lost its main communications antenna when it failed to fully deploy and recovered some capability by using a back-up omni antenna. Similarly, Alexis (a science SmallSat) recovered from a solar array panel and magnetometer broken during launch by using Sun and Earth sensing and considerable ground processing. Alexis continued to return good science data for more than a decade after a "failed" launch.

The major system reliability advantages of low-cost SmallSats are that they are simpler designs with fewer parts and larger margins and that they can be built to inventory and launched in hours or days, should any type of failure occur.

2.6 Space Debris

It has been suggested by some authors that the orbital debris problem, made much more visible by the Iridium 33/Comos 2251 collision, is an argument for large, multi-purpose space assets, rather than smaller, shorter-lived satellites or constellations. The essence of this argument is that fewer satellites leads to fewer collisions which leads to less debris. However, this is an incorrect argument for several reasons.

First, active satellites are only a very small part of the debris material in low Earth orbit. In LEO there are roughly 900 active satellites vs. approximately 500,000 debris particles larger than 1 cm, which is large enough to destroy virtually any satellite. [A 1 cm particle colliding with a satellite at 30 deg (i.e., 3.5 km/sec) delivers the same amount of energy as a baseball hitting the satellite at 500 mph. In the case of a head-on collision (the most common kind), the energy would be equivalent to a baseball at 2,000 mph. And a 1 cm particle is about 10 times smaller than the smallest particle that can be tracked.] Significantly increasing the number of active satellites doesn't change the amount of "dangerous stuff" in orbit by much at all.

Second, SmallSats have a much smaller collision cross section and, therefore, are much less likely to collide with other satellites. Traditional LEO satellites have a cross section of 20 to 200 m^2, largely due to the deployable solar arrays. On the other hand, SmallSats are typically 0.5 to 5 m^2 in cross section and CubeSats are about 0.01 m^2. Because of the much larger surface area to volume ratio, small satellites almost never have deployable arrays. Because of the small cross section, SmallSats have a much lower probability of hitting another satellite.

Most important, operational SmallSats are typically at low altitudes where the debris cloud decays and re-enters over months or a very few years. As shown in the figure below, single large satellites are typically at high altitudes where the debris cloud decays over 100's or 1000's of years. Of course, SmallSats deployed with large satellites and into the same orbit could begin to create a debris problem, which is a possible argument against using rideshare for SmallSat deployment.

In terms of space debris, altitude is far more important than the number of spacecraft. Even large numbers of SmallSats at low altitude will <u>not</u> create a long-tem debris hazard, simply because any debris will decay and re-enter in a very short time. Low altitude is essentially self-cleaning, even without an active deorbit system which adds another failure mode for large, high-altitude spacecraft.

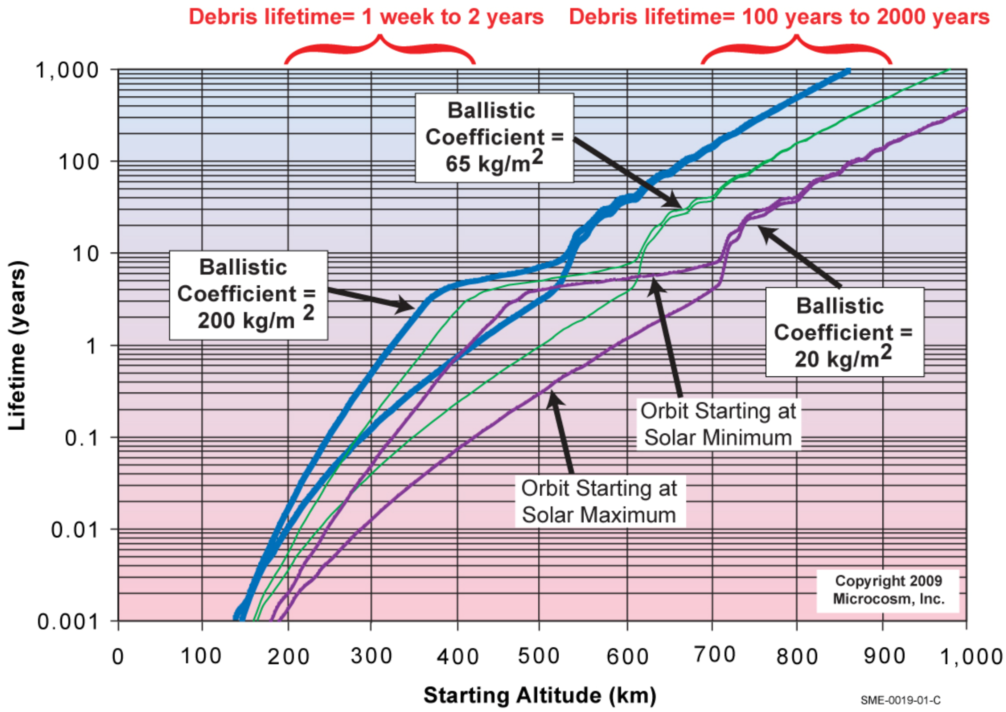

Fig. 11. Satellite lifetime as a function of altitude. Operational SmallSats will typically inhabit a regime where orbital debris cannot accumulate. (Underlying chart from Wertz [2009].)

2.7 Economically Sustainable Business Model

One of the principal problems that arise with the traditional approach of very high cost, very long lived systems is that they don't provide an economic basis for a sustained industrial base. The Space Shuttle was intended to meet the needs for human spaceflight and large payloads for the indefinite future. But, once the Shuttle was designed, built, and delivered, there was no way to maintain the skill base required to design and build it. There was no continuous production process that would provide for changes, upgrades, maintenance, and incorporation of new technology. The same is true of other large systems that are intended to live for a decade or more on orbit and for which only a relatively small number are needed. Similarly, the cancellation of a single large program can have a major impact on even large aerospace companies.

In contrast, SmallSats provide a much more robust economic basis to build on. Building a larger number of satellites with shorter lifetimes cannot only reduce the overall cost, but lead to a more sustainable manufacturing process as satellites can be built more-or-less continuously with some speed up and slow down to meet the changing demand for any particular type of satellite. New technology can be incorporated as it becomes available, the people who understand how the satellite is built are still around, and the component manufacturers can produce a small, but continuing stream of components, rather than one set of components every 5 or 10 years, which is often the case currently.

Unfortunately, the scientists, engineers, and technicians who form the underlying space systems knowledge base are not commodities that can be easily "stored" for the next time they are needed. SmallSats and SmallSat launches provide a continuous flow of business that allow SmallSat manufacturers, such as Surrey Satellite Technology Limited (SSTL) in the UK, to continue to grow over an extended period of time.

3. ARGUMENTS AGAINST SMALLSATS AND A DEDICATED, LOW-COST SMALLSAT LAUNCHER

3.1 Summary

Every realistic approach to developing and deploying space assets has meaningful arguments both for and against that approach. Consequently it is important to examine the principal arguments against any change in the current space mission development process and systems (i.e., against developing and deploying SmallSat systems in large numbers). We have identified 7 principal arguments against SmallSats and SmallSat launchers, or at least why it would be inappropriate to devote scarce resources to these areas in a time of very strong fiscal constraints and the need to significantly reduce overall mission cost. **Collectively, if correct, these arguments imply that we cannot and should not change the current process or approach to space systems.** Each of these arguments is summarized below and then discussed.

3.2 COST: ***With constrained budgets, we cannot afford <u>any</u> new systems and must devote scarce resources to those large systems that are critically needed by the warfighter.***

However, done appropriately, SmallSats can reduce overall space mission cost by millions of dollars in the near term and lead to potential cost reductions of billions of dollars in the moderate term. Therefore, rather than being a further drain on scarce resources, they can be a major part of the solution.

There is an initial cost of $10's of millions to get the low-cost process under way. However, even with the very low current launch rates, these costs can be quickly recovered, as discussed in Sec. 2.4. We can then use the near-term savings to fund development of both more SmallSats and technologies appropriate to reducing cost on more traditional systems. This, in turn, leads to both reduced cost on much larger, more traditional systems and a more economically sustainable industrial base as discussed in Sec. 2.7 and as envisioned by Dr. Rustan (Sec. 2.4.2).

3.3 RISK: ***100% mission assurance is critical — no level of risk is acceptable.***

Unfortunately, system risk is inevitable and, as recent history has shown, there is no failure-free space system (e.g., launch failures, system failures, debris collisions, ASAT attacks). There are 3 distinct reasons why risk can be significantly **reduced** by using SmallSats in conjunction with more traditional systems.

A. Technically, risk is defined as reliability times cost. For a commensurate level of reliability, low cost SmallSats carry much less risk than much more expensive large systems.

B. SmallSats are inherently reliable due to simplicity of design, large margins, small numbers of parts, and small teams, which reduce communications problems. This anticipated good reliability is consistent with the historical record — but no quantitative studies have been done.

C. Reduced risk and high **<u>mission</u>** assurance comes from robustness — having sufficient back-ups and options available to ensure mission success even when inevitable failures do occur. SmallSats and dedicated responsive launch can significantly reduce mission risk. If a launch fails, the satellite collides with an unseen piece of debris, or it is shot down by an enemy attack, it can be replaced quickly and at low cost, with minimum interruption to ongoing operations.

One element of risk that is a real and significant problem for SmallSats is the idea of ***perceived risk*** — i.e., the idea that what we are buying with the large amounts of money spent on traditional systems is a lower level of risk. If you reduce the amount of money, you increase the risk by, for example, performing one less test or reducing the level of redundancy. I believe that the only way to overcome the perceived risk is to look closely at the historical record, to examine in detail the cost and risk of SmallSats vs. traditional satellites, and, ultimately, to deploy SmallSats systems in sufficient numbers to demonstrate the cost vs. risk vs. benefit trade, much as has occurred with UAVs, for example.

3.4 UTILITY: ***SmallSats don't have adequate military utility and won't meet the needs of the military and intelligence communities.***

SmallSats are not intended to replace traditional programs, but can have high military utility, such as the hyperspectral imaging of the Artemis payload on TacSat-3. They can take advantage of new technology to provide capabilities to the warfighter in 1–2 years rather than decades, can be used to augment or replenish traditional capabilities in times of conflict or loss of assets, and can serve as tech demos, training satellites, experiments, and responsive space systems. (For a more extended discussion of mission utility for SmallSats and Responsive Space Missions, see Wertz [2008b].)

SmallSats cannot replace Hubble, the Chandra X-Ray telescope, or current military observation satellites, but they can be gap fillers that give our systems the robustness that they do not now have. For example, Chandra was delayed by nearly 20 years due largely to cost overruns on other programs. The SmallSat Alexis was used as a gap-filler to collect X-ray data during the period of extensive delays. In spite of a launch failure that broke off one of the solar arrays and one of the attitude instruments, Alexis returned useful data on orbit for over a decade.

Similarly, if the Chinese choose to shoot down one or more reconnaissance satellites, or there is a major problem in which several satellites experience orbital debris hits or launch or on-orbit failures, a set of ready-to-launch SmallSats put into much lower altitude orbits can create a back-up that provides the continuity of data that the warfighter needs. Perhaps equally important, if it is clear to our adversaries that satellites which are successfully attacked will be replaced tomorrow morning, or possibly this afternoon, there is significantly less motivation to attack them in the first place.

Finally, constellations of SmallSats can provide more frequent revisits and far higher delta V capability than large satellites. For example, NanoeEye is currently intended to have twice the mass of propellant on board as the dry mass of the spacecraft, which is reasonable to do when the dry mass is around 15 kg. Because the orbit is different than that of traditional satellites, a single satellite provides coverage for 4 to 6 successive orbits, which means that revisits can occur much more frequently than with traditional systems, and the high agility available from the large delta V provides the opportunity to adjust the timing, angle of approach, and altitude for coverage passes to best meet the needs of the mission. In addition, one could, for example, provide simultaneous views from two different angles to create stereoscopic images using two different satellites looking at the same scene. Specific examples of high-value SmallSat missions were given in Sec. 2.2. To achieve this desired level of operational utility, there must be an equivalent SmallSat launcher that is both responsive and low cost.

3.5 RELEVANCE OF LAUNCH COST: *Launch cost is a small fraction of the overall system cost — it's really spacecraft and payloads that must be reduced in cost to have a significant impact on the space budget.*

However, launch cost is actually a major driver for both spacecraft and mission cost and, for low-cost SmallSats, dedicated launch is often the biggest cost element. Bringing down spacecraft cost will hit a wall unless launches can be both readily available and lower cost. There needs to be an orderly progression of growth from capable SmallSats to highly capable "MidSats," with a commensurate growth in the availability of low-cost, responsive launch in multiple sizes. While launch costs themselves are not the major element of most space system costs, they drive the mission cost and, ultimately, prevent or enable the significant reducetion of overall mission cost.

3.6 ORBITAL DEBRIS: *SmallSats contribute to orbital debris more than traditional spacecraft and, therefore, should not be used as operational systems.*

As discussed in Sec. 2.6, SmallSats contribute significantly less to the orbit debris problem than traditional systems because of their much smaller collision cross section. But, the most important factor is that SmallSats will generally fly in much lower orbits where debris **cannot** accumulate. Thus, SmallSats and SmallSat constellations can be a major contributor to the solution of the debris problem, rather than a contributor to the problem.

3.7 NO VALIDATED NEED FOR RESPONSIVE LAUNCH: *There is no validated need for rapid spacecraft replenishment.*

Current systems are fragile and vulnerable. If there is no need to replenish them rapidly if they are lost, then there is no strong need for them in the first place and no need for high mission assurance. The need for rapid replenishment is at the same level and derives from the same source as the need for high mission assurance. Given that we cannot create failure-free systems, it is more important to be able to replenish them than it is to continue to drive individual spacecraft mission assurance. It is not fiscally responsible to overpopulate expensive space systems in order to avoid creating a low-cost responsive launch capability that the Soviets/ Russians have had for 30 years.

3.8 MAGNITUDE OF COST SAVINGS: *We need cost reduction in the billions, not millions. Therefore, SmallSats will not help us resolve either current or future financial problems.*

The only way to reduce cost by billions in the near term is by canceling programs or eliminating major payloads. To reverse the "Space Spiral" of ever-increasing cost and schedule, we need to initiate a cost reduction program that can demonstrate near-term success and create confidence in new, more robust, lower cost space processes. A low-cost, responsive launch vehicle alone has the potential to save over $15 billion in a 12 year period as discussed in Sec. 2.4.

4. LIMITATIONS OF SMALLSAT SOLUTIONS

SmallSats should not be viewed as a replacement for traditional, larger satellite systems because of the inherent limitations of SmallSats. Of these, perhaps the most fundamental is the limitation due to physical scale. Nearly all observation spacecraft use diffraction limited optics, such that the only way to improve angular resolution is to make them larger. (Linear resolution can be improved by flying lower as discussed in Sec. 2.4, and it is possible that better resolution can be achieved by using multiple small satellites in formation, although this creates a challenging control problem.) Similarly, high data rates require a large power-aperture, and high power implies the need for large solar arrays and a large satellite. Physically large satellite and launch systems will be required for human spaceflight until we can find a way to make people smaller, which is likely to be even more challenging. Of course, this doesn't mean that small responsive satellites cannot play an important role in human spaceflight, by for example, being able to rapidly deliver food, supplies, and a replacement part to astronauts in an emergency.

In addition, because SmallSats are inherently near-term and low cost, it doesn't make sense to spend billions in R&D for their development. If a particular problem requires billions of dollars in research investment, then it is likely that it will be implemented in a more traditional, unique, large spacecraft system.

Finally, there is also the limitation of perceived risk as discussed in Sec. 3.3. Fortunately, this is a problem that is being solved by the increasing number of SmallSat applications.

5. CONCLUSIONS

5.1 SmallSats vs. LargeSats

SmallSats built to inventory with launch-on-demand have significant economic and technological advantages over traditional large satellites for some applications. Large satellites need nearly all of the money spent up front before there is a return on investment. This is both economically adverse and tends to foster the approach of being very risk-averse, because there is no way to fix a problem once the system has been launched.

For SmallSat systems, money is spent and results are generated more-or-less continuously over the life of the program. This is both cheaper (money spent later costs less, due to the cost of money) and more amenable to a build, test, fly approach in which corrections can be introduced during the program, and new technology can be rapidly inserted.

SmallSats create a robust industrial base with multiple companies and continuous production by people who are thoroughly familiar with the system. SmallSats built-to-inventory with low-cost launch-on-demand have some significant technical and strategic advantages as well:

- They can respond rapidly to advances in technology
- They can respond to changing mission needs with sensors chosen for the current conflict
- They can respond to changing needs in the number of satellites, areas of coverage, and frequency and timing of coverage
- SmallSats are easier and cheaper to change orbits to provide better coverage or to make an enemy attack more challenging or more likely to miss

As with any other military asset, SmallSats should be used from inventory with production rates adjusted to meet current use rates or anticipated demand.

For SmallSats a launch failure, system failure, collision with orbital debris, or enemy attack results in a small to moderate dollar loss and brief loss of coverage. With traditional large satellites a similar launch failure, system failure, debris collision, or enemy attack results in lost capability for the duration of any current conflict, and likely much longer. In addition, 15 years after the successful launch of a large satellite with no failures, no collisions, and no enemy attacks, we have:

- A satellite built with 25-year-old technology to meet 25-year-old mission needs and trying to cover the entire world
- No production line and no one who knows how to build a replacement

With SmallSats in inventory and launch-on-demand, we can put whatever sensor we want, wherever we want it, when we want it there, at any future time, irrespective of launch system failures, collisions with debris, or enemy attack. The ultimate result of adding SmallSats and launch-on-demand to our inventory would be more resilient, up-to-date capabilities that could quickly take advantage of new technologies, survive unexpected damage, and respond to changing world events at greatly reduced cost.

5.2 Waiting for RLV

Should we put SmallSat responsive launch on hold until a low-cost reusable launch vehicle (RLV) is available? This is likely to be more than a decade and several billion dollars away. We have spent, or will spend, well over $100 billion on RLVs and RLV technology. The reusable Space Shuttle is an exceptionally capable and complex element of modern space technology. Nonetheless, in spite of spending nearly $50 billion (in current dollars) on its development, the Space Shuttle represents:

- A single point failure for the mission
- The highest per mission cost and cost per pound of any launch vehicle
- Two-year planning time for launch
- Higher spacecraft costs, because the spacecraft cannot be allowed to endanger the expensive Shuttle

Most small or non-NASA payloads have been banned from the Shuttle altogether. The Space Shuttle was built by some of the best and most competent engineers in the world. There are good technical and economic reasons for the adverse aspects of the resulting vehicle. It isn't simply bad engineering in the past that can be easily fixed by building a new and different RLV.

Because of the substantial potential economic advantages of an RLV, it is important to continue to fund R&D on this element of space technology. Nonetheless, had we spent the $100 billion on small expendable launchers, we could have launched 1000 SmallSats every year for the last 30 years. Risk, and the need for 100% mission assurance, would no longer be an issue. The RLV, while potentially very important for the long-term development of space, doesn't provide what is needed for current SmallSat launch — near term, low cost (NRE and recurring), responsive launch with options, alternatives, and a scalable growth path. (For a discussion of reusable vs. expendable launch costs, see Wertz [2000].)

5.3 Conclusions

Developing multiple SmallSat systems, coupled with a near-term, dedicated, low-cost, responsive launch capability, can return significant cost, risk, and performance benefits to both the warfighter and the civil space user in the near term. It can:

- Enable multiple operational military and civil missions of high utility to the end user
- Provide access to SmallSat orbits that provide more and better localized coverage than traditional orbits (and reduce the orbital debris problem)
- Reduce near-term space mission cost sufficient to recover development cost within the first few launches and reduce moderate term cost potentially by billions
- Provide for rapid insertion of new technology and greater responsiveness to both warfighter needs and world events
- Provide greater overall mission assurance for the warfighter by providing backups and alternatives for critical missions
- Reinvigorate NASA low-cost missions for Earth science and civil missions

A low-cost, small launcher is a mission enabling capability that can complement traditional launch systems, provide greater near-term mission assurance, enable the potential for moderate-term space cost savings of billions of dollars, and significantly improve the utility of space to the modern warfighter and civil user. The ability to respond to changing world events, the need to avoid creation of more orbital debris, and the availability of much better orbits (i.e., better and more frequent coverage than from traditional large satellite orbits), require that SmallSats be placed responsively into non-traditional orbit regimes, which, in turn, creates the need for a dedicated launch system for operational SmallSat systems.

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