Evaluating the Present and Potential Future Impact of Small Satellites

Andrew W. Lewin
Johns Hopkins University Applied Physics Laboratory (JHU/APL)
11100 Johns Hopkins Road, Laurel, MD 20723; (443) 778-8961
andy.lewin@jhuapl.edu

Abstract

The theme of the 18th Annual AIAA/USU Conference on Small Satellites questions whether small satellites are a complimentary or a disruptive technology. This paper addresses this question by performing an analysis of the role small satellites play in the space market. The market is segmented into three primary components, military space, civil space, and commercial space. Analysis focuses on the U.S. space market. The analysis shows that while small satellites perform some valuable missions, they represent only a small part of the overall space market. Furthermore, although there are some upcoming opportunities for small satellites, they do not appear to be poised for substantial growth in any of the markets. Interestingly, an ORBCOMM case study suggests that high launch costs are not a major obstacle to growth in the commercial space market since they represent just 10% of the total investment required. Overall, the study finds that small satellites are unlikely to be able to perform the roles played by large satellites, so any transition of small satellites from a complimentary to a disruptive technology must come through new applications that open up new markets.

INTRODUCTION

Proponents have long suggested that small satellites will transform the use of space. The advent of small satellites is often likened to the introduction of the personal computer. While PCs have become ubiquitous, small spacecraft have failed to generate broad interest. In 1980, 300,000 desktop computers were sold.[1] This figure has jumped more than 400 times to 130 million worldwide computers sold annually.[2] By 2002, more than one billion PCs have been produced.[3] As Figure 1 shows, small satellite launches have shown no secular growth over the last 15 years, except for a bulge in the period from 1998 to 2000. The launches of 25 ORBCOMM spacecraft in 1998-1999 and 6 CubeSat-class spacecraft in 2000 largely account for the departure from the historical norm of about 13 launches per year.

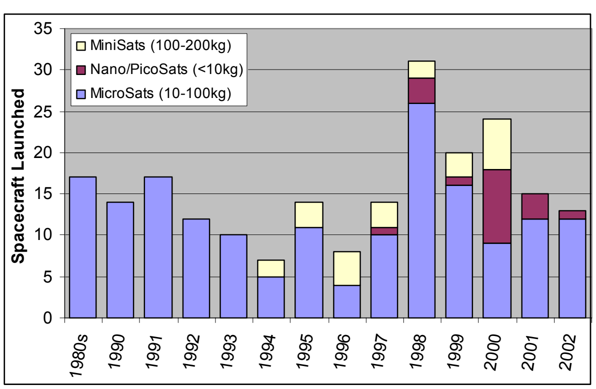

Figure 1: Small Satellite Launch History[4]

The figure suggests an answer to the central question of this year's conference: Are small satellites a complimentary or a disruptive technology. When making such an evaluation, one must carefully separate the issue of small satellite utility from the question of the market impact. Seventeen previous Conferences on Small Satellites have provided ample evidence of the capabilities of small satellites. From the ORBCOMM microsatellite constellation that helped save the lives of two sailors hundreds of miles off the coast of Australia to the Surrey Satellite Technology Limited (SSTL)-sponsored Disaster Monitoring Constellation that has the potential to save thousands more, small satellites have made important societal contributions. However, small satellites can achieve great things in targeted arenas without acting as a disruptive technology to the space market as a whole.

MARKET-BASED ANALYSIS

To answer this question, the space market is broken into three segments, military, civil, and commercial, with a focus on the U.S. market. In each case, qualitative metrics are used to assess the portion of the market being addressed by small satellites and the potential for small satellite activity to grow within that market. Fundamentally, growth can come from one of three methods: displacement of larger satellites, maintenance of existing market share within a growing space market, or creation of new markets. It is important to note that displacement of larger satellites does not necessarily mean that small satellites must perform the same functions as large satellites, particularly in the government space market. Rather, small satellites may provide a capability deemed higher priority than that of a large satellite, and therefore receive funding instead of the large satellite.

The growth potential by each of these means is considered for each market.

MILITARY SPACE

Unclassified military space spending is dominated by several large programs (see Table 1). Each of these programs uses large satellites; masses are provided for several of the existing spacecraft. Most are in geosynchronous or highly elliptical orbits, which drives the need for large launch vehicles or large on-board propulsion systems. Correspondingly, these programs can be extremely expensive. For instance, the Space-Based Radar program is estimated to cost nearly $30 billion.[5]

Small satellites face substantial hurdles when trying to perform these missions. For example, GPS satellites must transmit jam-resistant signals on multiple frequencies. Fitting all of these high power transmitters on a single platform requires a large satellite. In principal, a cluster of small satellites could be used, with one signal hosted by each vehicle. However, this would degrade system performance due to minute differences between the clocks on each platform. Furthermore, the system would be much more expensive to operate due to the increased number of spacecraft and clocks to be coordinated. This problem is particularly acute for clock management.

The Space-Based Infrared System-High (SBIRS-High) illustrates a second problem. The satellites are designed to provide early warning of missile launches and nuclear detonations. A small satellite-sized payload to satisfy this mission simply cannot be built using current technology. Furthermore, the payload cannot be built in multiple constituent parts flown on multiple small platforms.

Many of the defense satellite programs provide military communications. As the military shifts to a network-centric warfare philosophy, and as systems have become increasingly complex, military communications bandwidth requirements have grown steadily and are predicted to do so for the foreseeable future. To this end, the military-owned satellites only tell part of the picture. The military has become increasingly dependent upon commercial providers. As with the GPS satellites, the high powers required by the platforms make small satellites ill-suited to this mission.

A simple analysis of the challenges facing reconnaissance satellites suggests that small satellites are a difficult match with this application. Fundamentally, reconnaissance satellites are attempting to collect energy over an enormous range of frequencies with high resolution, excellent sensitivity, and continuous global coverage.

Even large spacecraft must make compromises among these objectives. However, these systems typically require large receiver apertures to gain sensitivity and resolution, and enormous data throughput to maximize coverage. Such requirements have precluded the use of small satellites. Studies have been performed that investigate the possibility of using distributed apertures for a variety of military and civilian space applications, but the technology is still too immature to support use on an operational mission.

Small satellites have been used by the military for ex-

Table 1: Major Military Space Programs as of 2001

Program	Lead Org.	Purpose	Mass (kg)
DSP	Air Force	Nuclear and missile warning	2400
DMSP	Air Force	Weather monitoring and prediction; to be replaced by NPOESS	1500
MilSatCom EHF	Air Force	Communications	~7000
MilSatCom Polar	Air Force	Communications	
T-SAT	Air Force	Communications	
GPS	Air Force	Precise position, velocity, and time transfer	1545
NPOESS	Air Force	Weather monitoring and prediction; co-sponsored by NOAA and NASA	~2000
SBIRS-High	Air Force	Nuclear and missile warning; replacement for DSP	
Space-Based Radar	Air Force	Moving target tracking; radar mapping	
Wideband Gapfiller	Air Force	Communications; successor to DSCS	6000
DSCS	Army	Communications	1235
MUOS	Navy	Communications	
Sat Comm Systems	Navy	Communications	

periments and technology demonstration. For example, the Office of Force Transformation (OFT) is developing TacSat-1, a small imaging satellite that will be tasked by commanders in the field. The Air Force's Space Test Program has sponsored several small satellites, the latest of which is the technology-demonstrator STPSat-1. However, this spending represents only a tiny fraction of the amount expended on operational space systems.

One bright spot for small spacecraft is an increased interest in space situational awareness and space control. Small satellites are ideally suited to many missions in this arena. For example, small spacecraft make excellent inspectors. These vehicles can be used to study friendly satellites to aid with anomaly resolution or damage inspection. The Air Force's XSS-10 and XSS-11 programs are demonstrating these capabilities, as is the Demonstration of Autonomous Rendezvous Technology (DART) mission. SSTL's 6.5 kg SNAP-1 nanosatellite demonstrated the ability of even very small spacecraft to perform these functions. In addition, small spacecraft could also be used for offensive or defensive purposes.

One sign of the DoD's commitment to small spacecraft is its investment in lower cost access to space. OFT purchased the inaugural launch of the SpaceX Falcon-1 launch vehicle for the TacSat-1 mission. In addition, DARPA initiated the FALCON program (separate from the SpaceX Falcon-1 launch vehicle) intended to lower both the cost and the time required to get small payloads on orbit. This so-called operational space launch capability could enable a host of new opportunities for small spacecraft.

Although these new opportunities have enormous potential value to the military, they are unlikely to cause a major displacement of existing military space programs or to justify a significant increase in space spending relative to other DoD expenditures, at least in the near- to medium term.

If small spacecraft cannot further penetrate the existing military market or create major new opportunities, the alternative is to maintain market share in a growth market. Figure 2 shows real (inflation-adjusted) DoD space-related expenditures. This includes not just satellites, but also ground systems, launch vehicles, systems engineering, management, and research and development. The figure shows a large build-up during the Reagan administration followed by net declines in the Bush and Clinton administrations. Although space spending is on the rebound, it is clear that the near-term growth rate is not sufficient to support a revolutionary role for small spacecraft in the military arena.

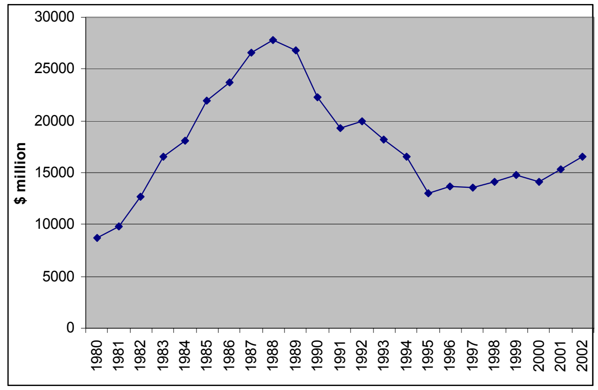

Figure 2: Military Space Budget Authority (constant 2005 dollars)[6,7]

NASA

The same fundamental analysis approach can be applied to small spacecraft for NASA. To date, NASA has spent relatively little of its budget on small spacecraft. Although NASA has a large annual budget of $15.4 billion, small satellites can only address a portion of this market. Table 2 lists the breakdown of NASA's 2004 budget.

Only $450 million of the $7.5 billion in the Space Flight Capabilities line item can be addressed by small spacecraft. Within the $7.85 billion Science, Aeronautics, and Exploration budget, $2 billion is spent on biological and aeronautical research. Nonetheless, this leaves more than $6 billion. This money covers far more than just spacecraft—it includes all phases and elements of program and technology development including launch vehicle expenses and science investigations.

A review of the missions in these categories highlights the difficulties small satellites face in NASA missions. These challenges are very similar to those encountered in military space missions. Within Space Science, the Solar System Exploration and Mars Exploration categories send interplanetary probes to various solar system destinations. Since these trajectories require high velocities, and therefore large launch vehicles, small satellites do not provide a cost effective option since the launch cost will be high regardless of the spacecraft size. Furthermore, the investigations frequently rely upon having multiple simultaneous, co-located measurements. The Astronomical Search for Origins relies upon both ground and space assets. This includes the large and very expensive Hubble and James Webb Space Telescopes. Since the science goals involve peering as deep as possible into the history of the universe, extremely sensitive instruments are required that frequently involve large apertures. In many cases, the

Table 2: 2004 NASA Budget[6]

Budget Line Item	Budget (US$m)
Science, Aeronautics, and Exploration	**7,853**
Space Science	*3,994*
Solar System Exploration	1,302
Mars Exploration	596
Astronomical Search for Origins	914
Structure and Evolution of the Universe	456
Sun-Earth Connection	726
Earth Science	*1,606*
Earth System Science	1,513
Earth Science Applications	92
Biological and Physical Research	*986*
Biological Sciences Research	368
Physical Sciences Research	357
Research Partnerships & Flight Support	260
Aeronautics	*1,037*
Space Flight Capabilities	**7,498**
Space Flight	*5,890*
Space Station	1,494
Space Shuttle	3,928
Space and Flight Support	468
Crosscutting Technology	*1,608*
Space Launch Initiative	938
Mission and Science Measurement	452
Innovative Tech. Transfer Partnerships	218
Inspector General	**27**
TOTAL	**15,378**

instruments alone weigh much more than a small spacecraft.

The Structure and Evolution of the Universe also requires very sensitive instruments, although the mission set shows that these spacecraft are somewhat smaller than those of the Astronomical Search for Origins. However, these spacecraft cannot be classified as especially small. The Sun-Earth Connection studies variability of the Sun and its effect on the Earth. This includes ionospheric and magnetospheric studies that can be addressed by small spacecraft. This theme includes the THEMIS mission that uses five 100 kg spacecraft to study the magnetosphere. NASA is also studying a mission with up to 100 micro-spacecraft also targeting magnetospheric research called the Magnetosphere Constellation.

The Earth System Science theme also has made very limited use of small spacecraft. As with other areas, the primary challenges are the demands of sensitive instruments performing ground-breaking science and the need to make multiple simultaneous measurements from a common platform.

The trend for small spacecraft at NASA has been neutral, at best. ST-5 and THEMIS are the only active programs using spacecraft weighing less than 100 kg. If it proceeds, the Magnetosphere Constellation would represent a major step forward. If the definition of small spacecraft is expended to include full Pegasus-class spacecraft, NASA recently launched the SORCE and GALEX spacecraft in 2003. These missions were part of the Small Explorers (SMEX) program. The next SMEX mission, AIM, is scheduled for launch in 2006. However, the University Explorers (UNEX) program was cancelled after approving just two missions. Also, NASA recently delayed by at least a year the Announcement of Opportunity for the Medium-class Explorers (MIDEX). Although these typically involve larger spacecraft, the last MIDEX award included the THEMIS mission.

If small spacecraft cannot significantly grow their share of the existing NASA market, the alternative is growth of the overall NASA budget, or identification of new applications that would displace NASA spending in other areas such as manned space flight. At present, no such missions are in formulation at NASA. Furthermore, as Figure 3 shows, the overall NASA budget trend has trended downward. Real spending at NASA has been declining for more than a decade. In January 2004, President Bush introduced an Exploration Initiative that would take humans back to the Moon and on to Mars. The initiative included a proposed modest increase in NASA funding, although Congress has given the concept a cool reception. Even if NASA's budget did grow modestly as proposed, the Exploration Initiative would increase emphasis on manned space activities that would likely decrease total spending on robotic missions of all sizes.

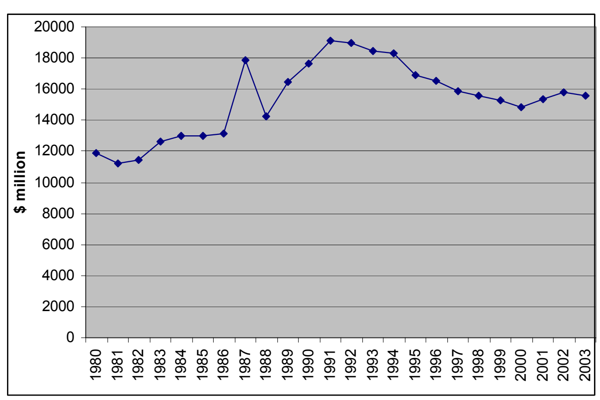

Figure 3: NASA Budget History (constant 2005 dollars)[9,10]

COMMERCIAL

The final venue for small satellite activity is the commercial market. This market is dominated by geosynchronous communications satellites providing a variety of services. Small satellites are ill-suited to these missions. First, most geosynchronous spacecraft are launched into a parking orbit known as geosynchronous transfer orbit (GTO). GTO has a low perigee (200 – 500km) and an apogee at the geosynchronous altitude. The satellites then boost themselves to a circular geosynchronous orbit (GEO). The energy required to accomplish this maneuver is very large. Consequently, even a "small" GEO spacecraft has a launch mass of over 1000 kg. This problem can be mitigated by using a launch vehicle that places the spacecraft directly in GEO. However, the same "small" GEO spacecraft have a 1.5 kW – 4.5 kW payload power requirement.[11] This amount of payload power cannot be accommodated by small spacecraft. While a cluster of multiple smaller spacecraft could theoretically perform the same task, this approach suffers from many of the same limitations discussed relative to GPS satellites.

Low Earth orbiting (LEO) communications constellations represent a much smaller part of the commercial landscape. The most prominent examples are Iridium and Globalstar. Although the underlying architectures are quite different, both companies use moderate size spacecraft—about 700kg and 450kg, respectively. The spacecraft size is again dominated by the required transmitter power. Small satellites have had some success in this environment. ORBCOMM operates a constellation of 35 micro-spacecraft that provide low rate two-way messaging and data services. Nonetheless, LEO communications has proven to be a very difficult market to establish. Each of the systems mentioned entered bankruptcies that have cost investors billions of dollars. After writing off their initial investments for pennies on the dollar, these companies are recovering, however, and are beginning to consider building replacement systems.

If small satellites are not able to replace existing commercial systems, then the alternative is to create new markets. The communications market provides a sobering example. At one point, at least three such LEO constellations were proposed. However, ORBCOMM was the only system built, and its survival is due only to its aforementioned bankruptcy.

It has widely been argued that high launch costs have been a key roadblock to broader use of micro-satellites. Indeed, the theme of the 17th Annual AIAA/USU Conference on Small Satellites proclaimed that "getting there is half the battle." ORBCOMM provides a useful example with which to test this theory. Although launch costs are not publicly available, educated guesses can be made regarding the ORBCOMM launch costs. Table 3 lists the ORBCOMM launches and the estimated prices. As the table shows, ORBCOMM orbited 35 spacecraft in six launches with a total estimated cost of $72 million. However, this represents just 9% of the total investment in ORBCOMM, which exceeded $800 million at the time of its bankruptcy.[12] Even assuming a 20% error in the launch cost estimate, the launch cost would be 7 – 11% of the total investment.

Table 3: Estimated ORBCOMM Launch Costs (real-year dollars)

S/C	Launch Vehicle	Year	Est. Cost
FM1-2	Pegasus (w/ MicroLab-1)	1995	$10m
FM5-12	Pegasus	1997	$14m
FM3-4	Taurus (secondary)	1998	$5m
FM13-20	Pegasus	1998	$14m
FM21-28	Pegasus	1998	$14m
FM30-36	Pegasus	1999	$15m
35 spacecraft, 6 launches			**$72m**

When evaluating a new concept, venture capitalists typically look for a rate of return of at least 30%. Since launch vehicles represent only about 10% of the total project investment, they will not have a significant impact on the viability of a proposed project. Even if the launch costs were zero, they would at best transform a marginal concept into a viable one.

This result may seem surprising, but it is supported by additional circumstantial evidence. Surrey Satellite Technology Limited has for many years offered low-cost spacecraft solutions. In 1996, Surrey quoted micro-satellite (10 – 100kg) costs from $2 - $3 million, and mini-satellite (100kg – 500kg) costs from $5 - $20 million.[13] Even allowing for inflation, these represent very modest cost numbers. Using secondary rides and Russian launch vehicles such as the SS-18 Dnepr, Surrey has been able to offer very low-cost turnkey solutions, as evidenced by the recent deployment of their Disaster Monitoring Constellation. Yet, this capability has not translated into substantial market activity. SSTL has launched just 12 spacecraft since 1996.

EDUCATIONAL INSTITUTIONS

The one growth "market" for small satellites is educational institutions. Twenty years ago, almost no educational institutions were involved in satellite development. Today, universities around the world are working on small satellites. For example, the CubeSat web site lists 66 universities and four high schools from

16 countries representing every (populated) continent.[14] Other universities have gained small satellite experience through the U.S. Air Force Nanosatellite-2 and Nanosatellite-3 effort. Finally, NASA's UNEX program offered universities an opportunity to implement low-cost missions.

Unlike the commercial market, the lack of low-cost launches has been a significant problem for university satellites. Launch cost and availability were major factors in the cancellation of the UNEX program and in the failure to launch the hardware produced under the University Nanosatellite-2 program. To date, a single CubeSat launch has taken place, releasing six CubeSat-class spacecraft. Another CubeSat launch is planned for late 2004 that could involve up to 15 such satellites from 12 institutions. However, this still represents only a fraction of the educational institutions interested in CubeSat development.

For educational institutions, small satellites are unquestionably a disruptive technology in the most positive sense. They have enabled universities to provide hands-on experience to thousands of students who would not have had such opportunities in the past. However, this is a change to the education market rather than one to the space market. While universities comprise a strong and vibrant component of the small satellite community, their efforts are primarily aimed at educating students and performing some technology development, not at identifying and exploiting the market potential for these spacecraft.

CONCLUSIONS

The failure of small satellites to generate new commercial markets is especially critical when evaluating the impact of small spacecraft on the space marketplace. Truly disruptive technologies typically gain acceptance and growth by enabling new capabilities and applications rather than by simply replacing existing technologies. The personal computer analogy is a perfect example. Although PCs replaced some mainframes, the main engine of growth for the PC was the new applications that it brought to the user. For the first time, personnel throughout an organization could have access to powerful word processing and spreadsheet tools. These same capabilities also drove a burgeoning home PC market. The displacement of mainframe computers was largely a secondary effect driven by the rapidly expanding capability of the PC.

Small satellites face a number of hurdles that make it very unlikely that they could replace the large satellites performing government military and scientific satellite missions. Furthermore, government space spending will not see the high long-term growth rates that are possible in commercial markets.

Thus, one must conclude that small satellites at present are a complementary technology fulfilling a set of niche applications in the government and commercial space marketplace. This does not diminish the utility or criticality of small satellites; it merely characterizes their role in the overall space marketplace.

Looking ahead, small satellites are being considered for broader use in each of the market areas considered, but this growth is small relative to the overall market. Therefore, barring the introduction of a revolutionary small satellite application, small satellites will remain a complementary technology for the foreseeable future.

ACRONYMS

AIM	Aeronomy of Ice in the Mesosphere
DARPA	Defense Advanced Research Projects Agency
DART	Demonstration of Autonomous Rendezvous Technology
DMSP	Defense Meteorological Satellite Program
DoD	Department of Defense
DSCS	Defense Satellite Communications System
DSP	Defense Support Program
EHF	Extremely High Frequency
FALCON	Force Application and Launch from Continental United States
FY	Fiscal Year
GALEX	Galaxy Explorer
GEO	Geosynchronous Earth Orbit
GPS	Global Positioning System
GTO	Geosynchronous Transfer Orbit
LEO	Low Earth Orbit
MIDEX	Medium Explorers
MUOS	Multi-User Objective System
NASA	National Aeronautics and Space Administration
NPOESS	National Polar Orbiting Environmental Satellite System
OFT	Office of Force Transformation
PC	Personal Computer
SBIRS	Space-Based Infrared System
SMEX	Small Explorers
SNAP	Surrey Nanosatellite Applications Platform
SORCE	Solar Radiation and Climate Experiment
SSTL	Surrey Satellite Technology, Limited
ST	Space Technology
THEMIS	Time History of Events and Macroscale Interactions during Substorms
T-SAT	Transformational Satellite
UNEX	University Explorers
XSS	Experimental Satellite system

REFERENCES

1. www.scienceblog.com/community/article2416.html, posted 8 Mar 2004.

2. Ibid.
3. Ibid.
4. Small Satellites Home Page, centaur.sstl.co.uk.
5. "House Cuts Funding for Space Based Radar," *Space News*, 14 June 2004, p4.
6. *Air Force Magazine*, August 2003, p. 28.
7. National Defense Budget Estimates for FY2005, Office of the Under Secretary of Defense (Comptroller), March 2004.
8. Letter from NASA Administrator Sean O'Keefe to Sen. Christopher Bond, Chairmand o fthe subcommittee on VA-HUT-Independent Agencies, Enclosure 1, 10 March 2004.
9. *Aerospace Facts and Figures 2002/2003*, Aerospace Industries of America, 2002, p. 66.
10. National Defense Budget Estimates for FY2005, Office of the Under Secretary of Defense (Comptroller), March 2004.
11. www.orbital.com.
12. Foley, T.: Bidders Plot comeback for a Satellite Network, *New York Times*, 2 April 2001.
13. Sweeting, M.N., "Network of Low Cost Small Satellites for Monitoring and Mitigation of Natural Disasters," *47th International Astronautical Federation Congress*, Beijing, China, 1996.
14. cubesat.calpoly.edu/developers.htm.