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Can Small Do What Big Does – Only Better? (An Update)

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ABSTRACT

In one form or another, small satellites have now been around for fifty years. Serious efforts to commercialize small satellite technology have commenced far more recently. ***Plans*** *to commercialize small satellite systems started somewhat earlier, however such initiatives did not result in hardware being flown until the early 1990s. At this point, satellite entrepreneurs and engineers have had nearly 20 years to perfect their business plans and system designs. How have they done? Have the businesses that depended upon this technology been profitable? Have the satellite systems been successful in meeting their long and short term requirements? Have they done better than their large space system counterparts?*

These questions will be examined from the perspectives of 1) advances in technology unique to small space systems, 2) small vs. large system development methodologies, 3) business success in various market applications and 4) the ability of small commercial systems to deal with sometimes "unfair" universal constrains imposed upon all space systems by external sources; some business related.

It is important, in prefacing this topic, to review the salient characteristics of "small" satellite systems as many who have not worked in this "subculture" of the space community may be surprised to learn that there is more than mass and power that separate big from small and it is these less obvious differences that are key elements in the ongoing debate between the true value of small vs. large satellite systems.

Finally, enough trending has been done by now, and enough attempts have been made in the marketplace to reach some general conclusions in several areas covered by this paper and these observations may possibly be useful in guiding future entrepreneurs as they approach this apparently illusive market sector. Efforts will be made here to summarize those findings.

This paper was originally presented at a workshop held at Stanford University, which addressed Emerging Commercial Applications for Small Satellite Technology. That conference was held March 24, 2009. The paper is being updated to add new information and changes in outlook since that time. This is the first official publication of the paper.

1.0 INTRODUCTION: SPACECRAFT ONE AND ALL (BIG and SMALL)

It's been a long standing joke in the commercial satellite world that if you want to make a *little* money in selling a hot new space application…well,…you start with a *lot* of money. The problem, during these leaner times, is that this little joke has been true far too often…and, just now, there isn't a lot of investment capital around…anywhere. Fortunately, there have been success stories in the commercial space world and these cases have fueled a fair number of entrepreneurial initiatives during the last 30 or more years. It's easy to review the business success of any venture after it has been going for awhile. Rate of Return (ROR) and net present value (NPV) are two awesome task masters when it comes to checking business success but, we will stop short of taking this sort of "hard-nosed" perspective, however, we will ask some tough questions, none-the-less. But first, perhaps it is worth trying to focus on the real differences between small and large satellite systems in terms of technology and manufacturing methodology as not everyone in the spacecraft world necessarily believes or understands the key distinctions between these sectors of the market. In fact, it should be made clear that some large spacecraft designers and engineers would not really recognize the existence of "small satellite" systems as distinct from spacecraft generally. It begs the question, is a small satellite just a small satellite?

It is also worth acknowledging that some things in life are just not fair and some factors influence the markets of small systems, just as they do large systems. It is essential to build the cost of these "constraints" into the business venture in every case. And, it could be that one or more of these constraints eradicates the advantage or "apparent" advantage of a small space system. As a minimum, one needs to be well aware of any such constraint before entering into business.

2.0 SMALL SPACE SYSTEM TECHNOLOGY

Detractors of and those not well acquainted with small spacecraft performance may not be aware of the recently demonstrated performance of a variety of very small space systems. It is perhaps useful to briefly establish the state-of-the-art for small space systems. As a part of the update to this paper, the realities of Nanosat and Picosat (a.k.a. Cubesat) technology are dealt with in terms of capability and their market potential, where applicable.

2.1 Attitude Control Systems (ACS) Performance of Small Satellites

The ability to accurately direct a sensor in space toward a desired target, intuitively, may seem to be size dependent. We all know that large telescopes in space can direct their boresight to a point in space with sub-arc second accuracy. Can small objects, even Cubesats do the same thing? Results are now at hand.

2.1.1 ACS Performance of Microsatellites

First we look at the ACS performance of the "best-of-class" for a group of Microsatellites. While mass and power might appear to be the most significant technology hurdles for small spacecraft entering commercial service, these two parameters have been counteracted by huge increases in performance of integrated electronics (in terms of parameters like MIPS/watt and bits/cm^{3}). Concurrently, the efficiency of power generation has nearly doubled in 15 years and the efficiency of RF generation equipment has slowly increased during that same time. In fact, the limiting performance subsystem holding back the promise of small systems has been within the attitude control regime. Fortunately, suppliers of sensors and actuators have now emerged and are supplying components specifically designed for small satellites. The particular enabling technology of note is the small, low cost reaction wheel. Reaction wheels along with suitable Earth and sun sensors and modest-to-high performance microprocessor system (suitably radiation tolerant), all taken together, allow pico-, nano-, micro- and mini-LEOs to achieve active 3-axis performance. In some instances advanced sensors such as star trackers, GPS receivers and inertial measurement units (IMUs) have now been flown on Microsatellites, Nanosats and Picosats. Table 1 summarizes the 3-axis stabilized performance of three Microsatellites among the first to use reaction wheels along with sun sensors, magnetometers and, another novel innovation – cheap rate gyros (one per axis ; packaged within each wheel). All three missions were science missions and all were successful. All were launched within approximately six months of one another, circa 2003. ChipSat (Cosmic Hot Interstellar Plasma Spectrometer) was a Berkeley University instrument (and PI), the platform was developed by SpaceDev, Inc. The mission was sponsored by NASA/GSFC. MOST (Microvariability and Oscillation of Stars) was a photometric astronomy mission which identifies micro variation in the emission amplitudes of selected stars. The instrument and PI is from the University of British Coloumbia and the platform was designed and built by Dynacon Corp and the University of Toronto (UTIAS). The customer for MOST is the Canadian Space Agency (CSA). FedSat was an Australian science/engineering spacecraft with multiple instruments and PIs from key universities around Australia. The platform was primarily built by Space Innovations Limited (SIL), however, that company ceased to exist before the project was completed. The satellite integration was completed by Auspace and Vipac Corporations in Australia under the direction of the Cooperative Research Center for Space for Space Systems (CRCSS). The customer for the spacecraft was the Commonwealth Scientific and Industrial Research Organization (CSIRO). Although from seemingly different parts of the world, all of these projects culminated at just about the same time; all achieved their mission objectives and all exceeded their mission design lifetimes. Most importantly, all three mission set new high water marks for attitude control system (ACS) performance standards for small satellites (See Table 1).

These seemingly disparate achievements, however, did have a common denominator. All of them used an ACS hardware suite and architecture provided by the Canadian company Dynacon. Dynacon took a large corporate risk for a small robotics company dabbling in space for the first time. They set about developing a low cost RWA (reaction wheel assembly). The unit used commercial components and traded high reliability components for a stress screening program using industrial grade ICs and SMDs. Dynacon received no shortage of oversight from NASA, CSA and CRCSS/CSIRO during the development phase of the wheels but, remained steadfast that such a wheel could be developed.

Table 1: Demonstrated Performance of ChipSat, MOST and FedSat

Spacecraft Parameter:	**ChipSat**	**MOST**	**FedSat**
Launch Date:	January 12, 2003	June 30, 2003	December 14, 2002
Mass:	64 Kg	60 Kg	58 Kg
Power:	40 Watts Orbit Avg.	45 Watts Orbit Avg.	60 Watts Orbit Avg.
ACS Type and Accuracy:	3-Axis	3-Axis	3-Axis
Pitch:	1.2° (3σ)	2.4 arcsec (3σ)	<1.0° (3σ)
Roll:	1.2° (3σ)	2.4 arcsec (3σ)	<1.0° (3σ)
Yaw:	<3.0° (3σ) in sun	4.2 arcsec (3σ)	<1.0° (3σ)
ACS Sensors:	3-Axis Flux Gate Mag. 3-Course Sun Sensors 1-Medium Sun Sensor 4-Single Axis Rate Gyros	3-Axis Flux Gate Mag. 1 Sun Sensor 4-Single Axis Rate Gyros 1- Integ. Star Tracker	3-Axis Flux Gate Mag. 3 Digital Sun Sensors 3-Single Axis Rate Gyros 1-Exper. Star Tracker
ACS Actuators:	4 RWAs; 3 Torque Rods	4 RWAs; 2 Torque Rods	3 RWAs; 3 Torque Rods
Other ACS Features:	Extended Kalman Filter	Extended Kalman Filter	Advanced GPS Receiver
Mission Cost:	$14.5M	$7.5M	$11.2M
Key Mission Obj. Met?	YES	YES; +Extended Mission	YES; + Extended Mission

The results are history.1,2,3 Figures 1 and 2 show typical one and two axis results for the ACS systems for ChipSat and MOST respectively. All three satellites, while operating fundamentally as 3-axis systems (with suitable de-tumble and safe-hold modes) were used in quite different ultimate fine resolution modes:

1) ChipSat performed an all sky survey pointing its unique UV spectrometer toward a sequence of *resels* (each resel being a 5° X 26.5 ° rectangle projected onto the celestial sphere). If one does the math, there are a total of 316 such resels on the sky. The mission plan accomplished was to survey the entire sky in resels (dwelling on each resel for 50,000 seconds or about 14 hours) within one year. This was carried out with an overall observation efficiency of greater than 90%. The results, shown in Figure 1, indicate what appears to be an attitude "glitch" which occurs at the time of eclipse exit from the ChipSat orbit.

While in eclipse the ACS solution depends only on a magnetometer (which provides two axes of attitude information) and a course rate sensor (one contained within each of the wheels). One course sensor completes the coordinate system. The low cost gyro drifts with time and temperature and the magnetometer accuracy is not excellent either. The net effect is that while the flight computer has done its best to integrate the inputs of the sensors available, by the end of eclipse, the satellite has accumulated (in the example of Figure 1) an error of about 2.1°. Once the sun sensor re-acquires, the error is corrected by the software loop and during the sunlit portion of the orbit, the system maintains the commanded 2.5 degree sun vector angle with an error of less than 0.5°. The referenced paper does not state whether the sun angle being referred to is the RSS sun angle with respect to all axes or is with respect to a particular S/C principle axis. So, the 3-axis system for ChipSat (which used 4 wheels) was capable

of pointing with a 3σ accuracy of something approaching 1.20° during sunlit portions of the orbit but, drifted to errors as large as 3 degrees by the end of spacecraft eclipse periods.

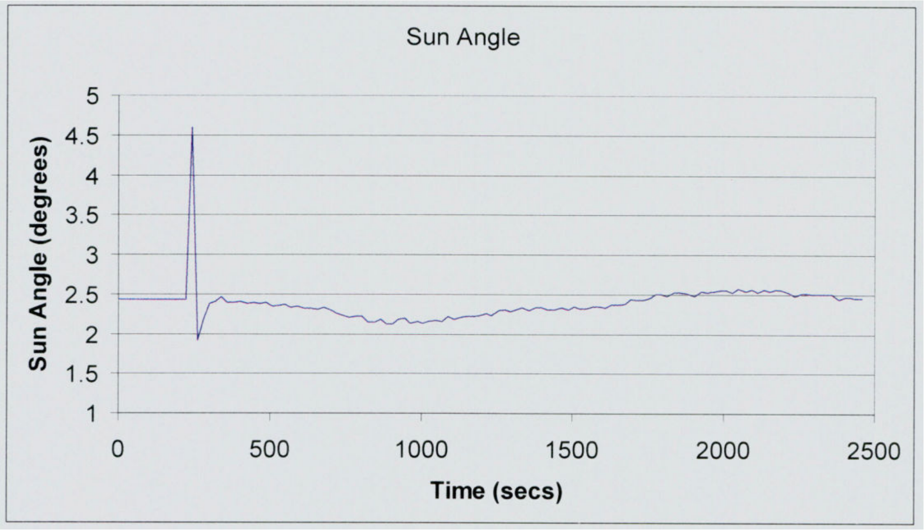


Figure 1: ChipSat Sun Angle During One Target Observation *(Janicik & Wolff)4*

2) MOST is operated in its fine pointing mode using a star sensor located inside the primary instrument telescope at the focal plane. This arrangement then forms a star tracker. The focal plane array sensor was included in a closed loop control system. As can be seen from the results given in Figure 2, the initial ACS configuration gave an RMS pointing error toward the "guide star" selected of approximately 13.8 arc-seconds in pitch and 12.6 arcseconds in yaw (both 3σ). This is to be compared against a program requirement of 37.5 arc-seconds (3σ). [Technically, the requirement was 25 arc-seconds, 2σ, in P and Y]. Not bad. But, after two on-board software algorithm improvements the 3σ accuracy in pitch and yaw was improved to 2.4 arc-seconds and 4.2 arc-seconds respectively. These improvements were made over the primary mission lifetime. This performance was also obtained for protracted observing periods staring at one source star and one to several guide stars. Typical star observation times have been between 14 and 45 days. In order to achieve this long observation time for target stars, a twilight sun-synchronous LEO orbit was used by MOST yielding a Constant Visibility Zone (CVZ).

3) The FedSat ACS system is not described in detail here but, was similar in terms of modes of operation to the other two systems. It was operated in a variety of modes depending upon which experiments were being performed at any given time. As many of the experiments were communications experiments or GPS receiver experiments, the spacecraft would have been pointed with one facet of the cubical structure to the NADIR (Earth facing) for protracted times. The system was different than the other two missions because FedSat contained a significant magnetometer boom which would have produced two disturbing torques: 1) a gravity gradient moment and 2) a solar torque. Thus,

the ACS system would have had to deal with both of these system bias conditions simultaneously. It is known that the ACS system consistently met its 1° pointing requirement per axis.

In parallel with these developments, in the United Kingdom, Surrey Satellite Technology (SSTL) had been developing an advanced platform for their remote sensing systems. Eventually, three platforms have evolved and the performance of these is summarized in Table 2.

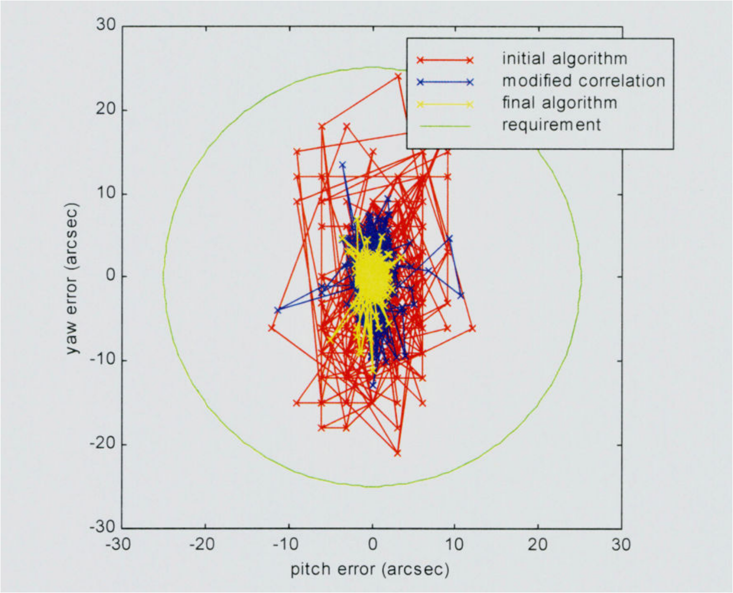


Figure 2: Improvements in MOST pointing accuracy and stability as a result of star tracker algorithm modification. (From Ref. 2).

Table 2: SSTL Standard LEO Platform Performances

Platform Type:	**SSTL 100**	**SSTL 150**	**SSTL 300**
Mass:	100 Kg Avg.	150 Kg. Avg.	300 Kg. Avg.
S/C Power:	100 W Peak/ 50 W Avg.	120 W Peak/60 W Avg.	200W Peak/100W Avg.
Payload Mass:	35 Kg	50 Kg	70 Kg
Downlink Data Rate:	8 Mbps (S-Band)	40 Mbps (X-Band)	105 MBps (X-Band)
On-Board Data Storage:	1 GByte S.S.	8 GBytes S.S.; 8 GB H.D.	128 GBytes Total O.B.S.
ACS Accuracy (P/R/Y)°:	Not Given Similar to UO-12 (See Table 3)	.05/.05/.05 knowledge 0.1/0.1/0.1 control 30° Slew Capability	.05/.05/.05 knowledge 0.1/0.1/0.1 control 30° Slew Capability
Propulsion ΔV:	10-15 m/s (Est.)	10-15 m/s (Est.)	Not Given
Design Lifetime:	5 years	5 years	7-10 years

Detailed information regarding the 3 axis attitude performance of the SSTL 100, SSTL 150 and SSTL 300 buses is proprietary to SSTL, however, all three platforms have a technology genesis starting with the UOSAT-12 technology demonstration spacecraft, launched in 1999 and the ACS performance of that mission is well reported in the literature. Employed here is only one reference.5 UOSAT-12 used a magnetometer, sun sensors, an Earth horizon sensor, a rate gyro and a GPS receiver for sensing and three reaction wheels and 12 magnetorquer coils for spacecraft actuation. The three reaction wheels consisted of two developed in-house by SSTL and one, used for comparison purchased from Ithaco. Table 3, taken from reference 4, shows the performance of the UOSAT-12 system in 3-axis zero momentum bias mode. The results are pitch, roll and yaw attitude error (mean value and standard deviation). Since SSTL has based its commercial platforms on UOSAT-12 technology (using the appropriate number of SSTL sensors and actuators for a commercial mission) it is reasonable to assume that the three platforms offered by SSTL have ACS performances similar to or better than the UOSAT-12 results cited here. SSTL began to use the SSTL 100 platform for the first remote sensing commercial mission (AlSat-1) in 2002. All three SSTL platforms will have now flown.

Table 3: UOSAT-12 ACS Zero Momentum Bias Performance

Param.	**Roll**	**Pitch**	**Yaw**	**ω_x**	**ω_y**	**ω_z**	**RWA-X**	**RWA-Y**	**RWA-Z**
Units	(deg.)	(deg.)	(deg.)	(mdeg/s)	(mdeg/s)	(mdeg/s)	(rpm)	(rpm)	(rpm)
Std-Dev	0.13	0.13	0.62	2.0	1.8	5.9	9.3	5.7	13.4
Mean	-0.05	-0.02	0.08	0.4	-60.6	-0.9	0.7	-5.0	5.1

We thus have two examples of Microsatellite 3-axis autonomous attitude control hardware systems emerging concurrently and now available for commercial exploitation. They are suitable for multiple mission types and applications. The emergence of the two capabilities matured to a point of practical exploitation within months of one other and both evolutionary tracks can cite multiple success stories, at least in terms of technological success. It is therefore, now easy to conclude: ACS subsystems for Microsatellite systems are capable of supporting space commercialization from a technological perspective.

2.1.2 The ACS Performance of Nanosats and Picosats (Cubesats)

It has now been eight years since the first Cubesat conference when educators, students and engineers first got together to discuss this novel spacecraft concept. Surprisingly, government involvement in this technology area has increased in recent times. In fact, in the past three years a very interesting change has occurred in this part of the Smallsat arena. Cubesats have been discovered by "big." AFRL, ARMY, DARPA, LANL, NASA, NOAA, NRL, NRO, NSF, and Boeing (hoping I haven't missed too many) have now gotten seriously involved in what had been the prime domain of universities and amateur radio enthusiasts. The U.S. military and 3 letter agencies have discovered that these small spacecraft might be capable of something approaching a significant mission. And, said agencies have begun to procure these tiny spacecraft and have made launch capacity on even large launchers available to Cubesat and Nanosat missions. Many of these agencies have launched Cubesats themselves already.

One can only imagine what an agency like NRO will do with a 3-axis stabilized Cubesat (1U to 3U) with a 5 to 10 arc-sec pointing capability – which is their ultimately capability (given star trackers we can now produce at low cost and tiny size). And, I've been told that the military rapid response crowd has now become enamored with their potential. Good show. But, if I were a university aero department chair, I'd be very concerned about all of this. Historically, whenever big gets involved (and you would have to agree that the aforementioned agencies represent big, if anything on this planet does) the price goes up. And, I think there is significant evidence that it has - noting the current going rate for launching a Cubesat, compared to eight years ago. The message of this paper, even though focused on commercial space, is – U.S. government: don't kill the golden goose! If, even inadvertently, a market is created, based only on the government's ability to pay, then the wonderful opportunity to allow young engineers to obtain experience via the construction of small satellites could be lost. This was their idea and you will have taken it from them. In summary, a Cubesat at $350,000 to $500,000 is ridiculous and is a death sentence to the university and amateur radio communities. These communities feed new blood into industry as well as government. So, you are cutting off the supply of more skilled young engineers to commercial enterprises as well as government. Don't do it and be aware of what you are doing! I hear you saying that you are funneling money back into these same institutions to make sure this doesn't happen. Well that may work for a few large universities that can compete in your game but, it doesn't help a university that has its own ideas and wants to buy a secondary launch opportunity for its students and has to pay your prices for them!

This increased awareness of the technical capabilities at the very small end of the industry has produced some reported ACS results but, not as many papers have appeared providing hard results as would be hoped. This fact, by itself is somewhat telling. We must remember, however, that these spacecraft were created to be "starter" satellites for students with no prior experience – and this is a wonderful thing. So, the point is not to be critical here but, simply to state that if such space systems are going to mature to be useful to industry, then more information about in-orbit performance is imperative, given industry's reliance on heritage as a selection criterion.

The best of the available results are reported here. It is clear the community is on a threshold where 3-axis technologies are being flown just about now and results will soon be available and reported at conferences held in the very near future. Due to the limited number of reported results on ACS performance to date, I have combined the categories of Nanosats and Picosats. In some cases (such as the 3U Cubesat) the categories between Nano and Pico are blurred in any case.

1) *CanX-2:* This spacecraft was launched in April 2008. 6 It was developed by the Space Flight Laboratory (SFL), at the University of Toronto Institute for Aerospace Studies (UTIAS). The spacecraft has been a technology pathfinder for a later set of spacecraft that will demonstrate formation flying. One of the technologies to be demonstrated was a Sinclair Planetary reaction wheel as a part of a 3-axis stabilized Y Thompson-configuration attitude control system. Over its two year life-time, to date, "a full demonstration of the attitude determination and control subsystem including capabilities in accurate payload pointing (including nadir-tracking), orbit-normal alignment, and long-duration reaction wheel operation has been carried out." CanX-2 is a 3U Cubesat with dimensions of 10 cm X 10 cm X 34 cm and weighs 3.5 Kg. "Attitude determination and control of the satellite [is based] on a conceptually simple system. An accuracy of about ±1.5° is achieved using a set of six SFL-developed sun sensors, supplemented by an SFL-developed, three-axis, magnetometer, which is deployed approximately 20 cm from the satellite. Orbit-normal alignment, of the satellite's minor (Y) axis, is achieved through simultaneous application of wheel bias and rate-damping control. Pitching, around the minor axis, is accurate to about 2°. The [one] reaction wheel (Figure 3), used by CanX-2, was developed in a partnership between SFL and Sinclair Interplanetary. It generates a maximum torque of 3 mN·m and has maximum momentum storage of 30 mN·m·s. Three hand-wound magnetorquers provide rate damping control and wheel-momentum management, as necessary." Unlike other SFL designs, this spacecraft does not use rate sensors to augment the spacecraft's attitude error during eclipse. In fact, the system has no attitude requirements defined during eclipse.

To date three attitude control adjustments (upgrades), in executable code have been made to the on-board software. "It is currently estimated that the attitude determination solution **is good to around 1.5 degrees in sunlight**; performance in eclipse is not within the mission scope. This performance estimate is derived through comparison of flight telemetry to modeled performance. The satellite's imager may be used in the future for further research into attitude determination and control performance. It also appears that the EKF [Extended Kalman Filter] is able to correctly estimate rates up to about 145 deg/s and control attitude at rates up to about 90 deg/s, beyond which the solution aliases."

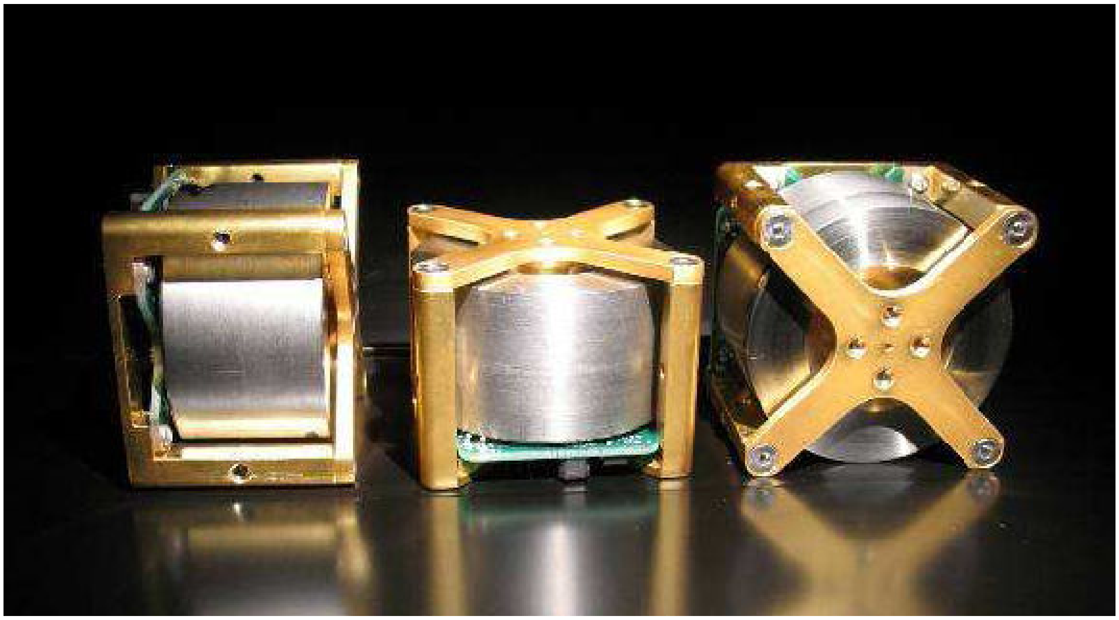


Figure 3: Three Sinclair Planetary Wheels – One is Used by SFL on CanX-2.

Since launch a B-dot law rate damper has been used on several occasions. The on-board propulsion system tends to spin up the spacecraft during the maneuver. To recover from high body rates two methods have been found to reduce the time to damp the spacecraft. One involves reversing the B-dot control gain and by-passing the EKF temporarily. The second method that has been effective is to use the wheel to "soak up" the additional angular momentum and then by applying rate damping while slowly reducing the wheel speed. Using these methods the **spacecraft has been able to handle recovery from rates as high as 190 °/sec.**

The wheel under flight test now has considerably more than two years of trouble-free performance on the CanX-2 mission. On-going observations during orbit-normal alignment and various pitch operations reveals "solid performance with no signs of wheel degradation." Although it is difficult to confirm, all indications are the torque ripple exhibited by the wheel meets mission requirements of 1.0 mN-m per sec.

One anomaly which occurred within the ACS system has been fixed via software and this demonstrates the system's flexibility. The wheel, on orbit was determined to generate a moderate static dipole magnetic field not detected during ground testing. This static field was corrected for by applying an opposing bias vector in order to null out the resulting stray dipole moment.

"Payload operations make use of the satellite's pitch controller, where the wheel (nominally in 'momentum mode,' during orbit-normal alignment) changes to 'reaction mode' in order to slew CanX-2 around its minor axis (ostensibly aligned with the orbit normal). The torquers are, here, used to trim momentum in the wheel. To date, payload pointing performance **appears to be good to about 2 degrees.**"

2) Norweigan/Canadian Nanosat AISsat: AISsat-1 is one of the AIS spacecraft we will discuss below. It was developed by SFL/UTIAS of Canada and is operated by a Norweigan consortium involving government and industry. It uses 3 reaction wheels, 6 course/fine sun sensors, 3 rate sensors and a 3 axis magnetometer. Touquercoils are used, as per usual, to dump angular momentum. The spacecraft should be capable of 1.0 to 1.5 degree pointing in all 3 axes , however, hard data was not available at the time of this paper submission. A paper on this mission has been accepted at this conference and will likely publish the ACS results.

3) *NRO satellites QbX-1 & 2 and U.S. Army satellite SMDC-One (Space Missile Defence Command):* At this time data has not been published about these spacecraft but, I understand they have superior ACS performance characteristics. I have no idea if the results of these missions will ever be published in the open literature. But, given the organizations that paid for them and built them, I can only say about the anticipated performance – it had better be good. I'm counting on it as a taxpayer!

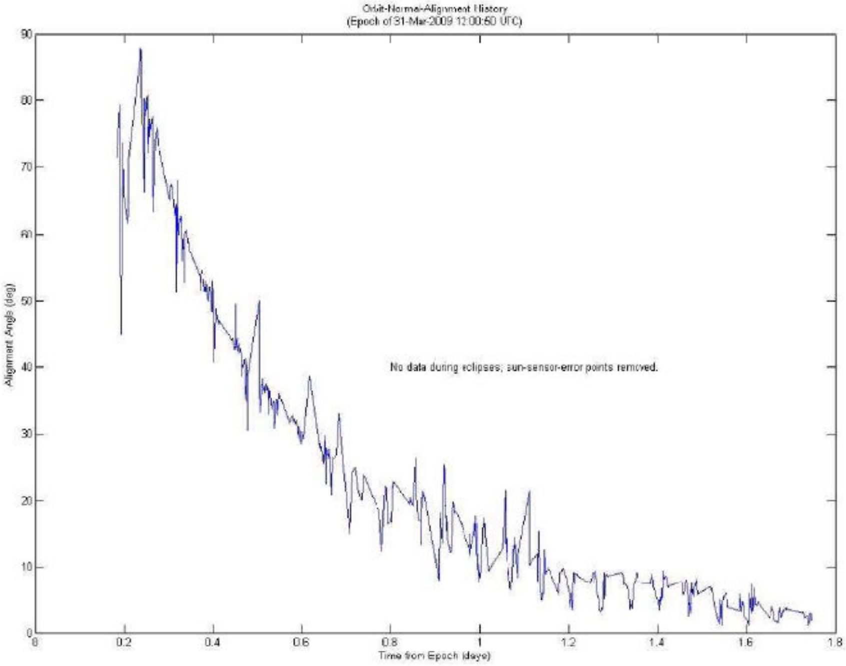


Figure 5: Alignment Angle Between S/C Y-Axis and Orbit Normal

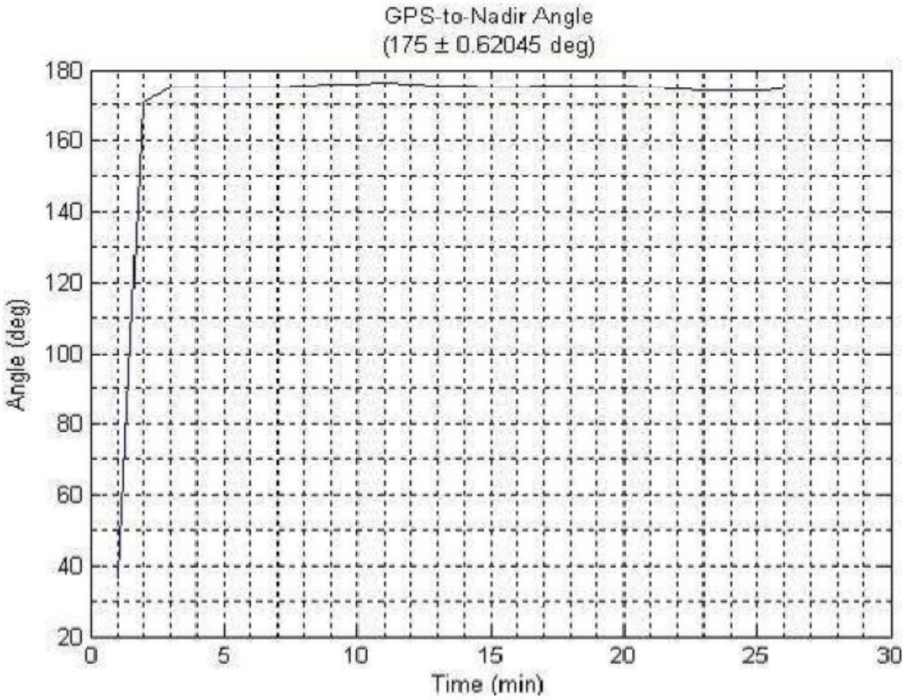


Figure 6: CanX-2 Wheel Pitch Controller: Aligning GPS Antenna to Zenith

In conclusion, what can we say about the current state of readiness Nanosat and Picosat categories in terms of ACS system readiness for use? It is probably fair to say that we can depend upon these platforms to be ready for commercial service within one to two years, given the number of organizations now involved and the level of commitment to this class of technology. Thus, the bottom end of the Smallsat family is becoming a solid contributor to the viable technology base on which industry can depend for operational missions. In Nano and Pico we're just one step away from hard data and closing fast.

2.2 Other Technologies

It is easy enough to lump all other technologies into one summary category as none quite match the importance of the progress made in ACS technologies, since the onset of the SmallSat era. However, some specific technologies should be highlighted here.

2.2.1 Optical Instruments

Clearly, Earth imaging telescopes have made similar advances in parallel with ACS technologies as they have been the rationale and focal point of the ACS mission demonstrations. UOSAT-12 for instance, not only flew a massive ACS demonstration package but, also a Wide Angle Camera with a 2 km resolution, a High Resolution Camera (panchromatic) with a 10 meter resolution and a Multi-spectral Camera with a 35 meter resolution capability. All of these cameras were low cost camera systems developed by SSTL and use a significant number of commercial components. SSTL is not the only entity to discover cheap optics. In the first decade of 2000 many initiatives of this kind have taken place.

2.2.2 Microprocessors and Data Processing

There is a natural tendency for spacecraft engineers to keep pace with the latest microprocessor technologies and the real problem in this area is slowing down the engineers. The serious problem is making really sure that appropriate commercial processors that are otherwise suitable for flight are really radiation tolerant. In general, however, microsatellites and small satellites are quite far ahead of large spacecraft in terms of computer performance parameters like MIPS/watt and Mbytes/cm^3. The question is, will such computers withstand the radiation total dose requirements of a commercial mission with lifetimes as long as 5 to 15 years and can they also meet the SEE needs for the mission type?

There is an interesting "trick" used by large spacecraft that requires capital investment, so it is often not a method that could be used by SmallSat systems but, it is a possibility. Often a specific analog capability or digital functionality is required for a mission. The overall system requirements may impose stringent total dose requirements on all circuitry as well. There are multiple ways to achieve high circuit density in order to meet packaging constraints in all spacecraft. The preferred methodology these days is to use ASIC technology and go digital right away. ASICs, of course, can be made incredibly dense with typical gate counts as high as millions per die. But, the capital investment in an ASIC for a spacecraft application is huge. But, there is another way. One of them is to use hybrid technology. Hybrids typically integrate multiple ICs into one monolithic package. While the ICs are often from the same technology family (e.g., all CMOS) this need not be so. In fact, sometimes the big guys integrate well known *old* rad-hard chips along with newer technology devices (or maybe with more old chips) just to be sure that the total integrated hybrid is radiation hard. So, one could have an LM-124 operation amplifier (designed in about 1974) sitting beside a state-of-the-art CMOS memory device inside a hybrid implementing some analog-to-digital transfer function. This trick assures that the building blocks used are known "heritage" parts with known radiation characteristics but, at much higher circuit density than ever before. It's not clear whether Microsatellites could benefit from such an approach but, certainly, in any case, if the new hybrid part was universal enough to have its cost amortized over many missions, this could also be a valid SmallSat technology as well.

Notwithstanding clever tricks, the small satellite community isn't standing still and is developing its own heritage. SmallSat vendors can now publish their own preferred parts lists based on successes and failures in orbit. Thus, it makes sense to always fly something one knows works; alongside the next generation device one want to space qualify, creating an alternative technology redundancy scheme. This allows a satellite vendor to always make the jump to the next step up…unless the advanced device has a massive radiation failure the last time around and the system had to fall back to the tried and true device.

All said, in the microprocessor category, the SmallSat world still has the edge compared to large satellite systems. In terms of MIPS/watt, where it really counts, SmallSats are ahead by a factor of between 100 and 1000. In terms of MIPS/$ SmallSats are ahead by a factor of between 10 and 100 (at the system level) and this fact can be taken to the bank!

2.2.3 Power Subsystems, Power Generation Efficiency, RF Power

In the late 1990s all advanced programs were flying GaAs solar cells with an efficiency of 18% and talking a lot about mulit-junction cells. In 2011, multi-junction solar cells are routinely flown and provide >28% efficient power to satellites. Engineers now are testing 34% efficient cells. But, these improvements are available and are exploited by both large and small satellites. So, there is no differentiator here except for the fact that this 56% increase in power over 10 years, arguably increases the performance of a small satellite by a larger factor than it does a large satellite. This level of power, in an absolute sense, may also *enable* certain small satellite mission types that were not possible before. So, that is a good thing. Clearly CubeSats become viable and NanoSats become far more capable because of high efficiency multi-junction solar cells.

The generation of RF power from DC power has continued to improve in efficiency over time. Newer technologies such as GaAs and InP heterojunction bipolar transistors (HBTs) promise to greatly improve the efficiency of RF generation at microwave frequencies, however, the absolute power levels that can be generated by this technology are not yet high enough. In the literature multiple discussions still suggest that devices with outputs as high as 10 Watts at microwave frequencies are viable and at high efficiency but, these parts do not yet exist. At the same time HBTs have now been qualified for space use so, they have leaped that hurdle, in terms of radiation hardness.

Even taking these two power design factors (DC and RF power generation efficiency) into account small satellite still have a difficult time entering classical large satellite telecommunications markets simply because the effective isotropic radiated power (EIRP) demanded by high capacity commercial services cannot easily be generated by one or even many small satellites operating over any area of the Earth. The phrase "cannot easily" obviously covers a host of sins. Some could argue, it may be possible for a very large constellation (100s to 1000s) of very small spacecraft, operating synergistically, to achieve system capacities as high as (or higher than) modern FSS, MSS or BSS GEO systems but, it is a stretch and it sounds very expensive as a business proposition. The laws of satellite scaling work against this approach. Satellite replenishment of constellations (even of big satellites) has been very problematic, to date, economically speaking. And, with such system concepts there remains a problem all system engineers are becoming acutely aware of. The spacecraft of such a system would necessarily be mass production items, which generates a classical concern: What do you do with the garbage? Note that every piece of this debris as it orbits the Earth, especially at lower altitudes, is travelling at speed of about 8 km/sec relative to the Earth. This problem will only become more acute with time and it is one more mess we humans must deal with – with priority.

In summary, while advances in power generation and efficiency are beneficial to small satellites, the case has not been made, technologically, for small satellites (meaning spacecraft less than 100 Kg) to assume the role of large satellites in the telecommunications arena. The physics just isn't there if maximized data rate and price/bit are program goals.

2.2.4 Structures, Mechanisms and Thermal Design Changes

If a spacecraft can generate 56% more power than it could ten years ago and if that spacecraft design doesn't radiate that power away as RF energy at some radio frequency or other, then the system must dissipate that power back to space as heat in the form of black body radiation as dictated by the radiance equation. Thus, new small spacecraft that wish to take advantage of high efficiency solar arrays may face new thermal dissipation challenges. Thermal radiating technologies have not changed much in 40 years (give or take a few improvements in the deterioration rate of white paint) so, the dissipation problem amounts to increasing the available satellite surface area in order to radiate the heat away at an acceptable temperature. In this way, small satellites have a big problem. However, there is another change in small satellite thinking that helps with this problem. Small satellites are beginning to become less timid about using deployment mechanisms. Thus, deploying a panel from a small satellite for the sole purpose of providing more thermal radiation area, while once unthinkable, is probably not anymore. And, if it were done for a commercial program so that the deployment and the heat transfer technology could be thoroughly tested (as money would be available) then taking full advantage of the power generation improvements possible for small satellites might still be possible, and in a commercial sense. After all, this is exactly what the "big guys" do. Such a technological approach as is used now by the largest GEOs may "scale" very well to SmallSats.

3.0 SATELLITE DEVELOPMENT METHODS, PROCEDURES AND PROCESSES

If you asked a large satellite system engineer (someone from Boeing, Lockheed-Martin or Astrium) to design and build a small satellite system meeting a certain set of requirements, including a reasonable mission lifetime, would they do it entirely in the same way as we would do it in the small satellite industry? Of course, the answer is no. And, many of us who have been in this "culture" for awhile would smile as we said *no* because, within the total answer to this question lies the true understanding of how money can be saved in small space systems and why commercial ventures are worth considering at the small end of the scale. It is also why eventually, in certain markets, large satellites will simply cease to exist.

You can look at the above question another way: How much would that SmallSat cost if it were built using large satellite rules (e.g., if it were built by Lockheed Martin…just to pick a large satellite company name)? Let's look at where the real differences are hidden.

3.1 Total System Approach and Mentality

Big vs. small really starts with a mind set and one works forward from there. Professor Sir Martin Sweeting, speaking on the very same topic upon which this paper focuses, was addressing a NASDA (now JAXA) Symposium in Tokyo.7 This was in September of 2003. [NOTE: I'm borrowing Martin's ideas here because he always barrows my ideas too and that's because we both have the same message and we are always trying to deliver it to those who would listen]. In that presentation Martin showed two slides about the difference in mind set between big and small. Referring to "big space" as the "traditional approach" one of the graphics was as show in Figure 7.

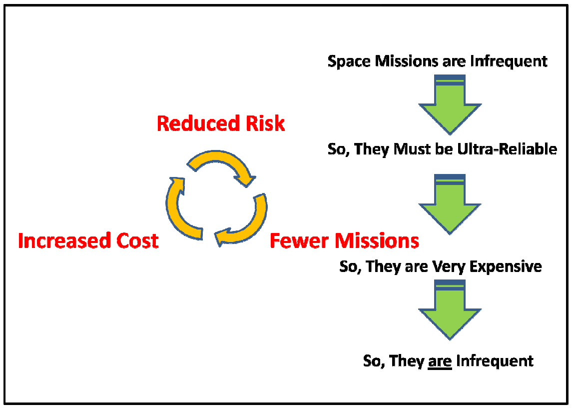


Figure 7: "BigSat" Thinking

In fact, I'm sure Martin would agree, this is not a planar figure. It eventually becomes an upward spiral (out of the plane of the paper) of increasing cost and reduced risk along with other factors like increased insurance premiums and longer schedules. But, there is an alternative way of thinking and it drives all that is done on small satellite programs and it fully changes the management, development mechanisms, procurement strategy and testing philosophy of a satellite program. We contrast the BigSat approach with that of Figure 8. Although a proof for this is not offered in this paper, the relationship between established reliability and mission cost is highly non-linear. Every small increase in established reliability is extraordinarily expensive, and we will see later some of the reasons why this is necessarily so.

Today, there are a handful of companies in the SmallSat community that are existence proofs that SmallSat thinking does pay off in terms of the cost and schedule of delivered spacecraft. Far more importantly, as can be observed by anyone on the Internet in a matter of moments, systems that use spacecraft built to this philosophy now exist; these satellites are in business and operate at a fraction of the cost of their counterparts using larger satellite systems and *they are making money*. We need no longer speculate or debate as to whether the philosophy of Figure 8 is valid.

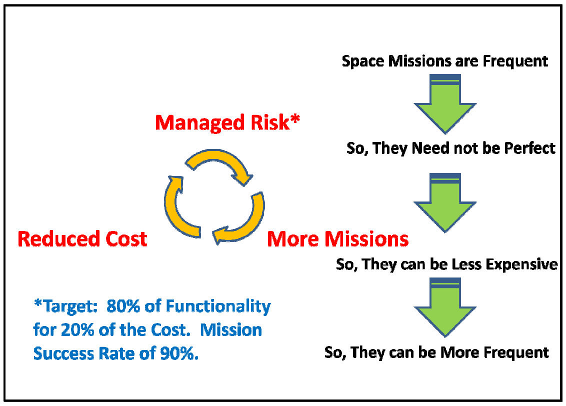


Figure 8: "SmallSat" Thinking

Sadly, however, just because we can fabricate a particular spacecraft cost effectively does not mean that the application to which it is put will make money. Engineers must keep reminding themselves that there is more to a business than just bits of hardware and software. It is also necessary to be clever enough to pick applications that can make money. We will examine these realities shortly.

None-the-less, sticking to the SmallSat philosophy for the moment, how does this philosophy manifest itself in terms of methods and processes at the design, development and manufacturing levels?

3.2 The Design Review Process

No one would ever argue that the design review is not a useful tool or that they are not necessary. They are essential to all space programs (and to many other industries other than our own – we aren't really as unique as we think we are sometimes). They are essential if for no other reason than to be sure the program office has itself fully organized – at least at the time each review is held. The question that arises is what is an adequate review schedule or sequence? Table 4 shows the design review matrix that might be used by a typical large space system program. The generalized example here is taken more from what would be the expectation in the European world. In Europe there is a tendency to have a full set of reviews for every single component (i.e. box) not previously qualified, for every single subsystem and, of course, a detailed review at the system level. In North America there are frequently fewer types of reviews and fewer reviews at the component level. Considering the cost of a review where everyone on a system or subsystem is side-tracked to generate the data pack for that review, and observing that this takes away from other essential on-going engineering activities, it is surprising that more adjustments to the review process are not made by large satellite companies in order to reduce their costs. The counter argument is that such a "review system" once perfected provides an air tight system for catching design, test and fabrication errors when they occur (and they will). The SmallSat counter to the counter is, "is such a system really air tight?" And, the answer is **no**. Some time ago, I encountered yet another example of human imperfection. In a review I attended, a design error *was caught* in the design review of a mechanical structure. A dimension was incorrect. The correction was straight-forward. The error was dutifully recorded in the DR minutes. But, there was inadequate follow-up. The error was not properly changed in the drawing system and the error remained in the high level and lower level documentation system; the CAD drawings went to manufacturing and a bad part was fabricated, delivered, quality checked (to the bad drawing) and integrated onto the satellite. Only at the time of a major mating event (payload to platform) was the error discovered. The lesson here is that the review process is no better than the people who are implementing it and people, by their nature, are not perfect. (This is a known fact, actually.) As the number of reviews increases toward an uncountable number, the DR tracking paperwork increases by a factor larger than that and the probability of errors creeping into the DR process itself reaches certainty in the limit. The conclusion here is that large programs are operating well beyond a practical limit where the cost of reviewing is justified by the number of problems found *and actually corrected* during the entire process. They are beyond the point of diminishing returns.

Table 5 is the SmallSat response to the design review process. Major reviews of subsystems and the system are still present. But, component level reviews are largely suppressed. Components/units of a very complex nature or utilizing very new technologies, of course, would be the focal point of review activities. Reviews such as Test Readiness Reviews and Test Review Boards do not typically exist at the component level because many environmental tests are not performed at the unit level in SmallSat programs (this will be addressed further in the discussion on test planning). A vast savings in design review labor takes place in the SmallSat case because of the reduction in review count at the component level multiplied by the number of components making up the system.

Table 4: Large Spacecraft Program Design Review Matrix

DESIGN REVIEWS (In Order): →	DRR	EQSR	PDR	CDR	MRR	TRR	TRB	QR	PSR	FRR	LRR	MORR	SIOTRR	IOTRB
↓ *UNITS:*														
Major Structural Components	X		X	X	X	X	X	X						
Battery	X	X	X	X	X	X	X	X						
Battery Charge Regulator	X	X	X	X	X	X	X	X						
Power Distribution Electronics	X	X	X	X	X	X	X	X						
Solar Array Peak Tracking Unit	X	X	X	X	X	X	X	X						
Solar Array Structure	X	X	X	X	X	X	X	X						
Solar Array Drive Unit	X	X	X	X	X	X	X	X						
Solar Array Rotary Joint	X	X	X	X	X	X	X	X						
Propulsion Tank(s)	X	X	X	X	X	X	X	X						
Fill and Drain Valve(s)	X	X	X	X	X	X	X	X						
Pyro Valve(s)	X	X	X	X	X	X	X	X						
Thrusters	X	X	X	X	X	X	X	X						
Kick Motor	X	X	X	X	X	X	X	X						
Pyro Initiation Unit(s)	X	X	X	X	X	X	X	X						
Command Detect and Decode	X	X	X	X	X	X	X	X						
Command Decryption	X	X	X	X	X	X	X	X						
Telemetry Conditioner/Encoder	X	X	X	X	X	X	X	X						
Telemetry Multiplexer	X	X	X	X	X	X	X	X						
Telemetry Transmitter	X	X	X	X	X	X	X	X						
Command Receiver	X	X	X	X	X	X	X	X						
Antennas	X	X	X	X	X	X	X	X						
Major RF Filters	X	X	X	X	X	X	X	X						
GPS Receiver	X	X	X	X	X	X	X	X						
Flight Computer	X	X	X	X	X	X	X	X						
Flight Software														
ACS	X		X	X		X	X							
C&DH	X		X	X		X	X							
Power	X		X	X		X	X							
Fault Tolerance	X		X	X		X	X							
Other Major	X		X	X		X	X							
Payload/Instrument														
All Payload Units	X		X	X		X	X	X						
SUBSYSTEMS:														
Structure	X		X	X										
Spacecraft Separation	X		X	X		X	X							
Harness	X		X	X										
RF Harness	X		X	X										
Thermal	X		X	X										
Power	X		X	X		X	X							
Propulsion	X		X	X		X	X							
Command & Data Handling	X		X	X		X	X							
Telecommunications	X		X	X		X	X							
Flight Computation	X		X	X		X	X							
Flight Software	X		X	X										
Payload Power	X		X	X		X	X							
Payload Computer(s)	X		X	X		X	X							
Payload Software	X		X	X										
EGSE	X		X	X		X	X							
MGSE	X		X	X		X	X							
SYSTEM:														
Payload/Instrument	X		X	X		X	X		X					
Assembly Integration & Test	X		X	X		X	X							
Spacecraft	X		X	X		X	X		X	X	X	X	X	X

But, there is one more key difference between reviews held by big and small companies. In large satellite systems the process known as *peer reviewing* is occasionally used. A peer review is almost always considered to be an informal process and is used as a tool at the discretion of technical mangers. In small satellite *systems discipline overlap* is necessarily greater than in programs with a very large staff size. For SmallSat projects, the peer review is a fundamental process. Discipline overlap is *key*. Small satellite engineers are encouraged to overlook the designs of their fellow engineers with an eye toward catching mistakes. This sort of behavior, in fact, is discouraged or prohibited (as a form of intellectual property protection, if nothing else) in large satellite companies. The ability for peer review to be effective depends upon the ability of say, a thermal engineer to overlook the design of a mechanical engineer as they both have the same background in finite element modeling.

Table 5: SmallSat Program Design Review Matrix

DESIGN REVIEWS (In Order): →	DRR	SCR	PDR	CDR	MRR	TRR	TRB	QR	PSR	FRR	LRR	MORR	SIOTRR	IOTRB
↓ *UNITS:*														
Major Structural Components														
Battery			X	X		X	X							
Battery Charge Regulator														
Power Distribution Electronics														
Solar Array			X	X	X	X	X							
Propulsion Tank(s)			X	X	X	X	X							
Fill and Drain Valve(s)														
Pyro Valve(s)														
Thrusters														
Kick Motor			X	X	X	X	X							
Pyro Initiation Unit(s)														
Command Detect and Decode														
Telemetry Conditioner/Encoder														
Telemetry Multiplexer														
Telemetry Transmitter														
Command Receiver														
Antennas														
Major RF Filters														
GPS Receiver														
Flight Computer			X	X	X	X	X							
Flight Software														
ACS			X	X										
C&DH			X	X										
Power			X	X										
Fault Tolerance			X	X										
Other Major			X	X										
Payload/Instrument														
All Payload Units			X	X		X	X							
SUBSYSTEMS:														
Structure														
Spacecraft Separation	X		X	X	X	X	X							
Harness	x													
RF Harness														
Thermal	X		X	X										
Power	X		X	X										
Propulsion	X		X	X										
Command & Data Handling	X		X	X										
Telecommunications	X		X	X										
Flight Computation	X		X	X										
Flight Software	X		X	X										
Payload	X		X	X	X	X	X							
EGSE				x	x									
MGSE				x	x									
SYSTEM:														
Payload/Instrument	X	N	X	X	X				X	X				
Assembly Integration & Test														
Spacecraft	X	N	X	X					X	X	X	X		
	x=mini review; X=major review; N = New = Review Not Typically Used by Large Spacecraft Progam													

In large satellite companies a "peer" is another "like kind" of engineer who is typically barrowed from another program for a short period of time in order to review a colleague's work. But, the barrowed engineer may not be familiar with the tradeoffs made in that program or may not be as familiar with the system design of that particular spacecraft as another member of the same satellite team. In some SmallSat programs peer review has become so important that it has become a formal process. In fact, technical peer reviews of subsystems are formally interspersed among the more "standard" reviews held. Customers are invited to such reviews.

3.3 Development Mechanisms

Arguably, this topic is a broad area to cover in the process of satellite creation. And, it is hard to cover properly in a survey paper of this nature. Since the effort here is to focus on the distinctions between large and small space systems, let's choose to point out only the largest differences. All manufacturing companies (not just aerospace) clearly have customers because they manufacture something that is needed and works. Product assurance is, of course, tied directly to the procedures and processes used to make things. Large, experienced satellite makers have mature procedures and processes. Small satellite manufacturers are younger companies making things a new way. Quite reasonably, their procedures and processes are going to be less mature as a consequence. One could certainly agree that it is likely that Boeing could make a better widget than AAA SatellitesRUs, Inc., who has only been in business for 10 years. The first question is: But, at what price? And the second question is: So, how long will both products work in space? Let's focus on these two questions.

3.3.1 Piece Parts

The specific use of piece parts in space systems is the absolute front line battle ground between big and small. There is no larger difference in approach or difference of opinion than on this topic. And, the cost differential associated with the two variant implementation approaches explains one of the largest cost disparities between large and small satellite systems. It is sheer stubbornness on the part of large satellite companies not to embrace a more liberal parts selection process, which results in the single largest advantage to SmallSat systems over big ones – and it makes possible a huge incremental performance improvement for small satellite systems, without R&D investment on their part.

The term "piece parts" is the traditional aerospace name given to the smallest component elements used in spacecraft. They are passive and active electronic and mechanical components (resistors, capacitors, ICs, transistors, screws, nuts, rivets, etc.) used in every aspect of spacecraft fabrication. For our purposes now, we will ignore mechanical piece parts, although we could also have an interesting discussion about them as well. Rather, because of their larger impact, let's focus on electronic components this time.

The aerospace industry, as a whole, has focused on a military approach to electronic piece part procurement. Under this process specific standards for quality and performance have been established and specific piece parts are built and screened to those standards and the parts thus produced are only used for military and space programs. No one else could or would afford to. Furthermore, large aerospace companies establish preferred parts lists which provide a framework for the selection of components based on past experiences with parts from within the entire range of parts that might be used, based on the military parts standards. A paper system has been put in place to track individually serial numbered parts along with their manufacturing date code and manufacturing location. In most instances a piece part can be traced to the raw materials from whence it came. Detractors would quickly point out that the same argument applies here as it did with the "over-reviewed" design review process. The human elements of the parts tracking process are not perfect and so, one must question at what point the errors in tracking and recording bad parts may allow as many bad parts to get through the system as might have gotten through using an alternative system - which didn't have all of the cost.

An alternative system certainly exists and is in effect, for one example, in the automotive industry. Automotive manufacturers, unable to afford the expense of a military piece parts tracking system, have worked with electronics (most notably semiconductor) manufactures to establish positive feedback assembly lines that randomly sample components from the output of a line of devices. The samples are functionally measured and statistically evaluated and, based on the results, automated process adjustments are made to the line in order to optimize (i.e., improve) performance and reliability. The finished parts are electrostatically protected and are usually vacuum packaged and shipped to the automotive assembly line, often in a "just in time" fashion, untouched by human hands. An example of this process is the "**Six Sigma**"® parts program of Motorola. Such parts are established to be sufficiently reliable to put into applications such as the breaking system of a Chrysler automobile, operating under all environmental conditions seen by a car during its design lifetime. Hopefully, there is no one reading this paper who thinks that the environment seen by an automobile during its entire lifetime is less harsh than that seen by a spacecraft during its lifetime, so I won't venture further on this point. While Chrysler and other clients of Motorola (by way of example) may have paid for the development of Six Sigma feedback technology, that certainly doesn't mean that Motorola was fundamentally prevented from applying this kind of reliability-enhancing technology to nearly their entire line of parts. It also does not prevent Motorola's competitors from offering similar technology enhancements which improve component reliability. And, absolutely nothing prevents the SmallSat community from taking advantage of any of these state-of-the art parts, produced originally for automotive applications (but, later on for many other applications) and applying those parts to space system designs. A smug SmallSat designer or project manager might be heard in the corridors at a conference saying, “If it’s good enough for BMW then it’s good enough for me” and, he or she would have some considerable basis in fact for such a statement. And, here is the significant advantage to SmallSat’s…the big guys are missing out on the state-of-the-art piece parts because they will not consider using them until they have been through the military screening process; a process that takes many years to complete, if at all. And, by definition, after the elapse of that much time, they will no longer be state-of-the-art piece parts. Moore’s law is real.

An example of using a specific automotive piece part may drive home the point. Many years ago the U.S. military was developing fighter aircraft like the F-18. Advanced fighters would not be stable in flight without servo feedback technology and thus *fly-by-wire* concepts emerged. From that set of requirements, eventually, a command and control data bus emerged which was given a military standard number: MIL-STD-1553. In its day it was state-of-the-art and met the requirements of the aircraft fly-by-wire community, despite some fairly hefty software overhead associated with the exchange protocols between the central processor and remote units sending and receiving data. Today this standard has been selected for use on many large space systems world-wide. The hardware, however, remains large and the software overhead for using MIL-STD-1553 is more significant than it needs to be. Meanwhile, in the 1980’s the automotive company Robert **Bosch**, GmBH developed a data bus intended for in-vehicle networking. It was called CAN (Controller Area Network) 8. Simply put, CAN allows multiple devices to be linked together on the same bus. As many of the functions envisioned were safety related (so far as automobiles were concerned) the standard incorporated two sub-buses; one for high priority needs (CAN-Hi) and one for lower level functions (CAN-Lo). The standard was quickly adopted and initially was certified as EOBD-ISO-15031, a European standard. The first chips available to support this standard were developed by Intel and Phillips. It is now used as the primary in-vehicle network standard by Ford, General Motors and Mercedez, to name but a few. So far, two billion cars contain hardware/firmware using the CANbus standard and devices. Does this sound like it might be useful for spacecraft systems? The non-profit organization AMSAT (The Radio Amateur Satellite Corporation) [German chapter] realized that the standard and the chips available were ideal devices for command and telemetry networking between a central flight computer and on-board remote controllers. AMSAT developed a very small CANbus remote terminal board concept that was used in its then current satellite project in order to implement a distributed command/control/telemetry capability. 9 SSTL, having worked closely with AMSAT over many years, then picked up the standard for use with many of their distributed control applications in SmallSats. Subsequently, many small satellites designed by many companies have used CANbus controllers with their own implementations. [NOTE the advantage in this example of an open system interface.] CAN is simple, reliable, capable, fast enough--- and vastly cheaper than 1553 protocol satellite bus systems. CAN is responsible for distributed processing even on very small, very low cost satellite systems. If small space systems would have had to depend upon military data protocols in order to implement distributed processing, this paper would certainly be irrelevant today.

But, the issue does not stop here. Certainly not all piece parts needed are of the “six sigma” variety. And not all six sigma parts are necessarily radiation tolerant, although they may be highly reliable, otherwise. In order to improve further the reliability of piece parts taken from industrial applications instead of preferred parts lists, some small satellite companies have subjected their piece parts to a process known as stress screening. Energies available here do not permit an exhaustive description of stress screening. This process, however, involves accepting parts directly from suppliers without specific pre-screening or serialization and then subjecting 100% of the parts to be flown to very rapid thermal cycling over a temperature range that “carefully and thoughtfully” exceeds the manufacturer’s data sheet for each device. During the thermal stress process (which translates to a mechanical stress when evaluated from a TCE perspective) some parts (particularly capacitors) also have an impressed terminal voltage applied. This voltage also exceeds the manufacturers’ recommended maximum values by a carefully selected amount. The parts are then selected and rank-sorted, based on performance after test and are subsequently installed on flight PCBs without further test or evaluation. In this process, the parts necessarily become temporarily serialized but, this is only for the purpose of performance scoring and ranking prior to installation on PCBs. This process has been found by many organizations to be a faster and cheaper way to obtain high reliability parts without going through the military parts selection process.

Radiation evaluation and testing remains the single "tough nut" issue and the potential stumbling block for SmallSat systems. No amount of clever parts selection can guarantee that each piece part will not be subjected to a potentially lethal cumulative radiation dose; at least over some period of time in orbit. The same could be true for single event effects (SEE) if not dealt with directly. In order for SmallSats to stay ahead of large systems and use state-of-the-art piece parts there are only a few options available to designers:

1) Use the same Single Event Effect analytical tools to evaluate the candidate parts as would be used by all spacecraft designers, big and small. This increases the SmallSat company's development (NRE) costs.

2) Perform sensible and prudently designed radiation testing using Co-60 sources that may be available but, might be intended for other applications (e.g., contracting with metallic weld survey facilities and specialized medical x-ray facilities may offer low cost solutions when compared with typical aerospace source options). [NOTE: The National Laboratory costs for testing military screened parts are never cheap.]

3) Use alternate technology redundancy as a mitigation to potential newly designed hardware so that there is a fail soft option on every spacecraft. This process should be a standard strategy for any company in the commercial SmallSat business.

4) Take advantage of all space flight opportunities to flight test very important technologies that may have a long term strategic value to the intended SmallSat enterprise. Cubesats could greatly assist here and money might be made in the bargain.

5) Use every prudent SEE design trick-in-the-book in order to avoid single event effects (e.g. EDAC memory augmentation and very frequent data re-writes of all potentially susceptible memory buffer areas).

6) Adopt a SmallSat preferred parts list, which is based on the company's current in-flight experience. This strategy, of course, starts the company down the slippery slope toward technological obsolescence, which, by-the-way, goes hand-in-hand with "flight heritage." Balance here is important and prudent.

7) Accept reasonable reductions in overall system reliability as a part of the cost savings equation presented above for big vs. small systems. (See Figure 4 above). Remember, within the SmallSat philosophy there is the concept of "reliability commensurate with cost."

The piece parts issue does not end here either but, carries on further into the test regime and that will be discussed separately.

3.3.2 Worst Case Analysis

If this paper is objective then I must report, this is one topic that runs afoul for SmallSat in the comparison between big and small. Large spacecraft companies produce many documents as a part of their analytical evaluation within the design process. Most of these documents are of questionable value to small satellite systems with their far fewer parts and lower system complexity. But one of these documents looms above the others in its importance to all satellite designers: it is called the Worst Case Analysis (WCA). I have seldom if ever seen a SmallSat company perform a proper WCA on a unit, subsystem or system. The WCA is simple in principle but, difficult in its detail. In the case of a circuit design, the WCA looks at the circuit performance (eventually using high performance software tools like SPICE, where applicable) under the following conditions:

1) End of life degradation, including cumulative dose radiation effects

2) Worst case high and low power supply voltage conditions

3) Worst case high and low temperature environments

4) Degradation due to any specialized effect that can be defined (e.g. materials degradation effects)

And the WCA insists on applying all of these factors, in a worst case manner…at the same time. That is, they are all turned ON at the same time during the analysis. For a formal space program of a large satellite, the requirement is that the unit under WCA conditions must still function…and with certain established margins.

WCAs are time consuming because it takes real time and effort, within each satellite program, to obtain all of the information implied by the conditions given in 1) to 4) above. Consequently, this analysis can usually not be completed much before the time of the Critical Design Review (CDR). While such an analysis is not a trivial exercise, it is potentially very valuable. It would be valuable to SmallSats as well as big ones. Such an analysis is reasonably costly but, it should result in satellites working longer and… in a commercial environment…that is everything. To the service provider it is a better return on investment (increased ROR) and longer lifetime will also improve net present values (NPVs). It is a recommendation of this paper that SmallSat companies should adopt this analytical tool and service providers should insist on it in their CDRL lists and end item data packages (EIDPs). The WCA, of course, poses an extreme scenario to the unit under evaluation. It may not be realistic but, if the system, subsystem or unit withstand such conditions, then system managers and clients alike can be relatively confident that lifetime requirements will be met – IF the analyses are VALID. And, that is what design reviews should be for.

There are, of course, WCAs for mechanical components and subsystems as well as electrical ones. The difference is that mechanical tolerances and Eigen frequencies are substituted for voltages and currents and radiation effects may be considered nil. However, once again, the conclusion is the same: WCA are an important tool for ALL spacecraft engineers and system engineers.

In our evaluation then, SmallSat companies today do not measure up on the issue of WCA but, it's an area where improvement can be relatively easily made. If one wants to have a major impact on the question, "So, how long will it work in space?" then the WCA is a very useful tool in answering the question before the satellite is launched. The final word - the answer to the system lifetime question isn't just given by the WCA, however. In orbit results are the final answer. And the history of SmallSats, fortunately, proves that there is no reduction in the lifetime of a satellite system, simply because of its size. Some small satellites have survived in space for more than 30 years and many have fulfilled mission objectives for well beyond their design lifetime, as has been demonstrated by ChipSat, MOST, FedSat, UOSAT-12 and DMC (all mentioned above).

3.4 Assembly, Integration and Test (AIT)

Assembly and Integration: The process of Assembly and Integration of space systems vary less between satellite classes than uninvolved individuals might think. Historically, excess capacity in clean room facilities has been available to all interested small satellite firms or organizations, simply because of the large excess capacity within the aerospace or related industries (e.g. semiconductor industry). Further, it is not difficult to construct a suitable clean room capability at low cost, thus anyone who has really needed to integrate small satellite systems under similar conditions to those of large satellite companies has been able to do so. Put simply, obtaining a Class 100,000 clean area for satellite integration is no big deal…and it never has been (i.e., HEPA filters are not scary). It is unlikely to be a problem into the future and is low on the list of issues or differences between big and small. The number of MGSE and EGSE tools required to integrate a large spacecraft vs. a small one is a somewhat larger issue. Still, we might say that MGSE and EGSE costs are more or less proportional to satellite size and leave it at that. In fact, in this paper we are trying to identify issues where there is a non-linear relationship between big and little, not linear differences.

One thing has always been clear to companies and individuals that were serious about small satellite systems for commercial use. A space system, used commercially, must perform its intended function reliably and for a prescribed period of time (or longer). In order to make small satellites really reliable and to convince others (customers, investors, primary payload operators [if the small satellite is flying piggyback], and even component vendors) extensive functional and environmental testing is the only answer. The tests must also be well documented.

Testing: We jump back immediately to the piece parts issue, since the first test we can perform to convince others that the parts will work is a demonstration test. Normally, in large satellite programs "burn-in" (meaning functionally testing a component) lasts for

150 to 300 hours. Despite the name, burn-in is a room temperature test using EGSE providing flight-like stimuli. In order to be convincing, small satellite programs have often offered to test their units for up to 1000 hours of burn-in. SpaceDev offered this test method to NASA for flight components used on the ChipSat program. NASA/GSFC accepted this approach and integrated this test into their program test plan. This is a simple thing to do and an easy offering to make to a client. Other things can be done on the project while each individual unit is accumulating these hours. It's not really that expensive to accomplish. This simple type of added testing provides a higher confidence in the piece parts and at the same time gives additional insight into the functional behavior of the component.

A second method of providing added confidence is to environmentally test all hardware at protoflight levels (qualification levels for acceptance duration) regardless of the components development status or heritage. This becomes an essential point (a necessary point) when one considers the next issue.

If piece parts are the *major battle ground* issue between big and small then the subject of component level environmental testing is at least a *major skirmish* issue. Figure 9 shows the test flow for a typical component in a big program

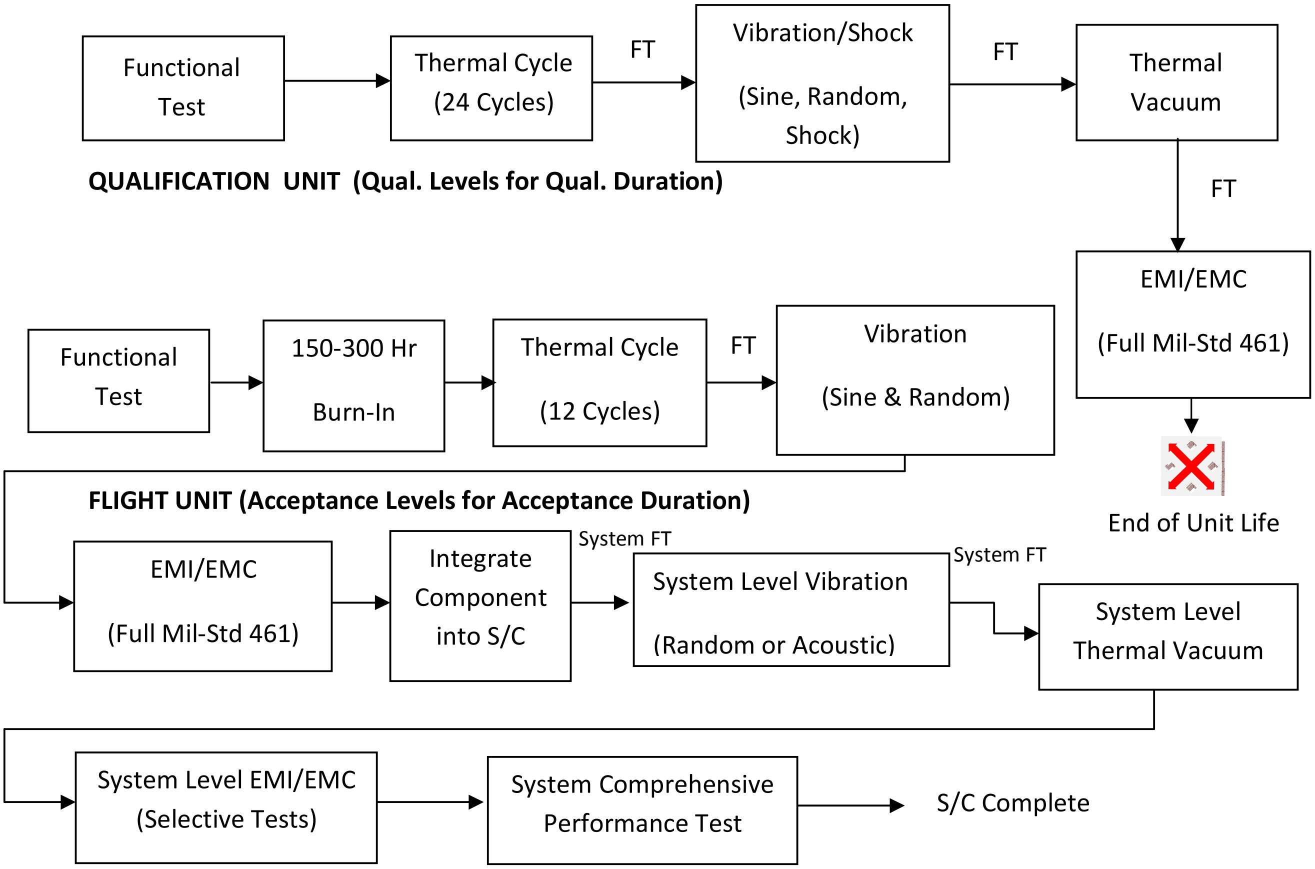


Figure 9: Large Spacecraft Component Test Sequence

Now we compare this to a typical SmallSat test sequence shown in Figure 10. We first notice that there is no real qualification for the small satellite component in that a unit is not tested to near its breaking point (i.e., until it is no longer considered flight-worthy and therefore it is retired). Rather a proto-flight approach is taken and a single flight unit undergoes some testing at the unit level but, goes all the way to flight. The contentious issue in this sequence for large satellite system engineers is that Smallsat companies usually do not subject the component to vibration or thermal vacuum at the unit level; only at the system level. The classical argument for *not doing it this way* is that having a component failure for the first time at the system level is far too risky. One should learn about the failure mechanisms of components soon after they are built. To wait until system level testing could be a disaster. But, that's big satellite thinking. One gets to system level testing much faster with the small satellite approach because one doesn't have to wait through the very long test program where units are, one after the other, put through vibration and thermal vacuum test sequences. So, one reaches TVAC at just about the same time as you would have with a big satellite approach, maybe even sooner. Once the components are integrated and functionally tested, the environmental levels established are proto-flight, not acceptance level. [NOTE: This is true regardless of the number of flight units built in the contract.] So, the system level test seen by the component prior to launch is more severe than the one seen by the large *flight* satellite system, on a per unit basis. The big satellite components, however, have seen two tests, which the small satellite community would say is unnecessary, wasteful and expensive. Just as important an argument in favor of this approach is the term "heritage" may now be applied to small satellite system testing. This process has been done this way for so long now and it has been so successful, that *success* is the strongest argument for continuing this methodology. *Small* can now play the same game as big.

PROTOFLIGHT UNIT (Qualification Levels for Acceptance Duration)

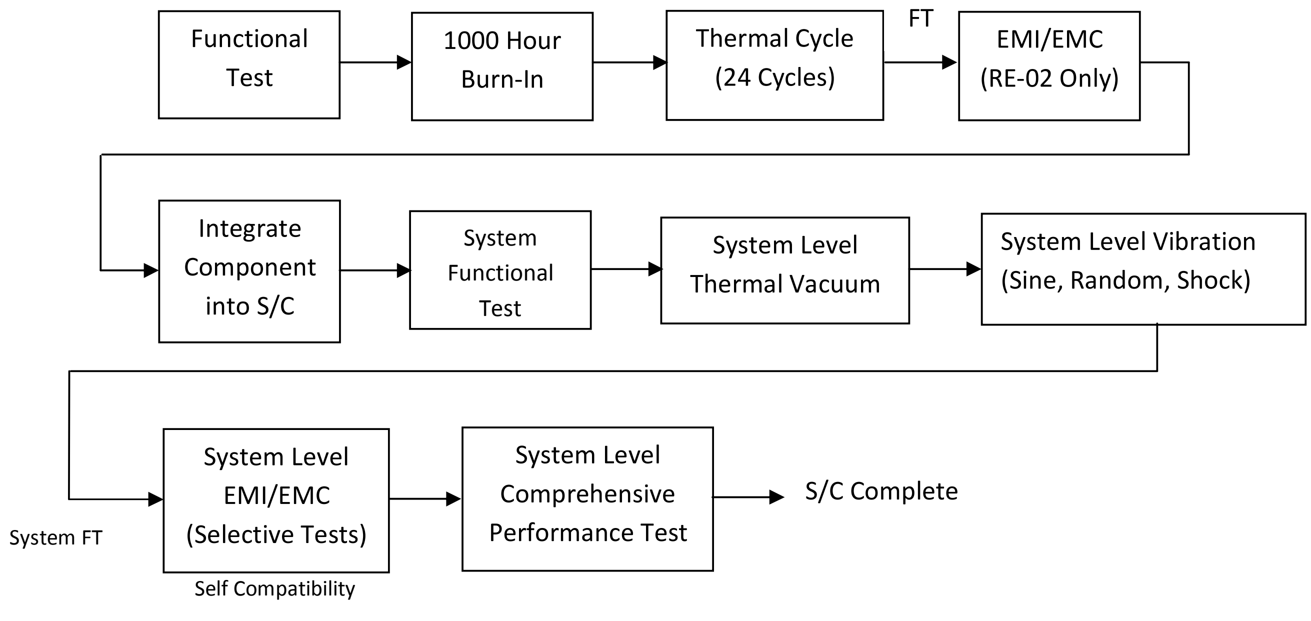


Figure 10: Small Spacecraft Component Test Sequence

Please note that I have ignored mass properties determination as a "test" here because it is a non-contentious activity and is not really relevant to the discussion. It would be accomplished in both cases.

We can take this one step further now. The SmallSat community has introduced the concept of a P-pod, or encapsulation device as a part of the separation system of a spacecraft from its host launch vehicle. A P-pod protects the launch vehicle or the primary satellite from a NanoSat or CubeSat which may become disassembled or which could otherwise cause damage during the dynamics of launch. For some spacecraft using this sort of separation system the launch authority has required them to environmentally test their spacecraft only to acceptance levels. The logic is clear, additional mechanical margin is not required to be demonstrated by test (only by analysis) and the P-pod acts as the safety valve in the event of a failure. Not all launch vehicle authorities have grated this reduced testing option, however, it is another example of how small is making advances and progressing in a direction that big can never go. If such a scheme can be adopted then Figure 10 is the same, except that Proto-Flight is replaced by Acceptance testing.

So what has happened here? We have reduced the schedule, cost and risk of over-testing every component in the spacecraft by modifying our test methodology. If the small satellite methods given here were applied to a large spacecraft it would indeed save a lot of money. As the system complexity of a small satellite is considerably less than a large one, then the savings for small systems themselves, by using these techniques, is only of a moderate value but, still quite significant. It is the comparison between small and big which is the important dynamic. What has been lost by adopting this approach? Only the possibility of not detecting a failure mechanism by test earlier than it would otherwise be found. In any case, if a TVAC or vibration test would catch a failure in the test sequence in Figure 7 then, it would also be caught in the test sequence of Figure 8.

3.5 The Role of Heritage

The role that heritage should play in space systems is another major skirmish area between big and small. Large satellite system programs often have a special design review known as an EQSR. That is, an Equipment Qualification Status Review. The purpose of such a review is to go over every component's design history and determine the need for additional testing or analysis in order to be certain that the component is ultimately "qualified" for flight BEFORE it is committed to flight. In a large satellite program an EQSR is held for every single component. In large satellite systems, one thing that can immediately qualify a unit for flight is if it has *flight heritage*. If the unit under question has successfully flown before, if the piece parts from which it was made are still available from the same manufacturers, and if the unit is fabricated with the same materials and to the same procedures and processes, then the unit is considered to have *heritage* with respect to the program holding the EQSR. Verification of qualification is indeed a worthwhile process. It is one of the steps toward improving overall system level reliability. But, the flip side to the heritage issue is "obsolescence." Are there competitive issues involved in continuously using heritage units? Competiveness factors are faced not only by the satellite vendor (where the engineers involved are well aware of advancing technology) but by the satellite customer as well. And, the customer may be far less aware when he attends an EQSR, that he has just accepted (by his approval) a unit that limits the competitiveness of his spacecraft, either immediately or some years down the road.

One would be much happier IF, at these EQSRs one more question were asked: "Is it likely that this component, if used in this current spacecraft system, will render it significantly less capable and competitive than a spacecraft I might buy from a competitor who is cautiously pressing forward toward the state-of-the-art in this area of technology?" Put differently, what performance is being lost (now or immediately into the future) by picking this oldie but, goodie? Competitiveness is important to all of us and so is reliability. Big and small must walk a fine line when it comes to heritage…BUT, small can take more risk than big is willing to take and, in the longer run…small will win this debate. Quoting Mr. Phil Davies, business development manager of SSTL in an editorial from Space News, *"The main reason that the performance of small satellites is improving at such a fast rate is their use of terrestrial electronics. As a result of using such electronics small satellite performance is improving at something approximating Moore's Law. The improvements are dramatic…"* 10. If anywhere, spacecraft technology is advancing at nearly Moore's Law pace, how much heritage can any of us afford in the commercial marketplace?

3.6 The Role of Redundancy

The role of redundancy is the final issue of contention between big and small.

Large space systems frequently use full redundancy. Everything that can be made redundant, is. In fact everything that can be made redundant and can be cross-strapped, is.

Small satellites use redundancy only when a critical component has been shown to have an unacceptable impact upon the system level reliability. Typically, power supplies and transmitters (both high dissipation components) are made redundant and, as discussed in section 3.3.1 of this paper, alternative technology redundancy is often used - where Side A is a state-of-the-art component which has risk but, addresses the competiveness factor we've just discussed and Side B is an older, slower heritage device. [NOTE that this latter alternative technology redundancy is not true redundancy, in every case. It may represent a "fail soft" strategy whereby, if the new, bright and shiny component fails, and if the heritage part is switched in, then some loss of performance results.] Ultimately, small satellites have the potential luxury of using alternative spacecraft redundancy. If the satellite total cost (including NRE) can be sufficiently amortized by a low recurring cost (made possible by mass production) then this strategy could be valid. This is certainly not an option for any large spacecraft systems. Launcher mass availability and cost alone would preclude such a strategy.

Redundancy always has a price. This fact is well known and frequently ignored. There are frequently multiple ways in which this price must be paid, depending upon the redundancy scheme. In the simplest case, if two redundant units must be functionally tested instead of one then it takes twice as long to do two tests than one. And, these two functional tests may have to be repeated many times during a satellite environmental testing program. That's obvious enough. But, if the unit is redundant and cross strapped to two other units the test time is now 4 X N, where N is the number of environmental tests requiring a verification of functionality. In actual fact, I once came across a group of engineers intent upon making a fault tolerant computer system which used triple redundancy; fully cross-strapped. Given the circuit topology with which they proposed to accomplish their redundancy scheme, they had 27 redundant paths to evaluate. The system never happened.

Another example of hidden cost and risk is also not new and also pretty obvious…but, worth ramming home again. If units A and B are redundant, how is the failure probability of the device that switches between A and B considered in the design? Is it redundant? In space system designs redundancy should not only be looked at in terms of reliability but, in terms of cost as part of a trade. This is just one more reason why big is non-linearly more expensive than small.

Another issue that surprisingly still remains between big and small is the use of an old analytical method used to estimate the system reliability of spacecraft. Large spacecraft manufacturers persist in using MIL-HDBK-217, version F or G, or whatever is current, for reliability calculation. It is still used by big GEO vendors for calculating "fits" and "9s." Clearly, if such an analytical method were valid, no satellite system using it (which meets the required analytical fit count or system reliability value) would ever fail to meet its mission lifetime. But, satellites do sometimes fail to meet their lifetime objectives. Even big ones sometimes fail. And, they fail more often than the handbook values would predict, all satellite systems which have used the handbook - taken as a group. Ergo, MIL-HDBK-217 doesn't work. It is not that the analytical methods given by the handbook don't work. It's the data put into the models created that is flawed. It's flawed because, by now just about everyone knows that the real reliability values for components (and sub-components and particularly, piece parts) cannot be accurately known or even properly estimated. It's curious that the handbook is still used by the satellite commercial sector when the U.S. Department of Defense (who originally drafted it) stopped using it about 25 years ago by Pentagon decree. Even NASA tends to rely far less on the handbook these days. The time and energy spent to properly construct and report the reliability of a satellite system using MIL-HDBK-217 is not insignificant when one considers it is applied in a large program to every component, every subsystem, and the spacecraft itself. It is another expense not incurred by SmallSats that the big guys routinely pay.

4.0 MARKETS AND APPLICATIONS

So far, we have looked at the distinctions between large commercial satellite systems and their small satellite counterparts – particularly with regard to their performance and design process. We've looked at why small satellites have a surprising comparative advantage such that the performance of a commercial spacecraft need not be proportional to the mass, power and volume differential between the two classes. We've looked at this from a technology perspective and from the perspective of the development approach that can and is being taken by both. Neither class of satellite system is new (as a product). Both classes are still evolving technologically and business-wise in their own right. Thus, we cannot claim or make a case that small satellites have suddenly appeared on the scene. They have not. They have been around for a pretty long time; long enough to be held accountable even in the commercial marketplace. Certainly the same is true for large systems. And from the perspective of this paper I am referring primarily to large GEO systems and large LEO systems used for non-communications applications as the points of reference. These large systems, to be sure, already are being held accountable for their performance in commercial markets. They are the benchmark against which SmallSat candidates can be compared. And the term SmallSat, once again, has been expanded to include the categories, MiniSat, MicroSat, NanoSat and PicoSat as evolving terminology within our industry.

Let's first look at the traditional commercial markets where today revenue (and in some cases, profits) are being made.

4.1 Telecommunications Satellite Systems

Communications satellites were unambiguously the first market in which any satellite made money. It should be the first mentioned in any market survey presentation.

4.1.1 Fixed Satellite Service, Broadcast Satellite Service and Broadband Communications Satellites

This topic is relatively easy to categorize. Despite the existence of small satellites in the commercial sector for 20 years there have been no commercial initiatives to provide communications services in the traditional Fixed Satellite Service or Broadcast Satellite Service frequency bands whereby the services would be provided exclusively, or even in part, by small satellite systems (once again, meaning Microsatellites or smaller). We know this because such systems must be licensed and the licensing process in almost every western country is a public process and applications for service are circulated publicly. When the notion of constellation satellite systems began to be seriously considered in the 1990s only a few constellation FSS applications were ever filed at the ITU. These included, in 1994/1995 Teledesic (a broadband system containing no less than 840 satellites) and in 2000/2001 a French system known as Skybridge (a system using 80 satellites in 1500 km orbits using 20 orbit planes) which was both a broadband and a digital media broadcast system but, the satellites in these constellations (all in the multi-kilowatt range) could hardly be thought of as small satellites. In any case, in the end, neither of these systems came to fruition and the enormous capital costs of these systems always made the programs dubious with investors. However, both organizations were instrumental in making changes to the ITU regulations and introducing the concept of non-geostationary satellite orbits into the table of frequency allocations. This paves the way for future non-GEO and potentially, Smallsat solutions for the provision of commercial satellite communications.

Entering the FSS marketplace with Smallsats has been and remains a scaling law problem. This was also noted in Section 2.3.3. In order to serve the same area of the Earth with multiple small satellites as one could do with one GEO, it is necessary to use many small satellites each contributing EIRP to a select and smaller portion of the service area in order to establish the same EIRP density over the total service area. This could also be done with larger small satellites using multiple beams. If you work it all out, accounting for the fact that the LEO smallsats are closer to the Earth and need less power but, the number of them is larger to cover the same region of the planet, you lose with a LEO Smallsat constellation because N Smallsats, each 1/N as powerful as the GEO are more expensive, because satellite scaling is not linear [I/Nth of a GEO in performance doesn't cost 1/Nth of a GEO - it costs more than that]. And the satellites move relative to the Earth as well as the subscribers being served. Thus, more satellites are once again needed to deal with this problem. It's a losing proposition. So, it is not surprising that there are no such systems. The reality is, the FSS and BSS market have, since the earliest commercial satellite days, been dominated by geostationary satellites, and other means of providing service are rarely even thought about. It's simply an area were small satellites are poorly suited – full stop. By the way, smallsat GEOs have been thought about and do exist but, these "small satellites" (used for place holders and gap fillers) are still in excess of 1000 watts. So, for this application, keep your Cubesats in your pocket.

4.1.2 Mobile Satellite Communications Systems (GEO; Big and Little LEO Systems)

The ITU category of service known as Mobile Satellite Service [which comes in sub-flavors such as Maritime Mobile Satellite Service (MMSS), Aeronautical Mobile Satellite Service (AMSS) and Land Mobile Satellite Service (LMSS)] exist for both GEO and Non-GEO systems and spectrum exists in these categories because companies have gone to battle at the ITU to win this spectrum. The dominant players, some would say, are still large GEO systems. In MSS, however, there are serious constellation contenders to the GEOs in the form of a service known as BIG LEO MSS. This is the realm of Iridium and Globalstar. These are satellite constellations with from 66 to 24 satellites (depending on when you count) which provide global telephone service and now, ever expanding data services. And these constellations have significant capacity. But, they are **BIG** LEO systems. The satellites weigh in at about 700 Kg and produce about 1500 watts of solar array power at the end of their lifetime. So, these don't count as a part of our community of SmallSats.

But, there is another service that is active within the MSS family and it is known as Little LEO. And Little LEO is the domain of small satellites. First championed by Orbital Sciences Corp. (Orbital) who created the subsidiary ORBCOMM, spectrum was allocated for this service for data-only mobile communications (by the ITU in 1992 and by the FCC in 1993). ORBCOMM launched a constellation of, ultimately, 38 spacecraft in its first generation. Each weighs 90 lbs and generates 160 watts. The constellation was in full service by 1998 and the first generation system is still operating today. 13 years have passed. The system, after a few start-up issues – works. However, it is a fact that the system, which cost in excess of $400M on-orbit, filed for Chapter 11 bankrupcy in October of 2000. The original investors did not prevail and the system survives under new ownership. The second time around, with a lower cost base, the system has grown. There are now more than 575,000 subscribers on the ORBCOMM system and the company is purchasing its second generation of satellites. For constellations, fielding the 2nd generation is a major hurdle, as the capital necessary to do this must come, ultimately from revenues earned from the first generation system plus new equity and loans – paid back, eventually, from service revenues from the second system. So, this is a major achievement, however, it is accomplished. While it has been a rocky road for ORBCOMM and while the original team (written about in books –see *Silicon Sky* by G. Dorsey) is no longer around, the dream lives on. And the dream has been expanded. The older notional digital mobile message concept has now become known as M2M or machine-to-machine communications. The focus of Little LEO is now to remove man from the loop. Perhaps, this is progress. Or at least it's packaged differently.

And, there is a particularly important achievement of ORBCOMM, accomplished along the way. ORBCOMM went public. So far as I've been able to determine ORBCOMM is the first and only Smallsat company who planned from the onset to build a business based on Microsatellite technology, raised money in the market place to do so, did battle successfully at the ITU in order to start an entirely new service and then completed a successful Initial Public Offering. Then, they built and launched the satellite constellation using OSC satellites and launch vehicles. So, while MSS in general – for any company in the business (big or small) - has been marginal – you can buy shares in ORBCOMM. Check it out. It is the only Small Satellite stock one can buy on the open market from a company that started life using small satellites as a part of their business plan and as their goal. By the way, just a small aside: The original reason for the creation of the air launched vehicle (ALV) known as Pegasus was because OSC wanted to have a means of launching their own small mobile satellite constellation into orbit. So, it looks like, for better or for worse, OSC was successful in what they set out to do technically – on all counts. It would be nice if there were a happier ending to this story for the original OSC investors.

There have been other companies that have been involved in the Little LEO world. SpaceQuest and VITA are two organizations who have launched satellites in Little LEO service technically, however, both of the systems fielded by these two entities actually fit better into our next category of commercial communications satellite system.

4.1.3 Niche Applications for Communications

It is this communications application where Smallsats have had great potential. And, despite the great potential opportunities the Smallsat community has gotten off to a very slow start. Many applications that have been identified for decades (from reading water and electric meters to monitoring the health polar bears) could have been done by small satellite. They weren't. We weren't fast enough and clever enough to figure it out. Some of these applications have now been aggregated by satellites offering MSS services, including ORBCOMM and their M2M but, many needs have been satisfied by NASA satellites or weren't served by satellite at all. Perhaps the best example of a missed opportunity by the community was in Supervisory Control and Data Acquisition (SCADA). SCADA is a term used primarily by the oil and gas industry. A very large number of valve manipulations and pipeline measurements are needed in that industry. Of course, originally these were done manually. By the late 1970s that industry was looking for an automated solution to SCADA. Oil and gas fields close to urban centers could use wireline solutions, however, more remote locations could have made use of small satellite data relay as their solution. But, we weren't there with the needed solution in the right time window. By the time most of us figured out how to solve various spectrum allocation and system financing problems (having a technical solution in our hands) the petroleum industry figured out that a variation to a form of packet radio would allow them to relay their data from one end of a vast oil field to another – via ground radio and then relay the aggregate block of data from one single point via VSAT terminal or microwave link to a central location. Arguably, some amount of this business may ultimately revert back to the Little LEO satellite systems as time impacts the technology cost equations but, the initial market need was satisfied by means other than via satellite. It was a definite opportunity missed. To be fair, it hasn't always been that opportunities were missed because our community wasn't trying or wasn't aware (SCADA being a case in point) but, in business, good intentions don't count. We didn't produce the goods when the gate was open.

Now, however, 20 years after searching the communications marketplace for niche opportunities it looks like we have found at least one winner.

AIS: AIS, is an **A**utomated **I**dentification **S**ystem and a tracking system for ships. The International Maritime Organization's (IMO) International Convention for the Safety of Life at Sea (SOLAS) requires AIS to be fitted aboard international voyaging ships with gross tonnage (GT) of 300 or more tons, and all passenger ships regardless of size. While originally intended as a VHF line-of-sight system, the small satellite community realized that, with certain limitations and with clever technology, it would be possible to extent the range of the system from line-of-sight (really meaning about 75 km range) to a global system. Many markets exist for the data, even beyond local port authority monitoring of equipped vessels. Both Microsats and Nanosat versions of in-orbit AIS receivers have appeared in orbit very rapidly. Two major players, ORBCOMM and COMDEV have fielded trial payloads on Microsatellites using two different technical approaches. ORBCOMM detects and analyzes the signals on-board, while COMDEV post-processes their received data on the ground. As AIS was originally intended only for local use, this adaptive TDM system cannot be used as-is by satellites, since the thousand of ships in view (as seen from orbit) produce too many packet collisions, resulting in significant data loss. The system occupies only a single VHF channel. However, these collisions can largely be sorted out by Doppler discrimination or by other proprietary methods and that can be achieved on-board the spacecraft or on the ground.

While these two larger companies have been competing for this new marketplace, a consortium of Norwegian organizations, working with Space Flight Laboratories of the University of Toronto (UTIAS) has launched AISsat as another entry into this market. AISsat is a Nanosat. The system is up and running and working with excellent performance. Results will be reported at this conference.

The U.S. company SpaceQuest has also been involved in AIS from the beginning of AIS space tracking. Using an on-board processing and decoding techniques and a simplified hertitage Nanosat platform, SpaceQuest launched an AIS "transponder" in 2007 and brought the VHF AIS signal composite down on an analog link at S-Band. Having the signal structure available to analyze on the ground, allowed them to determine the key characteristics of an on-board decoder system. In July of 2009 they launched two spacecraft (ApriseSats 3 and 4) which have AIS receiver/decoders that are now operational and provide daily data returns from 25,000 unique vessels every day. SpaceQuest expects to launch more of these spacecraft in 2011, 2012 and 2013, showing that even a small business can finally compete in the larger marketplace using Nanosat technology. 12, 13

This will not be the end of the AIS space systems deployed as ESA and other individual European countries are also developing receivers for small satellite platforms.

We find in this example what we should find in any vibrant marketplace – competition. Not something we've seen a lot of within our community in the services sector. However, there is a special kind of competition within AIS. Note that the bigger guys (in this case, COMDEV and ORBCOMM) are using Microsatellite technology while the smaller players are using Nanosat technology. And, to me as an unbiased observer, the results look about the same among all of the techniques being employed so, the best bang for the buck, looks like the Nanosat solutions. Perhaps I'm missing something, however, one can imagine that we aren't too far away from using 3U or even 1U Cubesat/Picosat technology for the next generation AIS system. In the end, as in all markets the best product with the lowest price will prevail. This is an exciting outcome in the Telecommunications satellite field. In the end, however, it may be value added services that discriminate these competitors, since the markets that consume the AIS data are vast and not at all those that you might first expect. For example, commodity traders are using this data to evaluate the distribution of world energy at every instant in time and at every location as an aid to setting short term (spot) oil prices. It is also likely that this application will show a merger of terrestrial and space technologies to provide holistic solutions to global transportation problems via the high seas.

Despite my own personal drive, energies and enthusiasm put into this arena over many years, current Smallsat (meaning very specifically microsatellites and smaller systems) results are rather disappointing. As was pointed out in section 2.2.3 above, small satellites of this class cannot compete with traditional large GEO systems due to fundamental EIRP limitations and reasons were pointed out why simple or even clever satellite proliferation is not really a very good or cheap answer either. Despite these limitations there are any number of communications niche markets that present themselves from time-to-time and are suitable for entry by SmallSats and yet, their exploitation has been slow on the uptake. And, there is no shortage of advanced available technology to do the job; quite the contrary. It is gratifying that AIS has truly taken off and is very competitive. This helps resurrect my earlier (2009) opinion about the telecommunications markets. The fact that ORBCOMM has struggled through incredible obstacles and survives today, as a public company, is also encouraging. These examples show that it is possible to make money with Small Satellites.

4.2 Earth Observation Satellite Systems

By "Earth observation" I include all remote sensing satellites that image the Earth. I do not include here other kinds of sensors that may observe the Earth in some other way. I'll include those instruments in a separate category. The results in this category are more favorable than the results-to-date in telecommunications. Having stated this, I'm fairly certain that it is still a rare occasion when, in the Earth Observation/Remote Sensing world a SmallSat dollar of profit is made.

For the moment, let's focus on markets other than the more dubious meteorological market as that one is so heavily dominated by government agencies worldwide that it is difficult to assess prospects even for large systems, let alone small ones. Thus, we are referring here to panchromatic and multispectral imaging systems that use wavelengths between the IR and the high end of the visible range (or, possiblly long UV range).

The first such satellites were large satellites. Landsat was the first. It wasn't originally commercial but, the system has tried to turn commercial but, with great difficulty. No wonder. The second system, which is commercial today, is Spot Image of France. It is a large system. Early satellites were built by Matra of France. Time moved on, slowly. The next to enter the market was Digital Globe with eventually three large satellites: QuickBird, WorldView-1 and WorldView-2. After Digital Globe, the next to enter the market were OrbView (an OSC company using OSC medium sized spacecraft) and Space Imaging. Space Imaging launched a large and well publicized satellite called IKONOS. Space Imaging was a spinoff of Lockheed-Martin and Raytheon. So, no surprise, IKONOS was certainly not a SmallSat system. In 2005, OrbView and Space Imaging merged and formed the survivor company, SpaceImage. NOTE: Both companies had filed Chapter 11 prior to the merger. So, apparently, even the government markets for sub-meter resolution images were insufficient for the two of these companies to survive in competition.

The U.S. government, under the Bush administration, introduced a relaxed remote sensing space policy in May of 2003. This policy allowed commercial remote sensing companies to provide to the open market (under certain conditions) imagery with a resolution below 1.0 meters for the first time. The certain conditions have to do with companies providing the government with a right-of-review, in some cases, before the imagery is released. This greatly increased activity and interest in the Earth imaging markets.

A final large satellite player entered the market in 2008. LAND *Info* with sub-meter imaging using a satellite called GeoEye-1.

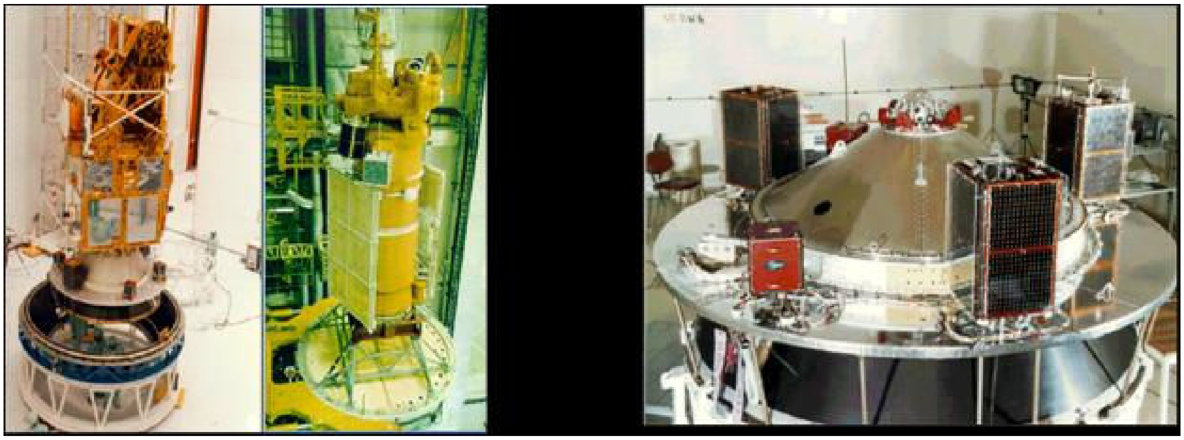
The above is the large satellite playing field as it is today, although there are more international players than are mentioned here. Russia, Israel, India and China all have quasi-commercial offerings available. Table 6 summarizes the system capabilities of the companies mentioned above.

Table 6: Large Earth Imaging Spacecraft Characteristics

SYSTEM CHARACTERISTICS: → *OPERATING ENTITY:* ↓	*Spacecraft:*	*M.S. Resolution (m):*	*PAN. Resolution (m):*	*Launch Mass (Kg):*	*Platform EOL Power (W):*	*Spacecraft Design Lifetime (years):*
Landsat	Landsat-7	15-60 m	15	2250	2600	10 years (beyond design life)
SPOT Image	SPOT-5	20-10 m	10-5 m	3030	>1500	5 (beyond design life)
Digital Globe	Quickbird	2.4	0.61	955	>2000	7.25
	Worldview-1	1.84	0.50	Full ΔII 7920 L/V	>2000	7
	Worldview-2	1.84	0.46	Full ΔII 7920 L/V	>2000	7.25
Orbimage (Space Imaging +ORBVIE	IKONOS-1,-2	3.28	0.82	818	>1500	7
	OBRVIEW 3,4	8.0	1.0 - 4.0	304	625	5
LAND*Info* . (+ Google)	GeoEye-1	1.65	0.41	1955	3860	7 years w. 0.75 Sys. Rel.

Approaching remote sensing from an entirely different perspective, in 2002 and 2003 Surrey Satellite Technology Limited (SSTL) launched a constellation of four satellites each weighing approximately 100 Kg each. Each spacecraft contains a Multispectral imager with a resolution of 32 meters and a scan width of 600 km. The spacecraft, taken together are known as the Disaster Monitoring Constellation (DMC). Each spacecraft was purchased by a different client country. The initial members of the DMC consortium (formed by the purchasing countries) were Algeria, Turkey, Nigeria and the UK. In 2005 China purchased a 5th DMC satellite from SSTL. Eventually, China also joined the consortium. That spacecraft is now known as Beijing-1. This added a satellite to the constellation, however, it is a slightly larger spacecraft weighing approximately 150 Kg. This spacecraft contains not only the standard 32 m GSD multi-spectral (3 band) imager but, also a 4m GSD panchromatic imager as well. Each DMC spacecraft contains the standard 32 m GSD multi-spectral camera plus one additional imaging instrument of the customer’s own choosing. The satellite orbits are arranged as a “string-of-pearls” and are spaced to give a one day repeat ground track. The countries who purchased the satellites have agreed to share the resources of the constellation and, in fact, sell imaging products to interested customers through a SSTL subsidiary DMCii (DMC International Imaging) as well as using the imagery for their own purposes. The DMC system trades resolution and a wide swath width for reduced revisit time. As its name suggests, the purpose of the constellation is to provide imagery for the monitoring of disasters and wide area dynamically changing events. The spectral bands chosen and the swath width are ideal for disaster monitoring. Images from the Beijing-1 4 m panchromatic camera are also for sale. An example of this imager’s capability (arguably, after image processing) is shown in Figure 11. To get the full impact of this amazing step forward have a look at Figure 12. Figure 12a is a photo of the SPOT-2 Earth Imaging spacecraft preparing for launch on an Ariane-4 in Kourou. If you look carefully below the SPOT spacecraft you will see several very small secondary payloads in that image. The largest of these is an SSTL satellite that is in the same general size class as the DMC spacecraft. Figure 12c is a photo showing three SSTL spacecraft affixed to the Ariane-ASAP secondary payload ring at much closer range. These are the same size SSTL-70 spacecraft platforms as the one seen in 12a. These spacecraft are about 30% smaller than the standard DMC spacecraft and about 50% smaller than the spacecraft that took the Figure 11 image. The Beijing-1 spacecraft, after completion of integration is shown in Figure 13. One cannot help but notice the size of the primary instrument aperture in comparison to the total spacecraft size. There seems to be very little spacecraft to point a lot of imager. Staying with the SPOT Image juxtaposition, we can compare Beijing-1 to SPOT 5, the most recently launch SPOT Image satellite (May 2002). See the summary in Table 7. Information for this table was taken from a variety of website sources.

Figure 11: 4m Resolution Image from Beijing-1



12 a 12 b 12 c

Figure 12: SPOT-2 vs. DMC Satellite Comparison

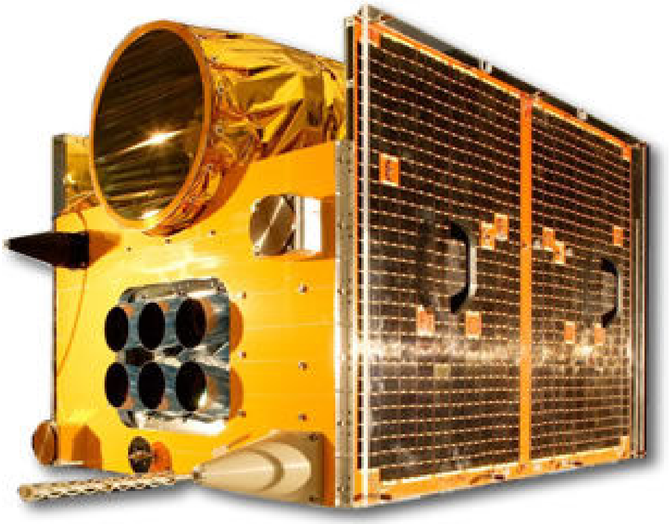


Figure 13: Beiging-1 DMC Spacecraft

Table 7: SPOT-5 vs. Beijing-1 (DMC)

Parameter:	SPOT Image - SPOT-5	DMC - Beijing-1
Mass	3030 Kg	150 Kg
Power	>1,500 Watts Orbit Average	110 Watts Orbit Average
Panchromatic Resolution (Raw)	5 m	4 m
Multispectral Resolution (Raw)	20 m	32 m
Estimated Cost	>$680M	<$15M

To be fair, the geometric distortion of images from the larger more expensive spacecraft is lower than those from these low cost missions. So, the markets for the imagery from the two classes of system are not quite the same. Nor were they intended to be. Presently, these disparate classes of space systems serve quite different markets. However, it is not very difficult to see where all of this is all headed.

In 2008, a firm called RapidEye AG took delivery from SSTL of five Earth observation satellites. These spacecraft were also intended to be flown as a constellation in order to significantly reduce revisit time to any location on Earth. In this case MDA (MacDonald, Dettweiler & Associates, Ltd.) of Canada acted as prime contractor for the system and SSTL provided the platform. The imagers were designed and fabricated by Jena-Optronik, GmbH of Germany. The five spacecraft were successfully launched (on one DNEPR launch vehicle) and were placed into service in August of 2008. The spacecraft (RE-1 through RE-5) are identical and carry 3-band multispectral imagers with a resolution of 8 meters. Each satellite's mass is 120 Kg and the platform produces just over 100 Watts of orbit average power. This program was a $100M effort for five spacecraft. RapidEye AG is a firm with long standing contracts for image analysis in the agricultural Earth observation market sector. They intend to expand into the forestry, energy & infrastructure, spatial solutions, environmental solutions and security and emergency markets. RapidEye has benefited from a public/private partnership with DLR, the German space agency. They were also co-funded for the development of the space segment by the European Regional Development Fund (ERDF).

So, now there are not just one but two, very serious entrants into the Earth Observation market using, indeed depending upon, small satellite technology. The bottom line in the Earth Observation market, given good quality control of the data product, is the price of the image per unit area. Tables 8A and 8B are an attempt to show how well Earth observation companies using SmallSat technology can compete within the overall market. It is worth noting that DMCii has made sufficient revenue to purchase one additional DMC second generation spacecraft which has now been launched as the sixth satellite in the constellation. This bodes well for the business success of the entity.

Table 8A: Large Earth Imaging Product Pricing

System:	Product:	Price Base:	Product:	Price Base:	Minimum Order:
Orbimage:	NO COMMERCIL PRICING AVAILABLE ON WEB				
SPOT Image:	Archived Image (1986-2006)	$0.44/km²			Depends on Sat. Viewing Angle 400-3600 km²
	Level 1A, 1B,2A 10m Color 5m B&W	$1.00/km²	Level 1A, 1B,2A 20m Color 10m B&W	$0.70/km²	
	Orthorectification	+$260/image	Orthorectification	+$260/image	
GeoEye: (Land*info)*	50 cm - 1.65 m PAN, PSM or MS GEO (Non-Ortho)	$25.00/km²	1m - 4m PAN, PSM or MS GEO (Non-Ortho)	$20.00/km	New Collection: 100 km²
	50 cm - 1.65 m PAN, PSM or MS GEO Professional Orthorectification	$30.00/km²	1m - 4m PAN, PSM or MS GEO Professional Orthorectification	$25.00/km²	

Table 8B: SmallSat Earth Image Product Pricing

System:	Product:	Price Base:	Product:	Price Base:	Minimum Order:
DMCii:	Programmed 32 M; 3 Band MS	\$0.164/km^2	Orthorectification	+\$734/image	Minimum Area: 160 km X 160 km
	Archived 32 M; 3 Band MS				
	< 1 year old	\$0.063/km^2	Orthorectification	+\$734/image	
	>1 year old	\$0.018/km^2	Orthorectification	+\$734/image	
	4m PAN	Call For Price			
RapidEye:	Standard from Kiosk 8m; MS	\$2.50/km^2			\$65 min.
	Standard from Library 8m; MS	\$1.25/km^2			\$3300 min.
	On Demand 8m; MS	\$1.25/km^2			\$6600 min.
	Geo Corrected Level 2A	Call for Price			
	Orto Corrected Level 3A	Call for Price			

4.3 Remote Sensing (Non-Imaging) Satellite Systems

We have a slight problem with terminology in this area. Nearly everyone would agree that remote sensing includes Earth imaging. However, the intent in this section is to describe commercial mission efforts using instruments that sense the Earth in some way but, do not image the Earth. Thus, I will refer to this class of systems as simply "Remote Sensing (Non-Imaging). "

Since the 1980s when SmallSat technology became feasible for non-imaging remote sensing commercial missions, several initiatives have been tried. Most of the instruments of interest in this category measure quantities that would be generally categorized as meteorological. Thus, the primary customers for such data products are government meteorological organizations around the world. NOAA is the best U.S. example and the European Centre for Medium Range Weather Forecasts (ECMWF) is a European example. And, as it turns out, such government organizations don't always make the best clients for emerging remote sensing technology, even if the entrepreneur might offer a much lower cost data product for weather forecasters. Other clients for mature data from remote sensing instruments exist. The airline industry is an example of a potential consumer for certain specialized weather prediction data products. But, one needs an "anchor tenant" for such businesses. And, that customer must first embrace the value of the new remote sensing information in the context of improved weather prediction/forecasting. Realize also, that the same organizations that predict weather also develop their own instruments to predict or forecast weather (NOAA and NASA, working together, are a prime example). This puts emerging remote sensing technology in immediate competition with sensors being developed by these agencies if the government instruments might happen to measure anything similar to the data products being proposed by the entrepreneur. Also realize that such organizations have been around for a very long time and are conservative by nature. The National Weather Service, the forecasting branch of NOAA is, interestingly enough, the most sued organization in the United States. They are sued; it seems, by everyone who has a "bad day" when a weather forecast is less than accurate. This would explain why NWS is conservative. Now we begin to see the stage that an entrepreneurial remote sensing CEO would have to occupy as he/she strides into the NOAA Administrator's office with a bright new idea for a service that, once installed, would improve weather prediction and save taxpayer dollars.

Several instruments that fit this general scenario have been offered, none-the-less. These include small satellite scatterometers, radar and laser altimeters, radiometers and various forms of what has generally been categorized as GPS Occultation Receivers. Other kinds of instruments such as various space weather detection devices and even earthquake detection sensors have also made attempts at starting new niche markets of one sort or another. None have been successful so far.

Perhaps the best attempt, to date, was made by two entrepreneurs who also happen to work at the National Center for Atmospheric Research in Boulder, Colorado. By name they were Mike Exner and Randolph Ware. In fact, they worked for a spin-off of NCAR known as UCAR, the University Center for Atmospheric Research. Both of them were fascinated by the opportunities being opened by the GPS system (once Selective Availability was turned off). Mike and Randolph had worked with JPL on research which demonstrated, as with any planetary atmosphere (the JPL connection comes in here), a radio wave transmitted from outside the Earth's atmosphere will bend toward the normal as it passes through the ionosphere and atmosphere of that planet. This process, of course, is simply, RF diffraction. If the signal source happens to be a very well calibrated source in both phase and frequency (like GPS) then a satellite in LEO orbit can observe this ray diffraction whenever a GPS satellite rises or sets on the LEO's horizon. Since there are lots of GPS satellites (and there could be lots of LEOs containing a receiver to make such measurements) then such a system of LEOs and GPSs could observe many risings and settings (called occultations) every day. The precise amount of bending of the ray (measured in terms of phase and frequency change of the GPS signal), it turns out, allows a very precise measurement of temperature and relative humidity as a function of precise altitude. Working with a variety of small companies and JPL, Exner and Ware developed an instrument (a specialized GPS receiver with specialized antennas) that was then flown on a target of opportunity mission offered by Orbital Sciences Corp. The target mission, called Microlab-1 was executed as planned and the instrument (called GPS-MET) worked wonderfully well. All, including NSF, NCAR, NOAA and NASA/JPL were impressed with the proof-of-concept data. Time went by. It was very difficult for Exner and Ware to convince NWS/NOAA, the obvious client for the data, to sponsor an operational set of small satellites. The ideal system would be a mini-constellation of SmallSats carrying the receivers in a near polar orbit. Such a system would produce thousands of occultations per day distributed fairly evenly around the globe. The real time nature of the data set was determined to be sufficiently good to predict winds and wind gradients over ocean areas, as well. Wind vectors and wind gradients, particularly over ocean areas, are data products that have long been sought after by forecasters.

Exner and Ware, after trying to make the economics of their venture work domestically but, without the U.S. weather forecasting community finally decided to try another tack. The business case did not close. It turns out the country of Taiwan is very interested in weather forecasting. This has something to do with the Typhoons that rack their shores every few months, one supposes. NCAR has a long standing relationship with Taiwanese weather forecasters and with NSPO, the National Space Planning Organization of Taiwan. NSPO was interested, in fact motivated, to find a mission that would provide some scientific return that would help Taiwan and at the same time had potential commercial viability. What emerged was apublic/private partnership and a mission called COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate). The mission was developed largely by NSPO using $80M of Taiwan funding and $20M in U.S. funds to construct six Microsatellites, each carrying a GPS occultation receiver. Two other smaller instruments are also on-board the COSMIC satellites. In Taiwan, the system is now also known as FORMOSAT-3. Eventually, the constellation was launched in 2006. The satellite platform contract went to OSC in the U.S. but, the spacecraft were integrated by NSPO engineers and technicians in Taiwan. The GPS receivers, I believe, were provided by JPL. They are known in JPL circles as “turbo-rogue” receivers. Taken together, the constellation has observed over 2.9 million GPS occultations to date, providing a wealth of precise altitude temperature data as well as space weather data products pertaining to the E and F layers of the ionosphere. No such similar capability exits: a clear success for SmallSats. The spacecraft weigh 70 Kg each and are based on the ORBCOMM platform design.

But what happened to the entrepreneurs, Michael Exner and Randolph “Stick” Ware and their corporate venture to sell GPS occultation data to the meteorological community? Well, who knows where they are today? The governments of Taiwan and the United States managed to make sure that the project became *a government program* within their respective domains. No small company was set up, as promised, to process and provide data to the government forecasters around the world. No private capital was ever even allowed to be raised so that the system raw data and processed services could be offered on a commercial basis. Even though Exner and Ware managed to get the U.S. congress to set aside funding from NOAA and NSF creating a process called a “data buy” (whereby the government can procure data from a private firm who can offer special, one-of-a-kind data or information to those needing it within the government), NOAA and NSF never used that feature to obtain GPS occultation information. Even though an American company, with a sister organization in Taiwan would have been ready to approach the capital markets to fund the venture themselves, it never happened. This ends my sad tale about GPS-MET and the adventures of two remote sensing entrepreneurs. [NOTE: World governments - 2; SmallSat entrepreneurs – 0]. This story ends curiously: NSPO, it turns out, was set up under Taiwanese law, not to build satellites but, to fund space-based applications that could be spun-off into the public sector so that the funding would create jobs and economic opportunities in Taiwan. FORMOSAT-3 (COSMIC) was NSPO’s “last chance” to accomplish a successful spinoff. It’s curious how things turn out sometimes, isn’t it? Anyway, it is a success story for small satellites, just not for commercial small satellites. You can read about how this venture progresses on the web.11 It’s an on-going saga. The latest from the COSMIC website, www.cosmic.ucar.edu is that there will be a FORMOSAT 7/COSMIC-2 collaborative between NSPO and NOAA but, this constellation of 6 satellites will use different instruments, which could still be categorized as Remote Sensing (Non-imaging). Perhaps the Taiwanese government gave NSPO another last-last chance? There doesn’t look to be too much room for entrepreneurs here either.

There is a new initiative involving space weather missions. NSF is funding a series of space weather payloads and platforms by means on an annual “Cubesat-based Science Missions for Space Weather and Atmospheric Research” solicitation. The first solicitation was initiated in 2009 and it appears that the program will be re-funded annually. Early results appear promising. The University of Michigan RAX mission is the first of these missions to obtain orbit. While the spacecraft encountered a premature failure of its solar array, this did not occur until the instrument had been calibrated using a real PAVE PAWS radar signal. It is clear that there will be other Cubesat spacecraft to follow carrying an array of space weather instruments. This is an excellent outcome, generally but, it doesn’t really say anything new about the potential for Cubesats or Nanosats to make money in the marketplace. There is the possibility, however, that if one of the space weather data products has a long term value, particularly in forecasting, then it may be commercially viable to provide that data service by means of the “data buy” mechanism mentioned above so far as the U.S. is concerned, or via a similar means in other countries. Once again, a Public/Private partnership, if it really worked, could be employed.

Thus, there is no really good news to report in the commercial category: Remote Sensing (Non-Imaging). This category gets a zero in the matrix for now but, there is potential promise for the future. There is room for some optimism – but, not much.

4.4 Small Satellites and Science as a Commercial Business

This too has been tried. It has been shown definitively, by way of an existence proof, that small satellites can do good science. The Canadian MOST project is probably the most successful and productive example. How can this process be turned into a commercial business? The late Jim Benson, founder of SpaceDev, had a few good ideas in this regard and perhaps, some we shouldn’t talk about as well. One of his good ideas failed, unfortunately, in the execution phase. The idea is simple enough in principle. If one builds a reasonably standard bus or platform, much like SSTL has done with their SSTL-70 or SSTL-100 product, then it is possible for an enterprising company, given the availability of such a product, to approach a principle investigator (PI) [typically a professor at a university] and form a partnership with the university. A joint proposal could then be submitted at the time of the next satellite mission proposal opportunity (e.g. NASA or ESA solicitation). They would work as a team. The thought process here is logical. More often than not, PIs and universities are not satellite platform experts and having to do all of the non-recurring development of a space platform at the university would add unnecessary cost to a program. Of course, large spacecraft suppliers can and do do the same thing but, their bus products are more expensive. Even some companies (Ball Aerospace comes to mind) specialize in medium to small sized science spacecraft and they are a significant competitive force for the far less well known SmallSat companies. The real advantage of a SmallSat science approach is that the cost of the overall mission is low enough that the spacecraft can be dedicated to (i.e. focused upon) a single mission purpose – a single instrument spacecraft mission – no design compromises would be necessary.

The problem that arises first: such an approach is not traditional. Traditionally, NASA flies what could be called "theme" missions. All PIs that have developed instruments which support or lend credibility to a particular theme, and may provide the answer to yet another riddle of the cosmic puzzle, are invited to propose. This scenario, while increasing mission risk, makes considerable sense in the context of instrument synergy. One instrument may not answer a certain scientific question but, two or three instruments, each of which measures a synergistic quantity, may indeed answer the scientific question. So, there is little room here for SmallSats performing theme missions unless the PI instruments are all very small and not very power hungry. This is somewhat unlikely.

The problem that arises next: We all know you can never have the fox watching the chicken coop. Consider the following: NASA funds PIs to provide scientific instruments for spacecraft. And no one else in the government does (we ignore a similar path in the DoD here where USAF plays a role – let's stick to civil side science). Some may think that NSF could provide funding for science instruments or spacecraft. This is, generally, incorrect. [NOTE: With the Space Weather solicitations, this may be changing and it is good news.] We also note that NASA builds spacecraft platforms for scientific instruments. NASA/GSFC in its hay-day built dozens of these spacecraft. Thus, the entrepreneurial SmallSat bus provider finds itself competing directly with NASA, in offering a bus that NASA, particularly one of its field centers, might also want to build. Certain mission categories have been set up by NASA Headquarters so that a PI can, in fact, team with a bus supplier to put forward a single instrument or small number of instrument mission. Two categories or classes of missions come to mind: SMEX and UNEX. SMEX simply means small explorer. Several SMEX missions were launched and were quite successful. These missions are not SmallSats per se, but, the spacecraft are only slightly larger than the top end of the microsatellite range. Most would be considered Mini-Sats. Usually, the instrument PI resides at a university and the PM is at NASA (in this case NASA/GSFC). The problem for the participating platform supplier is one of "oversight." Extreme oversight one might argue. The platform "supplier," in fact, becomes an engineering support services organization to NASA. All primary design decisions are made by the government. All design reviews are scheduled and planned by the government. All procedures and processes are reviewed and modified by the government. The resulting product is very unlikely to bear any resemblance to the proposal that was submitted by the platform vendor and there is no profit motive for the entrepreneur anywhere to be seen. One might make money by creating change order modifications to fixed price contracts but, there's very little "up-side" there. In any case, the government has now cancelled this mission category and has gone back to the old Explorer Mission concept.

UNEX means university explorer. This was the same concept as SMEX only smaller and it did cater to Microsatellites and smaller spacecraft. The PI was to be king and NASA was to have an arms-length involvement in the spacecraft development. That was the plan. The only spacecraft successfully developed under the UNEX program was ChipSat (discussed in section 2.1 above). ChipSat was a very successful spacecraft with a good instrument. But, once again the issue that emerged as the real process for UNEX unfolded at NASA was the same as always. The fox could not keep his eye off of the chickens. The oversight on ChipSat was devastating. SpaceDev, the platform contractor, was new, energetic and innovative. The ChipSat proposed management scheme, which was agreed to by NASA/GSFC and Berkeley at the beginning of the program, had a limited number of design reviews, the peer process was a key element of the system strategy and the platform contractor was to have free reign in key design elements of the bus, particularly where they did not impact the instrument development. The contract was FFP and was based on the above assumptions being true. The fastest way to summarize what went on over the two plus year development of ChipSat is to review the cost impact of NASA's actions taken to contain SpaceDev's free thinking. The FFP for the platform was initially approved at about 4 million dollars. At the end of the program the figure for the platform alone was approaching 8 million dollars (due to change order modifications, one would presume). The number of design reviews held had more than doubled. The oversight from NASA/GSFC was intense and continuous. This was not a happy experience for any party involved. Some of SpaceDev's ideas were ultimately accepted as being novel and useful. Most of those had to be fought for ruthlessly. All of the ChipSat satellite engineers working at SpaceDev have left the company. Some of them left the aerospace industry at the end of the program. The Berkeley PI left the university and now teaches high school in the Berkeley area. All of the Berkeley and SpaceDev engineers contributed significantly to a program that produced the first U.S. SmallSat to provide accurate 3-axis attitude control and the first U.S. satellite to communicate directly via the Internet. All involved were excellent, young spacecraft engineers. The program was considered by everyone to be a success. The UV spectrometer Berkeley created worked fine but, most astronomers consider ChipSat to be an example of a negative science mission. The short wavelength UV photons predicted by the astronomy community were not observed in the numbers expected during the all sky survey with the instrument developed and fabricated by Berkeley. Negative science; the absence of observables; can be good science and ChipSat is considered by the astronomy community to be an example of a good but, negative scientific results. However, such a mission is not always the most exciting thing to work on. It is most unfortunate that the negative science aspect of ChipSat was combined with a bad platform development experience. NASA, for its part, cancelled the UNEX program outright after ChipSat was completed. I guess we can simply say…commercial space science (or something approximating it) just got off to a bad start.

I should try to leave this topic on a more optimistic note. It may be possible in the future to create a more innovative and rewarding commercial opportunity in the space science area. It is likely that a viable business model for cooperation between industry and universities on scientific missions can be developed. But, first we must either kill the fox or move the chickens. Perhaps our government should consider re-arranging science instrument and research funding so that it is managed by the National Science Foundation (or a similar organization), leaving NASA to fund space and air flight technology research. [NOTE: In fact, for the first time, in 2009, with it's Nanosat space weather solicitation NFS has done exactly that. One can hope that the U.S. government will extend this approach to a larger range of space missions with larger implied budgets.] In effect, under this concept, NASA would become more nearly a pure engineering research organization, leaving science to other qualified agencies. This would at least eradicate what appears to be a clear conflict of interest if viewed from the perspective of the commercial private sector. It then should be possible to set up a process whereby mission standards are adopted so that space science does not always have to reinvent the wheel every time a mission flies (or at least not so much of the time). Europe, Japan, China and other space player nations should adopt a similar approach. ESA is every bit as heavy handed in its dealings with scientists as NASA is, and even more expensive. Eventually, as Jim Benson envisioned, space will be explored by adventurers and contractors that have a profit motive for going into space. We may or may not like the mental image this summons in our mind, however, it has been our past way of proceeding on planet Earth and it may necessarily be our future path as we head outward away from home.

4.5 Entertainment, Education and Training Satellite Systems as a Commercial Business

Satellites, particularly small ones, have been used for the education and training of individuals (young and old) in the aerospace arts since the beginning of the space age in the late 1950s. Until recently providing satellites, satellite components, satellite ground stations or even training software/documentation has not really been thought of as a money making activity. One does not seriously conjure up entrepreneurial thoughts as one thinks about educational space systems. There are currently at least five companies selling Cubesats, Cubesat and Nanosat parts and Satellite Training Devices that are really satellites that don't fly (instead, they stay in the class room and send telemetry and receive commands from student laptop ground stations). We can call the providers of these tools commercial companies but, I'd rather think of them as spending creative time in the interest of supporting the future of the aerospace industry. I don't think educational or training systems will ever be big money making ventures but, I'm very pleased that educational satellites exist and I'm very proud to have played an active role in this arena of space technology.

Entertainment spacecraft! What a topic this is. By the way, it should be noted that within the concept of entertainment systems we could certainly add education and training. Good entertainment, I think, is almost always educational and could provide some form of training.

In discussing entertainment systems, we certainly have to clarify what we are referring to in the context of big and small. Large GEO satellites carry TV and audio programming that is clearly intended for entertainment. However, that's not what is intemated here. In this context, the satellite itself is a form of entertainment. And, yes, this concept too has been tried. And, there is a spectacular example of an attempt to provide an entertainment spacecraft and create a satellite entertainment "empire," …well nearly an empire.

It has to be ask, if one wanted to start a deep space entertainment satellite empire…where would one start? Answer: How about Pasadena, CA; not far from JPL, not far from Hollywood and in the middle of a hotbed of dot.com entrepreneurial activity. And, then one asks, who might be good candidates to start such a company and provide seed capitalization? Answer: How about Bill and Larry Gross (of Google fame) who collectively own Idealab and how about Steven Spielberg (an investor only) and how about James Cameron (as an investor and an active participant). You could also throw in Bob Weiss the former director of the movie "Blues Brothers" and Tony Spear the JPL Program Manager of the highly successful Mars Pathfinder mission. You add to that august group a team of 40 top rate spacecraft engineers and managers; veterans of JPL deep space missions and successful small satellite missions and finally there is a "sprinkling" of Hollywood high tech animators and model builders and camera experts. Many small satellite subcontractors and even astronauts were then added as consultants. Now, what do you have?

BlastOff!

The year was 1999. BlastOff! the company was set up from the onset to be an Internet delivered streaming media entertainment company. The entertainment was to be live video from the moon (that would be the first mission). The spacecraft was to be of a unique design as it would have to be both a lander and a rover. That has never been done before so it was a tremendous and exciting challenge. The spacecraft was very small and the total propellant mass fraction had to be carefully managed. To make the mission meaningful back on Earth (to those watching over the Internet) there would not just be a camera suite on the "mother" lander/rover but, there would also be two *scout* rover vehicles both carrying cameras to look back at the mother and record her motions. As I recall, this concept was one of James Cameron's main contributions to the mission concept. To make the mission totally appealing the mother was to land as near as possible to an Apollo landing site (I believe the Apollo 16 site was preferred due to its interesting terrain). And, as you've now guessed, that mother and the two scouts were to traverse from the landing spot to the LM decent stage and revisit the scene of that great historic event. Everything about the mission was to be "monetized" (a cute dot.com term from that time). There would be logos all over the vehicle (except where the thermal control materials and solar panels had to be). There were to be student "sponsored" experiments that would be carried out on the moon. There were to be country sponsored flags at appropriate places on various pieces of hardware.

There was to be a contest to pick an individual to drive one of the scout rovers on the lunar surface for 15 minutes from mission control HQ. There would be others who got to drive the rovers, of course, but, not for free. The list went on and on. There were even serious discussions about carrying human cremation remains to the surface of the moon, although the intention was for them to stay in receptacles on the underside of the mother spacecraft.

Things moved forward. As PDR was approaching (JPL was hired as the independent review team) BlastOff! purchased (made the first down-payment on) the last remaining Athena launch vehicle from Lockheed-Martin. Propulsion systems, a structure, a coherent ranging transponder and other critical mission components were put under contract. In parallel, a streaming video company was being launched because Internet network technology was not yet up to the task that BlastOff! had in mind for streaming video. Special robotics experts were doing design trades and running performance trials in the hallways of the BlastOff! building in downtown Pasadena. Perhaps one of the most exciting things about the process of creating the lander/rover was that both serious spacecraft design engineers AND Hollywood set designers were working together…well sort of working together…to create the system. First the real spacecraft engineers came up with a design. The concept would then be handed over to the "Hollywood spacecraft engineers" whose job it was to make sure that the design was maximally anthropomorphic and that there was enough room on the bird for corporate logos to be placed. Then it went back to the real spacecraft engineers again who would carefully explain why the exterior surface of the spacecraft couldn't be painted candy apple red or why it was not possible to spray paint a logo on the solar cell cover slides. It was all tremendously stimulating work for this team…right through the 23rd design iteration sequence (literally) of the mother spacecraft. That took about nine months. AND…then it happened. The dot.com stock bubble burst in mid-2000. Within days the Gross brothers lost a fortune in terms of the stock value of their Idealab incubator companies. While Spielberg and Cameron were willing to continue to support the company, their support was not enough to fund rocket launches and propulsion systems and so, this grand idea and assembly of great people was in serious trouble. With only a month of money remaining, all of the engineers in the company stopped work on the spacecraft and went into fund raising mode. At that time nearly $20M had been spent and another $30M or more was needed to get to launch. Everyone worked frantically in an effort to save BlastOff! But, a month was not enough time to raise that sort of capital (as any good entrepreneur knows) and just as quickly as it started, BlastOff! was gone. The JPL engineers went back to JPL. The SmallSat engineers went back to their small satellites (or bigger ones) and the "Hollywood types" did whatever Hollywood types do. I'm sure they are all making exciting movies somewhere in the world today.

Now, this was an idea that should have been a dream-come-true. It had success written all over it. All the right people with all the right skills were together in the same place and BlastOff! could muster support from anywhere and everywhere it wanted. Everyone wanted to help. The biggest problem that came up from time-to-time was keeping the company and the concept a total secret. This was to be sprung upon the world as a well thought-out process at precisely the right moment to generate TOTAL excitement (and revenue). But, it didn't happen. The last thing that did happen before BlastOff! shut-down was the construction of a full scale model or prototype of the mother spacecraft. Several of the team went to a nearby garage shop and molded fiberglass body parts that were of the same shape as Version 23 of the lander/rover. A complete mockup of the spacecraft antennas, solar panels and propulsion system were made. The wheels were not quite to specification. Electric motors were installed on the drive wheels so that the prototype, in fact, had motion. Figures 14 - 16, I believe are never-before-actually-published photos of the BlastOff! mother rover/lander prototype that might have eventually made history. The rover mockup, I think, still lives in Bill Gross's office at Idealabs in Pasadena.

As the former Chief Technical Officer of BlastOff! I was more than proud to have worked with such an incredible team of multi-talented individuals. Every day at BlastOff! was a blast. The excitement of the project was palpable. One can only say, there may yet be another opportunity; another chance for this dream to catch hold; another space and time where and when the conditions will be right for such an exciting activity to take place.

So, if I’m asked if I think an entertainment spacecraft could be commercially viable, I‘d say, history says NO but, my heart say YES. So, when do we start!

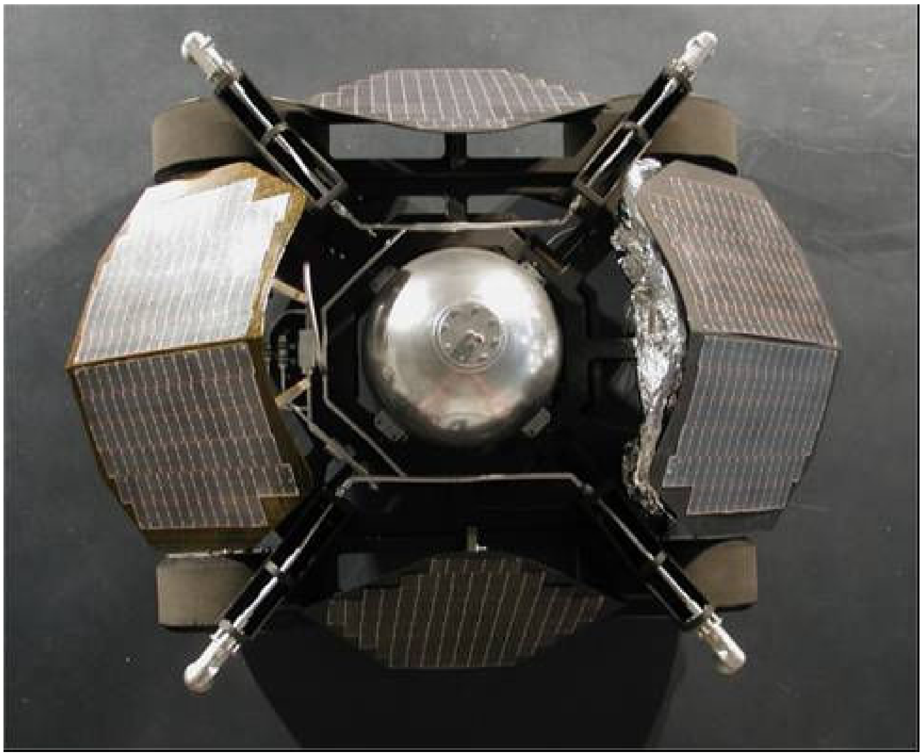


Figure 14: Rover/Lander Top View Showing Propulsion System

Figure 15: Aft View of Rover/Lander Showing High Gain Antenna

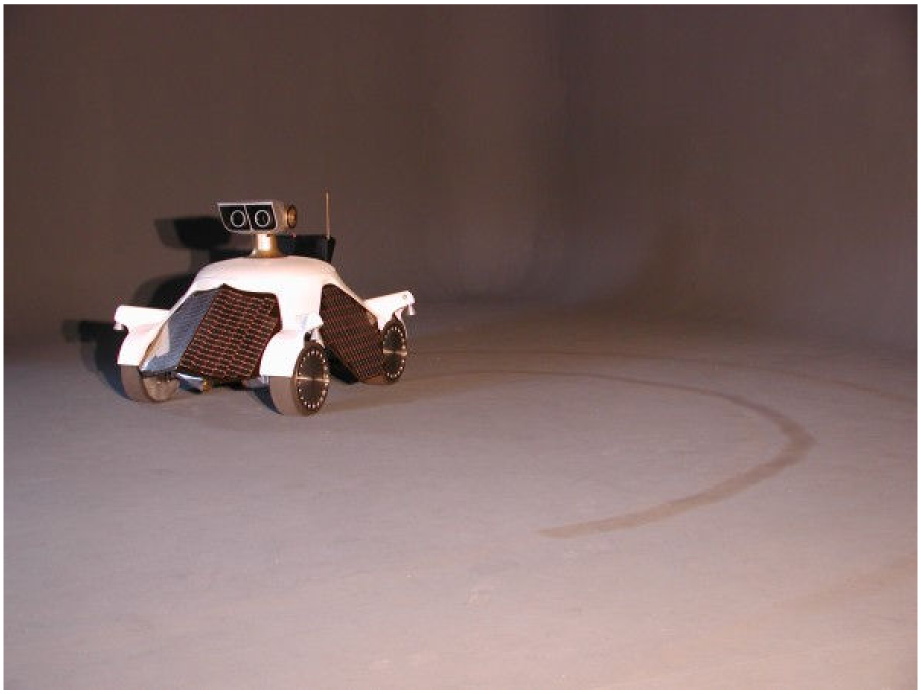


Figure 16: Rover/Lander During a U-Turn Driving Test

5.0 CONSTRAINTS

Some things in life are not fair. So it can also be for small satellite missions and business ventures. While reasonable engineers and managers might disagree about the definitions of "fair" or "unfair," some aspects of our business are just plain disagreeable. A definite example of that would be the International Traffic in Arms Regulations" (ITAR) but, I'm not going there with this paper. Deal with it!

1) The first example which is a reasonable topic for discussion is somewhat less polarizing than ITAR, but, it is still harsh. That is the availability of radio spectrum for space missions; all space missions. Small satellite proponents have yet to deal squarely with this issue but, as the goal here is to discuss commercial missions, this issue becomes paramount and expensive. Commercial users, nowadays, should even be prepared to have to pay for the use of the radio spectrum once a particular commercial application has shown itself to be commercially viable. "Procurement" of new radio spectrum for a project is a highly political process and it takes a lot of time and it takes lawyers (and, therefore a lot of money). One could spend volumes discussing this issue. I will not do that here. What I would strongly suggest is making sure that in the business plan which is developed for your product you prominently feature the cost of license procurement and the risk(s) associated with not successfully obtaining the license by the intended use date, should that eventuate.

2) Launch cost: Since the dawn of the space age, telecommunications technology, in terms of bits transmitted per second or data stored per spacecraft, has improved by about 10 orders of magnitude. The specific impulse of rocket engines, over that same period of time, has improved by less than 25%. The point is, not all technologies are equal and that has had a huge impact on space system costs. The telecommunications improvement of 10^{10} is an incentive to build telecommunications spacecraft. The improvement in Isp of 25% or less in 50 years is a disincentive to stay in the satellite business at all. Savior companies have been going to provide a windfall price improvement in launcher cost for a long time. That too, has not transpired. My suggestion is that $10,000 USD per Kg into orbit is the price of doing this business (plus or minus a factor of 2). [NOTE: If you are a Cubesat multiply this figure by X4 to X8.] And, I think it will stay that way for a long time to come. This cost too should be built into your business plan. I would not bet my company on something hugely significant happening in the next five to ten years regarding launch cost.

3) Just because the objects that aerospace engineers create go into space and are gold plated or covered with Kapton doesn't change our human nature. People *pollute*. Space debris *is* a unique form of pollution. It isn't every day on Earth that garbage travels past you at between 1 and 15 km/second. So, this form of pollution is really dangerous. It's clear that this situation must, and is changing. Curiously, the Federal Communicaitions Commission (FCC) is the agency in the U.S. which now has the mandate to minimize commercial space debris. Now when you file for a transmitting license you also have to explain how you will "take out the garbage" and eliminate your spacecraft debris from orbit. This is a good thing. It will cost money to clean up orbit space. I also recommend that this be considered in the business plan, the spacecraft system design and the operations planning for your commercial system. I note that there were multiple papers presented at the 8th Cubesat Conference held at California Polytechnic Institute earlier this year on the subject of space debris. Thus, the message is getting out. This is good, because as a space entrepreneur you will have to deal with it.

As I have alluded to, there are other space system constraints that enter into business planning but, these are the ones that are perhaps most important for the immediate consideration of any serious space entrepreneur planning a space venture or adventure.

6.0 CONCLUSIONS

I have thus exhausted my knowledge, opinions and observations regarding the potential for commercial small satellites to be successful and how companies might go about doing so. Following is a summary table of the key elements presented above. See Table 9.

I've worked and waited my whole life to find the first small satellite break-away commercial technology – the SmallSat "killer ap." I'm still working and waiting.

Table 9: Commercial Mission Success and Success Prospects

Commercial Mission Application:	Have SmallSats been Commercially Successful in this Application in the Past?	Is the Prognosis for Success Good in the Near Future?
Telecommunications	SOFT YES	Niche Markets Only; Good Possibility
Earth Imaging	YES	Yes, Considering Cost & Price *
Remote Sensing [Non-Imaging]	NO	Some Possibility
Science	NO	Some Possibility; Changes Required
Entertainment, Education, Training	NO	Maybe. It's worth a try!
Deep Space (Com., Science, Ent.)	NO	Some Possibility; Changes Required

From Table 9: * I believe small satellites will dominate this market within 10-15 years. Another quotation from a Phil Davies' (SSTL) Space News editorial from about 2 years ago, is still relevant today. 14:

"Considering all of these developments we are now convinced that everything is in place to implement a sub-meter resolution imaging mission using current small satellite technology. To do so would lead to a system costing less than $70 million to build, insure and launch. The system would be capable of imaging over half a billion square kilometers (three times the Earth's land surface) over 3 years. This would give a cost per unit area of less than 15 cents per square kilometer after accounting for operations costs. This technology will change the economics of high-resolution imagery over the next few years with new business cases for constellations becoming viable and eventually replacing large satellites for many applications. Constellations of such satellites will provide a much richer source of consistently high quality data across the globe for the rapidly expanding location-based services and will also allow much timelier imaging when up-to-date information is important."

7.0 ACKNOWLEDGEMENTS

This paper summarizes one person's lifetime of experiences with small and large satellite systems. The rate at which things are changing, even within the small satellite world is now fast and I find myself barely able to keep up with the annual changes taking place. The fundamentals don't change but, the details do. My thanks to all of those individuals within our community who have been keeping me up-to-date. My special thanks for help in updating this paper go to Andrew Kalman, Pumpkin, Inc.; Robert Twiggs, Moorehead State College; Craig Clark, Clyde-Space; Gil Moore, RAMPART Project Lead; Jim White, Colorado Satellite; Joost Elstak, ISIS; Jordi Puig-Suari, Cal Poly; and Rex Reidenoure, Ecliptic Enterprises, Inc.

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