

Silicon Sky Volume II: What has changed in the Last 15 Years?

Phil Davies, Alex da Silva Curiel, Arnaud Lecuyot, Prof Sir Martin Sweeting
 Surrey Satellite Technology Ltd,
 Surrey Space Centre, Guildford, Surrey GU2 7YE, UK
 Tel: +(44) 1483 803803 Fax: +(44) 1483 803804 Email: p.davies@sstl.co.uk

Jan King
 Southern Cross Space & Communications Pty Ltd
 Email: jking@eclipticentprises.com

ABSTRACT

In the 1990's three large and relatively expensive constellations of small to medium sized communication satellites flying in Low-Earth Orbits (LEO) were deployed, namely Orbcomm, Iridium, and Globalstar. The experience of building one of these constellations of "little-LEOs", Orbcomm, was captured in the book "Silicon Sky". Although these systems addressed existing and new niche markets compared to terrestrial or GEO communications, the business cases for Orbcomm, Iridium and GlobalStar were not achieved. Indeed, due to the very large infrastructure costs of setting up the space segment, all three initial systems failed commercially.

Technically, however, all three systems were a success and all three continue to operate, with satellite performance and longevity generally being better than the original specifications. The service they provide also demonstrates a real need, after commercial actions allowed offsetting the initial debts, such as bankruptcy under Chapter 11 of US Law, or asset buyout, or government involvement. Thus, it is assumed that, if the costs or the value of the constellation deployment can be reduced significantly, "LEO Comms" does have a business case.

Given these systems were launched in the 1990's, all three systems need to replenish their satellites in the next few years if they are to continue providing services or upgrading them. Indeed, in 2006 both Orbcomm and GlobalStar initiated procurements leading to the replenishment of their constellations.

This paper analyses what has changed in the last 15 years to enable the replenished systems to be delivered at much lower cost than the original systems allowing updated business cases to be profitable for the owners. The paper will also look at areas where there has been little change and analyse why this should be the case. It will also perform a parametric market analysis to support the technical trade-offs. The paper will look at all aspects of the missions covering ground systems, launch, bus and payload technologies. Eventually it will conclude as to the suitability and advantages of using so-called "low-cost approach" to space mission design for these application, at technical and commercial level.

1 OVERVIEW

The story of the development of the Orbcomm system is provided in Gary Dorsey's excellent book "Silicon Sky: How One Small Start-Up Went Over the Top to Beat the Big Boys Into Satellite Heaven" [1].

Small satellite missions in the early 1990's were typified by projects which were either educational in nature or were pseudo-operational in the sense of being operational but with other justifications for the mission such as technology validation. Examples of two SSTL missions in this period are the store-and-forward communication mission Healthsat-2 launched in 1993 and the Earth observation satellite FASAT-A launched in 1995. There were no real examples of missions being justified on the basis of

a government of commercial "business case" where the users of the mission were prepared to pay the full economic cost of the mission products taking account of all costs incurred. This changed starting in the early 1990's in the field of LEO satellite communications with the development of the Orbcomm system and, a decade or so later Earth Observation followed suit with missions such as SSTL's Beijing-1, Rapideye and Deimos-1 justified by business cases.

In the remainder of this paper we take a broad look at the technologies applied to typical missions of the 1990's looking at the Orbcomm design and the SSTL Microsat. We then analyse what has changed over the last 15 years and, we sometimes allow our minds to imagine what things might be like in the future.

2 MISSION LEVEL

At mission level the typical 1990's small satellite was very mass and volume constrained driven, primarily, by the available launch opportunities. Most small satellites "hitch-hiked" a ride with a larger satellite. SSTL's 1990's microsats were typically launched on the Ariane 4's Structure for Auxiliary Payloads (ASAP) which limited the mass of the satellite to around 50kg. It is interesting to compare such small satellites with those that had different constraints, driven by business plans, such as the Orbital Sciences Orbcomm satellites to provide commercial Store and Forward communication services.

Orbcomm was designed to make use of the Orbital Sciences Corporation dedicated Pegasus vehicle. In the case of Orbcomm, as both satellites and launch vehicle were developed by the same company the design of the satellite was optimised for the mass and volume constraints of Pegasus with no alternative launch vehicle seriously considered. The Orbcomm satellites were comparable in mass to SSTL's Microsat, weighing in at a little over 45kg [2].



Figure 1. Healthsat-2

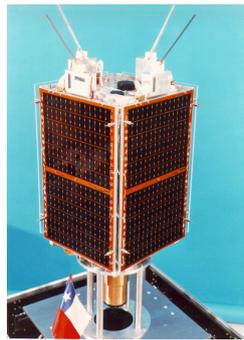


Figure 2. FASAT-A

One trend apparent at mission level is the increasing design life associated with small satellites. In the early 1990's the lifetime of small missions was typically 1 year, if stated at all. In recent years, a design life of 3-5 years is becoming commonplace, and some business plan driven systems such as RapidEye and next generation Orbcomm are being designed for 5-10 years.

Few missions are repeated exactly, and so it is difficult to demonstrate the advances of miniaturisation at mission level. Unless mass and volume reduction leads to the choice of a smaller/cheaper launch vehicle, there is no pressure to reduce mass or volume. There is more pressure for those procuring launchers to utilise the launch volume. Although the general trend is for spacecraft

to get lighter, the majority of missions utilise the "extra payload capacity" to carry additional or more complex payloads. In the figure below the mass for a few samples of near-recurring missions is plotted over time. It appears to indicate order of magnitude changes in mission mass over the period of approximately a decade.

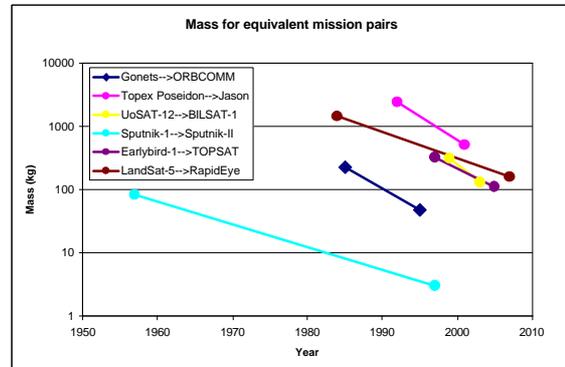


Figure 3. Mass evolution for "fixed" mission goal

3 SYSTEM

One of the major hurdles for developers of small satellite mission was the lack of availability of small satellite sub-systems and components on the market. Components developed for conventional satellites did not take account of the specific cost, mass, volume, power and schedule constraints of small satellite projects, and hence many developers were forced to design the majority of their own hardware.

Conventional space systems did not have the same urgent drivers for cost, miniaturisation and power efficiency, as it was considered more important to avoid accepting development risk inherent in new designs. As a result a gap grew between the capabilities of terrestrial technology and "proven" space technology. Smallsat developers had to leverage the capabilities of Commercial-Off-The-Shelf (COTS) components, in order to design systems within modest budgets, rapid timescales, and with low mass, power and volume.

Systems engineering for current small satellites is becoming more complex, as propulsion, navigation, deployable, complex attitude control modes and more demanding payloads are being flown.

4 STRUCTURE

The shape and mass of satellites is closely linked to the capacity of launchers. Once accommodation for a particular spacecraft is well defined, spare capacity is sometimes identified, providing an opportunity for piggyback launch.

The shape and mass of small spacecraft is therefore determined by the specific circumstances of a piggyback launch opportunity. As these only become apparent once the launch accommodation of the primary payload identifies spare capacity, spacecraft structures needed to be developed to meet particular specifications on very tight schedules. It is rare for similar opportunities to occur again, and as such, the structure of small satellites was generally developed using materials that permit rapid and concurrent engineering. Aluminium was widely used, so that the structure could still be modified late in the program.

The emergence of the Ariane ASAP launch capability with frequent LEO launches permitted SSTL to develop a novel “standard” small satellite structure, which could be re-used without significant re-design and structural qualification. The SSTL Microsat used a design whereby the electronics was loaded into stackable Aluminium “micro trays” which also provided the primary structure for the satellite. The approach reduced the development time that was required for each mission, and allowed SSTL to adopt an evolutionary approach

Multiple launch was possible with SSTL’s design through its compatibility with the Ariane ASAP, and this is demonstrated by the ARIANE-4 V59 launch which carried 3 SSTL spacecraft as part of its 6 available slots.



Figure 4. Three SSTL spacecraft on ASAP

With the development of a constellation of spacecraft, all of which were to be manifested together as the primary payload on a launcher, the structural design for ORBCOMM was more conventional. The main driver was in minimising mass and volume, in order to permit 8 spacecraft to be accommodated within the mass and volume limits of the Orbital Pegasus launcher.

Given the constraints of Pegasus, mass was a major driver for Orbcomm and consequently a lightweight

Aluminium alloy, AlBeMet, was used in the structure. Multiple launch was required from the Orbcomm design (shown below) so it was designed as a stackable structure almost completely filling the available launch volume.

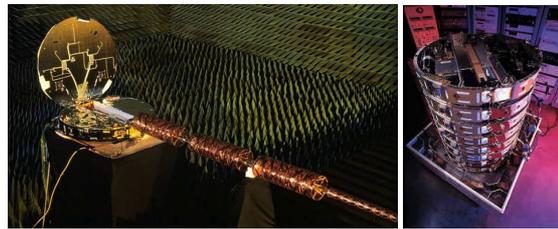


Figure 5. Orbcomm Satellite

Increasingly now, lightweight materials such as carbon fibre composites are being used in small spacecraft structures. Support components for small mechanisms have also become available permitting deployable solar panels, booms and other appendages.

5 POWER GENERATION AND STORAGE

Due to the launcher imposed mass and volume restrictions, small satellites were generally highly constrained in power generation capability. There were no “small satellite” components on the market, and the budgets available for smallsat missions were modest. Technology to fold and deploy small panels was not available, and consequently, most small satellites generated power using fixed body-mounted solar arrays, mounted onto Honeycombed Aluminium.

Attitude control and determination systems were also limited in both capability and modes of operation, and as a consequence multiple body mounted solar arrays were often used to ensure a suitable power profile over an orbit. Panels were often arranged so that whatever attitude the spacecraft is in there is still enough power being generated to safely operate the satellite.

Despite the higher costs and difficulty in laydown, GaAs cells were used to make best use of the small area available for solar cells. Efficiencies in the order of 18% were common, compared with 12% for Silicon cells. GaAs cells were typically small – measuring just 20x40mm, but this allowed these more fragile cells to be mounted on Aluminum panels without incurring thermal stress problems.

A practical problem faced by all small satellite developers was that their panels were often low priority, and of limited commercial interest for the established panel suppliers. This sometimes also led smallsat developers to adopt silicon cells and perform the laydown themselves.

In this respect the Orbcomm design was unusual consisting of a pair of single degree-of-freedom sun-tracking panels. Cells were initially Silicon, but eventually GaAs was also used. Currently, GaAs cells with efficiencies of 26-28% are available, and standard cell sizes are significantly larger (e.g. 40x60mm).

For energy storage, NiCd was commonly used as batteries could be assembled using COTS cells, or from cells qualified for space use. SSTL used the former method for its missions, based on NASA qualification programmes for assembling NiCd battery packs for its early satellite missions. Some small dedicated batteries were available on the market, and Orbcomm used NiH2. Typical storage densities were 30-40 Wh/kg for NiCd and 60 Wh/kg for NiH2 (at cell level). More recently, Lithium-Ion batteries have become popular due to their higher storage density, allowing batteries to become smaller and lighter for the same performance.

In future we expect Lithium-Ion and Lithium-Polymer to continue as the storage means of choice. Lithium-Polymer has the possibility of being integrated into small volumes within the structure where the design is volume limited rather than mass limited.

The size of the satellites often limited the number of battery cells that could be accommodated in series, and so limited the bus voltages on the smaller spacecraft. Power converter technology was not commonly used yet, and efficiencies of 80-85% were common. Nowadays, DC/DC power converters with 92-93% efficiency are available. This trend in power converter efficiency is likely to continue.

6 DATA HANDLING

In the early 1990's, a wide range of microprocessors and solid state memory chips were available to use in on-board computers, but few, if any, off-the shelf systems were available that were suitable for small satellites.

The processes and level of integration used in microprocessors and memories permitted the use of such COTS devices in LEO, although memories would need protection from Single Event Upsets (SEU) through Error Detection and Correction (EDAC) or Triple Voting schemes.

With the inherent short timescales of small satellite, the choice of processor was sometimes dictated by the experience of the responsible engineer.

The Intel x86 family (and its NEC V5# clones) were a popular choice, and although Intel had released the Pentium in 1993, SSTL adopted the 80186

microcontroller on its early missions because of its modest power requirements, integration of the 8086 peripheral chips, and widespread availability of software and tools due to the use of the common Instruction Set Architecture (ISA) with Intel based "IBM PC compatible" terrestrial computers. Its computers carried initially just 4Mbytes of memory, with up to 16Mbytes five years later.

The same power drain limitation turned out to be a problem for battery powered consumer products, and in August 1994 Intel released an embedded version of its popular 80386, 80486 and Pentium processor families – the 80386EX. This was rapidly adopted by the smallsat community including NASA on its Sampex, WIRE, SMEX, SWAS, TRACE, WIRE and FUSE missions. SSTL initially flew a 386 computer in 1995 alongside its x186 based computer, supporting up to 128MByte of memory.

| Processor | MIPS | Clock (MHz) | (µm) | Power Drain (W) |
|-----------|------|-------------|------|-----------------|
| 80186 | 0.3 | 4 | 3 | 1 |
| 80386EX | 2.7 | 25 | 1 | 1.25 |
| T805 | 10 | 25 | 1 | 0.65 |
| 68302 | 1.6 | 16/20 | | 0.9 |

Table 1. Processors as used on early smallsats

Another processor that was quite widely adopted was the transputer, designed for parallel processing, which had been introduced by INMOS in 1985. Before the introduction of the x386ex this would serve more processor intensive applications. For instance SSTL employed several such processors in its early image processors for on-board data compression. However, this processor suffered from lack of software support and development tools and was eventually dropped for that reason.

Orbital selected a specially manufactured radiation tolerant version of the 68302 processor which was introduced by Motorola in 1989. The computer was equipped with 3MB of memory and equipped with serial (RS-422/RS-485) interfaces.

Although the processing capability in COTS processors increased dramatically over the last decade, there have been few requirements for spacecraft processors to adopt these, other than obsolescence, and the ability to address increasingly larger memory banks.

For small satellites, it appears that data rates and data storage have kept pace with Moore's law [3], and this is expected to continue. The trend is towards higher and higher levels of integration whereby many of the digital electronics functions of

a spacecraft can be implemented on a single FPGA, the so called ‘System on a Chip’ approach to the avionics.

7 ATTITUDE DETERMINATION AND CONTROL

Without access to appropriate small sensors and actuators, early smallsat attitude control systems were limited in capability. In the early 1990’s, the common attitude stabilisation modes were to leave the spacecraft unstabilised, magnetically locked to the Earth’s magnetic field, or gravity-gradient controlled. Only a few experimental systems would use something more advanced. Pointing accuracies in the order of 1 degree were state of the art.

Common sensors were magnetometers and coarse sun-sensors, whilst magnetic torque rods and gravity gradient booms were the primary actuators used.

In the mid and late 1990’s momentum-bias and experimental three-axis systems were deployed as sufficiently small wheels became available on the market, and it was not until after 2005 that agile 3-axis controlled small satellites were becoming commonplace.

SSTL employed gravity gradient controlled systems augmented with magnetic torquers to provide nadir pointing control. On most missions a slow spin about the yaw axis was used to improve stability.

One significant driver in the progression of performance in smallsat attitude control systems, has been the desire to demonstrate and operate remote sensing missions using small satellites. This is illustrated for SSTL missions in [Figure 6](#) and [Figure 7](#). Gravity gradient missions are adequate for many communication missions and technology demonstrators. Instruments based on Area CCD sensors are also compatible, but to carry higher resolution and wider swath linear sensors, three axis control systems became necessary.

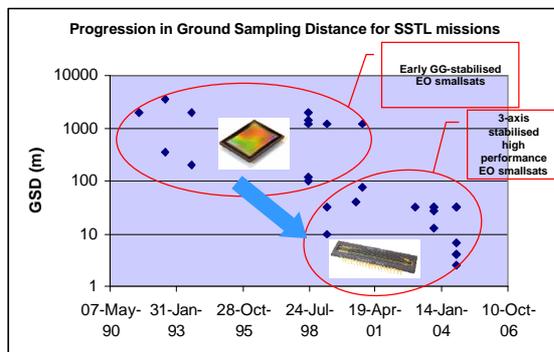


Figure 6. GSD progression

Reaction wheels were used more regularly in missions in the late 1990’s, and star trackers

compatible with smallsats were developed and marketed

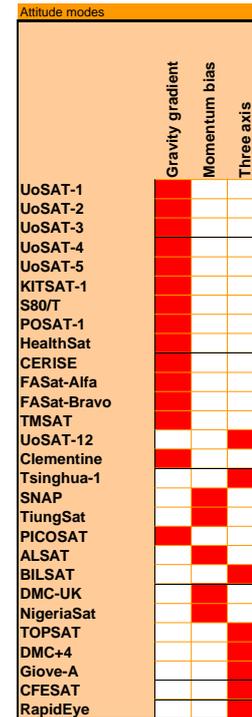


Figure 7. Attitude Control

Agility is now enhanced by the use of control moment gyros (CMG), with SSTL’s first CMG flown on BILSAT-1 in 2003. It is expected that the same level of ADCS capabilities will become available on smaller and smaller satellites in future. MEMS sensors and actuators are the key enabling technologies for the miniaturisation of the ADCS subsystem.

8 PROPULSION

In the early 1900’s it was unusual for small satellites to fly a propulsion system. SSTL’s first propulsion system was flown on UoSAT-12 in 1999, and then on its Nanosatellite SNAP-1 in 2000 and the Disaster Monitoring Constellation in 2001. Orbcomm, being a constellation programme, had requirements for phasing of the satellites around the orbital plane so was fitted with a small Gaseous N_2 system with 0.83 kg of propellant providing ΔV of 11 ms^{-1} . This ΔV was adequate for the mission because once formed as a constellation the relative orbit positions could be maintained by altering the drag of the satellites by actuating small differences in the solar panel aspect angles.

It is only in recent years that miniaturised propulsion components have become available, permitting wider use of propulsion systems on small satellites. For small satellites, volume tends to be more constraining than on larger satellites, and trades towards volume efficient propulsion systems have

led towards the wider use of Butane and Xenon systems.

It is expected that the trend of including propulsion systems on small satellites will continue. The increasing deployment of constellations, debris legislation, and the desire to select the operational orbits after launch are the major drivers. Due to its inherent efficiency we expect electric propulsion to play a bigger role in future as the very high ISP allows a small mass and volume to be carried. This is somewhat offset by the mass and volume of the electric propulsion system itself but it is clearly an enabler for some missions, especially those with enough power available to operate the propulsion system and a requirement for a high ΔV e.g. multiple launch of LEO comsats with final orbits in different orbital planes.

9 RF PAYLOADS & COMMUNICATIONS EQUIPMENT

In the early 1990's, communication technologies were very much focused on VHF/UHF systems for in the amateur and commercial service, and some limited activity in S-band.

Again, few communication sub-systems suitable for small satellites were available, and many smallsat manufacturers developed their own systems. Modelling tools and test equipment were very limited.

Due to the huge investments in RF technology to support terrestrial mobile and wireless communications systems, the modelling tools, test equipment, technologies and RF components have improved dramatically. This has benefited the baseband and IF processing technology on spacecraft to keep pace with terrestrial technology. Improvements in digital electronics, especially through the use of FPGA's, have permitted more sophisticated coding schemes to be implemented in smaller volumes and using less power. The advances in modelling have also improved the DC-to-RF power efficiency of power amplifiers from about 30% in the early 1990's to almost 50%. However as satellite equipment operates at different frequencies when compared with terrestrial equipment, the advances have not led to the same improvements in cost and miniaturisation in Low Noise Amplifiers, Power amplifiers, antennas and filters.

Improvements in the speed and power consumption of microelectronics will continue to lead to improvements in baseband and IF processing, and it is likely that within the next decade software configurable radio receivers will become competitive in power consumption to current systems.

10 GROUND SYSTEMS

Ground systems for small satellite missions generally kept with the philosophy of keeping things simple to keep them low-cost. As much as possible the ground systems were built with commercially available equipment and based on personal computers rather than the more expensive mainframe computers and top of the range Unix workstations common in the large satellite industry at the time. Communications to/from the satellite used the VHF and UHF bands well suited to a low-cost approach in terms of the cost of the equipment and antennas. For SSTL's satellites the communications protocol in use was based on AX.25, a standard used by amateur radio operators based on the ITU X.25 protocol. At the same time Orbcomm used the OX.25 variant of the protocol.

Driven by a desire to keep mission costs low SSTL designed its small satellites for very low operational costs. The missions generally could not afford "24/7" operations and this had impacts on both the spacecraft and the ground systems. Within the ground system, automation was used so that handling of simple anomalies and routine operations could be performed without operator intervention. The human interface was generally at the level of "mission planning" where several days of operations could be planned and defined in a single session with the ensuing mission plan automatically implemented by the ground system. Anomalies requiring operator intervention could be signalled via pagers and cellular phones, with the satellite's failure detection, isolation and recovery function (FDIR) maintaining mission safety in the meantime.

In future we see the main change will be the adoption of internet protocols (IP) and use of standard equipment and software designed for IP. In 2003 SSTL launched the UK-DMC satellite with a CISCO IP Router on board. This allowed communications between standard IP applications on the ground and on-board equipments as the two communication end-points.

11 LAUNCH

Small spacecraft generally require low-cost launch opportunities. In the early 90's, launchers had already progressed towards larger volumes and masses, and piggyback opportunities were available occasionally on the larger launchers for microsattellites below 100kg. Minisattellites tended to be launched as primary or on shared launches.

In the USA, The Scout vehicle was phased out, and the Pegasus and Athena small launch vehicles were introduced, with capacities suitable for 300-500kg

minisatellites. For microsattellites, opportunities were very limited.

In Europe, Ariespace had introduced the Ariane-4 ASAP as a means of carrying small payloads to LEO. It used a standard interface limiting spacecraft to 50kg, and 400x400x600mm. The regular availability of this platform helped SSTL in its definition of a modular microsattellite platform, and eventually led to the launch of 10 of its spacecraft using this launcher.

In the mid-90's the ASAP was largely discontinued which would have presented a major problem for small satellite launch. Fortunately, at that time it had just been decided in Russia to meet their internal requirements for launch by converting active missiles into launchers which would otherwise need to be destroyed under the arms limitation agreements.

Launch remains a complex issue to date for those looking for shared or piggyback launch. Although the rate of piggyback launches has not changed significantly over the years, there is an increasing trend for small satellites to be prime payload, shared payload or batch launched as constellation. This highlights the fact that smallsat missions are moving from opportunistic piggyback mission, to planned, operational missions.

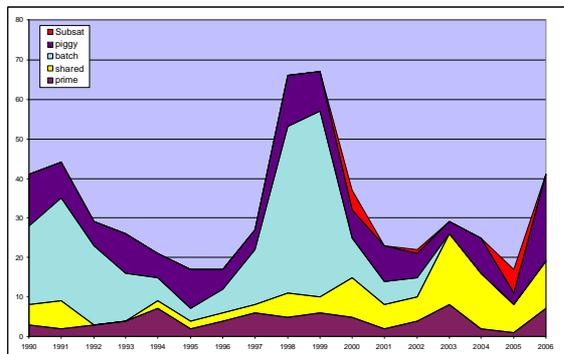


Figure 8. Smallsat launch methods over the years

It does not look like the issue of smallsat launch is something that will be solved rapidly. There are a number of small launcher initiatives that will help get the larger smallsats in orbit, but there are not many prospects for improvements in piggyback launch.

12 LEGAL & REGULATORY ISSUES

Legal and regulatory requirements were largely limited to import/export licensing, and the allocation and coordination of frequencies. These were the same for all satellites, but the timescales for some small satellites sometimes became problematic when

spacecraft were developed on very tight schedules. One response to this for SSTL was the development of frequency synthesised radio frequency systems, so that frequencies could be modified if needed.

Many of the small satellites were technology demonstrators, experimental, or pilot missions, and so operational limitations imposed through frequency licensing often were not so important. For operational missions such as ORBCOMM, frequency licensing became a major issue.

The launch of constellations of satellites in the late 1990's focused major attention onto the potential for space debris, and increasingly governments are signing up to a "code of conduct" for reducing the potential for catastrophic build-up of debris through collisions. As such, there is a need for spacecraft to remove themselves within 25 years from the protected LEO region. In practice this means that spacecraft launched into orbits between 650km and 2000km in altitude will need to carry a means of removing themselves from orbit.

Import/export restrictions have also tightened worldwide, as all space technology is potentially dual-use, and the interpretation and implementation of ITAR is particularly severe in the USA. As a consequence, this is creating schedule risk for projects that integrate imported sub-systems and components. Furthermore, it restricts some of the information exchange in the research and development of space technology.

13 SUMMARY AND CONCLUSIONS

Small spacecraft have matured significantly since the early 1990's. Initially innovation in this area was driven by the desire to use piggyback launch opportunities, emphasising the need for rapid schedules, low cost, as well as mass, volume and power efficiency.

Once the utility of these satellites was proven, highly capable smallsats could be used as part of business plans. There is a significant contrast in capabilities between "piggyback-launch-driven" smallsats and those The ability to spend significant time and effort on the non-recurring engineering of the ORBCOMM spacecraft still makes the performance of these spacecraft appear quite advanced a decade on.

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