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30 Years of Commercial Components In Space: Selection Techniques Without Formal Qualification

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ABSTRACT

From the earliest pioneering scientific missions to the sophisticated small satellite programmes of today there has been a continuity in the use of commercial-off-the-shelf (COTS) components. Recent advances in VLSI electronic components has accelerated their use in small satellite programmes, significantly contributing towards a ‘faster, cheaper and arguably better’ approach to space missions. Such applications however, in combination with the fundamental inconsistencies of COTS heritage require some differing techniques to those of the established space engineering regimes. Furthermore, the rapid development cycle of modern microelectronics devices and their packaging profiles for the commercial and domestic markets constitute a radical departure from the assurance base offered by the now dwindling Mil Standard component lines.

This paper presents a summary of techniques employed during 30 years of designing space hardware systems during which an increasing proportion of “COTS” general electronic components have been utilised. It describes techniques that have been undertaken within small/medium-sized organisations producing research instrumentation and microsatellite platform systems where conventional component qualification by long-term environmental test regimes is unavailable. Results from the long established University of Surrey (UK) small satellite programme are used to support this regime and provide good indicators of reliability and failure mechanisms. The data comes from the 15 small satellites using Surreys bus design that have been launched to date and have now accumulated more than 70 orbit-years operation in LEO.

A total engineering philosophy has evolved addressing the many different issues that are relevant to “COTS” usage. Essential elements include, a component selection processes with verification of their suitability for space applications; a hardware design concept that reflects system reliability requirements; addressing the more essential bus services with higher levels of partial or full redundancy and a conservative design change cycle that utilises components with an established pedigree. This philosophy relies on sound engineering practice whilst ensuring that the specified quality of a component is not given a completely inappropriate status. Factors such as component handling, board level design, build quality, sub assembly compatibility, system structure, interconnection techniques and modes of operation are all factors of the total reliability. The ultimate test is long term exposure to the space environment and this paper details the results to date from the Surrey programme. The conclusion of this work is that the component selection and usage regime provides a viable alternative to that of conventional qualification methods and if this regime is fully adopted will provide predictable results.

INTRODUCTION

Space, with vast investment in man hours and mission costs has for several decades relied totally on mil standard components as the essential system building blocks. The historic reasons for dismissing COTS devices in such a role are still a forceful consideration. Factors such as lack of hermeticity, inadequate manufacturing tracability and a reduction in environmental specification are highly significant. The approach to hardware design in space applications has evolved along traditionally conservative lines and this has promoted an inflexible component selection culture especially within the established industries. With many missions requiring faultless operation over very long time spans it is hardly surprising that COTS have not been considered a viable alternative to their high reliability counterpart.

Very sophisticated and costly missions often require funding by internationally collaborative efforts. Many take up to ten years or more to come to fruition whilst consuming a significant portion of a participating nations budget. Within such a framework of infrequent opportunities each mission is highly significant with considerable pressures for success. This reinforces the demand for components offering the highest theoretical reliability combined with the most formal Quality and Product Assurance regimes. Sadly, this alone does not guarantee success and failures continue to occur.

Within the past months failures in the conventional space sector have been significant with insurance companies projecting an overall loss during the year.

Fairly recent and far reaching changes in the supply of mil and hi-rel devices in general have compelled many traditional establishments to look at alternatives, one of these being the use of COTS devices. Given this radical departure from the conventional approach most institutions feel they can only venture into this territory if the components are subjected to a comprehensive qualification programme along similar lines to that of mil components.

There have always been research groups working within the space community who, for a variety of reasons made an early decision to use COTS devices in certain applications.

Many specialist areas have never been well served with an appropriate supply of suitable mil components. Frequently, very long delivery times or other restrictive practices such as, excessive minimum purchase requirements place mil components out of reach for the small manufacturer.

Some groups with a high research content that have remained reasonably autonomous of the institutionalised funding regimes have accumulated much experience of using COTS in space. The early acceptance of such devices and the experience gained over the intervening years ensure such groups now had a definite advantage over those who wait at the fringes. A dramatic user culture change would now seem to be inevitable with a learning curve that grows ever steeper to overcome the longer one delays.

With today's emphasis on moving towards a more frequent "smaller, faster, cheaper" approach to space access there is no alternative to increasingly adopting the use of COTS components. However, without the data derived from conventional qualification methods the unknown factors associated with the variability of such devices would make this approach appear foolhardy, highly risky and certainly difficult to quantify. There is however a compromise approach, still devoid of conventional qualification techniques but contained within a structured regime based on good engineering practice, selective use of redundant or semi-redundant design criteria and an appropriate level of quality control. With heritage of technique the final product becomes more quantifiable and may offer access to space at the best price/reliability ratio for applications not requiring the highest level of product assurance and reliability.

BACKGROUND

Much early research started with sounding rocket programmes and it was in such instrumentation flown on sounding rockets that many COTS devices were first exposed to space. Although the actual flight duration's were short these proved to be very valuable vehicles for developing rugged instrumentation since surviving the launch phase of small, multiple stage solid propellant vehicles was very demanding. Such instrumentation often gained related environmental exposure as many items could only be operated and hence developed under conditions of high vacuum.

With progress to orbital flight opportunities and generally more ambitious programmes, participating groups were slowly brought into line on build standards by the funding agencies. Initial such mandates were aimed at materials control, however this soon expanded into quality driven pressure to adopt only mil spec devices. General reductions in funding levels has tended to bring about high levels of international collaborative projects, generally further reinforcing build quality mandates. Such projects tend to be large scale and with a high degree of sophistication. This is usually at the expense of frequent, less complex missions with much faster response times. Such a shift in direction resulted in a void to routinely trial new instrumentation and to rapidly investigate new phenomena.

Groups, not centrally funded by research councils and substantially independent of the main space agencies and administrations had maximum freedom to set their own build standards. When such establishments fund their research activities from the proceeds of a commercial programme then quality judgements, however unorthodox, have to be based on sound financial practices. Being outside of large bureaucratic regimes can offer enormous flexibility to customer requirements and have a very rapid design to launch response time. Mission costs can be kept low by having an appropriately high Quality and Product Assurance regime based on low levels of delivered documentation. Such documentation, although a factor in the overall quality scenario, will certainly increase the cost but will not necessarily improve the reliability.

Research activities within the UK based Surrey Space Centre in combination with its parallel marketing and manufacturing regime under the commercial logo of Surrey Satellite Technology Limited (SSTL) have provided ideal opportunities to evaluate commercial components in a space application. In the past two decades SSTL has built 16 small satellites in the 50-70 kg mass category and a larger 300kg platform. Two other spacecraft are under construction and further missions involving both types of satellite are in the planning phase. The 50-70 kg satellites put them in a mass category commonly described as "Micro-satellites" and the 300kg versions would be similarly classified as "Mini-satellites". Additionally an enhanced 100 kg Micro satellite is in the design stage along with a much smaller 5kg Nano satellite. The vast majority of the spacecraft have been constructed as commercial platforms to support payloads either specified or provided by the customer. From 1981 to date, 15 Surrey platforms have been launched providing data in excess of 70 orbit years.

With modular construction techniques these spacecraft bus systems are offered as a standard platform. This however does not mean that every feature is frozen in design. Indeed the bus has been subject to a gradual progression benefiting from advances in new technologies and adapting to the discontinuation of established component items. The manufacturing processes are subject to continual improvements by attempting to replace all of the complex construction details. COTS components have routinely been included in every satellite as part of the main bus systems but at the start of the programme it would be true to say that this was the exception as opposed to routine practice.

Mission characteristic factors such as useful lifetime, internal test processes and build costs favoured an appropriate component quality level in line with specifications such as JANTX and MIL883/B. Initial deviations from this route were in specific cases where commercial parts offered a genuine advantage which was predominately one of size. There was also the occasions when individual mil parts could not be obtained in time or the minimum purchase quantity was excessively high when only one or two items required. Today's situation is such that commercial components offer massive increases in coverage and performance. The scaling down in manufacture of mil components with a stream of "last chance to purchase" notifications leaves one in no doubts that the change to COTS components is totally unavoidable.

COMMERCIAL COMPONENTS

There is every indication of improving quality when components are manufactured by highly automated processes and in vast quantities. At the same time, the diminishing supply of mil devices has shown some evidence of a quality reduction, perhaps as a result of smaller manufacturing runs and more manual interventions. A cost saving and (technical) performance improvement is generally associated with commercial devices but must be offset in comparison to the potential for increased costs associated with their decreased (environmental) performance specification. There are definite limits to the amount of effort that any small manufacturer can put into the qualification of new components. Even if sufficient resources were available for conventional qualification methods, the time to obsolescence is constantly reducing making continuity of product line a difficult issue. This requires an alternative strategy to quickly exploit the component supply while attempting to quantify the apparent risks associated with non qualification methods.

The quality in component manufacturing processes has been steadily increasing over the years and at first such improvements probably ran ahead of the post manufacturing, handling, packaging and storage regime of the distributors. Today, although there are no guarantees regarding the repeatability in any part of the process there continues to be an improvement in the overall quality of the delivered item.

Although a small sample of the commercial semiconductor devices that provide an input for this paper have been in existence in excess of 30 years the trend is for a design to obsolescence roll in very much less and ever decreasing time spans. To make use of new devices for a viable period before obsolescence it is necessary to make an early evaluation of the component and be ready to have a replacement in line before this product becomes unavailable. This situation can only be fully exploited within a programme of frequent mission opportunities with rapid turn around times. With missions that require 10 years or so to make a launch slot such hardware would be a record of obsolescence.

Since the focus of this discussion is of an uncontrolled process outside of the customer's control, then look into the items that are within your sphere of influence and in particular those which provide quality indicators. Visit the distributors and check out their handling, storage, packaging and pre-delivery general processes. Always look at the delivered state of goods from the distributor in addition to a later individual components inspection. Components should be in sealed bags and it is preferable they remain in these until required for use. Set up suitable in-house regimes to provide secure storage with an aim of using the components as soon as possible. Although the quality of manufacturing continues to increase, the move to higher density devices is tending towards components that are not as physically robust as earlier versions. Wall packaging thickness have decreased to allow higher densities. Internal component structures are now becoming so small creating a new set of problems.

Without the information provided by conventional component qualification regimes the initial selection process for new items has to draw very heavily on the experiences gained to date coupled with good engineering principles and practices.

ENGINEERING PHLILOSOPHY

The component standard within all but the most crucial single point sub systems may contribute a relatively insignificant role in overall system reliability. Factors such as component handling, board level design, build quality, sub assembly compatibility, system structure, interconnection techniques safe software and modes of operation are all similarly vital.

To achieve an acceptable level of reliability from a small but highly sophisticated satellite in the space environment is demanding. When the majority of components lack pre delivery qualification, offsetting the potential effects of this short fall in standard by all other means available becomes essential. All the processes and steps in the chain, from initial design, to operation in orbit, provide areas where this can be implemented.

At the design stage a prime consideration should be to best match the reliability requirement as dictated by sub-system importance with the product assurance confidence level in a selected component set. Such confidence perhaps coming from previous flight heritage coupled with ground based testing. Clearly a high reliability requirement should be matched to similar level of product assurance confidence. This same line of reasoning would allow the least essential sub systems to host a trial on the components with little or no flight heritage

Decide where in your processes items such as inspection and test provide the greatest levels of confidence for the least amount of effort. Simple components such as passives or discrete semiconductor devices may provide valuable pre assembly screening information with a test of one or two parameters. More sophisticated components are easier to screen when part of an assembly tested as a sub system.

COMPONENT SELECTION

The initial steps away from established component regimes are the hardest to make and it really helps if one has been able to gain experience in a small and controlled fashion over a number of mission years.

When making a selection from unknown COTS components what factors in addition to the application requirement should influence your choice? For a component to be around for a useful period of time it must be sufficiently in demand to remain in production. This usually requires a high volume usage with products definitely outside of the space sector.

Radiation hardness is an obvious concern although in many applications results have shown the space radiation environment to be less demanding than originally envisaged. As an example, a mission lifetime of 3 to 5 years in LEO can be achieved with a vast range of components and minimal levels of shielding since the radiation environment is tolerably benign. When one only compares radiation hardness, a non rad hard mil part has no advantage over a commercial equivalent component. A workable compromise could be to purchasing rad hard or qualify only the inherently more vulnerable devices such as A/D converters. Significantly, some component sets turn out to be inherently radiation hard and considerable information is published to support selection such as the NASA listings :
http://radnet.jpl.nasa.gov/

Making the initial move towards flying a device from, for instance, a surface mount commercial component set is difficult. Having made that first decision to include one such device within a definitive sub-system you may just as well build the entire sub assembly from the same technology. Choose components that allow one to be conservative with the parameters within their control such as power dissipation and voltage stress. Handling and mounting techniques are important considerations when initially evaluating new component styles. It maybe necessary to introduce more stringent measures with different classes of new components. Generally one's concerns of mechanical issues such as launch survivability of the component and its method of mounting can be evaluated fairly easily with a vibration proof test using a representative sub assembly housing a test board populated with all new components requiring evaluation.

If one successfully flies a particular commercial component on several different missions spanning many years with purchases at mission intervals what exactly are you qualifying? Those particular components were good and it is an indication that other items in the same batches also stood a better than average chance of being to the same standard. This however does not guarantee the integrity of future batches. On the other hand it is confirmation that the design regime is adequate for the task in hand and when those components have accumulated vast quantities of orbit years service then the level of confidence increases proportionally. It is not the component that one is qualifying but is a statement concerning the entire engineering philosophy!

Some manufacturers of COTS components have a less than positive view of their products being used in aerospace applications. A fear of litigation and the knowledge that such components may be subjected to environmental conditions in excess of their specification values can result in difficulties with obtaining detailed product information. In extreme cases this may escalate into a reluctance to sell the product into aerospace applications.

DESIGN REGIMES

Component specifications are always held prominent in any review of hardware since such a specification or its absence is easily to identify. Quality of design however is far more subjective and further complicated when power and mass constraints promote high levels of innovation.

The location of sub assemblies within the overall build is important. Some areas of the spacecraft may provide improved screening for items with a greater susceptibility to the radiation environment. Thermal modelling and accumulated flight data can identify locations that offer the most benign locations for items unable to withstand large thermal excursions. Thermal blankets and thermal surfaces can do much to improve the environment of external sub assemblies.

SYSTEM REDUNDANCIES

Identical, dual or triple, cold redundant sub system items is an established routine for increasing reliability if one has the real-estate to accommodate such a policy. With the emphasis on "faster, smaller, cheaper" the preferred route is with a sub system configuration providing a level of semi redundancy. Here many separate and different sub assemblies all work together to form the bus systems. There maybe duplication or greater of function but here the sub systems are composed of non identical hardware and in a regime where the majority of the sub systems are all operating at the same time. The complete failure of one or more subsystems will in most cases still allow total functionality but perhaps with reduced speed/accuracy /power. By having hardware of different designs configuration and component sets every mission has an aspect of a reliability trial. Having a make up of different processors that can accept data from all of the sub systems instead of the bunch they routinely service is one such example. Alternatively, in tasks that require the control of higher power loads then sharing the total task load with several smaller devices processing smaller powers can provide a system with adequate semi-redundancy.

All sub systems that can survive a power down should be protected with an essential automatic power shut off facility. This level of autonomy provides an automatic first line of defence to cope with survivable sub system failure modes such as single event latch up. Such rapid intervention will prevent escalating problems where sub systems fail in a power hungry manner.

UPGRADING SUB-SYSTEMS

If you have a subsystem that has been proven, it still provides the necessary facilities and does not present construction difficulties or mass penalties then stick with it until you have a proven replacement. During testing you will have the heritage of previous builds from which to make a direct comparison. If you lose the ability to obtain a small quantity of devices then replace these with alternatives with which you have already gained some flight confidence. Don't be rushed into a total redesign before it really becomes necessary, and by then, you may have gained enough experience with a component set, initially flown in a more experimental role.

Push the new and unfamiliar devices in the subsystems that you can fully work around in the event of failure. The ultimate advances that may bear the maximum risk of failure should me made within the very sub systems that are themselves of an experimental nature.

COMPONENT INSPECTION AND TEST

From the moment a component is removed from the distributors packaging you the customer influence its life expectancy. With any non hermetic component the environmental conditions that can lead to moisture ingress should be carefully controlled. A long duration bake out with a slowly increasing temperature profile will do most to minimise the effects of moisture ingress and should certainly be implemented just prior to conformal coating or other encapsulation. Every component should be inspected with a view to determining exactly what has been delivered and to confirm its suitability. Ensure that the product is undamaged and always look for differences that may indicate changes in specification, variations from the constructors batch or maybe differences in materials.

It may be possible to adequately screen non complex components with a test regime that only considers a minimum of parameters. Again one should be looking for deviations from an average value. High volume mass produced techniques in general produce little spread in characteristics with items from a same batch.

CONSTRUCTION AND ASSEMBLY

Any hardware for use in a space application must at all times be part of an overall quality regime. The skills level of personnel, construction processes and build quality standards are vitally important, regardless of component status. The advantages offered by a small medium sized organisation in the construction of small platforms is essentially one of visibility and control. Keeping all subsystems construction under one roof and within the control of a small number of persons, build anomalies are much easier to pick up and the build quality can be readily checked. Small dedicated highly skilled teams are very capable of turning out work of a consistently high standard. This can be further reinforced by having company policies that ensure all individuals are aware of their responsibilities to maintain high standards of quality.

The use of company procedures that are concise and produced by individuals who have hands on experience of performing the desired tasks. This will ensure that said procedure has the maximum chance of complementing the task in hand. Procedural documents produced in departments remote from the workplace are often generated to justify the existence of such departments. The documents are generally difficult to use and contain pitfalls that were impossible to comprehend while seated at a desk remote from the hardware

TESTING

IN-HOUSE REGIMES

Sophisticated environmental test facilities may be outside of the scope of a small company making it necessary to visit an approved test house. A thermal vacuum facility is highly desirable but even this can be accomplished at a test house provided that a high level of confidence exists with the product.

It is at the module level ambient testing phase that many sophisticated COTS components are initially subjected to a functional test. Apart from providing the obvious success or failure result such conditions are really useful for providing comparison data. Ensure that precise records of results are retained for comparison with previous module builds and for follow up tests. Pay particular attention to parameters such as quiescent current values. Thermal vacuum testing sessions can bring about subtle component failures or changes in characteristics. There is value in being able to repeat detailed subsystem level testing following any environmental sessions. Sub system temperature cycling or a burn in at elevated temperature will enhance the chances of detecting early failures.

Additional thermal cycling of a fully assembled spacecraft within a temperature regime of -20°c to +60°c will further increase the chances of detecting early failures or more serious problems which would otherwise show up in thermal vacuum. Some customers have specified increases to the temperature limits of this thermal testing and have included an additional accelerated burn in test of three weeks continuous at +70°c. Additionally the satellite should be operated at ambient temperature for as long as can be accommodated within the confines of a rapid response mission.

AT A TEST HOUSE

Using the facilities of a Test House can provide a capability lacking in house of simply reinforce internal results.

EMC Testing, for spurious emissions in compliance with the specifications as requested by the launch service provider or payload provider.

Magnetic Testing, additionally to in house testing in order to validate magnetometer calibrations and to quantify magnetic anomalies.

Vibration Testing, to our own specification. Surrey has a general policy of purchasing a launch from the most suitable provision available at the time. To this end we have taken the qualification levels from all the launch service providers and made a common test specification with the combined severity of all features. Because of the uncertainties regarding launch opportunities this policy gives sufficient versatility to take very late launch opportunities.

Thermal vacuum testing has been optimised to a 1 week period covering 3 complete cycles to further show up any early component failures and to determine thermal balance. A Surrey Microsatellite is tested with an input temperature range of -30°c to +70°c. This gives a profile distribution across the satellite with the external exposed areas such as solar panels and external instrumentation reaching peaks of -20°c to +50°c. The well thermally isolated areas such as the battery sub system achieving much smaller excursions.

RESULTS

The 14 Microsatellites and the 1 Minisatellite platforms launched to date have now accumulated a total in excess of 70 years in orbit. This represents an enormous achievement in scientific and technological data gathering at a very small fraction of the cost when compared to the conventional space industries. This data covers the period from the first launch in 1981 to the middle of 1999. There have been failures, some routine and only having limited effect. One early total failure, difficult to diagnose and another in the launch/separation phase. The launch service providers were:- NASA/Delta, Ariane ASAP, CIS-Tsyclon, Yuzhnoye Zenit and the converted SS18 Dnepr. The majority were launched into circular, sun-synchronous, polar LEO with a range of altitudes from 670km to 810km. Two satellites however were launched into a much higher orbit of some 1330km altitude 66° inclination. The profile of each missions duration in orbit years, coupled with all failure events is shown in Fig 1.

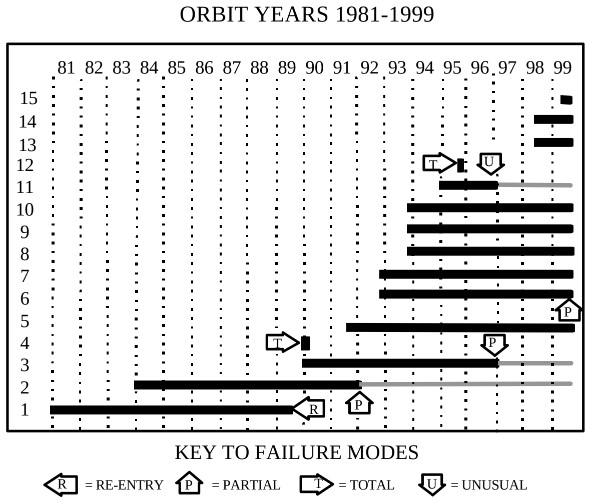

Fig 1.Mission Duration Profile and Failure Events

The missions that have experienced some form of failure:

1. End of life re-entry after orbit decay following 8 years operation with no obvious in orbit failures.

2. Still fully functional following some 15 years in orbit. Suffered a failure of one commercial A/DC after 8 years. The failure was almost certainly caused by radiation and the data from the affected sub system is now processed via an alternate path.

3. Still functioning but at greatly reduced capacity following the failure after 7 years operation of an 80C186 **MIL** Processor. Possible latchup!

4. Early total failure with communications after some 30 hours of less than nominal operation. Failure believed to be within a common RF transmit filter system and probably caused by coronal discharge before the system had fully vented.

6. This is in the higher 1330 km orbit and has been subjected to high total dose levels. Having performed faultlessly for 7 years one of the processors has just started to be shut down by its power level protection switch.

11. After nearly 2 years of operational life this satellite was in collision with a small remnant of debris, thought to be part of an Ariane launch vehicle. The impact sliced off the gravity gradient boom and imparted a violent motion to the satellite. The satellite attitude was eventually recovered and all systems were found to be fully functional. Unfortunately the damage to the boom assemble has imposed substantial limitations to the pointing accuracy.

12. Total loss due to failure within the separation system. Satellite was never in a position to be checked out as power is held off automatically until after separation.

Satellites 5, 7, 8, 9, 10, 13 and 14 have so far survived without failures of any kind. Significantly, mission 5 was the point of introduction for commercial surface mounted devices and these have been incorporated in significant and increasing quantities from this time onwards. Satellites 6 and 7 are in the higher 1330km orbits and receive up to a factor of 10 times higher radiation levels compared to the other satellites in lower orbits.

Satellites 15 was launched less than 3 months before the cut off date for this paper. This is our 300 kg Minisatellite and has a vast array of new experimental systems. To date many of the systems have returned excellent results but others still have to be commissioned.
The results from these missions show that overall failure rates are far too low to make meaningful comparisons between mil and COTS components. This low rate however does indicate that the COTS components are a viable alternative to mil components in such an application.

CONCLUSIONS

With MIL devices having a very small share of the total component market their future is far from assured. COTS components will undoubtedly be used in ever increasing quantities in all applications, including that of space. Many users will employ differing methods and levels of qualification in order to obtain a sufficient level of confidence for the required application. For very high rel applications, such a level of confidence may only be unobtainable by reverting to separate fabrication lines, loosing many of the advantages offered by high volume, mass production

This paper has shown that COTS components can be successfully selected for a range of space applications within a regime using only low levels of selection by screening. Such components having provided a high performance, low cost alternative when used within a fully supportive engineering regime.

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