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Use COTS or Not Use COTS in Space Applications?

Addressing concerns over this growing question.

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With the recent shift in space electronics using ruggedized commercial components as a cost-efficient alternative to 'space-grade' devices, the question of reliability has been asked repeatedly. And rightly so, as there are a number of variables to consider when factoring in the effects of space on non-qualified components.

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Space is not only one of the harshest environments that electronics need to operate in, but it's also one of the hardest to replicate. Testing and validation of mission critical systems used in space exist for a reason, as success is defined by the continued reliability, autonomous operation and unwavering communication of a space system within its network.

So, while the answer isn't simply yes or no, there are certain instances where a more definitive answer can be found. Depending on the program's mission requirements, some limits may be OK to push, while others may yield catastrophic failures. This paper looks at reliability requirements today, but as limitations become more clearly defined within specific applications, the logical course of events would lead to a continued increase of COTS components in space.

A Look Towards COTS

Why did the space industry look towards commercial components in the first place? The answer is two-fold. First, designers were looking to emulate the functionality they can employ on their desktop PCs in the space environment, but more often than not, space-qualified components were limited in certain abilities. Only so much could be done with the traditional set of component earmarked for in-orbit applications.

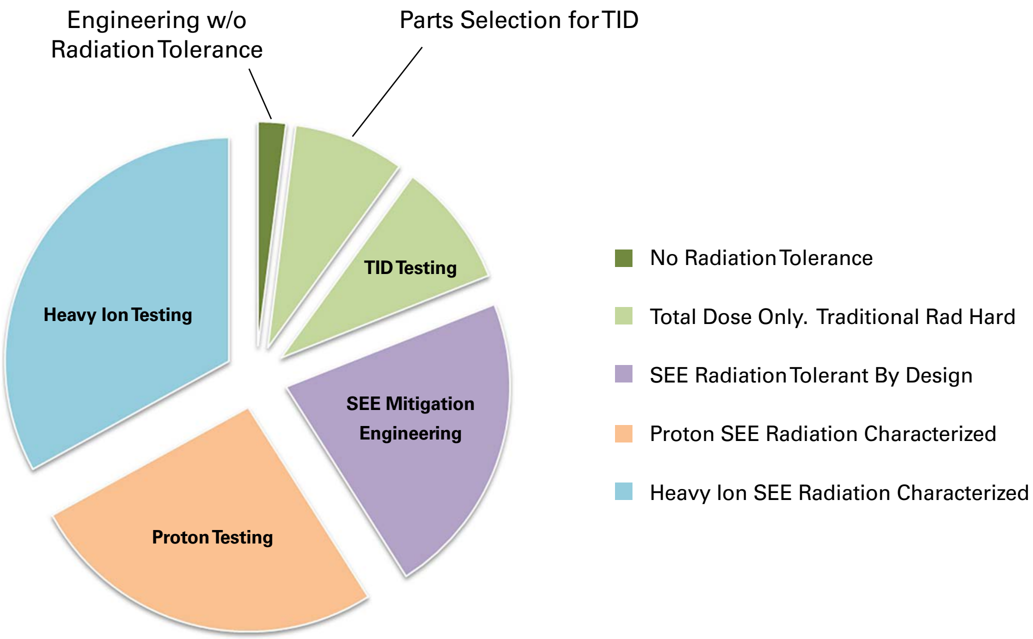
Second, as its moniker suggests, a space-qualified component has undergone rigorous, and therefore costly, testing and validation. With research and development budgets being cut tremendously across several areas of defense and military programs, ways to reduce overhead and extend the value of each dollar was high on the designers' priority list. And not having to wait for testing results would certainly speed up time to market.

Ruggedizing less expensive, yet more feature-rich, commercial components for space seemed like the Holy Grail. And commercial components themselves had advanced in form and function, making them potentially viable alternatives to qualified components. This provided a new way of thinking for space electronics.

Defining EEE Parts and Usability

NASA's Office of Safety and Mission Assurance notes that a main objective of the Electrical, Electronic and Electromechanical (EEE) Parts discipline is to "assess the reliability of newly available electronic parts and packaging technologies for NASA projects through validations, assessments and characterizations, and the development of test methods and tools."

RELATIVE PROJECT COSTS VS. RADIATION TOLERANCE LEVEL



A recent example is launching a cluster of small satellites, instead of one large unit, to help spread the overall system functionality across multiple units. If one satellite fails, and if the system is designed as such, another in the cluster can either pick up where the failed unit left off, so there is no or little loss in functionality and the 'constellation' stays operational. This is a shift from the traditional method of launching one super rad-hard mega-satellite solely responsible for the mission's entire operation.

However, most clusters are launched in low earth orbit, so commercial components may make sense in this environment. But for longer missions, and deeper space applications, these components typically have not been proven to possess the needed endurance to withstand repeated and prolonged exposure to harmful radiation. (Figure 1)

FIGURE 1

Small satellite clusters currently used in LEO environments, strengthen system reliability by spreading overall functionality across multiple units. In the event of one failure, other units can continue the mission operations.

The first step in evaluating whether COTS components are right for your space application is to identify your mission, determine the level of reliability needed, then address budget and time constraints in relation to the components you are selecting.

Considerations for COTS in space

From a general sense, as far as computational performance, functionality, cost and size are concerned, COTS parts fit the bill, and reliability is getting better and better, mainly driven by automotive applications. So why aren't they as widely used in space? The big problem is that manufacturers don't characterize parts sensitivities to radiation effects.

According to collected experimental evidence, there are three broad classes of radiation effects to consider in evaluating the applicability of COTS for a space mission.

1 | **Total Ionizing Dose (TID)** is related to damage of the device resulting from long-term exposure to protons, electrons and heavy ions. Some devices, like bipolar transistors, are very sensitive to ionizing radiation applied at a low dose rate (as is typically the case for most of space missions).

2 | **Displacement Damage (DD)** is related to the disruption in the crystal lattice structure of the semiconductor device. It is a non-ionizing damage. The DD mainly affects bipolar transistors, solar cells, LEDs, laser diodes and opto-couplers.

3 | **Single Event Effects (SEEs)** are related to direct or indirect ionization of a sensitive area of the semiconductor circuit. There is a long list of specific SEEs, but the most common to note are:

- **Single Event Latch-up (SEL)** causing high current flowing through the device
- **Single Event Upset (SEU)** causing a change of state in flip-flop or memory cell
- **Single Event Transient (SET)** occurring both in analog and digital circuits

The typical design process with COTS EEE parts should start with a parallel evaluation of the parts' reliability as well as checking for the presence of forbidden substances within a part and, last but not least, radiation testing of a candidate part. Radiation testing should characterize the part for sensitivity to TID, protons and heavy ions.

Take a comparative look at the “dimensions” needed for an electronic system design for commercial, military and space applications:

TYPICAL DESIGN CONSIDERATIONS FOR DIFFERENT TYPES OF MISSIONS

Activity	Considerations	Mission Type		
		COTS	MIL	SPACE
Mechanical Design				
	Size and mass	X	X	X
	Shock and vibration		X	X
	Heat transfer	O	X	X
	Shielding from energetic particles			X
	Materials and out-gassing			X
Electrical Design				
	Functionality and performance	X	X	X
	Radiation effects and mitigation			X
FPGA Design				
	Performance	X	X	X
	Radiation effects and mitigation			X
Software Development				
	Required functionality	X	X	X
	Radiation effects and mitigation			X
System Reliability Assessment				
	Classic reliability assessment (MTBF)	O	X	X
	Total dose effects			X
	Single effect functional interrupts			X
	Other SEE			X

X - Mandatory: always performed

O - Optional: not always required or performed

The design activities for the COTS missions are practically independent, but this is not the case for a space system design, where radiation effects and mitigation of these effects form a common thread between all of the design activities. This mandates good teamwork and an agile structure that accommodates feedback from other members, as related to mitigating radiation effects.

A typical example is an increase in the wall thickness of the system chassis to accommodate EEE part(s) with a lower total ionizing dose (TID). This may cause an excessive increase in mass, so a more detailed radiation analysis is required to provide new guidance for the parts placement, which may conflict with the optimal electrical or thermal placement.

Avoiding Common Misconceptions

It's unfortunate that frequently used phrases like "Space Grade" or "Space Qualified" hardware are oftentimes used universally, without thinking about all the issues and considerations associated with the application of hardware for a specific space mission.

Space, weight, functionality, extended operating temperature, EMI/EMC and radiation shielding and a host of other attributes are all taken into account when specifying components for a space system. One small shift in a component's internal functional thermal envelop and the entire system architecture can be sent out of whack.

When radiation effects are added to the already complex mix, it's clear why parts should be evaluated for each space mission rather than indiscriminately called "Space Grade" and used for every mission.

The "EEE-INST-002: Instructions for EEE Parts Selection, Screening, Qualification, and Derating" from NASA classifies parts into three levels, based on their reliability:

Level 1 | For missions 5 years or longer,

Level 2 | For missions 1 to 5 years,

Level 3 | (High risk parts) for programs less than 1 year to 2 years.

This classification requires additional screening of military parts manufactured according to the MIL-STD-883 to meet even the requirements of Level 3. Therefore, some companies refer to Level 1, 2 or 3 parts as "Space Grade," but it is evident these parts have different reliability bounds as well as preferred area of applications. It will be very risky to use Level 3 parts for an 18-year mission.

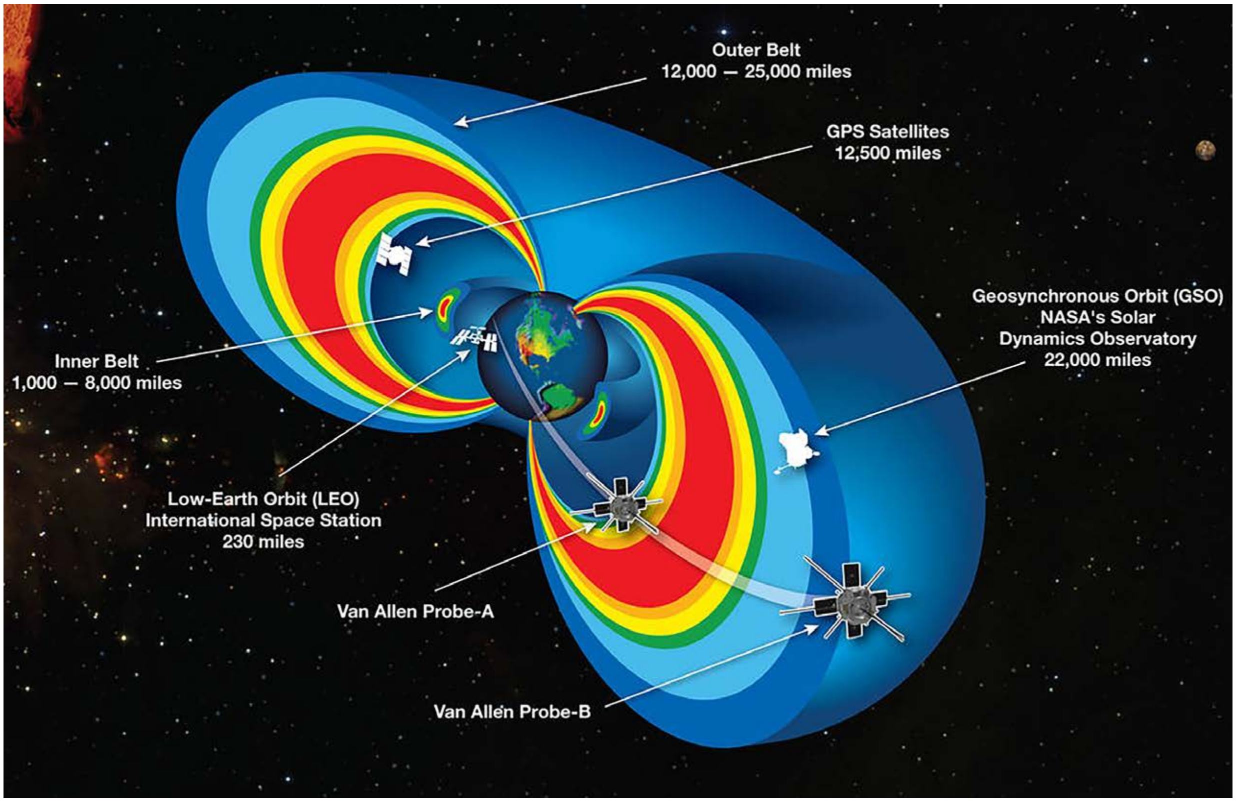
Radiation has one of the largest impacts on Earth orbital systems, and two of the most important aspects to consider are the length of the mission and which orbit will the system operate in, since these determine the type and quantity of radiation that a system will be exposed to. (Figure 2)

Reliability Defined by the Application

Because they are used in the rapidly changing world of consumer electronics, commercial components are much more dynamic by nature. Frequently, technology changes happen with barely enough time for designers to learn the full part numbers of the parts they are using. And the sheer quantity of components produced precludes many manufacturers from employing a decent traceability system.

Sending hardware to space is very expensive, so maximizing the mission's success and lifetime has always been a top priority. This comes down to the reliability of the parts used for the mission. Different orbits and mission length are critical factors in the levels of reliability needed, as well.

The traditional approach to EEE parts with desired reliability was based on parts that were well-designed both electrically and mechanically as well as manufactured using the same process and materials in quality controlled production lots. These parts were later subject to a screening process intended to identify and remove those few parts that exhibited infant mortality failures.



Credit: NASA

FIGURE 2

The length and orbit of a space mission are critical to determining the level of reliability required for electronics used in space.

Addressing design concerns are a critical part of the test and evaluation of the parts you intend to use.

SCREENING. An important aspect of the screening process is the electrical test performed at three point temperatures (minimum, ambient, maximum), since COTS parts are not typically tested at these three temperatures. Part failure is declared when, after exposure to temperature cycling and dynamic burn-in, the electrical parameters exceed the range published in the datasheet.

The electrical measurements are evaluated for parameter "drift" or changes that occurred when parts were subjected to screening. The parameter drift must be limited, otherwise one may extrapolate the drift and argue that the part will be out of specification within the expected lifetime. Parts with excessive drift are declared failing.

LOT INTEGRITY. There is a limit on the number of parts from the same lot that may fail the screening. If this limit is exceeded, the entire lot is discarded because this points to something having clearly gone wrong during the manufacturing process. The screening is not intended to find the few good parts, but to verify lot integrity and remove a few bad parts (typically we should not be surprised to see 1% to 2% failure rate).

It's often asked if the board can be screened, instead of the parts, but it is then impossible to perform parametric measurements of parts at the board level and calculate the drift. The testing at a board level can't be compared to testing at the component level. Although board level testing may be an acceptable approach for certain missions willing to accept high risk, there are several critical parameters that will be missed using board level screening.

If the parts are determined to be free from infant mortality failures, but we still don't know if they will meet the useful life expectations for a space mission, we look to the qualification process by randomly selecting a small subset of parts and subjecting them to life tests. All parts must pass the life test. If one or more failure is encountered, the entire lot is discarded.

PROTON TESTING. This offers an easy way to look into device degradation as a function of total ionizing dose (TID), and evaluate the single event effects (SEE) in a limited range of ionizing energies. There are very good NASA and JPL guidelines for testing EEE parts with protons [1], [2]. Access to a proton beam is less cumbersome than access to a heavy ion beam, therefore it's used as a first step in parts evaluation for space missions.

We should expect parts failing the radiation test and bring few similar parts to the test and select the best one. The proton test may demonstrate several surprising results, including:

- your favorite switching power supply fails destructively after few seconds of exposure to high energy protons,
- a newer microcontroller with a rich set of peripherals loses functionality after <400 rads,
- an older microprocessor passes 100 krads with minimal degradation.

For the EEE part that survived the test without destruction or significant degradation, the vital statistics are the sensitivities (cross-sections) calculated as the number of observed SEE divided by the fluence of protons (typically 1E10 or 10 billion per square centimeter). The cross-section calculated from this experiment used to be fairly representative of the part sensitivity, but with smaller geometries, we're hitting lower and lower percentages of transistors with 1E10 protons/cm^2. The detailed analysis of this underlying phenomenology is presented in [3].

Evaluating Results for COTS Components

Hopefully after the proton test, we have parts that didn't suffer from SEL and survived the expected TID within a reasonable margin. The testing with protons gives us visibility to the device sensitivity in a narrow range of the Linear Energy Transfer (LET) spectrum, which defines the amount of energy an ionizing particle transfers to the material traversed per unit distance.

The LET encountered in testing with 200 MeV protons does not exceed the 15 MeV*cm^2/mg, but the mission may need characterization to LET of 35 MeV*cm^2/mg (the typical value for LEO missions) or higher. To perform such characterization, one needs to perform testing with heavy ions, which is more complicated than proton testing, mainly due to very low ranges of the ions in silicon.

The proton test will most likely uncover SEFI (Single Event Functional Interrupt) in the candidate parts and, with well-designed test boards, ways of mitigating them (reset, power cycle) will be determined. Electrical designers use this information to design the circuits and, in the reliability analysis, to predict system availability values or upset rates.

The SEU sensitivity allows upset rate calculations for the mission and establish the proper mitigation, such as memory scrubbing, ECC (Error Check & Correct), TMR (Triple Module Redundancy), etc.

Deciding on a Part's Readiness

The radiation test and the analysis will determine the TID as well as find if the part is free from SEL in the LET range specified for the mission and will establish modes and frequencies of SEE and SEFI. The information about SEE and SEFI will be used by the electrical and software design teams to find mitigation means. Some SEFI modes may prevent the part from being designed-in and the same applies to SEE, but to a lesser extent, particularly to SETs on the outputs of the voltage regulators.

The part has to be approved by the reliability team for its expected failure rates. This assessment is based on the available qualification data from the manufacturer (not all parts have this information available) and on the construction analysis (also known as Destructive Part Analysis).

All these tests and evaluations take some time. Once you are satisfied with the results and ready to purchase parts for screening, you need to recognize and address some other design issues, like making sure the radiation tested parts are the same as parts procure for screening.

Manufacturers tend to perform die shrink, which changes the radiation performance of parts. Some manufacturers fabricate the part in a few locations around the world, with each location using a slightly different process. So, parts from multiple locations are packaged in one facility and marked the same way, but most likely, will have different radiation performance.

During the screening process parts are subject to electrical test. The data sheet for simpler parts may not even show an equivalent electrical circuit, only a block diagram, yet the part typically has lot more functionality than what is depicted. (Figure 3)

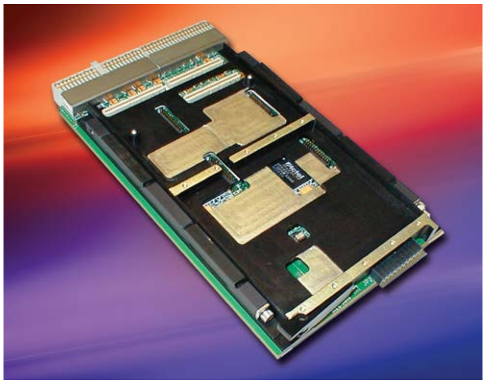


FIGURE 3

Space-qualified boards include parts that have been screened and tested for operation at altitudes greater than 100 km above the Earth's surface.

Using COTS for Space Missions

As noted, getting COTS EEE parts to level 1 or 2 is quite expensive, time consuming and still risky, as candidates may fail. So for now, the best use of COTS in space is if components offer a performance level or functionality not available from the existing portfolio of high-reliability, radiation characterized parts. No matter how the question is asked, the proper use of COTS requires a critical look at the mission itself, and how the parts are expected to perform.

As trials and testing of COTS components continue, the places and applications where it makes sense to use these parts will increase. Keep in mind the reliability needed for your mission, and how much risk your program is able to sustain.

Footnotes:

1. Proton Single Event Effects (SEE) Guideline, Kenneth LaBel 2009
2. Proton Test Guideline Development – Lessons Learned, NEPP 2002
3. Proton Testing: Opportunities, Pitfalls and Puzzles, Ray Ladbury, NASA Goddard Space Flight Center

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