Radiation Hardness Assurance Issues Associated with COTS in JPL Flight Systems: The Challenge of Europa

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Abstract

With the decreasing availability of radiation hardened electronics and the new NASA paradigm of faster, more aggressive and less expensive space missions, there has been an increasing emphasis on using high performance commercial microelectronic parts and circuits in NASA spacecraft. The use of commercial off-the-shelf (COTS) parts and circuits in space systems poses many potential problems, especially with regard to radiation hardness assurance (RHA) for JPL planetary missions. This is particularly true for the proposed JPL mission to Europa where the radiation requirement is very high. In this paper, we discuss COTS RHA issues within the context of the needs of a mission like Europa.

Life on Europa?

An important focus of future planetary exploration by the Jet Propulsion Laboratory is the search for evidence of life elsewhere in our Solar System. Beginning with the Voyager spacecraft and continuing through to the present day with recent data from the Galileo mission, a variety of scientific information has accumulated that suggests that Europa, one of the moons of the planet Jupiter (roughly the same size as Earth's moon), possesses the attributes that may have led to the existence and support of life. An example of such information is shown in Figure 1, an image of about a 10 km square of the surface of Europa acquired by the Galileo spacecraft at an altitude of 1250 km. The striations and other surface features are believed to be due to the actions of a subsurface liquid water ocean under an approximately 1 km-thick layer of ice that makes up the surface. The energy source that allows the subsurface liquid water layer to exist is the strong tidal action due to the immense gravitational pull of Jupiter. In addition, recent data from Galileo suggest that Europa also possesses an atmosphere and a metallic, possibly molten core. Thus, there are several similarities between Europa and Earth, further suggesting that a search for evidence of past or present life on Europa is a worthwhile endeavor.

Figure 1. Surface features of Europa suggesting cracking and upheaval due to tidal motion of a subsurface liquid water ocean under a layer of ice.

Europa Mission Radiation Environment

Another similarity between Earth and the Jupiter system that will unfortunately cause missions to Europa to be quite difficult is the existence of a strong magnetosphere around Jupiter. Like Earth, the presence of the magnetosphere has led to the formation of belts of trapped radiation.

Compared with the Earth's Van Allen radiation belts, the belts around Jupiter are much more extensive. This is due in part to the simple fact that Jupiter is much larger than Earth: the radius of Jupiter = R_J = 71,500 km, while Earth's radius is 6,380 km. In addition, particle densities are high within the belts partly because they are fed by the release of various atomic elements from the volcanic action on Io, another of Jupiter's moons. This situation is illustrated in Figure 2 which shows estimated >1 MeV electron isoflux contours around Jupiter. Note the comparison with the much more limited extent of the Earth's outer Van Allen electron belt.

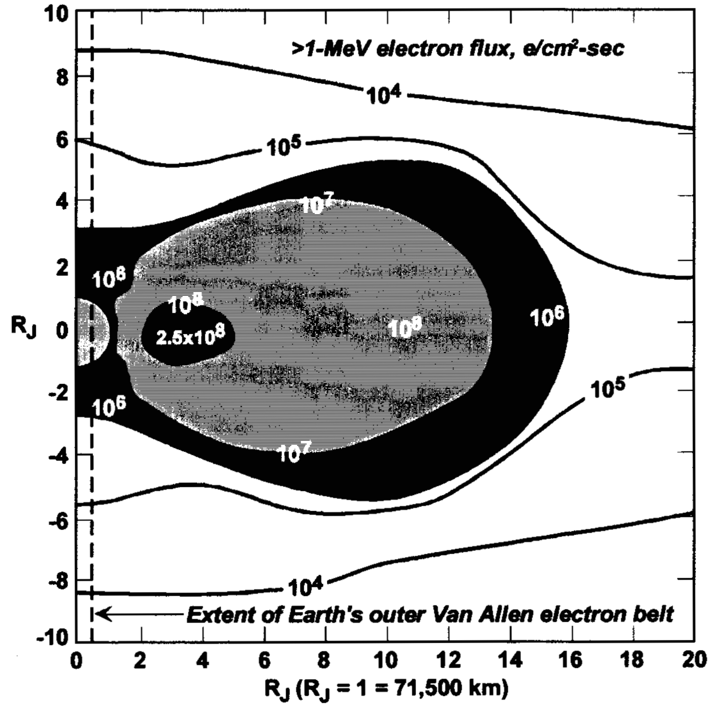

Figure 2. Greater than 1 MeV electron isoflux contours in the magnetosphere of Jupiter. Note that the belts extend further than a factor of 30 times the extent of the outer Van Allen electron belt.

The total amount of radiation that will be received by the Europa spacecraft depends on the complete mission profile, the final portion of which, the "Endgame", is shown in Figure 3 [1]. The Endgame will take approximately 3 months, finishing with the ballistic capture of the spacecraft by Europa for the primary 30 day mission around Europa. Note that in Figure 3 we have superimposed the electron isoflux contours, turned on their side relative to looking down on the Jupiter system, on the Endgame mission trajectories. Note also that except for the three most eccentric orbits, the spacecraft spends its entire Endgame within the belts at a flux of at least $1x10^6$ electrons/cm^2–sec. The result of this mission trajectory is that the spacecraft receives a total of approximately 4 Megarads(Si) behind 100 mils of aluminum during the entire mission with 2 Megarads(Si) received during the 30 day primary mission around Europa. Of this total, approximately 60% is due to electrons, and the remainder to protons.

The contrast between the Europa mission dose, as a function of Al shield thickness, and a typical low Earth orbit (LEO) mission dose is shown in Figure 4. Note the much higher total doses for the Europa mission (the Al shield thickness scale for the Europa mission is a logarithmic scale). These doses are so high that extremely thick shields are of no value for sensitive (~ 1 to 10 krad(Si)) electronic parts because the Bremsstrahlung radiation, created in the shield material itself, is so large. Another interesting comparison with the LEO mission is that the radiation environment at Jupiter has a much harder (more energetic) electron energy spectrum resulting in a more rapid drop off with shielding thickness of the proton dose, the opposite of the LEO case. Considering that the Europa spacecraft is of a new class of smaller, less massive spacecraft, for which weight is a primary consideration, it is clear that the radiation problem cannot be solved entirely be shielding, especially if one were to contemplate using a high percentage of commercial electronics.

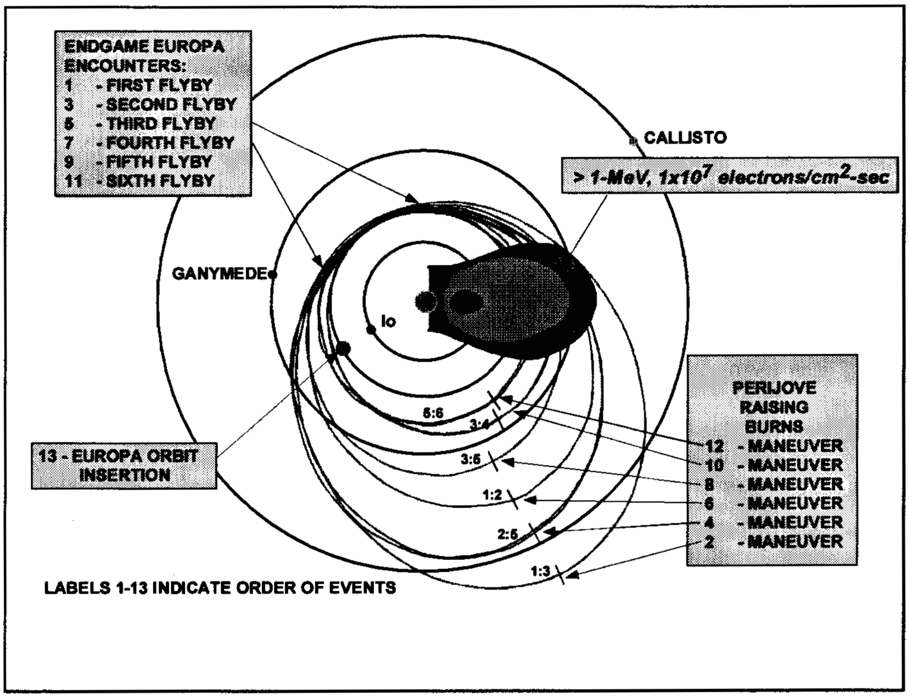

Figure 3. Final portion, "Endgame", of the mission to Europa. The isoflux contours are turned on their side for illustrative purposes and Europa is shown relatively larger for clarity [1].

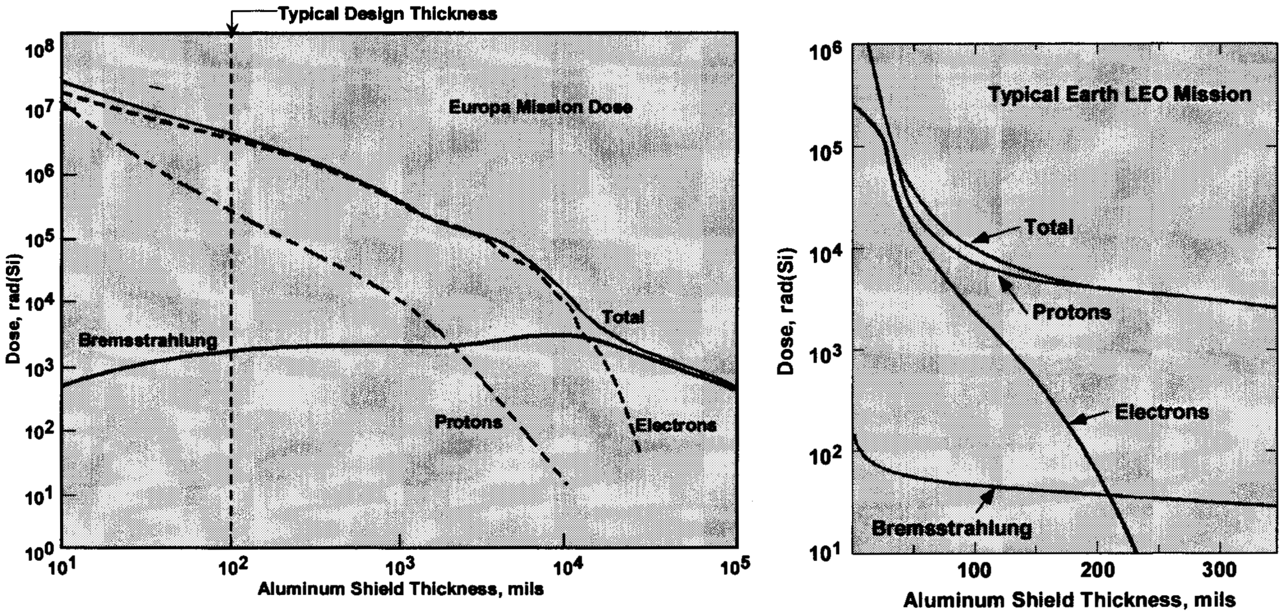

Figure 4. Comparison of projected mission dose for Europa with a typical mission dose for a low Earth orbit (LEO) mission. Note the much higher doses for the Europa mission and the logarithmic scale for shield thickness for this mission.

New Electronic Parts Paradigm for NASA

Several changes, some initiated by NASA, have contributed to a significantly different paradigm for electronic parts usage in NASA space systems. The demise of the cold war has led to a broad reduction in the development and production of radiation hardened microelectronics within the US. At the present time, there are only two major producers of hardened electronic parts – Honeywell SSEC and Lockheed-Martin-Manassas. While there are other suppliers with limited offerings of hardened products, such as Harris and UTMC, and third party custom foundries, it is clear that radiation hardened microelectronics availability has dropped significantly in recent years.

Another change that has taken place recently, partially stimulated by reduced hardened electronic part availability, is the shift by NASA toward a new paradigm characterized by the phrase, "faster, better, cheaper" (FBC). Very large, expensive flight projects with many science instruments on board have given way to several series of rapid, inexpensive spacecraft with more focused performance and science acquisition goals. In spite of the more limited objectives of individual spacecraft, these FBC missions can have considerable impact and can provide important science return, as in the case of the recent Mars Pathfinder mission [2].

The FBC paradigm has several features that influence the selection of microelectronics and photonics for both spacecraft engineering systems and on-board science instruments. Of particular relevance to parts selection is the willingness of flight projects to accept and manage risk, rather than attempting to completely avoid risk. In effect, this allows one to at least partially deal with parts radiation hardness assurance (RHA) issues at the system level by using various mitigation techniques such as error detection and correction (EDAC), and latchup protection circuitry. Thus, rather than using only radiation hardened parts, one can employ radiation tolerant parts and even commercial off-the-shelf (COTS) microelectronics.

The use of a series of smaller, less expensive spacecraft launched at frequent intervals to achieve an overall planetary science objective also affects the selection of microelectronics. Even when radiation hardened parts were more readily available, the delivery time was quite long, often of the order of six months or more. With spacecraft launches at a rate of more than one per year, and total project development cycle times of two or three years, such long lead times for parts procurement are difficult to accommodate. Thus, it is tempting to employ COTS parts that can be obtained quickly. It is worth noting, however, that the added radiation testing often required for COTS parts can increase the effective parts acquisition, build and insertion schedule.

Under the FBC paradigm, the drive to reduce spacecraft cost, weight and power usage also impacts electronic parts selection. The cost of radiation hardened parts is typically quite high, sometimes approaching $10,000 per part. COTS and radiation tolerant parts are usually much less costly, although added testing and screening can add significantly to total parts life cycle cost. In order to achieve reductions in cost, weight and power without sacrificing performance, one wishes to use the most advanced, highly scaled microelectronic components. Since advanced commercial parts are usually one to three generations ahead of available radiation hardened parts, reductions in overall electronic subsystem size, weight and power usage can often be accomplished by selecting advanced COTS parts. Unfortunately, the high performance and miniaturization achieved through the use of highly scaled COTS is often offset by increases in weight due to required radiation shields, and radiation-induced increases in leakage current and power consumption.

Use of COTS in Space Systems

The above discussion demonstrates that NASA flight project electronic system designers are strongly motivated to employ COTS parts in their system designs. However, there are issues that must be dealt with when using commercial parts in the natural space radiation environment. Potential problems include the following:

1. Because the space community represents a very small customer, high-volume parts manufacturers will not consider process and design alterations to improve radiation hardness levels of their COTS devices and circuits.
2. RHA is a unique requirement, in contrast with reliability, so that the space user cannot leverage off of high volume customers, such as the automotive industry, who require fairly stringent reliability features in their electronic parts and systems.
3. Intense competition within the commercial marketplace to improve performance and reduce cost can jeopardize the availability of specific parts that have been tested and upscreened

for future space systems.

4. Space applications, with the exceptions of the Shuttle, the International Space Station and some Earth-orbiting satellites like the Hubble Space Telescope (HST), do not allow for COTS part replacement and repair during the mission.
5. The response of electronic parts to total ionizing dose (TID) often depends critically on the details of the fabrication process. In addition, process changes implemented to improve performance can result in greater susceptibility to TID effects, and these changes are often made without the knowledge of the small customer end user. Thus, frequent radiation testing is necessary to insure against unexpected increases in radiation sensitivity.
6. In contrast with TID effects, single event effects (SEE) can depend strongly on circuit design. Even if major changes in circuit design are known to the user, and these changes are detrimental to SEE resistance, there is not much the small customer can do to retain the SEE tolerant design.
7. Advanced packaging techniques employed for COTS circuits often result in packaging configurations that are particularly difficult to adapt to radiation testing. Examples, are flip-chip bonded parts, 3-D stacks and multichip modules (MCMs). Heavy ion testing to establish SEE susceptibility becomes very difficult because of ion penetration limitations.
8. It is clear that the use of COTS with proper maintenance of RHA will require increased radiation testing. Lot-to-lot variations, even wafer-to-wafer variability, is often seen in the radiation response of COTS parts. An example is shown in Figure 5 where we illustrate the lot-to-lot variation in radiation response of field programmable gate arrays (FPGAs). It is rather ironic to note that in this case a commercial lot actually had better TID hardness than parts "space qualified" for SEE resistance. We note, however, that other commercial lots of this device showed reduced radiation hardness.

In spite of the difficulties listed above, it is possible, and more or less inevitable, that COTS parts will be used in a significant way in space systems. Indeed, today many operating satellites contain COTS circuitry. It is important to note, however, that there is no single solution that will facilitate large scale insertion of COTS into space flight systems. Among the possible approaches to using COTS parts in space are the following:

1. Work with commercial parts suppliers to obtain reliability and radiation data, and circuit design features. While as noted above, this is generally not possible with very high volume suppliers, there are companies, such as Honeywell, Lockheed-Martin, Temic, and others, who are responsive to the semi-custom radiation tolerant parts market even though it is small.
2. Through government contracts and collaborative technology development and testing, encourage data and information sharing among parts vendors and space users.

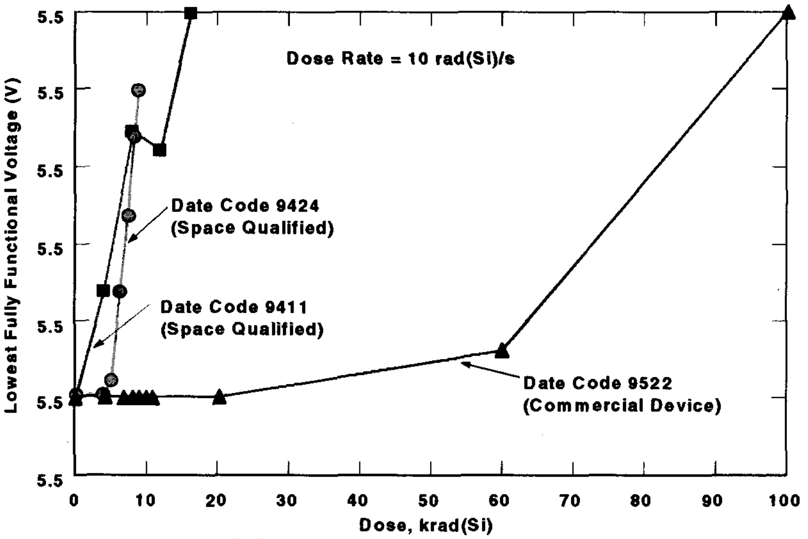

Figure 5. Lot-to-lot variation in total dose response for commercial FPGAs.

3. When possible, evaluate commercial process lines through inspection, failure analysis and radiation testing to determine workmanship quality, reliability and radiation tolerance.
4. Re-examine mission requirements and test procedures to be sure they are relevant to COTS in space, and to a paradigm which accepts risk. An example is the requirement for single event latchup (SEL) immunity, a nearly universal requirement until a few years ago.
5. Work with selected parts vendors to develop process line "tweaks" that will enhance radiation tolerance, but are minor enough to be implemented by the vendor. This technique is particularly adaptable to third party, custom fabrication lines.
6. Develop circuit design techniques that will increase radiation tolerance of the circuit even though the components making up the circuit may not possess good radiation resistance.
7. Maintain a vigorous and healthy radiation test capability that supports flight projects.
8. Develop standards, specifications and procurement methods which maximize RHA.
9. Develop system level hardware and software techniques, such as EDAC and redundancy, for enhancing RHA of subsystems containing COTS parts.
10. For CMOS-intensive circuitry, employ "smart" power techniques that allow circuitry to be powered off so that radiation degradation is minimized.
11. Make use of innovative radiation shielding methods, such as spot shielding and lightweight composite shield materials, to facilitate COTS use with minimum increases in weight.
12. Retain captive processing lines, such as the facility at Sandia National Laboratories, to build radiation hard and radiation tolerant parts when there is no other alternative.

Europa: A Difficult Environment for COTS

Bearing in mind the issues discussed above concerning COTS use in space, it becomes immediately clear that the extensive use of COTS in the Europa mission radiation environment described earlier will be particularly challenging. In addition, in keeping with the FBC paradigm, the Europa Orbiter spacecraft will incorporate advanced, high performance technologies to achieve its mission objectives. The X2000 Program Office at JPL will facilitate the insertion of advanced technologies into Europa and other new missions through technology development and delivery of spacecraft engineering subsystems, such as avionics, to these flight projects. In addition to the science instruments (radar sounder, laser altimeter, imagers/optical instruments) needed to study the characteristics of the ice layer and detect an underlying ocean, several subsystems will require electronics that can withstand the radiation environment. These include overall avionics system, attitude control system, stellar reference unit, sun sensor assembly, inertial measurement unit, reaction wheel assemblies and optical communication units.

In most cases, a combination of the most radiation tolerant microelectronics available along with shielding will be used to achieve RHA goals for TID effects. Of particular concern are optical surfaces which must "look at" objects and therefore cannot be entirely covered by radiation shielding elements, although serpentine optical pathways, if viable, will alleviate this concern to some degree. Clearly, in view of the tight mass budget on the spacecraft, clever uses of various shielding techniques will be critical for the insertion of high performance, radiation tolerant microcircuits in the various Europa mission systems and assemblies. Indeed, highly innovative combinations of radiation tolerant COTS, shielding techniques and system level mitigation methods will be required to realize a viable Europa mission. In the case of the avionics system, now being developed by X2000, certain critical parts, such as the flight computer processor, will be radiation hardened in SOI technology, but other elements, in particular flash memory and DRAM memory are only expected to be able to withstand approximately 40 to 100 krad(Si). The avionics system is made up of functional "slices", and the non-volatile memory (NVM) slice shown in Figure 6 is a prominent example of the need for a combined approach to RHA. Note that the NVM slice contains flash memory, characteristic of radiation susceptible, but sometimes tolerant COTS, and also ferromagnetic RAM, a technology still requiring more development. The challenges posed by this slice alone are considerable and, when met, should lead to important new spacecraft capabilities.

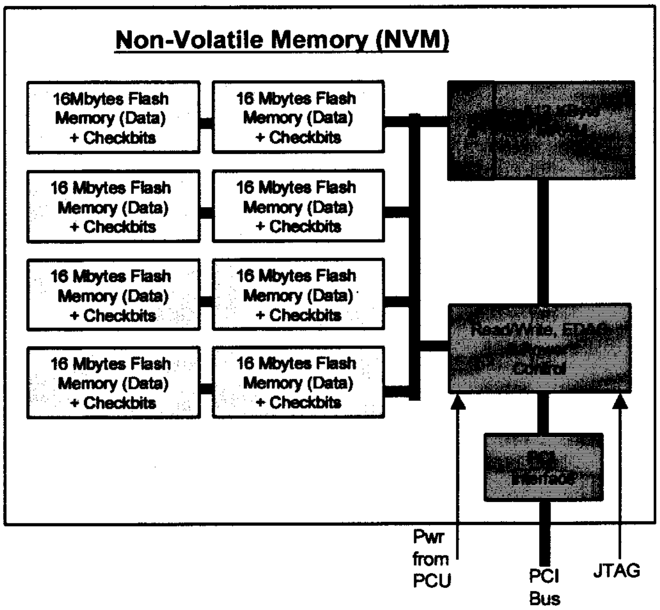

Figure 6. Europa Orbiter avionics system non-volatile memory slice.

The very high TID requirement of 4 Megarads(Si) for the Europa mission naturally focuses attention on TID effects. However, one must also consider the impact of single event effects (SEE) in order to establish overall RHA. As in the case of the TID environment, Europa also presents some unique features with regard to SEE. While energetic ions from solar flares and galactic cosmic rays (GCRs) are a source of concern during transit to Europa, once in the vicinity of Jupiter and its magnetosphere, the spacecraft will be exposed to a somewhat different distribution of particles that can cause significant SEE. Volcanic activity on the moon Io has resulted in the injection of copious amounts of light ions like sulfur, oxygen and silicon into the magnetosphere where they become trapped. These ions generally have a linear energy transfer (LET, a measure of how intensively an ion deposits energy in a device, which if high enough, can cause upset) value of less than 20 MeV/cm^2-mg. Since SEE are generally threshold effects in that below a threshold value of LET, LET$_{th}$, the SEE rate is very small and suddenly increases above this value, one can minimize SEE by selecting COTS parts with LET$_{th}$ values above 20. While certain types of COTS parts have quite low LET$_{th}$, most notably commercial DRAMs, many COTS devices do not, and can be used with caution in this environment. In addition, non-catastrophic SEE, such as upset, can be accommodated with system level techniques such as EDAC. Thus, the SEE issues associated with COTS in the Europa mission are not generally as severe as the TID effects in COTS. In any case, the Europa mission represents an exciting challenge which will assist NASA in leading planetary exploration into the future.

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2. See for example, M. Golombek, "The Mars Pathfinder Mission", p. 32 in *The Future of Space Exploration,* Scientific American Quarterly, May, 1999.