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Assessment of Commercial-Off-The-Shelf Electronics for use in a Short-Term Geostationary Satellite

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Abstract

Commercial-Off-The-Shelf (COTS) electronics offer cutting-edge capability at lower prices compared to their space-grade counterparts. However, their use in space missions has been limited due to concerns around survivability in a space environment; COTS devices are not designed to survive the harsh radiation environment of space. Nonetheless, for space missions with short durations it may be possible to use COTS electronics. This study evaluates the use of several families of COTS electronics for a specific short-term mission.

An assembled database including selected space grade and COTS components is discussed. High confidence FPGAs, microprocessors, and optocouplers COTS are identified. Medium confidence Memory, ADCs, DACs, power electronics, and RFMMICs COTS are also included, as well as testing to improve confidence in medium confidence parts. An experimental approach for evaluating tin whisker susceptibility for tin-leaded COTS components is described. Using COTS electronics in Short-Term Geostationary Satellites is feasible; this report includes enabling tools.

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EXECUTIVE SUMMARY

Geo Node Endurance COTS was a DARPA seedling effort carried out by Sandia National Laboratories in collaboration with Jet Propulsion Laboratory. DARPA's Tactical Technology Office is tasked with providing high-risk, high-reward innovative platforms. COTS electronics enable space platforms with advanced capability and rapid development cycles, however they may not fulfill radiation, reliability, or security requirements. Sandia National Laboratories performed a viability study for COTS electronics in short-term geostationary satellites to examine this potential application. The interdisciplinary team included Radiation and Electrical Sciences, Advanced Microelectronics and Radiation Effects, Microsystems Integration, and Sandia's Threat Intelligence Center.

Commercial-Off-The-Shelf (COTS) Electronics have become a necessary inclusion in mission-critical systems. The rapid pace of COTS technology development has left space grade components generations behind in some cases. A small-scale feasibility study was carried out on the viability of using COTS for a short-mission geostationary earth orbit(GEO) satellite. We formulated requirements for a hypothetical short GEO mission in terms of Total Ionizing Dose(TID=100kRad) and Single-Event Latch-up (SEL LETth=30 MeV-cm2/mg). These requirements were used to evaluate the suitability of both space grade and COTS parts.

We created a database with candidate COTS parts where existing radiation test data exists. The database includes high promise COTS FPGAs, microprocessors, and optocouplers. High Promise parts have available radiation data that satisfy mission requirements and are viable COTS options for short-duration space missions. The database also includes Medium Promise memory, ADCs, DACs, RFMMICs, and power devices. Medium Promise parts need additional radiation data, and there is a tradeoff between the cost of additional testing and more expensive space grade parts that was examined. This project also considered additional risks associated with COTS, including Sn Whiskers and Trust.

The use of COTS electronics in short-term space missions with limited radiation requirements offers several advantages that have significant impact on the pace and capability of space applications. High performance COTS enable more complex missions than would be possible using only space-grade parts. For missions with lower performance requirements, COTS devices could lead to smaller, lighter payloads which lower the costs for entire programs. Additional cost savings can be recognized as COTS are cheaper than their space grade counterparts. COTS electronics also have a shorter lead time and are more readily available. These factors could lead to an acceleration in the design, qualification, production, and deployment of space systems.

NOMENCLATURE

Abbreviation	Definition
AD	Analog Devices
BS	BAE Systems
BNL-NSRL	Brookhaven National Laboratory NASA Space Radiation Laboratory
COTS	Commercial-Off-The-Shelf
GEO	Geostationary Earth Orbit
GNEC	Geo Node Endurance COTS
IR	International Rectifier
JPL	Jet Propulsion Laboratory
LT	Linear Technology
SEE	Single-Event Effects
SEFI	Single-Event Functional Interrupts
SEL	Single-Event Latchups
SET	Single-Event Transients
SNL	Sandia National Laboratories
TAMU-CI	Texas A&M University Cyclotron Institute
TI	Texas Instruments

1. GEO NODE ENDURANCE COTS

Geo Node Endurance COTS(GNEC) was part of a DARPA seedling effort carried out by Sandia National Laboratories(SNL) in collaboration with Jet Propulsion Laboratory(JPL). Geo Node is an innovative DARPA Tactical Technology Office proposal for a persistent space platform that supports modular, replaceable, short-term payload modules. A robust platform skeleton can provide mechanical, power, and data architecture for hosted payloads. Various commercial and international payloads can be interchangeably hosted on this skeleton for short-term missions(<2 years).

These payloads can have significant cost savings by leveraging ongoing DARPA initiatives. They can be delivered to GEO using the Payload Orbital Delivery(POD) system developed as part of the DARPA Phoenix program[1]. Payload deployment and skeleton maintenance could be carried out by the Robotic Servicing of Geosynchronous Satellites(RSGS) program[2]. For GNEC, the goal of the project was to evaluate the feasibility of using COTS electronics instead of more expensive and difficult to acquire Space grade electronics for such a limited lifetime mission.

In order to perform this evaluation, the following steps were taken:

1. Identify the full life cycle radiation exposure for a Geo Node module
2. Generate a table containing both High Confidence Class S and High Promise COTS parts and available radiation data for those parts
3. Determine the cost of additional radiation testing that is needed for COTS devices with insufficient radiation data
4. Recommend if COTS parts can be used instead of Class S parts and any additional considerations for using COTS electronics

SNL and JPL carried out the workflow described above as seen in Figure 1 using a parallel path approach. This report captures the SNL efforts for GNEC.

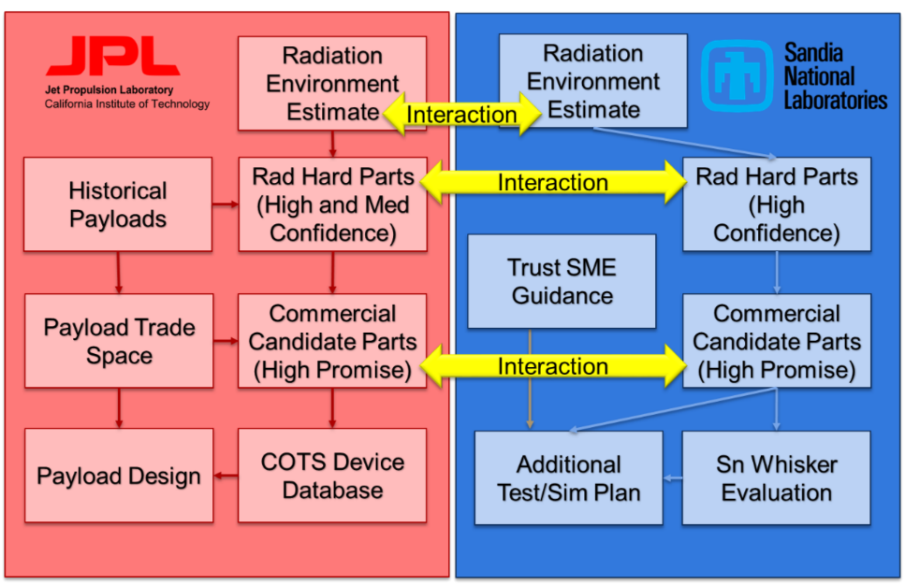

Figure 1. Workflow for GNEC project. Report captures SNL efforts.

2. SPACE ENVIRONMENT EFFECTS

The first step for the Geo Node Endurance COTS project was understanding the exposure for a Geo Node Endurance module throughout its lifecycle. It is expected that modules would be deployed for 18 to 24 months at geostationary earth orbit(GEO). For such a deployment there are concerns with the harsh radiation environment of space and the growth of Sn Whiskers.

2.1. Radiation Environment

Satellites in GEO do not have the protection of the Earth's geomagnetic shielding and are thus exposed to a severe radiation environment. The effects of this radiation environment on satellites can be broken down into (1) total dose effects, (2) single event effects, and (3) charging effects[3].

2.1.1. Total Dose Environment

Energetic particles in space can damage materials though ionizing and non-ionizing mechanisms. For a satellite in GEO, total ionizing dose effects have a greater contribution than total non-ionizing dose effects[3]. To estimate these total ionizing dose effects, it was assumed that there would be 200 mils of aluminum shielding, the payload would be spherical, and that the system would be in GEO for the 2 year maximum. These assumptions gave estimated TIDs of 10-50 kRads[4-8]. We chose to use a nominal TID level of 50 kRads and a worst-case TID level of 100 kRads that includes a 2x margin. These targets were independently arrived at by SNL and JPL and mutually agreed upon through discussion.

2.1.2. Single Event Environment

Particles in space can also interact with electronic components and cause Single Event Effects (SEE). SEE can include Single Event Transients(SET), Single Event Upsets (SEU), Single Event Functional Interrupts (SEFI) and Single Event Latchup (SEL) among other mechanisms. For this work, we focused on SEL as the criteria for evaluation as design-based solutions can be implemented for the other effects and having a component latch-up is a destructive mechanism[9]. Ion flux levels in GEO start dropping significantly at just under 30 MeV-cm^2/mg[9]. We chose an SEL threshold of 37 MeV-cm^2/mg, which is the lower end of the drop-off[9]. This target was agreed upon by SNL and JPL subject-matter experts.

2.1.3. Charging Environment

Charging effects can include both surface charging or internal charging phenomena. However, these effects can be mitigated through payload design and layout[1]. As GNEC focuses on individual components, charging effects were excluded from our analysis.

2.2. Sn Whisker Growth

With the increasing adoption of Pb-free initiatives more COTS components utilize pure tin plating and high tin content solders. Tin can grow whiskers that can cause electrical shorts that can lead to catastrophic failure of critical systems, especially in space applications. Whisker growth time and maximum whisker length are highly variable, making it difficult to predict the susceptibility of a component to whisker-related failure. The current approach to determine whisker susceptibility is to test components using established methods that are known to promote whisker growth.

The following test methods are standard for Pb-free surface finish evaluation:

Thermal cycling: -55 to 85°C, 20 min. per cycle.

Elevated temperature and high relative humidity (RH):

- 85°C/85% RH, 4,000 hours
- 60°C/85% RH, 4,000 hours

Previous Sandia studies have observed whisker growth on pure tin-plated multilayer ceramic capacitors (size 1210) and transistors (SOT23) that were exposed to -55 to 85°C (1,500-2,000 cycles) and 60°C/93% RH (4,000 h). Most whiskers grew to be 10-20 μm long and were found on all of the terminations and leads that were inspected. The lengths of the longest whiskers on temperature-cycled components were 35μm and 75 μm after 1,500 cycles for transistors and capacitors, respectively. After 4,000 h at 60°C/93% RH, the longest whiskers were 40 μm and 25 μm long on transistors and capacitors, respectively.

Other studies reported that in addition to long whisker growth, regions of localized corrosion were observed on tin-plated quad flat package (QFP) leads exposed to 60°C/93%RH and whiskers appeared in these regions [10]. The 93% RH environment led to condensation which complicated the tests. Preventing condensation in the chamber can reduce or eliminate localized corrosion and associated whisker growth, so 85% RH has since been adopted by the electronics industry for whisker susceptibility testing.

Arrested whisker growth can occur in pure tin and high tin content solders. When the pure tin-plated capacitors used in the Sandia studies described previously were exposed to -55 to 85°C and inspections every 500 cycles, whiskers that were observed after 1,000 cycles were the same length after 1,500 cycles [11]. The same type of capacitor exposed to long-term storage and with inspections every 2-3 years resulted in whiskers that reached their maximum length after ~5 years [11]. Whisker growth from Sn-Ag-Cu (SAC) 305 on SOT23 package leads was compared after 1,000 and 4,000 h of exposure to 85°C/85% RH. Most whiskers inspected after 4,000 h had not grown any longer than they were after 1,000 h. New whiskers appeared but were not as long as those that grew during the first 1,000 h [12]. Similar observations were made for chip resistors soldered with SAC305 and low silver content micro-alloyed solders [13]. It has been suggested that longer whiskers would be obtained if longer, uninterrupted tests were conducted [12].

3. CANDIDATE PARTS

The Geo Node Endurance module is yet to be designed, but the goal of having a capable short-term payload was used to identify candidate electronic parts. A variety of electronic part types were considered, including FPGAs, Memory, ADCs, DACs, power electronics, RFMMICs, optocouplers, and microprocessors. These part types capture key components for the major subsystems for a GEO satellite, including power, command/control, and communications. Available radiation data was gathered for both space grade and COTS parts. Data was gathered from both published sources and ongoing work at JPL and SNL. This was put into a Geo Node Endurance COTS(GNEC) database (Appendix A).

The GNEC database in Appendix A captures a broad spectrum of information. Part information such as part type, manufacturer, part number, and part description are provided. The database was designed to be relatively inclusive, and parts cover a wide range of performance criteria. The database also includes both US and non-US manufacturers, something that may be of concern for creating a trusted system.

The database has all identified radiation data as well as the source of that data. Parts are classified as Space Grade or COTS in the database. In addition to the specific part types identified earlier, electronic parts with radiation data that may be of use in a short-term satellite were included in the database. For each of the identified part families, the criteria outlined in section 2 was used to evaluate the parts. The categories that were used can be seen in Table 1 below.

Color coding was used to classify the parts with respect to the available TID and SEL radiation data. Medium confidence parts have high promise data for one criteria and high confidence parts have high promise data for both. Table 2 through Table 8 below are intended to be high-level overviews that capture crucial part and radiation information. For each of the parts in these tables additional information can be found in the GNEC database (Appendix A) using the part number.

Table 1. Criteria for Data Tables

Category	TID Threshold	SEL Threshold
High Promise	Good data for TID >100kRad	SEL >37 MeV-cm^2/mg
Medium Promise	Good data for TID >50kRad	Additional data needed
Low Promise	No good data for TID >50kRad	SEL <37 MeV-cm^2/mg
Data Unknown	Data unknown; Test recommended based on part	

3.1. Field Programmable Gate Arrays (FPGAs)

Selected FPGA data is seen in Table 2. There are COTS high promise parts for both evaluation criteria.

Table 2. COTS and Class S FPGAs

Type	Man.	Part #	Group	TID (krad [SiO_2])	SEL (MeV-cm2/mg)
FPGA	Microsemi	AGLN250V2-VQG100	COTS		>51
FPGA	SiliconBlue	iCE65	COTS		>83
FPGA	Altera	EP4SGX230KF40	COTS		>112
FPGA	Xilinx	XC4	COTS	>240	>58
FPGA	Xilinx	XC5VFX130T	COTS	340	>75
FPGA	Xilinx	XC6	COTS	380	>37
FPGA	Xilinx	XCKU040-2FBVA1156E	COTS	>1000	>63
FPGA	BAE	197A805	S	>150	*Immune
FPGA	Microsemi	RTAX-2000s	S	>300	>117
FPGA	Xilinx	XQR4V	S	300	>100
FPGA	Xilinx	XQR5VFX130	S	>1000	>100

3.2. Memory

Selected memory data is seen in Table 3. There are few high promise COTS parts for both evaluation criteria. Additional TID or SEL data would be useful for most COTS.

Table 3. COTS and Class S Memories

Type	Man.	Part #	Group	TID (krad [SiO_2])	SEL (MeV-cm2/mg)
Memory	Alliance	AS6C1608	COTS	>200	
Memory	Alliance	AS6C4016	COTS	125	
Memory	Cypress	CY14B101I	COTS	>1000	
Memory	Cypress	CY15B104Q	COTS	400	
Memory	Cypress	FM24V10	COTS	200	
Memory	Hynix	HY27UF084G2M	COTS	50	>55
Memory	Hynix	H27QDG822C8RBCG	COTS	200	>85
Memory	Innodisk	DS2M-08GI81AW1ST	COTS		>37
Memory	ISSI	IS42S16400J-5BL	COTS		
Memory	ISSI	IS4TR81280-15GBLI	COTS		>75

Memory	ISSI	IS61WV20488BLL	COTS	>100	
Memory	ISSI	IS61WV25616BLL	COTS	>100	
Memory	Samsung	K4B1G0446G-BCH9000	COTS		>75
Memory	Samsung	K9F4G08U0A	COTS	100	>87
Memory	Samsung	K9F8G08U0M	COTS	400<X <500	>83
Memory	Fujitsu	MB85RC256V	COTS	75	
Memory	Fujitsu	MB85RS1MT	COTS	75	
Memory	Fujitsu	MB85RS64V	COTS	60	
Memory	Freescale	MR2A16A	COTS	90	
Memory	Everspin	MR2A16A	COTS	70	
Memory	Everspin	MR4A08B	COTS	70	
Memory	Micron	MT29F16G08ABABAWP	COTS		
Memory	Micron	MT29F4G08AAAWP	COTS	65	31<X<54
Memory	Micron	MT29F8G08AAAWP	COTS	50<X <75	
Memory	Micron	MT46H64M16LFB	COTS		
Memory	Micron	MT41J128M8JP-15E	COTS		>75
Memory	Austin	MT5C2564	COTS		37
Memory	Austin	MT5C2568	COTS		58
Memory	Micron	N25Q128	COTS		
Memory	Micron	NP8P128A13TSM60E	COTS	400	
Memory	Fairchild	R29773	COTS	>200	>37
Memory	White	WMS128K8	COTS		37
Memory	Xilinx	XCF128XFTG64C	COTS		>40
Memory	BAE	8394325	S	>500	*Immune
Memory	BAE	8427352	S	>1000	*Immune
Memory	BAE	8464575	S	>100	*Immune
Memory	BAE	8497642	S	>1000	*Immune
Memory	BAE	238A790	S	>500	*Immune
Memory	BAE	251A172	S	>100	*Immune

3.3. Microprocessors

Selected microprocessor data is seen in Table 4. There are several high promise COTS parts based on SEL. These parts also have small geometries, which improves TID hardness[14].

Table 4. COTS and Class S Microprocessors

Type	Man.	Part #	Group	TID (krad [SiO_2])	SEL (MeV-cm2/mg)
µProcessor	AD	AD9361	COTS		>37
µProcessor	Qualcom	APQ8064	COTS		>75
µProcessor	Amtel	AT91SAM9G20	COTS		>86
µProcessor	Intel	ATOME620	COTS		>85
µProcessor	TI	MSP430FR5739	COTS		>85
µProcessor	Saronix-ecera	SHPCIE100	COTS		>43
µProcessor	BAE	8447257	S	>1000	*Immune
µProcessor	BAE	8488960	S	>1000	*Immune
µProcessor	BAE	251A161	S	>200	*Immune
µProcessor	Intel	Pentium III SL5EM	S	500	>15
µProcessor	Atmel	TSC695F	S	100	>75

3.4. Analog-to-Digital and Digital-to-Analog Converters(ADCs & DACs)

Selected ADC and DAC data is seen in Table 5. There is one high promise COTS part identified, but additional data is needed for other candidates.

Table 5. COTS and Class S ADC/DACs

Type	Man.	Part #	Group	TID (krad[SiO_2])	SEL (MeV-cm2/mg)
ADC/DAC	AD	AD5622	COTS		>24
ADC/DAC	AD	AD6640	COTS	>100	>37
ADC/DAC	AD	AD7712ANZ	COTS		>85
ADC/DAC	AD	AD7714	COTS	10<X<15	<27
ADC/DAC	AD	AD7760	COTS	30	
ADC/DAC	AD	AD7821	COTS	>30	>80

ADC/DAC	AD	AD7885	COTS	>50	
ADC/DAC	AD	AD7991	COTS		>24
ADC/DAC	AD	AD9257	COTS		>86
ADC/DAC	AD	AD977	COTS	4	>84
ADC/DAC	TI	ADS1258	COTS		>85
ADC/DAC	TI	ADS1281	COTS		>85
ADC/DAC	TI	ADS5483	COTS		>75
ADC/DAC	AD	DAC08	COTS	25	>119
ADC/DAC	LT	LTC1417	COTS	20	>67
ADC/DAC	LT	LTC1418	COTS		>76
ADC/DAC	LT	LTC1419	COTS		>78
ADC/DAC	LT	LTC1604	COTS		>65
ADC/DAC	Maxim	MAX529	COTS	>5	>84
ADC/DAC	Maxim	MX7225UQ	COTS	>10	>90
ADC/DAC	Maxwell	7872	S	>100	>60
ADC/DAC	AD	AD571S	S	>200	>60
ADC/DAC	AD	AD574S	S	>100	>83
ADC/DAC	AD	AD6645S	S	>100	>83
ADC/DAC	AD	AD768S	S	>100	>83

3.5. Power Electronics

Selected power electronics data is seen in Table 6. There are some high promise COTS parts for one criteria, but additional test data is needed for most COTS.

Table 6. COTS and Class S Power Electronics

Type	Man.	Part #	Group	TID (krad[SiO_2])	SEL (MeV-cm2/mg)
Power	Micropac	53278	COTS		50
Power	Microsemi	2N3439	COTS		>77
Power	Interpoint	AFL2828	COTS		>53
Power	LT	LTC3428	COTS		>37
Power	LT	LTC6103	COTS		>86

Power	LT	LT1019AMH-2.5	COTS	>50	Immune
Power	LT	LT1175	COTS	>10	Immune
Power	LT	LT1172MJ8	COTS		Immune
Power	Fairchild	NDS352A	COTS	>50	
Power	AD	REF02	COTS	30<X<50	>75
Power	AD	AD780S	S	>100	>85
Power	AD	AD8210S	S	>100	>80
Power	AD	AD8212S	S	>100	>84
Power	IR	IRHF7110SCS	S	>1000	>37
Power	IR	IRHLF87Y20	S	>300	>81
Power	IR	IRHYS67234T3	S	>1000	>90
Power	Intersil	IS139ASRH	S		>83
Power	Intersil	ISL70001	S		>86
Power	IR	JANSF2N7484T3	S		>60
Power	TI	LM193AxRLQMLV	S	>100	>98
Power	IR	LS2805S	S	100<X<300	>90
Power	LT	RH1011	S		>114
Power	Interpoint	SMSA2815S	S	>50	>74

3.6. Radio Frequency Monolithic Microwave Integrated Circuits (RFMMICs)

Selected RFMMIC data can be seen in Table 7. There are no high promise COTS parts for both criteria. Additional TID data would be useful for most COTS.

Table 7. COTS and Class S RFMMICs

Type	Man.	Part #	Group	TID (krad[SiO_2])	SEL (MeV-cm2/mg)
RFMMIC	Microchip	TC4423	COTS	>30	>86
RFMMIC	AD	AD7306	COTS		>37.7
RFMMIC	AD	AD9364	COTS	>50	>87
RFMMIC	Intersil	ISL32602	COTS		>37.7
RFMMIC	LT	LTC2872	COTS		>37.7
RFMMIC	TI	MAX3223	COTS		>37.7

RFMMIC	LT	LTC1157	COTS	<15	
RFMMIC	AD	AD8346S	S	>100	>83
RFMMIC	AD	AD8351S	S	>100	>83
RFMMIC	AD	ADL5501	S	>100	>84
RFMMIC	AD	ADL5513	S	>100	>80

3.7. Optocouplers

Selected optocoupler data can be seen in Table 8. There are several high promise COTS parts based on SEL. Optocouplers are relatively hard to TID [15,16].

Table 8. COTS and Class S Optocouplers

Type	Man.	Part #	Group	TID (krad[SiO_2])	SEL (MeV-cm2/mg)
Optocoupler	Micropac	66183	COTS		>60
Optocoupler	Micropac	66252	COTS		>60
Optocoupler	Micropac	66260	COTS		>76
Optocoupler	Micropac	66266	COTS		>60
Optocoupler	Vishay	ILD2	COTS		>60
Optocoupler	Iso Link	OLF300	S		>77.3
Optocoupler	Iso Link	OLI249	S		>75.7

3.8. Summary of Candidate Part Data

For each of the part types discussed in this section, available radiation data can be used to evaluate confidence in those COTS part. High confidence parts are parts that have both high promise data for TID and SEL. Medium promise parts are parts that have at least medium promise data for one criteria and no low promise data.

FPGAs, microprocessors, and optocouplers have several high confidence COTS options. Other part families have medium confidence COTS options where data is needed for TID or SEL performance. Memory, ADCs, DACs, and power electronics have medium confidence candidates where additional SEE or TID test data is needed. Additional TID data is also needed for medium confidence RFMMICs. These data needs are summarized in Figure 2.

	Part Class		COTS Info.	
Part Type	Space	COTS	TID	SEE
FPGAs	Data Sufficient	Data Sufficient	Data Sufficient	Data Sufficient
Memory	Data Sufficient	Data Needed	Data Needed	Data Needed
Processors	Data Sufficient	Data Sufficient	Data Sufficient	Data Sufficient
ADC/DAC	Data Sufficient	Data Needed	Data Needed	Data Needed
Power	Data Sufficient	Data Needed	Data Needed	Data Needed
RFMMICs	Data Sufficient	Data Needed	Data Needed	Data Sufficient
Optocouplers	Data Sufficient	Data Sufficient	Data Sufficient	Data Sufficient

(green)	Data Sufficient
(amber)	Data Needed

Figure 2. Summary table for data needs

4. ADDITIONAL TESTING

For COTS parts where available data is insufficient, additional radiation testing can be carried out to increase confidence in their ability to survive in a space mission. Memory, ADCs, DACs, and power electronics have parts where there is insufficient TID or SEE data. There were also RFMMICs with insufficient available TID data. Additional costs for both TID and SEE testing were calculated for these part families.

4.1. Total Ionizing Dose Testing

Total Ionizing Dose(TID) testing can be carried out at several SNL facilities. Gammacell220 in TA-I and the Gamma Irradiation Facility in TA-V both use a Cobalt-60 gamma source to carry out TID testing. High dose rate TID testing can be done at the Annular Core Research Reactor in TA-V. Off-site TID testing can be carried out at White Sands Missile Range's Gamma Radiation Facility.

For each of the parts that needs additional TID testing, the cost of this additional testing was estimated as can be seen in Table 9. The hardware estimate includes both the part cost for five COTS devices as well as fixturing needed for testing. The test estimate is the cost of test development and electrical pre/post testing assuming a $6K/week cost. The radiation estimate is the cost of a 1 day 100Krad exposure at either Gammacell220 or the Gamma Irradiation Facility. These costs are based on testing at an SNL facility during a low demand period and cost may vary based on facility availability and program flexibility.

Table 9. TID Testing Estimates

Part Type	Hardware ($K)	Test ($K)	Radiation ($K)	TID Estimate($K)
Memory	6	26	2	34
ADC/DAC	2	14	2	18
Power	2	14	2	18
RFMMICs	8	26	2	36

Table 9 shows the cost of additional TID test cost is between $18K-$36K depending on the part being tested. However, it is important to note that if multiple part types are tested there will be synergies that reduce total cost. For example, it is possible to dose multiple parts in the same TID exposure. It may also be the case where the same test programs could be used for similar parts, reducing test development costs. Alternatively, real-time electrical testing could be desired for certain parts which could change test costs.

4.2. Single-Event Effect Testing

Single-Effect Event(SEE) testing can be done at non-SNL facilities. Texas A&M University's Cyclotron Institute(TAMU-CI) and Brookhaven National Laboratory's

NASA Space Radiation Laboratory(BNL-NSRL) both offer heavy ion beam facilities where SEE testing can be carried out.

The cost of additional SEE testing was estimated for the parts with insufficient data and can be seen in Table 10. The hardware estimate includes part cost for five samples, sample preparation, and fixturing. Test costs includes costs associated with electrical test development, travel, and electrical testing assuming a $6K/week cost. The radiation estimate is the cost of a half day at either TAMU-CI or BNL-NSRL, and includes beam-time and labor costs. These costs are based on estimates from past work at TAMU-CI and actual costs may vary with schedule or facility availability.

Table 10. SEE Testing Estimates

Part Type	Hardware ($K)	Test ($K)	Radiation ($K)	SEE Estimate($K)
Memory	8	28	8	44
ADC/DAC	3	16	8	27
Power	3	16	8	27

The estimates in Table 10 are between $25K-$45K for additional SEE testing. Testing multiple part simultaneously can reduce these costs. For example, testing multiple part types in the same trip reduces travel costs and could affect beam-time needed. On the other hand, there may be particular parts that should be evaluated using a wider spectrum of ions, driving up radiation costs.

4.3. Sn Whisker Evaluation Testing

Based on the available data from the GNEC database, testing is needed that evaluates the whisker susceptibility of COTS components and devices that represent a variety of materials, packages, and manufacturers. The devices listed in Table 11 and Table 12 satisfy these criteria, but are not a comprehensive list of all parts with Sn Whisker concerns. The selected components enable the influence of several factors on whisker growth to be evaluated including: (i) mitigation method (nickel underlayer; Sn-Pb solder dipping; Sn-Pb plating); (ii) type of solder (90Sn-10Pb, 63Sn-37Pb, SAC305), (iii) interconnect geometry (leaded device or ball grid array, BGA), and (iv) device manufacturer.

Table 11. Leaded COTS for whisker susceptibility evaluation

Component	Leads	Package	Manufacturer
2N3439 NPN low power transistor	Sn-Pb solder dip	TO-39	Microsemi
2N3439 NPN low power transistor	Sn on Au	TO-39	Microsemi

2N3439 NPN low power transistor	Sn-Pb plating	TO-5	Microsemi
2N3439 NPN low power transistor	Sn on Ni	TO-5	Microsemi
AD6640 A/D converter	Sn on Ni	44 LQFP	AD
NAND Flash Memory	Sn or 90Sn-10Pb plated	48-pin TSOP	Micron

In Table 11, the devices include NPN low-power silicon transistors (TO-39 and TO-5 packages); an analog-to-digital converter packaged in a 44-lead quad flatpack (LQFP); and a NAND flash memory packaged in a 48-pin thin small outline package (TSOP).

Table 12. COTS surface mount and ball grid array packaged components

Component	Solder pad/ball composition	Package	Manufacturer
2N3439 NPN low power transistor	Au on Ni	U4	Microsemi
2N3439 NPN low power transistor	Au on Ni	UA	Microsemi
AD9364 RF Agile Transceiver	SAC305	144 bump CSP-BGA, 0.8 mm pitch	AD
Snapdragon 600 processor APQ8064	SAC305	784-pin FCBGA, 0.8 mm pitch	Qualcomm
Snapdragon 600E processor	SAC305	784-pin FCBGA, 0.8 mm pitch	Qualcomm
Virtex 5 FF1738	63Sn-37Pb	1738-bump FCBGA, 1 mm pitch	Xilinx
Virtex 5 FFG1738	SAC305	1738-bump FCBGA, 1 mm pitch	Xilinx

The devices in Table 12 include NPN low-power transistors in surface mount U4 and UA packages; a RF agile transceiver in a chip-scale package (CSP) BGA; flip-chip (FC) BGA-packaged processors; and field programmable gate array (FPGA) devices in fine-pitch BGA packages. The U4 and UA packages are not tin plated, but when soldered to assemblies, whiskers could grow in areas of the lead where the solder fillet is thin [12]. Whisker growth from SAC solder balls has been observed and was found to depend on the alloy composition; the use of rare-earth additives; and manufacturing process variables [12]. Additionally, component suppliers are shifting to lower cost solder alloys such as Sn-Cu with additives (e.g., Ni, Ge); and SAC alloys that contain 1 wt.% or less of silver [17]. The whisker susceptibility of these alloys requires further study.

The following aging conditions are recommended: -55 to 85^{o}C temperature cycling (2,000 cycles with and without inspections every 500 cycles); 60^{o}C/85% RH for 4,000 h with and without inspections every 1,000 h; 85°C/85%RH for 4,000 h with and without inspections every 1,000 h; and voltage cycling at 60oC, 20-30% relative humidity for 10 days [18]. The whisker growth characteristics to be monitored during these experiments include: the incubation time; average whisker length; maximum whisker length; whisker density; and whisker diameter. Whisker inspection criteria are documented in a JEDEC standard [19].

In a real application, the devices will be soldered to assemblies using Pb-free solder. This introduces additional considerations for whisker susceptibility, particularly for leaded devices. During reflow, dissolution of the tin in the molten solder will change the elemental composition of the lead. The composition may vary along the lead, especially if solder wicking was incomplete.

Thermal cycling (-55 to 85°C) and 85°C/85% RH exposures each led to whisker growth from solder joint fillets of leaded components where the solder was <1 mil thick [3]. Another concern for Pb-free soldered components is that whisker growth depends on process variables such as the type of flux, cleaning method, and reflow atmosphere. The effect is so pronounced that 85°C/85% RH exposure was used to distinguish between parts soldered in air or nitrogen and whether they were soldered with or without halogen-free fluxes [20]. The whisker susceptibility of the devices in Table 11 should also be evaluated after soldering to boards by more than one assembly house.

5. RECOMMENDATIONS

The viability of using COTS in a short-term space mission can be evaluated using the GNEC database. Recommendations below examine the database parts and paths forward for using COTS in space systems.

5.1. Radiation Evaluation

A radiation evaluation is provided based on GNEC database data. Part types could be separated based on whether High Confidence COTS candidates existed or whether the best available were Medium Confidence COTS. For FPGAs, microprocessors, and optocouplers High Confidence COTS were identified. Memory, ADCs, DACs, power electronics, and RFMMICs only had Medium Confidence COTS for which additional testing would be needed.

5.1.1. High Confidence COTS

High Confidence COTS FPGAs have been identified with available radiation data that satisfies our radiation environment evaluation criteria for TID and SEE. These COTS devices are viable for use in a short-term space missions. It may be that these devices have lower single-event thresholds than their Space Grade counterparts, however these issues may be mitigated through circuit architecture and payload design.

High Confidence COTS microprocessors in the GNEC database are suitable for inclusion in short-term space missions with limited radiation exposure. These parts have available radiation data that satisfies our SEE criteria and based on the technology size is hard enough to satisfy our TID criteria. Additional TID testing on these parts could be done to confirm that this assumption holds true.

COTS optocouplers that are High Confidence can be found in the GNEC database. These parts are viable for use in short-term space missions. Their radiation data satisfied our SEE criteria and SEE is the major concern for optocouplers.

FPGAs, microprocessors, and optocouplers are electronic part families for which High Confidence COTS exist for a short-term space mission. High Confidence parts in these families can be used with minimal additional testing.

5.1.2. Medium Confidence COTS

Medium Confidence parts are available for Memory, ADCs, DACs, power electronics, and RFMMICs. For these part families additional analysis must be done to determine if it is worth doing radiation testing on COTS parts or if space grade parts are the path forward. Using cost analysis, the Break-Even Point(BEP) can be between COTS with additional radiation testing and more expensive Space Grade parts. The BEP is equal to the fixed cost of additional radiation testing divided by the difference between the variable costs for Space Grade and COTS parts. If the number of parts is expected to exceed the BEP, then COTS parts would provide a cheaper alternative to Space Grade parts. Examples of this process were carried out for Medium Confidence Memory and power electronics to demonstrate how this analysis can be applied.

One part that was identified in the GNEC database as medium confidence was the Alliance AS6C1608 SRAM that needed additional SEE testing. This part had a cost per part of around $7.60 and from Table 10 the SEE test costs would be about $44200. The AS6C1608 is SRAM with 16 Mbit of total storage as is BAE System's Space Grade 8427352 Independence SRAM which costs around $6,500 per part. Performing the BEP calculation we find that BEP=(44,200)/(6500-7.6)=6.8. Geo Node would theoretically have more than 7 SRAM parts in all payloads so it would be better to use COTS parts, based on this analysis. This comparison does not compare two parts with identical performance specifications, but focuses on trying to find the most comparable space grade part. In this comparison there is a clear advantage to using COTS in Geo Node.

Another part that was identified as medium confidence in the GNEC database was the Fairchild NDS352A MOSFET that had medium promise TID data but no available SEE data. This part had a cost per part of just under $0.12 and additional SEE testing was estimated to cost $27,200. The International Rectifier JANSF2N7484T3 is a space-grade MOSFET that costs around $536.50 per part. Calculating BEP, we find BEP=(27,200)/(536.50-0.12)=50.7. It is likely that Geo Node payloads would use more than 51 MOSFETs across all expected payloads, so using COTS would be cost-effective. For this comparison, the space grade component is higher capability than the COTS part, but it is possible that short-term payloads would have reduced performance requirements that could be met by COTS parts. This comparison demonstrates that using COTS is based on the number of expected parts of that type in the lifetime of the program.

As has been demonstrated, there are cases where additional radiation testing on Medium Confidence COTS parts could end up being a cheaper option to space grade electronics. The cost of additional testing and the difference in prices between space grade and COTS can be used to find a Break-Even Point. Based on the number of devices used in the lifetime of the program, it is possible to figure out when Medium Confidence COTS should undergo additional testing.

5.2. Sn Whisker Evaluation

Sn Whisker Evaluation Testing for COTS devices with Sn leads should be performed as described earlier in this report. Those tests should be done on a per-part basis and can include several materials, packages, and manufacturers. The cost of these studies can differ based on parts tested, sample size, conditions used, and examination procedure. It is recommended that for mission-critical components a more thorough process is followed than for components in non-core subsystems. Mitigation strategies may be beneficial to reducing the risks associated with Sn Whisker growth.

The parts identified in section 4.3 are some examples of parts with identified Sn Whisker risk, but is not comprehensive. It is recommended that for each component that packaging is examined in detail to better understand Sn Whisker risks.

5.3. Summary

The GNEC database created as part of this effort can be found in Appendix A. This database includes both Space Grade and COTS parts. These parts have existing radiation data, and have been evaluated with respect to the expected environment for a Short-Term Geostationary Satellite mission. The criteria used were for TID and SEL, as other effects can be mitigated by system architecture solutions.

This report has identified specific risks of using COTS in a space environment; radiation survivability and Sn Whisker susceptibility. High Confidence COTS have been identified, where available radiation test data supports the use of these devices for short-term space missions. Medium Confidence COTS parts have also been identified. For these parts a method for determining if the additional testing is beneficial based on part type and program needs has been outlined and demonstrated on some example parts. A strategy for evaluating Sn Whisker risks on a part-by-part basis has also been described. These tools can be used by satellite designers for short-term GEO missions.

When designing a satellite, there are many things that must be considered to create a robust, reliable design. The GNEC database provides available information on radiation survivability for some crucial components. However, system designers must remain vigilant and ensure that the risks of their system are understood. Component-level reliability data must be aggregated to get a clear picture of system-level risk. Design for reliability and survivability can be used to create system-level mitigation for known risks. Paying attention to supply chain is also of critical importance, especially since the GNEC database includes both US and non-US vendors. Designing Trusted systems requires an understanding of supply chain risks and reducing them when possible.

The GNEC database identifies COTS components that could are promising candidates for short-term GEO space missions. This report provides tools for effectively using the database and evaluating radiation and Sn Whisker risks. These resources, when properly used, enable the use of high-performance, low-cost, accessible COTS in short-term geostationary satellites, allowing for more capability and faster turnaround for future space systems.

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APPENDIX A: GNEC DATABASE

Type	Man.	Part #	Desc.	Cat.	TID	SEL	TID Source	SEL Source
ADC/ DAC	AD	AD5622	I2C Comp. 12-bit DAC	COTS		>24 MeV-cm2 /mg		Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
ADC/ DAC	AD	AD6640	12-bit, 65 MSPS, A/D Converter	COTS	>100K	>37 MeV-cm2/mg	O'Bryan et al. "Current Single Event Effects and Radiation Damage Results for Candidate Spacecraft Electronics ", NSREC 2002.	O'Bryan et al. "Recent Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics", NSREC 2001.
ADC/ DAC	AD	AD7712AN Z	24 bit ADC	COTS		>85 MeV-cm2 /mg		Allen et al., "2015 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group ", NSREC 2015.
ADC/ DAC	AD	AD7714	24 bit ADC	COTS	10K <X< 15K	<27 MeV-cm2 /mg	O'Bryan et al. "Current Single Event Effects and Radiation Damage Results for Candidate Spacecraft Electronics ", NSREC 2002.	O'Bryan et al. "Current Single Event Effects and Radiation Damage Results for Candidate Spacecraft Electronics ", NSREC 2002.
ADC/ DAC	AD	AD7760	24-Bit ADC	COTS	30K		JPL	
ADC/ DAC	AD	AD7821	8 Bit ADC	COTS	>30K	>80 MeV-cm2/mg	O'Bryan et al. "Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics", NSREC 2000.	O'Bryan et al. "Current Single Event Effects and Radiation Damage Results for Candidate Spacecraft Electronics ", NSREC 2002.
ADC/ DAC	AD	AD7885	16-bit ADC	COTS	>50K		O'Bryan et al. "Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics", NSREC 2000.	
ADC/ DAC	AD	AD7991	12-bit Bias converter ADC	COTS		>24 MeV-cm2 /mg		Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
ADC/ DAC	AD	AD9257	14 bit ADC; 18 nm CMOS	COTS		>86 MeV-cm2 /mg		O'Bryan et al., "Compendium of Current Single Event Effects Results from NASA Goddard Space Flight Center and NASA Electronic Parts and Packaging Program", NSREC 2017.
ADC/ DAC	AD	AD977	Serial 16-Bit ADC	COTS	4K	>84 MeV-cm2 /mg	JPL	JPL
ADC/ DAC	TI	ADS1258	24 bit ADC	COTS		>85 MeV-cm2 /mg		Allen et al., "2015 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group ", NSREC 2015.
ADC/ DAC	TI	ADS1281	24 bit ADC	COTS		>85 MeV-cm2 /mg		Allen et al., "2015 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group ", NSREC 2015.
ADC/ DAC	TI	ADS5483	16 bit ADC	COTS		>75 MeV-cm2 /mg		O'Bryan et al. "Current Single Event Effects Compendium of Candidate Spacecraft Electronics for NASA ", NSREC 2010.
ADC/ DAC	AD	DAC08	8-Bit, High Speed, Multiplying DAC	COTS	25K	>119.6 MeV-cm2 /mg	O'Bryan et al. "Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics", NSREC 2000.	O'Bryan et al. "Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics", NSREC 2000.
ADC/ DAC	LT	LTC1417	14-Bit ADC	COTS	20K	>67 MeV-cm2 /mg	JPL	JPL
ADC/ DAC	LT	LTC1418	14-Bit ADC	COTS		>76 MeV-cm2 /mg		Allen et al., "2015 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group ", NSREC 2015.
ADC/ DAC	LT	LTC1419	14-Bit ADC	COTS		>78.2 MeV-cm2 /mg		O'Bryan et al. "Recent Single Event Effects Results for Candidate Spacecraft Electronics for NASA", NSREC 2005.

Type	Man.	Part #	Desc.	Cat.	TID	SEL	TID Source	SEL Source
ADC/ DAC	LT	LTC1604	Parallel 16-Bit ADC	COTS		>65 MeV-cm2 /mg		O'Bryan et al. "Current Single Event Effects and Radiation Damage Results for Candidate Spacecraft Electronics ", NSREC 2002.
ADC/ DAC	Maxim	MAX529	8 Bit DAC	COTS	>5K	>84 MeV-cm2/mg	Cochran et al. "Recent Total Ionizing Dose Results and Displacement Damage Results for CandidateSpacecraft Electronics for NASA", NSREC 2005.	O'Bryan et al. "Recent Single Event Effects Results for Candidate Spacecraft Electronics for NASA", NSREC 2005.
ADC/ DAC	Maxim	MX7225UQ	8 Bit DAC	COTS	>10K	>90 MeV-cm2/mg	O'Bryan et al. "Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics", NSREC 2000.	O'Bryan et al. "Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics", NSREC 2000.
ADC/ DAC	Maxwell	7872	14-bit A/D Converter	S	>100K	>60 MeV-cm2/mg	Maxwell Technologies, "7872A 14-Bit A/D Converter Data Sheet", 2012.	O'Bryan et al. "Recent Single Event Effects Results for Candidate Spacecraft Electronics for NASA", NSREC 2005.
ADC/ DAC	AD	AD571S	10-bit ADC	S	>200K	>60 MeV-cm2/mg	O'Bryan et al. "Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics", NSREC 2000.	O'Bryan et al. "Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics", NSREC 2000.
ADC/ DAC	AD	AD574S	12-bit A/D Converter	S	>100K	>83 MeV-cm2/mg	Analog Devices, "RADIATION TEST REPORT for AD574ATDQMLR", 2005.	Analog Devices, "SINGLE EVENT LATCH-UP TEST REPORT AD574S", April 2010.
ADC/ DAC	AD	AD6645S	14-bit A/D Converter	S	>100K	>83 MeV-cm2/mg	Analog Devices, "RADIATION TEST REPORT for AD6645ASQ/QMLR", 2008.	Analog Devices, "SINGLE EVENT LATCH-UP TEST REPORT AD6645S", April 2010.
ADC/ DAC	AD	AD768S	16-bit, High Speed, DAC	S	>100K	>83 MeV-cm2/mg	Analog Devices, "RADIATION TEST REPORT for AD768AF/QMLR", 2008.	Analog Devices, "SINGLE EVENT LATCH-UP TEST REPORT AD768AF/QMLR", April 2011.
FPGA	Micro-semi	AGLN250V 2-VQG100	68 I/O Flash FPGA	COTS		>51 MeV-cm2/mg		Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
FPGA	Silicon Blue	iCE65	iCE65 FPGA Family	COTS		>83 MeV-cm2/mg		JPL
FPGA	Altera	EP4SGX23 0KF40	Stratix 40nm IV GX FPGA	COTS		>112 MeV-cm2 /mg		JPL
FPGA	Xilinx	XC4	Virtex4	COTS	>240K	>58 MeV-cm2 /mg	Cochran et al. "Compendium of Recent Total Ionizing Dose Results for Candidate Spacecraft Electronicsfor NASA", NSREC 2008.	O'Bryan et al. "Compendium of Current Single Event Effects Results for Candidate Spacecraft Electronics for NASA", NSREC 2007.
FPGA	Xilinx	XC5VFX13 0T	Virtex-5QV FPGAs.	COTS	~340K	>75 MeV-cm2 /mg	Jano Gebelein, "An approach to system-wide fault tolerance for FPGAs", ESA ESTEC 2009.	O'Bryan et al. "Current Single Event Effects Compendium of Candidate Spacecraft Electronics for NASA", NSREC 2010.
FPGA	Xilinx	XC6	Virtex-6	COTS	~380K	>37 MeV-cm2 /mg	Jano Gebelein, "An approach to system-wide fault tolerance for FPGAs", ESA ESTEC 2009.	JPL
FPGA	Xilinx	XCKU040-2FBVA115 6E	Kintex 20nm Ultrascale FPGA	COTS	>1M	>63.91 MeV-cm2/mg	Matthew Gadlage, "Radiation Hardening and Trust in a COTS Age", Navsea Crane presentation.	Lee et al., "Single-Event Characterization of the 20 nm Xilinx Kintex UltraScale Field-Programmable Gate Array under Heavy Ion Irradiation", IEEE Radiation Effects Data Workshop (REDW) 2015.
FPGA	BS	197A805	RH1020B FPGA	S	>150K	*Immune	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.
FPGA	Micro-semi	RTAX-2000s	Rad-tol Flash-FPGA	S	>300K	>117 MeV-cm2 /mg	Microsemi, "Radiation-Tolerant FPGAs", available on webstire in 2018.	Microsemi, "Radiation-Tolerant FPGAs", available on webstire in 2018.
FPGA	Xilinx	XQR4V	Virtex-4 Space Grade	S	~300K	>100 MeV-cm2 /mg	Xilinx, "Space-Grade Virtex-4QV Family Overview", 2014.	Xilinx, "Space-Grade Virtex-4QV Family Overview", 2014.

Type	Man.	Part #	Desc.	Cat.	TID	SEL	TID Source	SEL Source
FPGA	Xilinx	XQR5VFX130	Radiation-Hard, Virtex-5QV	S	>1M	>100 MeV-cm2 /mg	Xilinx, "Radiation-Hardened, Space-Grade Virtex-5QV Family Data Sheet: Overview", available on website in 2018.	Xilinx, "Radiation-Hardened, Space-Grade Virtex-5QV Family Data Sheet: Overview", available on website in 2018.
Memory	Alliance	AS6C1608	SRAM 16Mbit	COTS	>200K		Data from ongoing unpublished work at SNL. (Tom Buchheit+Kenny Leeson)	
Memory	Alliance	AS6C4016	SRAM 4Mbit	COTS	~125K		Data from ongoing unpublished work at SNL. (Tom Buchheit+Kenny Leeson)	
Memory	Cypress	CY14B101I	1Mb SONOS	COTS	>1M		Gadlage et al., "Total Dose and Dose Rate Radiation Effects in Emerging Commercial Non-Volatile Memories", 2017.	
Memory	Cypress	CY15B104Q	4 Mbit FRAM	COTS	400K		Gadlage et al., "Total Dose and Dose Rate Radiation Effects in Emerging Commercial Non-Volatile Memories", 2017.	
Memory	Cypress	FM24V10	1Mb FRAM	COTS	200K		Gadlage et al., "Total Dose and Dose Rate Radiation Effects in Emerging Commercial Non-Volatile Memories", 2017.	
Memory	Hynix	HY27UF084G2M	4 GB Flash	COTS	50K	>55 MeV-cm2 /mg	Cochran et al., "Total Ionizing Dose and Displacement Damage Compendium of Candidate Spacecraft Electronics for NASA", NSREC 2009.	O'Bryan et al. "Compendium of Recent Single Event Effects Results for Candidate Spacecraft Electronics for NASA", NSREC 2008.
Memory	Hynix	H27QDG822C8RBCG	128 Gb Multi-Level Cell 3D NAND Flash	COTS	200K	>85 MeV-cm2 /mg	Gadlage et al., "Total Dose and Dose Rate Radiation Effects in Emerging Commercial Non-Volatile Memories", 2017.	O'Bryan et al., "Compendium of Current Single Event Effects Results from NASA Goddard Space Flight Center and NASA Electronic Parts and Packaging Program", NSREC 2017.
Memory	Inno-disk	DS2M-08GI81AW1ST-B050	8 GB MicroSD Card	COTS		>37.7MeV-cm2/mg		Allen et al., "2017 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group", NSREC 2017.
Memory	ISSI	IS42S16400J-5BL	64Mb SDRAM	COTS				
Memory	ISSI	IS4TR81280-15GBLI	15Gb DDR3	COTS		>75 MeV-cm2 /mg		Allen et al., "2015 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group ", NSREC 2015.
Memory	ISSI	IS61WV20488BLL	SRAM 16Mbit	COTS	>100K		Data from ongoing unpublished work at SNL. (Tom Buchheit+Kenny Leeson)	
Memory	ISSI	IS61WV25616BLL	SRAM 4Mbit	COTS	>100K		Data from ongoing unpublished work at SNL. (Tom Buchheit+Kenny Leeson)	
Memory	Samsung	K4B1G0446G-BCH9000	1G-Bit DDR3	COTS		>75 MeV-cm2 /mg		Allen et al., "2015 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group ", NSREC 2015.
Memory	Samsung	K9F4G08U0A	4 GB NAND Flash	COTS	100K	>87 MeV-cm2 /mg	Cochran et al., "Total Ionizing Dose and Displacement Damage Compendium of Candidate Spacecraft Electronics for NASA", NSREC 2010.	O'Bryan et al., "Compendium of Single Event Effects for Candidate Spacecraft Electronics for NASA", NSREC 2012.
Memory	Samsung	K9F8G08U0M	8 GB NAND Flash; 60 nm CMOS	COTS	400K <X< 500K	>83 MeV-cm2 /mg	Cochran et al., "Recent Total Ionizing Dose and Displacement Damage Compendium of Candidate Electronics for NASA Space Systems", NSREC 2011.	Allen et al., "2015 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group ", NSREC 2015.
Memory	Fujitsu	MB85RC256V	FRAM; I2C; 256Kbit 1 Mhz	COTS	75K		Gadlage et al., "Total Dose and Dose Rate Radiation Effects in Emerging Commercial Non-Volatile Memories", 2017.	
Memory	Fujitsu	MB85RS1MT	1Mb FRAM	COTS	75K		Gadlage et al., "Total Dose and Dose Rate Radiation Effects in Emerging Commercial Non-Volatile Memories", 2017.	

Type	Man.	Part #	Desc.	Cat.	TID	SEL	TID Source	SEL Source
Memory	Fujitsu	MB85RS64V	64 Kb FRAM	COTS	60K		Gadlage et al., "Total Dose and Dose Rate Radiation Effects in Emerging Commercial Non-Volatile Memories", 2017.	
Memory	Free-scale	MR2A16A	4 Mbit MRAM	COTS	90K			
Memory	Ever-spin	MR2A16A	MRAM 16Mbit	COTS	~70K		Data from ongoing unpublished work at SNL. (Tom Buchheit+Kenny Leeson)	
Memory	Ever-spin	MR4A08B	MRAM 16Mbit	COTS	~70K		Data from ongoing unpublished work at SNL. (Tom Buchheit+Kenny Leeson)	
Memory	Micron	MT29F16G08ABABAWP	128 GB NAND Flash	COTS				
Memory	Micron	MT29F4G08AAAWP	4 GB NAND Flash	COTS	65K	31 <SELth< 54.8	Cochran et al., "Total Ionizing Dose and Displacement Damage Compendium of Candidate Spacecraft Electronics for NASA ", NSREC 2009	O'Bryan et al., "Single Event Effects Compendium of Candidate Spacecraft Electronics for NASA", NSREC 2009.
Memory	Micron	MT29F8G08AAAWP	8 GB NAND Flash	COTS	50K <X< 75K		Cochran et al., "Recent Total Ionizing Dose and Displacement Damage Compendium of Candidate Electronics for NASA Space Systems", NSREC 2011.	
Memory	Micron	MT46H64M16LFB	1 Gb DDR memory	COTS				
Memory	Micron	MT41J128M8JP-15E	1 Gb DDR3	COTS		>75 MeV-cm2 /mg		Allen et al., "2015 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group ", NSREC 2015.
Memory	Austin	MT5C2564	156 kbit SRAM(64 kx4)	COTS		~37.6 MeV-cm2 /mg		Scheick et al., "SEU Evaluation of SRAM Memories for Space Applications", IEEE Transactions on Nuclear Science 2000.
Memory	Austin	MT5C2568	156 kbit SRAM(32 kx8)	COTS		~58 MeV-cm2 /mg		Scheick et al., "SEU Evaluation of SRAM Memories for Space Applications", IEEE Transactions on Nuclear Science 2000.
Memory	Micron	N25Q128	128 Mbit Flash memory	COTS				
Memory	Micron	NP8P128A13TSM60E	PCRAM	COTS	400K		Gadlage et al., "Total Dose and Dose Rate Radiation Effects in Emerging Commercial Non-Volatile Memories", 2017.	
Memory	Fair-child	R29773	2Kx8 PROM	COTS	>200K	>37 MeV-cm2 /mg	O'Bryan et al. "Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics", NSREC 2000.	O'Bryan et al. "Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics", NSREC 2000.
Memory	White	WMS128K8	1 Mbit SRAM	COTS		~37.6 MeV-cm2 /mg		Scheick et al., "SEU Evaluation of SRAM Memories for Space Applications", IEEE Transactions on Nuclear Science 2000.
Memory	Xilinx	XCF128XFTG64C	FLASH non-volatile Memory	COTS		>40 MeV-cm2 /mg		Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
Memory	BS	8394325	Magnum SRAM (512k x 8)	S	>500K	*Immune	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.
Memory	BS	8427352	Independence SRAM (512k x 32)	S	>1M	*Immune	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.
Memory	BS	8464575	Titan SRAM (2M x 32)	S	>100K	*Immune	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.

Type	Man.	Part #	Desc.	Cat.	TID	SEL	TID Source	SEL Source
Memory	BS	8497642	L2 Cache SSRAM (128k x 72)	S	>1M	*Immune	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.
Memory	BS	238A790	EEPROM (32k x 8)	S	>500K	*Immune	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.
Memory	BS	251A172	Millennium SRAM (512k x 32)	S	>100K	*Immune	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.
Memory	Xilinx	SCF128XF TG64C	128M NV Flash ROM	S				
Optics	Micro-pac	66183	Opto-coupler	COTS		>60 MeV-cm2 /mg		Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
Optics	Micro-pac	66252	Opto-coupler	COTS		>60 MeV-cm2 /mg		Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
Optics	Micro-pac	66260	Opto-coupler	COTS		>76 MeV-cm2 /mg		Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
Optics	Micro-pac	66266	Opto-coupler	COTS		>60 MeV-cm2 /mg		Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
Optics	Vishay	ILD2	Opto-coupler	COTS		>60 MeV-cm2 /mg		Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
Optics	Iso Link	OLF300	Opto-coupler	S		>77.3 MeV-cm2/mg		Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
Optics	Iso Link	OLI249	Opto-coupler	S		>75.7 MeV-cm2 /mg		Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
Optics	South-west Research Institute	SW15-802	Opto-coupler	Special	8K <X< 75K		Topper et al., "Compendium of Current Total Ionizing Dose and Displacement Damage Results from NASA Goddard Space Flight Center and NASA Electronic Parts and Packaging Program", NSREC 2017.	
Other	AD	AD654	Op Amp	COTS	>40K		Topper et al., "Compendium of Current Total Ionizing Dose and Displacement Damage Results from NASA Goddard Space Flight Center and NASA Electronic Parts and Packaging Program", NSREC 2017.	
Other	AD	AD8000	Op Amp	COTS	>75K		Danzeca et al., "Compendium of Radiation-Induced Effects for Candidate Particle Accelerator Electronics", NSREC 2017.	

Type	Man.	Part #	Desc.	Cat.	TID	SEL	TID Source	SEL Source
Other	AD	AD8029	Op Amp	COTS	>75K		Danzeca et al., "Compendium of Radiation-Induced Effects for Candidate Particle Accelerator Electronics", NSREC 2017.	
Other	AD	AD8030	Op Amp	COTS	>75K		Danzeca et al., "Compendium of Radiation-Induced Effects for Candidate Particle Accelerator Electronics", NSREC 2017.	
Other	AD	AD8219	Current Amp	COTS		>37.5 MeV-cm2/mg		Allen et al., "2017 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group", NSREC 2017.
Other	AD	AD829	Op Amp	COTS	>75K		Danzeca et al., "Compendium of Radiation-Induced Effects for Candidate Particle Accelerator Electronics", NSREC 2017.	
Other	Nat. Semi.	LMC6484	Quad Op Amp	COTS		>87 MeV-cm2 /mg		Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
Other	TI	LMH6552	Op Amp	COTS	>75K		Danzeca et al., "Compendium of Radiation-Induced Effects for Candidate Particle Accelerator Electronics", NSREC 2017.	
Other	LT	LTC6268-10	Op Amp	COTS		>86 MeV-cm2 /mg		O'Bryan et al., "Compendium of Current Single Event Effects Results from NASA Goddard Space Flight Center and NASA Electronic Parts and Packaging Program", NSREC 2017.
Other	AD	OP27	Quad Op Amp	COTS	20K <X< 30K	>75.6 MeV-cm2/mg	Cochran et al. "Compendium of Current Total Ionizing Dose Results and Displacement Damage Results for Candidate Spacecraft Electronics for NASA", NSREC 2007.	Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
Other	TI	TLC2201	OP Amp	COTS		>76.7 MeV-cm2/mg		Allen et al., "2015 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group ", NSREC 2015.
Other	TI	TLC2254	Op Amp	COTS		>42 MeV-cm2/mg		Allen et al., "2015 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group ", NSREC 2015.
Other	AD	AD8671S	Precision Op Amp	S	>50K	>55 MeV-cm2/mg	Analog Devices, "RADIATION TEST REPORT for AD8671ALQMLL", 2005.	Analog Devices, "SINGLE EVENT LATCH-UP TEST REPORT AD8671S", April 2010.
Other	AD	ADA4077-2S	High Precision Amplifiers	S	>100K	>80.7 MeV-cm2/mg	Analog Devices, "RADIATION TEST REPORT for ADA4077-2S", 2015.	Analog Devices, "SINGLE EVENT LATCH-UP TEST REPORT ADA4077-2S", September 2015.
Other	Intersil	ISL78845	Pulse Width Modulation	S		>77.4 MeV-cm2/mg		Allen et al., "2017 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group", NSREC 2017.
Other	LT	RH1013MW	Quad Op Amp	S	>50K	>75 MeV-cm2 /mg	Topper et al., "Compendium of Current Total Ionizing Dose and Displacement Damage Results from NASA Goddard Space Flight Center and NASA Electronic Parts and Packaging Program", NSREC 2017.	Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.

Type	Man.	Part #	Desc.	Cat.	TID	SEL	TID Source	SEL Source
Other	LT	RH1014MW	Quad Op Amp	S	>50K	>87 MeV-cm2 /mg	AD Website	Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
Other	AD	RH1499	Quad Op Amp	S		>80.2 MeV-cm2/mg		Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
Other	LT	RH6105	Current Sense Amp	S	>50K	>75 MeV-cm2 /mg	AD Website	Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
Other	ST-Micro	RHF43B	Op Amp		>100K		Topper et al., "Compendium of Current Total Ionizing Dose and Displacement Damage Results from NASA Goddard Space Flight Center and NASA Electronic Parts and Packaging Program", NSREC 2017.	
Power	Micro-pac	53278	Solid State Power Controller	COTS		~50 MeV-cm2/mg		O'Bryan et al. "Recent Single Event Effects Results for Candidate Spacecraft Electronics for NASA", NSREC 2005.
Power	Micro-semi	2N3439	350V, NPN BJT	COTS		>77.4 MeV-cm2/mg		Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
Power	Inter-point	AFL2828	DC-DC Converter	COTS		>53.5 MeV-cm2/mg		O'Bryan et al. "Compendium of Recent Single Event Effects Results for Candidate Spacecraft Electronics for NASA", NSREC 2008.
Power	LT	LTC3428	DC/DC Step-Up	COTS		>37.7MeV-cm2/mg		Irom et al., "Single-Event Latchup Measurements on COTS Electronic Devices for Use in ISS Payloads", NSREC 2017.
Power	LT	LTC6103	Current Sense Amp	COTS		>86 MeV-cm2 /mg		O'Bryan et al., "Compendium of Current Single Event Effects Results from NASA Goddard Space Flight Center and NASA Electronic Parts and Packaging Program", NSREC 2017.
Power	LT	LT1019AMH-2.5/883	Precision Vref	COTS	>50K	Immune	JPL	JPL
Power	LT	LT1175	Regulator, -5V	COTS	>10K	Immune	JPL	JPL
Power	LT	LT1172MJ8	Microcircuit, Linear, IC-switching Regulator	COTS		Immune		JPL
Power	Fair-child	NDS352A	Power MOSFET	COTS	>50K		O'Bryan et al., "Current Single Event Effects and Radiation Damage Results for Candidate Spacecraft Electronics ", NSREC 2002.	
Power	AD	REF02	Voltage Regulator	S	30K <X< 50K	>75.7 MeV-cm2/mg	Analog Devices, "RADIATION TEST REPORT for REF02AJQMLR", 2001.	Reddell et al., "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
Power	AD	AD780S	2.5 V/3.0 V High Precision Reference	S	>100K	>85 MeV-cm2/mg	Analog Devices, "RADIATION TEST REPORT for AD780AFQMLR", 2014.	Analog Devices, "SINGLE EVENT LATCH-UP TEST REPORT AD780S", April 2016.
Power	AD	AD8210S	HV Current Shunt Monitor	S	>100K	>80 MeV-cm2/mg	Analog Devices, "RADIATION TEST REPORT for AD8210AFQMLR", 2013.	Analog Devices, "SINGLE EVENT LATCH-UP TEST REPORT AD8210S", April 2016.

Type	Man.	Part #	Desc.	Cat.	TID	SEL	TID Source	SEL Source
Power	AD	AD8212S	HV Current Shunt Monitor	S	>100K	>84.85 MeV-cm2/mg	Analog Devices, "RADIATION TEST REPORT for AD8212ALQMLR", 2010.	Analog Devices, "SINGLE EVENT LATCH-UP TEST REPORT AD8212S", April 2010.
Power	IR	IRHF7110SCS	100V, N-Channel MOSFET	S	>1M	>37 MeV-cm2/mg	IR HiRel, RAD-Hard MOSFETs and Ics Product Selection Guide, 2016	IR HiRel, RAD-Hard MOSFETs and Ics Product Selection Guide, 2016
Power	IR	IRHLF87Y20	Power MOSFET	S	>300K	>81 MeV-cm2/mg	IR HiRel, RAD-Hard MOSFETs and Ics Product Selection Guide, 2016	IR HiRel, RAD-Hard MOSFETs and Ics Product Selection Guide, 2016
Power	IR	IRHYS67234	250V, N-Channel MOSFET	S	>1M	>90 MeV-cm2/mg	IR HiRel, RAD-Hard MOSFETs and Ics Product Selection Guide, 2016	IR HiRel, RAD-Hard MOSFETs and Ics Product Selection Guide, 2016
Power	Intersil	IS139ASRH	Quad Voltage Comparator	S		>83.9 MeV-cm2/mg		Reddell et al. "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
Power	Intersil	ISL70001	DC-DC Converter	S		>86.4 MeV-cm2/mg		O'Bryan et al. "Current Single Event Effects Compendium of Candidate Spacecraft Electronics for NASA", NSREC 2010.
Power	IR	JANSF2N7484T3	MOSFET	S		>60 MeV-cm2 /mg		Reddell et al., "Compendium of Single Event Effects Test Results for Commercial-Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications", NSREC 2017.
Power	TI	LM193AxRLQMLV	Comparator	S	>100K	>98.6 MeV-cm2 /mg	Bozovich et al., "Compendium of Single Event Transient (SET) and Total Ionizing Dose (TID) Test Results for Commonly Used Voltage Comparators", NSREC 2017.	Bozovich et al., "Compendium of Single Event Transient (SET) and Total Ionizing Dose (TID) Test Results for Commonly Used Voltage Comparators", NSREC 2017.
Power	IR	LS2805S	DC-DC Converter	S	100K <X< 300K	>90 MeV-cm2 /mg	In ternational Rectifier, "HYBRID - HIGH RELIABILITY RADIATION HARDENED DC-DC CONVERTER - LS-SERIES DATASHEET", 2012.	O'Bryan et al. "Recent Single Event Effects Results for Candidate Spacecraft Electronics for NASA", NSREC 2005.
Power	LT	RH1011	Comparator	S		>114 MeV-cm2/mg		Bozovich et al., "Compendium of Single Event Transient (SET) and Total Ionizing Dose (TID) Test Results for Commonly Used Voltage Comparators", NSREC 2017.
Power	Inter-point	SMSA2815S	DC-to-DC converter	S	>50K	>74.8 MeV-cm2/mg	Cochran et al. "Compendium of Recent Total Ionizing Dose Results for Candidate Spacecraft Electronicsfor NASA", NSREC 2008.	O'Bryan et al., "Recent Single Event Effects Compendium of Candidate Electronics for NASA Space Systems.", NSREC 2011.
RFMMIC	Micro-chip	TC4423	Driver, MOSFET	COTS	>30K	>86 MeV-cm2/mg	Cochran et al. "Compendium of Recent Total Ionizing Dose Results for Candidate Spacecraft Electronicsfor NASA", NSREC 2008.	O'Bryan et al. "Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics", NSREC 2000.
RFMMIC	AD	AD7306	Transciever	COTS		>37.7MeV-cm2/mg		Irom et al., "Single-Event Latchup Measurements on COTS Electronic Devices for Use in ISS Payloads", NSREC 2017.
RFMMIC	AD	AD9364	Transciever	COTS	>50K	>87 MeV-cm2 /mg	Topper et al., "Compendium of Current Total Ionizing Dose and Displacement Damage Results from NASA Goddard Space Flight Center and NASA Electronic Parts and Packaging Program", NSREC 2017.	O'Bryan et al., "Compendium of Current Single Event Effects Results from NASA Goddard Space Flight Center and NASA Electronic Parts and Packaging Program", NSREC 2017.
RFMMIC	Intersil	ISL32602	Transciever	COTS		>37.7MeV-cm2/mg		Irom et al., "Single-Event Latchup Measurements on COTS Electronic Devices for Use in ISS Payloads", NSREC 2017.
RFMMIC	Mini-Circuits	KSW-2-46+	GaAsRF Switch	COTS				
RFMMIC	LT	LTC2872	Transciever	COTS		>37.7MeV-cm2/mg		Allen et al., "2017 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group", NSREC 2017.

Type	Man.	Part #	Desc.	Cat.	TID	SEL	TID Source	SEL Source
RFMMIC	TI	MAX3223	Transciever	COTS		>37.7 MeV-cm2/mg		Allen et al., "2017 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group", NSREC 2017.
RFMMIC	LT	LTC1157	Driver, MOSFET	COTS	<15K		O'Bryan et al. "Radiation Damage and Single Event Effect Results for Candidate Spacecraft Electronics", NSREC 2000.	
RFMMIC	AD	AD8346S	RF Quadrature Modulator	S	>100K	>83 MeV-cm2/mg	Analog Devices, "RADIATION TEST REPORT for AD8346AFQMLR", 2010.	Analog Devices, "SINGLE EVENT LATCH-UP TEST REPORT AD8346S", April 2010.
RFMMIC	AD	AD8351S	RF Amplifier	S	>100K	>83 MeV-cm2/mg	Analog Devices, "RADIATION TEST REPORT for AD8351ARC/QMLR", 2009.	Analog Devices, "SINGLE EVENT LATCH-UP TEST REPORT AD8351S", April 2010.
RFMMIC	AD	ADL5501	RF Power Detector	S	>100K	>84.85 MeV-cm2/mg	Analog Devices, "RADIATION TEST REPORT for ADL5501ALQMLR", 2012.	Analog Devices, "SINGLE EVENT LATCH-UP TEST REPORT ADL5501", Feb 2013.
RFMMIC	AD	ADL5513	Demod. Logarithmic Amplifier	S	>100K	>80.2 MeV-cm2/mg	Analog Devices, "RADIATION TEST REPORT for ADL5513AFQMLR", 2012.	Analog Devices, "SINGLE EVENT LATCH-UP TEST REPORT ADL5513/QMLR", Feb 2013.
µProc.	AD	AD9361	RF Transceiver Module	COTS		>37.5 MeV-cm2/mg		Allen et al., "2017 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group", NSREC 2017.
µProc.	Qual-com	APQ8064	28nm CMOS Snap dragon Microproc.	COTS		>75 MeV-cm2/mg		Allen et al., "2015 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group ", NSREC 2015.
µProc.	Amtel/ Micro Tech.	AT91SAM9G20	CMOS Microproc.	COTS		>86 MeV-cm2/mg		Allen et al., "2015 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group ", NSREC 2015.
µProc.	Intel	ATOME620	45nm CMOS Microproc.	COTS		>85 MeV-cm2/mg		Allen et al., "2015 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group ", NSREC 2015.
µProc.	TI	MSP430FR5739	Mixed-Signal FRAM Microcon	COTS		>85 MeV-cm2/mg		Allen et al., "2015 Compendium of Recent Test Results of Single Event Effects Conducted by the Jet Propulsion Laboratory's Radiation Effects Group ", NSREC 2015.
µProc.	Saronix-ecera	SHPCIE100	100MHz Crystal Oscillator	COTS		>43 MeV-cm2/mg		Irom et al., "Single-Event Latchup Measurements on COTS Electronic Devices for Use in ISS Payloads", NSREC 2017.
µProc.	BS	8447257	RAD750 V2	S	>1M	*Immune	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.
µProc.	BS	8488960	RAD750 V3	S	>1M	*Immune	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.
µProc.	BS	251A161	RAD750 V1	S	>200K	*Immune	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.	BAE Systems, "Radiation-hardened electronics product guide", available on website in 2018.
µProc.	Intel	Pentium III SL5EM	Pentium III S-spec	S	500K	>15 MeV-cm2/mg	O'Bryan et al. "Current Single Event Effects and Radiation Damage Results for Candidate Spacecraft Electronics ", NSREC 2002.	O'Bryan et al. "Current Single Event Effects and Radiation Damage Results for Candidate Spacecraft Electronics ", NSREC 2002.
µProc.	Atmel	TSC695F	SPARC Microproc.	S	100K	>75 MeV-cm2/mg	JPL	JPL

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