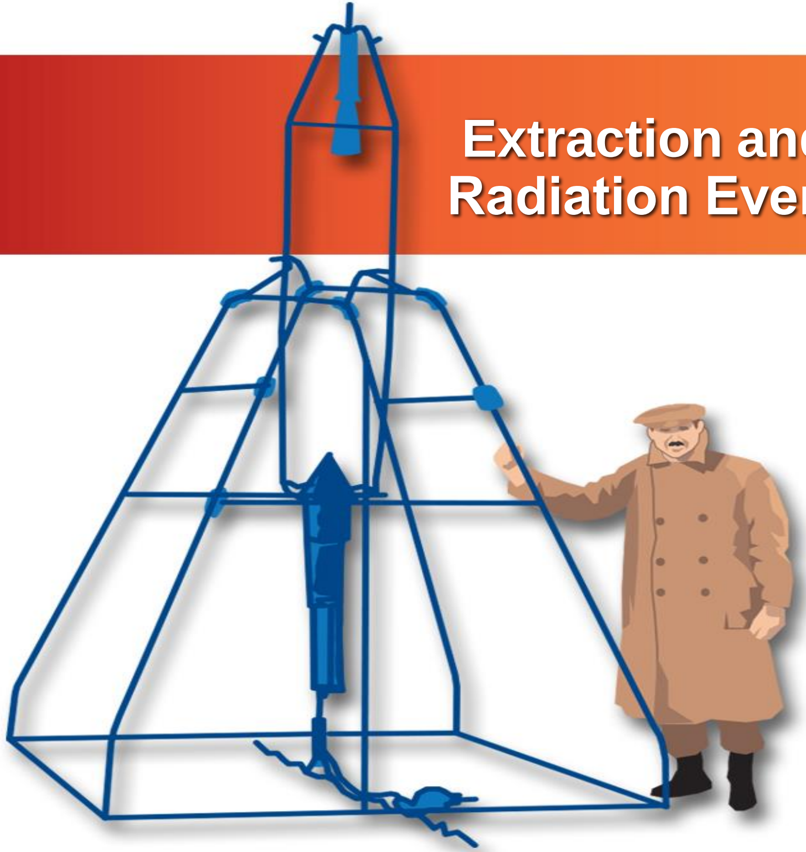
Extraction and Analysis of 4 Decades of Radiation Events from GSFC's SOARS database



Jesse Leitner
SMA Chief Engineer
NASA GSFC Code 300

Supported by Walt Thomas (Code 371 - reliability) and Rebekah Austin (Code 561 – radiation)

SAFETY and MISSION ASSURANCE DIRECTORATE Code 300

SMA SAFETY and MISSION ASSURANCE NASA Goddard

Outline

- Background
- Scope of presentation
- Definitions
- Early lessons
- Data gathering and review from SOARS
- On-orbit experiences of nonconventional space electronics
- Mystery electronics failures
- Conclusions

Definitions (as used in this document)

- COTS parts: Parts for which the part manufacturer solely establishes and controls the specifications for performance, configuration and reliability, including design, materials, processes, and testing without additional requirements imposed by users and external organizations. The use of any particular MIL-PRF or MIL-STD test, or performance of any type of testing is at the manufacturer's discretion, as would be the decision to issue a product change notice.
- FMRR*: fully manufacturer radiation rated, to be used with rated levels for each radiation variant - includes manufacturer-rated radiation assurance for TID, SEE, and DDD
- PMRR: partially manufacturer radiation rated – includes manufacturer-rated radiation assurance for one or two of TID, SEE, and DID
- RHA: Radiation Hardness Assurance – the overall practice of assuring a mission's performance in a radiation environment
- Radiation-tolerance: ability to sustain performance and reliability under some level of radiation exposure
- Radiation design margin (RDM): the multiple of the expected amount of time that a particular part, component, or system can survive in the given radiation environment. We recommend discontinuing the use of this term, not just due to ambiguity, but because RDM has never proven to be a valid predictor or limiter of time or exposure of a mission or its individual parts to radiation
- Strategic testing: testing performed from a general, focused testing effort outside of a project or program, generally in contrast to lot-specific testing.

*often the RHA term is used accordingly, but we introduce these terms to avoid conflict with the general process of radiation hardness assurance and to allow for specification of the manufacturer rated values when pertinent, e.g. FMRR 100 krad (TID), 37 MeV cm^2/mg (SEE), 1e12 Neutrons/cm^2 (DDD)

Early Lessons from study

- While some passive devices might experience radiation effects (part-level radiation testing has shown some examples), rarely is radiation hardness assurance performed on passives, no NASA missions require it, and there is no evidence discovered yet that passive part radiation susceptibility has contributed to any on-orbit events
  - Circuit effects due to radiation are always possible and often do not rely on susceptibility of individual parts. These are often missed since there is rarely a test as you fly approach that involves radiation and the traditional space community has implemented RHA as a parts assurance function
  - Radiation should not be a consideration for resistors or capacitors
  - Actives generally represent < 10% of parts counts
- Radiation is not in opposition to COTS (nor is there any relationship at all between radiation and COTS)
  - Most MIL-SPEC parts do not have FMRR (or even PMRR)
    - Ex: JANS2N2907AUB (numerous similar examples exist)
  - Many COTS parts do have FMRR or PMRR
    - Ex: IRHM57160 (numerous similar examples exist)
  - Unfortunately, the term "COTS" is often selectively misused today to mean "non-FMRR" (among other things)
- There are a wide range of successful approaches to address radiation
  - Lot-specific radiation testing of all susceptible part types combined with circuit level analyses (this largely will not work with broad use of non-FMRR parts)
  - Strategic testing of parts (not lot specific) with periodic retesting to check variability combined with radiation-tolerant design
  - Use of familiar parts
  - Strict radiation-tolerant design and rad-hard by design methods using FMRR parts as front-end defenders

Using non-FMRR parts demands a holistic approach at radiation, but most parts we use today are non-FMRR

Data gathering

- GSFC effort has combed all the tens of thousands of Spacecraft On-orbit Anomaly Records (SOARs) since the late 1980's to cull out radiation-related anomalies
  - Initial broad search identified ~140
  - Subsequent poring through data opened up over 850 more
  - None with catastrophic mission results
  - Currently correlating against pertinent hardware, events, and locations
  - Many radiation effects have been experienced on FMRR parts and other parts deemed "space-grade*"
- Collecting mission experiential data for missions broadly flying non-FMRR parts
  - Substantial datasets from GSFC and some other organizations
- Reviewed mission lifetime data compared to radiation-driven design lifetimes for GSFC-managed missions since 2000
  - One conclusion: radiation-driven lifetime (RDM) has no connection to actual lifetime
- Reviewed numerous parts lists from high-end missions, such as SDO and JWST

*space-grade is a highly-renowned marketing term that can best be defined as "designed and tested to endure the historical ground testing regimens employed to spacecraft and space instruments to provide confidence to survive a lengthy development time on the ground, the launch, and finally many years on-orbit"

Typical BOM excerpt from high-end mission (Class B GEO)

102	5962H0254301VXC	UT54ACS162245S	Microcircuit, Digital, CMOS, Radiation hardened, S	2			
103	5962F9674202VXC	HS9-508BRH	Microcircuit, Linear, 8-Bit Channel Analog Multipl	2			
104	5962F9563002VYC	HS9-1840ARH	Microcircuit, Linear, Radiation Hardened, Single 1	4			
106	311P407-5S-B-15	HD-22	Connector, Electrical, Rect., HD, D-Sub, Receptacl	1			
107	311P407-2S-B-15	HD-22	Connector, Electrical, Rect., HD, D-Sub, Receptacl	1			
108	311P409-1P-B-15	HD-20	Connector, Electrical, Rect, Standard Density, D-S	1			
109	5962-9689202VJA	AD565ATD/QMLV	Microcircuit, Linear, 12-Bit D/A Converter	1			
111	5962-8686103XA	AD580	Microcircuit, Linear, 2.5V Precision Voltage Refer	1			
112	5962R8776001S2A	54ACT244LMQB	Microcircuit,Digital,Advanced CMOS,Octal Buffer/Li	8			
113	D55342E07B10B0R	RM1206	Resistor, Fixed, Film, 10K**, 0.1%, 125mW, 25PPM	8			
114	D55342E07B10E0R	RM1206	Resistor, Fixed, Film, 10K**, 1%, 125mW, 25PPM	25			
116	D55342E07B68D1R	RM1206	Resistor, Fixed, Film, 68.1**, 1%, 125mW, 25PPM	4			
117	D55342E07B20E0R	RM1206	Resistor, Fixed, Film, 20K**, 1%, 125mW, 25PPM	12			
118	D55342E07B11B3R	RM1206	Resistor, Fixed, Film, 11.3K**, 0.1%, 125mW, 25PPM	1			
119	D55342E07B71B5R	RM1206	Resistor, Fixed, Film, 71.5K**, 0.1%, 125mW, 25PPM	2			
120	D55342E07B21B5R	RM1206	Resistor, Fixed, Film, 21.5K**, 0.1%, 125mW, 25PPM	1			
121	D55342E07B2E00R	RM1206	Resistor, Fixed, Film, 2K**, 1%, 125mW, 25PPM	2			
122	D55342E07B4B99R	RM1206	Resistor, Fixed, Film, 4.99K**, 0.1%, 125mW, 25PPM	28			
123	D55342E07B100DR	RM1206	Resistor, Fixed, Film, 100**, 1%, 125mW, 25PPM	4			
125	CWR06KC106KCA	CWR06	Capacitor,Tantalum,Solid,Chip, Fixed,10uF,25V,10%	2			
126	SR0805X7R103#011F	SR0805X7R	Capacitor, Ceramic, Chip 0805, 0.01**F, 25V	15			
127	SR0805X7R104#00VR	SR0805X7R	Capacitor, Ceramic, Chip 0805, 0.1**F, 25V	22			
128	CDR01BP101BKUS	CDR01	Capacitor, Ceramic, BP Dielectric, 100pF, 10%, 100	2			
129	CDR01BP100BKUS	CDR01	Capacitor, Ceramic, BP Dielectric, 10pF, 10%, 100V	10			
130	CDR33BX473AKUS	CDR33	Capacitor, Fixed, Ceramic, 47000pF, 50V, 10%	27			
131	TLW-101-05-G-S	TLW-101-05-G-S	Header, Low Profile, 0.025`` Square Post	25			
132	1-102972-0	1-102972-0	Header, 10 Positions, Breakaway, Single Row, 0.100	10			
133	M32159B06T	S0705CPX000	Resistor Chip, Fixed, Film, Electrical, Zero **, J	1			
134	CDR33BX273BKUS	CDR33	Capacitor, Fixed, Ceramic, 27000pF, 50V, 10%	1			
135	5-0085	BJ376	Connector, Receptacle, Twianx/Triax, TRB Rear Moun	2			
136	311P407-1S-B-15	HD-22	Connector, Electrical, Rect., HD, D-Sub, Receptacl	1			
137	CWR19MC106JCHA	CWR19	Capacitor, Tantalum, Chip, Fixed, 10uF, 5%, 35V	4			
138	CDR31BP680BKUS		Capacitor, Fixed, Ceramic, 68pF, 10%, 100V	12			
139	M55342K11B49D9R	RM0402	Resistor, Fixed, Film, 49.9**, 1.0%, 40mW, 100PPM	4			
140	M55342K11B30D1S	RM0402	Resistor, Fixed, Film, 30.1**, 1.0%, 40mW, 100PPM	1			
141	M55342K11B10D0R	RM0402	Resistor, Fixed, Film, 10**, 1.0%, 40mW, 100PPM	3			
142	D55342K07B499DS	RM1206	Resistor, Fixed, Film, 499**, 1.0%, 205mW, 100PPM	4			
143	M55342K11B10E0S	RM0402	Resistor, Fixed, Film, 10K**, 1.0%, 40mW, 100PPM	36			
144	M55342K11B33D2R	RM0402	Resistor, Fixed, Film, 33.2**, 1.0%, 40mW, 100PPM	56			
145	D55342K07B357DR	RM1206	Resistor, Fixed, Film, 357**, 1.0%, 250mW, 100PPM	1			
146	D55342K07B2E94S	RM1206	Resistor, Fixed, Film, 2.94K**, 1.0%, 250mW, 100PP	1			
147	D55342K07B2E43S	RM1206	Resistor, Fixed, Film, 2.43K**, 1.0%, 250mW, 100PP	1			
148	M55342K11B68D1S	RM0402	Resistor, Fixed, Film, 68.1**, 1.0%, 40mW, 100PPM	12			
149	M32159B11T	RCZ0402	Resistor Chip, Fixed, Film, Electrical, Zero Ohm,	9			
150	RH1499MW#50326	RH1499	Microcircuit,Linear,Precision Rail-to-Rail I/O, Qu	4			
151	5962F0151705VXA	UT28F256LVQLC-	Microcircuit, Digital, Radiation Hardened, PROM, 3	2			
				38		0.03646833	
				10		0.00959693	
				16		0.01535509	
			total parts count	1042			

Yellow highlight
MIL-SPEC FMRR

Orange highlight
COTS FMRR

Gray/purple highlight
Actives with no FMRR

Total parts count: 1042
Total MIL-SPEC FMRR: 3.6%
Total COTS FMRR: 10: 0.96%
Total non-FMRR and discrete semiconductors (requiring radiation testing or other forms of analysis: 16 (1.5%)

What do this BOM and other similar BOMs tell us?

- Total active parts generally < 10% of part count (example has 6.1%)
- FMRR parts are a mix of COTS and MIL-SPEC parts (example has 3.6% MIL/0.96% COTS)
- Remaining active parts make up the rest, requiring radiation testing, ray-tracing, or other forms of analysis (example has 1.5% non-FMRR)
- Non-FMRR parts were most likely not selected to save money (because cost for radiation testing was much higher than the savings, and thus cost was much higher)
- If COTS were broadly permitted, then this would have no effect on the FMRR parts, but it would have simply opened more options for the non-FMRR parts, which all required radiation testing anyway (and which would require radiation testing whether COTS or MIL-SPEC)
- Furthermore, the biggest drivers for the use of COTS are passives, e.g., needed to support modern FPGAs (extremely high capacitance with limited real estate).

Expanded use of COTS does not increase radiation risk for a project; however advanced technology missions enabled by high-performance COTS microcircuits will often demand new approaches to address radiation

Radiation and on-orbit non-RHA performance data sources

- Test data:
  - Traditional: radhome.gsfc.nasa.gov, transitioned to https://nepp.nasa.gov/pages/pubs.cfm
  - New: esarad.esa.int
  - New: pmpedia.space
- On-orbit experiences (“fact of” - some info available)
  - Spacecube data (LEO on-orbit – extensive non-FMRR and COTS – 10+ yr)
  - Aerocube data (LEO on-orbit – 100% non-FMRR COTS – 10+ yr) (Aerospace Corporation)
  - Swift data (585km x 604km, 20.6 deg - extensive COTS ~ 19 yrs)
  - Ascent (GEO cubesat – launched 12/2021) (AFRL)
  - Biosentinel (deep space cubesat – launched with Artemis)
  - Newspace – extensive, limited data availability

GSFC On-orbit Radiation Effects: Current Results

Methods: Each anomaly record, including any attached data and information, was reviewed and scored according to the text descriptions for its "credibility" that the anomaly was, in fact, caused by space radiation (June - October 2023):

- Anomaly record text describing a *possible* space radiation cause was coded **PS**.
- Anomaly record text describing a likely, probable, or definite space radiation cause were coded **PR**, **LK**, and **Y**, respectively.

The rationale for using these three categorical codes was to capture as accurately as practical the text descriptions used in each record; **LK** and **PR** have approximately equal credence and **Y** is more definitive.

➢ **Overview facts**:

- 852 Flight SOARS records indicated either possible (**PS** = 271) or combined likely, probable, or definite (**LK**, **PR**, **Y** = 581) radiation affected anomalies.

NOTE: Henceforth, **LK**, **PR**, and **Y** *combined* will be called **PR**, for brevity.

- Records covered 73 spacecraft and 4 instruments, launched between 1983 and 2022. Thirty-seven (37) of those still are operating as of 31 December 2023.

GSFC On-orbit Radiation Effects: Overview Facts

- 56/77 missions (either spacecraft or instruments) were in either in LEO or geostationary orbits. The others included highly elliptic GEO, LaGrange point, heliocentric, and several other orbits. Three of the four instruments were hosted on ISS
- 56% of all radiation affected anomalies were recurring events; possible (**PS**) included 51% and probable (**PR**–combined, per above) included 59% of recurring events.
  - 10 spacecraft (FUSE, IBEX, LRO, POLAR, RXTE, SAMPEX, SWIFT, TERRA, THEMIS, and WIND) accounted for **83%** of all recurring anomalies. All 10 had 20 or more radiation-induced anomalies. Excepting IBEX, they also were ones having the greatest numbers of SOARS Flight records – from over 125 to more than 1100 records for each.
  - These large numbers of radiation-affected and recurring events reflects non-uniform reporting into the SOARS database by operational missions. Some missions reported all anomalies, including all recurring events. Others reported only a portion of their flight anomalies or only an initial event that later recurred.
- Spacecraft operating times range from 416 to 12,308 days (*circa* 31 December 2023); the longest operating "grandfather" spacecraft is the Hubble Space Telescope – at 33.7 years.

GSFC On-orbit Radiation Effects: Overview facts (cont'd)

- Mission occurrence frequency data for radiation-induced events:

- For each mission, occurrence frequencies were computed as the number of specified events divided by mission operating time, in days (to 31 December 2023, if the mission still is operational). This was performed for all (**PS** + **PR**), **PR** only, and **PR** discrete.
- **PR only** removes the less credible *possible* events data; **PR** discrete data are the **PR only** data with associated *recurring* events discounted.
- These extant frequency data are ***biased***, when viewed from a *mission risk perspective*, because missions operating with no recorded radiation-affected events during its operating timeframe are not considered. (This is analogous to performing a Weibull analysis with only the failures and discounting the non-failed operating times.)
- When viewed in the context of a technical mission risk, where the lower limit for a *credible* risk is a 0.1% likelihood (p_{occ} = 0.001):
- 35 missions (of 77) exceeded this threshold when All (**PS** + **PR**), including recurring events, were analyzed.
- When PS and recurring events were excluded, this number decreased to 18 missions.
- 6 missions had credible likelihoods (p_{occ} > 0.001) simply because they had limited operating times, generally less than their design lifetimes (DLs).

GSFC On-orbit Radiation Effects: Overview facts (cont'd)

- Only one mission mission recorded a radiation-induced anomaly mission impact as "Catastrophic." However, this event occurred several years after the mission's design life – at 2.9 times DL. Thus, from a mission success perspective, it had completed its mission requirements to its design life and the Catastrophic ranking likely overstated the mission impact.
- 803 of the 852 Flight radiation-induced anomalies had either "No effect" or "Minor" mission impacts (94%). This proportion is actually greater as several missions, particularly older ones, cited "- No data -" for mission impacts.
- Several missions had listed mission impacts as "Significant," though a detailed reading of those anomaly records showed that the impacts were ranked incorrectly since most all had sustained only data or service losses that were restored after the causes were determined and corrected.

GSFC On-orbit Radiation Effects: Forward work

1. For occurrence frequency statistics, correct the computations to remove the bias.

   This will entail collecting appropriate SOARS Flight data on non-radiation-affected missions and integrating those data into the computations for each mission. Only non-affected missions operating at times of radiation-induced events for the radiation-affected missions would be applicable.

2. For the following analyses, we will use only the **PR** (combined) data subset.

   Rationale: The above observed (to-date) frequency statistics indicate the **PS** data subset is substantially smaller (271 vs. 581 records) and those are "less credible" than the **PR** data subset.

   The size of the **PR** data subset should provide adequate data for statistical comparisons and analyses.

3. Parse the data (**PR** combined) by orbit type to determine if there are significant differences between the orbit effects on mission radiation-induced anomalies.

4. Analyze the data to determine occurrence frequencies chronologically by launch dates.

   Annual frequency data must be normalized via number of missions having radiation-induced anomalies to avoid biasing those data.

   Consider analyzing data by launch decades or half decades to determine any significant findings.

5. Analyze chronological data to determine if on-orbit radiation-induced anomalies associate or correlate with the periodic solar cycle.

SOARS data review (1)

Meta: RadOnly

Row	SOAR ID	Radn Caused	Anomaly Time (Date)	Rcurrg Anom	Status	Anomaly Title	Anomaly Description	Mission / Spacecraft	Product Element/ Subsys/Instr	Component/ Assy/Part Name	Attc'd Data?	Investigation Log	Cause of the Anomaly	Corrective Act
04							team. SMS Latch up #49 recovery was							
05	S-WIND-2-CTT-10	Y	05/11/22	YES	Closed	SMS (MASS/STICS component) Latchup #34	*SMS (MASS/STICS component) Latchup #50 Anomaly Description: SMS (MASS/STICS component)Latch up #50 occurred on 2022/131/14:51:33z. **Cause of the Anomaly: Due to High Proton Storm**. Corrective Action: Notified the instrument team. SMS Latch up #50 recovery was	WIND	Solar Wind Ion Composition Study the Mass Sensor and Supra	Solar Wind Ion Composition Study the Mass Sensor and Supra				
06	S-WIND-2-CTT-11	Y	05/07/23	YES	Closed	SMS (MASS/STICS component) Latchup #51	*SMS (MASS/STICS component) Latch-up #51 Anomaly Description: SMS (MASS/STICS component)Latch-up #51 occurred on 2023/127/18:51:54z. **Cause of the Anomaly: Due to High Proton Storm**. Corrective Action: Notified the instrument team. SMS Latch up #51 recovery was	WIND	Solar Wind Ion Composition Study the Mass Sensor and Supra	Solar Wind Ion Composition Study the Mass Sensor and Supra				
08	S-WIRE-0020	Y	05/02/99	No	Closed	EDAC Hardware and Memory Scrub Task Disabled	*The EDAC hardware and memory scrub task were disabled during WIRE's passage thru the South Atlantic Anomaly. **WIRE's passage through the South Atlantic Anomaly caused us to receive more than 256 Multi Bit errors and this inturn autonomously disabled the memory scrub task and EDAC hardware.**	WIRE	C & DH - COMMAND AND DATA HANDLING SUBSYSTEM	EDAC	N	*The preceding anomaly has been reported. The MS task and EDAC was restarted using a procedure taken from TRACE and converted for WIRE use on 99/123. Procedure name: RCMBFIX.		*This event is very similar t have occured on TRACE whi SAA. The cause appears to higher than normal radiatio SAA causing bit flips in the There is no corrective actio
	S-WIRE-0040	LK	01/06/00	No	Closed	TRIAD Coalignment Error incremented by 1	*TRIAD Coalignment Error incremented by 1. This error increments if the Sun vector and Magnetic Field vector are pointed in approximately the same direction as determined by the Coalignment Tolerance (checked in both the Inertial Frame and the Body Frame by ACS FSW). If the on-line documentation reflects the current s/c setting, then the tolerance is 5	WIRE	ACS - ATTITUDE CONTROL SUBSYSTEM	TRIAD Coalignment Error Counter	N	*The preceding anomaly has been reported. WIRE ACS FSW Algorithm Document Build 1B, Rev. 15, sec. 11.10 The s/c Flight Software does not update the Triad Direction Cosine Matrix when the above tolerance is violated. No other action is taken.	*This anomaly is currently being investigated and is still within the six month time limit.The status of this anomaly was changed to inactive on 07/11/2000 due to the 6 month time limit. The counter again incremented by 1 on DOY 020/00-01:54:45. Mike Lee says that such an error may occur if there was a corruption of the Mag Field vector. Was torquing going on? Nothing	

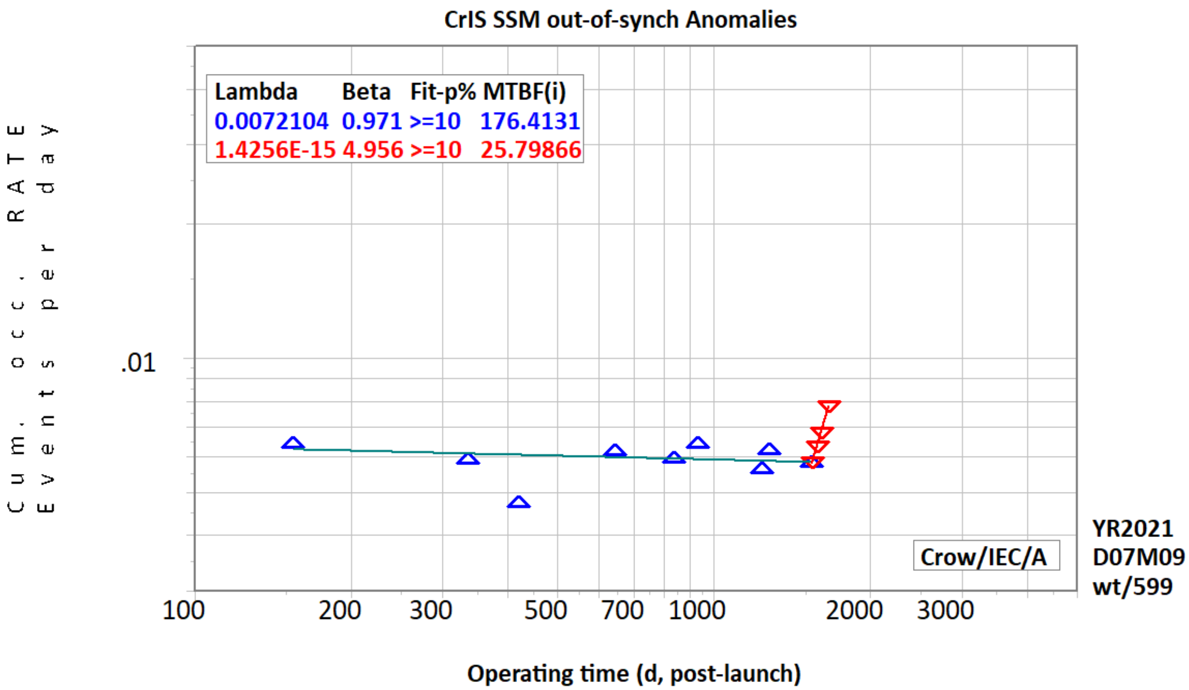
SOARFLT-RADOnly_5_Alphab | SOARFLT-RADOnly_5_Date | Mission Orbit | JPSS1 CrIS-SSM | +

SOARS data review (2)

1	**List of GSFC Spacecraft/Missions having Flight Anomalies in SOARS Database**							
2			= Updated RAD records entered, from previous key word searches					
3			= New RAD records entered.					
4	~~ABCDEF~~		= NO RAD events for this SC/Mission					
5						RAD Events		
6	SC/Mission	RAD Cmpltd	# Anoms	Notes	Cum Sum Rvw'd	PS	[LK PR Y]	
7	ACE	✓	155		155	2	1	
8	AIM	✓	15		15	1	0	
9	AQUA	✓	86		86	2	15	
10	~~ASTRO-D~~	✓	4		4	0	0	
11	AURA	✓	58		58	3	7	
12	CHIPSAT	✓	9		9	0	7	
13	~~CLOUDSAT~~	✓	2		2	0	0	
14	~~COBE~~	✓	1		1	0	0	
15	DSCOVR	✓	26		26	4	4	
16	EO-1	✓	99		99	1	7	
17	EOS-AQUA	✓	6		-			Incl'd/ AQUA
18	EOS-AURA	✓	14		-			Incl'd/ AURA
19	ERBS	✓	69		69	4	0	
20	~~ETS-7~~	✓	6		6	0	0	
21	FAST	✓	259	Incl. FASTGSFC	259	0	7	
22	Fermi (GLAST)	✓	157		157	5	5	
23	FUSE	✓	526	Incl. -OLD, -TEST	526	13	63	
24	GALEX	✓	*73*		73	2	11	
25	GEDI	✓	16		16	0	1	
26	~~GEOTAIL~~	✓	30		30	0	0	
27	~~GOES-4 (D)~~	✓	1		1	0	0	
28	GOES-8 (I)	✓	159		159	2	3	
29	GOES-9 (J)	✓	82		82	2	0	
30	GOES-10 (K)	✓	38		38	1	1	
31	GOES-11	✓	23		23	2	1	
32	GOES-12	✓	39		39	0	5	
33	GOES-13	✓	42		42	0	3	
34	~~GOES-14~~	✓	11		11	0	0	11 SOARS still DRAFT; none appear RAD affected.

AllFLT-SOARS-alphab | AF-SOARS-date | **List** | List2 | +

NPP CrIS Crow-AMSAA



CrIS out-of-synchronization (OOS) on-orbit anomalies.

For the first ~ 4.2 years, these anomalies were occurring randomly with time (β ~ 1). At day 1542 post-launch, anomalies began occurring at a significantly increasing rate. It appears that something changed in the system that induced OOS events to occur no longer randomly and at an increasing rate. The "system" includes the instrument itself, any possible spacecraft effects on the instrument, and any space environmental changes.

WT/599/2109007/Fn: CrIS-OOS-Anom's.pptx

On-orbit experiences outside of SOARS

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SpaceCube Time-on-orbit

As of Oct 2021 (STP-H6 was turned off Dec 9, 2021 to make room for the next instrument)

Project	Version	Part Req	BOM Count	Operation Months	Xilinx Quantity	COTS %	COTS Months
RNS	v1.0	2+	3700	0.0833333	4	1%	3.08333
MISSE-7	v1.0	N/A	3100	90	4	2%	5580
SMART	v1.5	N/A	1000	0.0333333	1	95%	31.6667
STP-H4 CIB	v1.0	N/A	1500	30	2	1%	450
STP-H4 ISE2.0	v2.0-EM	N/A	1250	30	3	98%	36750
STP-H5 CIB	v1.0	N/A	1500	46.933333	2	1%	704
STP-H5 ISEM	v2.0 Mini	N/A	1000	46.933333	1	26%	12202.7
STP-H5 Raven	v2.0-EM	N/A	1500	46.933333	3	99%	69696
RRM3	v2.0	N/A	1429	36.666667	2	65%	34057.8
STP-H6 CIB	v1.0	N/A	1500	31.833333	2	1%	477.5
STP-H6 GPS	v2.0	N/A	1157	31.833333	2	65%	23940.3
Restore-L Lidar	v2.0	3	2000		2	0%	N/A
STPSat6	v2.0 Mini	N/A	1500		1	98%	N/A

Totals	Units Flown	11
	Commercial FPGAs	26
	Commercial FPGA Device-Years	83
	Part Years	57213
	COTS Parts Years	15324

Also to note: We flew many COTS components on some of these projects:

- ISE2.0, SMART, and ISEM all flew COTS cameras that were ruggedized. SMART flew COTS SATA drives.
- Raven flew a $5 USB interface card to an IR sensor
- STP-H5 and -H6 have CHREC Space Processors (CSPs) that were 95% COTS components. See references for more info on CSP results (no failures to date)
- RRM3 suffered a failure (outside of SpaceCube) that may have involved a specific COTS part, but the part was used in a stressing condition that any part would eventually fail.
- NavCube Commercial vendor populated PWBs

AeroCube Orbits

Missions launched 2012-2021

No FMRR or PMRR parts used

Launched	End of Use	Years	Sum years	Vehicle	Initial perigee km	Initial apogee km	Inclination deg
09/13/12	6/17/20	8	8	AC4 A	495	800	66.4
09/13/12	09/20/12	0	0	AC4 B	495	800	66.4
09/13/12	01/30/20	7	7	AC4 C	495	800	66.4
12/06/13		9	18	AC5 A,B	469	972	120
06/19/14		8	8	AC6 A	650	650	98
06/19/14	9/16/21	7	7	AC6 B	650	650	98
10/08/15		7	7	AC5 C	500	780	64
10/08/15		7	7	AC7 A	500	780	64
05/20/15	10/9/2021	6	6	AC8 A	390	700	60
05/20/15	10/1/2021	6	6	AC8 B	390	700	60
11/11/16		5	10	AC8 C,D	550	580	98
11/12/17	8/4/2022	5	5	AC7 B	450	450	51.6
11/12/17	8/12/2022	5	5	AC7 C	450	450	51.6
11/12/17	2/21/2022	4	4	ISARA	450	450	51.6
12/16/18		4	8	AC11 A,B	500	500	85
05/21/18		4	8	AC12 A,B	450	450	51.6
04/15/19		3	6	AC10 A,B	450	450	51.6
11/02/19		3	6	AC14 A,B	450	450	51.6
11/02/19		3	6	AC15 A,B	450	450	51.6
12/01/21	6/25/22	0.5	0.5	DAILI	420	420	51.6

Chart from: "Overview of the AeroCube Program and Experience with Alt-Grade Parts Usage”

Aerospace Corp, “MICROELECTRONICS RELIABILITY AND QUALIFICATION WORKSHOP”, Feb, 2023

Brian Hardy, The Aerospace Corporation

Variety of orbits. Usually, a pair of vehicles launched together.

What Have We Seen?

- 133 satellite years in LEO
  - *Derated parts* [1]
  - *Micro controllers, FPGAs* [2]
  - *Industrial, commercial, automotive*
  - *Active components that have/may have flown*
    - 457 Ics 154 diodes and transistors
- Many (dozens) non-destructive single-event latchup events
  - *Cleared by satellite resets*
  - *Zero corruption in stored memory or microcontroller code*
- Four destructive SEEs
  - *Two memory chips (charge pump)*
    - Happened on two AC15 satellites, months apart. Why? Lot? Usage?
  - *Two failed circuits (most likely failure of transistor)*
    - Happened on both AC5 A/B, same payload subcircuit a year apart
  - *One failed RTC 1-Hz output*

[1] *We do not have a strict derating standard, but we try to follow TOR-2006(8583)-5236 "Technical Requirements for Electronic Parts, Materials, and Processes Used in Space and Launch Vehicles" when it is straightforward*

[2] *Microcontrollers (Microchip PIC18, PIC24), FPGAs (Xilinx Spartan, Artix, Kintex, Zynq; Microchip PolarFire)*

TID effects not noticed. We have confidence in LEO.

No FMRR or PMRR parts used

Chart from: "Overview of the AeroCube Program and Experience with Alt-Grade Parts Usage"

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AeroCube FPCB (flight computer) rev H2 BOM

example

QFP50P1400X1400X120-80N	U1	PIC18LF8722	4-106	
SOT95P238X112-3N	U2	MAX6145	4-015	EUR
SOIC127P1041X419-8N	U3	MPXA6115A	4-049	
SOP65P490X110-8N	U4	TMP275	4-159	
SOP65P478X110-8N	U6	LT6004H	4-214	
CASON-8CN3	U7	AT45DB642D-CNU	4-137	
CASON-8CN3	U26	AT45DB642D-CNU	4-137	
SOIC127P1032X265-16N	U8	DS1337C	4-161	
SOIC127P1032X265-16N	U17	DS1337C	4-161	
SOIC127P600X175-8N	U9	TPS2013D	4-208	
SOP65P640X110-14N	U10	74AHC126PWR	4-204	
SOP65P640X110-14N	U11	74AHC126PWR	4-204	
SOT65P210X110-5N	U12	TPS22942	4-224	
SOT65P210X110-5N	U13	TPS22942	4-224	
SOP65P490X110-8N	U14	IRF7509	3-024	
SOP65P490X110-8N	U20	IRF7509	3-024	
SOP65P490X110-8N	U22	IRF7509	3-024	
SOP65P490X110-8N	U23	IRF7509	3-024	
QFP50P1200X1200X120-64N	U15	PIC18LF6722	4-175	
TSSOP65P640X120-14N	U16	SN74AHC125PWR	4-212	
TSSOP65P640X120-14N	U19	SN74AHC125PWR	4-212	
SOIC127P600X175-16N	U18	SN74LV123ADR	4-210	
SOIC127P600X175-16N	U27	SN74LV123ADR	4-210	
SOIC127P600X175-8N	U21	MAX604CSA+	4-039	ESA = Industrial
SOP65P640X120-14N	U24	AHC32	4-205	
SOP65P640X120-14N	U25	AHC32	4-205	
SOIC127P600X175-8N	U28	IRF7389	3-077	
TSSOP65P640X120-14N	U29	SN74AHC126PWR	4-204	
TSSOP65P640X120-14N	U30	SN74AHC126PWR	4-204	
XTAL-CM309S	Y2	7.3728 MHz	5-079	
XTAL-CM309S	Y3	7.3728 MHz	5-079	

No FMRR or PMRR parts used

Chart from: "Overview of the AeroCube Program and Experience with Alt-Grade Parts Usage”

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All AeroCube missions combined used more than 457 Ics and 154 diodes and

Current on-orbit findings summary

- Mission degradation or failure due to SEEs is most likely a circuit design problem (in good circuit designs, vulnerable parts largely threaten availability)
  - HST optocoupler (should have included a filter)
  - NASA ARC watchdog proximity failure (non realtime, > 2 sec, overcurrent protection)
  - SMAP radar power supply (coupled voltage spikes with SETs)
  - 2 pair of Aerocube circuit failures (circuit not designed to mitigate radiation effects)
  - Suspect: SNPP CrIS detector electronics failures (3)
- Cumulative damage from SEEs is somewhat common but observed TID degradation is rare
  - Going through verification process across all events
- Nondestructive SEEs are continuous and ever-present, with no apparent bias towards parts with or without RHA (protected by circuit designs and ops rules)
- Place a vulnerable part outside a spacecraft in a simple circuit and the result will be certain
  - 17 AD590s failed installed outside of AMPTE spacecraft (ELDRS)
- System effects overcome component susceptibility (detectors on Chandra)

If you focus your radiation concerns at the part level, you will likely miss something

Mystery electronics failures

- ICON: complete loss of power, mission ended after just over 3 years on Nov 25, 2022 (no event or location of incident identifiable).
- CYGNSS: loss of command transmitter on one of 8 spacecraft after just over 6 years on Nov 26, 2022 (no event or location of incident identifiable). Remaining electronics remain functional as S/C is three-axis stable.
- JPSS-2 Ka-band transmitter: failure after weeks on orbit just exiting the SAA. Redundant transmitter working.

- Each incident has been thoroughly investigated with no cause determined. Radiation eliminated by review of parts. No thorough review of circuit radiation effects.

Conclusions

- First-time broad review of about four decades of on-orbit anomaly data combined with about two decades of nonconventional electronics flight experiential data point to the need to re-evaluate our approaches at developing flight electronics
- Across a wide spectrum of orbits (LEO, GEO, HEO, Lagrange point, heliocentric) single event effects have dominated our radiation experiences over the past 20 years with few noticeable effects of total ionizing dose
  - Many cases perceived to be total ionizing apparently were cumulative damaging single event effects
- Events and incidents have no apparent correlation with FMRR, PMRR, or parts with no manufacturer radiation rating
  - Nonvolatile memory virtually always needs some form of protection
- While many missions have had design lifetimes limited by radiation, radiation has not been life-limiting for any in the GSFC missions launched since 2000, even going well over 10x the original lifetime.

Backup

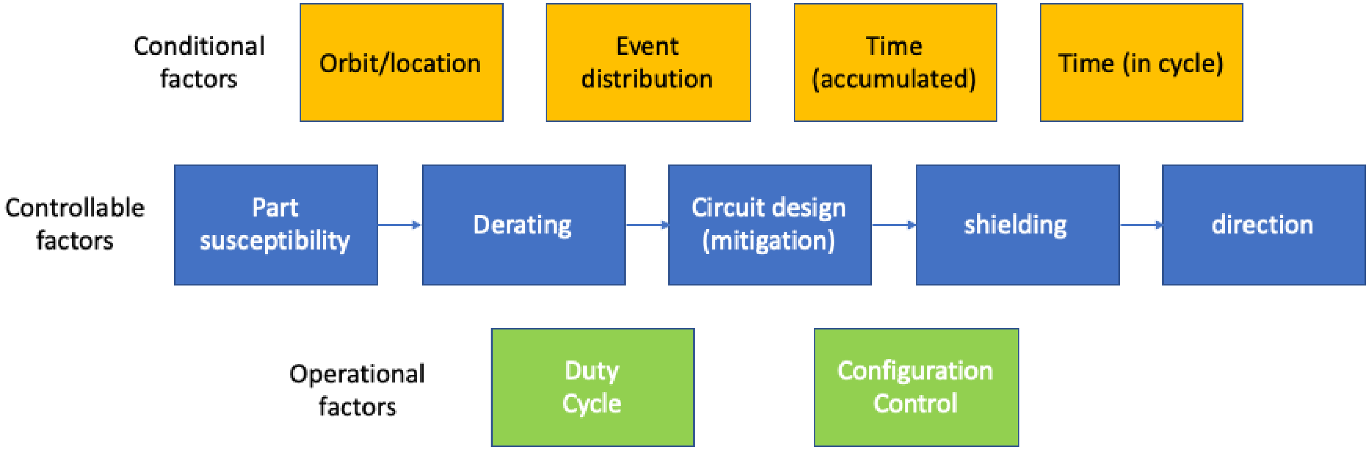
SAFETY and MISSION ASSURANCE DIRECTORATE Code 300

Source of Mission Risks

- Primary elements of technical risk for space missions are the departures from
  - The system being tested in its flight configuration
  - The system being tested in a way that replicates its time on-orbit
  - The system being tested in a way that replicates its on-orbit operation
- Combined with the remnant problems that have been unresolved from that testing
- Risk is minimized by using components that have been proven in the environment for the necessary lifetime, when possible, without interfering with their design or development
- Not testing in flight configuration drives
  - Technical risk
    - That of not catching something important that threatens the system on-orbit
    - That of limiting the performance or reliability through unnecessary or irrelevant restrictions
  - Programmatic risk
    - The use of time and money to address things that do not or are not likely to occur on-orbit

Review of on-orbit experiences is essential to validate items and approaches that cannot be tested in flight configuration

The multi-dimensional radiation problem

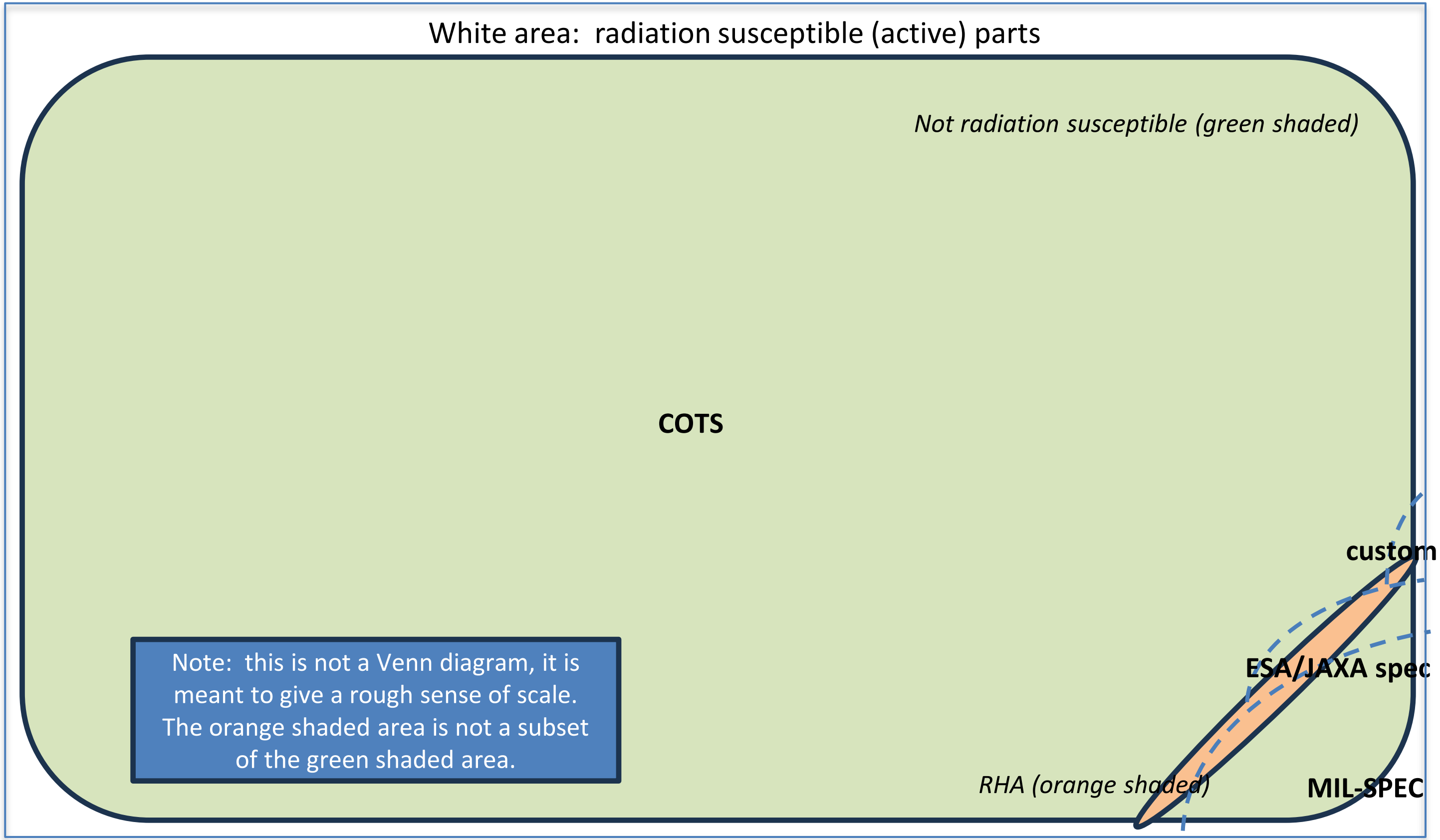


The charge

- This effort must be driven by and informed from on-orbit experiences and data
- On-orbit data show lack of correlation between piece-part radiation data and on-orbit experiences of spacecraft systems
  - Hubble
  - SMAP
  - Chandra
  - Swift
  - Others
- Benchmark problem
  - Consider on-orbit experiences of non-RHA FPGA in a range of different regimes and lifetimes to estimate risk in new regime not enveloped by any of the other regimes

Status

- First “skeleton draft” complete
  - Includes the basic risk assessment principles
  - Includes basic concepts relating radiation to risk
- Effort on-going for several months
  - Reliability expertise on board
  - Radiation expertise on board
  - Completed review of 30+ years of on-orbit anomaly data from GSFC missions (~9000 flight anomalies)
  - Over 1000 hits associated with radiation-related search terms, pared down to ~140 that are due to radiation or possibly due to radiation.
    - Subsequently, manual searches revealed that global searches were not sufficient, uncovering approximately 1000 more
  - Hits are being correlated against regions, events, designs, components, and parts
- Interacting with NOAA endorsed SBIR, which is developing a tool to broadly characterize and display space weather and radiation events
- Presentation completed proving that expanded use of COTS parts does not increase radiation risk


White area: radiation susceptible (active) parts
Not radiation susceptible (green shaded)
COTS
custom
ESA/JAXA spec
RHA (orange shaded)
MIL-SPEC
Note: this is not a Venn diagram, it is meant to give a rough sense of scale. The orange shaded area is not a subset of the green shaded area.

Radiation risk and traceability

- Traceability to wafer lot feeds radiation risk if you are using parts from multiple lot date codes and are not testing or demonstrating all lot date codes in space.
  - Strategic testing can retire most of that risk
  - The same points that are required about ILPMs, statistical process controls, and volume, all play into such risk in the same way
  - If you purchase cheap consumer grade parts, then there may be uncertainty as to the origins of the parts or whether they really came from the same lot.
  - Even ”hi-rel” parts might have multiple wafer lots in a single lot
  - In general, the same features required to assure the selection and procurement of reliable COTS parts also address traceability concerns within a lot.
  - Any part that is not process-controlled for radiation susceptibility can have variability throughout the lot, COTS or MIL-SPEC

Risk of failing radiation tests

- This is not an artifact of using COTS; it's an artifact of requiring a function that has no available solution that meets the radiation requirements, and the concern would apply to COTS and MIL-SPEC parts
- Many developers use almost exclusively non-RHA parts very successfully, so this is not a significant concern
- In some cases, the higher performance you are trying to achieve and the newer technology, the greater the challenge.
  - In that case the choice is use what's available or don't execute the mission

Radiation-tolerant design and Rad-Hard By Design techniques will be needed to keep us moving forward