Total Ionizing Dose Effects on Commercial Electronics for Cube Sats in Low Earth Orbits

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Abstract-- Modest total dose in low earth orbit and short cube sat missions provide an opportunity for using commercial electronics. We present the results of high and low dose rate testing of candidate commercial microcircuits.

I. Introduction

Electronics in Cube Sats operating in orbits from 400 km to 1200 km and inclinations from 45º to 90º with 100 mils of aluminum shielding experience a typical total ionizing dose between 200 rad(Si) and 10K rad(Si) per year. [ref. 1] This amounts to an average dose rate between 6.3 µrad(Si)/s and 0.32 mrad(Si)/s. At these values of total dose and dose rate, many commercial microcircuits will perform throughout the 1 to 2 year missions typical of Cube Sats. The cost and performance of contemporary microcircuits are well suited for the low budgets, reduced power, and small volume of Cube Sats

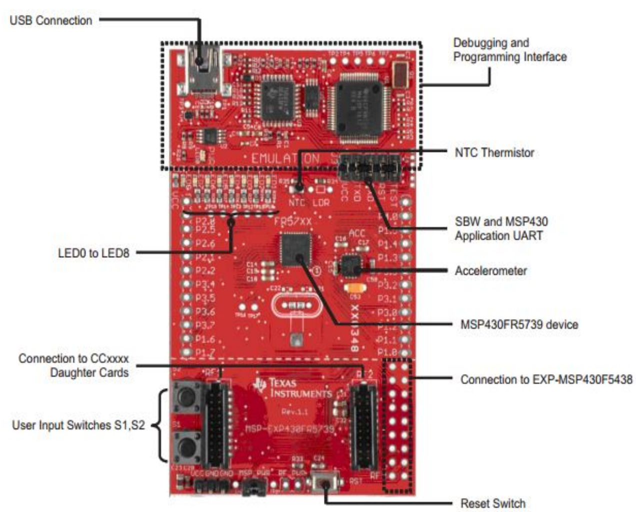
The following paper describes the results of total dose testing performed on the Texas Instruments MSP430FR5739 ultra-low power microcontroller, the Beagle Bone Black computer development platform, and eight JFET and CMOS op amps from three manufacturers. The objective was to evaluate these candidates for Cube Sat missions for performance in both high dose rate and low dose rate exposures. High dose rate (50 to 80 rad(Si)/s) tests were conducted in the AFRL Co-60 source and low dose rate (10 mrad(Si)/s) were conducted in the AFRL Cs-137 source.

II. Test Results

A. *MSP430FR5739 Microcontroller*

The MSP430FR is a 16-bit RISC microcontroller that is an excellent candidate for cube sat missions due to its low power characteristics (81.4 µA/MHz) coupled with (1) 16 KB of ferroelectric non-volatile memory, (2) a 14 channel/10 bit ADC, (3) a 16 channel analog comparator, and (4) a variety of communication options including UART, SPI , and I^2C. An MSP-EXP430FR5739 development board shown in Figure 1 was used to implement the test. The microcontroller is located in the center of the board with no other active components around it or behind it. Since the board is usually powered through a USB, a modified cable was used to permit power to be applied from a lab supply so that current could be monitored during test

Fig. 1. MSP430 Evaluation Board.



Two units were subjected high dose rate irradiation at the Co-60 source with a collimator used to shield everything on the development board except the MSP430. Dosage values were determined with a RadCal 2026 with a 0.18 cc ionization chamber for Co-60 and a180cc ionization chamber for the Cs-137. RadCal calibration is traceable to NIST standards. The microcontroller was operating continuously throughout the test. The test software was designed primarily to access the memory, communication, and computational circuitry of the MSP-430FR. Data were logged every 10 seconds during the test. The Co-60 source was dropped every 10Krad(Si) to permit the supply current to be logged without any contributions from ionization currents.

MSP430 test article 1 failed at 244 Krad(Si), and test article 2 failed at 248 Krad(Si). The supply currents for each device are shown in Figure 2 as a function of total dose. The currents showed relatively minor (5mA) fluctuations up to 200Krad(Si), but dropped precipitously between 200

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Krad(Si) and failure. Functionality could not be recovered by annealing at 100ºC for 168 hours.

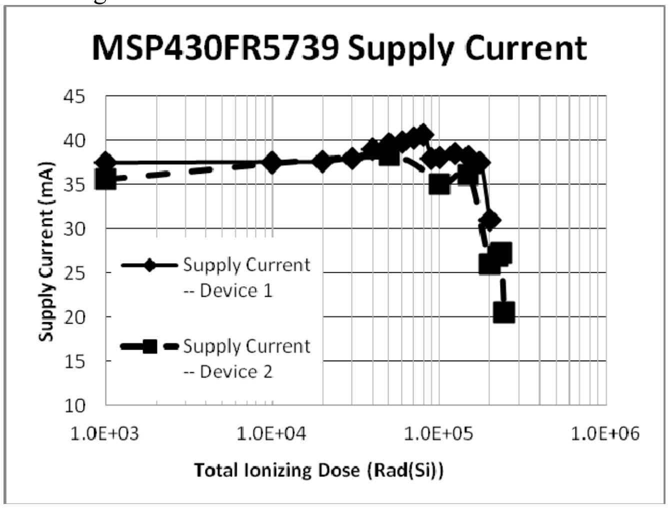

Fig. 2. Supply Current for MSP430.

A third test article was irradiated in the Cs-137 source at 10 mrad(Si)/s. The device loged data every 10 minutes and was removed from the source on after 250 days of continuous operation and a total accumulated dose of 212.8 Krad(Si). The device remained fully functional. The test was halted due to unreliable serial to USB conversion in the emulation chip incorporated on the evaluation board. The emulation chip incorporates flash memory and although it was shielded during the CS-137 irradiation, it still received 21Krad(Si) of dose, which is a typical failure level for embedded flash. The MSP430 has proved to be quite robust in its TID response and is under consideration for several Cube Sat missions.

B. *Beagle Bone Black Test Results*

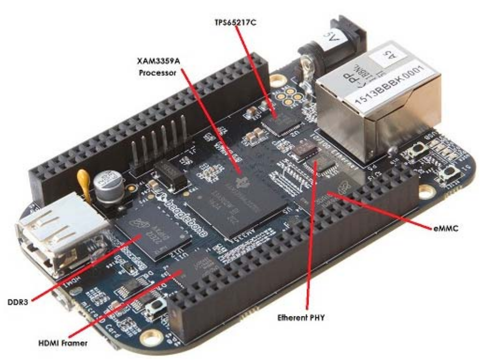

Fig. 3. Beagle Bone Black Platform

The Beagle Bone Black, shown in Figure 3, is a low cost ($45), open source computer development platform based on an AM335x ARM® Cortex-A8. It incorporates 512 MB DDR3 Ram, 2GB flash storage, a microSD card slot, 3D graphics accelerator, 2 Ethernet ports, 2 USB ports, an HDMI port, UART access, 69 general purpose I/O, SPI, and I^2C ports. A single 5 volt supply is used to power the board. Up to 4 boards can be stacked. This extensive capability has generated interest throughout the Cube Sat community in the possibility of flying one or more boards without modification. Consequently, two of the units were tested in the Co-60 source at a dose rate of 53 rad(Si)/s. The test software was designed primarily to access the memory or file system (residing either in the eMMC or SD card memory). The test also exercised the I^2C port and the Ethernet interface. The Ethernet interface was exercised as the main channel of communication with the monitoring equipment in the instrumentation cell. The test unit was fully operational during the test and communicated with a data logging computer in the instrumentation shack over the Ethernet port, through a CAT 5 cable. Data were logged every 10 seconds during the test. The radiation source was dropped periodically to record the supply current.

For the initial irradiation of the first test unit, no shielding was used. The unit quit operating after 17.9 Krad(Si). The failure was due to the loss of functionality in the SD card which contained the operating code. A new SD card was inserted and the unit began full operation again with the SD card shielded. The unit continued to function until 23.3Krad(Si). The current increased dramatically as shown in Figure 4, and no communication could be established. The second test unit was irradiated under the same test conditions with the SD card shielded. It failed at 17.3 Krad(Si). A third unit was irradiated to 15K rad(Si) without failure, and all three units were subjected to an anneal at 100ºC for 168 hours. Unit 1 recovered full operation and unit 3 remained operational.

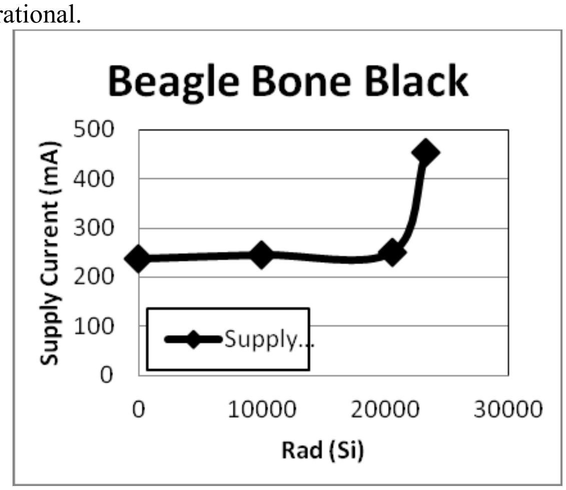

Fig. 4. Beagle Bone Black Platform

Although the Beagle Bone Black failed at a relatively low total dose, its performance would be adequate for short duration Cube Sat missions in low earth orbits. The flash memory in the SD card was the most vulnerable element, and additional shielding or a replacement device should be considered for mission application.

C. *Op Amp Test Results*

Operational amplifiers are used throughout Cube Sats to amplify sensor signals, filter out noise, act as impedance buffers, perform sample and hold, and myriad other signal conditioning functions. Unfortunately, many bipolar op amps exhibit ELDRS (Enhanced Low Dose Rate Sensitivity) [ref.2], and no universally effective screening procedures have been identified other than long duration, expensive, low dose rate tests. However, CMOS technologies have not been found to exhibit ELDRS effects, and CMOS op amp performance has significantly improved in recent years as a result of new designs to capitalize on their low power advantages in cell phones and other consumer electronics. To investigate the potential of CMOS op amps in Cube Sat missions, eight types of commercial op amps were irradiated under high (80 rad(Si)/s) and low (10 mrad(Si)/s) dose rate conditions to determine their failure threshold to total ionizing dose and to evaluate any susceptibility to ELDRS. Devices fabricated with either CMOS or JFET technologies were selected because they exhibit attractive parametric characteristics such as very high input impedance and very low power consumption.

Except as noted below, irradiations were performed under four different bias conditions – (1) all pins grounded; (2) output set to 0 volts with a gain 10; (3) output set to 50% of minimum output with gain 10; (4) output set to 50% of maximum output with a gain 10. The "all pins grounded" condition was chosen because in some cases it is the worst case bias condition for ELDRS. The other bias conditions were chosen to be representative of typical op amp applications. The irradiation bias circuit for the LMV341 is shown in Figure 5. The same circuit topography was used for all other devices with appropriate changes in resistor values to reflect the manufacturer's recommended load conditions.

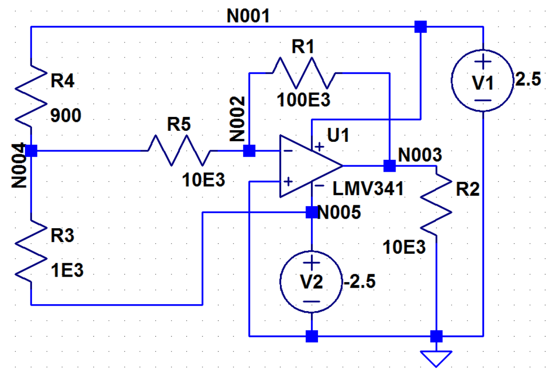

Fig. 5. Op Amp Irradiation Bias Circuit

Pre- and post-irradiation characterization for all devices was performed on Credence ASL1000 automated tester. All parametric values were logged by the tester to track changes with accumulated dose. Low dose rate irradiations were performed at the AFRL Cs-137 source at a dose rate of 10 mrad(Si)/s. High dose rate irradiations were performed at the AFRL Co-60 source at a dose rate of 80 rad(Si)/s. All post-irradiation measurements were made within an hour of the devices being removed from the radiation test cell. All parts were irradiated simultaneously with the test boards being configured to provide the four bias conditions listed previously.

A summary of low dose rate and high dose rate failure levels for all device type is presented in Table 1. A discussion of the failure characteristics of each op amp type is presented below.

Table 1. Op Amps Selected for TID Investigation

Vendor	**Part Number**	**Application**	**Supply Voltage**	**Gain Bandwidth Product**	**Slew Rate**	**Max Input Offset Voltage**	**High Dose Rate Fail Level Rad(Si)**	**Low Dose Rate Fail Level Rad(Si)**
Texas Instruments	OPA656	Wide Bandwidth, FET Input	±5 V	500 MHz	290 V/µs	±1.8 mV	4.7K – 7.7K	>32K
Texas Instruments	TLC2272	Low Noise,Linear CMOS	±5 V	2 MHz	3.6 V/µs	±3.0 mV	12K	12K
Texas Instruments	LMC6062	Precision Micropower CMOS	4.5 to 15V	100 KHz	35 V/ms	350 µV	15K – 25K	15K – 25K
Linear Technology	LTC6081	Low Offset, CMOS	5.5 V	3.5 MHz	1 V/µs	±90 µV	5K	>32K
Linear Technology	LTC1150	High Voltage CMOS	±15 V	2.5 MHz	3 V/ µs	±10 µV	2.5K	5K – 10K
National Semiconductor / Texas Instruments	LMV341	General Purpose w/Shutdown CMOS	5.4 V	1.0 MHz	1 V/µs	±0.025 mV	20K	22K – 27K
Analog Devices	AD8657	Micropower Rail-to-Rail CMOS	18 V	230 KHz	80 V/ms	350 µV	15K – 25K	15K – 25K
Analog Devices	AD8662	Low Noise Precision CMOS	5 to 16V	4.0 MHz	3.5 V/ µs	1 mV	10K- 15K	10K – 15K

1) OPA656 Test Results

The OPA656 is a wideband, unity gain stable op amp with a FET input stage. It showed only minor effects from the low dose rate Cs-137 irradiations with all parameters remaining in spec through 32 Krad(Si). The only noticeable parametric changes occurred in the output sink and source currents. They surpassed the data sheet specifications (± 70 mA) prior to irradiation, changed slightly after irradiation, and continued to exceed data sheet values after 32 Krad(Si) as shown in Figure 6. High dose rate Co-60 irradiations were much more damaging to the OPA656. Figure 7 shows the output source currents failing precipitously between 4.7K and 7.7 Krad(Si). The parts in all bias conditions were non-functional after 7.7 Krad(Si). No ELDRS effects were identified in the OPA656.

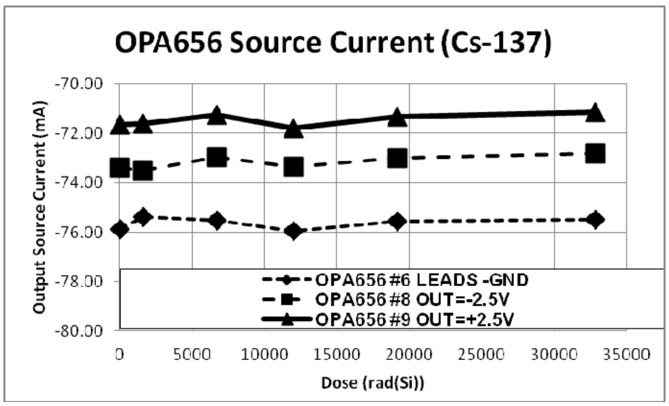

Fig. 6. OPA656 source current at 10 mrad(Si)/s.

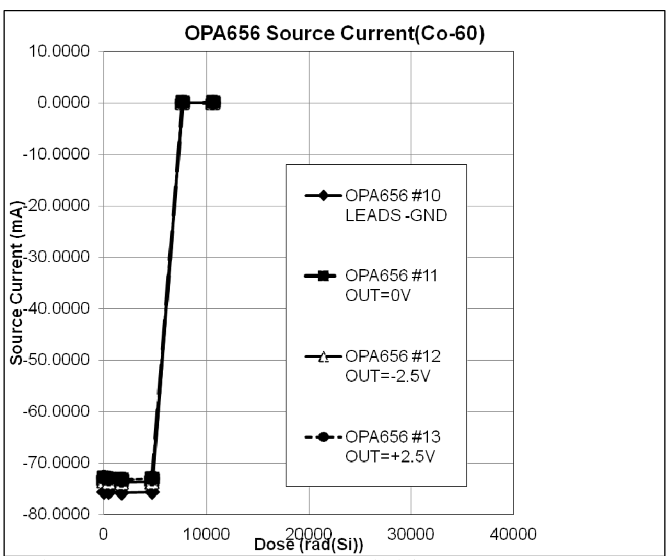

Fig. 7. OPA656 source current at 80 rad(Si)/s.

2) TLC2272 Test Results

The TLC2272 is a low noise CMOS op amp that was tested at supply voltages of ± 5V. The input offset voltage was the most radiation sensitive parameter. As shown in Figure 8, the initial low dose rate parametric failure occurred at 12 Krad(Si) in the device biased at -5V. Other bias conditions had failed the specification limit by 25 Krad(Si). The test devices exposed with all leads grounded were least affected by irradiation. The devices tested at high dose rate were all outside the input offset specification. A value 2x the average pre-radiation measured value was selected as the failure level. By this criterion, the parametric failures at high dose rate were very similar to the low dose rate results. As shown in Figure 9, the devices that were biased to set the output at either +5V or -5V showed the earliest and largest shifts in input offset. The all leads grounded parts were slightly less susceptible. No ELDRS effects were identified in TLC2272.

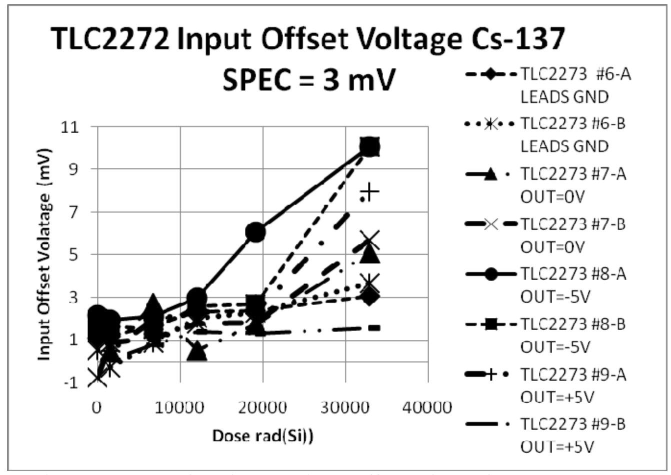

Fig. 8. TLC2272 low dose rate input offset voltage changes.

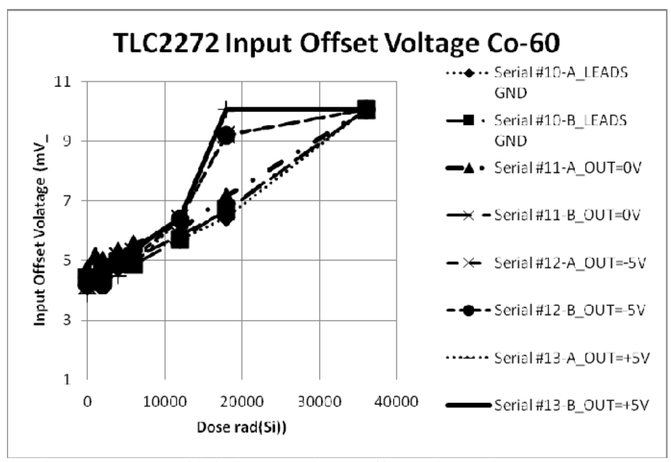

Fig. 9. TLC2272 high dose rate input offset voltage change.

3) LMC6062 Test Results

The LMC6062 is a precision, micro-power, CMOS op amp with an operating range between 4.5V and 15V. It can be operated from a single supply or a dual supply. The standby supply current is specified as 16μA. The part was irradiated with a dual supply of ±7V. The output sink current was indicative of the radiation sensitivity of the part. Figure 10 shows that at low dose rates the configuration with the output biased midway to the negative rail was most sensitive to degradation and failed the 8mA specification near 16 Krad. As shown in Figure 11, the high dose rate performance was similar with the "all leads grounded" configuration being less radiation sensitive at both dose rates. No indication of ELDRS effects was found.

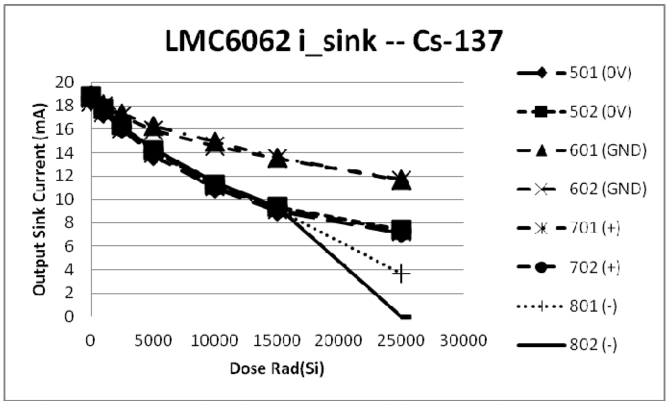

Fig. 10. LMC6062 low dose rate output sink current changes.

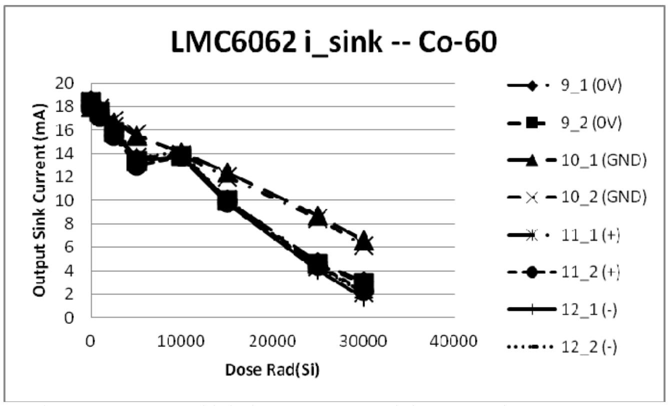

Fig. 11. LMC6062 high dose rate output sink current changes.

4) *LTC6081 Test Results*

The LTC6081 is a precision CMOS rail-to-rail op amp designed for low offset and low drift. It has a supply voltage range from 2.7 -to- 5 V with a maximum of 6V and is capable of single supply or dual supply operation. It was irradiated with a ±3 V dual supply and the outputs biased near the voltage rails (i.e. ±2.75V). The input offset current was indicative of the radiation sensitivity of the part. Figure 12 is a plot of the input offset current at low dose rate. Although the current is increasing significantly for the outputs biased near the rails, it has not exceeded the 15 pA specification at 32 Krad(Si). (The all-leads-grounded devices in the low dose rate tests were damaged during electrical test) The high dose rate data in Figure 13 shows the offset current to exceed the specification between 5K and 7.5K rad(Si) for the devices biased near the rail. The devices with all leads grounded or the output set to 0V showed essentially no change. No evidence of ELDRS effects was identified for the LTC6081.

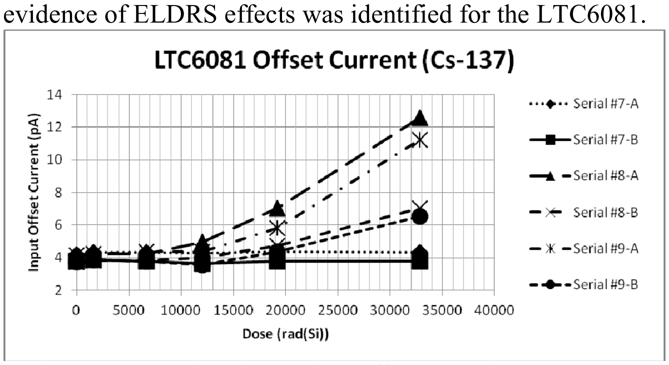

Fig. 12. LTC6081 low dose rate input offset current changes.

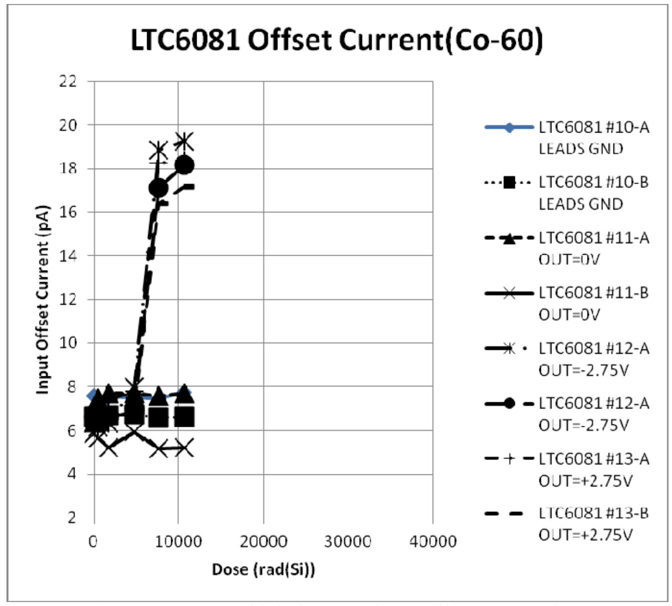

Fig. 13. LTC6081 high dose rate input offset current changes.

5) *LTC1150 Test Results*

The LTC is a high voltage (±16V), high performance, CMOS op amp with very low offset voltage drift with temperature. It is capable of operation from either a single ended or dual supply voltage. It was tested with dual ±7V supplies. The input bias current is indicative of the radiation sensitivity of the part. The specification for the bias current is ±100 pA. As shown in Figure 14, it was exceeded between 5K and 10K rad(Si) for the low dose rate tests for the three devices tested under bias. The all-leads-grounded part did not exceed the specification through 25K rad(Si).

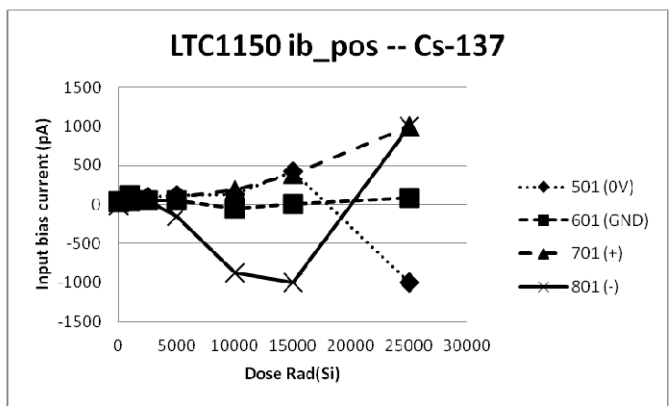

Fig. 14. LTC1150 low dose rate input bias current changes.

In the high dose rate tests, the positively biased device and the all leads grounded device exceed the specification at 2.5 Krad(Si) and all devices exceeded the specification by 10 Krad(Si) as shown in Figure 15. No evidence of ELDRS effects was identified for the LTC1150.

6) *LMV341 Test Results*

The LMV341 is a low voltage, low power CMOS op amp capable of operation from either a single or dual power supply with voltages up to 5.5 volts. Its design incorporates a shutdown mode that can reduce the supply current to 1μA. It was irradiated with a dual supply of ±2.75 V. The outputs were biased near the voltage rails. The results of the low dose rate tests are shown in Figure 16 for the current in the shutdown mode which was the most radiation sensitive parameter. The devices biased near the voltage rails exceeded the specification between the 20Krad(Si) and 32Krad(Si) irradiation with an estimated failure level of 22-27Krad(Si). The high dose rate data shown in Figure 17 indicate that the biased devices exceed the specification at 20Krad(Si). No evidence of ELDRS effects was identified for the LMV341.

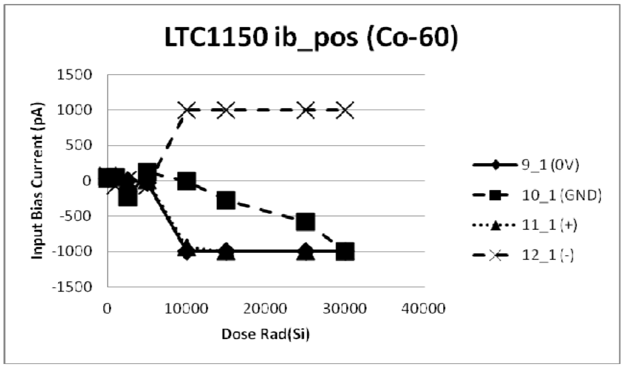

Fig. 15. LTC1150 high dose rate input bias current changes.

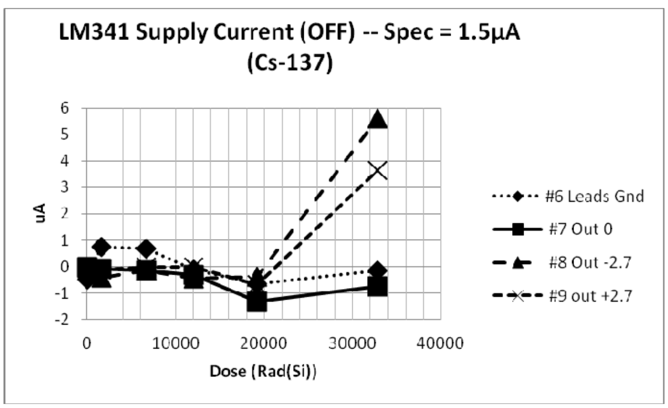

Fig. 16. LMV341 low dose rate supply current off state changes.

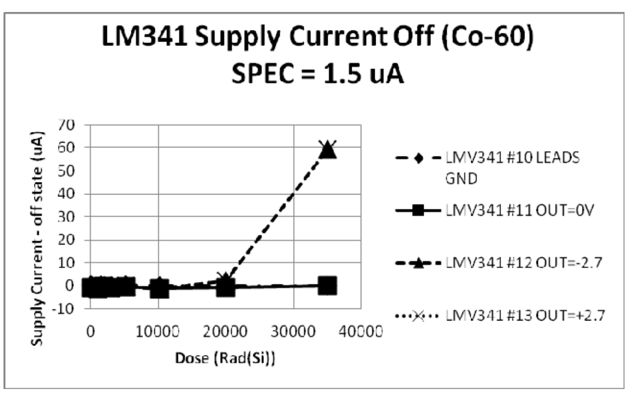

Fig. 17. LMV341 high dose rate supply current off state changes.

7) *AD8657 Test Results*

The AD8657 is a high voltage (18V) , low offset CMOS op amp with the capability of rail-to-rail output voltage. The device was irradiated with ±9V supply voltage. The low dose rate data shown in Figure 18 indicate that the source current fails the specification of 12 mA between the 15 K and 25 Krad(Si) irradiation test points. The all-pins-grounded devices show little degradation at the tested levels. The high dose data shown in Figure 19 show a similar failure threshold with the reduction in source current being more severe than the low dose rate tests. No evidence of ELDRS effects was identified for the AD8657.

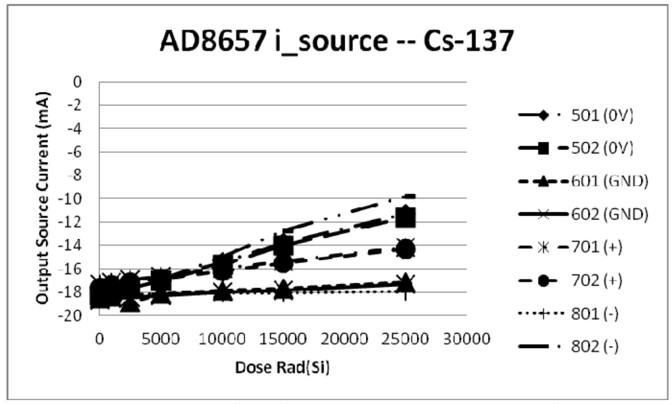

Fig. 18. AD8657 low dose rate output source current changes.

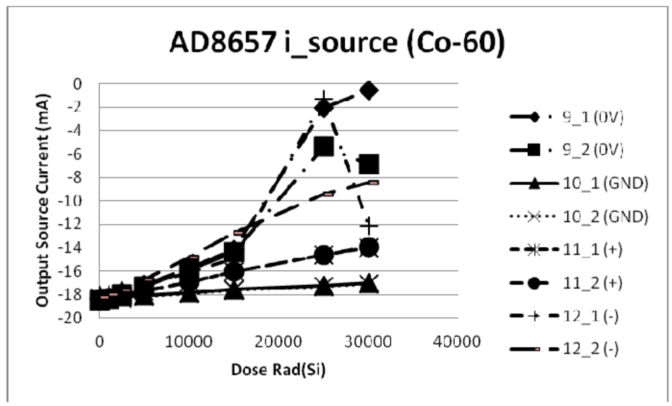

Fig. 19. AD8657 high dose rate output source current changes.

8) *AD8662 Test Results*

The AD8662 is a low noise, precision, 16V CMOS op amp with extremely low input bias current (1pA) and capable of rail-to-rail output voltage. It was irradiated with a dual supply of ±7V. The low dose rate data shown in Figure 20 indicate that one of the devices biased near the negative rail failed the source current specification (19mA) between the 10Krad(Si) and 15Krad(Si) test points. All other devices remained within specification through 25Krad(Si).

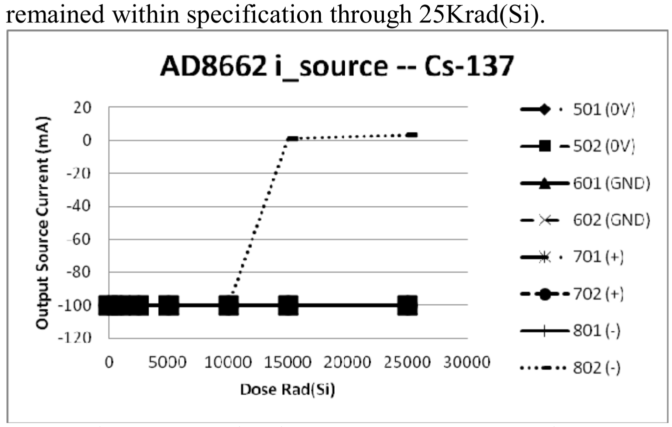

Fig. 20. AD8662 low dose rate output source current changes.

Evaluation of other parameters indicates that device 802 was particularly sensitive to radiation although it was within specification during pre-radiation testing. The high dose data shown in Figure 21 also indicate an early failure between 10Krad(Si) and 15Krad(Si) for one of the device (#12-2) biased near the negative rail. Other devices fail the specification at the 25Krad(Si) test point. No evidence of ELDRS effects was identified for the AD8662.

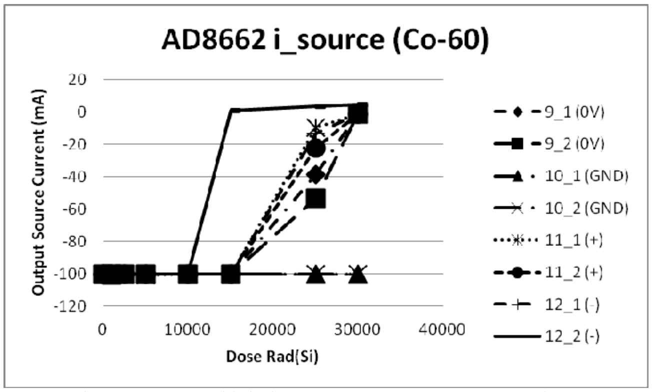

Fig. 21. AD8662 high dose rate output source current changes.

III. Summary

Commercial high performance, low power microcircuits have many attributes of interest to the cube sat community. The MSP430 and the Beagle Bone Black offer excellent performance and low power. The MSP430 is particularly of interest due to its robust radiation performance. The use of CMOS technology offers an opportunity for ELDRS free analog parts with low power requirements. The survey of 8 op amps has indicated that design parameters are generally well behaved up to TID levels encountered in short duration LEO missions with reasonable shielding.

IV. References

[1] IEEE Standard for Environmental Specification for Spaceborne Computer Modules, IEEE Std 1156.4-1997, Appendix A, pp. 21-23, 20 March, 1997

[2] Pease, R.L. ; Schrimpf, R.D. ; Fleetwood, D.M., ELDRS in bipolar linear circuits: A review , *Radiation and Its Effects on Components and Systems (RADECS), 2008*, pp 18 – 32