COTS ADC & DAC Selection and Qualification for the GLAST Mission

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***Abstract*— Low-voltage low-power ADCs were radiation tested for selection to use on calorimeter instrument of the Gamma-ray Large Area Space Telescope (GLAST). The GLAST instrument will detect the most energetic photons, gamma rays, and pinpoint their source direction and energy. The GLAST instrument will have a low-earth orbit with an expected lifetime total-dose radiation exposure less than 5 krad. Both the Maxim MAX145 and MAX1241 CMOS ADCs were tested to be single event latchup (SEL) immune to an LET of 60 Mev/mg/cm^2. The MAX145 is used on the GLAST instrument. A companion device MAX5121 was selected as the flight DAC that also did not show SEL to 60 MeV/mg/cm^2. In presenting the data from all the ADCs and DACs tested, and explaining our test and qualification process, we hope to aide other designers with this difficult process.**

***Index Terms*—Radiation effects, Semiconductor device radiation effects, Analog-digital conversion, Digital-analog conversion.**

I. INTRODUCTION

The calorimeter subsection of the Large Area Telescope (LAT) instrument on the Gamma-ray Large Area Space Telescope (GLAST) mission is a large space-electronics endeavor built with over three thousand custom Application Specific Integrated Circuits (ASICs) and a similar number of commercial Analog to Digital Converters(ADCs). Figure 1 shows one calorimeter module and electronics. Usage of devices with previous space flight history was not possible due to the need for low-power low-voltage devices. Searching for and qualifying devices is a route normally viewed as crazy in the modern electronics world, but our results show that it is possible to find modern commercial Complementary Metal-Oxide Semiconductor (CMOS) devices that are usable for space flight.

The calorimeter subsection of the GLAST performs energy deposition and position measurements (1 cm resolution) of hadrons (gamma rays and cosmic rays) [1]. GLAST is a gamma-ray pair conversion telescope consisting of a silicon-strip detector tracker and a Cesium-Iodine (CsI) hodoscopic calorimeter. The launch of the GLAST instrument is in 2007. The calorimeter subsection consists of a modular 4x4 grid of calorimeter modules. Each calorimeter module consists of 96 CsI crystal logs configured in 8 layers of 12 crystals. Alternating layers crystals are orthogonal to each other in a hodoscope arrangement. The calorimeter performs energy deposition and position measurements (1 cm resolution) of gamma-rays and cosmic rays. Position measurement is determined by the ratio of pulse heights from opposite ends of the CsI crystal "logs". To reduce the measurement deadtime, a single Analog to Digital Converter (ADC) per log-end is used to digitize the pulse height information of the 192 log ends per calorimeter tower.

Completion of the instrument design required finding a low-power, serial-output 12 bit ADC with conversion time under 10 usec, that does not exhibit SEL to an LET of 60 MeV/mg/cm^2. Five commercial ADCs available in 2000-2001 that met mission requirements were investigated, along with Digital to Analog Converters (DACs) that would be used for the calibration of the front-end electronics. As the electronics system design matured, it was decided that all electronics would run off a 3.3V supply. Of the two ADCs which did not exhibit Single Event Latchup (SEL) to a Linear Energy Transfer (LET) of 80 MeV/mg/cm^2, the MAX145 was chosen as it has a faster data readout time. The three types of testing performed on the candidate devices were picosecond laser energy deposition, heavy ion testing, and total-dose testing.

Following our selection of the components to use for flight, the second problem was procurement and qualification for space flight. Engineering best practices require that devices intended for space flight be purchased as single lots that have gone through no less than a MIL-STD-883 manufacturing and testing flow. After much conversation with Maxim (even a purchase of ten thousand devices may not get a commercial semiconductor manufacturer's attention), they did agree to sell us components from a single lot that had been 100% screened to their normal test flow. For further qualification testing, a subset of the procured devices (subset not to be used for flight) was given additional tests of Highly Accelerated Stress

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Testing (HAST), radiography (X-ray), scanning acoustic microscopy (CSAM), unpowered thermal cycles, and life tests. The HAST, radiography, CSAM, and thermal cycle tests are more for testing the assembly and packaging of the microelectronics, which is important for the Commercial Off-The-Shelf (COTS) plastic packaging. The Maxim components fully passed the qualification tests. In addition, 100% of the flight components also successfully went through dynamic board-level burn-in and instrument-level thermal vacuum tests.

II. Radiation test results

A. COTS ADC Test Results

Selected ADCs were first tested at the Naval Research Lab (NRL) picosecond laser SEU simulator [2]. The picosecond laser energy deposition, in pJ, is converted to equivalent LET by an empirically-derived multiplying factor of three [3]. Devices exhibiting a high SEL LET threshold with the laser, plus one initial favorite device, were then tested at the Tandem Van de Graff (TVDG) Single Event Upset (SEU) facility at Brookhaven National Lab (BNL), as shown in Figure 2. The initial heavy-ion SEL testing at the TVDG was performed with Bromine (LET = 37), Iodine (LET = 60), and Gold (LET = 82), all at room temperature and normal incidence. The flight operational temperature of our GLAST instrument is zero Celsius, so all radiation measurements performed at room temperature is an upper-limit for our flight requirements. As can be seen in Table I, the picosecond laser results matched fairly well with the heavy-ion SEL results. In fact, in our multiple trips to the NRL picosecond laser lab, we often used the MAX189 device as a laser SEL calibrator check. The LET values given in the table for the picosecond laser are in accordance with the best current theory relating laser energy to equivalent heavy ion energy.

It is worth mentioning that the MAX194 ADC, a 14-bit converter that exceeds the practical 12-bit resolution limit of switched-capacitor converters by using built-in self calibration, gets “knocked silly” by the ion beam induced upset events. The calibration registers get obvious bit flips, which can add significant offsets to the converted output code. Therefore this device dropped out of consideration due to catastrophic upsets.

All of the selected flight components were more thoroughly tested again at the Brookhaven TVDG. Table II shows the SEU and SEL results for the MAX145 from heavy-ion testing with more particle species.

Figure 3 shows a typical SEU spectrum from Bromine ions. The low SEU rate of the MAX145 is understood to be due to the short amount of time (microseconds) that the digitized values are held in flip-flops prior to being shifted out.

Due to concerns that the ion penetration depth at BNL was insufficient to simulate actual space heavy ions, the MAX145 was tested by NASA GSFC Code 561.4 with heavy ions at the Texas A&M University Cyclotron Facility (TAMU). The devices were exposed to Krypton (LET = 29.3 MeV•cm^2/mg, range = 116µm(Si)) and Xenon (LET = 53.9 MeV•cm^2/mg, range = 102µm(Si)). The MAX145 ADC did not exhibit SEL at TAMU with any of these LETs.

Total ionizing dose testing also performed by NASA GSFC Code 561.4, showed that the MAX145 integral and differential non-linearity stay constant and within data sheet specifications up to the test limit of 10krads(Si).

Integration and testing results with the MAX145 have been acceptable for the project’s needs. It has been necessary to replace approximately one out of every 50 ADCs for poor differential non-linearity (but still within manufacturer’s specification), which typically occurs during the board-level –30C cold temperature test.

B. COTS DAC Test Results

Following the initial ADC SEL testing results, Maxim was contacted about the fabrication process used for the MAX145 and the MAX1241. Those two ADCs are both fabricated on Maxim’s S12EIFX (1.2um Silicon Gate Epitaxial) process. Maxim’s RR-1L Reliability Report shows a cross section figure of the 1.2u Silicon Gate process, indicating a N+ buried layer under the CMOS transistors [4]. We theorize that the buried layer, similar to what is found in bipolar or Bi-CMOS processes, helps to dissipate the charge generated by ions. We then inquired about DACs that are fabricated on the same process. The list of low voltage DACs fabricated on the S12EIFX process includes the MAX5130/5120, MAX5131/5121, MAX5132/5122, and MAX5133/5123 devices.

We then chose some of the Maxim DACs from the S12EIFX process to test, along with other manufacturer’s devices that met our requirements. Table III shows the DACs that we tested with a picosecond laser. Again, the LET values given in the table for the picosecond laser are in accordance with the best current theory relating laser energy to equivalent heavy ion energy.

The MAX5121 was chosen for flight over the Texas Instruments devices due to commonality of fabrication process and manufacturer with the chosen flight ADC. The Max5121 was then thoroughly tested with heavy ions at the Brookhaven TVDG. Table IV shows the results of the heavy-ion SEU and SEL testing.

An interesting observation between the Table III and Table IV results is that the picosecond laser did not cause any SEUs while SEUs occurred easily with the ion beams. Since the picosecond laser testing occurred first and we were mainly trying to induce SEL, the sensitive analog reset circuits may not have been hit with the laser (manually scanning the die with a 1um diameter laser spot, including maintaining focus, can take a long time).

Figure 4 shows an oscilloscope trace (one second per horizontal division) of typical upsets with the MAX5121 DAC under heavy ion beams. The MAX5121 analog output upsets have a higher probability to reset either to mid-range (600 mV) or zero volt output. The MAX5121 DAC has both external reset and an automatic power-on reset. The reset can be controlled to either zero or midrange, with selection being controlled by a package pin being wired high or low. The larger upset probability to reset indicates that there are larger area analog circuits (amplifiers and/or comparators) on the die, which are more easily upset by the heavy ions.

Due to the MAX5121 having a high probability of being reset, the method of SEU crossection measurement was changed from the initial planned procedure. The procedure was changed from simply counting the effects of register bit flips during long ion beam runs to measuring the time-to-first-upset for many runs. This procedure change was needed for the following two reasons:

a. In a procedure counting upsets, subsequent similar resets following the first reset cannot be counted due to no external indication of change.
b. The length of time that the device is held in automatic reset will have some effect upon the measurement.

Of course with humans in the loop for beam starting and stopping control, the simple counting upsets method (if possible to be used) gives better measurement accuracies than the time-to-first-upset method (especially for short upset intervals). The exact procedure consisted of first programming the DAC output to a non-reset state with the ion beam blocked, then concurrently opening the ion beam gate and starting the oscilloscope trace recording. Time-to-first-upset was then measured on the horizontal scale of the oscilloscope. For calculation of SEU crossection, the number of upsets is the number of runs and the time interval is the sum of time-to-first upsets.

The MAX5121 SEUs shown are not a concern in our application since we need the DAC to maintain each output value only for a few seconds. However, for users requiring DACs to hold values for long periods of time, the obvious conclusion from our results is to stay clear of devices with internal reset circuits.

As with the MAX145 ADC, the MAX5121 was tested with heavy ions at the Texas A&M University Cyclotron Facility (TAMU) for increased ion penetration depth. The devices were latchup tested with Krypton (LET = 29.3 MeV•cm^2/mg, range = 116µm(Si)) and Xenon (LET = 53.9 MeV•cm^2/mg, range = 102µm(Si)). The MAX5121 DACs did not latchup at TAMU with these energies.

Total ionizing dose testing also performed by NASA GSFC Code 561.4, showed that the MAX5121 parameters are within data sheet specifications up to the test limit of 10krads(Si).

III. Conclusion

Commercial off-the-shelf CMOS low-voltage and low-power ADCs and DACs have successfully been chosen for the GLAST satellite instrument. The Maxim Electronics components were successfully radiation tested for latchup, single event upsets, and total-dose effects. Data for other converters initially tested were also presented. Lessons learned during this investigation are:

a. For finding modern devices which are SEL immune, investigate CMOS chips made in Bi-CMOS processes.
b. Picosecond lasers can help perform initial SEL/SEU screening.
c. Stay away from devices with built-in reset capability unless inadvertent resets are acceptable.
d. Stay away form devices that are self calibrating, unless the registers are known to be radiation tolerant.

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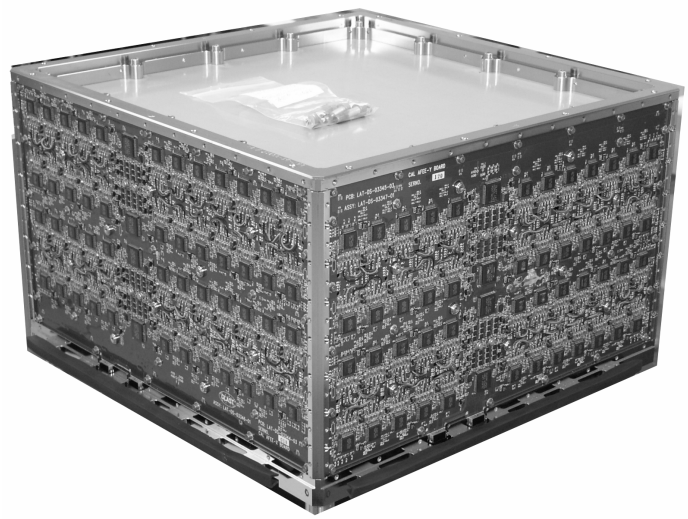

Fig. 1. GLAST flight Calorimeter module completing Assembly. Each of the four Calorimeter sides contain 48 MAX145 ADCs in tiny uSOP-8 packages, and 4 MAX5121 DACs in QSOP-16 packages, located along the center vertical board axis The larger quad flat pack chips seen are custom analog and digital ASICs.

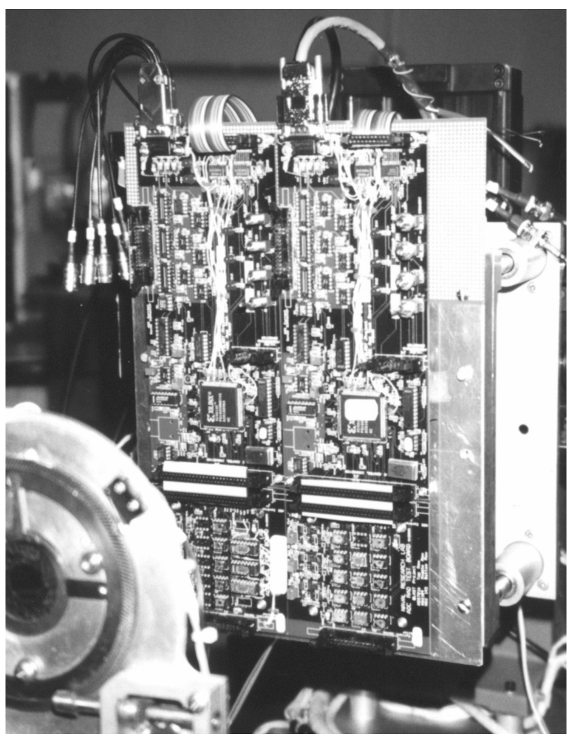

Fig. 2. Initial ADC SEU/SEL testing at Brookhaven TVDG. The Two ADC test boards contain rows of de-capsulated chips to be tested. The test boards are mounted on a 3-axis platform behind the mechanical iris, (shown at the bottom left). The platform is then placed in a vacuum chamber at the end of the beam path. A selectable laser in the beam path helps to visually align the chip-under-test to the iris opening.

TABLE 1 ADC LATCHUP AND SEU RESULTS MADE WITH LASER AND HEAVY ION BEAM. 25C, 5V OPERATION.

Parameter	Burr-Brown ADS7816	Maxim MAX189	Maxim MAX194	Maxim MAX145	Maxim MAX1241	Analog Devices AD7475
Device Operating Voltage Range, Vdd, volts	4.5 – 5.5	4.5 – 5.5	+5 and -5	2.7 – 5.2	2.7 – 5.2	2.7 – 5.2
Laser Test SEL Threshold, LET (MeV * cm^2)/mg	15 - 20	~ 70	~ 70	> 150	> 150	30 - 40
Bromine, LET=37 (MeV * cm^2)/mg, Range = 36.2 µm	SEL σ = $2.28x10^{-5}$ cm^2 SEU σ = $3.26x10^{-6}$ cm^2	No SEL SEU σ = $5.52x10^{-6}$ cm^2	No SEL SEU σ = $1.37x10^{-1}$ cm^2	No SEL SEU σ = $1.92x10^{-6}$ cm^2	No SEL SEU σ = $1.34x10^{-6}$ cm^2	Not Tested
Iodine, LET=60 (MeV * cm^2)/mg, Range = 32.7 µm	SEL σ = $3.5x10^{-5}$ cm^2 SEU σ = $5.0x10^{-6}$ cm^2	SEL σ = $2.54x10^{-6}$ cm^2 SEU σ = $1.35x10^{-5}$ cm^2	SEL σ = $3.44x10^{-6}$ cm^2 SEU σ = $4.70x10^{-1}$ cm^2	No SEL SEU σ = $6.43x10^{-6}$ cm^2	No SEL SEU σ = $2.46x10^{-6}$ cm^2	Not Tested
Gold, LET=82 (MeV * cm^2)/mg, Range = 28µm	SEL σ = $5.20x10^{-5}$ cm^2 SEUs are all SELs	SEL σ = $2.63x10^{-6}$ cm^2 SEU σ = $1.41x10^{-5}$ cm^2	SEL σ = $6.27x10^{-7}$ cm^2 SEU σ = $6.07x10^{-1}$ cm^2	No SEL SEU σ = $3.61x10^{-6}$ cm^2	No SEL SEU σ = $4.63x10^{-6}$ cm^2	Not Tested

TABLE II: MAX145 FLIGHT LOT SEU MEASUREMENT RESULTS MADE WITH HEAVY IONS. 25C, 3.3V OPERATION.

Ion, LET (MeV/mg/cm^2), Range	Total Fluence, ions/cm^2	SEL/SEU Results
Silicon, LET = 7.99, Range = 73.6µm	$9.75x10^7$	No SEL, No SEU
Titanium, LET = 19.79, Range = 39.9µm	$3.54x10^6$	No SEL, No SEU
Bromine, LET = 37.4, Range = 36µm	$4.78x10^7$	No SEL, SEU σ = $3.77x10^{-7}$ cm^2
Iodine, LET = 59.7, Range = 31.0 µm	$2.65x10^7$	No SEL, SEU σ = $5.28x10^{-7}$ cm^2
Gold, LET = 81.4, Range = 27.5µm	$2.34x10^7$	No SEL, SEU σ = $4.27x10^{-7}$ cm^2

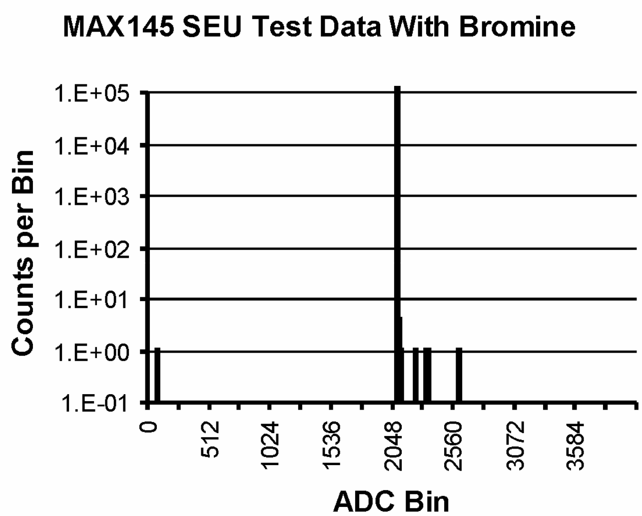

Fig. 3. Histogram of MAX145 Bromine ion testing showing the expected mid-range peak and few outlier SEUs. With a mid-range fixed input voltage to the ADC, the five SEUs are visible amongst the 10,000+ good conversions.

TABLE III: DIGITAL TO ANALOG CONVERTER LASER TEST SEL AND SEU RESULTS. 25C, 3.3V OPERATION.

Manufacturer	DAC Part No.	Minimum Supply Volt	Laser Test SEL Threshold LET, (MeV * cm^2)/mg	Laser Test SEU Threshold LET, (MeV * cm^2)/mg
Maxim	Max5121	3V	> 200	> 200
Maxim	Max5131	3V	> 200	> 200
Maxim	Max5133	3V	> 200	> 200
Texas Instruments	TLV5616	3V	> 200	< 200, not measured
Texas Instruments	TLV5636	3V	> 200	~ 20
Linear Technology	LT1453	3V	~ 5	Not tested
Linear Technology	LT1659	3V	~ 33	~ 33
Analog Devices	AD5320	3V	~ 4	Not tested

TABLE IV: MAX5121 FLIGHT LOT SEU MEASUREMENT MADE WITH HEAVY IONS. 25C, 3.3V OPERATION.

Ion ,LET (MeV/mg/cm^2), Range	Total Fluence, ions/cm^2	SEL/SEU Results
Silicon, LET = 7.99, Range = 73.6µm	$1.35x10^7$	No SEL, SEU σ = $1.48x10^{-6}$ cm^2
Chlorine, LET = 11.7, Range = 59.4µm	$7.96x10^5$	No SEL, SEU σ = $1.13x10^{-5}$ cm^2
Titanium, LET = 19.79, Range = 39.9µm	$4.15x10^6$	No SEL, SEU σ = $3.13x10^{-6}$ cm^2
Bromine, LET = 37.4, Range = 36µm	$7.22x10^5$	No SEL, SEU σ = $1.94x10^{-5}$ cm^2
Iodine, LET = 59.7, Range = 31.0µm	$3.17x10^5$	No SEL, SEU σ = $4.10x10^{-5}$ cm^2

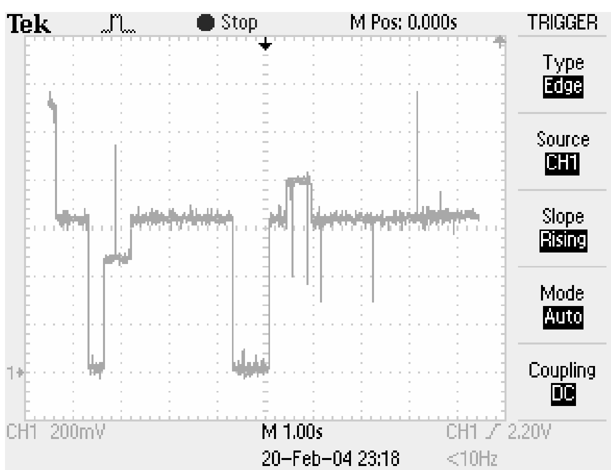

Fig. 4. Scope Plot of MAX5121 DAC output during Bromine ion beam at the fluence level in Table IV. The initial starting DAC value at the left of the plot is near DAC full range, and the first SEU, reset to mid-range, occurs in less than one-half second. Shown in the plot are two SEUs to reset-zero, two SEUs to a non-reset value (bit flip), and a higher probability of resetting to the mid-range value. Spikes are electrical system noise. Horizontal 1.0 sec/division. The vast majority (estimated 95%) of SEUs under any ion were resets.