Measurements of Single Event Effects in ADCs

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Abstract

The preliminary results of heavy ion irradiation with Californium-252 for the detection of single event up-sets are presented for Analog Devices' ADCs AD676, AD7884 and AD7893. Both short-lived and "lingering" errors were found.

Details of the test equipment and method are also given.

I. INTRODUCTION

Although there has recently been considerable interest in single event effects (SEE) in logic devices such as memories and processors, relatively little has been published on SEE in small signal analogue or mixed signal devices. However this is a subject of increasing interest as the trend for higher performance in space borne instruments leads to the use of faster and more precise signal processing electronics. This paper presents the first results from a program to study single event effects in ADCs, DACs and precision amplifiers with a view to selection for use on future space missions. Presented here are the results of tests carried out on 12 and 16 bit ADCs. These have been tested with ^{252}Cf fission fragments as a prelude to comprehensive heavy ion testing at an accelerator. This preliminary investigation has been used to commission the test equipment, to identify the type of events that can occur and to establish a reasonable estimate of the saturation event cross section prior to accelerator testing. A program of heavy ion testing has since been performed and results are briefly compared with the ^{252}Cf data. However a detailed discussion of the heavy ion data is deferred to a later paper.

II. EXPERIMENTAL

Test facilities and equipment

Testing was performed on de-lidded devices using the ^{252}Cf Assessment of Single-event Effects (CASE) facility at The European Space Research & Technology Centre (ESTEC). ^{252}Cf produces a wide range of fission particles with LET in the range 42-45MeVcm^2/mg at the surface of the die. [1, 2]. The devices tested were the 12 bit AD7893 and the 16 bit AD7884 and AD676, all manufactured by Analog Devices inc. At a distance of 2cm from the source, a surface area of 4cm^2 was known to be "illuminated" by the particle beam to a uniformity of ±10%. The irradiations were performed in November 1996. The particle flux at the time of testing was extrapolated from a calibration carried out at ESTEC in July 1996. A decrease of 9% was predicted to have occurred over the intervening 4 months. The source flux was $3.4x10^3$ particles/cm^2/min at typical 2 cm working distance from the source.

The test equipment has been designed such that each device under test, (ADC, DAC or amplifier) can be mounted in a dedicated daughter board interfaced to a motherboard containing a saw-tooth wave form generator, multiplexers, buffers and interface drivers and receivers (Figure 1). The motherboard is connected via a custom designed data memory board with four 64kword, 32 bit deep arrays to an Analog Devices 32 bit DSP ADSP-21020 EZ-Lab evaluation board with 30ns instruction cycle time. This DSP system allowed high speed acquisition of ADC data. For example, tests of the type described below typically involved 33 software instructions to be carried out between consecutive ADC conversions, allowing for testing of ADCs with conversion times as low as 1μs. Faster acquisition rates are possible for simpler tests involving fewer DSP instructions. The three devices that were tested all had conversion times between 5.3 and 10μs. An ADSP-21020 EZ-ICE emulator tool was used for program debugging and passage of data to a personal computer for later analysis.

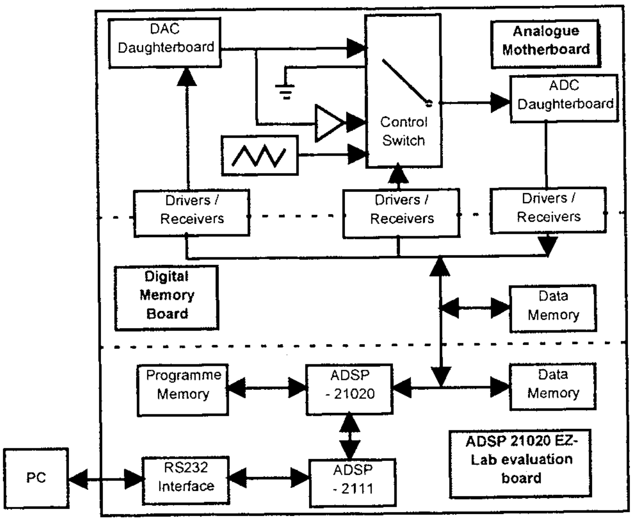

Figure 1 A schematic diagram of the test equipment consisting of an analogue motherboard, custom designed digital memory board, ADSP 21020 EZ-Lab evaluation board and a personal computer.

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The motherboard provides the analogue signals for testing the devices and provides an interface for communication with the digital memory board and ADSP-21020 evaluation board, via three ports. One port provides a connection for control of the analogue multiplexors, allowing selection of one of the possible inputs provided by the analogue board. The two remaining ports connect the ADC and DAC sockets on the analogue board to the digital board. Communication of converted data between the Device Under Test (DUT) and the digital memory board is then possible. Either a constant voltage (which can be 0 Volts) or a saw-tooth wave form can be applied to the ADC input. The user is able to select the slope and speed of the saw-tooth wave produced by an op-amp integrator circuit on the analogue board. The ramp input produced in this way has been measured to be linear to within ±0.4%, apart from small regions within ±5% of the turning points of the saw-tooth signal which are linear to within ±1%. Input of signals to the ADC from the DAC daughter board is also possible. Ground and d.c. test signals are available via an op-amp circuit.

The power supply for the analogue board is ±15 Volts. After passing through a power filter and a system of regulators, this provides, ±5, ±12 and ±15 Volt supplies for the ADC and DAC connectors.

The principle task of the custom memory board is to act as an expansion card for the data memory banks of the ADSP-21020 board. Ten Micron Semiconductor 128kx8 SRAM, (Static Random Access Memory), chips provide between them memory for two, 64kword arrays, both 32 bits deep. Data collected during the run time of the program is stored in this data memory for later retrieval by the PC. The digital board is interfaced to the analogue motherboard via the three input/output ports; ADC, DAC and control. (These are the opposite ends of the three ports on the analogue motherboard). Although present, a fourth port on the digital board is redundant for this particular ADC/DAC testing application. Similarly, the digital board has sockets for expansion of the program memory of the DSP board, but this facility was not required during this program of study.

Test method

Two core programs for ADC testing were developed. A ground (0 Volts) input test providing a static input and a dynamic saw-tooth input test. Consequently, any changes in ADC performance between static and dynamic inputs under irradiation conditions could be observed. The ground input test yielded information about the magnitude and bin location of radiation induced transient upsets. The saw-tooth wave test provided similar data, although for a dynamic range of input voltages. In addition, the approximate time at which events occurred during the test was recorded during saw-tooth testing. This was in order to detect any dependence on fluence and to measure the distribution of events over time. The ADC converted value and expected ADC converted value were also recorded when saw-tooth input testing as well as a differential non-linearity histogram for the device.

During the ground input test the analogue to digital conversions were continuously recorded in an ADC output code histogram, (i.e. the number of ADC conversions versus ADC output code). All conversions recorded in bins of the output code histogram except the central bin of the distribution are the result of noise. Under control (un-irradiated) conditions the standard deviation of the ground input histograms for each of the AD676, AD7884 and AD7893 samples tested was consistently measured to be of the order of 1 Least Significant Bit (LSB). The standard deviation was 1.0±0.1bins for the AD676 and AD7884 sample devices and 0.9±0.5bins for the AD7893 samples. A typical ground test histogram recorded for the AD676 sample labeled 'B' before it was de-lidded or irradiated, (Figure 2) shows an offset of minus 2 bins from the true location (i.e. bin 0) for zero volts. An ADC has a nominal internal gain for its output range which can be adjusted using external potentiometers such that a ground input signal would produce a bin 0 output from the ADC. However for the purposes of this program of study it was desirable to keep the DUT daughter board circuits as simple as possible without any gain adjustments.

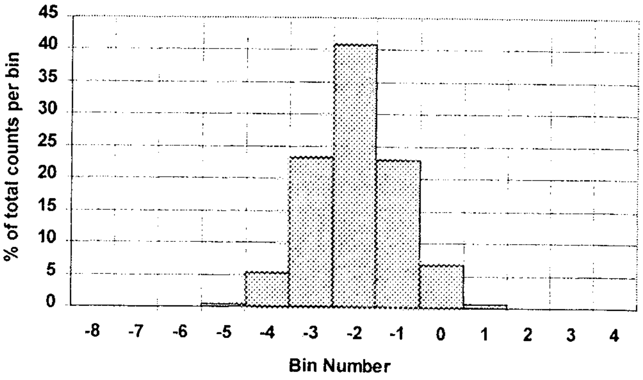

Figure 2 A ground input test histogram recorded under control conditions for the 16 bit self calibrating ADC; AD676. Two billion conversions were recorded in total.

The saw-tooth wave test recorded the number of conversions for each code of the ADC under test in a frequency histogram from zero to 2^N bits for an N-bit ADC, (Figure 3). This measurement yields the Differential Non Linearity, (DNL) of the device. DNL is a measure of the width of each code normalized relative to the ideal code width. If n_i is the number of conversions recorded for code i of the ADC and $\bar{n}$ is the mean number of counts per code;

$$DNL\,for\,code\,i = \frac{(n_i - \bar{n})}{\bar{n}}$$

The DNL for the ADC is defined as the maximum DNL recorded for all bins of the ADC under test. A DNL of -1 indicates a missing code, 0 DNL is the ideal output code bin width and a DNL of +1 indicates an output code bin is twice as wide as it should be.

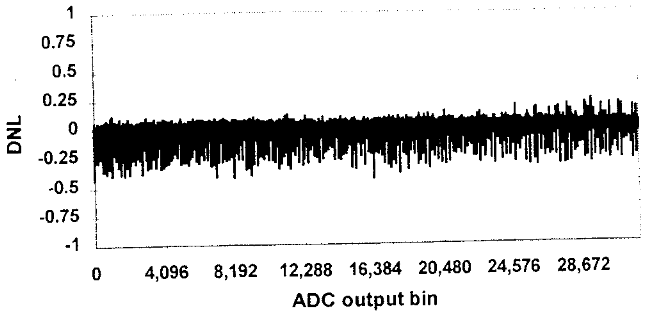

Figure 3 A DNL histogram recorded for the AD676 sample B under control conditions. Two billion conversions were recorded.

In addition to the DNL measurement the expected value of the next conversion of the ADC is calculated in real time and compared with the actual conversion result. Any significant deviation from the expected value is recorded for closer examination as a potential transient SEE event.

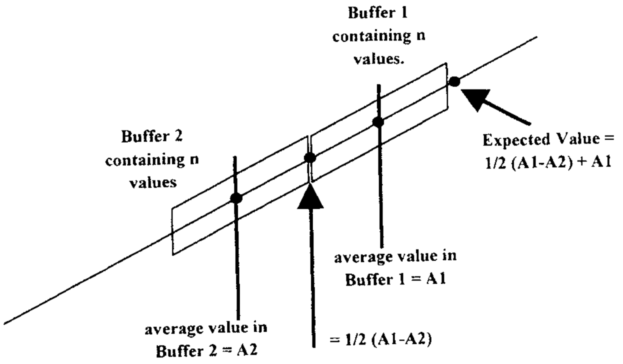

Figure 4 Calculation of the expected value during saw-tooth wave testing.

With reference to Figure 4:

$$\text{Expected Value} = \frac{1}{2}(A1 - A2) + A1 \qquad (1)$$

Where A1 and A2 are the average values in buffers 1 and 2. Equation 1 simplifies to:

$$\text{Expected Value} = \frac{\left(3 \times \sum_n \text{Buffer1}\right) - \sum_n \text{Buffer2}}{2n} \qquad (2)$$

The number of terms held in each of the two buffers, n, is set at 64 in the software code. By modeling possible inputs to the calculation, the value of 64 was found to be an optimum buffer length.

Each new conversion completed by the ADC under test is compared with the calculated expected value for the conversion. A second frequency histogram records the difference between the latest ADC conversion and its corresponding expected value (Figure 5). If the new conversion value differs from the expected value by more than ±15 units, it is recorded as a possible SEE induced transient upset event. The value of the ADC's conversion, the expected value and the location of the conversion during the testing procedure are all separately recorded. A flow chart for the saw-tooth input test software is given in Figure 6.

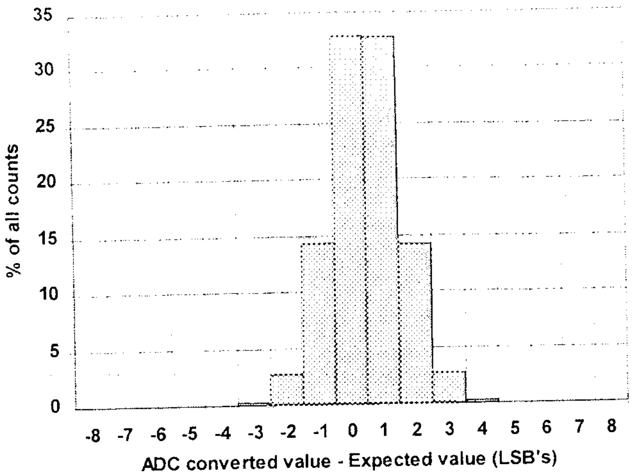

Figure 5 A frequency histogram for the difference between the expected and actual ADC conversion value for the AD676. Two billion conversions were recorded under control conditions.

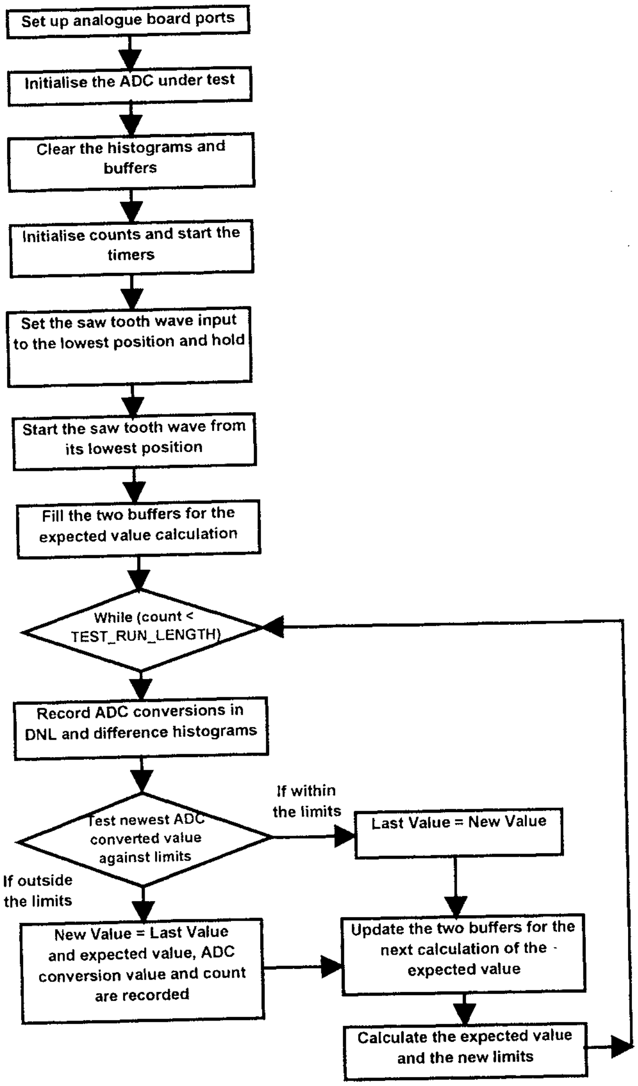

Figure 6 A flowchart for the saw-tooth wave input test software. "New Value" is the latest ADC converted value introduced to the expected value calculation. "Last Value" is the previous ADC converted value introduced to the expected value calculation.

Table 1 A summary of the devices tested. All the devices are manufactured by Analog Devices Inc.

ADC	Technology	Architecture
AD676AD 16 Bits	Digital control die: Analog Devices' DSP CMOS process Analogue die: Bi-MOS II	Parallel interface, successive approximation, 10μs conversion time.
AD7884AQ 16 Bits	LC^{2}MOS	Parallel flash, 5.3μs conversion time.
AD7893SQ-10 12 Bits	CMOS(LC^{2}MOS)	Serial interface, successive approximation, 5.5μs conversion time.

III. RESULTS

The AD7893 and AD7884 have not been previously tested as far as the authors are aware. Results for the AD676 have been reported in reference [3]. The AD676 is a parallel output version of the AD677. The results of testing the AD677 for SEE is reported in reference [4].

A. The 16 bit AD676AD

As might be expected, the relatively complex self calibrating 16 bit AD676 was the most susceptible device of those tested to SEE. This device package contains two die; one is an analogue circuit and the other a digital circuit. AD676 performance is optimized by correction of internal non-linearity by the digital die auto-calibration circuit which applies a correction factor to the ADC output from the digital die RAM. Data was collected for whole AD676 die irradiation and for isolated irradiation of the digital and analogue circuits.

Whole AD676 die irradiation

Figure 7 illustrates a set of ground input histogram data all obtained for the same AD676 device, labeled sample "B." The first graph in the series is an ADC conversion output histogram recorded under control conditions, displayed on the same scale as the histograms recorded under radiation conditions for convenient comparison. (Only the central bins of the output histogram are shown. The histogram actually spans from bin -32,768 to +32,768). The effects of radiation upon the AD676 are quite apparent. In one case (radiation #3) a possible bit flip has occurred, displacing almost the whole body of the histogram along the positive x axis (for all of the remaining duration of the test until an ADC calibration cycle is initiated). This type of "lingering error" has previously been observed by Wilson and Dorn [4] and Turflinger [5].

Three saw-tooth input radiation tests were carried out on the AD676. The first of these tests terminated after approximately 4.5 minutes; the anticipated test duration being 15 minutes. Figure 8 shows a graph of the difference between the ADC converted value and the expected value, versus count for this first saw-tooth test. "Count" is a running tally of the number of ADC conversions completed during the test. The graph shows how the difference between the ADC converted value and the expected value fluctuates, (because of transient events) until the test fails after approximately 13.4 million conversions. At this point the ADC became jammed, repeatedly converting the same value. This is another symptom of the "lingering error" observed by Wilson and Dorn [4] in the AD677. The first lingering error resulted in the early termination of the test.

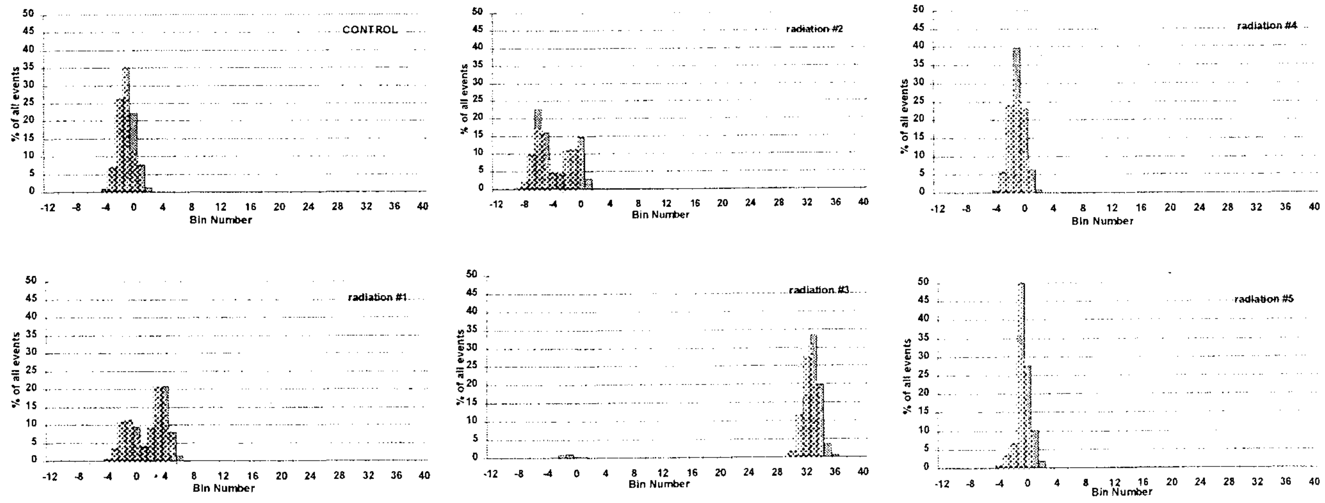

Figure 7 A selection of ground input histograms for the AD676. All tests illustrated are 15 minutes in duration under a flux of 3.4×10^3 particles/cm^2/min, except radiation #5 which is 60 minutes duration and flux 0.9×10^3 particles/cm^2/min. The whole of the AD676 was exposed to the source.

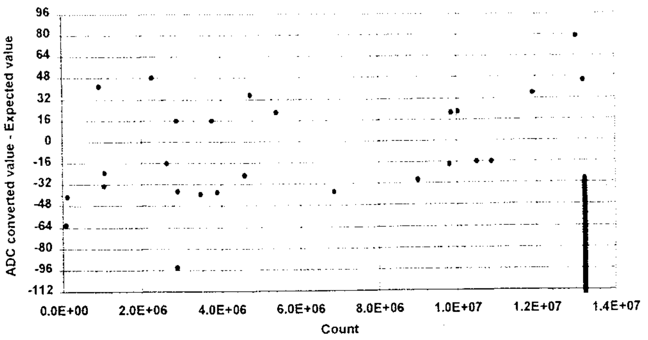

Figure 8 Transient noise events recorded for the first whole die irradiation of the AD676 sample B, using a saw-tooth input. The estimated fluence reached at the time of failure was $15.1\mathrm{x}10^3$ particles/cm^2.

No DNL data was recorded for the first saw-tooth test because of the lingering error. The DNL histogram recorded during the second saw-tooth input radiation test (Figure 9) had two bins with significantly larger values of DNL than the other bins of the ADC. Bin 16,383 (lying on the threshold between bit 13 and 14) had a DNL of 3.25, indicating that this bin was just over three times wider than ideal. Bin 49,151 (a combination of bits 14 and 15) had a DNL of 3.96, meaning that this bin was almost five times wider than it should have been. All the other bins have a DNL within the range -0.6 to +0.2.

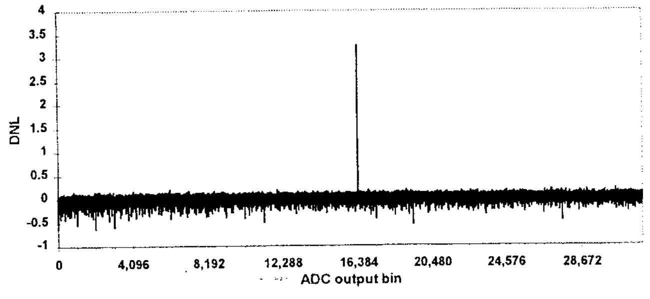

Figure 9 The DNL plot recorded for the second whole AD676 die irradiation with ^{252}Cf. The fluence reached was $50.3\mathrm{x}10^3$ particles/cm^2 during the 15 minute test.

The DNL histogram recorded during the third irradiation of the whole AD676 die, (Figure 10) had 127 bins that had a value of DNL greater than 1.0. Of these 127 bins, all were roughly three to five times wider than the ideal and occurred at intervals of every 512 bins. No missing codes were observed in any AD676 whole die irradiation data.

Figure 11 shows the difference histogram recorded during the third whole AD676 die irradiation test, which illustrates the effect of bit 3 of the ADC flipping during the test.

The SEU cross section for transient noise events greater than ±4bits measured for whole die irradiation of the AD676 with the ^{252}Cf source, using a ground input test signal was measured to be $(1.7\pm0.2)\mathrm{x}10^{-3}$ cm^2/device. Similarly, the SEU cross section for transient noise events greater than ±4bits measured with a saw-tooth input was $(1.6\pm0.2)\mathrm{x}10^{-3}$ cm^2/device. Lingering errors were also observed during subsequent heavy ion tests carried out at the cyclotron facility, where it was possible to separate two SEU cross section values for transient and lingering errors. This data will be published at a later date.

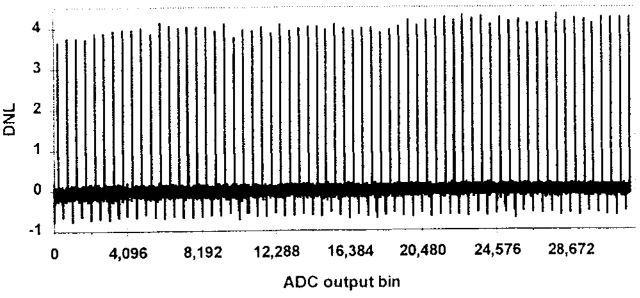

Figure 10 The DNL plot recorded for the third whole AD676 die irradiation with ^{252}Cf. The fluence reached was $50.3\mathrm{x}10^3$ particles/cm^2 during the 15 minute test.

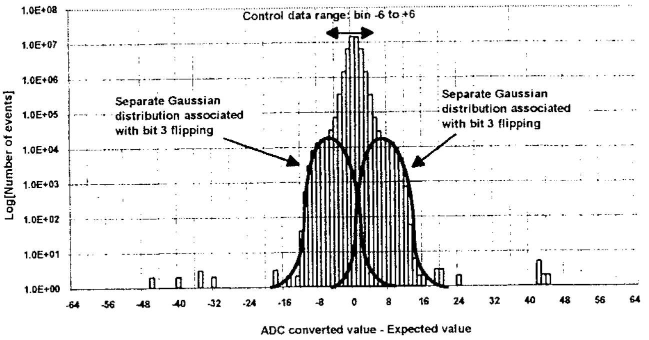

Figure 11 The difference histogram recorded for the third irradiation of the whole AD676 die with ^{252}Cf. The control data for this device all occurred between bins ±6 of the histogram. During this test it seems that bit 3 has flipped. Hence the two separate distributions centred about bin -8 and the other at bin +8.

Digital AD676 die irradiation

Four irradiation tests were carried out using ^{252}Cf ions incident on the digital circuit using a saw-tooth input as a test signal. The first two radiation runs terminated prior to the anticipated 15 minute test duration in the same way that was observed in the whole die irradiation tests following a lingering error. Consequently no DNL data was recorded for the first two irradiations.

The third irradiation test carried out on the digital die was deliberately stopped prematurely after only 2 minutes in the hope of observing the early signs of test failure. However, no transient events or bins with unusual values of DNL were observed.

The fourth radiation test ran without failure or interruption for a full 15 minute period. This was the only radiation run for the digital die where any transient events were observed and therefore a single event upset cross section could be calculated for the digital die. The SEU cross section for transient noise events greater than ±4bits, measured from this single set of data was measured to be $(2.0\pm2.0)\mathrm{x}10^{-5}$cm^2/device. Although 244 transient events were observed outside bins -5 to +6, no events of any great magnitude were recorded. The greatest difference between the ADC converted value and the expected value was only -18 bins. The DNL histogram recorded during this fourth irradiation test is shown in Figure 12. The number of bins with DNL greater than 1.0 per bit occurred at intervals of every 256 bins. The incident ^{252}Cf heavy ion fragments are clearly having an effect upon the DNL of individual bins of the device.

The data collected during the four digital die irradiation tests was not very conducive to establishing a reliable transient noise SEU cross section value for the chip. The first two tests terminated prematurely due to the effect of a single lingering error. The third test was deliberately halted early, but no upset events had occurred. The fourth test recorded only transient noise events of small magnitude. These results imply that the digital chip is more prone to lingering errors, rather than transient noise events of significant magnitude. However, a single lingering error is able to halt any further conversions made by the AD676, unless a re-calibration of the device is initiated.

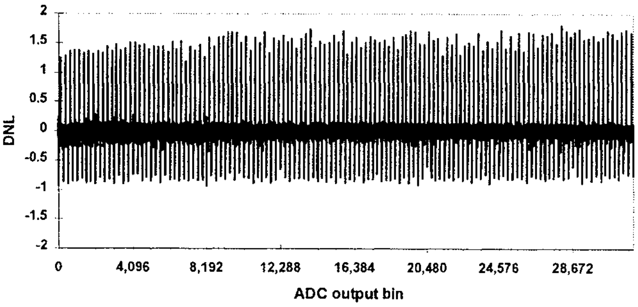

Figure 12 The DNL histogram recorded during the fourth isolated irradiation of the digital die on board the AD676. The test duration was 15 minutes under an incident flux of 3.4x10^3 particles/cm^2/min. A transient upset event has occurred which gives a large DNL value every 256th code.

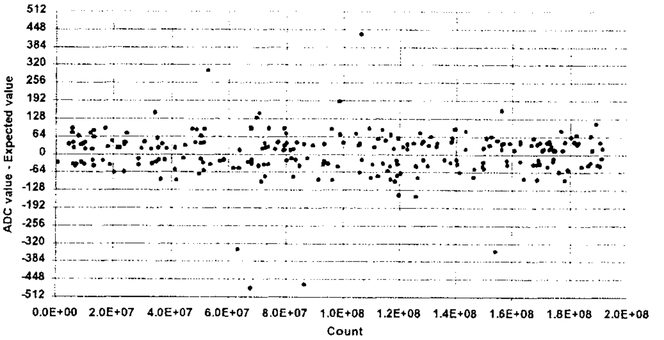

Figure 13 The transient upset events observed during the first isolated irradiation of the analogue die of the AD676 sample B using ^{252}Cf ions. The test duration was 65 minutes and the fluence reached was 0.2x10^6 particles/cm^2.

Analogue AD676 die irradiation

The analogue die of the AD676 was tested using a dynamic saw-tooth input test. Static testing was not carried out using ^{252}Cf. Of the data collected during the two irradiations of the analogue die with ^{252}Cf ions, neither demonstrated any of the alterations in individual bin DNL observed while the digital die was exposed to the ^{252}Cf source. No bins were observed to have a DNL which extended beyond the range of ±1.0, although transient noise events were observed. The SEU cross section for transient noise events greater than ±4bits was measured to be (1.5±0.2x10^{-3}) cm^2/device for irradiation of the analogue die alone. This value is consistent with that measured for the whole AD676 die.

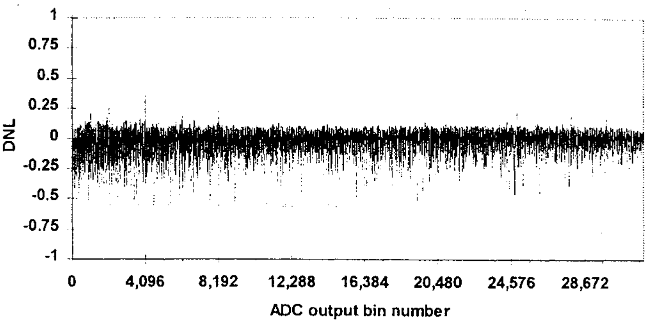

Figure 14 The DNL histogram recorded during the first isolated irradiation of the analogue die of the AD676 sample B under irradiation with ^{252}Cf ions. The test duration was 65 minutes and the fluence reached was 0.2x10^6 particles/cm^2.

B. The 16 bit AD7884AQ

The data collected for the 16 bit AD7884 indicated that the single event up-set cross section for transient noise events was of the order of 5x10^{-3}cm^2/device. Two AD7884 samples were tested which were designated A and B. The date codes indicated that samples A and B were from different manufactured batches. The mean transient noise SEU cross section measured for all irradiation tests carried out on sample A with ^{252}Cf was (6.1±0.4)x10^{-3}cm^2/device. Similarly for sample B the mean measured transient noise SEU cross section was (4.0±0.3)x10^{-3}cm^2/device.

Figures 15, 16 and 17 illustrate some of the saw-tooth input test data recorded for the AD7884 sample B. The DNL of the device was not observed to be affected by the presence of the ^{252}Cf source.

Figure 21 to 21 illustrates a set of ground input histograms recorded for the AD7884 sample A. In this case the number of events per ADC output bin has been plotted on a logarithmic scale. The incident flux was 3.4x10^3 particles/cm^2/min. Transient upset events under irradiation conditions can clearly be seen to occur some distance from the central distribution. No events of this magnitude were ever observed under control conditions.

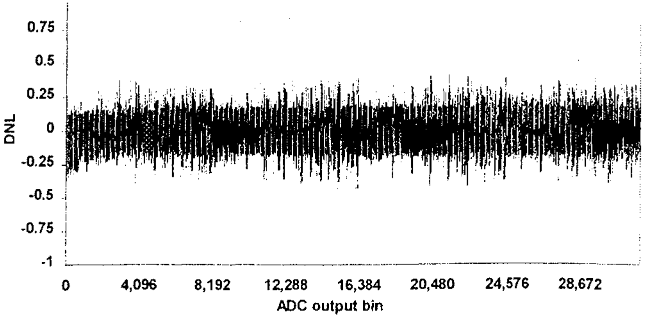

Figure 15 The DNL histogram recorded during irradiation of the AD7884, sample B. Test duration was 446 minutes with incident flux 3.4x10^3 particles/cm^2/min.

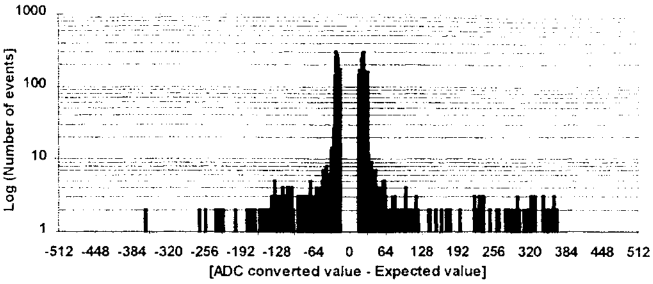

Figure 16 The difference histogram recorded for the 16 bit AD7884 sample B. The test duration was 446 minutes and the flux $3.4x10^3$ particles/cm^2/min. The central bins of the difference histogram indicated events within the normal noise distribution of ADC conversion and so were not recorded due to the memory capacity constraints of the test equipment. Hence the gap in the center of the difference histogram plot.

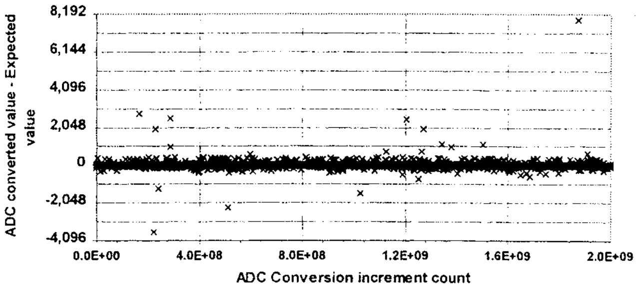

Figure 17 A plot of the difference between the ADC converted value and the expected value versus ADC conversion increment count for the 16 bit AD7884 sample B. The test duration was 446 minutes and the flux $3.4x10^3$ particles/cm^2/min.

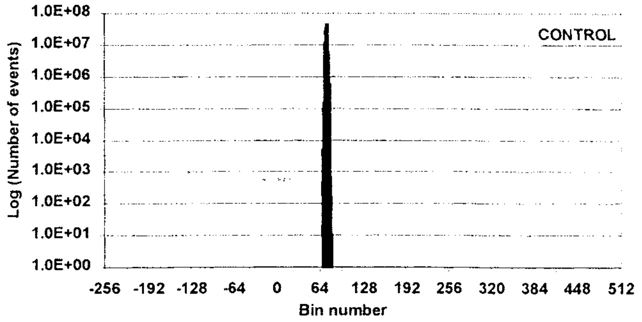

Figure 18 Ground input test data recorded under control (un-irradiated) conditions for the 16 bit ADC AD7884 sample A. (Note logarithmic scale here).

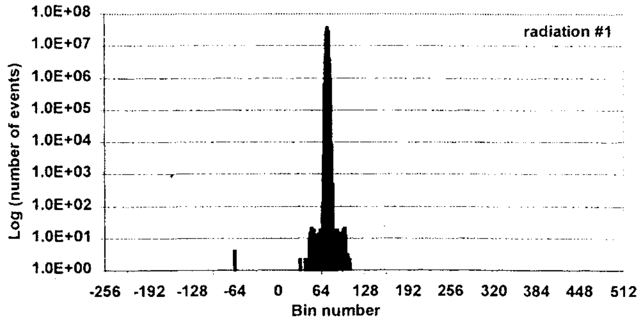

Figure 19 Ground input test data for the 16 bit ADC AD7884 sample A. (Note logarithmic scale here). The test was 15 minutes in duration and the incident flux was $3.3x10^3$ particles/cm^2/min.

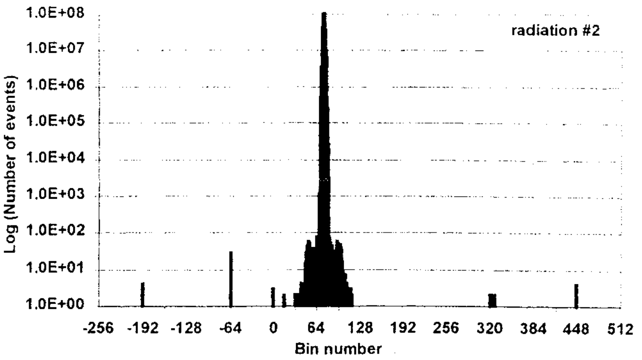

Figure 20 Ground input test data for the 16 bit ADC AD7884 sample A. (Note logarithmic scale here). The test was 60 minutes in duration and the incident flux was $3.3x10^3$ particles/cm^2/min.

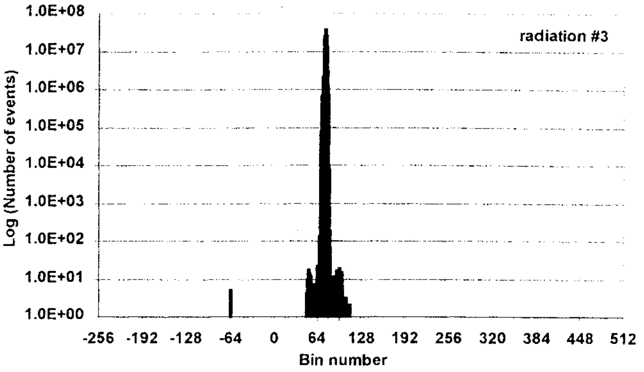

Figure 21 Ground input test data for the 16 bit ADC AD7884 sample A. (Note logarithmic scale here). The test was 15 minutes in duration and the incident flux was $3.3x10^3$ particles/cm^2/min.

C. The 12 bit AD7893SQ-10

The 12 bit AD7893 was the least susceptible to transient up-sets and the measured single event device cross section was low at approximately $(4\pm2)x10^{-6}$cm^2/device. Only one AD7893 sample was tested.

Under ground input irradiation testing, no SEU events were observed during five separate tests carried out to a fluence of $50.3x10^3$ particles/cm^2. One event was observed during a single test where the fluence reached $6.6x10^3$ particles/cm^2. The greatest fluence reached was $9.5x10^6$ particles/cm^2 during a 15 hour long saw-tooth input test where only 28 transient noise SEU events occurred out of the nearly 2 billion conversions recorded. The DNL of the device was not observed to be affected by the presence of the ^{252}Cf source.

IV. CONCLUSION

The conversion rates of the three ADC types which were tested were not observed to alter significantly under ^{252}Cf irradiation. At a system level, the lingering errors observed in AD676 performance could result in unexpected output level shifts under static d.c. input operation, or changes in the DNL of certain output codes of the device unless a re-calibration of the AD676 die was regularly initiated. Disruption of the DNL of the device was not observed during isolated irradiation of the analogue die. This indicates that SEU events occurring in the digital die are responsible for serious disruption of the DNL of individual output codes of the AD676.

The SEU cross section measurements made with ^{252}Cf for the AD676 were in reasonable agreement with the saturation cross section value, 1.1x10^{-4}cm^2 at an LET of 20MeV cm^2/mg for irradiation of the whole AD676, observed by LaBel et al [3]. LaBel observed single event latch-up in the AD676 at an LET of 25MeV cm^2/mg. Despite the higher surface LET of ^{252}Cf ions in silicon, latch-up did not occur while irradiating the AD676 during this test program. This may have been a consequence of the rapidly decreasing effective LET of ^{252}Cf in silicon perhaps in conjunction with small variations in the depth of sensitive volumes within the AD676 between different manufactured batches of device samples. The digital die of the AD676 was the most sensitive region to heavy ion induced lingering error events. This coincides with observations made by Wilson and Dorn [4] when irradiating analogue and digital regions of the AD677. Lingering errors were not observed in the AD7884 or AD7893 data.

Subsequent heavy ion testing using the CYCLONE irradiation facility at The Université Catholique de Louvain-la-Neuve, Belgium has allowed a threshold SEU cross section to be measured for each of the three ADC's. A more detailed characterization of each device under heavy ion irradiation was carried out. This work will be published at a later date.

V. ACKNOWLEDGMENTS

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VI. REFERENCES

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