TID Performance Degradation of High Precision, 16-bit Analog-to-Digital Converters

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Abstract

16-bit analog-to-digital (A/D) converters were evaluated for performance and linearity degradation due to the total dose induced shifts in the voltage reference. Test data and analysis of three A/D converters is presented.

Introduction

High-resolution analog-to-digital converters, mainly 16-bit and above, have been particularly difficult devices to test and qualify for space. In particular, the testing of these components is complicated by the challenge of electrically testing non-linearity as a function of total dose. Usually, the radiation performance of these parts is tied directly to the voltage reference, which, in turn, affects other parameters. Single event data on these parts is available in the literature [1][2][3][6]. We will discuss in this paper the issues of total dose testing several 16-bit A/D converters.

Production testers and their software code are designed to test certain parameters within set limits. Nonlinear responses to signals in test heads created apparent errors that did not show up on control parts. We found that a small degradation in certain parameters (primarily the voltage reference), while not necessarily out of specification, caused non-linearity failures in the measurements. We will discuss the particular challenge of measuring these precision analog-to-digital converters with radiation-induced drifts.

This paper will focus in particular on three 16-bit A/D converters: Maxwell's 5016RP (based on Crystal Semiconductor's CS5016B die) 7805ALPRP (based on Burr Brown's ADS7805 die with latchup protection circuitry) and 7809LPRP (based on Burr Brown's ADS7809 die with latchup protection circuitry). The 7805ALPRP and 7809LPRP have an internal voltage reference, while the 5016RP does not. Our results show that the TID performance is tied directly to the voltage reference, which in turn, affects the performance of other parameters, even when the voltage reference is functioning within specification.

Facilities

All testing was conducted at Maxwell's Co-60 room irradiator with dose rates between 0.01 rad(Si)/sec and 0.1 rad(Si)/sec. Electrical testing was performed at Maxwell using production testers described below.

TEST METHODOLOGY

Production tests for these parts utilized a combination of at least two testers for each device; the 5016RP used a LTS 2020 and TMT tester along with a bench test for dynamic parameters, the 7805ALPRP utilized a LTS 2020 and Trillium tester, while the 7809LPRP used a LTS2020 and the TMT tester. Initially, it appeared that changes in the voltage reference dramatically affected certain measurements including non-linearity. We decided to look into whether ranging of the production software was the cause of some of these unexpected failures. Additionally, since the internal voltage reference increased with TID, we looked at whether using an external voltage reference affected performance of the parts, as well as how changes in the voltage reference affected other parameters—specifically linearity measurements.

Linearity measurements were performed using a LTS 2020 tester. Integral non-linearity (INL) is measured using two D/A converters. The main D/A is used to generate a rough voltage, while the other D/A is used for fine adjustments. The two D/A's are used collectively to generate precise voltages to determine when LSB changes occur between adjacent codes on the output.

To measure INL, first the minimum and maximum end point voltages are determined and readings are taken at +/-3 codes around the major transitions and folded (MSB on) major transition points. For a 16-bit converter, there are 31 bit transition points, 15 with the MSB off and 16 points with the MSB on. Therefore, for a 16-bit converter, there are 217 (31 codes * 7) readings, minus off-scale and overlapping readings. Once this is done, a least squares, best-fit algorithm is used to establish a new ideal line with new end points. Readings are taken again at the points described above and the actual voltage is compared to the 'ideal' voltage at each code transition. Once the readings are taken, non-linearity measurements are calculated as the difference between the ideal line and the actual readings. This difference is expressed in +/- LSB's (least significant bit). In the case of a 16-bit ADC at 5V, each LSB represents 76.3 uV ($5V/2^{16}$).

INL is calculated as the deviation of a code on the actual (measured) curve from that code on the ideal line. Therefore, an ideal measurement for INL is 0 LSB. The equation for calculating INL is [Actual(code) – Ideal(code)]/LSB. The test system then reports the worst-case positive and negative INL along with the codes at which they occurred.

Differential non-linearity (DNL) is measured as the deviation of the voltages between adjacent code transitions as compared to the ideal. The ideal measurement is 1 LSB, which is 76.3 uV for a 16-bit ADC at 5V. The equation is:

[Actual(code)-Actual(code-1)]/LSB. The test system reports the worst-case delta between code and code-1 as DNL Short and DNL Long, along with the codes at which they occurred. DNL is measured +/-3 codes around the major transition and folded major transition points.

5016RP

Maxwell's 5016RP is a monolithic A/D converter that utilizes a successive approximation algorithm technique to convert analog signals into a digital output. The 5016RP also incorporates self-calibration circuitry that improves linearity with no missing codes. The 5016RP has both parallel and serial outputs and operates at low power (150 mW).

Previous total dose testing by JPL [4] on Crystal Semiconductor's CS5016B die indicated dose rate dependence of this device on TID performance. In particular, the 5016 die failed catastrophically at 4 krad(Si) from exposure to a high dose rate of 50 rad(Si)/s, but was able to recover after room temperature annealing. At lower dose rates of 0.005rad(Si)/s, INL started exceeding specifications at 25 krad(Si), however, the output buffer of the amplifier showed significant degradation already at 2 krad(Si)[4]. The 5016RP has internal error-correcting circuitry, along with microprocessor controlled operation. This circuitry helps the device minimize the large changes in the reference buffer output voltage.

Maxwell and Northrop Grumman performed a series of low dose rate (0.01 rad/sec) TID tests on the CS5016B die, lot number G010201F. The electrical testing was performed using Maxwell's LTS2020 and TMT tester for most parametric and functional tests, with an additional bench test to validate dynamic parameters. The LTS 2020 tested analog and digital current (IA+/-, ID+/-), IIH, IIL, VOL, VOH, IOZH, conversion time, Unipolar and Bipolar offset error and gain error, and +/- Integral non-linearity, while the TMT tested timing. The bench test tested for SINAD (signal to broadband noise) both for 1 and 12 kHz. The two parameters measured were SNR (signal-to-noise ratio) and PHN (peak harmonic noise). The parts were tested both biased and unbiased.

The first parameter to go out of specification of 1 LSB is positive integral non-linearity (INL) at around 9.5 krad(Si) shown in Figure 1. As can be seen by the variation in the graphed data, the variability in the test measurements is close to the actual 1 LSB specification, so this could be more from statistical variation in the data than from an actual increase in the non-linearity. The JPL test, which was done at a lower dose of 0.005 rad/sec, showed less degradation, in which INL started exceeding specification at 25 krad(Si). As expected, the parts that were unbiased after 4.3 krad(Si) have a lower degradation in linearity. The linearity is for the most part flat up to 12 krad(Si) and then shows significant degradation beyond 12 krad(Si). There is a spike in the graph at the 7 krad(Si) measurement due to a test board error that induced non-linearity's into the non-linearity measurement and noise in the signal to noise measurements (see Figures 2 and 3). The bench test measured two parameters: SNR and PHN at 1 and 12 kHz. Figures 2 and 3 show the measurements at 1 kHz.

Taking into account the noise spike at 7 krad(Si), the noise ratio appears to have a gradual degradation up to 10 krad(Si) and then degrades much more rapidly after 10 krad(Si). As can be seen by the figures, degradation of the parts continue when irradiated unbiased after 4.3 krad(Si). Additionally, there was little to no improvement from biased annealing. Unipolar and Bipolar offset gain started exceeding specification at around 15 krad(Si).

The 5016RP, as expected, degrades at a slower rate when unbiased. Comparing our data to JPL's TID test data at a dose rate of 0.005 rad(Si), it appears that dose rate plays a significant role in the performance of these parts.

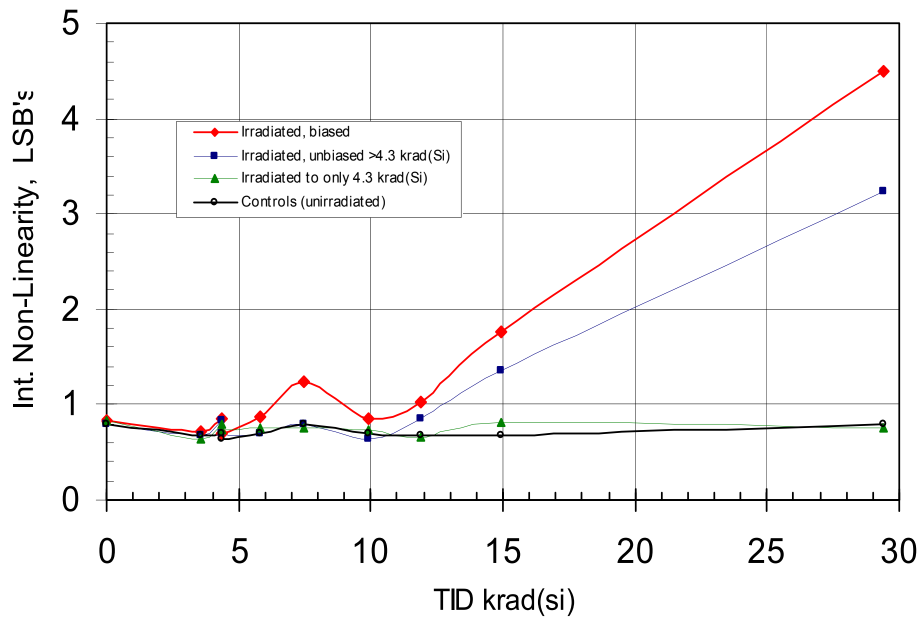

Figure 1. 5016RP positive Integral Non-Linearity, both biased and unbiased

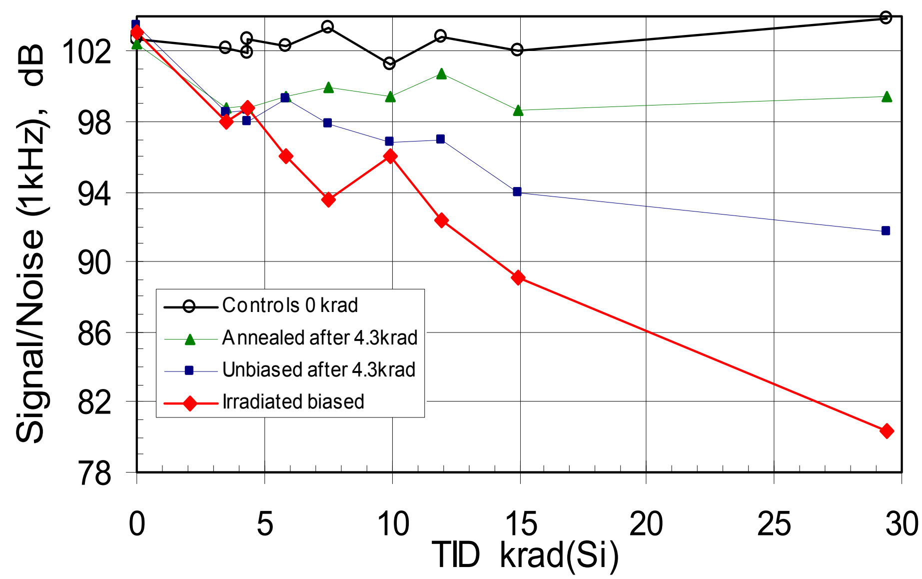

Figure 2. 5016RP PHN signal–to-noise ratio at 1 kHz as a function of TID.

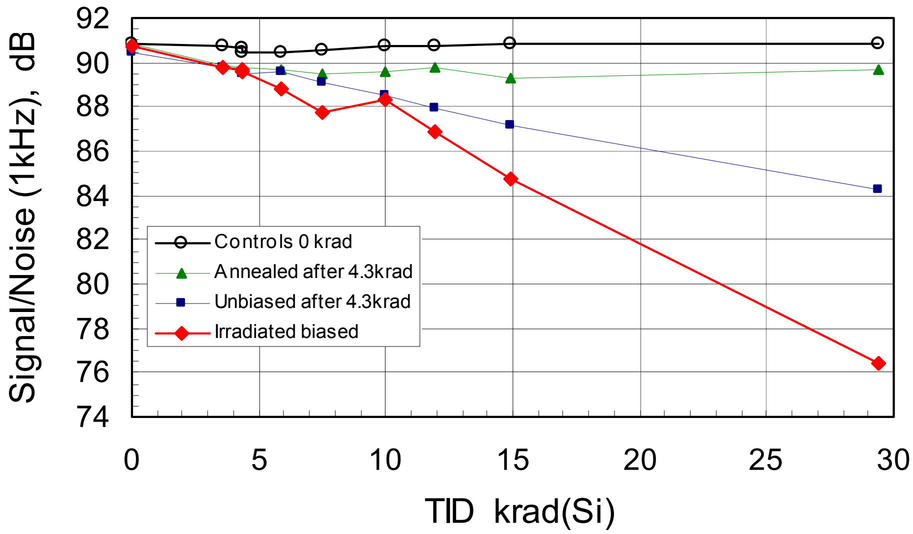

Figure 3. 5016RP SNR signal to noise ratio at 1 kHz, as a function of TID.

7805ALPRP

The 7805ALPRP from Maxwell is a 16-bit capacitor-based, successive approximation analog-to-digital converter with sample and hold, internal voltage reference, an interface for use with a microprocessor, an output synchronization pulse for use with DSP processors and three-state output drivers. Maxwell's 7805ALPRP is rated at 100 ksps and operates from a 5V power supply, dissipating 100mW.

Maxwell performed 3 TID tests on the 7805ALPRP; two at 0.01 rad(si)/sec and one at 15.7 rad(Si)/sec. Maxwell's tests showed that production range software created artificial errors due to nonlinear responses to TID induced changes. When these ranges were expanded, the linearity measurements were found to still be in specification and in some cases, the parameters didn't vary considerably from pre-radiation levels until well after the Vref parameter had exceeded specification. For some parameters, the production range software went out of specification prior to Vref exceeding specification.

The reference voltage increases linearly at a rate that is dependant on the dose rate. Figure 4 shows voltage reference curves for two different dose rates, one at 0.01 rad(Si)/sec and the other at 15.7 rad(Si)/sec. The 0.01 rad(Si) test has a drift slope of 0.0029 volts/rad, in comparison to the 15.7 rad(Si)/sec test that had a drift slope of 0.0037 volts/rad. Table 1 shows a comparison of the average voltage reference slope for three different dose rates. The voltage drift increases with increasing dose rate, so the typically lower dose rate space missions would see a reduced shift in voltage then found in these TID tests. Similar results were seen in an independent test conducted by Hirex [10]. In this test, a lower Vref initial offset brought the voltage reference out of specification later when compared to Maxwell's test, although the slope was similar.

Once the issue with the testers dependence on the shifts in the voltage reference was determined, we found that the DNL was not as dependent on the voltage reference as originally anticipated. As can be seen in Figure 5, DNL stays uniformly flat until somewhere around 15 krad(Si) and then starts taking off after 20 krad(Si), exceeding specification at approximately 25 krad(Si). Similar to DNL, INL started to degrade at 15 krad(Si), but at a lower rate and was still within specification at the last tested level of 24.4 krad(Si). As a comparison, the production software had measurements over an order of magnitude higher.

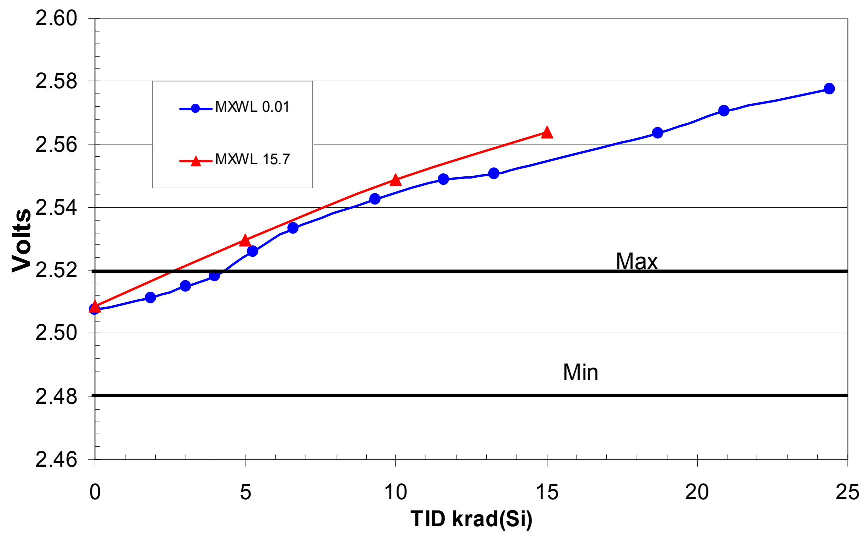

Figure 4. 7805 Voltage reference drift for two dose rates

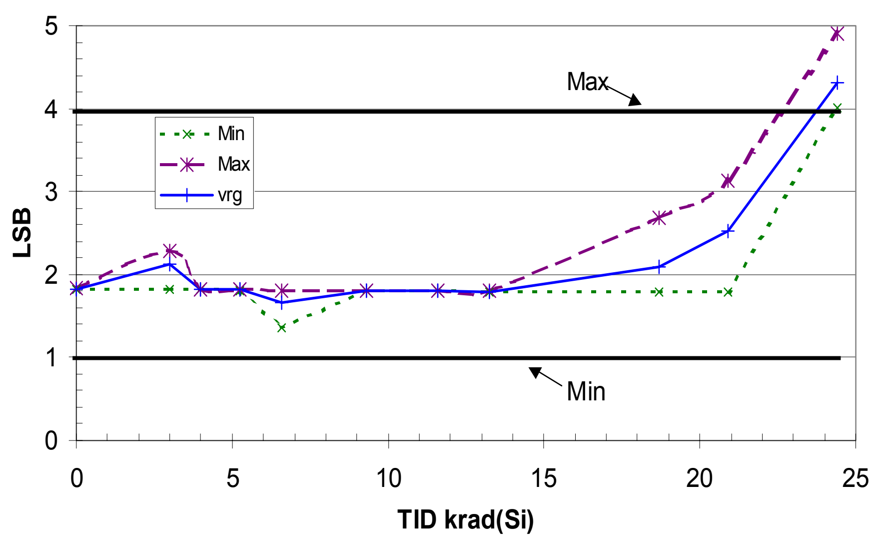

Figure 5. 7805ALPRP DNL as a function of TID.

Table 1: 7805ALPRP voltage reference shift over TID for several dose rates

Dose Rate (rad(Si)/sec	0.01	0.032	15.7
Voltage Drift volts/rad	0.0029	0.0032	0.0037

7809LPRP

Maxwell's 7809LPRP has a serial output in comparison to the parallel output for the 7805ALPRP. Like the 7805ALP, It is also a 16-bit capacitor-based, successive approximation analog-to-digital converter that incorporates a sample and hold, internal reference clock, and provides an output synchronization pulse for use with DSP processors. The 7809LPRP is specified to operate at 100 ksps.

The 7809LPRP alsohas an internal voltage reference. This causes certain parameters of the 7809LPRP (similar to the 7905ALPRP) to be more susceptible to total dose in comparison to the 5016RP. Several tests were performed on the 7809LPRP for the same die lot using production test software and extended range software. The tests were performed at dose rates of 0.01 and 0.033 rad(Si)/sec. Like the 7805ALP, it was found that the finer resolution used in the production software on the LTS2020 caused nonlinear results when TID induced changes caused some parameters to drift outside the specification range, especially for linearity measurements.

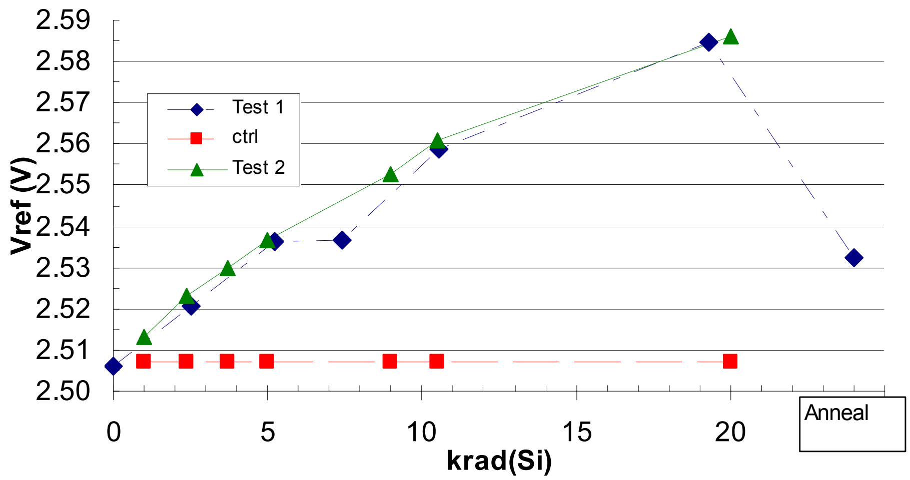

Figure 6. 7809LPRP Vref degradation with TID for 2 separate tests.

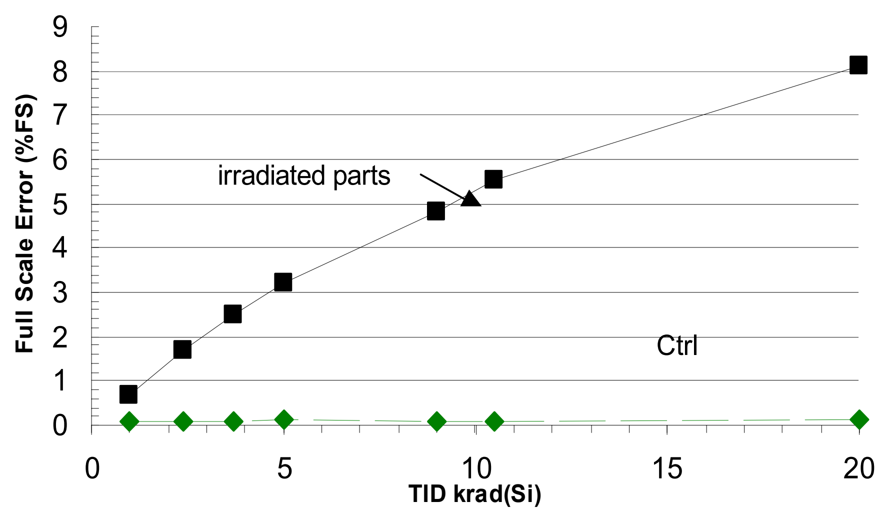

Figure 7. 7809LPRP Unipolar Full Scale Error TID degradation.

Figure 6 shows the internal Vref as a function of TID for two separate tests. The specification limits for VREF are 2.48 to 2.52 volts. The voltage reference is the first parameter to exceed specification. Except for one data point at 7.5 krad(Si) for test number 1, the degradation is consistent. As can be seen by the graph, the degradation is linear and the change in voltage starts almost immediately with total dose. It starts to drifts out of specification at 2.4 krad(Si). Unipolar full-scale error appears to change linearly along with the voltage reference, as can be seen in Figure 7. Bipolar error appears to similarly follow with the reference voltage with a uniform linear degradation.

Compare this to PSRR shown in Figure 8, which is reasonably flat until around 7 krad(Si) and then starts to rapidly drift around 8 krad(Si).

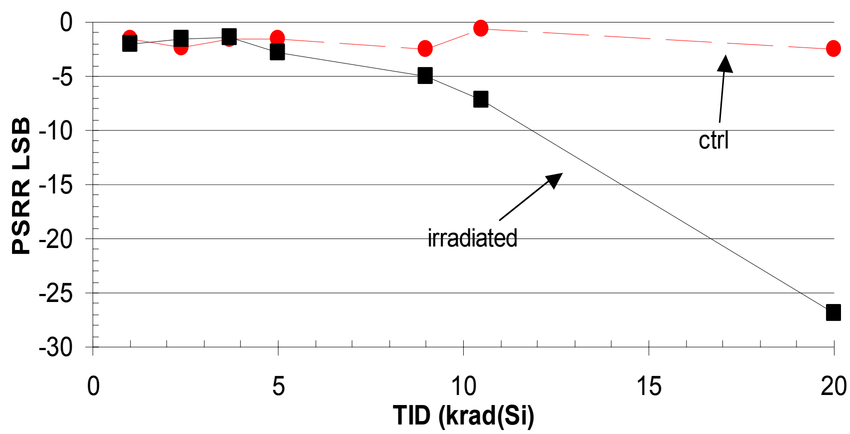

Figure 8. 7809LPRP PSRR degradation with TID.

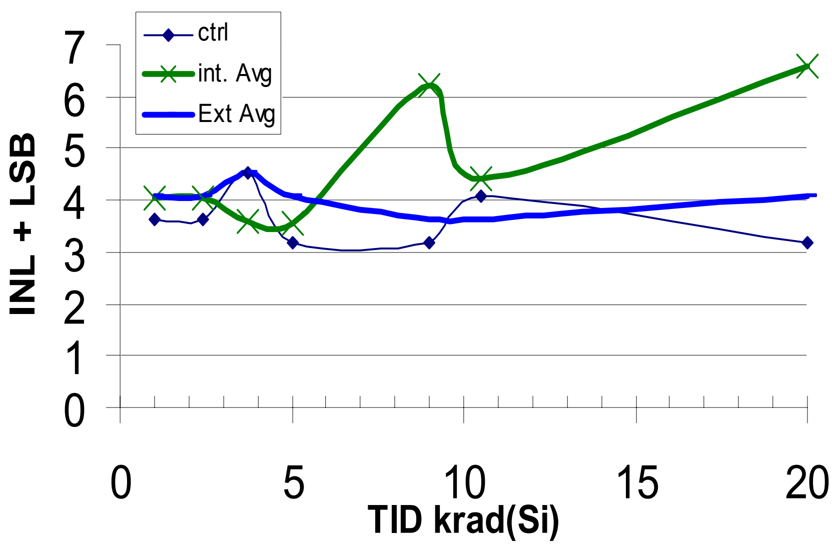

Figure 9. 7809LPRP INL+ using an internal (int. avg) and external (ext. avg.) voltage reference.

When an internal voltage was used, unipolar full-scale error and INL+, started exceeding specification at the first tested level of 1 krad(Si). When using an external voltage reference, INL + didn't exceed specification up to the highest level tested of 20 krad(Si). Figure 9 shows the two test measurements. The test data has significant variations especially with the internal voltage reference. Interestingly, INL- went out of specification between 5 and 9 krad(Si) when using an internal voltage reference and between 10.5 and 20 krad(Si) when using an external voltage reference. As a result, it appears that INL- is less dependant to changes in the voltage reference then INL+, but more susceptible to degradation associated with TID.

Discussion

The degradation from TID in the internal voltage reference for both the 7805ALPRP and 7809LPRP appears to be linear and dose rate dependent. However, the test equipment is also effected by the drift in Vref. Once the voltage reference was isolated by measuring the parameters with internal and external voltage references and the software ranges were extended, we were able to measure the effects of TID on non-linearity measurements. We found that non-linearity does not change linearly with Vref. For all three parts, the linearity measurements shown in Figures 1, 5 and 9 have little to no degradation until around 12 to 15 krad(Si), at which point all three start diminishing non-linearly.

One of many potential causes of the TID induced non- linearity degradation could be tied to the response of the op amps in the device. Since the gain error is correlated to the voltage reference, the changes in the voltage reference also shift the gain error such that op amps in the device may go out of their linear response range. The 5016RP signal-to-noise response appears to show a similar change in the rate of the response around the same level as the non-linearity in the 7805ALPRP and the 7809LPRP. It appears that there is some inherent design limitations in these devices, which are manufactured by different vendors, that occur at the 10 to 15 krad(Si) level.

Dose rate data taken by JPL [4][9] and Maxwell suggests that the level in which these non-linear shifts will occur varies with dose rate. Since most space applications have dose rates considerably lower than 0.01 rad(Si), the point where the linear shift occurs appears to be at a higher TID level at lower dose rates.

SUMMARY

The 16-bit A/D converters studied here have similar TID susceptibilities despite their different design and functionality. The non-linearity response of these A/D converters does not directly correlate to the change in the voltage reference. It appears a certain amount of voltage reference change is required before the non-linearity measurements start drifting. This has been seen before in other high-resolution A/D converters [7][8]. Maintaining a clear understanding of the expected responses and ranging of the testers is important to obtaining accurate data. Because of their total dose degradation and single event susceptibility, these devices require comprehensive testing and mission specific modeling to be used effectively in a space environment.

References

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