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Radiation Behavior and Test Specifics of A-D and D-A Converters

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Abstract: ADC/DAC radiation failures are mainly due to radiation-induced degradation of precision parameters of the transfer characteristic such as gain, zero offset, full-scale voltage, integral and differential non-linearity, conversion error. ADC/DAC radiation failure specifics is that even a slight deviation of electrical parameter of internal elements (comparator threshold, internal reference voltage, switch leakage, operational amplifier gain, etc.) often leads to significant degradation of ADC/DAC accuracy. ADC/DAC radiation test procedure and facilities are developed and test results are introduced.

Keywords: analog-to -digital converter (ADC); digital-to-analog converter (DAC); radiation; test technique

Sevalno obnašanje in testne posebnosti A-D in D-A pretvornikov

Izvleček: ADC/DAC sevalne napake so običajno posledica radiacijsko pogojenega staranja natančnosti parametrov prenosnih karakteristik, kot je ojačenje, ničelni odmik, polna napetost, linearna in diferencialna linearnost in napaka pretvarjanja. Posebnost ADC/DAC sevalnih napak je, da že majhna sprememba električnih lastnosti elementov (prag primerjalnika, interna referenčna napetost, uhajanje preklopnika, ojačenje…) v veliki meri vpliva na degradacijo natančnosti pretvornika. Predstavljeni so razviti postopki testiranja in rezultati meritev.

Ključne besede: analogni digitalen pretvornik (ADC); digitalno analogen pretvornik (DAC); sevanje; tehnike testiranja

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1 Introduction

Analog-to-digital and digital-to-analog converters (ADC and DAC) are widely used in space, collider physics, avionics, nuclear power plants, etc. applications, being the essential parts of data pre-processing and control units. Therefore important issues are to analyze radiation behavior particularities and to develop informative radiation test procedures and technique to estimate ADCs and DACs radiation sensitive parameters and characteristics degradation [1], [2].

The most radiation sensitive feature of ADCs and DACs is accuracy which is determined by the transfer characteristic parameters of such as gain, zero offset, full-scale voltage, integral and differential non-linearity, conversion error. ADC and DAC radiation failure specifics as compared with digital integrated circuits (ICs) is that even a slight deviation of a parameter (comparator threshold, internal reference voltage, switch leakage, operational amplifier gain, etc.) often leads to significant degradation of ADC/DAC accuracy [3].

Total ionizing dose (TID) accumulation in ADC and DAC results in continuous degradation of static and dynamic conversion parameters, while transient irradiation (gamma flesh or single charged particles) may result in ADC output code failures or in DAC output voltage transients. The radiation behavior of various ADCs and DACs is rather complicated and significantly depends on the particular IC architecture and on the bias and operation conditions during irradiation and testing. This should be considered in development of ADC/DAC radiation tests techniques and facilities.

A lot of radiation tests of various ADC and DAC were carried out in the MEPhI-SPELS radiation test laboratory (Moscow, Russia) [4]. The analysis of test data demonstrates the critical importance of ADCs and DACs functional tests as compared to other IC groups. ICs dominant failure types (parametric or functional) statistics from our test experience is presented in Fig. 1. One can see the essential prevalence of parametric TID failures for simple logic while other (complex) ICs are characterized by subsequent or even dominant functional failures [5], and ADC/DAC ICs are the leaders.

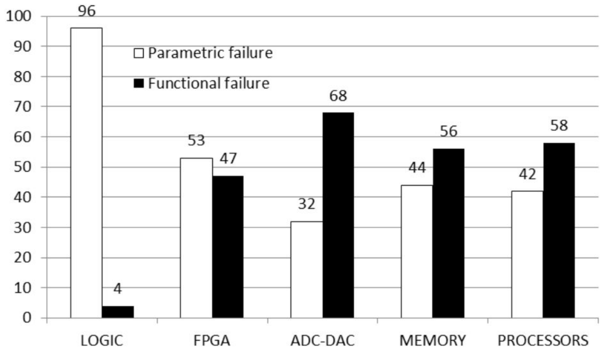


Figure 1: Relative part (%) of parametric and functional radiation failures for different ICs classes

Variety of hardware and software solutions has been developed to provide reliable and informative testing of different ADC/DAC ICs directly under irradiation within -60…+125 C temperature range. The system implements both operational modes under irradiation assignment and monitoring of the entire set of static and dynamic parameters which characterize ADC/DAC radiation hardness. We present the structure, the operation principles and the basic technical specifications of the system in this paper.

The used set of original compact radiation test basic facilities is introduced ([2], [4], [6]) including Co-60 and Cs-137 isotopic gamma-sources, electron linear accelerator, flash X-ray machine – all with minimum possible signal cables length (about 1 m only). The used ions cyclotron (in Dubna) and high energy proton synchrocyclotron (in Gatchina) were rather traditional. And we widely used laser and X-ray simulators which give us the unique possibility to measure all ADC/DAC informative parameters and characteristics.

The paper also contains numerous test results of ADCs and DACs which designed by various manufacturers by using various architectures and technologies. We concentrate on TID effects, single event effects (SEE), and transient radiation effects (TRE). The data presented is mostly experimental – the theory of ADC/DAC radiation effects is well known and has been widely presented [7]-[9]. The purpose of this paper is to demonstrate the variety of these effects. We present here the most typical results, which cause the specific ADC-DAC radiation test technique development.

2 Total ionizing dose effects

The typical TID effect in ADC and DAC is transfer function (TF) degradation and the associated degradation of a converter precision parameters (DAC TF – dependence of output voltage/current vs. input code, ADC TF – dependence of output code vs. input voltage). For example, in Fig. 2 TFs of ADC (Fig. 2a) and DAC (Fig. 2b) within the Data Acquisition System (DAS) ADuC812BS (Analog Devices) at different TID values is presented. Fig. 3 shows the TF degradation of ADC AD1671SQ/883B (Analog Devices) with TID accumulation. One can see that TF degradation can be gradual and smooth or sharp and abrupt [10].

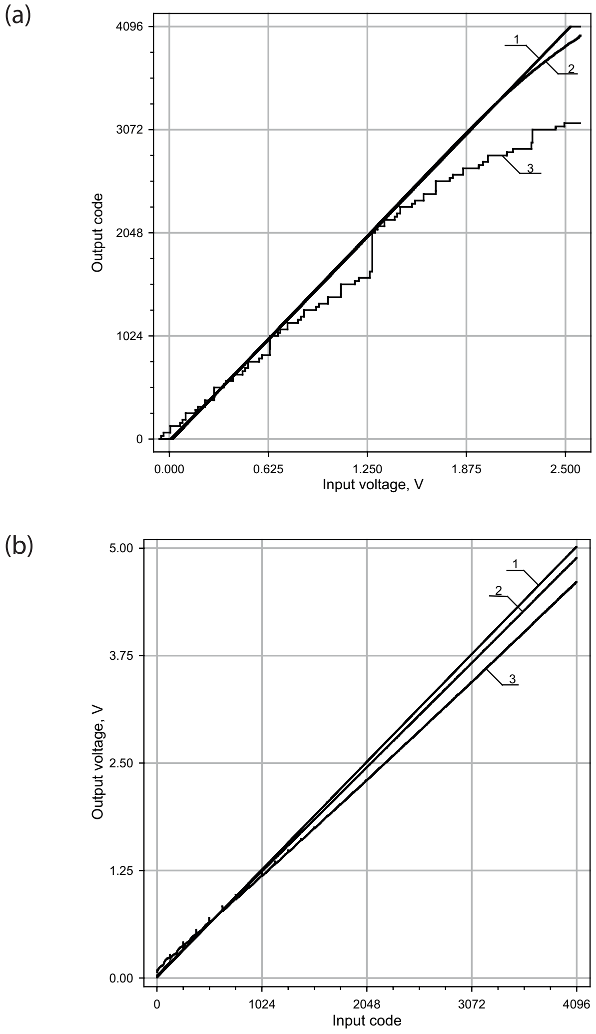


Figure 2: ADC (a) and DAC (b) within the DAS ADuC812BS – TFs at different TID values: 1 – initial, 2 – 12 krad(Si), 3 – 16 krad(Si)

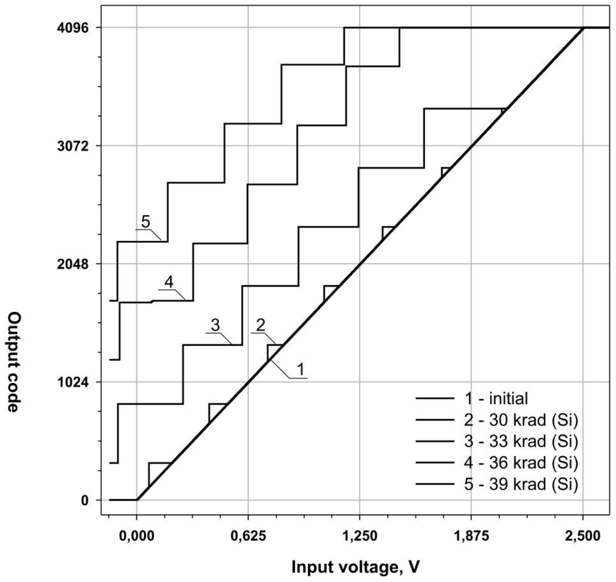


Figure 3: ADC AD1671SQ/883B TF degradation with TID accumulation

ADC/DAC TF degradation results in their accuracy parameters degradation – integral nonlinearity (INL), differential nonlinearity (DNL), offset and gain errors. INL is the measure of the deviation values on the actual TF from a straight line. DNL is the difference between an actual step width (for an ADC) or step height (for a DAC) and the ideal value of 1 least significant bit (LSB). Offset error is defined as the difference between the nominal and actual offset points when the digital output (for an ADC) or digital input (for a DAC) is zero. Gain error is defined as the difference between the nominal and actual gain points on TF when the digital output (for an ADC) or digital input (for a DAC) is full scale [11]. As an example, a number of INL and DNL TID-dependencies of DAC within ADuC812BS is shown in Fig. 4. The curves are plotted for several irradiated samples and correspond to average TF changes which are presented in Fig. 2b [12].

It is important to mention that not only the maximum values of ADC/DAC accuracy parameters degrade under irradiation, but the dependencies of these parameters vs. input or output signals (codes) vary too. For example, the dependencies of INL and DNL of ADC PV2 are presented in Fig. 5 and 6 respectively. The different TID behavior of these two parameters may be noted. In the INL graphs there is a rise of "teeth" and general distortion increase (bending). At the same time, the degradation of DNL appears as increase of the spikes amplitude at certain ADC output code. The values of DNL for the rest of the codes do not increase practically [3].

Thus, to determine the radiation behavior of ADCs and DACs with TID accumulation, a set of TFs should be recorded during irradiation, which is used to calculate TID dependencies of a converter accuracy parameters.

It should be noted that such "standard" analog and digital parameters of converters as supply current, output voltage, maximum operating frequency etc. also changes under irradiation. However, ADCs and DACs have no specifics when compared with other functional classes of ICs both in these parameters degradation and in their control procedures during testing. Therefore this is not the issue of this paper.

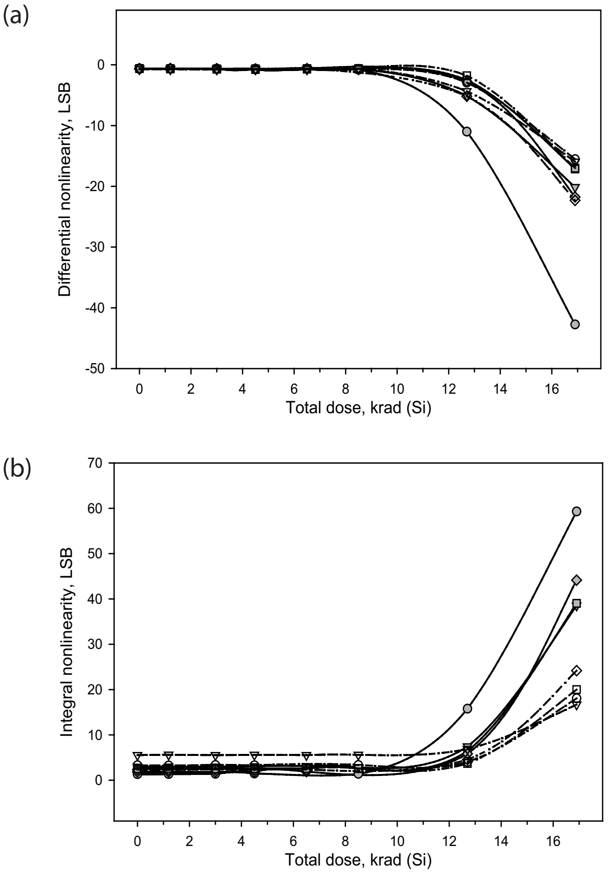
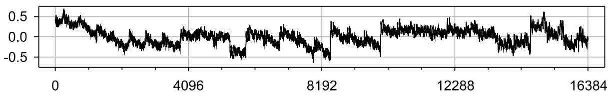


Figure 4: TID dependencies of DAC within ADuC812BS samples DNL (a) and INL (b)

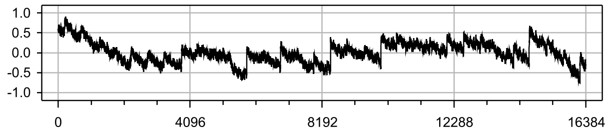
ADC output code on X-axes and DNL (in units of LSB) on Y-axes

3 Single event effects

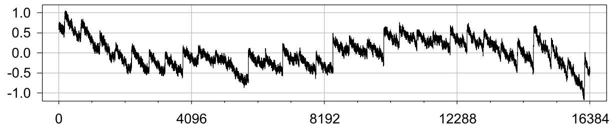
Single event effects (SEE) due to single nuclear particles (such as heavy ions and protons) may result in either failures (latch-up, burn-out and so on) or single event upsets (SEU). Failures, as well as the experimental methods of their detection are well known and presented in a large number of publications [13], [14].



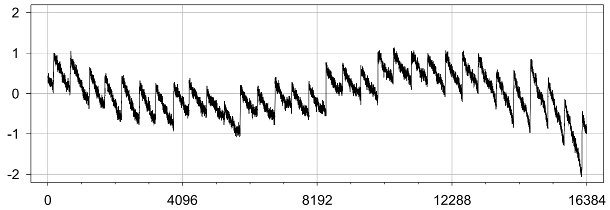
initial



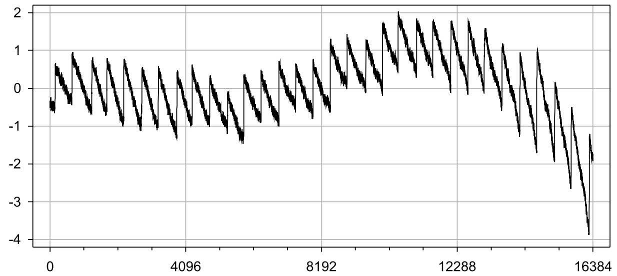
84 krad (Si)



120 krad (Si)



160 krad (Si)



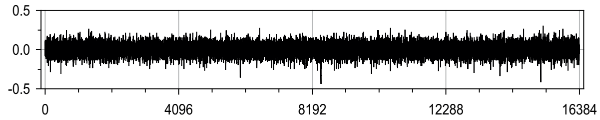
200 krad (Si)

Figure 5: Total ionizing dose degradation of ADC PV2 integral nonlinearity: ADC output code on X-axes and INL (in units of LSB) on Y-axes

There is no specifics of SEE failures in ADC and DAC, so in this paper we focus on converters SEU.

There are two types of ADC-DAC SEU. First, DAC SEU may lead to the output voltage (current) spikes during irradiation. Similarly, ADC SEU may occur as the output code pulse (reversible change). Fig. 7 shows the output voltage transients of DAC TLV5638MFKB (Texas Instruments) during irradiation by Xe-ions in the Dubna cyclotron [13].

The second type of SEU is upset of ADC-DAC internal flip-flops and registers as a result of nuclear particles influence. The upsets of data registers can change DAC output voltage (current) or ADC output code while the upsets of control registers can lead to a converter operational mode change. In either case it is usually necessary to restart a converter in order to restore its normal operation.



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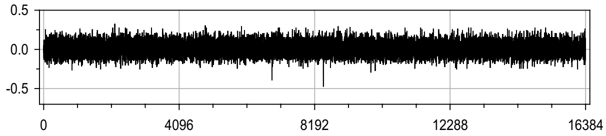

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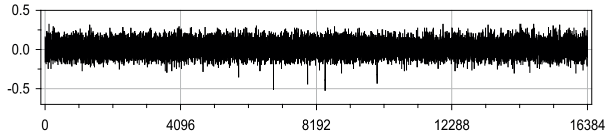
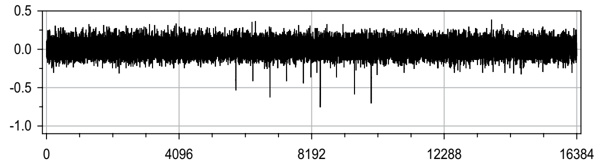
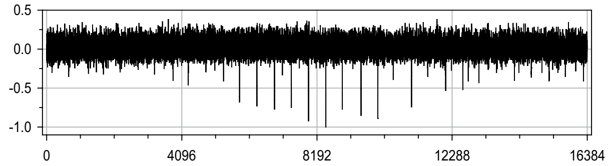


120 krad (Si)



160 krad (Si)



200 krad (Si)

Figure 6: Total ionizing dose degradation of ADC PV2 differential nonlinearity:

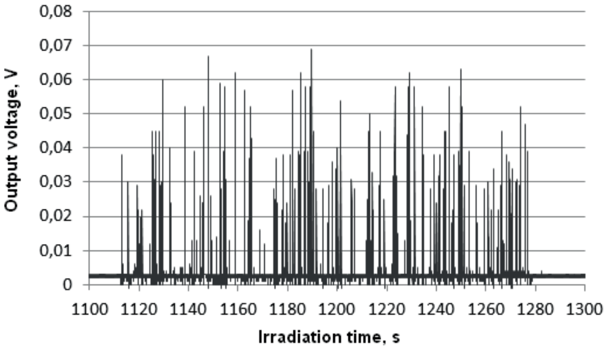


Figure 7: DAC TLV5638MFKB output voltage transients during Xe-ions irradiation.

The purpose of experimental research is to detect ADC and DAC SEU during irradiation at nuclear particle accelerators. Several ions with different Linear Energy Transfers (LET) are usually used. For each ion a SEU cross-section is determined by the equation:

$$\sigma_{SEU} = N_{SEU} / (\Phi \times N_B), \quad (1)$$

where N_{SEU} – number of upsets detected, Φ – particles fluence at irradiation session, N_B – number of bits under test. The approximating curve is to be plotted based on these data, and a converter SEU parameters – the threshold LET and the saturation cross-section – are determined. Weibull-function is used for the experimental data approximation. Fig. 8 shows such a curve and SEU parameters for sigma-delta ADC AD7711ASQ (Analog Devices) [14].

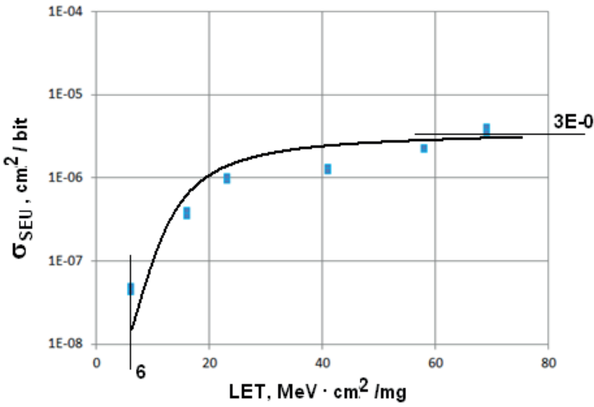


Figure 8: ADC AD7711ASQ SEU experimental data, Weibull approximation, and SEU parameters (LET and cross-section)

4 Transient radiation effects

Transient radiation effects (TRE) or dose-rate effects are caused by pulsed gamma irradiation. These effects in ADC and DAC are similar to SEE – both failures and upsets are also possible. The difference is that in SEE case only a single circuit element is locally affected by the particle every moment while TRE specific is that all functional elements and parasitic structures are jointly affected by radiation. Upsets are characterized by the threshold level of gamma dose rate and by the recovery time. Moreover, as a rule, there is a clear dependence of an output signal (voltage or current of DAC and code of ADC) pulse response amplitude and duration on the dose rate.

As an example, Fig. 9 shows a set of radiation pulse waveforms of the DAC PA1 output voltage at different dose rates. It is seen the increase of pulses both amplitude and duration. The performance criteria are typically established by the maximum allowable amplitude and duration of the ionization pulses, and are determined by the particular equipment application conditions [15].

Generally, tested DAC and ADC are set to a static operation mode with a certain output level/code, and the output response at the moment of gamma-ionization pulse is registered. But the upsets may occur in the dynamic operation modes of a converter as well. For example, the waveforms in Fig. 10 illustrate the gamma pulse upset of DAC PA3 when operating in the dynamic mode of sine signal generation [16].

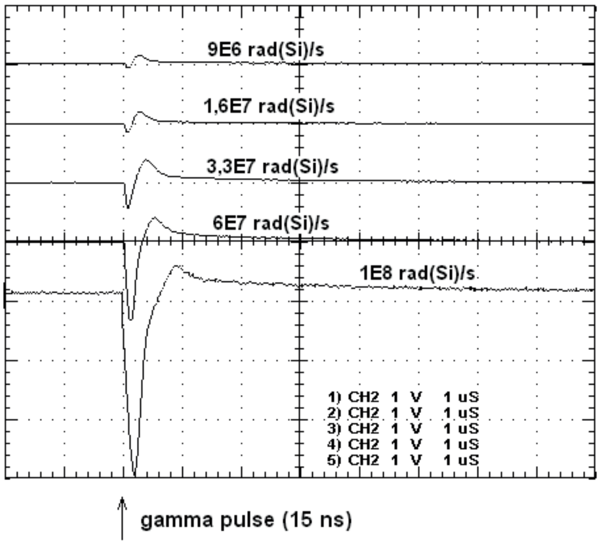


Figure 9: DAC PA1 output voltage pulses at different dose rates

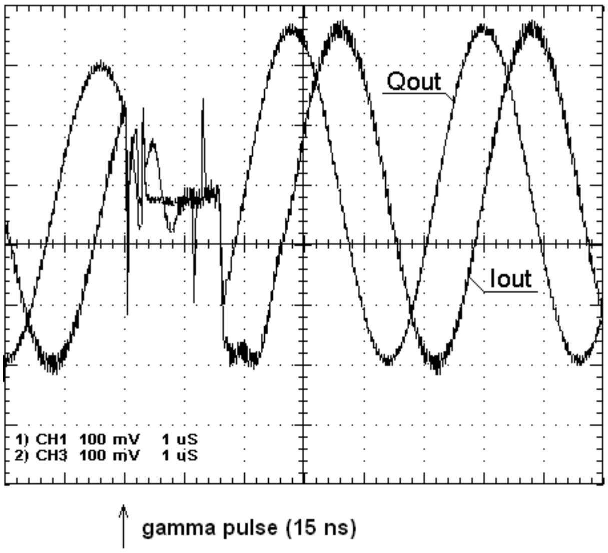


Figure 10: Dose rate upset of DAC PA3 in dynamic mode

5 Radiation test technique

As it was already mentioned above, the accuracy parameters of ADC and DAC are determined by the transfer function (TF). For its measurement during a TID test, full range linearly increasing voltage (code) is to be put on an ADC (DAC) under test inputs, and output ADC code (DAC voltage/current) is to be measured. This procedure should be repeated for all TID values we are interested in, thus it is necessary to carry out the measurements as fast as possible to satisfy the condition [2]:

$$T_{MEAS} < 0.1 \cdot T_{RAD}, \tag{2}$$

where T_{MEAS} – full TF measurement duration, T_{RAD} – time between measurements. The 0.1 factor is normally used in TID test practice to provide relatively short measurement duration as compared to irradiation time. It allows to minimize the influence of annealing during measurement and eliminating test result distortion.

One more test procedure feature is also provided by the timing requirements. According to our experience and data it is very important to measure TF directly during irradiation. Measuring after irradiation would distort the real radiation behavior picture and hardness level because of annealing that can result even in full operation recovery. In Fig. 11 two graphs of CMOS ADC nonlinearity are shown: the first is measured immediately after the 100 krads(Si) irradiation and the second – 12 hours later [3]. One can see that 12-hours annealing leads to an ADC's operation recovery.

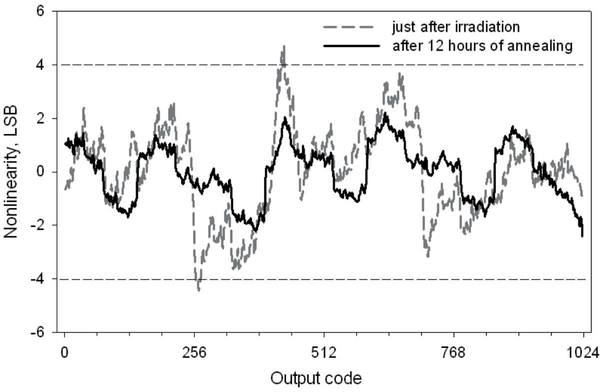


Figure 11: ADC nonlinearity measured immediately after 100 krads(Si) irradiation and 12 hours later (datasheet margins are shown by dashed lines at ±4 LSB)

Another problem is caused by the TF standard measuring procedure [3], which requires the error of a measuring device (accuracy of the input voltage) should be within 1/16 of a DAC (ADC) LSB value in the range of measurement corresponding to the full range of a DAC (ADC) output (input) voltage.

To satisfy these conditions it is necessary to use the special methods of high accuracy voltage biasing, as well as multiple measurements and averaging the measured values. These procedures should be hardware-implemented to meet ultra hard restrictions on measurement speed. The hardware structure based on a differential amplifier is shown in Fig. 12 [17]. One input of the amplifier is connected to DAC under test voltage output, and another input – to the bias voltage. Direct measurement of the output voltage is replaced by measurement of the adjacent codes output voltages difference.

The specialized ADC and DAC testing system based on the National Instruments hardware, LabView software, and a set of device-under-test boards, adapted to different converters, is developed [18]. The results of radiation tests of several dozen converters carried out using this equipment, have confirmed its effectiveness [19].

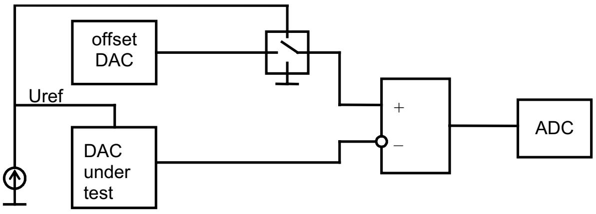


Figure 12: Voltage biasing structure for precision DAC TF measuring

6 Conclusions

The article presents the typical radiation effects in DACs and ADCs when exposed to different types of ionizing radiation. It can be seen that the converters specifics, which are characterized by both digital and analog parameters, leads to their radiation behavior specifics – the effects are caused by both digital registers and control circuits failures and failures and parameters degradation of analog units.

This feature of ADCs and DACs leads to the fact that the procedure of radiation test has some specific features when compared with test procedure of "pure" digital or analog integrated circuits. It is necessary to use the special control and monitor technique, which combines software control and data processing with precise measurements. The implementation of this technique requires specialized test equipment that should be compatible with the specialized radiation facilities with short signal cables.

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