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Nuclear Instruments and Methods in Physics Research A 560 (2006) 517–523
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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Digital-sampling systems in high-resolution and wide dynamic-range energy measurements: Comparison with peak sensing ADCs

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Received 5 August 2005; received in revised form 18 October 2005; accepted 2 December 2005
Available online 3 February 2006

Abstract

The use of fast digital sampling techniques in Nuclear Physics experiments as a replacement of the standard analog signal processing methods is discussed for applications needing high-resolution signal amplitude measurements. This is for example the case of a solid-state detector with a charge-sensitive preamplifier, processed using fast digital sampling methods. Under very general assumptions, an expression for the achievable resolution and dynamic range of the system is reported, valid for any detector/digitizer/digital-filter combination, taking into account the detector noise and the ADC properties, namely the Effective Number of Bits (ENOB) and the sampling frequency. The system properties are summarized using the parameter PSENOB, i.e. the "Peak-Sensing-Equivalent Number of Bits". These results can be used to predict the attainable performances in various applications, possibly requiring a resolution/dynamic-range trade-off. Numerical examples for some representative cases in γ-ray spectroscopy and charged particle experiments are reported, demonstrating that the equivalent performances of a 15 bit peak-sensing ADC are feasible with today-available sampling ADCs. For ease of presentation, other non-trivial effects as baseline- and non-linearity-related issues as well as experimental tests of the proposed approach are presented in a companion paper [L. Bardelli, G. Poggi, Digital sampling-systems in high-resolution and wide dynamic-range energy measurements: finite time window, baseline effects, and experimental tests, this issue].

PACS: 84.30.Sk; 07.50.Hp; 84.30.Vn; 29.40.Wk

Keywords: Digital sampling; Effective number of bits; High resolution energy measurements; Dynamic range; Semiconductor detectors

1. Introduction

For many Nuclear Physics applications high-resolution amplitude (i.e. energy) measurements of the output of a detector are of paramount importance, as for example in γ spectroscopy measurements or in charged particle detection/identification.

In experiments and proposals where hundreds of detectors are used (for example [2–4]), the standard analog signal processing methods are often replaced by digital sampling systems. The output of the preamplifier (usually a charge-sensitive one) is directly fed into a fast digitizer that produces many sampled points for each detector signal. This data stream is numerically processed with a digital shaping filter in order to improve the signal-to-noise ratio (SNR) and to obtain the desired high-resolution amplitude measurement. Using dedicated hardware, the computation can be performed in real-time, thus realizing a digital spectrometer system.

The properties of the used Analog to Digital Converter (ADC) play a significant role to maintain the intrinsic detector amplitude resolution over a wide dynamic range. For this purpose, the two key parameters are the ADC Effective Number of Bits (ENOB) and its sampling frequency. An increased dynamic range can be obviously achieved using an ADC having a higher resolution, although this usually comes at the expense of a significantly lower sampling rate. This choice is thus not feasible for many applications where energy measurement is not the only parameter of interest. For example in spectroscopy experiments like [3,4], where large volume germanium

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doi:10.1016/j.nima.2005.12.249

detectors are used, an analysis of the pulse shape of the signal is needed in order to reconstruct the γ interaction point. As a further example, in charged particle experiments time coincidences and time of flight measurements are often required, and moreover an analysis of the signal pulse shape is needed in order to identify charge and mass of the detected particles (some experimental results obtained with digital sampling methods are reported for example in Refs. [5–10]). Sampling frequencies in the 50–200 MSamples/s range are needed in order to satisfy most of the experimental needs. For example in Ref. [8], where a 10.8 effective bits, 100 MSamples/s converter is used, a timing resolution of 100 ps FWHM using a silicon detector is presented and discussed. The same system provides a 1.9 ns FWHM resolution at 1.3 MeV with a 30% efficiency germanium detector [10]. From the experimental point of view the possibility of performing energy, timing, and pulse-shape related measurements with a *single* AD converter coupled to the preamplifier is obviously very attractive, and thus a detailed understanding of the relative importance of the ADC ENOB and of the sampling frequency is needed.

Although it is well known in the literature that the availability of many sampled points for each event allows for a kind of "bit-gain" effect [11] (i.e. the finally achievable resolution and dynamic range of a B-bits ADC is higher than naïvely expected for the nominal B value), this issue has been quantitatively addressed only in a few special cases (see for example Ref. [12]). In this paper a quantitative expression for the contribution to the achievable resolution and dynamic range due to the used fast AD converter and digital filter is proposed, under very general assumptions regarding the various system properties. The relevant ADC and experimental parameters are considered and summarized using the quantity PSENOB (Peak-Sensing-Equivalent Number of Bits). The results are also presented in a plot that can be used as a recipe for simply determining the overall system performances (in terms of energy resolution and dynamic range) in any given experimental condition.

In Section 2 the concept of ADC ENOB is recalled and discussed in view of energy measurement applications, whereas in Section 3 the computation of the achievable performances is carried out under very general hypotheses. In Section 4 the results are discussed and applied to representative examples in the field of Nuclear Physics.

In order to keep the presented discussion as clear as possible, the inclusion of important effects—present in Nuclear Physics experiments—requiring an elaborate discussion (like the use of a finite number of samples and a non-zero baseline) are explicitly addressed in a companion paper [1], where a general expression for the final resolution is given. In Ref. [1] it is also demonstrated that these experimental effects can be kept sufficiently small so that the conclusions of the present paper are not altered. In the same work, the results have been verified with experimental tests on a germanium detector as well as on $\Delta E - E$ charged particle identification.

The reported discussion and results can be directly extended to various experimental arrangements.

2. Effective Number of Bits for energy measurement applications

Besides the sampling rate f_S, a fast sampling ADC is characterized by its resolution, i.e. the number of bits. An input signal fed into an ADC having B "physical" bits is quantized into 2^B levels.

In the case of a noiseless constant input signal an ideal AD converter should produce a constant conversion code. This is not the case of real ADCs, that output a digital data stream with values fluctuating around the nominal conversion code. The amount of this fluctuation can be quantified with the ENOB (in general a non-integer quantity). Typical values for high-speed ADCs are 1–2 bits below the "physical" number of bits B (for example a 12 bit converter usually has 10–11 effective bits). More technical definitions as well as useful conversion formulæ regarding the ADC SNR, ENOBs, and related quantities, are given in Ref. [13].

The ENOB of an ADC is usually extracted from the SNR obtained from a measurement of a fixed frequency sinusoidal input signal [13,14]. This definition provides an ENOB value that depends on the test frequency and includes various ADC parameters, i.e. thermal noise, non-linearities, aperture- and clock-jitter (see also Ref. [14]). In particular, aperture- and clock-jitter effects give a contribution that is proportional to the derivative of the input signal. Whereas this is the proper definition for applications dealing with fast periodic signals (for example in RF or telecommunication applications), not all these parameters are important for the purpose of amplitude measurements with Nuclear Physics detectors.

A charge preamplifier signal is normally characterized by a preceding nearly constant baseline value, a fast rise and a subsequent much slower decay. The ADC-related noise is thus clearly influenced by ADC thermal noise and non-linearity effects, whereas aperture- and clock-jitter give negligible contributions, as it will be quantitatively shown later (see Appendix A). Accordingly, in the following discussions as well as in the examples of Section 4 the used ENOB value of ADCs does not include jitter effects, i.e. it always corresponds to the value declared by the manufacturer at low frequency. Under these hypotheses, the effect of the sampling process on the overall system noise can be schematized as an additional white-noise source with no correlation with the input signal [15]. The ADC noise variance is given by

$$\sigma^2_{\mathrm{ADC}} = \frac{R^2}{12}\frac{1}{4^{\mathrm{ENOB}}} = \frac{R^2}{12}\left[\sigma^2_n + \frac{1}{4^{\mathrm{B}}}\right] \tag{1}$$

where R is the AD converter range in the used configuration, B the number of "physical" bits (i.e. the quantization