

Using the Effective Number of Bits to Evaluate the Measurement Uncertainty

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ABSTRACT

The paper deals with the measurement uncertainty evaluation of the A/D conversion based instruments, by using the effective number of bits (ENOB), which is a well known parameter, employed to characterize the overall behavior of an A/D converter. In order to verify if the ENOB can be also used to assess the measurement uncertainty, we use an ad hoc developed software tool. The results show that using the ENOB can lead to an underestimate of the uncertainties.

Keywords: Analog-Digital Conversion, Data Acquisition Boards, Digital Signal Processing, Measurement Uncertainty, Virtual Instrumentation.

1. INTRODUCTION

The measurement instruments based on analog to digital conversion of acquired signals and their successive processing are becoming more and more common in each sector of the measurement field.

Besides the traditional stand-alone measurement instruments, these days the so called "Virtual Instruments" (VI), usually assembled and programmed by the users, are more and more frequently utilized mainly in the industrial environment.

For their correct employment, both categories of instruments have to be characterized and it is necessary to evaluate the uncertainties associated with the measurement results.

This task can be carried out by means of a black-box approach in the case of stand-alone instruments, since these ones are designed to perform just one task or a very limited set of tasks.

As regards the VIs it is necessary to do some specific considerations, given that these instruments are usually designed, assembled and programmed by the users.

In this paper we pay our attention to the VIs and we do some considerations about the assessment of their uncertainty.

We can shortly define the typical VI as an assembled measurement instrument constituted of transducers and

signal conditioning accessories, a data acquisition board and a personal computer, which processes the sampled data.

For the characterization of the whole measurement chain is essential to consider all the uncertainty sources that are present in the various blocks of the chain and evaluate the standard uncertainties associated with each source.

This evaluation can be carried out by means of statistical methods performing a Type A evaluation according to the ISO-Guide to the Expression of Uncertainty in Measurement (GUM) [1], or it is also possible turning to manufacturers' specifications (Type B evaluation). Of course the second way is less expansive and less time consuming, since it does not require any kind of test from the user.

Nevertheless in this case the homogeneity of the specifications becomes very important.

As for transducers and signal conditioning accessories, the specifications are enough standardized. On the contrary as regards the data acquisition boards, each manufacturer furnishes the specifications in an arbitrary way, sometimes inventing some new parameter.

Moreover to characterize the data acquisition boards are often used some parameters that consider their overall behavior. Among them there is the very famous "Effective Number of Bits" (ENOB) [2,3].

Actually these parameters are arisen to characterize the A/D converters; anyway their extension to the entire data acquisition board is spontaneous and could be useful.

At this point the doubt arises if these parameters can be utilized to assess the measurement uncertainties, in case these boards are used to assemble a VI, or if it is absolutely necessary to start from the standard uncertainties associated with each error source, as prescribed by the GUM.

We already dealt with the uncertainty estimation of the VIs, proposing a theoretical method based on the uncertainties propagation law of the GUM [4]. The starting point is the evaluation of the standard uncertainties associated with each source. On the contrary other Authors use the ENOB to estimate the uncertainties [5].

In this paper we do some considerations to find out if the ENOB can be actually used for the uncertainties estimation of the measurement results.

For this purpose, we make use of an ad hoc developed software tool, which simulates the behavior of a generic data acquisition board and the introduction of the errors generated during the A/D conversion.

Without any loss of generality we do not consider the errors generated by transducers and conditioning accessories, even if these are often predominant if compared with the other errors.

In this framework, we do not consider either the uncertainties generated during the digital data processing.

In chapter II, after the description of a typical data acquisition board, the main error sources are identified. In chapter III we describe the software tool and how to use it to estimate the measurement uncertainties. In chapter IV we apply the proposed uncertainty evaluation procedure to various basic digital signal processing blocks, typical of a measurement chain, comparing the so obtained results with experimental tests. In chapter V, after the definition of the ENOB, we use the software tool to verify if the ENOB can be used to evaluate the uncertainties. The conclusions are presented in chapter VI.

2. THE ERROR SOURCES IN THE A/D CONVERSION PROCESS

There are two typical configurations for a generic multi-channel data acquisition board: with n channels and with n A/D converters; with n channels, a multiplexer and a single A/D converter.

We consider the second configuration that presents greater problems from the uncertainties viewpoint, since the acquisition channels are more strictly coupled one another.

The main components of this kind of boards are: multiplexer, amplifier (usually with programmable gain), the sample and hold circuits, the clock generator, the A/D converter and the memory buffer. Each one of these components can generate uncertainties.

The main errors sources are: offset and its temperature drift, gain and its temperature drift, long term stability and temperature drift of the possible onboard calibration reference, integral non-linearity (INL), noise, cross-talk, settling time, timing jitter, quantization and differential non-linearity (DNL) [2,3].

Some of these errors are generated in a particular component of the board, for instance the quantization is generated by the A/D converter and the time jitter is generated by the clock generator; other source of errors are distributed among various components, for instance the non-linearity arises both in the amplifier than in the A/D converter.

The following step to do is evaluating the standard uncertainties associated with these uncertainty sources starting from the manufacturers' specifications.

Usually the specifications are given for the entire data acquisition and not for each single component.

For the offset, gain, temperature drift and long term stability errors, the manufacturers declare an interval $\pm a$ where the error surely lies. According to the GUM, provided that there is no contradictory information, each

input quantity deviation is to be considered equally probable to lie anywhere within the interval given by specification, that is modeled by a rectangular probability distribution. The best estimate of the uncertainty is then $u=a/\sqrt{3}$.

As for the non-linearity errors, the worst case values of INL and DNL are usually reported in the specifications.

The quantization error is generally considered uniformly lying within an interval of 1 LSB, so the best estimate of the standard uncertainty is $1/\sqrt{12}$ LSB.

The standard uncertainty related to noise can be directly obtained from the technical specifications, since it is usually expressed as rms value.

The cross-talk errors are produced by the interference in the multi-channel acquisition. Its related uncertainty is expressed as minimum ratio between the signal rms value and the interference signal rms value.

The settling time is the amount of time required for a signal that is amplified to reach a certain accuracy and stay within the specified range of accuracy. The manufacturer declares this range for the maximum sampling rate and for the full scale step, but the errors on the measured signal depend on the actual sampling rate and on the actual step.

Impact of timing jitter uncertainties of measuring chain is transformed on amplitude uncertainty as a function of signal derivatives. The manufacturer declares the aperture jitter value, typically expressed as rms value.

3. THE SOFTWARE TOOL FOR THE UNCERTAINTY EVALUATION

After the identification of the uncertainty sources and the evaluation of the associated standard uncertainties, to evaluate the combined standard uncertainty of the measurement results, we propose a numerical approach using a dedicated software tool.

The software tool takes into account all the uncertainty sources and simulates a set of M measurements performed on the same signal and using M different instruments of the same type. In the following its working principle is described.

The input signal simulator generates N samples as if they were obtained from an ideal sampling process of the signal.

The core of the tool is a FOR loop executed M times. The N samples vector, inside the loop, is modified in order to simulate the errors generated during the A/D conversion process.

To simulate the offset, a constant value is added to each sample of the signal. This value is a random number within the range declared by the manufacturer. For each simulated measurement, the generated random number changes so that it lies in the specification range according to the chosen distribution.

In the same way, gain errors are simulated. In this case each sample of the signal is multiplied by a constant value.

A white noise is added to simulate the thermal noise, and to simulate the crosstalk interference, another signal is added.

The INL errors are simulated distorting the transfer function with components of second, third, fourth and

fifth order and with other two spurious components, so that the maximum deviation from a linear transfer function is always equal to the maximum INL value declared in the specifications.

As regarding the settling time errors, the software tool calculates the range of accuracy for the actual sampling rate, starting from the settling time accuracy at the maximum sampling rate; a random number within that range is generated and added to each sample.

The timing jitter errors are simulated by multiplying a random number, within the range of aperture jitter declared in the specifications, by the derivative of the signal; the so obtained values, which are the amplitude errors caused by the sampling time errors, are added to each sample.

At last, after the simulation of the quantization process, random number equally distributed in the range \pm DNL are added to each quantization level, simulating the DNL errors.

The so modified N samples are sent to the software block of the instrument, which calculates the measurement result. The M measures are collected outside the loop and the standard deviation of the measurements results, that is the combined standard uncertainty, is calculated.

4. VALIDATION OF THE NUMERICAL METHOD AND OF THE SOFTWARE TOOL

It is obvious that the effectiveness of the described approach is strictly depending on how the A/D conversion process and the introduction of the errors are simulated. So with the aim of verifying its usefulness, we applied the numerical method on various DSP basic blocks, which are typical of a measurement chain. The obtained results have been compared with the ones obtained by means of experimental tests.

For example, in the following we report the results of some tests carried out on a virtual instrument.

It is constituted of a IV order lowpass filter, the National Instruments™ AT-MIO-16E10 data acquisition board (16 single-ended or 8 differential channels, successive approximation 12 bit ADC, 100 kS/s max sampling rate, \pm 10 V maximum input signal range) and a PC with an INTEL™ 866 MHz processor; LabView™ 6.0 is the programming language used to drive the acquisition board, to process the acquired samples and to realize the user interface.

The considered test signals (generated, for the experimental tests, by the National Instruments™ PCI-MIO-16XE10 board with a 16 bit D/A converter) are:

- 9 V peak value, 2 kHz sinusoidal waveform;
- 9 V peak value, 100 Hz rectangular waveform;
- 9 V peak value, 5 Hz triangular waveform.

The implemented algorithms are:

- mean value calculation;
- RMS value calculation;
- lowpass FIR filter;

- lowpass IIR filter;
- DFT;
- THD.

The measurands are respectively the mean value, the RMS value, the peak values of the filtered signal, the amplitude of the fundamental frequency and the THD value.

In all cases the used sampling rate is 10 kS/s.

Supposing to operate within \pm 1 K of the data acquisition board self-calibration temperature, within \pm 10 K of factory calibration temperature, after one year of the factory calibration and with the gain set to 0.5, from the manufacturer specifications we get the values of table I.

Table I

National Instruments AT-MIO-16E10 Specifications

Uncertainty source	Manufacturer specification
offset	\pm 1109 μ V
gain	502 ppm
INL	\pm 1 LSB
DNL	\pm 0.5 LSB
noise	0.07 LSB rms
settling time	\pm 0.1 LSB in 100 μ s
timing jitter	\pm 5 ps
cross talk	- 80 dB

These values are inserted as inputs of the software tool, which calculates the uncertainty values (reported in tables II, III and IV) from a set of 10000 simulated measurements.

In tables II, III and IV we report also the results of the experimental tests, obtained, also in this case, from a set of 10000 measurements. The experimental obtained uncertainties are (as prescribed in the GUM) the root sum square of the uncertainty actually measured and of the uncertainties due to offset, gain, temperature drift and integral non-linearity because the last ones, having a systematic behavior, cannot be pointed out as uncertainty in a single instrument test.

Table II

Combined standard uncertainties for the sinusoidal waveform

Algorithm	Expected value	Numerical uncertainty	Experimental uncertainty
Mean	0.000 V	647 μ V	512 μ V
RMS	6.364 V	1859 μ V	1532 μ V
FIR filter	6.143 V	3001 μ V	2365 μ V
IIR filter	5.811 V	2096 μ V	1688 μ V
DFT	9.000 V	2620 μ V	2043 μ V
THD %	0.000	$1394 \cdot 10^{-6}$	$1012 \cdot 10^{-6}$

Table III

Combined standard uncertainties for the rectangular waveform

Algorithm	Expected value	Numerical uncertainty	Experimental uncertainty
Mean	0.000 V	646 μV	501 μV
RMS	9.000 V	2644 μV	2144 μV
FIR filter	11.124 V	3407 μV	3011 μV
IIR filter	10.775 V	3199 μV	2899 μV
DFT	11.461 V	3339 μV	2947 μV
THD %	45.689	1884·10 ⁻⁶	1617·10 ⁻⁶

Table IV

Combined standard uncertainties for the triangular waveform

Algorithm	Expected value	Numerical uncertainty	Experimental uncertainty
Mean	0.000 V	647 μV	494 μV
RMS	5.198 V	1522 μV	1177 μV
FIR filter	7.047 V	2444 μV	1966 μV
IIR filter	6.883 V	2079 μV	1671 μV
DFT	7.298 V	2121 μV	1876 μV
THD %	12.107	2642·10 ⁻⁶	2128·10 ⁻⁶

The experimental results are lower than the numerical obtained ones, also without considering the uncertainties introduced in the signal generation process and in anti-alias filtering. It means that the uncertainty values of some source are actually lower of the worst cases declared in the specifications. Therefore, these results validate the considered approach and the values of the various uncertainty sources of the utilized data acquisition board, declared in the manufacturer specifications.

5. CAN THE ENOB BE USEFUL TO EVALUATE THE MEASUREMENT UNCERTAINTIES?

The ENOB is defined in [2] as “A measure of the signal-to-noise ratio used to compare actual ADC performance to an ideal ADC”.

For an input sine wave of specified frequency and amplitude, after correction for gain and offset, the effective number of bits is:

$$ENOB = N - \log_2\left(\frac{rms\ noise}{ideal\ rms\ quantization\ error}\right)$$

where N is the number of bits of the converter.

Starting from the definition of ENOB, we did another verification of the software tool, by using the same data acquisition board described in chapter IV. A 9.9 V peak value 100 Hz sinusoid was generated by the National Instruments™ PCI-MIO-16XE10 board and applied as input to the board sampling at 2000 S/s. In these conditions we measured the values of each uncertainty source (table V) and a value of ENOB equal to 11.26 bits.

Table V

Measured values of the tested data acquisition board

Uncertainty source	Measured value
offset	750 μV
gain	200 ppm
INL	0.9 LSB
DNL	0.5 LSB
noise	0.07 LSB rms
settling time	negligible
time jitter	negligible
cross talk	one channel acquisition

Simulating the same signal, applying it at the simulation tool and using the measured values, we found a value of ENOB equal to 11.29 bits. This is another proof of the efficiency of the software tool.

Let’s now verify which ones of the considered uncertainty sources give a contribution to the value of the ENOB.

Analyzing the definition, we can notice that offset and gain errors do not give contribution to the ENOB. All the other uncertainty sources, generating rms noise, lower the ENOB value. Moreover the ENOB is calculated for a particular signal (sinusoid) and for a particular frequency and amplitude.

Only making these considerations, we should deduce that the ENOB cannot be used to evaluate the measurement uncertainties, since it does not take into account two of the main uncertainty sources and it is defined only for sinusoidal signals.

However it could be useful to verify if the three specifications of ENOB, offset and gain can be used to estimate the uncertainties. For this purpose we utilized the numerical method, by using a simplified version of the software tool. Offset and gain errors are simulated in the same way; than a noise equivalent to ENOB is simply added.

At this point to give an answer to the question in the title of this paper, it is enough to apply the modified simulation tool to various basic measurement algorithms and to compare the results with the ones obtained by using the already validated version of the software tool.

The compared results are reported in tables VI, VII and VIII.

Table VI

Combined standard uncertainties for the sinusoidal waveform

Algorithm	Uncertainty calculated by using the ENOB	Experimental uncertainty
Mean	521 μV	512 μV
RMS	1733 μV	1532 μV
FIR filter	2144 μV	2365 μV
IIR filter	1344 μV	1688 μV
DFT	2412 μV	2043 μV
THD %	648·10 ⁻⁶	1012·10 ⁻⁶

Table VII**Combined standard uncertainties for the rectangular waveform**

Algorithm	Uncertainty calculated by using the ENOB	Experimental uncertainty
Mean	544 μV	501 μV
RMS	2275 μV	2144 μV
FIR filter	2778 μV	3011 μV
IIR filter	2649 μV	2899 μV
DFT	3078 μV	2947 μV
THD %	$945 \cdot 10^{-6}$	$1617 \cdot 10^{-6}$

Table VIII**Combined standard uncertainties for the triangular waveform**

Algorithm	Uncertainty calculated by using the ENOB	Experimental uncertainty
Mean	521 μV	494 μV
RMS	1288 μV	1177 μV
FIR filter	1844 μV	1966 μV
IIR filter	1417 μV	1671 μV
DFT	2121 μV	1876 μV
THD %	$1285 \cdot 10^{-6}$	$2128 \cdot 10^{-6}$

The results show that using the ENOB generally leads to underestimate the uncertainties, mainly in the THD measurement.

The reason is that using the ENOB to evaluate the uncertainties is the same as not considering the harmonic and spurious components, which are always present in a real data acquisition board. Not taking into account these components, which show a systematic behavior, implies that the evaluated uncertainties are smaller than the true values.

Moreover the crosstalk is not usually considered in the ENOB calculation. Therefore, since the crosstalk is often one of the greatest sources of errors, to ignore it could lead to a heavy underestimate of the uncertainties.

6. CONCLUSIONS

In this paper the problem of the uncertainty estimation of the virtual instrument measurements has been considered.

According to the GUM the measuring model and the various sources of uncertainty have been taken into account, and a numerical method is applied to obtain the values of the standard uncertainty of the VI measurement result.

By means of these simulations we found out that the ENOB cannot be generally useful to correctly evaluate the measurement uncertainties.

The main reason is that this parameter does not take into account some of the error sources, as offset, gain and crosstalk.

Furthermore the ENOB is defined just for sinusoidal signals at a particular frequency and amplitude, so it loses its validity if used with generic signals.

If well measured, the ENOB is useful to characterize the overall performance of a data acquisition board, whereas to evaluate the VI measurement uncertainties, it is our opinion that the starting point should be the evaluation of the standard uncertainties associated with each error source.

7. REFERENCES

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