Baltic J. Modern Computing, Vol. 2 (2014), No. 4, 215-226

An Approach to Enhancing the Design of Analog-to-Event Converters

Ivars BILINSKIS, Eugene BOOLE, Armands MEZERINS, Vadim VEDIN

Institute of Electronics and Computer Science
14 Dzerbenes St., LV-1006, Riga, Latvia.

bilinskis@edi.lv, buls@edi.lv, armands.mezerins@edi.lv, vedinv@edi.lv

Abstract. At analog signal digitizing, performed on the basis of timing information provided by the high precision Event Timer A033-ET, the basic structural elements of the involved analog-to-event converter have to be enhanced to achieve their functioning at equally high performance level. This problem is considered in the paper with the focus on search for the best approach to forming the reference function essential for achieving effective reconstruction of the original signals after their PPM based transmission over communication lines.

Keywords: signal digitizing, analog-to-event converting, event timing, signal reconstruction

1. Introduction

The unusual signal digitalization, based on event timing information, the representative event transmission over communication lines and the original signal reconstruction, based on picosecond resolution timing of the received events, is the subject discussed in this paper. The considered type of analog signal converting into their digital counterparts can be performed in various ways (Bilinskis, 2007), (Bilinskis and Sudars, 2008a, 2008b), (Kumaresan and Wang, 2001), (WEB, a), and the essence of this approach is relatively simple. The variable input signals are compared with some predetermined reference and the events of their equality, considered as representative events, are fixed on the time axis. Timing of these events then shows exactly when the analog signal particular values are equal to the reference function and the obtained information is used for recovery of the original signal. This approach to signal digitizing is well suited for analog signal transmission over communication lines and that is discussed in this paper. If identical reference functions are used at both the transmitting and receiving sides, then the input signal and the reference function crossing event sequence, representing the analog input signal $x(t)$ in this case, is encoded on the basis of the Pulse Position Modulation (PPM) and it can be transmitted and reconstructed at the receiving side. In contrast to the usual digital data transfer, when the precision of the transmitted instantaneous value of the signal is proportional to the number of transmitted bits (pulses), in our case each crossing event is marked by a single rectangular pulse representing a multi-bit word and the number of the transmitted pulses is the same for any degree of sample value precision. It means that the transmitted data then actually are compressed and the precision of the analog signal transmission basically depends on the quality level of the hardware implementation of the mentioned crossing event forming and on the precision of the received event timing.

As it is shown in (Bilinskis et al. 2013a), (Bilinskis et al., 2013b), (Mezerins, 2014), the picosecond resolution and precise Event Timer A033-ET represents a high performance tool very well suited for executing the essential timing function. On the other hand, it is needed and possible to widen the application range of this Event Timer currently used in many countries mostly for high-precision time-of-flight measurements in Satellite Laser Ranging and Laser Time Transfer systems (Zhongping et al., 2008). This event timing system has high performance characteristics, first of all in terms of precision/speed ratio (Artyukh et al., 2011). Specifically, the typical single shot RMS errors at time interval measurements between two events is in the range of 3 to 4 ps with normally distributed errors of a single time measurements approximately equal to 2.5.

While using the referred to Event Timer significantly improves the conditions for analog signal digitizing performed on the basis of the obtained timing information, not only event timing operation is responsible for obtaining information needed for representing the analog input signals digitally with high precision. Whenever analog signal digitizing is based on timing the signal and reference sine-wave crossings (SWC), as it is in this case, generation and using the reference function play an equally important role. Indeed, duration of the time intervals between SWC events then apparently varies whenever the input signal is not a constant level and specifics of these variations depend on the conditions under which the reference function is used. These considerations are explained in Section 2. Various options in forming this reference functions are discussed in Section 3. As the time intervals between SWC events are not always constant, the signal sample value $x(t_k)$ sequences usually are non-uniform. This fact is significant and how this non-uniformity of time intervals ($t_k - t_{k-1}$) depends on the conditions of using the reference sine-wave is discussed in Section 4 on the basis of the obtained MATLAB simulation results.

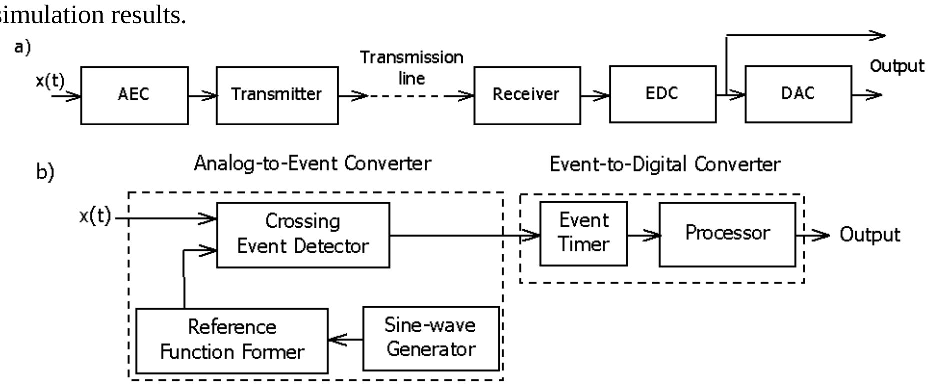

Fig. 1. Block diagrams of two systems based on the considered Analog-to-Event Converter.

This paper, in general, is focused on considering problems related to optimizing the design of the further considered involved converters, carried out to improve conditions for the analog input signal digital representation and reconstruction of the original signals. That is also needed for widening the application area of Event Timer A033-ET by adding to it, in particular, the analog input signal digital representation and the compressive analog signal Pulse Position Modulated transmission functions. Block diagrams of the two subsystems used for that are shown in Figure 1.

2. Design enhancing task

At analog signal digitizing, performed on the basis of timing information provided by the high precision Event Timer A033-ET, the basic structural elements of the involved converters have to be optimized to achieve their functioning at equally high performance level. This problem is considered in the paper with the focus on optimized forming of the reference function vital for effective digital representation of the original signals by SWC event sequences, these sequences transmitting over communication lines and reconstructing the original analog signals from the received and precisely timed SWC event sequences. Specific converters are used for that: Analog-to-Event Converter (AEC), Event-to-Digital Converter (EDC) and Digital-to-Analog Converter (DAC) which is quite specific in this case. Structures of the two basic systems, fulfilling the functions of analog signal digital representation and analog signal transmission, are given in Figure 1a and 1b, respectively. As both systems are built on the basis of the same set of converters, let us start description of these systems by explaining the functions of the involved converters first. In general, the functions of high performance detecting and timing of SWC events are subdivided between AEC and EDC, respectively. Under the conditions where the precise timing function is fulfilled by Event Timer A033-ET, the considered in this paper optimization task is focused on improving the AEC design. Typical interconnection of the involved converters in a system used for analog signal transmission is shown in Figure 1a. The structure of the system used for digital representation of analog signals is given in more detail in Figure 1b.

Analog-to-Event Converter contains only a small number of functional blocks: Sine-wave Generator, Former of the reference function and Crossing event detector. Basic structure of AEC is shown in Figure 1b. It generates (by Sine-wave Generator) a sinusoidal waveform with stable parameters and high spectral purity, uses the Reference Function Former for converting this sine-wave into the reference function which is then compared with the input signal. The Crossing Event Detector forms sharp pulses at the time instants when signal crossings (SWC events) with the reference function occur. The pulse stream at the AEC output, the nonuniform pulse train just marking the time instants of the SWC event happening, actually is a Pulse Position Modulated signal.

Event-to-Digital Converter transforms this PPM signal, containing only time information, into the input signal sample value sequences taken at the time instants of the SWC event occurrence. High performance Event Timer is used for precise picosecond resolution SWC event timing and the reconstructed signal sample values are calculated on the basis of the obtained timing results.

Digital-to-Analog Converter, used for reconstruction of the original signal transmitted over optical transmission lines, is specific. In general, this type of DAC has to reconstruct the transmitted original analog signal from the nonuniform signal sample value sequences at its input. Various methods for reconstruction of non-uniformly sampled signals can be used for that, including the reconstruction methods based on direct and inverse Fourier transforms. To reduce the complexity of the DAC design, in this case the cubic spline interpolation of the nonuniform digital signal, taken from the EDC output, is used for reconstruction of the original analog signal. Precision of this interpolation depends on the non-uniformity of the respective digital signal. To achieve the best conditions for reconstruction of the original signals from the nonuniform EDC output signals, the design of the Reference Function Former must be enhanced in a way leading to this goal.

The described types of signal converters, discussed in more detail in (Bilinskis et al., 2013a), actually are modifications of the devices that have been used before in the application area of multi-channel data acquisition (WEB a). In particular, zero crossings of the difference of the input signal and the reference function difference are used in this case instead of direct forming the crossing events. The earlier used methods and techniques have been theoretically and experimentally studied (for example, in (Bilinskis et al., 2013a), (Bilinskis et al., 2013b), (Mezerins, 2014) and the obtained results show that this event timing approach is well suited also for Event Timer A033-ET applications related to analog signal digitizing and transmission.

Indeed, achieving precise digital representation of the analog input signals based on event timing depends on both mentioned functions: forming SWC events and their timing. As the used Event Timer A033-ET system provides for really high precision timing of SWC events, the AEC design enhancing, considered in this paper, is based on improvement of the representative SWC event sequences. Focus is on search for the best approach to forming these event sequences vital for digital representation of the input signals in a way providing for their compressive PPM based transmission over communication lines and precise reconstruction of the original signals from the received and precisely timed SWC events.

3. Various sine-wave reference functions

Although the reference function used for digitizing analog signals in this case always is formed from a generated stable frequency basic sinusoid, the reference function used in the process analog-to-event timing conversion is some derivative of this sinusoid. The following three different approaches to reference function forming from this basic sinusoid are considered:

1. Enabling only ascending or descending half-periods of the used basic reference sinusoid for detecting the SWC events as it is shown in Figure 2a.
2. Enabling both half-periods of the reference sinusoid for detecting the SWC events (Figure 2b).
3. Forming the reference function from ascending (or descending) half-periods of both the direct and inverted versions of the used basic reference sinusoid (Figure 2c).

These reference function modifications are illustrated in Figure 2. While all three of them can be used for signal digitizing based on forming and timing the SWC events, the conditions for obtaining the digital signals representing one and the same analog signal depend on the used type of the reference function. Some differences in using the considered three approaches can be easily seen. For example, using the reference function formed according to Approach 1 leads to twice lower mean SWC event rate than it is in the cases of Approaches 2 and 3.

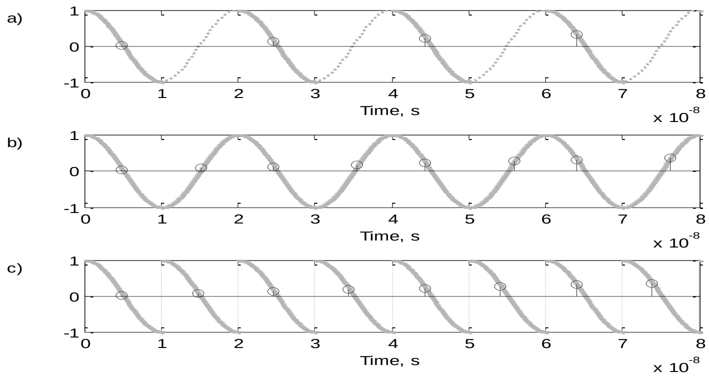

Fig. 2. Time diagrams of three reference function modifications. (a), (b) and (c) diagrams illustrate discussed approaches 1, 2 and 3, respectively. Parts of the involved sine-waves enabled for SWC event forming are shown as solid lines.

It is less evident how differ the conditions for obtaining the representative digital signals in the cases where Approaches 2 and 3 are used. To get the answer to this question, let us compare SWC event forming in the cases where the analog signal to be digitized is given as a constant level and the refence function is formed in accordance with the Approaches 2 and 3. Diagrams illustrating event forming in this case are given in Figure 3.

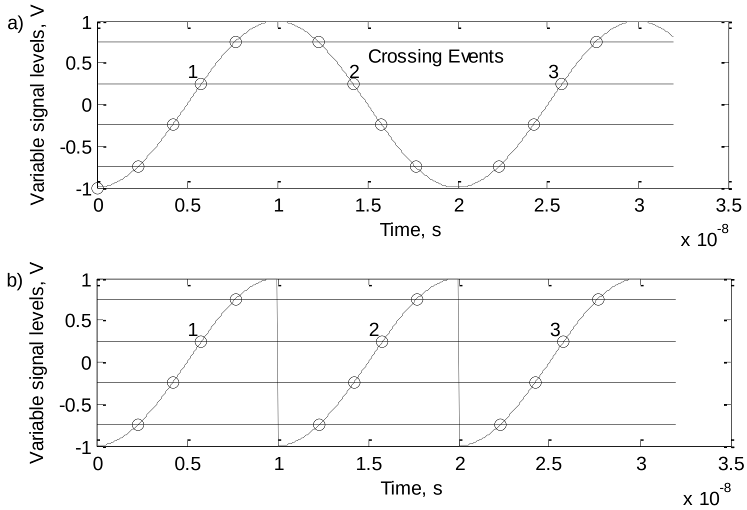

Fig. 3. Variation of intervals between SWC events: (a) in the case of using Approach 2 to forming the reference function; (b) in the case of using the described Approach 3.

Sampling rate that usually is the key factor defining the achievable upper frequency (half of the highest sampling rate) in this case is tied to the frequency of the used reference sine-wave and the upper limit of the mean sampling rate then depends on the smallest achievable time interval between two adjacent event timings. The timed event sequences are not equidistant and sampling actually is nonuniform rather than periodic. Moreover, the sampling process is specifically nonuniform, the intervals between the timed events depend on the input signals. However it should be taken into account that this type of sampling non-uniformity does not provide for alias-free signal digital representation. Consequently, the upper frequency bound for the input signal cannot exceed half of the mean sampling rate. In addition, timing of SWC events evidently cannot be performed at intervals between the SWC events that are shorter then so-called deadtime. Signal sampling based on SWC event timing has been studied is discussed in some detail in (Artyukh et al., 2011), (Bilinskis et al., 2013b), (Mezerins, 2014). To enhanse the analog-to-event timing converter design, it is essential to provide the best possible conditions both for representative event forming and for reconstructing the original analog signals. The last aspect is considered in the following Section.

4. Reconstructing the original signals.

Search for the best approach to enhancing the design of the AEC in this case is based on the considerations related to optimized recovery of the original signals from the representative digital sample value sequences. While that obviously is essential at compressive transmission of analog signals over optical transmission lines by the system illustrated in Figure 1a, performance of EDC at digital representation of analog signals by the input signal sample value sequences, carried out by the system having the block diagram as shown in Figure 1b, depends on the output of AEC as well.

Converting the analog signals into the SWC events (or analog signal sampling in other words) always is based on reaching the equality $r(t_k) = A_r \sin(2\pi f_r t_k + \varphi_r)$ of the signal $x(t)$ and the reference function $r(t)$ at time instants t_k, $k = 0, 1, 2, \ldots,$ when the SWC events occur. On the other hand, the distribution of the distances between the sampling time instants t_k and t_{k+1} depends on the used approach to the reference function forming from the generated stable parameter sine-wave. Actually using various reference function modifications leads to different patterns of SWC event sequences. And that does change the conditions for the signal recovery from the representative digital sample value sequences significantly. Time diagrams of three SWC event sequences, obtained at digitizing the same sinusoidal signal by using three different reference functions formed according to approaches 1, 2 and 3, are shown in Figure 4.

The basic specifics of the illustrated representative SWC event streams are more or less evident. According to the basic Approach 1 to analog signal digitizing, SWC event forming is based on enabling detection of the events occurring only within the falling (or rising) half-waves of the reference function. Then a crossing events happens only once per the reference sine-wave period as it is shown in Figure 4a. Enabling only half of the reference sinusoid for event forming is done to avoid errors due to the used comparator different behaviour at rising and falling reference voltage.

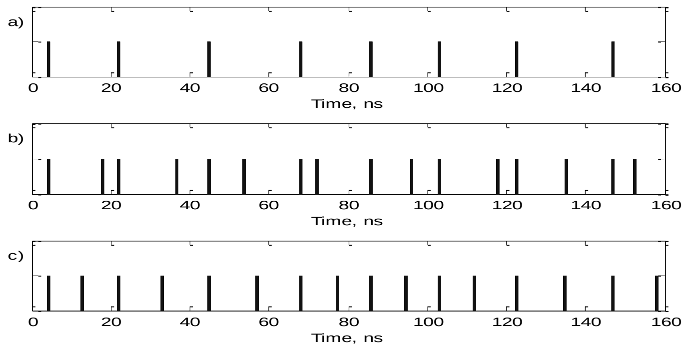

Fig. 4. Representative SWC event streams (a), (b) and (c) in the case where they are formed according to the described approaches 1, 2 and 3, respectively.

In all three caseis the event streams are nonuniform as the distances between events usually are not equal, they are signal dependent. The nonuniformity of the event stream on Figure 4b is especially strong. The mean event rate per second for both streams shown in Figure 4b and 4c is twice higher then the frequency of the respective basic reference sine-wave. Thus the same desirable effect can be achieved at least in two different ways and the question arises which of the two alternatives leads to better results of representing analog signals digitally. Although diagrams in Figure 3 show that Approach 3 has a significant advantage as it provides for more regular happening of the SWC events, the analog signal reconstruction precision has to be evaluated and compared in all three considered approaches to the reference function forming.

5. Impact of various reference functions on the signal reconstruction

To see exactly what can be achieved by using various approaches to forming the reference function, let us compare results of analog signal reconstruction from their sample value sequences in the case where these sample values are given as the timed SWC events. Whenever this signal sampling method is used, the instantaneous values of the reference function $r(t_k) = A_r \sin(2\pi f_r t_k + \varphi_r)$, corresponding to the crossing time instants $\{t_k\}$, obviously are equal to the respective sample values $x(t_k)$ of the input signal. The signal sample values x_k in this case are taken at time instants t_k when the signal and the reference sine-wave crossings happen rather than at pre-determined time instants t_k as it is at classical signal sampling. In general, they are given as

$$x_k = A_r \sin(2\pi f_r t_k + \varphi_r) \qquad (1)$$

where A_r, f_r, φ_r are amplitude, frequency and phase angle of the used reference function.

Therefore the SWC event timing results $\{t_k\}$ directly lead to estimation of the signal sample values on the basis of equation (1). The signal sample values are obtained by EDC in this way at the reference function forming according to the Approaches 1 and 2.

When both the basic and the inverted reference sinusoids are used in parallel for forming the odd and even number SWC events, as it is in the case of Approach 3, the digital sample values x_k of the original analog signal are obtained as follows:

$$x_k = A_r \sin(2\pi f_r t_k) \text{ for odd } k = 1, 3, 5, \ldots$$

$$x_k = A_r \sin(2\pi f_r t_k + \pi) \text{ for even } k = 0, 2, 4, 6, \ldots \quad (2)$$

As can be seen from (1) and (2), the specific signal sample value taking process, or signal sampling, basically is the same no matter which of the discussed 3 various approaches to forming the reference functions is used. True, in the case where reference function is formed according to Approach 2, additional hardware errors, caused by using both reference sine-wave half-periods, might appear as it is mentioned above. Otherwise varying the approaces to the reference function forming does not affect the conditions for signal sampling, using various reference function modifications just leads to different non-uniformity of SWC event sequences as it is shown in Figure 4.

This non-uniformity of SWC event streams substancially impact reconstructing of the original analog signals. As the sample value sequences then are nonuniform, special techniques have to be used for that and the reconstruction errors due to this non-uniformity factor evidently depend also on the method used for the analog signal reconstruction. Experimental studies described in (Mezerins, 2014) provided results showing that application of the cubic spline interpolation is well suited for analog signal reconstruction in this case.

Let us compare application of all three approaches to forming the reference function under the conditions of detecting and timing crossing events with following calculation of cubic spline interpolation (approximation) of the input signal that is a sinusoid of constant amplitude (A = 0.5), zero phase angle and frequency. Results obtained at 19 MHz sine wave signal sample value cubic spline interpolation are displayed in Figure 5.

Diagrams (a), (b) and (c) given in Figure 5 illustrate sampling of the same sinusoidal signal under conditions of using Approach 1, Approach 2 and Approach 3, respectively. Attention is drawn to the fact that varying these approaches directly affects the signal sampling conditions. Specifically: the signal sampling rate at Approach 1is twice lower than in the cases (b) and (c); distance variation between the subsequent signal sample values obtained under the conditions of Approaches 1and 2 takes place in wider intervals than in the case where the reference function is formed according to the Approach 3. It means that using the Approach 3 to forming the reference function leads to improved sampling conditions, to reduced reconstruction errors of the sampled signals. As these errors, shown in the diagrams (a), (b) and (c) as the differenece between the true signal (shown as a solid line sinusoidal waveform) and the reconstructed signal (shown as a dashed line waveform), actually are small, it can be seen only that they are larger in the case illustrated by the diagram (a). More clearly the typical approximation error sequences in time are shown in Figure 6 for all three approaches.

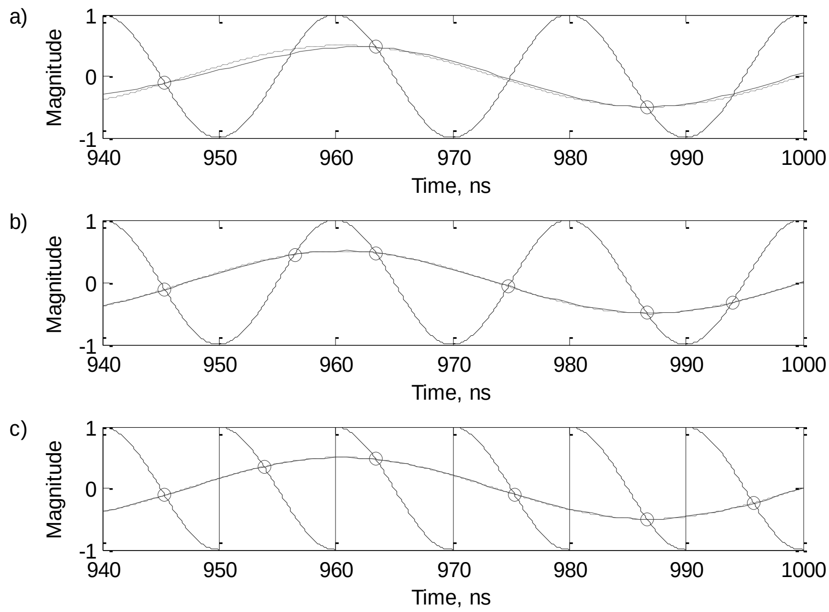

Fig. 5. Cubic spline interpolations (a), (b) and (c) of a 19 MHz sine-wave obtained by applying approaches 1, 2 and 3 to forming the reference function respectively.

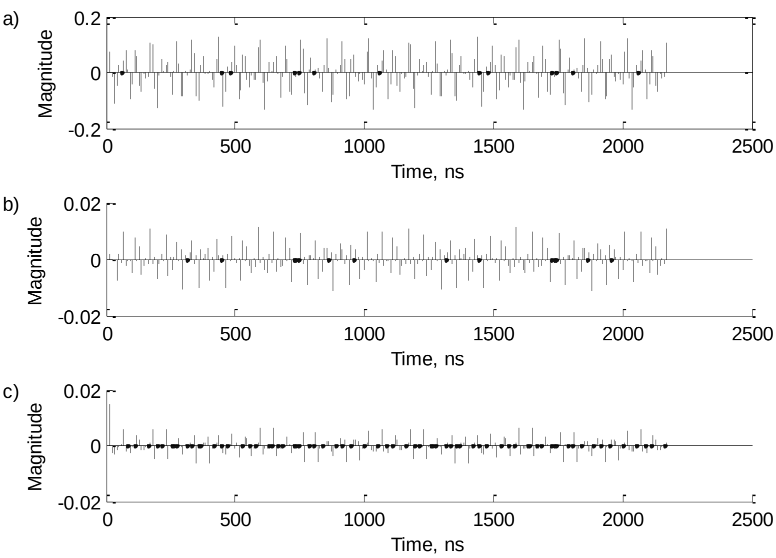

Fig. 6. Sine-wave approximation sample value error sequences (a), (b) and (c) characterizing application of Approaches 1, 2 and 3, respectively, in the case where the frequency of the approximated sinusoid is 19 MHz.

As can be seen from the diagrams given in Figure 6, application of method 3 provides for much more precise cubic spline approximation of the considered sine-waves than methods 1 and 2. That can be seen also from these error spectra shown in Figure 7.

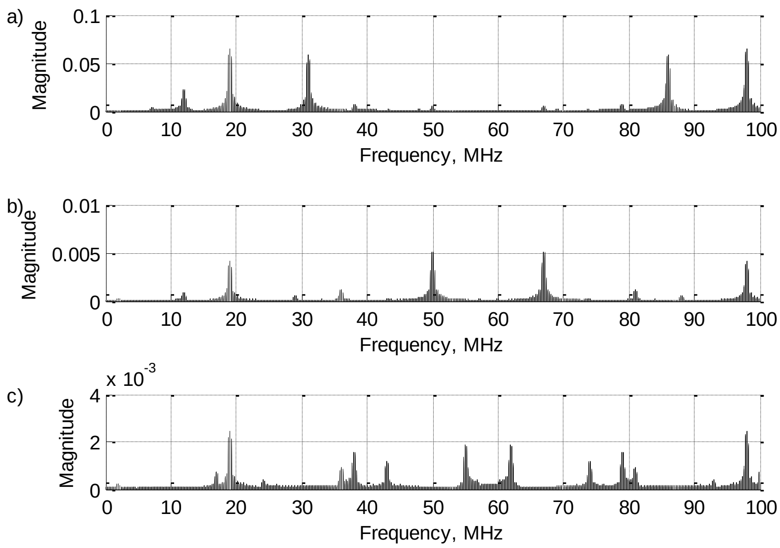

Fig. 7. Spectra (a), (b) and (c) of the 19 MHz sine-wave approximation errors under the conditions of Approaches 1, 2 and 3, respectively.

Mean absolute error and mean error power versus frequency have been calculated and the obtained results are given in Figures 8 and 9.

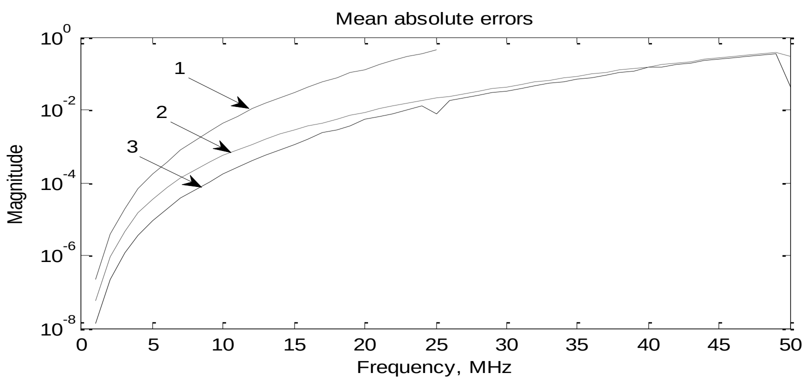

Fig. 8. Mean absolute error versus frequency for three cases of various application of 50 MHz sine-wave reference.

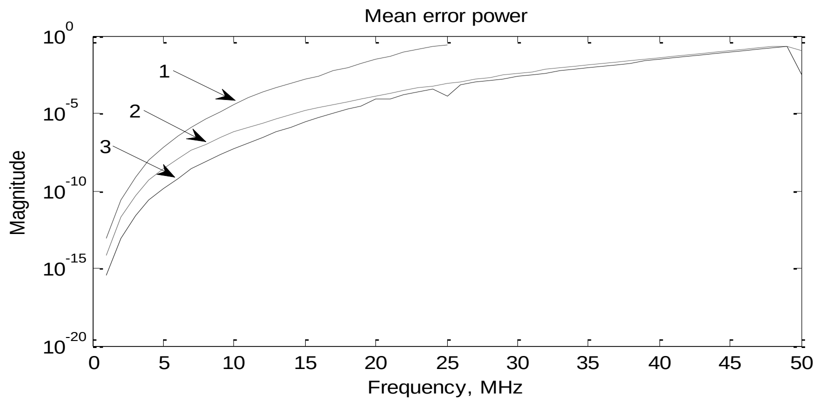

Fig. 9. Mean error power versus frequency for three cases of various application of 50 MHz sine-wave reference.

Using the proposed Approach 3 to forming the reference function leads to obtaining significantly more precise reconstructed original analog signal, as it can be seen from diagrams given in Figures 6, 7, 8 and 9. Enhancing of the AEC design is based on this conclusion.

To avoid misunderstandings, note that all three diagrams shown in Figures 8 and 9 are given in the frequency ranges from DC to half of the sampling rate (25 MHz for Approach 1 and 50 MHz for Approaches 2 and 3), while the spectrograms in Figure 7 are shown in the frequency range up to 100 MHz so that they display also the aliasing frequencies.

Conclusion

Considered two types of typical systems, developed for widening the functional capabilities of Event Timer A033-ET, are based on analog signal digitizing, performed on the basis of event timing information. Both of them, the system for analog signal digital representation and the system for compressive transmission of analog signals over optical transmission lines, are built on the basis of specific converters, AEC, EDC and DAC. It is shown that:

- Performance of these systems to a large extent depends on the perfection of the Analog-to-Event Converters fulfilling the essential digitizing function.
- The basic structural element, the Reference Function Former, of the involved analog-to-event converter has to be enhanced to improve performance of both mentioned systems.
- An innovative approach to forming the reference function from the direct and inverse versions of the generated stable parameter sine-wave is proposed.
- Using of this new approach, studied in comparison with two other usually used approaches of this type, leads to significant reduction of the original signal reconstruction errors when the signal reconstruction is based on the cubic spline interpolation of the signal sample values recovered from the SWC event timing results.

Acknowledgment

This paper reflects research results that were obtained in frameworks of the R&D project No. 2013/0036/2DP/2.1.1.1.0/13/APIA/VIAA/032 co-sponsored by the EU.

References

Artyukh, Yu., Bespal'ko, V., Boole, E., Vedin, V. (2011). Event Timer A033-ET: Current State and Typical Performance Characteristics, 17th International Workshop on Laser Ranging (Bad Kotzting, Germany, May 16-20, 2011), pp. 107-110.

Bilinskis, I. (2007). Digital Alias-free Signal Processing, John Wiley & Sons, Ltd, UK, 430 p.

Bilinskis, I., Sudars, K. (2008a). Digital representation of analog signals by timed sequences of events, "Electronics and Electrical Engineering", No. 3(83), March, 2008.

Bilinskis,I., Sudars, K. (2008b). Specifics of constant envelope digital signals, "Electronics and Electrical Engineering", No. 4(84), March, 2008.

Bilinskis, I., Boole, E., Sudars, K., Vedin, V. (2013a). Digital Representing of Analog Signals Using Event Timing Information, Automatic Control and Computer Sciences, 2013, Vol. 47, No. 6, 300-309.

Bilinskis, I., Boole, E., Mezerins, A., Vedin, V. (2013b). Alias-free compressed signal digitizing and recording on the basis of Event Timer, Proceedings of 2013 21st Telecommunications Forum TELFOR, Serbia, Belgrade, November 26 -28, 2013, 443-446.

Kumaresan, R., Wang, Y. (2001). On representing signals using only timing information, Journal of Acoustic Society of America, 110 (5), Pt. 1, Nov. 2001.

Mezerins, A. (2014). Experimental Studies of Analog Signal Digital Representing Based on a High Performance Event Timer, Proceedings of BEC2014, 2014 14th Biennial Baltic Electronics Conference, Tallinn, Estonia, October 6-8, 2014, 169-172.

Zhongping, Z., Fumin,Y., Zhibo, W., Haifeng, Z., Juping, C., Si, Q., Pu, L. (2008). The Experiment of kHz Laser Ranging with Nanosecond Pulses at Shanghai SLR, Proceedings of the 16th International Workshop on Laser Ranging, October 2008, Poznan, Poland, 316-325.

WEB (a). ERAF Project Nr.VDP1/ERAF/CFLA/05/APK/ 2.5.1./000024/012 "Development of multi-channel systems for acquisition of data from biomedical, ecological and industrial systems and transferring them to computerized systems", Co-sponsored by the European Union, http://www.edi.lv/lv/petijumu-virzieni/petijumi/

Received June 18, 2014, revised October 8, 2014, accepted October 8, 2014