A New Approach for Estimating High-Speed Analog-to-Digital Converter Error

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Abstract—One of the most significant types of error in digital signal processing (DSP) systems working with wideband signals is the error introduced by the analog-to-digital converter (ADC). This paper investigates an accurate, simple, and low-cost method, which can be used for calibrating, testing, and quick-monitoring ADC. The proposed method analyzes the deviation of a value of the converted signal, which is similar to the ADC working signal, from its true value. The deviation represents the tested ADC error evaluated for both frequency and voltage ranges of ADC operations using statistical data processing. It gives the only necessary ADC accuracy characteristic to a user leaving the rest to the designer. Comparisons between the proposed ADC testing approach and the known techniques are provided. The errors incurred by the method are analyzed. A special source of random signal with controlled statistical parameters and its calibration technique are also described.

Index Terms—Analog-to-digital converter (ADC), digital signal processing (DSP), error, evaluation, high-speed ADC, random signal, test, working conditions.

I. INTRODUCTION

KNOWN analog-to-digital converter (ADC) testing techniques deal with the evaluation of many accuracy characteristics (AC) of the converter but the conversion error of any value of an ADC input signal in working conditions, i.e., the ADC error, is not evaluated. This observation is supported by an IEEE standard [1], which is providing the globally accepted methods for measuring numerous ADC specifications without specifying the ADC error [1]. However, there are publications dedicated to automatic ADC testing and aimed at the ADC error evaluation [2]–[7]. In these references, it is recognized that the most difficult aspect of testing is the test signal source organization. In [3] “stepped input changes” are used in dynamic ADC testing. In [4], a sinewave is accepted for dynamic operating conditions. In [5], a maximum length sequence (M-sequence) is suggested in static testing and in [6] it is used in dynamic testing for special data acquisition and data processing based on Walsh functions. In [7], a complex signal with controlled statistical parameters is formed from the M-sequence. This signal is similar to ADC working signals.

In modern production of IC’s (ADC is one of them), the industry has found that the costs of test equipment, time to test and test procedures are the dominating manufacturing

costs. There are publications which suggest methods in order to simplify the procedures and to shorten the time for finding some AC in dynamic testing of IC’s [8].

The proposed testing approach takes into account the user and industry needs and provides automatic evaluation of the ADC error in static and dynamic actual operating conditions. It follows the global strategy described in [2], [3], [6], [7], applies the test signal from [7], but introduces a new data acquisition mode and statistical data processing.

II. GENERAL APPROACH AND PRINCIPLE

In an ADC manual [9], the AC are represented by their *transfer characteristics* and *dynamic characteristics*.

If the highest frequency f_H of the converted signal is significantly lower than the frequency f_{conv} which can be converted by ADC, the ADC input signal may be considered as a constant. AC for $f_H \ll f_{conv}$ are *transfer characteristics* which characterize the systematic component of the ADC error for these operations.

For a higher frequency of the converted signal, or for $f_H \leq f_{conv}$, AC are *dynamic characteristics* which characterize the random and systematic components of the ADC error for these operations.

All AC specified in the manual contribute to the ADC error. Therefore the ADC error may be calculated using these AC. Obtaining the ADC error in such a way may be considered as an indirect way because this error is calculated after direct evaluation of the AC. Indirect calculation of the ADC error contains significant approximation errors. That is why the ADC error obtained is not useful for an evaluation of the DSP error.

The new testing approach uses the direct way for determining the ADC error which may be described as

$$\Delta_{ADC} = y_{real, for f_H \ll f_{conv}} - x_{true} \quad \text{for } f_H \ll f_{conv}$$

and

$$\Delta_{ADC}(\Delta f) = y_{real, for f_H \leq f_{conv}} - x_{true} \quad \text{for } f_H \leq f_{conv}$$

where x_{true} is a test signal quantity which is received by the most accurate measurement, $y_{real, for f_H \ll f_{conv}}$ and $y_{real, for f_H \leq f_{conv}}$ are the ADC corresponding responses, measured in static and dynamic operations. The quality of such an ADC error evaluation depends on accuracy of y_{real} and x_{true} measurement only which can be sufficiently high.

The main idea of the method is as follows. A scale is used for the representation of variables of a signal. When the signal runs slowly enough, an accurate voltmeter can be used and the

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Fig. 1. Distortion test circuit for testing high speed ADC's in static and dynamic operations by the proposed method.

variables, converted by the tested ADC simultaneously with the voltmeter readings, are compared. From this comparison the real ADC response function is obtained, the ADC error for $f_H \ll f_{conv}$ is determined and then the transfer characteristics are calculated. When the signal frequency increases, the time axis is compressed and the signal varies faster over each variable. The same variables are converted by ADC again and compared with their estimates for $f_H \ll f_{conv}$. The ADC error for $f_H \leq f_{conv}$ is determined from this comparison.

III. CHOICE OF THE TEST SIGNAL

The following requirements are considered for choosing the variables scale of the test signal, or test variables.

- 1) The maximum spacing between neighboring quantities Δx_{interp} , must be chosen taking into account the ADC response function interpolation error. This spacing defines the minimum number N_{interp} , of variables within the voltage range on the function.
- 2) The minimum test variables separation time must be longer or equal to the ADC conversion time for the highest frequency f_H in order to avoid dropping out some test variables from the scale.
- 3) The test signal reproduction error should be minimum.

The test signal initial model is an M-sequence with a period L of nonrepeating binary numbers. An analog signal realization is obtained after passing this sequence through a digital linear system, a digital-to-analog converter (DAC) and a low-pass filter (LPF) (see test signal generator (TSG) in Fig. 1). Any test variable can be calculated and reproduced in a fixed order of specific times $k_1 t_{clock}$ where $k_1 = 0, 1, 2, \dots, (L - 1)$; t_{clock} is the time interval between neighboring numbers. The amplitude-frequency-time parameters of such a signal are known and controlled. The signal period is $T = t_{clock} L$. By changing t_{clock} , the signal realization can be "compressed" or

Fig. 2. Realizations of signals with Gaussian probability density and correlation functions $R_{xx}(\tau) = \sigma^2 \exp^{-\alpha|\tau|}$ (a) and $R_{xx}(\tau) = \sigma^2 \exp^{-\alpha|\tau|} \cos \omega_0 \tau$ for $\frac{\omega_0}{\alpha} \approx 7.9$ (b) at the output of test signal generator in Fig. 1.

"stretched," i.e., its bandwidth is changed without changing the signal waveform. The minimum difference between the signal quantities is $\Delta x = \frac{x_{nom}}{L}$. The conditions $\Delta x_{interp} \gg \Delta x$, and $N_{interp} \ll L$ suffice for practically any set interpolation error as L is of the order 10^6 . The test variables scale of this signal satisfies the above requirements. Once the test variables are determined, their ordinal numbers in the M-sequence must be stored in memory.

The advantages of the algorithm are the similarity of the simulated signal to the ADC working signals in all frequency ranges and the flexibility of signal parameters. Two realizations of such a signal, simulated by TSG shown in Fig. 1, are shown in Fig. 2.

IV. PROCEDURES

For data processing the matrix is used

$$[A] = \begin{bmatrix} \hat{A}_{11} & \cdots & \hat{A}_{1j} & \cdots & \hat{A}_{1N} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \hat{A}_{i1} & \cdots & \hat{A}_{ij} & \cdots & \hat{A}_{iN} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \hat{A}_{M1} & \cdots & \hat{A}_{Mj} & \cdots & \hat{A}_{MN} \end{bmatrix} \quad (1)$$

where $i = 1, 2, \dots, M$; M is the sample size for the ADC error estimation; $j = 1, \dots, q, \dots, p, \dots, N$; N is the number of the test variables ($N \geq N_{\text{interp.}}$, for ADC calibration $N = 2^R$ where R is the ADC resolution); $\hat{A}_{ij}$ is the i th reading of the j th test variable.

For $f_H \ll f_{\text{conv}}$ each $\hat{A}_{ij}$ obtained at the tested ADC output, $\hat{A}_{ij\text{ADC}}$, is made up as follows:

$$\hat{A}_{ij\text{ADC}} = A_{j\text{TSG}} + \Delta_{ij\text{ADC}} + \Delta_{ij\text{TSG}} \quad (2)$$

where $A_{j\text{TSG}}$ is the ideal j th test variable; $\Delta_{ij\text{ADC}}$ and $\Delta_{ij\text{TSG}}$ are the ADC error and the TSG error for the j th test variable in its i th reading. Simultaneously, at the voltmeter output

$$\hat{A}_{ijV} = A_{j\text{TSG}} + \Delta_{ij\text{TSG}} + \Delta_{ijV} \quad (3)$$

where Δ_{ijV} is the voltmeter error for the j th test variable in the i th reading. An accurate enough voltmeter must be used, so that its error may be neglected in solving this problem. Therefore

$$\Delta_{ijV} = 0, \quad (4)$$

For $M \geq 50$ it is possible to neglect the statistical scattering of the estimates of the sample means of $\hat{A}_{ij\text{ADC}}$ and $\hat{A}_{ijV}$ and to accept

$$\begin{aligned} m_{j\text{ADC}} &= \frac{1}{M} \sum_{i=1}^M \hat{A}_{ij\text{ADC}} \\ &= A_{j\text{TSG}} + \Delta_{\text{syst.},j\text{ADC}} + \Delta_{\text{syst.},j\text{TSG}} \end{aligned} \quad (5)$$

$$\begin{aligned} m_{jV} &= \frac{1}{M} \sum_{i=1}^M \hat{A}_{ijV} \\ &= A_{j\text{TSG}} + \Delta_{\text{syst.},j\text{TSG}} = m_{j\text{TSG}} \end{aligned} \quad (6)$$

where $\Delta_{\text{syst.},j\text{ADC}}$ and $\Delta_{\text{syst.},j\text{TSG}}$ are the systematic components of the ADC and TSG errors. The value m_{jV} , or $m_{j\text{TSG}}$, is considered as the true j th quantity of the ADC response function and $m_{j\text{ADC}}$ as its real j th quantity. The maximum random component of the ADC error obtained for j th quantity of the ADC response function is

$$\begin{aligned} \Delta_{\text{rand.},j\text{ADC}} &= \pm |\hat{A}_{ij\text{ADC}} - \hat{A}_{ijV} - m_{j\text{ADC}}|_{\text{max}} \\ &= \pm |\Delta_{\text{rand.},ij\text{ADC}}|_{\text{max}} \end{aligned} \quad (7)$$

and the systematic component for the same quantity is

$$\Delta_{\text{syst.},j\text{ADC}} = m_{j\text{ADC}} - m_{jV}. \quad (8)$$

As is seen from (7) and (8), for $f_H \ll f_{\text{conv}}$ the TSG error does not influence the ADC error.

Now the ADC response function for $f_H \ll f_{\text{conv}}$ can be plotted in the following way. The sample means m_{jV} are placed on the horizontal axis and the sample means $m_{j\text{ADC}}$ are placed on the vertical axis. So curve 2 is obtained in Fig. 3. Calculation of the AC specified in the ADC certificate is presented in the Appendix.

The next step is finding the ADC error for $f_H \leq f_{\text{conv}}$. For the tested frequency range Δf_k , where $k = 1 \dots N_f$, the matrix (1) consists of $\hat{A}_{ij\text{ADC}}(\Delta f_k)$, which are the same test

Fig. 3. ADC response function. Clarification of transfer characteristics.

variables as above, but now they are in the faster running test signal. By analogy with (2), (5), (7), and (8) it may be written

$$\hat{A}_{ij\text{ADC}}(\Delta f_k) = A_{j\text{TSG}} + \Delta_{ij\text{ADC}}(\Delta f_k) + \Delta_{ij\text{TSG}}(\Delta f_k)$$

$$\begin{aligned} m_{j\text{ADC}}(\Delta f_k) &= A_{j\text{TSG}} + \Delta_{\text{syst.},j\text{ADC}}(\Delta f_k) \\ &\quad + \Delta_{\text{syst.},j\text{TSG}}(\Delta f_k) \end{aligned}$$

$$\begin{aligned} \Delta_{\text{rand.},j\text{ADC}}(\Delta f_k) &= \pm |\hat{A}_{ij\text{ADC}}(\Delta f_k) - m_{j\text{ADC}}(\Delta f_k)|_{\text{max}} \\ &= \pm |\Delta_{\text{rand.},ij\text{ADC}}(\Delta f_k) \\ &\quad + \Delta_{\text{rand.},ij\text{TSG}}(\Delta f_k)|_{\text{max}} \end{aligned} \quad (9)$$

$$\begin{aligned} \Delta'_{\text{syst.},j\text{ADC}}(\Delta f_k) &= m_{j\text{ADC}}(\Delta f_k) - m_{jV} \\ &= \Delta_{\text{syst.},j\text{ADC}}(\Delta f_k) + (\Delta_{\text{syst.},j\text{TSG}}) \Delta f_k \end{aligned} \quad (10)$$

where $(\Delta_{\text{syst.},j\text{TSG}}) \Delta f_k$ is variation of $\Delta_{\text{syst.},j\text{TSG}}$ with frequency and $\Delta_{\text{rand.},ij\text{TSG}}(\Delta f_k)$ is the TSG error random component for j th test variable in i th reading.

As is seen from (9) and (10), for $f_H \leq f_{\text{conv}}$ the systematic component of the TSG error does not influence the ADC error as well as for $f_H \ll f_{\text{conv}}$, but the changes of this component with frequency and the random component of the TSG error are involved in the ADC error.

The ADC error obtained is a function of frequency and voltage ranges and is represented by nomograms in the most common case.

V. METHOD ERRORS

A. General Approach

The only distortion test circuit (DTC) shown in Fig. 1 contributes in the new approach error $\Delta_{\text{test.new}}$ and allows to determine the ADC error directly. The new approach DTC is similar to the known technique DTC used in dynamic testing but synthesizers and LPF's are replaced by TSG.

TABLE I
MAIN SOURCES OF THE TEST SIGNAL GENERATOR ERROR

TSG error sources	Error character	Dependence on frequency
1. DAC of TSG		
a. Reference voltage variations	random	independent
b. R-2R ladder imperfection	systematic	independent
c. Switches imperfection	systematic	dependent
2. LPF of TSG		
a. Attenuation in the stopband	systematic	dependent
b. Ripple in the passband	systematic	dependent
3. Simulation algorithm		
Limited memory of digital linear system	systematic	independent
4. Data processing algorithm		
Finite sample size	systematic	independent

The known ADC testing techniques are realized by some DTC's, whose number is usually not more than three. As the ADC error may be calculated indirectly in this case, each of the DTC's contributes in the ADC tested error through the AC estimated before. The indirect calculation of the ADC error, implemented with some assumptions and restrictions, also contribute to the known technique error $\Delta_{\text{test known}}$. Taking into account these facts, it is possible to accept

$$\Delta_{\text{test new}} < \Delta_{\text{test known}}.$$

B. Analysis

For $f_H \ll f_{\text{conv}}$, the new approach accuracy is only determined by the voltmeter accuracy as the method procedures eliminate Δ_{TSG} from the ADC error [see (7) and (8)]. The modern voltmeter error may be 0.001%. Today it is enough to observe condition (4) for evaluating even the advanced ADC error. The accuracy of the method may be estimated by

$$\Delta_{\text{test new } f_H \ll f_{\text{conv}}} = \Delta_V.$$

For $f_H \leq f_{\text{conv}}$, $\Delta_{\text{test new}}$ depends on the random component of the TSG error and on the variations of its systematic component [see (9) and (10)] and may be written as

$$\Delta_{\text{test new } f_H \leq f_{\text{conv}}} = F_{\text{new}}[(\Delta_{\text{rand.TSG}})_{\Delta f_k}, (\Delta_{\Delta_{\text{syst.TSG}}})_{\Delta f_k}].$$

Considering sources of the TSG error, shown in Table I, it is possible to accept

$$(\Delta_{\text{rand.TSG}})_{\Delta f_k} = \Delta_{\text{rand.TSG}} \quad (11)$$

where $\Delta_{\text{rand.TSG}}$ is a characteristic of the statistics found using (3) and (6) as

$$\Delta_{\text{rand.}ij\text{TSG}} = \hat{A}_{ijV} - m_{jV}. \quad (12)$$

Three sources from Table I, contributing in $\Delta_{\text{test new } f_H \leq f_{\text{conv}}}$ through $(\Delta_{\Delta_{\text{syst.TSG}}})_{\Delta f_k}$, must be discussed in 1c, 2a, 2b (see Table I).

The factor 1c may give a significant contribution depending on the relationship between the switch response and the frequency range of the signal at its input. In the new approach

this factor influence is minimized by using the same test variables for different Δf_k and observing the condition

$$T_{\text{settL.DAC}} \text{ for all procedures} = T_{\text{settL.DACmin}} = \text{const} \quad (13)$$

where $T_{\text{settL.DAC}}$ is the settling time of the DAC used in TSG for all frequency ranges. Considering (13) and that the maximum DAC frequency is about two orders higher than that in the ADC, the factor 1c contribution may be neglected.

Contributions of the factors 2a and 2b are the most significant. The LPF of TSG, used for eliminating the frequency $f_{\text{clock}} = \frac{1}{t_{\text{clock}}}$ from the test signal, changes the test signal spectrum. The smaller the part of the test signal spectrum located nearby f_{clock} is, the smaller this change is. In the approach for all frequency ranges, the condition observed is

$$f_{\text{clock}} = k_2 f_H \quad (14)$$

with $k_2 = 10$. The stopband start frequency is equal f_{clock} . The TSG digital linear system taking into account (14) locates 95% of the test signal spectrum inside 0.1% of the passband and minimize the influence of the factor 2a.

The factor 2b cannot be minimized by the method. This factor is specified for the commercial LPF [10] and evaluated with sufficient accuracy by LPF testing techniques. There are LPF's having possibilities for outside connections for getting different frequency ranges. In this case, using the known LPF testing techniques, the ripple is evaluated for each f_k . Then $(\Delta_{\Delta_{\text{syst.TSG}}})_{\Delta f_k}$ may be found as

$$(\Delta_{\Delta_{\text{syst.TSG}}})_{\Delta f_k} = (m_{j\text{TSG}})_{\text{max}}(K_{\text{ripp},f_k} - K_{\text{ripp}}) \quad (15)$$

where K_{ripp,f_k} and K_{ripp} are the maximum LPF response gains in the frequency range f_k and in the frequency range used in static testing. The value, found from (15), turns out to be excessive. Finally, considering (11) and (15)

$$(\Delta_{\text{test new}})_{f_k} \leq |(\Delta_{\text{rand.TSG}})| + |m_{j\text{TSG}}|_{\text{max}}(K_{\text{ripp},f_k} - K_{\text{ripp}}). \quad (16)$$

Decreasing $\Delta_{\text{test new } f_H \leq f_{\text{conv}}}$ may be reached by the careful tuning up of a commercial LPF or by a special LPF design, e.g., the second-order Butterworth LPF.

C. The TSG Calibration

The TSG must be calibrated for testing each ADC type, at least. The reason is that the test variable set depends on the ADC frequency range, on the plotting accuracy of the ADC tested response function and on the ADC working signal area. If the synthesizer of the known techniques is used as TSG, it must be calibrated in the same way as TSG in order to obtain the test variable set and the synthesizer error, which is not included in its certificate. The TSG calibration has three steps.

The first step is the evaluation of ripple K_{ripp} and K_{ripp,f_k} for each frequency range f_k of the ADC tested by the known LPF testing techniques, if the LPS commercial specifications are not enough.

The second step is the evaluation of $\Delta_{\text{rand.TSG}}$ by the way described in Section IV and using appropriate data processing for statistics from (12). In this step, the range of $(m_{j\text{TSG}})$ [see (6)] is found.

$$\begin{aligned}
n_{\text{zeroLSB}} &= \frac{m_{qV}}{m_{NV}} 2^R & n_{\text{gainLSB}} &= \frac{m_{NV} - m_{pV}}{m_{NV}} 2^R \\
n_{\text{int.LSB}} &= \left| \left(m_{j\text{ADC}} - (m_{jV} - m_{qV}) \frac{m_{p\text{ADC}}}{m_{pV} - m_{qV}} \right. \right. \\
&\quad \left. \left. + \Delta_{\text{rand.}ij\text{ADC}} \right)_{\max} \right|_{\max} \times \frac{2^R}{m_{NV}} \\
n_{\text{diff.LSB}} &= \frac{|A_{j\text{ADC}} - A_{(j-1)\text{ADC}}|_{\max} - |A_{j\text{ADC}} - A_{(j-1)\text{ADC}}|_{\min}}{m_{NV}} 2^R
\end{aligned}$$

The third step is the calculation of the set of $\Delta_{\text{test new } f_k}$ using (16) and making decision about possibility to use the TSG signal as a model.

VI. CONCLUSION

An innovative method for testing high speed ADC has been described. Its main characteristics are as follows.

- 1) The ADC error, found by the new approach, is the nearest to the real ADC error as it is obtained for the actual ADC environment.
- 2) The ADC error obtained allows the user to calculate his DSP error expected and choose optimum ADC operating conditions.
- 3) The error incurred by the new approach is smaller than the error incurred by the known techniques for testing high speed ADC's.
- 4) The new test cost is less than the known one as the procedures are automated, the time required is less and the equipment used is simpler.

The method features have been achieved by applying a classical method for estimating an error, known as "comparing to a measure," followed by statistical data processing. The measure is the particular sequence of the test signal variables estimated by a precise voltmeter. Practical realization of the method needs a PC with a built-in relay board, a precise programmable voltmeter, and a special program package.

The new approach may be used also for testing another circuit or electronic equipment working with complex signals. In such cases the concept developed is applied but with modified data processing.

APPENDIX

CALCULATION OF ADC TRANSFER CHARACTERISTICS

The transfer characteristics, which characterize the systematic component of the ADC error, are provided in LSB units [9], composed by the *differential linearity* ($n_{\text{diff.LSB}}$), the *integral linearity* ($n_{\text{int.LSB}}$) the *gain error* (n_{gainLSB}) and the *zero error* (n_{zeroLSB}) and written as

$$\begin{aligned}
n_{\text{zeroLSB}} &= \frac{x_{\text{zero}}}{h}, & n_{\text{gainLSB}} &= \frac{x_{\text{nom}} - x'_{\text{nom}}}{h} \\
n_{\text{int.LSB}} &= \frac{|\Delta y_{\text{int.max}}|}{h}, & n_{\text{diff.LSB}} &= \frac{|\Delta y_{\text{max}}| - |\Delta y_{\text{min}}|}{h}
\end{aligned} \quad (17)$$

where Δy_{max} , Δy_{min} , $\Delta y_{\text{int.max}}$, x_{nom} , x'_{nom} , x_{zero} and $h = \frac{x_{\text{nom}}}{2^R}$ are shown in Fig. 3.

If $m_{j\text{ADC}} = \text{const}$ for $j = N, N-1, \dots, p$ and if $m_{j\text{ADC}} = \text{var}$ for $j = p-1, \dots, q+1$, then

$$x_{\text{nom}} = m_{NV} \quad x'_{\text{nom}} = m_{pV}$$

If $m_{j\text{ADC}} = 0$ for $j = 1, 2, \dots, q$ and if $m_{j\text{ADC}} \neq 0$ for $j = q+1, \dots, N$, then

$$x_{\text{zero}} = m_{qV}.$$

The $\Delta y_{\text{int.max}}$ is found as: $\Delta y_{\text{int.max}} = ((\Delta_{ij\text{ADC}})_{\max})_{\max}$. This parameter is the maximum difference between the curve 2 and the curve 1 in Fig. 3. Actually, for calculating $n_{\text{int.LSB}}$ (17), the real ADC response is compared with the approached ADC response from curve 3 in Fig. 3. Therefore the ADC error systematic component (8) has to be corrected as

$$\Delta_{\text{syst.}j\text{ADC}} = m_{j\text{ADC}} - f(m_{jV})$$

where $f(m_{jV}) = (m_{jV} - m_{qV}) \frac{m_{p\text{ADC}}}{m_{pV} - m_{qV}}$; $j = q \dots p$, and the parameter used practically is

$$(\Delta y_{\text{int.max}})' = ((m_{j\text{ADC}} - f(m_{jV}) + \Delta_{\text{rand.}ij\text{ADC}})_{\max})_{\max}.$$

The $|\Delta y_{\text{max}}| - |\Delta y_{\text{min}}|$ is found for $j = q \dots p$ as

$$\begin{aligned}
|\Delta y_{\text{max}}| - |\Delta y_{\text{min}}| &= |A_{j\text{ADC}} - A_{(j-1)\text{ADC}}|_{\max} \\
&\quad - |A_{j\text{ADC}} - A_{(j-1)\text{ADC}}|_{\min}.
\end{aligned}$$

The values (17) written in the terms of the new approach are shown at the top of the page.

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