

IEEE Trial-Use Standard for Digitizing Waveform Recorders

Circuits and Devices

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Sponsored by the
Waveform Measurement and Analysis Committee of the
IEEE Instrumentation and Measurement Society

*Signals and
Applications*

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Digitizing Waveform Recorders**

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IEEE Instrumentation and Measurement Society**

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Foreword

(This Foreword is not a part of IEEE Std 1057, IEEE Trial-Use Standard Digitizing Waveform Recorders.)

Work on this trial-use standard unofficially began with the "Seminar on Waveform Recorder Measurement Needs and Techniques for Evaluation/Calibration," hosted by the National Bureau of Standards in 1981. Dissatisfied with the state of measurement standards and test techniques for waveform recorders, a group of concerned users, manufacturers, and researchers who attended the seminar formed a committee to crystalize waveform recorder specifications and achieve consensus on them. This effort gathered additional members and became affiliated with the IEEE Instrumentation and Measurement Society in 1983. Work was substantially completed on the trial-use standard in 1988.

The purpose of this trial-use standard is to provide common terminology and test methods for describing the performance of waveform recorders. Since these devices give only digital answers that are intended to be sent to a computer for analysis, a highly analytical approach has been taken, perhaps more than other instrumentation standards committees. A report on the user's reaction to this approach and also any additional information needed to make it work will be welcomed.

At the time this standard was approved for trial-use the members of the working group had the following membership:

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Philip Crosby
John Kuffel
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Thomas Linnenbrink
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Draft American National Standard

IEEE Trial-Use Standard for Digitizing Waveform Recorders

1. Scope

1.1 Coverage. Instruments covered by this trial-use standard are electronic digitizing waveform recorders, waveform analyzers, and digitizing oscilloscopes with digital outputs. This trial-use standard is directed toward, but not restricted to, general-purpose waveform recorders and analyzers. Special applications may require additional manufacturer information and verification tests.

1.1.1 Comments on Equivalent-Time Sampling. Waveform recorders and digital oscilloscopes may employ either real-time or equivalent-time sampling, or both, at different times. With real-time sampling, samples of the input signal are acquired sequentially, at the stated sampling rate. However, with equivalent-time sampling, the samples may be acquired sequentially or otherwise, at a rate usually much lower than the stated equivalent-time sampling rate. Equivalent-time sampling requires that input waveforms be repetitive, since a waveform sampled in equivalent time is reconstructed from samples taken over many repetitions. This restriction does not apply for recorders employing real-time sampling.

In this trial-use standard, the recommended test methods were designed with real-time sampling instruments specifically in mind. Nevertheless, the test methods will generally still be valid when applied to recorders that use equivalent-time sampling. A few additional points should be kept in mind in such cases.

A common feature of equivalent-time sampling instruments is the ability to perform waveform averaging. This is useful in reducing noise components, both originating in the waveform source and also in the recorder. Therefore, tests that in some way measure the recorder's noise processes will be affected by the amount of averaging applied in the recorder. Examples of such tests are effective bits, signal-to-noise ratio, peak error, random noise, and aperture uncertainty. The results of any such tests performed on recorders employing equivalent-time sampling should include the number of samples or records averaged.

As noted in 4.9.2, the use of equivalent-time sampling also affects the time over which the aperture uncertainty is measured. Therefore, the results of this measurement should include the time required to capture a record, or equivalently, the real sampling rate and the record length.

Finally, some tests of equivalent-time sampling recorders will actually be easier to perform, or will have less uncertainty because the sampling is often phase-locked to the trigger signal. As an example, the measurement of trigger delay and jitter may be more accurate (see 4.10.1.3).

1.1.2 References. The following publications shall be used in conjunction with this trial-use standard:

[1] ANSI/IEEE Std 181-1977, IEEE Standard on Pulse Measurement and Analysis by Objective Techniques.

[2] CARRIER, PHIL. A Microprocessor Based Method for Testing Transition Noise in Analog to Digital Converters. *Proceedings 1983 IEEE International Test Conference*, Oct 1983.

[3] DOERNBERG, LEE, and HODGES. Full-Speed Testing of A/D Converters. *IEEE Journal of Solid-State Circuits*, vol SC-19, no 6, Dec 1984, Appendix A, pp 826-827.

[4] HAMMING, R. W. Digital Filters. Englewood Cliffs, NJ: Prentice Hall 1983, 2nd ed.

[5] HARRIS, FREDRIC J. On the Use of Windows for Harmonic Analysis with the Discrete Fourier Transform. *Proceedings of the IEEE*, vol 66, no 1, Jan 1978.

[6] KUFFEL, McCOMB, and MALEWSKI. Comparative Evaluation of Computer Methods for Calculating the Best Fit Sinusoid to the High-Purity Sine Wave. *IEEE Transactions on Instrumentation and Measurement*, vol IM-36, no 2, June 1987.

[7] LINNENBRINK, THOMAS. Effective Bits: Is That All There Is? *IEEE Transactions on Instrumentation and Measurement*, vol IM-33, no 3, Sep 1984.

[8] NUTTALL, ALBERT H. Some Windows with Very Good Side Lobe Behavior. *IEEE Transactions on Acoustics, Speech, and Signal Processing*, vol ASSP-29, no 1, Feb 1981.

[9] SOUDERS, T. M. and FLACH, D. R. Accurate Frequency Response Determinations from Discrete Step Response Data, *IEEE Transactions on Instrumentation and Measurement*, vol IM-36, no 2, June 1987.

[10] STEARNS, S. D. Digital Signal Analysis. Rochelle Park: Hayden Book Co. 1975.

[11] STRICKLAND, J. A. Time-Domain Reflectometry Measurements. Beaverton: Tektronix Inc. 1970.

1.2 Purpose. The purpose of this trial-use standard is to provide common terminology and test methods for describing the performance of waveform recorders. It is meant for users and manufacturers of these devices. The main body presents many performance features, sources of error, and test methods. The tests are meant to be used by manufacturers to locate and, it is hoped, correct sources of error in the hardware.

They can also be applied by users to correct some of the errors by software processing after the signal has been recorded. Another planned use for this trial-use standard is for users when writing specifications for purchasing new or existing waveform recorders.

This trial-use standard presents a large number of possible waveform recorder error sources and test methods for quantifying them. Some of these methods are cumbersome in that they require sophisticated test equipment and signal processing, or they require a considerable amount of time. It is generally not necessary to perform all of these tests to adequately characterize a particular waveform recorder for a particular application. Also, the existence of some errors can preclude measuring others. For many applications, the two relatively easy tests for determining effective bits and step response may suffice or at least point the user in a direction to pursue other tests. These tests require a high purity sine-wave source and a clean, fast leading-transition step generator. A recommended algorithm for performing the sine fit used in determining effective bits is described in 4.1.3.

The sine-fit test will show the effect of such errors as noise, nonlinearities, and aperture uncertainty. A qualitative feel for the magnitude of these errors may be gained by examining a plot of the residuals and of the Fourier transform of the

digitized sine wave. When the errors are concentrated near the peaks of the sine wave, the errors are probably due to nonlinearities. When the errors are concentrated near the zero crossings, then they are probably due to aperture uncertainty. Nonlinearities cause harmonics of the original sine wave to appear in the residuals and in the Fourier transform. An estimate of the recorder's noise floor may be made by examining its Fourier transform well away from the fundamental and harmonic lines.

The sine-fit test does not measure amplitude flatness and phase linearity. Deviations from the ideal in these parameters will show up as aberrations in the recorder's step response. The step response parameters should be determined over a range of levels to detect amplitude nonlinearity and slew limit effects. When the recorder is not too noisy, the impulse response may be approximated by differentiating the step response.

Waveform recorders often have various controllable settings such as gain, offset, filtering, sampling rate, trigger level, and trigger slope. The performance parameters and test methods described in this trial-use standard apply to a single set of settings. Changing a setting can affect the recorder's performance. This is particularly true of gain, offset, and sampling rate. Thus a waveform recorder should be characterized over the range of settings at which the instrument will be used.

Drift in performance over time and temperature are not specifically addressed for most parameters in this trial-use standard. An exception is long-term sample time drift. The manufacturer should specify the operating temperature range and recalibration intervals.

Many test methods call for test equipment whose performance is better than that expected from the waveform recorder being measured. The required test equipment may not be available. This is especially the case for recorders at the state of the art in sampling speed or accuracy, or both. A paradox may exist in that high-performance waveform recorders are required to develop and evaluate new test equipment. When this is the case, clever engineering is required to develop techniques to measure the parameters of interest using available equipment.

2. Manufacturer Supplied Information

2.1 General Information. Manufacturers should

supply the following general information:

- (1) Model number
- (2) Dimensions and weight
- (3) Power requirements
- (4) Environmental conditions: Safe operating, nonoperating, and specified performance temperature range; altitude limitations; humidity limits, operating and storage; vibration tolerance; and compliance with applicable electromagnetic interference specifications
- (5) Any special or peculiar characteristics
- (6) Compliance with military specifications
- (7) Available options and accessories, including their impact on equipment performance.
- (8) Exceptions to the above parameters where applicable
- (9) Calibration interval, if required

2.2 Performance Specifications (See appropriate sections for definitions).

2.2.1 Minimum Specifications

- (1) Number of digitized bits
- (2) Sample rates
- (3) Memory length
- (4) Input impedance
- (5) Analog bandwidth
- (6) Input signal ranges

2.2.2 Additional Specifications

- (1) Gain
- (2) Offset
- (3) Differential nonlinearity
- (4) Harmonic distortion and spurious response
- (5) Integral nonlinearity
- (6) Maximum static error
- (7) Signal-to-noise ratio
- (8) Effective bits
- (9) Peak error
- (10) Random noise
- (11) Frequency response
- (12) Settling time
- (13) Transition duration of step response (rise time)
- (14) Slew limit
- (15) Overshoot and precursors
- (16) Aperture uncertainty (short-term time-base stability)
- (17) Long-term time-base stability
- (18) Fixed error in sample time
- (19) Trigger delay and jitter
- (20) Trigger sensitivity
- (21) Trigger hysteresis band
- (22) Trigger minimum rate of change
- (23) Trigger coupling to signal

- (24) Crosstalk
- (25) Monotonicity
- (26) Hysteresis
- (27) Overvoltage recovery
- (28) Word error rate
- (29) Cycle time

3. Definitions

3.1 Definitions of Common Terms

amplitude flatness. The variation in output amplitude as a function of frequency in response to a constant amplitude sine-wave input.

code bin k . A digital output that corresponds to a particular set of input values.

Code Transition Level	Code Bin	Code Bin Width
	$2^N - 1$	
$T[2^N - 1]$	$2^N - 2$	$W[2^N - 2]$
$T[2^N - 2]$		
.	.	.
.	.	.
.	.	.
$T[k + 2]$	$k + 1$	$W[k + 1]$
$T[k + 1]$		
	k	$W[k]$
$T[k]$		
	$k - 1$	$W[k - 1]$
$T[k - 1]$		
.	.	.
.	.	.
.	.	.
$T[2]$	1	$W[1]$
$T[1]$		
	0	

Fig 1
Definitions Pertaining to Input Quantization

code bin width $W[k]$. The difference of the code transition levels that delimit the bin. $W[k] = T[k + 1] - T[k]$.

code transition level $T[k]$. The value of the recorder input parameter at the transition point between two given, adjacent code bins. The transition point is defined as the input value that causes 50% of the output codes to be greater than or equal to the upper code of the transition, and 50% to be less than the upper code of the transition. The transition level $T[k]$ lies between code bin k and code bin $k-1$.

data window. A set of coefficients with which corresponding samples in the data record are multiplied so as to more accurately estimate certain properties of the signal, particularly frequency domain properties. Generally, the coefficient values increase smoothly toward the center of the record.

full-scale. A full-scale signal is one whose peak-to-peak amplitude spans the entire amplitude range of the instrument.

ideal code bin width Q . The ideal full-scale input range divided by the total number of code states.

large signal. One whose peak-to-peak amplitude is as large as practical but is recorded by the instrument within, but not including, the maximum and minimum amplitude data codes. As a minimum, the signal must span at least 90% of the amplitude range of the instrument.

noise. Unwanted disturbances superimposed on a signal that tend to obscure its information content. Unless referred to as *random*, noise may include systematic distortion or spurious response.

phase nonlinearity. The deviation in phase from a perfectly phase-linear response as a function of frequency. The phase response of a perfectly phase-linear system is directly proportional to frequency.

3.2 Symbols Used in this Trial-Use Standard

$\alpha_n = \cos(\omega t_n + \theta)$
 $\bar{\alpha}$ = average of α_n over M samples
 $\beta_n = \sin(\omega t_n + \theta)$
 $\bar{\beta}$ = average of β_n over M samples
 ϵ = error, used for total error and error band
 ϵ_{rms} = root-mean-square value of ϵ
 $\epsilon[f_s]$ = error in sampling rate

$\epsilon[f_r]$ = measured error in input reference frequency
 $\epsilon[k]$ = difference between $T[k]$ and ideal value of $T[k]$ computed from G and V_{os}
 θ = phase, expressed as radians
 π = constant, ratio of the circumference of a circle to the diameter
 ρ = reflection coefficient
 σ = standard deviation; sometimes used as noise amplitude, which is the standard deviation of the random component of a signal
 σ_σ = standard deviation of the standard deviation (for example, standard deviation of the noise amplitude)
 σ_t = aperture uncertainty
 τ = sampling period, the inverse of f_s
 $\Phi[X]$ = cumulative density function for a Gaussian distribution (The fraction of the total distribution covered from negative infinity to X)
 ϕ = phase estimate, expressed in radians
 Ω = frequency estimate, expressed in radians per second
 ω = frequency, expressed in radians per second
 A = amplitude, usually of a sine wave
 $A_{\cos}$ = amplitude of a cosine wave
 A_D = amplitude denominator, when A is expressed as a fraction
 A_N = amplitude numerator, when A is expressed as a fraction
 $A[i]$ = average of a record whose dc input is identified by i
 $a_{11}, a_{12}, a_{21}, a_{22}$ = linear equation matrix elements for four parameter fit iteration
 B = test tolerance in fractions of a least significant bit (lsb). Also used as an amplitude
 B_D = amplitude denominator, when B is expressed as a fraction
 B_N = amplitude numerator, when B is expressed as a fraction



C = offset	R = error parameter
$C[k]$ = number of samples accumulated in code bin k	$R+, R-$ = rising and falling regions of a sine wave
DNL = maximum differential nonlinearity over all k	S = set of samples collected over more than one record, also used as an error parameter
$\text{DNL}[k]$ = differential nonlinearity of code k	S' = qualified subset of S
E = number of effective bits	snr = signal-to-noise ratio
ENBW = effective noise bandwidth	Δt = interval between equivalent time samples
$e_m[f]$ = aliasing and first differencing magnitude errors	$T[k]$ = code transition level between code k and code $k-1$
$e_p[f]$ = aliasing and first differencing phase errors	T_1 = ideal value of $T[1]$
f = frequency, Hz	T_{MIN} = minimum trigger delay required for a large pulse
f_{co} = upper frequency for which the amplitude response is -3 dB	T_{OD} = trigger delay for a pulse value V_{OD}
f_{eq} = equivalent sampling rate	t_n = discrete sample times
$f[k]$ = correction function converting sine-wave probability distribution function to uniform distribution function	u = confidence level expressed as a fraction
f_r = input signal reference frequency	V = full-scale input range of waveform recorder
f_s = sampling frequency	V_{HYST} = the trigger hysteresis level
G = gain of waveform recorder, ideally = 1	$V(s)$ = magnitude spectra (from the DFT of a time record)
$hn(i)$ = hanning window time coefficients	$V(t)$ = the settled value after a specified time
INL = integral nonlinearity	V_{OD} = a small trigger pulse level
i = general purpose index	V_{TH} = minimum level that will trigger the recorder
K = number of data records	V_{os} = input offset of waveform recorder, ideally = 0
k = code bin	$W[k]$ = code bin width of code bin k
L = equivalent time sampling parameter	w = estimated word error rate
l = general-purpose factor	w' = worst-case word error rate
M = number of sequential samples	$w(i)$ = window function (for a DFT)
M_c = number of input sine-wave cycles	X = number of standard deviations of a Gaussian distribution
MSE = maximum static error	x = number of errors detected
m = average of rising and falling slopes of selected portions of a waveform	$\bar{y}$ = average of y_n over M samples
mse = mean square error	y_n = data samples within a record
N = number of digitized bits	y_n' = best fit points to a data record
n = sample index within a record	Z_0 = transmission line impedance
$P+, P-$ = maximum and minimum peak regions of a sine wave	Z_r = waveform recorder input impedance
p = probability	$Z_{u/2}$ = number of standard deviations that encompass 100 (1- u)% of a Gaussian distribution about the center
Q = ideal code-bin width, expressed in input units	

4. Test Methods

4.1 General Methods

4.1.1 Taking a Record of Data. A record of data is a sequential collection of samples acquired by the waveform recorder. The action of taking a record of data is defined as creating the record of data in the recorder by making a measurement, and then transferring the data record to a computer for analysis.

4.1.2 Locating Code Transition Levels. Since a waveform recorder digitizes the signal for storage, many of the specifications describe the fidelity of the digitization process. The fidelity of digitization depends on how well the code bins into which the samples fall match the ideal. The only way of directly measuring the code bins is to identify the end points of the bins. The end points are called code transition levels. Measurement of the code transition levels is used to determine conformance to several specifications.

The integer k is the recorder's output code, which ranges from 0 to $2^N - 1$, where N is the number of digitized bits. The k^{th} code transition level $T[k]$ is defined to be the input value corresponding to the transition between codes k and $k - 1$. Therefore $T[k]$ is the input value for which 50% of the output codes will be less than k , and 50% will be greater than or equal to k .

4.1.2.1 Test Method. A programmable source (for example, a digital to analog converter) is required whose range and output parameter (voltage or current) is compatible with the waveform recorder, and whose resolution is at least four times that of the waveform recorder. The static transfer characteristic of the source should be known. The code transition levels are then determined as follows:

The output of the source is connected to the input of the waveform recorder. Perform the following steps:

- (1) Begin with $k = 1$.
- (2) Apply an input level slightly lower than the expected code transition level. For $k = 1$, begin with a value slightly lower (for example 2%) than the minimum level recordable by the waveform recorder.
- (3) Take a record of data. Evaluate the record to determine the percentage of codes in the record that are less than k . Temporarily store the percentage along with the corresponding input value.
- (4) If the percentage from Step (3) is greater than 50%, then raise the input value by $\frac{1}{4} \text{ lsb}$ (of the waveform recorder) or less,

and repeat (3), updating the stored input value and percentage.

- (5) The first time the percentage drops to 50% or less, the transition has been crossed. The code transition level is computed by linear interpolation based on the recorded percentages at this level and the previous level. Record the interpolated value as the code transition level $T[k]$.
- (6) After finding $T[k]$, repeat (2) to find $T[k + 1]$ [The final level of Step (5) for the k^{th} code transition level will generally be a satisfactory starting point for code transition level $k + 1$, Step (2)].
- (7) Repeat Step (6) until all T have been found.

Care should be taken to ensure the impedance of the source and the input impedance of the recorder do not affect this measurement.

4.1.2.2 Significance of Record Length and the Presence of Noise. The location of code transition levels is a probabilistic process because of the inevitable presence of noise. As a consequence, the percentages estimated by the measurements of 4.1.2.1 have an associated standard deviation. Corresponding uncertainties in the estimates of the code transition levels result. The uncertainties can be reduced by choosing larger record lengths.

Assuming the noise to have zero mean and a normal distribution, the size of the record required for a given precision in the estimates of code transition levels can be computed. Table 1 gives the precision with a 99.9% (3σ) confidence level, expressed as a percentage of the root-mean-square (rms) noise value, computed for several record lengths.

If the precision must be known absolutely (that is, in terms of input units) rather than as a percentage of the noise, then the noise level must be determined. Section 4.5.5 gives procedures for

Table 1

Record Length (samples)	Precision of Estimates of Code Transition Level (times σ -noise)
64	45%
256	23%
1024	12%
4096	6%