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IEEE Standard for Transitions, Pulses, and Related Waveforms

IEEE Instrumentation and Measurement Society

Sponsored by the
Waveform Generation, Measurement, and Analysis Committee

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IEEE Std 181™-2011
(Revision of
IEEE Std 181-2003)

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Approved 16 May 2011

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Abstract: Approximately 100 terms and their definitions, for accurately and precisely describing the waveforms of pulse signals and the process of measuring pulse signals, are presented in this standard. Algorithms are provided for computing the values of defined terms that describe measurable parameters of the waveform, such as transition duration, state level, pulse amplitude, and waveform aberrations. These analysis algorithms are applicable to two-state waveforms having one or two transitions connecting these states. Compound waveform analysis is accomplished by decomposing the compound waveform into its constituent two-state single-transition waveforms.

Keywords: aberration, algorithms, compound waveform, histogram, IEEE 181, levels, pulse, pulse amplitude, pulse definitions, pulse measurement, states, state boundaries, state levels, transients, transitions, transition duration, waveforms, waveform analysis, waveform definitions, waveform parameters, waveform terms

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Introduction

This introduction is not part of IEEE Std 181-2011, IEEE Standard for Transitions, Pulses, and Related Waveforms.

This standard was developed by the Subcommittee on Pulse Techniques (SCOPT). It supersedes IEEE Std 181-2003[a]. The SCOPT is a subcommittee of the Waveform Generation, Measurement, and Analysis Committee (TC-10) of the IEEE Instrumentation and Measurement (I&M) Society. The SCOPT comprises an international group of electronics engineers, mathematicians, and physicists with representatives from national metrology laboratories, national science laboratories, academia, and electronic industries (semiconductor, computing, telecommunication, test instrumentation, and so forth).

This standard facilitates accurate and precise communication concerning parameters of transition, pulse, and related waveforms, and the techniques and procedures for measuring them. Because of the broad applicability of electrical pulse technology in the electronics industries (such as computer, telecommunication, and test-instrumentation industries), the development of unambiguous definitions for pulse terms, and the presentation of methods and/or algorithms for their calculation is important for communication between manufacturers and consumers within the electronics industry. The availability of standard terms, definitions, and methods for their computation helps improve the quality of products and helps the consumer better compare the performance of different products. Improvements to digital waveform recorders have facilitated the capture, sharing, and processing of waveforms. Frequently these waveform recorders have the ability to process the waveform internally and provide pulse parameters. This process is done automatically and without operator intervention. Consequently, a standard is needed so that the definitions and methods of computation for pulse parameters are consistent.

The purpose of this revision was to update terminology, correct errors in the previous revision, and add a newly developed method for computing state levels. A Project Authorization Request (PAR) was submitted to the IEEE Standards Board in March 2008 to develop this revision. The PAR was approved on 19 May 2008.

History

Between 1996 and 2003, the SCOPT prepared a revision to the now withdrawn IEEE Std 181-1977, Standard on Pulse Measurement and Analysis by Objective Techniques, and withdrawn IEEE Std 194™,[b],-1977, Standard Pulse Terms and Definitions. These standards dealt with terms and definitions for describing and computing waveform parameters and for describing the waveform measurement process. IEEE Std 181-2003 combined the information of and superseded IEEE Std 181-1977 and IEEE Std 194-1977, both of which were withdrawn. IEEE Std 181-1977 superseded IEEE Std 181-1955. Information about IEEE Std 181-1955 and the history of the development of IEEE Std 181-1977 is located in the Foreword of the latter. The IEEE Std 194-1977 superseded IEEE Std 194-1951, IEEE Standard on Pulses: Definition of Terms—Part 1. Information about IEEE Std 194-1951 is also located in the Foreword of IEEE Std 194-1977.

The work that resulted in IEEE Std 181-2003 began in September 1996, when SCOPT submitted a PAR to the IEEE Standards Board to combine IEEE standards 181 and 194 into a single document and revise the subsequently merged document. The PAR was approved on 11 December 1996 and work on the revised and combined draft began in February 1997. The PAR expiration date was December 2002. Because of delays, SCOPT and TC-10 received approval from the IEEE for a one-year extension to enable balloting and revision as required. The draft went through several major revisions that resulted in IEEE Std 181-2003.

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Other than the merger of the two withdrawn standards, IEEE Std 181-1977 and IEEE Std 194-1977, respectively, the two major changes to the content of the standard were in the parameter definitions and algorithms. Changes to the definitions included the addition of new terms and definitions, deleting unused terms and definitions, expanding the list of deprecated terms, and updating and modifying existing definitions. This standard contains definitions for approximately 100 terms commonly used to describe the waveform measurement and analysis process and waveform parameters. Many of the terms in the 1977 versions of these standards have been deleted entirely or deprecated. Deprecated terms were kept in the standard to provide continuity between this and the withdrawn standards. Terms are deprecated whenever they cannot be defined unambiguously or precisely. Terms that were deleted had to do with signal shaping terminology and pulsed radio frequency signals, which were not within the scope of the standard, as determined by SCOPT. Development of a set of agreed-upon terms and definitions presented the greatest difficulty because of the pervasive misuse, misrepresentation, and misunderstanding of terms. Legacy issues for instrumentation manufacturers and terms of common use also had to be addressed.

These revisions also resulted in the development of algorithms for computing the values of certain waveform parameters in all cases where these algorithms could be useful or instructive to the user of the standard. The intention of the SCOPT in adding these algorithms, which are recommended for use, was to provide industry with a common and communicable reference for these parameters and their computation. Heretofore, this was not available and there existed much debate and misunderstanding between various groups measuring the same parameters. Similarly, this is the reason the SCOPT decided to add several examples of basic waveforms, with formulae. The SCOPT focused these algorithms on the analysis of two-state, single-transition waveforms. The analysis of compound waveforms (waveforms with two or more states and/or two or more transitions) is accomplished by first decomposing the compound waveform into its constituent two-state, single-transition waveforms. A method for performing this decomposition is provided.

Algorithms for the analysis of fluctuation and random jitter of waveforms were also introduced into the standard. These algorithms describe the computation of the mean and standard deviation of jitter and fluctuation. The standard also contains methods to estimate the accuracy of the standard deviation and to correct its value.

The SCOPT added Annex A into this standard, which contains numerous figures depicting different types of waveforms. These waveform examples, with the associated expressions used to generate them, help the reader understand the use of certain defined terms and provide a common ground for communicating waveform types and how they can be computed.

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Participants

At the time this standard was completed, the Transitions, Pulses, and Related Waveforms Working Group had the following membership:

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IEEE Standard for Transitions, Pulses, and Related Waveforms

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1. Overview

1.1 Scope

This standard defines terms pertaining to transitions, pulses, and related waveforms and defines procedures for estimating their parameters.

1.2 Purpose

The purpose of the standard is to unambiguously and accurately define terms pertaining to transitions, pulses, and related waveforms and the algorithm for their computation. This helps to communicate requirements between vendors and users, improves understanding and readability of instrument performance specifications, and provides a common ground for parameter and performance comparisons.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ISO/IEC Guide 98-3:2008, Uncertainty of measurement—Part 3: Guide to the expression of uncertainty in measurement (GUM).[1]

ISO/IEC Guide 99:2007, International Vocabulary of Metrology—Basic and general concepts and associated terms (VIM).

ISO 10012:2003, Measurement management systems—Requirements for measurement processes and measuring equipment.

3. Definitions, symbols and deprecated terms

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary: Glossary of Terms & Definitions*[2] and ISO/IEC Guide 99:2007 should be referenced for terms not defined in this clause.

Along with the recommended terms and their definitions, a number of deprecated but widely used terms are listed in 3.3. The reasons for their deprecation are noted after the definition of the recommended term. All defined terms are italicized in this document.

Throughout this standard, time is an independent variable, symbolized with the letter *t*. *Waveform* value is used to refer to the dependent variable, symbolized by *y(t)*. For particular waveforms, *waveform* value will be synonymous with terms such as *voltage, current, power,* or some other quantity.

aberration region

> **aberration region, post-transition:** The *interval* between a user-specified *instant* and a fixed *instant*, where the fixed *instant* is the first sampling i*nstant* succeeding the 50% *reference level instant* for which the corresponding *waveform* value is within the *state boundaries* of the state succeeding the 50% *reference level instant*. The user-specified *instant* occurs after the fixed *instant* and is typically equal to the fixed *instant* plus three times the *transition duration*.
>
> **aberration region, pre-transition:** The *interval* between a user-specified *instant* and a fixed *instant*, where the fixed *instant* is the first *sampling instant* preceding the 50% *reference level instant* for which the corresponding waveform value is within the state boundaries of the state preceding the 50% *reference level instant*. The user-specified *instant* occurs before the fixed *instant* and is typically equal to the fixed *instant* minus three times the *transition duration*.

accuracy: The closeness of agreement between the result of a measurement and the true value of the measurand.

[1]ISO/IEC publications are available from the ISO Central Secretariat, Case Postale 56, 1 rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iso.ch/). ISO/IEC publications are also available from the American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036 (http://ansi.org).
[2]The *IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at http://shop.ieee.org/.

amplitude

amplitude, impulse: The difference between the specified *level* corresponding to the *maximum peak* (*minimum peak*) of the positive (negative) *impulse-like waveform* and the level of the state preceding the first *transition* of that *impulse-like waveform***.**

amplitude, waveform: The difference between the *levels* of two different *states* of a *waveform*. Two different definitions for *amplitude* are authorized by this standard because they are both in common use. In all applications of this standard, the chosen definition shall be clearly identified. The two definitions are as follows:

amplitude, waveform, signed: The *level* of the *state* succeeding a *transition* minus the *level* of the *state* preceding the same *transition*.

amplitude, waveform, unsigned: The absolute value of the *signed amplitude*.

correction: This operation combines the results of the conversion operation with the transfer function information to yield a *waveform* that is a more accurate representation of the *signal*. *Correction* shall be performed to an *accuracy* that is consistent with the overall *accuracy* desired in the *waveform measurement process*.

NOTE—*Correction* may be effected by a manual process by an operator, a computational process, or a compensating device or apparatus. See 4.1.[3]

cycle: A portion of a *periodic waveform* with a *duration* of one *period*.

delaying: A process in which a *signal* is caused to occur later in time.

differentiation: A shaping process in which a *waveform* is converted to a *waveform* whose shape is, or approximates, the time derivative of that *waveform*.

duration: The difference between two specified *instants*.

duty factor: Unless otherwise specified, for a *periodic pulse train*, the ratio of the *pulse duration* to the *waveform period*.

NOTE—The term *duty cycle* is deprecated because the word *cycle* in this standard refers to the *period* of a *signal*.

fluctuation: Variation (dispersion) of a *level* parameter of a set of *repetitive waveforms* with respect to a *reference amplitude* or a *reference level*.

NOTE—Unless otherwise specified by a mathematical adjective, *rms fluctuation* is assumed.

frequency: The reciprocal of *waveform period*.

glitch: A *transient* that leaves an *initial state*, enters the *boundaries* of another *state* for a *duration* less than the *duration* for *state occurrence*, and then returns to the *initial state*.

instant: A particular time value within a *waveform epoch* that, unless otherwise specified, is referenced relative to the *initial instant* of that *waveform epoch*.

instant, final: The last sample *instant* in the *waveform*.

instant, impulse center: The *instant* at which a user-specified approximation to the *maximum peak* (*minimum peak*) of the positive (negative) *impulse-like waveform* occurs.

[3]Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

instant, initial: The first sample *instant* in the *waveform*.

instant, pulse center: The average of the two *instants* used to calculate the *pulse duration*.

instant, reference level: An *instant* at which the *waveform* intersects a specified *reference level*.

instant, transition occurrence: The first 50% *reference level instant*, unless otherwise specified, on the *transition* of a *step-like waveform*.

NOTE—See 5.3.3.1 and Figure 2 through Figure 6.

integration: A shaping process in which a *waveform* is converted to a *waveform* whose shape is or approximates the time integral of that *waveform*.

interval: The set of all values of time between a first *instant* and a second *instant*, where the second *instant* is later in time than the first.

NOTE—These first and second *instants* are called the endpoints of the *interval*. The endpoints, unless otherwise specified, are assumed to be part of the *interval*.

jitter: The variation (dispersion) of a time parameter between successive *cycles* of a *repetitive signal* and/or between successively acquired *waveforms* of a *repetitive signal* for a given *reference level instant* or *duration*.

NOTE—Unless otherwise specified by a mathematical adjective, *rms jitter* is assumed.

jitter, cycle-to-*n*th-cycle: The *jitter* between specified *reference level instants* of any two specified *cycles* of a *repetitive signal*.

jitter, period: The *jitter* in the *period* of a *repetitive signal* or its *waveform*.

jitter, pulse duration: The *jitter* in the *pulse duration* of a *signal* or its *waveform*.

jitter, trigger: The *jitter* between a *repetitive signal* and the trigger event that is used to generate or measure that *signal*.

level: Constant value having the same units as y.

level, average: Pertaining to the value of the mean of the *waveform level*. If the *waveform* takes on n discrete values, y_j, all equally spaced in time, the *average level* is,

$$\overline{y} = \left(\frac{1}{n}\right)\sum_{j=1}^{n} y_j$$

If the *waveform* is a continuous function of time $y(t)$,

$$\overline{y} = \left(\frac{1}{t_2 - t_1}\right)\int_{t_1}^{t_2} y(t)\,dt$$

The summation or integral extends over the *waveform epoch* for which the *average level* is desired or, if the function is *periodic*, over any integral number of *periodic* repetitions of the function.

level, average absolute: Pertaining to the mean of the absolute *waveform* value. If the *waveform* takes on *n* discrete values y_j, all equally spaced in time, the *average absolute level* is,

$$\overline{|y|} = \left(\frac{1}{n}\right)\sum_{j=1}^{n}\left|y_j\right|$$

If the *waveform* is a continuous function of time *y(t),*

$$\overline{|y|} = \left(\frac{1}{t_2 - t_1}\right)\int_{t_1}^{t_2}\left|y(t)\right|dt$$

The summation or the integral extends over the *waveform epoch* for which the *average absolute level* is desired or, if the function is *periodic*, over any integral number of *periodic* repetitions of the function.

level, percent reference: A *reference level* specified by:

$$y_{x\%} = y_{0\%} + \frac{x}{100}\left(y_{100\%} - y_{0\%}\right)$$

where

$0\% < x < 100\%$

$y_{0\%}$ is the *level* of *low state*
$y_{100\%}$ is the *level* of *high state*
$y_{0\%}$, $y_{100\%}$, and $y_{x\%}$ are all in the same unit of measurement

NOTE 1—Commonly used reference levels are: 0%, 10%, 50%, 90%, and 100%.

NOTE 2—See Figure 2 through Figure 5.

level, reference: A user specified *level* that extends through all *instants* of the *waveform epoch*.

NOTE—*Mesial, proximal,* and *distal* lines are deprecated terms because 1) line refers to consideration of and computations using a *pictorial waveform representation,* whereas *waveforms* today are primarily stored in *digital waveform representations* and computation and viewing are done using a computer; 2) they refer to user-defined *reference levels,* and it is not necessary to have redundant definitions for these *reference levels*; and 3) the terms *proximal* and *distal* cannot be used unambiguously to describe lines or points on either side of a *transition* of a *step-like waveform* because they depend on whether the *step-like waveform* is for a *positive pulse* or a *negative pulse.* In other words, the proximal line and points if referenced to the 10% *reference level* will appear to the left of a *transition* for a *positive pulse* and to the right for a *negative pulse*.

level, root-mean-square (rms): Pertaining to the value of the square root of the average of the squares of the *waveform* values. If the *waveform* takes on *n* discrete values y_j, all equally spaced in time, the *rms level* is,

$$y_{\text{rms}} = \sqrt{\left(\frac{1}{n}\right)\sum_{j=1}^{n}y_j^2}$$

If the *waveform* is a continuous function of time *y(t),*

$$y_{\text{rms}} = \sqrt{\left(\frac{1}{t_2 - t_1}\right)\int_{t_1}^{t_2}y^2(t)\,dt}$$

The summation or the integral extends over the *waveform epoch* for which the *rms level* is desired or, if the function is *periodic*, over any integral number of *periodic* repetitions of the function.

level, root sum of squares (rss): Pertaining to the value of the square root of the arithmetic sum of the squares of the *waveform values*. If the *waveform* takes on *n* discrete values y_j, all equally spaced in time, the *rss level* is,

$$y_{\mathrm{rss}} = \sqrt{\sum_{j=1}^{n} y_j^2}$$

If the *waveform* is a continuous function of time *y(t)*,

$$y_{\mathrm{rss}} = \sqrt{\int_{t_1}^{t_2} y^2\left(t\right) dt}$$

The summation or the integral extends over the *waveform epoch* for which the root sum of squares *level* is desired.

offset: The algebraic difference between two specified *levels*. Unless otherwise specified, the two *levels* are *state* 1 and the *base state*.

NOTE—See Figure 2 through Figure 5.

overshoot: A *waveform aberration* within a *post-transition aberration region* or *pre-transition aberration region* that is greater than the *upper state boundary* for the associated *state level*.

NOTE 1—If more than one such *waveform* aberration exists, the one with the largest magnitude is the *overshoot* unless otherwise specified.

NOTE 2—See Figure 9 and Figure 10.

parameter: Any value (number multiplied by a unit of measure) that can be calculated from a *waveform*.

parameter, level: A *parameter* whose units are the same as the units of *levels*.

parameter, time: A *parameter* whose units are a unit of time.

peak, maximum (minimum): Pertaining to the greatest (least) value of the *waveform*.

peak-to-peak: Pertaining to the value of the difference between the extrema of the specified *waveform*.

periodic (aperiodic): Having the properties of a *periodic* (*aperiodic*) function.

precision: The degree of agreement between independent measurements of the same parameter.

pulse duration: The difference between the first and second *transition occurrence instants*.

NOTE 1—See Figure 4 and Figure 5.

NOTE 2—*Pulse width,* as well as *full width at half maximum* (FWHM) and *half width at half maximum* (HWHM) are, in general, deprecated terms, because *width* is a word that denotes a spatial parameter whereas the parameter of interest is time. However, in some applications, it may be desirable to discuss the spatial location of a propagating pulse and its spatial distribution, i.e., *pulse width* in matter or space. FWHM, HWHM, and *full duration at half maximum* (FDHM) are deprecated terms because of the reference to the maximum value of the *waveform,* where the *waveform amplitude* may be either positive or negative and the *waveform* may contain noise.

pulse separation: The *duration* between the 50% *reference level instant*, unless otherwise specified, of the second *transition* of one *pulse* in a *pulse train* and that of the first *transition* of the immediately following *pulse* in the same *pulse train*.

pulse train: A *repetitive* sequence of *pulse waveforms*. Unless otherwise specified, all of the *pulse waveforms* in the sequence are assumed to be identical.

NOTE—See Figure A.12.

pulse waveform: A *waveform* whose *level* departs from one *state*, attains another *state*, and ultimately returns to the original *state*.

NOTE 1—As defined here, a pulse waveform consists of two *transitions* and two *states*. Alternatively, a *pulse waveform* can be described as a *compound waveform* consisting of the sum of a positive (negative) *step-like waveform* and a *delayed* negative (positive) *step-like waveform* both having the same *unsigned waveform amplitude*.

NOTE 2—*Leading edge* and *trailing edge* are deprecated terms because 1) the word *edge* describes the property of a geometric figure, which is not contained by or representative of the physical signal that corresponds to the *waveform*, and 2) the terms *first* and *second* adequately and unambiguously describe the meanings of leading and trailing.

NOTE 3—See Figure 4 and Figure 5.

pulse waveform, negative: A pulse waveform whose first transition is a negative-going transition.

NOTE—See Figure 5.

pulse waveform, positive: A pulse waveform whose first transition is a positive-going transition.

NOTE—See Figure 4.

reference: Of or pertaining to a time, *level*, *waveform feature*, or *waveform* that is used for comparison with, or evaluation of, other times*, levels, waveform features,* or *waveforms*. This type of entity may, or may not, be an ideal entity.

repetitive (nonrepetitive): Of or pertaining to a series of specified *waveform features* or *waveforms* that repeat or recur (do not repeat or recur) in time.

resolution: The smallest distinguishable increment into which a measured quantity is divided.

ringing: An *aberration* in the form of a superimposed oscillatory *waveform* that, when present, usually follows a *transition*.

runt: A *transient* that leaves an initial *state*, does not attain the *level* of anther *state*, and returns to the initial *state*.

sampling: A process of determining representative *levels* at selected *instants* of a *waveform* for the purpose of determining parameters or characteristics of the whole *waveform*.

signal: A physical phenomenon that is a function of time and space.

spike: A *transient* that leaves an initial *state*, exceeds the farthest *state boundary* of any other state, and returns to the initial *state*.

state: A particular *level* or, when applicable, a particular *level* and upper and lower limits (the upper and lower *state boundaries*) that are referenced to or associated with that *level*.

NOTE 1—Unless otherwise specified, multiple *states* are ordered from the most negative *level* to the most positive *level*, and the *state levels* are not allowed to overlap. The most negative *state* is called *state* 1. The most positive *state* is called *state n*. The *states* are denoted by $s_1, s_2, \ldots, s_n$; the *state levels* are denoted by *level*(s_1), *level*(s_2), …, *level*(s_n); the upper *state boundaries* are denoted by upper(s_1), upper(s_2), …, upper(s_n); and the lower *state boundaries* are denoted by lower(s_1), lower(s_2), …, lower(s_n).

NOTE 2—*States*, *levels*, and *state boundaries* are defined to accommodate pulse metrology and digital applications. In pulse metrology, the *levels* of a *waveform* are measured and *states* (with or without associated *state boundaries*) are then associated with those *levels*. In digital applications, *states* are defined (with *state boundaries*) and the *waveform* values are determined to either lie within a *state* or not.

state, base: The *state* of a *waveform* that, unless otherwise specified, possesses a *level* closest to zero.

NOTE—See Figure 2 through Figure 6.

state, high: The most positive *state* within the *waveform epoch*, unless otherwise specified.

NOTE—For *waveforms* with exactly two *states*, such as the single *transition waveform,* the terms *low state* and *high state* may be used in lieu of the terms *state* 1 and *state* 2, respectively.

state, low: The most negative *state* within the *waveform epoch*, unless otherwise specified.

NOTE—For *waveforms* with exactly two *states*, such as the single *transition waveform,* the terms *low state* and *high state* may be used in lieu of the terms *state* 1 and *state* 2, respectively.

state, positive (negative): A *state* whose *level* is greater (less) than zero.

state boundaries: The upper and lower limits of the *states* of a *waveform*. All values of a *waveform* that are within the boundaries of a given *state* are said to be in that *state*.

NOTE—The *state boundaries* are defined by the user.

state occurrence: A contiguous region of a *waveform* that is bounded by the upper and lower *state boundaries* of a *state*, and whose *duration* equals or exceeds the specified minimum *duration* for state attainment.

NOTE—The *state occurrence* consists of the entire portion of the *waveform* that remains within the boundaries of that *state*. *State occurrences* are numbered as ordered pairs (s, *n*), where s_i refers to the *i*th *state*, and *n* is the number of the occurrence of that particular *state* within the *waveform epoch*. In a given *waveform epoch*, when the *waveform* first enters a state, s_1, that state occurrence is (s_1, 1). If and when the *waveform* exits that *state*, that *state occurrence* is over. If and when the *waveform* next enters and remains in *state* s_1, that *state occurrence* would be labeled (s_1, 2); and so on. Thus, the *state occurrences* for a single *pulse* (see Figure 4 and Figure 6) are (s_1, 1), (s_2, 1), (s_1, 2). The *state occurrences* for the *compound waveform* (see Figure 6) are (s_2, 1), (s_4, 1), (s_3, 1), (s_5, 1), (s_1, 1). Note that a *waveform* can exit one *state occurrence* without (necessarily) immediately entering another *state occurrence.* That is, the *waveform state* between *state occurrences* can be undefined for some time *interval*, for example, during *transitions* and in the case of *transients* (such as, *runt* pulses).

synchronizing: The process of aligning the *transition occurrence instant* of one *pulse* or other event with the *transition occurrence instant* of another *pulse* or event. If two series of events, such as two *pulse trains,* are synchronized, then their *periods* shall be integer multiples of one another.

terminal feature: Any contiguous region of a *waveform* that is neither a *state occurrence,* nor a *transient,* nor a *transition*. This feature, if present, occurs only at the beginning and/or end of a *waveform*.

tilt: A distortion of a *waveform state* wherein the overall slope over the extent of the *waveform state* is essentially constant and other than zero. This distortion may be of either polarity.

NOTE—The term *droop* is deprecated because it implies a negative slope and therefore cannot be applied unambiguously to both *positive pulse waveforms* and *negative pulse waveforms*.

transient: Any contiguous region of a *waveform* that begins at one *state*, leaves and subsequently returns to that *state*, and contains no *state occurrences*.

transition: Contiguous region of a *waveform* that connects, either directly or via intervening transients, two *state occurrences* that are consecutive in time but are occurrences of different *states*.

transition, negative-going: A *transition* whose terminating *state* is more negative than its originating state.

NOTE 1— The endpoints of the *negative-going transition* are the last exit of the *waveform* from the higher *state boundary* and the first entry of the *waveform* into the lower *state boundary*.

NOTE 2— The term *falling edge* is deprecated because 1) the word *edge* describes the property of a geometric figure, which is not contained by, or representative of, the physical signal that corresponds to the *waveform*, and 2) the word *falling* refers to motion or position of physical objects.

transition, pass through: The *transition* from an initial *state* to a nonconsecutive *state* through any number of other *states* where the *duration* in these other *states* is less than the *duration* for *state occurrence*.

transition, positive-going: A *transition* whose terminating *state* is more positive than its originating *state*.

NOTE 1— The endpoints of the *positive-going transition* are the last exit of the *waveform* from the lower *state boundary* and the first entry of the *waveform* into the higher *state boundary*.

NOTE 2— The term *rising edge* is deprecated because 1) the word *edge* describes the property of a geometric figure, which is not contained by, or representative of, the physical signal that corresponds to the *waveform*, and 2) the term *rising* refers to motion or position of physical objects.

transition duration: The difference between the two *reference level instants* of the same *transition*. Unless otherwise specified, the two *reference levels* are the 10% and 90% *reference levels*.

NOTE 1—See Figure 2 and Figure 3.

NOTE 2—The following terms are deprecated: *risetime (rise time), falltime (fall time), leading edge, rising edge, trailing edge, falling edge,* and *transition.* The terms *risetime, falltime,* and *transition time,* although widely used, are deprecated because they are ambiguous and confusing. First, the use of the word *time* in this standard refers exclusively to an *instant* and not an *interval*. Also, if the first transition of a *waveform* within a *waveform epoch* happens to be a *negative-going transition,* some users may refer to its *transition duration* as its *risetime*, and some others may refer to its *transition duration* as its *falltime*. If the use of these deprecated terms is required, then *risetime* is synonymous with the *transition duration* of a *positive-going transition,* and *falltime* is synonymous with the *transition duration* of a *negative-going transition*. If the *upper* and lower *state boundaries* of the two *states* are not the user-defined *reference levels* (for example, the 10% and 90% *reference levels*), then the *duration* of a *transition* is not equal to the *transition duration*.

transition settling duration: The time interval between the 50% *reference level instant*, unless otherwise specified, and the final *instant* the *waveform* crosses the *state boundary* of a specified *state* in its approach to that *state*.

NOTE—The term *settling time* is deprecated because the word *time* in this standard refers exclusively to an *instant* and not an *interval*.

transition settling error: The maximum error between the *waveform* value and a specified *reference level* within a user-specified *interval* of the *waveform epoch*. The *interval* starts at a user-specified *instant* relative to the 50% *reference level instant*.

triggering: A process in which a *step-like signal, pulse,* or *compound* signal initiates a predetermined event or response.

undershoot: A *waveform aberration* within a *post-transition aberration region* or *pre-transition aberration region* that is less than the lower *state boundary* for the associated *state level*.

NOTE 1—If more than one such *waveform aberration* exists, the one with the largest magnitude is the *undershoot* unless otherwise specified.

NOTE 2—See Figure 9 and Figure 10.

NOTE 3—The term *preshoot* is deprecated because the prefix, pre,*"* is temporal and the root word, *shoot*, in this context, refers to a *level parameter*.

waveform: A representation of a *signal* (for example, a graph, plot, oscilloscope presentation, discrete time series, equations, or table of values). This term refers to a measured or otherwise-defined estimate of the physical phenomenon or *signal*.

NOTE—See Figure 2through Figure 6, and the figures in Annex A.

waveform, compound: A *waveform* that may be completely represented by *m states* and *n transitions* where $(m + n) \geq 4$.

NOTE 1—See Figure 6.

NOTE 2—Any *compound waveform* can be parsed (see 5.5).into *n* two-state *waveforms*.

waveform, impulse-like: A *waveform* that, when convolved with an ideal step, yields a step-like *waveform*.

NOTE—See Figure 6.

waveform, reference: A *waveform* against which other *waveforms* are compared.

NOTE—Annex A contains figures that depict different *reference waveforms*.

waveform, step-like: A *waveform* whose *level* departs from one *state* and attains another *state*.

NOTE 1—Unless otherwise specified, multiple transitions are ordered from the earliest transition occurrence *instant* to the latest occurrence in time.

NOTE 2—See Figure 2 and Figure 3.

waveform, transition: A *waveform* consisting of a *transition* and the two *states* joined by that *transition*.

waveform aberration: The algebraic difference in *waveform* values between all corresponding *instant*s in time of a *waveform* and a *reference waveform* in a specified *waveform epoch*.

NOTE—See Figure 8.

waveform aberration, percent: For a two-state *waveform,* this is expressed as a percentage of the *waveform amplitude* of the *reference waveform*, unless otherwise specified.

NOTE—Compound waveforms may be parsed (see 5.5) into a set of two-state waveforms after which percent *waveform aberration* may be defined for each two-state *waveform* of that set.

waveform delay (advance): The *duration* between the first *transition occurrence instant* of two *waveform*s.

waveform epoch: An *interval* to which consideration of a *waveform* is restricted for a particular calculation, procedure, or discussion. Except when otherwise specified, it is assumed to be the span over which the *waveform* is measured or defined.

NOTE—See Figure 2 through Figure 5.

waveform feature: A specified portion or segment of a *waveform*.

waveform measurement process: A realization of a method of *measurement* in terms of specific devices, apparatus, instruments, auxiliary equipment, conditions, operators, and observers. In this process, a value (a number multiplied by a unit) of measurement is assigned to the elements of the *waveform*.

waveform period: The minimum *duration* after which a *periodic waveform* repeats. The period of a *repetitive* two-state *waveform* is the *duration* between specified *reference level instants* for the same *transition*, either the *negative-going transition* or the *positive-going transition,* of two consecutive *pulses* in a *pulse train*. The period is equal to the sum of the *pulse separation* and the *pulse duration*.

waveform representation

waveform representation, pictorial: A pictorial format is a graph, plot, or display in which a *waveform* is presented for observation or analysis.

NOTE—Any of the *waveform* formats defined in the subclauses to follow may be presented in the pictorial format.

waveform representation, sampled: A sampled format is a *waveform* that is a series of *sample* numerical values taken sequentially or nonsequentially as a function of time. It is assumed that nonsequential samples may be rearranged in time sequence to yield the following sampled formats:

waveform representation, sampled, aperiodically: A format that is identical to the *periodically sampled format*, above, except that the sampling in real time is not *periodic* and wherein the data exists as coordinate *instant* pairs, t_1 , y_1; t_2 , y_2; ... ; t_n , y_n .

waveform representation, sampled, periodically: A finite sequence of *levels* y_0 , y_1 , y_2 , ... , y_n each of which represents the value of the *waveform* at times t_0, $t_0 + \Delta t$, $t_0 + 2\Delta t$, ... , $t_0 + n\Delta t$, respectively, wherein the data may exist in a pictorial format or as a list or table of numbers.

3.2 Symbols

A	*waveform amplitude*
d_f	*duty factor*
i	discrete time index
n	number of elements in a *waveform*
O_{post}	*overshoot* in the *post-transition aberration region* of a *waveform*
O_{pre}	*overshoot* in the *pre-transition aberration region* of a *waveform*
s_k	*state level k*
t	continuous time
$t_{x\%}$	*x% reference level instant*
t_0	*initial instant*
T	*waveform period*
t_d	*transition duration*
T_D	*waveform delay*
T_p	*pulse duration*
T_s	*pulse separation*
U_{post}	*undershoot* in the *post-transition aberration region* of a *waveform*

U_{pre}	*undershoot* in the *pre-transition aberration region* of a *waveform*
W_a	*waveform aberration,* given as percentage of *waveform amplitude*
$y(t)$	*waveform amplitude* values for a continuous-time signal
y_i	*waveform amplitude* values for a discrete-time *waveform,* with discrete time index i
y_{rms}	*rms level*
y_{rss}	*rss level*
$y_{x\%}$	*x% reference level*
$\bar{y}$	*average level*
$\bar{y}_i$	mean over a collection of *waveforms* $y_{k,i}$, where k is the *waveform* index
Σ_i	the standard deviation of a set of standard deviations

3.3 Deprecated terms

Deprecated terms are listed below in the left-hand column, in alphabetical order, and the terms on the right are the accepted terms.

Droop	*tilt*
Duty cycle	*duty factor*
Falling edge	*negative-going transition*
Falltime (Fall time)	*transition duration*
Leading edge	*first transition*
Preshoot	*overshoot* or *undershoot* in the *pre-transition aberration region*
Pulse width	*pulse duration*
Risetime (Rise time)	*transition duration*
Rising edge	*positive-going transition*
Trailing edge	*second transition*
Transition	*transition duration*

NOTE—The word *transition* is deprecated when used to refer to an *interval* within a *waveform epoch* but when referring to an event, as defined in 3.1, it is not deprecated.

4. Measurement and analysis techniques

4.1 Descriptions of techniques and procedures

This subclause provides descriptions of the techniques and procedures for time-domain *waveform* measurements. The descriptions provided are independent of specific devices, apparatus, instruments, or computing devices that may be used in these measurements and are prerequisite to the following:

a) Efficient communication of the results of *transition, pulse,* and *compound waveform* measurements

b) Development and use of physical artifact standards for *transition, pulse,* and *compound waveform* apparatus

c) Development and use of procedures for apparatus that employ *transition, pulse,* and *compound waveform* techniques

4.2 Method of waveform measurement

A method of making a *waveform* measurement comprises the following:

a) The complete specification of all relevant functional characteristics of the devices, apparatus, instruments, and auxiliary equipment to be used

b) The specification of all essential corrections required to compensate or adjust for departure of the measurement process from ideality

c) The procedures to be used in making essential corrections

d) The operations to be performed and their sequence

e) The conditions under which all operations are to be carried out

4.3 Description of the waveform measurement process

The object of any *waveform measurement process* is the determination to some accuracy, either expressed or implied, of the value of one or more *parameters* of a *waveform*. Requirements for measurement processes are described in ISO 10012:2003. Figure 1 shows the constituent steps of any *waveform measurement process* where, as indicated, the process involves two distinct sequential subprocesses: 1) *signal*-to-*waveform* conversion, and 2) *waveform* analysis. Thus, the *waveform measurement process* involves:

a) The conversion of a *signal* into its transform, which is called its *waveform*

b) Analysis of the *waveform* to determine the value of one or more *parameters*

c) The assertion or assumption that the value of the *waveform parameter* thus determined is, to some *accuracy,* identical to the value of the *signal parameter*. The validity of the final assertion or assumption is dependent on the combined validity of the first two steps.

The vast array of devices, apparatus, instruments, and techniques, which may be configured in virtually limitless combinations to provide *signal*-to-*waveform* conversion, renders the discussion of specific implementations beyond the scope of this standard. Such discussion is deferred to other standards, documents, or specifications that describe or define the characteristics or methods of specific devices, apparatus, instruments, or techniques.

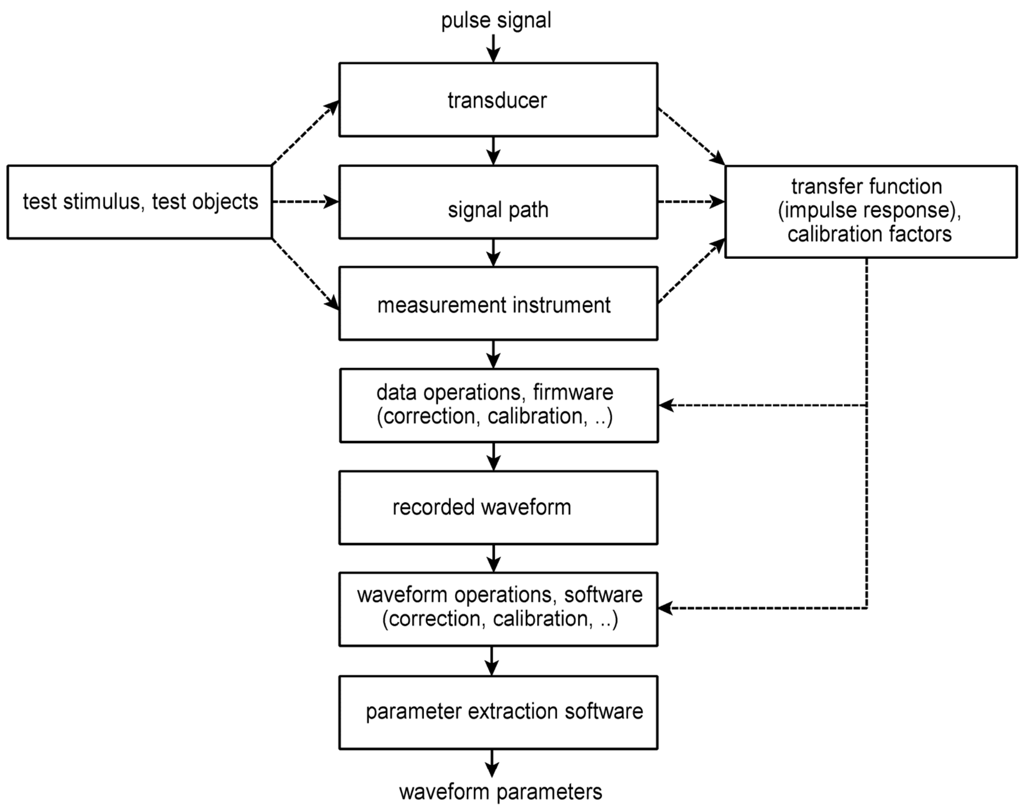


Figure 1—Waveform acquisition and measurement process

4.4 Waveform epoch determination

4.4.1 Selection of waveform epoch

A *waveform epoch* shall contain the *waveform features* under analysis. The *waveform epoch* shall contain sufficient data to yield all necessary *state levels* to the desired *accuracy* prescribed in the measurement process. These data may be augmented by *reference levels* that are determined using another *waveform epoch*.

4.4.2 Exclusion of data from analysis

A *waveform* may include *waveform features* or events that are nonpertinent in the circumstances of or to the application of the *waveform*. Nonpertinent data may be excluded from analysis; however, the basis for any such exclusion shall be stated.

When data within a *waveform epoch* are excluded from analysis, the following shall be specified:

a) The extent, in time or waveform value, of the excluded data

b) The basis for excluding the data

c) Whether the excluded data is ignored (that is, the *waveform* that is analyzed is discontinuous) or replaced (that is, the excluded data are replaced with other assumed or derived data).

5. Analysis algorithms for waveforms

5.1 Introduction and guidance

The analysis of a two-*state waveform* requires the sequential determination of the following:

a) Low or first *state leve*l and high or second *state level*

b) *Transition* or *waveform amplitude*

c) Necessary *percent reference levels* and corresponding *reference level instants* (unless otherwise specified, these are assumed to be the 10%, 50%, and 90% *reference levels* and *reference level instants*).

d) Values of all other *waveform parameters* as computed from *level* or *instant* pairs

a) Parameters contributing to the uncertainty in the computation of the *waveform parameters* should be identified and their relative importance assessed. For guidance in the computation and propagation of uncertainties, ISO/IEC Guide 98-3:2008 should be consulted as well as NIST Special Publication 811:2008 [B3].[4]

5.2 Selecting state levels

Algorithms for determining *state levels* are described in this subclause. There is no requirement that the same algorithm be used for determining different *state levels*. (These algorithms are described for single *transition waveforms* or single *pulse waveforms*, but they may also be applied to *compound waveforms* if desired.)

5.2.1 Data-distribution-based methods—Histograms

A histogram is an amplitude density representation of a *signal* whereas, for comparison, a *waveform* is an amplitude-versus-time representation of a *signal*. The amplitude density representation shows the number of occurrences of a given amplitude versus amplitude. To generate a histogram, the amplitude range shall be divided into M unique, but not necessarily equal, amplitude intervals. For simplicity, however, consider only the equal-amplitude-interval case. The amplitude interval is called the histogram bin width and M is the number of bins or the histogram size. The histogram is formed by counting the number of times a *waveform* value fits within a particular histogram bin; this is referred to as the bin count.

5.2.1.1 Algorithm

The determination of the *states* in a *waveform* using histogram methods requires the following steps:

a) Determine the maximum and minimum amplitude values, $y_{\max}$ and $y_{\min}$, of the *waveform* or data using step a.1) or step a.2):

   1) Search the *waveform* or data for $y_{\min}$ and $y_{\max}$.

   2) Set $y_{\min}$ and $y_{\max}$ from criteria specified by the user of this standard or knowledge of the *waveform* or data.

b) Calculate the amplitude range, y_R, of the *waveform* or data using: $y_R = y_{\max} - y_{\min}$.

[4]The numbers in brackets correspond to those of the bibliography in Annex A.

c) Calculate the bin width:

1) for equal-sized bins, Δy is found by dividing y_R by M by using:

$$\Delta y = \frac{y_R}{M} = \frac{y_{\max} - y_{\min}}{M} \tag{1}$$

where

Δy is the histogram bin width
M is the number of histogram bins (selection of M is discussed in 5.2.1.2)
$y_{\max}$ is the maximum *amplitude* value of the *signal*, y
$y_{\min}$ is the minimum *amplitude* value of the *signal*, y
y_R is the range of the *signal* values

2) for unequal-sized bins, the user of this standard specifies an array of bin widths, Δy_i.

d) Initially set $B_j = 0$ for $j = 1 \ldots M$, where B_j is the count for the jth histogram bin. Sort through the *waveform* or data values, y_i, $i = 1$, N, where N is the number of waveform values, and if y_i lies within the range of a bin, that is, if: $(y_{\min} + [\,j - 1]\,\Delta y) < y_i < (y_{\min} + j\,\Delta y)$, for $1 \leq j \leq M$, for equal-sized bins, or $(y_{\min} + \Delta y_j) < y_i < (y_{\min} + \Delta y_{j+1})$, for $1 \leq j \leq M$, for unequal-sized bin widths, then set $B_j = B_j + 1$, where B_j is the count in the jth histogram bin. If a data value equals the value of a bin boundary, that data value shall be assigned to one of the bins located on either side (below or above) of that bin boundary. The side that is selected shall be consistently applied to all such data values and specified by the user of this standard.

5.2.1.2 Selection of the number of histogram bins, *M*

Two methods are described in this clause to select M for a waveform that exhibits a bimodal amplitude distribution and contains one *transition*. N_S*-state waveforms* ($N_S > 2$) and N_T*-transition waveforms* ($N_T > 1$) can also be operated on with the techniques mentioned here. However, these techniques will require that the *waveform* be parsed (see 5.5) into subwaveforms where each subwaveform contains one *transition* and two *states*. The limitations of each method for determining M are indicated. All of these methods are based on the requirement that the extracted pulse parameters agree with observation. The value of M has an upper and lower limit. The value of M should be large enough so that the desired amplitude resolution of the parameters that are derived from the histogram is not degraded or reduced. The value of M should not be so large that the histogram bin width is smaller than the amplitude quantization of the waveform. The amplitude quantization is dependent on the input range of the instrument over which the input range of the analog-to-digital converter (ADC) is applied, the number of bits in the ADC, and whether or not waveform averaging was performed.

If the data for which a histogram is being made is obtained from an ADC, then it is usually important to make the histogram bin width compatible with the width of the quantization bins of the ADC. The width of the quantization bin of an ADC is the interval of input values that produce a single output value, that is, the interval between transition *levels* of the ADC. If the data is the average of N readings of the ADC, then each ADC bin is effectively divided into N equal-sized smaller bins. (Averaging effectively reduces the bin size of the ADC.)

Each histogram bin width shall be an integer number of ADC bin widths. If the histogram bin width used in 5.2.1.1 is equal to $(n + x)$ ADC bin widths, where n is an integer and x is less than 1, then each histogram bin will actually have a width of either n ADC bin widths or $(n + 1)$ ADC bin widths. If n is very large, so that the relative difference between n and $n + 1$ is small, then this error in histogram bin width is not important.

There is an additional consideration if the selection of *state levels* is based on the mode of a histogram. Bin widths, which are intended to be equal, can be unequal due to the differential nonlinearity of the ADC. In this case, the mode may occur in the widest bin rather than in its correct bin. When this is a possibility, the histogram counts (the number of *waveform* values that lie within each histogram bin) should be corrected for the bin widths before the histogram is analyzed.

5.2.1.2.1 Method 1

Select a fixed value of M. The selection of M may be based on observation, common practice, or some other valid means.

5.2.1.2.2 Method 2

A large (or small) value of M is selected as initial value. The value of M is then decremented (or incremented) until a particular histogram criterion is attained. One criterion that has been used is that the least populated of the two mode bins contains a count that is equal to at least 1% of the number of elements, N_e, in the *waveform*. This method assumes the *waveform* exhibits a bimodal amplitude distribution and that it is positioned such that the bin corresponding to *level*(s_2) and *level*(s_1) has a count greater than or equal $0.01N_e$. Typically this latter requirement is assured by positioning the *waveform* such that either the *duration* of *level*(s_2) or *level*(s_1) is no less than 10% of the *waveform epoch*. (Although shorter *durations* may work, this has not been tested.) This method can be adapted to apply to *waveforms* containing more than one *transition* and more than two modes in the amplitude distribution if the *waveform* is appropriately parsed. However, for each segment, the *duration* of the *level*(s_2) or *level*(s_1) in that *waveform* segment shall provide at least $0.01N_e$ amplitude occurrences. If this method is implemented automatically, that is, without operator intervention, it requires that the *level*(s_2) and *level*(s_1) are located in opposite halves of y_R. An implementation of this method using equal-sized bins is described in NIST Special Publication 811 [B4], which also shows the effects of varying bin width on computed pulse parameters.

5.2.1.3 Splitting the bimodal histogram into two parts (subhistograms)

This procedure conceptually separates the histogram, computed as described in 5.2.1, into upper and lower histograms from which the modes for each are computed and subsequently used to determine *waveform state levels*. This procedure is based on the values of two *parameters*, f_1 and f_2, where $f_1 \le f_2$, defined by the user of this standard. Typical values for this pair of variables are $(f_1, f_2) = (0.5, 0.5)$ or $(f_1, f_2) = (0.4, 0.6)$. Let B_j, for $j = 1 \ldots M$ be the bin counts in a histogram as defined in 5.2.1. Let j_{low} be the smallest value of j for which $B_j > 0$, and let j_{high} be the largest value of j for which $B_j > 0$. The range of the lower histogram is $j_{\mathrm{low}} \le j \le f_1 (j_{\mathrm{high}} - j_{\mathrm{low}})$. The range of the upper histogram is $(j_{\mathrm{low}} + f_2 [j_{\mathrm{high}} - j_{\mathrm{low}}]) \le j \le j_{\mathrm{high}}$.

Waveform aberrations and/or other spurious artifacts may adversely affect the ability of automated algorithms to find the appropriate *waveform level* around which the histogram is split. On the other hand, manual (operator) selection of the appropriate *waveform level* will not be confounded by spurious content

5.2.1.4 Determining state levels from the histogram

Split the bimodal histogram into two parts as described in 5.2.1.3. Find the means or modes of the two subhistograms found in 5.2.1.3. The *low state level* is given by the mode or mean of the lower histogram and the *high state level* is given by the mode or mean of the upper histogram. Solomon et al [B6] examine the effect of different histogram methods on the values of the state levels.

5.2.2 Data-distribution-based methods—Shorth estimator

This discussion will address *step-like waveforms*. The shorth of a finite collection of data values is the shortest interval comprising a certain fraction, f_S, of the data values. The fraction $f_S = ½$ unless otherwise specified. The shorth estimator is a location estimator, similar to the least median of squares (LMS) estimator (Rousseeuw et al [B5]). The first step in the shorth estimator method is to label or group *waveform* values as belonging to a particular *state*. The *k*-means method (Hartigan [B2]) is an effective approach for grouping the *waveform* values. In this method, the *waveform* values are grouped according to their difference relative to a particular *average level*, where in this case *average levels* are computed for the two *state occurrences* of the *step-like waveform*.

a) To group *waveform* values:

1) Initialize the *average levels*, $\bar{y}_1$ and $\bar{y}_2$, for the two *states occurrences,* $(s_{1,}1)$ and $(s_{2,}1)$ (note in a *step-like waveform*, there are only two *state occurrences*):

i) $\bar{y}_1 = y_{\min,}$ or as otherwise specified by the user of this standard

ii) $\bar{y}_2 = y_{\max,}$ or as otherwise specified by the user of this standard, where $y_{\min}$ and $y_{\max}$ are the minimum and maximum amplitude values of the *waveform, y*

2) Segregate each *waveform* value, $y_{i,}$ into $(s_{1,}1)$ or $(s_{2,}1)$ based on the difference in amplitude between y_i and the *average levels*. The *average levels* are then updated by calculating the average values of the y_i assigned to each *state occurrences*. The process continues until the y_i*s* no longer switch *state occurrences*, or, equivalently, until the *average levels* no longer change. The following algorithm is now given:

do

$$\bar{y}_{1,\text{old}} = \bar{y}_1$$

$$\bar{y}_{2,\text{old}} = \bar{y}_2$$

for $i = 1 .. N$

if $| y_i - \bar{y}_1 | < | y_i - \bar{y}_2 |$ then assign y_i to $(s_{1,}1)$

else assign y_i to $(s_{2,}1)$

endfor

$\bar{y}_1$ = *average level* of $(s_{1,}1)$

$\bar{y}_2$ = *average level* of $(s_{2,}1)$

while $\bar{y}_1 - \bar{y}_{1,\text{old}} \neq 0$ and $\bar{y}_2 - \bar{y}_{2,\text{old}} \neq 0$

where N is the number of samples in y.

After the algorithm converges, typically in two or three iterations, it yields $(s_{1,}1)$ and $(s_{2,}1)$, the two *state occurrences* of the *step-like waveform*.. The set of N_1 *waveform* values in $(s_{1,}1)$ (the first *state occurrence*) is given by $\left(s_{1,1}\right) = \left\{ y_1^{(1)}, y_2^{(1)}, \ldots, y_{N_1}^{(1)} \right\}$ and the set of N_2 *waveform* values in $(s_{2,}1)$ is given by $\left(s_{2,1}\right) = \left\{ y_1^{(2)}, y_2^{(2)}, \ldots, y_{N_2}^{(2)} \right\}$.

The next step in this process is to obtain the shorth and the corresponding shorth collection for both $(s_{1,}1)$ and $(s_{2,}1)$. The shorth collection comprises the data values that are contained in the shorth. As used here, the shorth of the *i*th *state occurrence* is the shortest *interval* containing the specified fraction of the values assigned to the *i*th *state occurrence*.

b) Determine the shorth collection. The shorth collection is computed independently for $(s_{1,}1)$ and $(s_{2,}1)$ per the following procedure:

1) reorder $(s_{1,}1)$ into a nondecreasing sequence to give:

$$\left(s_{1,1}\right)_{nd} = y_{(1)}^{(1)} \le y_{(2)}^{(1)} \le \ldots \le y_{(N_1)}^{(1)}$$

2) reorder $(s_{2,}1)$ into a nondecreasing sequence to give:

$$\left(s_{2,1}\right)_{nd} = y_{(1)}^{(2)} \le y_{(2)}^{(2)} \le \ldots \le y_{(N_2)}^{(2)}$$

where

N_1 is the number of samples in $(s_{1,}1)$
N_2 is the number of samples in $(s_{2,}1)$

For clarity, $y_i^{(1)}$ is not necessarily equal to $y_{(i)}^{(1)}$ and $y_i^{(2)}$ is not necessarily equal to $y_{(i)}^{(2)}$.

3) Perform the following to compute the shorth collection for $(s_{1,}1)$:

$h = \lfloor f_s N_1 \rfloor + 1$,
$d = N_1 - h + 1$
$min\_diff = 10^9$
for $i = 1 .. d$
    $diff = y_{(h+i-1)}^{(1)} - y_{(i)}^{(1)}$
    if ($diff < min\_diff$) then
        $min\_diff = diff$
        $m = i$
    endif
endfor
where $\lfloor x \rfloor$ is the greatest integer less than or equal to x.
The shorth collection for $(s_{1,}1)$: $= \left(y_{(m)}^{(1)}, \ldots, y_{(h+m-1)}^{(1)}\right)$.

4) Perform the following to compute the shorth collection for $(s_{2,}1)$:

$k = \lfloor f_s N_2 \rfloor + 1$
$d = N_2 - k + 1$
$min\_diff = 10^9$
for $i = 1 .. d$
    $diff = y_{(k+i-1)}^{(2)} - y_{(i)}^{(2)}$
    if ($diff < min\_diff$) then
        $min\_diff = diff$
        $n = i$
    endif
endfor
The shorth collection for $(s_{2,}1)$: $= \left(y_{(n)}^{(2)}, \ldots, y_{(k+n-1)}^{(2)}\right)$.

The algorithm in step 3 and step 4 (above) produces a shorth collection that, if two or more successive intervals qualify for the shorth, selects the first interval. If the user of this standard implements a shorth collection criterion different from that used here, the user of this standard shall indicate the criterion used.

c) Finally, the mean of the value, unless otherwise specified, of the shorth collection is used to estimate *levels* of each *state* (Hale et al [B1]).

1) The *level* of s_1 is computed using: $level(s_1) = \frac{1}{h}\sum_{j=m}^{h+m-1} y_{(j)}^{(1)}$.

2) The *level* of s_2 is computed using: $level(s_2) = \frac{1}{k}\sum_{j=n}^{k+n-1} y_{(j)}^{(2)}$.

As a simple illustration, suppose N_1 = 11 and $\left(y_{(1)}^{(1)},\ldots,y_{(N_1)}^{(1)}\right)$ = (10, 45, 50, 53, 56, 58 60, 62, 63, 65, 75). Then, $h = \lfloor 11/2 \rfloor + 1 = 6$, and the smallest of the differences in the corresponding set of differences, 58-10, 60-45, 62-50, 63-53, 65-56, and 75-58 is 9, which corresponds to the interval (56, 65), which is the shorth. The values contained in the shorth are 56, 58, 60, 62, 63, and 65. *Level*(s_1) is calculated as *level*(s_1) = (56+58+60+62+63+65)/6 = 60.67.

5.2.3 Other methods

5.2.3.1 Peak magnitude

Determine the *maximum peak* and *minimum peak* values of the single *transition waveform* or the single *pulse waveform*:

a) Take the *minimum peak* value as the *low* or first *state level.*

b) Take the *maximum peak* value as the *high* or second *state level*. This algorithm is best suited to the analysis of waveforms with *state levels* of negligible or relatively short *duration*.

5.2.3.2 Initial (final) instant

For a single *transition waveform*, determine the values of the *initial instant* and the *final instant.* Take the value at either the *initial instant* or the *final instant,* whichever is the more *negative,* as the *low* or *first state level.* Then, take the value at either the *initial instant* or the *final instant,* whichever is the more *positive*, as the *high* or *second state level*.

For a single *pulse waveform*, only one of the two *state levels* can be determined by the *initial (final) instant* method. In this case, determine the value of the *initial (final) instant*. For a *positive pulse waveform* take this value as the *low* or *first state level*. For a *negative pulse waveform* take this value as the *high* or *second state level*.

5.2.3.3 User defined

This method is based on assumptions made by, or expectations of, the user of this standard regarding the behavior of the waveform generator. These assumptions or expectations should be based on knowledge of, for example, the waveform generator circuitry, the interaction between the waveform generator and the load (measurement instrument), and/or previous observations. Using this information, the user of this standard states what the values are for the *low* and *high states* of the *waveform*.

5.2.3.4 Use other waveform epochs

Two or more *waveform epochs* may be necessary because the *waveform* from which a given *parameter* is to be computed may not contain enough information for that computation. For example, in computing *transition duration*, if the *waveform* has not settled to its final or initial *states* within a shorter *waveform epoch* from which *transition duration* can be computed, and the *waveform* of longer *epoch*(s) does not have the temporal resolution required to accurately compute the *transition duration*, then two or more *epochs* are necessary to compute *transition duration*. At least two *waveforms* will be required, one or more having a long *epoch* from which the *state levels* will be obtained, and one having a short *epoch* from which the *transition duration* will be computed.

a) Identify the *waveform epochs* to be used, E_1, E_2, and possibly E_3. Three *waveforms* are necessary if the *low state* and *high state* are to be computed from different *waveforms*.

b) Acquire the *waveform*(s) from which the *low state* and *high state* are to be determined.

c) Compute the *low state* and *high state* of the appropriate *waveforms* by a method specified by the user of this standard.

The *low state* and *high state* thus determined are the *low state* and *high state* of the *waveform*.

5.2.3.5 Static levels

This method requires that the pulse generator used to generate the *step-like waveform* can be operated such that it also provides two direct current (dc) *levels*, one corresponding to the *low state* of the pulse to be measured and the other to the *high state* of the same pulse. Furthermore, these dc *levels* shall be supplied at the same connector from which the pulse is output and that these *levels* can be uniquely selected.

a) Operate the pulse generator so that it outputs a dc *level* that is equal to the *level* of the *low state* of the pulse.

b) Acquire a *waveform* of this *low state level* and compute its value by a method specified by the user of this standard; this is the *low state* of the *waveform*.

c) Operate the pulse generator to output a dc *level* that is equal to the *high state* of the pulse and measure this *level*.

d) Acquire a *waveform* of this *high state level* and compute its value by a method specified by the user of this standard; this is the *high state* of the *waveform*.

5.2.4 Algorithm switching

The above methods may be dynamically chosen based upon the input *waveform*. For example, some algorithms use a histogram method or a peak magnitude method depending upon the shape of the histogram. If several methods are combined or employed, the criterion for when a particular method is used should be stated.

5.3 Determination of other single transition waveform parameters

After the *low* or *state* 1 *level* and the *high* or *state* 2 *level* of a single *transition waveform* or a single *pulse waveform* have been determined, all other *transition* or *pulse waveform parameters* defined in this standard are calculable directly from the definitions of those *parameters* presented in this standard.

Some *waveform* recorders contain internal hardware or firmware for calculating *waveform parameters*. In the process of calculating these *waveform parameters*, the recorder may filter the *waveform* prior to interpolation. Consequently, the user of this standard should be aware of any internal filtering performed by the *waveform* recorder because this filtering may affect the value of the *parameter*. If filtering is performed in the process of calculating *waveform parameters*, the type of filter and its defining variables shall be specified.

5.3.1 Algorithm for calculating signed waveform amplitude

Determine the *signed waveform amplitude* using the following steps:

a) Determine s_1 and s_2 using a method described in 5.2.

b) The *waveform amplitude, A,* is the difference between *level*(s_2) and *level*(s_1).

1) For *positive-going transitions*, *A* is given by:

$$A = level(s_2) - level(s_1) \tag{2}$$

where

A is the amplitude of the *waveform*
$level(s_1)$ is the *state level* of s_1
$level(s_2)$ is the *state level* of s_2

2) For *negative-going transitions*, *A* is given by:

$$A = level(s_1) - level(s_2) \tag{3}$$

5.3.2 Algorithm for calculating percent reference levels

Determine the *percent reference levels* using the following steps:

a) Calculate the *waveform amplitude, A,* as described in 5.3.1.

b) Calculate the value for the *percent reference level,* $y_{x\%}$, using:

$$y_{x\%} = level(s_1) + \frac{|A|}{100} x\% \tag{4}$$

where

$y_{x\%}$ is the value of the *percent reference level*
x represents the percentage for the *percent reference level* specified by the user of this standard

NOTE—$y_{x\%}$ may or may not equal the value of a sample in the *waveform*.

5.3.3 Algorithms for calculating reference level instants

The algorithms for calculating *reference level instants* use linear interpolation between the *instants* at which the *waveform* is sampled. If the *interval* between successive *waveform* samples is too large for linear interpolation to be sufficiently accurate, the *accuracy* of the computed *reference levels* and associated *reference level instants* will be reduced. If this limitation causes errors in parameter values that are larger than a tolerance specified by the user of this standard, then a more sophisticated interpolation method based on more than two adjacent samples may be used. The selection of an alternate interpolation method depends on knowledge of the *waveform* and is beyond the scope of this standard. The interpolation method and the conditions in which it is used shall be specified.

5.3.3.1 Algorithm for calculating the 50% reference level instant

Determine the 50 % *percent reference level instant* using the following steps:

a) Calculate the 50% *reference level* as described in 5.3.2.

b) Calculate the 50% *reference level instant* for $y_{50\%}$ using:

$$t_{50\%} = t_{50\%-} + \left(\frac{t_{50\%+} - t_{50\%-}}{y_{50\%+} - y_{50\%-}} \right) \left(y_{50\%} - y_{50\%-} \right) \tag{5}$$

where

$t_{50\%}$	is the 50% *reference level instant*
$t_{50\%-}$ and $t_{50\%+}$	are two consecutive sampling *instants* corresponding to data nearest in value to $y_{50\%}$ such that $y_{50\%-} \le y_{50\%} \le y_{50\%+}$ and
$y_{50\%-}$ and $y_{50\%+}$	are the two consecutive *waveform* values corresponding to $t_{50\%-}$ and $t_{50\%+}$

NOTE—If there is more than one 50% *reference level instant,* the first one is the 50% *reference level instant,* unless otherwise specified.

5.3.3.2 Algorithm for calculating other reference level instants

Determine other *reference level instants* using the following steps:

a) Supply a *reference level*, $y_{x\%}$, by either calculating the $y_{x\%}$ as described in 5.3.2 for a value of x or of $y_{x\%}$ specified or provided by the user of this standard

b) Calculate the *reference level instant* for $y_{x\%}$ using:

$$t_{x\%} = t_{x\%-} + \left(\frac{t_{x\%+} - t_{x\%-}}{y_{x\%+} - y_{x\%-}} \right) \left(y_{x\%} - y_{x\%-} \right) \tag{6}$$

where

$t_{x\%}$	is the *reference level instant* for the *reference level* selected by the user of this standard
$y_{x\%}$	is the *reference level* specified by the user of this standard
$t_{x\%-}$ and $t_{x\%+}$	are two consecutive sampling *instants* corresponding to data nearest in value to $y_{x\%}$ such that $y_{x\%-} \le y_{x\%} \le y_{x\%+}$ and
$y_{x\%-}$ and $y_{x\%+}$	are the two consecutive waveform values corresponding to $t_{x\%-}$ and $t_{x\%+}$

NOTE—If there is more than one *reference level instant,* the *reference level instant* closest to the 50% *reference level instant* (see 5.3.3.1) is used, unless otherwise specified.

5.3.4 Algorithm for calculating transition duration between *x*1% and *x*2% reference levels

Determine other *reference level instants* using the following steps:

a) Calculate the *reference level instant*, $t_{x1\%}$, for the $x1\%$ *reference level* in accordance with 5.3.3 that is nearest to the 50% *reference level instant*, unless otherwise specified.

b) Calculate the *reference level instant*, $t_{x2\%}$, for the $x2\%$ *reference level* in accordance with 5.3.3 that is nearest to the 50% *reference level instant,* unless otherwise specified.

c) Calculate the *transition duration*, $t_{x1\%\text{-}x2\%}$ using:

$$t_{x1\%-x2\%} = \left| t_{x1\%} - t_{x2\%} \right| \tag{7}$$

where

$t_{x1\%\text{-}x2\%}$ is the duration between the $x1\%$ *reference level* and the $x2\%$ *reference level*
$t_{x1\%}$ is the *reference level instant* for the $x1\%$ *reference level*
$t_{x2\%}$ is the *reference level instant* for the $x2\%$ *reference level*

5.3.5 Algorithm for calculating the undershoot and overshoot aberrations of step-like waveforms

Determine the *undershoot* and *overshoot* aberrations of step-like *waveforms* using the following steps:

a) Determine *level*(s_1) and *level*(s_2) using a method described in 5.2 and define the *upper boundary* and *lower boundary* for the *states* corresponding to these levels.

b) Determine the maximum and minimum *waveform* values, y_{max} and y_{min}.

c) Calculate the *waveform amplitude, A,* as described in 5.3.1.

d) Calculate the $x1\%$ and $x2\%$ *reference levels* and the 50% *reference level* as described in 5.3.2. Typically used *reference levels* are the 10% and 90% *reference levels*.

e) Calculate the *reference level instants*, $t_{x1\%}$, $t_{50\%}$, and $t_{x2\%}$, as described in 5.3.3, for the *reference levels* determined in step d).

f) Calculate the *transition duration,* for the *reference levels instants* determined in step e), as described in 5.3.4.

g) Calculate the *overshoot* and *undershoot* in the *pre-transition aberrations region*:

   1) Calculate the last *instant*, t_{pre}, that occurs before $t_{50\%}$, when the *waveform* exits the upper (lower) *state boundary* of the *low state* (*high state*) for a *positive-going* (*negative-going*) *transition* using the method described in 5.3.3.

   2) Define the *pre-transition aberration region* as that between $t_{\text{pre}} - 3t_{10\%-90\%}$ and t_{pre} (or as specified by the user of this standard).

   3) Search the *pre-transition aberration* region for the maximum value, $y_{\text{max, pre}}$, and the minimum value, $y_{\text{min, pre}}$. The value $y_{\text{max, pre}}$ is the maximum y_i in the *pre-transition aberration region* and $y_{\text{min, pre}}$ is the minimum y_i in the *pre-transition aberration region*.

   4) If $y_{\text{max, pre}}$ is equal to or less than the upper *state boundary* of s_1 (s_2) for a *positive-going* (*negative-going*) *transition,* then the *overshoot* in the *pre-transition aberration region*, O_{pre}, is zero, otherwise compute the percentage *overshoot* in the *pre-transition aberration region* using:

$$O_{\mathrm{pre}}(\%) = \frac{y_{\mathrm{max,\,pre}} - level(\mathrm{s}_k)}{|A|} 100\% \tag{8}$$

where

O_{pre}	is the *overshoot* value in the *pre-transition aberration region*
$y_{\mathrm{max,pre}}$	is the maximum *waveform* value in the *pre-transition aberration region*
A	is the *waveform amplitude*
$level(\mathrm{s}_k)$	is the *state level* of the *k*th *state*
$level(\mathrm{s}_k)$	is $level(\mathrm{s}_1)$ for a *positive-going transition*
$level(\mathrm{s}_k)$	is $level(\mathrm{s}_2)$ for a *negative-going transition*

5) If $y_{\mathrm{min,pre}}$ is equal to or greater than the lower *state boundary* s_1 (s_2) for a *positive-going* (*negative-going*) *transition*, then the *undershoot* in the *pre-transition aberration region*, U_{pre}, is zero, otherwise compute the percentage *undershoot* in the *pre-transition aberration region* using:

$$U_{\mathrm{pre}}(\%) = \frac{level(\mathrm{s}_k) - y_{\mathrm{min,pre}}}{|A|} 100\% \tag{9}$$

where

U_{pre}	is the *undershoot* value in the *pre-transition aberration region*
$y_{\mathrm{min,\,pre}}$	is the minimum *waveform* value in the *pre-transition aberration region*

h) Calculate the *overshoot* and *undershoot* in the *post-transition aberration region*.

1) Calculate the first *instant*, t_{post}, that occurs after $t_{50\%}$ when the *waveform* enters the lower (upper) *state boundary* of the *high state* (*low state*) for a *positive-going* (*negative-going*) *transition* using the method described in 5.3.3.

2) Define the *post-transition aberration region* as that between t_{post} and $t_{\mathrm{post}} + 3t_{10\%\text{-}90\%}$ (or as specified by the user of this standard).

3) Search the *post-transition aberration region* for the maximum value, $y_{\mathrm{max,\,post}}$, and the minimum value, $y_{\mathrm{min,\,post}}$. The value $y_{\mathrm{max,\,post}}$ is the maximum y_i in the *post-transition aberration region* and $y_{\mathrm{min,\,post}}$ is the minimum y_i in the *post-transition aberration region*.

4) If $y_{\mathrm{max,post}}$ is equal to or less than the upper *state boundary* of s_2 (s_1) for a *positive-going* (*negative-going*) *transition,* then the *overshoot* in the *post-transition aberration region*, O_{post}, is zero, otherwise compute the percentage *overshoot* in the *post-transition aberration region* using:

$$O_{\mathrm{post}}(\%) = \frac{y_{\mathrm{max,post}} - level(\mathrm{s}_k)}{|A|} 100\% \tag{10}$$

where

O_{post}	is the *overshoot* value in the *post-transition aberration region*
$y_{\mathrm{max,\,post}}$	is the maximum *waveform* value in the *post-transition aberration region*

5) If $y_{\mathrm{min,\,post}}$ is equal to or greater than the lower *state boundary* s_2 (s_1) for a *positive-going* (*negative-going*) *transition*, then the *undershoot* in the *post-transition aberration region*, U_{post},

is zero, otherwise compute the percentage *undershoot* in the *post-transition aberration region* using:

$$U_{\text{post}}(\%) = \frac{level(\mathrm{s}_k) - y_{\text{min,post}}}{|A|} 100\% \tag{11}$$

where

U_{post} is the *undershoot* value in the *post-transition aberration region*
$y_{\text{min, post}}$ is the minimum *waveform* value in the *post-transition aberration region*

5.3.6 Algorithm for calculating waveform aberrations

Determine *waveform aberrations* using the following steps:

a) Calculate the $x1\%$ and $x2\%$ *reference levels* as described in 5.3.2. Typically used *reference levels* are the 10% and 90% *reference levels*.

b) Calculate the *reference level instants*, $t_{x1\%}$ and $t_{x2\%}$, as described in 5.3.3, for the *reference levels* determined in step a).

c) Determine the *pre-transition aberration region* and *post-transition aberration region* as described in 5.3.5 and exclude those regions in the calculation of *waveform aberration*.

d) Calculate the parameters for generating the *reference waveform, r(t)*. Unless otherwise specified, the trapezoidal *pulse waveform* (see Figure A.6) will be used as the *reference waveform* for calculating *waveform aberrations*.

   1) Calculate the slope through the *reference levels* and *reference level instants* of the *waveform* using:

$$S = \left(\frac{y_{x2\%} - y_{x1\%}}{t_{x2\%} - t_{x1\%}} \right) \tag{12}$$

   2) Calculate the *reference level instants*, $t_{0\%}$ and $t_{100\%}$, that will be used to generate $r(t)$ in step e) below.

      i) The *reference levels* and their associated *reference level instants* of the *reference waveform* should be chosen such that the slope of the line through these points is a close fit to the corresponding *waveform* values.

      ii) Compute the $t_{100\%}$ *reference level instant* using:

$$t_{100\%} = t_{x2\%} + \frac{level(\mathrm{s}_2) - y_{x2\%}}{S} \tag{13}$$

      iii) Compute the $t_{0\%}$ *reference level instant* using:

$$t_{0\%} = t_{x1\%} + \frac{level(\mathrm{s}_1) - y_{x1\%}}{S} \tag{14}$$

e) Generate the trapezoidal *reference waveform*, $r(t)$, using:

$$r(t_n) = \begin{cases} y_{0\%}, & \text{for } t_{0\%} \\ S(t_n - t_{0\%}) + y_{0\%} & \text{for } t_{0\%} \le t_{\mathrm{n}} \le t_{100\%} \\ y_{100\%} & \text{for } t_{\mathrm{n}} > t_{100\%} \end{cases}$$

f) The *waveform aberrations* are calculated as the maximum positive and negative deviation of the measured *waveform* from the *reference waveform* and are presented as a percentage of the *waveform amplitude*. Calculate *waveform aberration* using:

$$W_{\mathrm{a}} = \begin{cases} \left(\dfrac{\max\{y_n - r(t_n)\}_{T_{\mathrm{ab}}}}{y_{100\%} - y_{0\%}} \right) 100\% \\ \left(\dfrac{\min\{y_n - r(t_n)\}_{T_{\mathrm{ab}}}}{y_{100\%} - y_{0\%}} \right) 100\% \end{cases} \tag{15}$$

where

W_{a}	is the *waveform aberration*
$\max\{...\}$	returns the maximum value of its argument
$\min\{\ldots\}$	returns the minimum value of its argument
$y_{100\%}$	is the value of the 100% *reference level*
$y_{0\%}$	is the value of the 0% *reference level*
$r(t_n)$	is the *reference waveform*
n	is the discrete time index of the *waveform*
T_{ab}	is the interval over which the *waveform aberration* is being calculated

5.3.7 Algorithm for calculating transition settling duration

Determine *transition settling duration* using the following steps:

a) Calculate the 50% *reference level*, as described in 5.3.2.

b) Calculate the 50% *reference level instant* as described in 5.3.3.

c) Specify the *state boundaries* of the specified *state* (usually *state* 2).

d) Determine the *instant* at which the *waveform* enters and subsequently remains within the specified *state boundary*:

  1) Starting at the end of the *waveform epoch*, check each *waveform* value against the specified *state boundaries*.

  2) Record the sampling *instant* of the first *waveform* value encountered that is found outside the *state boundary*.

  3) Calculate the *instant* that the *waveform* crosses the *state boundary* using the method described in 5.3.3.

  4) Calculate the *transition settling duration* by finding the difference between the *instant* determined in step d.3) and the 50% *reference level instant* determined in step a).

5.3.8 Algorithm for calculating transition settling error

Determine *settling error* using the following steps:

a) Calculate the 50% *reference level instant* as described in 5.3.3.1.

b) Specify which *state level, level*(s_1) or *level*(s_2), will be used to compute the *transition settling error*.

c) Specify the *instant,* t_s, for $t_s > t_{50\%}$, and its corresponding *waveform* sample index, i_s, at which *interval* over which the *transition settling error* is to be determined starts.

d) Specify the *instant* t_f after t_s, and its corresponding *waveform* sample index, i_f, at which *interval* over which the *transition settling error* is to be determined ends.

e) *Transition settling error,* E_{settling}, is determined using:

$$E_{\text{settling}} = \max\left\{\left|\frac{y_i - level(\mathrm{s}_k)}{level(\mathrm{s}_2) - level(\mathrm{s}_1)}\right|\right\}, i_s \le i \le i_f \tag{16}$$

where k is 1 or 2, depending on whether the *state level* selected in step b) was s_1 or s_2.

5.4 Analysis of single and repetitive pulse waveforms

The algorithms in this subclause assume the *repetitive pulse waveform* is a *compound waveform* comprised of either *positive pulse waveforms* or *negative pulse waveforms*. In either case, the user of this standard shall specify whether the computed parameters of the *repetitive pulse waveform* were based on it being comprised of *positive pulse waveforms* or *negative pulse waveforms.*

5.4.1 Algorithm for calculating pulse duration

Determine *pulse duration* using the following steps:

a) Select a *waveform epoch* or subepoch that contains exactly one *pulse waveform*.

b) Select the *x% reference level*. Typically the $y_{50\%}$ is used.

c) Calculate the *reference level instant*, $t_{1,x\%}$, for the *x% reference level* in accordance with 5.3.3 for the *positive-going* (*negative-going*) *transition* of the *waveform* selected in step a).

d) Calculate the *reference level instant*, $t_{2,x\%}$, for the *x*% *reference level* in accordance with 5.3.3 for the *negative-going* (*positive-going*) *transition* of the *waveform* used in step c) above.

e) The *pulse duration*, T_P, is the absolute value of the difference between the *reference level instants* found in step c) and step d):

$$T_P = \left|t_{2,x\%} - t_{1,x\%}\right| \tag{17}$$

5.4.2 Algorithm for calculating waveform period

Determine *waveform period* using the steps to follow:

a) Select a *waveform epoch* or subepoch that contains exactly two *pulse waveforms* within that *waveform epoch*.

b) Determine *level*(s_1) and *level*(s_2) using a method from 5.2.

c) Select the $y_{x\%}$ *reference level*. Typically the $y_{50\%}$ is used.

d) Calculate the *reference level instant*, $t_{1,\,x\%}$, for the $y_{x\%}$ *reference level* in accordance with 5.3.3 for either the *positive-going* (or *negative-going) transition* on a *pulse* in the *waveform.*

e) Calculate the *reference level instant*, $t_{2,\,x\%}$, for the $y_{x\%}$ *reference level* in accordance with 5.3.3 for either the *positive-going* (or *negative-going) transition* [(consistent with the choice made in step d) on a *pulse* immediately following or preceding the *pulse* used in step d)].

f) The *pulse period, T,* is the difference between the *reference level instants* found in step d) and step e):

$$T = \left| t_{2,\,x\%} - t_{1,\,x\%} \right| \tag{18}$$

5.4.3 Algorithm for calculating pulse separation

Two methods for calculating *pulse separation* are as follows:

a) Method 1

   1) Select a *waveform epoch* or subepoch that contains exactly two *pulse waveforms* within that *waveform epoch*.

   2) Determine *level*(s_1) and *level*(s_2) using a method from 5.2.

   3) Select the $y_{x\%}$ *reference level*. Typically the $y_{50\%}$ is used.

   4) Calculate the *reference level instant*, $t_{1,\,x\%}$, for the $y_{x\%}$ *reference level* in accordance with 5.3.3 for the second (or first) *transition* of a *pulse* in the *waveform.*

   5) Calculate the *reference level instant*, $t_{2,\,x\%}$, for the $y_{x\%}$ *reference level* in accordance with 5.3.3 for the first (or second) *transition* on the *pulse* immediately following or preceding the *pulse* used in step a.4) above.

   6) The *pulse separation*, T_S, is the difference between the *reference level instants* found in step a.4) and step a.5):

$$T_S = \left| t_{2,x\%} - t_{1,x\%} \right| \tag{19}$$

b) Method 2

   1) Calculate the *pulse duration* according to 5.4.1.

   2) Calculate the *waveform period* according to 5.4.2.

   3) The *pulse separation, T_S,* is the difference between the *waveform period* and the *pulse duration* using:

$$T_S = T - T_P \tag{20}$$

5.4.4 Algorithm for calculating duty factor

Determine *duty factor* using the following steps:

a) Calculate the *pulse duration* according to 5.4.1.

b) Calculate the *waveform period* according to 5.4.2.

c) The *duty factor*, d_f, is given by the ratio of the *pulse duration* to the *waveform period* using:

$$d_f = \frac{T_P}{T} \tag{21}$$

where d_f is the *duty factor.*

5.5 Analysis of compound waveforms

Typically, the analysis of a *compound waveform* involves three steps. The first step is to decompose the *waveform epoch* of the *compound waveform* into subepochs, where each subepoch contains an elementary component of the *waveform*. An elementary component includes those defined in this standard (*transitions*, *state levels*, *runts*, *spikes*, *transients*, *terminal features*) and those that may be defined by the user of this standard. This decomposition of the *waveform epoch* into appropriate subepochs is the parsing process. The second step of *compound waveform* analysis is to classify or categorize the *waveform* subepochs. This process involves identifying each subepoch as containing a specific elementary component of a *waveform*. The last step in compound waveform analysis is to recombine those subepochs required to compute the desired waveform parameter. In any analysis of *compound waveforms,* the algorithms or procedures used in these processes shall be specified.

5.5.1 Waveform parsing

This clause contains a set of algorithms for decomposing the *compound waveform* into subepochs that contain *transitions, transients, terminal features,* or *state levels*.

INPUTS

The inputs for this process are as follows:

a) *y*[] is the array containing the *waveform amplitude* values.

b) *i* is the *waveform* sample index, $i = 1, .. N\_samples$.

c) *N_samples* is the number of samples in the *compound waveform*.

d) *state_upper*[] is the array containing the values defined by the user of this standard for the upper *boundary* for each *state* in the *waveform*.

e) *state_lower*[] is the array containing the values defined by the user of this standard for the lower *boundary* for each *state* in the *waveform*.

f) *j* is the *state* index, $j = 1,.., N\_states$. $j = 1$ is the *base state* (see 3.1).

g) *N_states* is the number of states in the *compound waveform*. For example, for a *pulse train* of *pulses* having equal *pulse amplitude*, $N\_states = 2$.

h) $d_{\min}$ is the minimum *duration* (given in number of samples) required for a *state occurrence*.

OUTPUTS

The outputs of this decomposition process are as follows:

a) *assigned_state*[] is an integer array containing *state* assignments for each sample of the *waveform*. These assignments are necessary to complete the parsing process.

b) *N_sub* is the number of subepochs determined.

c) *sub_start*[] is the array containing the starting *waveform* sample index for each subepoch.

d) *sub_end*[] is the array containing the ending *waveform* sample index for each subepoch.

e) *k* is the subepoch index, *k* = 1, .. *N_sub*.

f) *sub_type*[] is an array containing a temporary subepoch classification index.

If *sub_type*[*k*] is a positive integer, then the associated subepoch contains a *state occurrence* and the value of *sub_type*[*k*] is the state number. The value of *sub_type* = 0 is used as a temporary classification to indicate that a subepoch is not a *state occurrence* but has not yet been further classified.

The first step in the parsing process assigns *state levels* to each *waveform* value by comparing the *waveform* value to the upper and lower *boundaries* of all the *states* defined for the *compound waveform*. If the *waveform* value is contained within *state boundaries* of a *state*, then that *waveform* value is assigned a *state level* indicator, such as "1" for s_1, "2" for s_2, and so forth. If the *waveform* value is not within the *state boundaries* of any *state*, then the value of its associated *assigned_state*[] is set to zero. Once this step is completed, each *waveform* value has an associated value in the array *assigned_state*[].

```
for i = 1 .. N_samples
        assigned_state[i] = 0
        for j = 1 .. N_states
                if(state_lower[j] ≤ y[i] ≤ state_upper[j]) assigned_state[i] = j
        endfor
endfor
```

The following algorithm decomposes the *compound waveform* into subepochs based on values in the array *assigned_state*[]. This is the second step in parsing the *compound waveform*. The subepochs provided at the end of this step are not the final subepochs because they may contain parts of *transitions* or *transients*. These parts will be recombined in a subsequent step (see Merge function described later in this subclause). Once this step is complete, each temporary subepoch has an associated starting *waveform* sample index (found in *sub_start*[]), an associated ending *waveform* sample index (found in *sub_end*[]), and an assigned classification (found in *sub_type*[]).

```
i = 1
k = 1

do
        current_assignment = assigned_state[i]
        sub_start[k] = i
        sub_type[k] = current_assignment
        while( (assigned_state[i] = current_assignment) and i < N_samples) i = i + 1 endwhile
        sub_end[k] = i − 1
        if(sub_end[k] − sub_start[k] < d_min − 1) sub_type[k] = 0
        k = k + 1
        i = i + 1
while(i < N_samples)
N_sub = k − 1
```

The next step in parsing the *compound waveform* is to examine the temporary subepochs created in the previous step and merge those temporary subepochs that together form a *transition* or a *transient*. This step is performed by the algorithm to follow:

```
j = 1
while(j < N_sub)
        if (sub_type[j] = 0)
                while (sub_type[j+1] = 0) Merge(j) endwhile
        endif
        j = j + 1
endwhile
```

This algorithm uses the function Merge(j), which merges the jth and (j + 1)st subepochs into one subepoch.

This function is given by the following:

```
Merge(j)
        sub_end[j] = sub_end[j+1]
        N_sub = N_sub − 1
        for i = j+1 .. N_sub
                sub_start[i] = sub_start[i+1]
                sub_end[i] = sub_end[i+1]
                sub_type[i] = sub_type[i+1]
        endfor
end Merge
```

Once this parsing process is complete, the *compound waveform* has been decomposed into subepochs containing *state levels, terminal features, transients,* and/or *transitions*. The next step in the analysis of the *compound waveform* is to classify the subepochs.

5.5.2 Subepoch classification

The subepochs found using the process described in 5.5.1 will be classified. The following algorithm provides a classification scheme. This classification scheme will only classify subepochs as *terminal features, state levels, transients,* or *transitions*. Subepochs that contain a *state occurrence* are given a number corresponding to the *state level* numbering described in 3.1, in which the number is related to the *level* of the *state*. When this process is complete, each subepoch will be uniquely defined by its classification and stop and start indices. The input for this algorithm is array *sub_type*[] and output is the array *sub_class*[]. The array *sub_class*[] contains the final classification of each subepoch.

```
terminal  = -1
transient = -2
transition = -3
if (sub_type[1] = 0) sub_class[1] = terminal
if (sub_type[N_sub] = 0) sub_class[N_sub] = terminal
for k = 2 ..N_sub − 1
        if ((sub_type[k] = 0) and (sub_type[k + 1] ≠ sub_type[k − 1])) then sub_class[k] = transition
        else sub_class[k] = transient
        endif
if (sub_type[k] ≠ 0) sub_class[k] = sub_type[k]
endfor
```

5.5.3 Waveform reconstitution

Once the original *waveform epoch* has been parsed into subepochs and these subepochs appropriately classified, the appropriate sequential subepochs shall be selected for calculating the desired *waveform parameters*. These sequential subepochs create a new *waveform,* which is a subset of the original *waveform* and that has a *duration* shorter than the original *waveform*. For example, if the first *transition duration* of the nth *pulse* in a *pulse train* of *positive pulses* is desired, where this *transition* is located in the jth subepoch, then the $(j-1)$th, jth, and $(j+1)$th subepochs are selected to create the new *waveform*, which starts at $sub\_start[j-1]$ and ends at $sub\_end[j+1]$. The algorithms for computing the *transition duration* (see 5.3.4) are then applied to this new *waveform*.

5.6 Analysis of impulse-like waveforms

5.6.1 Algorithm for calculating the impulse amplitude

Determine *impulse amplitude* using the following steps:

a) Determine $level(s_1)$ using a method described in 5.2.

b) Determine the maximum *waveform* value and the sampling *instant* at which it occurs.

c) Fit a parabola (or function specified by the user of this standard) to five (or a number specified by the user of this standard) points of the *waveform* with the third (middle) point being the maximum *waveform* value determined in step b).

d) The *impulse amplitude* is the value of the fitted parabola at the vertex.

5.6.2 Algorithm for calculating impulse center instant

Determine *impulse center instant* using the following steps:

a) Determine the *amplitude* of the *impulse-like waveform* as described in 5.6.1.

b) The *impulse center instant* is the *instant* associated with the vertex of the fitted parabola.

5.7 Analysis of time relationships between different waveforms

The time relationships between different *waveforms* may be analyzed by the following:

a) Apply the methods described earlier in the analysis of the different *waveforms*.

b) Determine the time relationships between different *waveforms* as computed *intervals* or *durations,* as described in 5.3.4 and 5.4.1.

5.7.1 Algorithm for calculating delay between different waveforms

Determine the *delay* between different *waveforms* using the following steps:

a) Calculate $t_{50\%}$ for each *waveform* as described earlier in the algorithm for calculating *transition duration* between the $x1\%$ and $x2\%$ *reference levels*.

b) Calculate the *delay,* T_D, as the difference between $t_{50\%}$ for the different *waveforms*:

$$T_D = t_{\text{mid},W1} - t_{\text{mid},W2} \tag{22}$$

where

$t_{\text{mid},W1}$ is the 50% *reference level instant* for one of the *waveforms*
$t_{\text{mid},W2}$ is the 50% *reference level instant* for the other *waveforms*

NOTE—Delay can be either positive or negative (negative delay can also be called advance).

5.8 Analysis of waveform aberration

The analysis of *waveform aberration* (see 5.3.6) entails the determination of the differences between a *waveform* and a *reference waveform*. In any *aberration* determination the type of *reference waveform* shall be specified.

The *reference waveform* shall be properly located, in time and in *level*, relative to the *waveform* being analyzed.

5.9 Analysis of fluctuation and jitter

The analysis of *fluctuation* and *jitter* involves making repeated independent measurements of the same quantity and evaluating the standard deviation of the results. In many cases, the measurement of *fluctuation* and *jitter* includes the *fluctuation* and *jitter* of the instrument used for the measurements, and this should be taken into account. Also, in many cases, the result of a measurement of either *fluctuation* or *jitter* is influenced by the presence of the other. The correct determination of *fluctuation* and *jitter* often requires multiple measurements taken under different conditions and the solution of simple algebraic equations to determine the individual *parameters*.

5.9.1 Determining standard deviations

There are two commonly used methods for determining the standard deviations required for *fluctuation* and *jitter* analysis: the direct method and the histogram method. Both will be described here. Any method of measuring a standard deviation includes an inherent statistical error. An estimate of that error will be given here. This subclause also provides the standard method for correcting standard deviation results for the contributions from interfering sources.

5.9.1.1 Standard deviation—Direct method

A number, M, of independent measurements are made of the same *parameter,* p_i. The standard deviation of these measurements is determined as follows:

a) Calculate the mean value, $\overline{p}$, using:

$$\overline{p} = \frac{1}{M}\sum_{i=1}^{M} p_i \tag{23}$$

where

M is the number of independent measurements
p_i is the value of the *i*th measurement of the parameter

b) Calculate the standard deviation, σ_p, using:

$$\sigma_p = \sqrt{\frac{1}{M-1}\sum_{i=1}^{M}(p_i - \bar{p})^2} \tag{24}$$

5.9.1.2 Standard deviation—Histogram method

The histogram method has the advantage that it does not require storage of each of the M measurement values. This method is often incorporated into instruments. In this method, a histogram is generated of the M measurement values using the method in 5.2.1.1 if applicable. The histogram is comprised of B histogram bins numbered from 1 through B. The value at the center of the kth histogram bin is denoted by v_k, and the count in the kth bin is denoted by c_k. The standard deviation is calculated as follows:

a) Determine the mean of the *parameter* value by using:

$$\bar{p} = \frac{1}{M}\sum_{k=1}^{B} c_k v_k \tag{25}$$

where

c_k is the count in the kth bin
v_k is the center of the kth bin
B is the number of histogram bins

b) Calculate the standard deviation, σ_p, of the *parameter* value using:

$$\sigma_p = \sqrt{\left(\frac{1}{M-1}\sum_{k=1}^{B} v_k^2 c_k\right) - \bar{p}^2} \tag{26}$$

For these results to be valid, there are restrictions on the histogram parameters. First, the bin width (the value of $v_k - v_{k-1}$) should be small compared to the value determined for the standard deviation. The histogram calculation of the standard deviation can be as large as one-half of the bin width. Second, the values associated with the most negative bin and with the most positive bin should be sufficient to include the tails of the distribution. If the bins include $\bar{p} \pm 3\sigma$, this error will be less than 3% of σ.

5.9.1.3 Accuracy of standard deviation

The value of the standard deviation calculated by either of the above methods is a random variable and has an inherent statistical error. Under the assumption that the values of the *parameter* for which the standard deviation was found have normal distributions, the standard deviation of the calculated standard deviation is given by:

$$\Sigma_p = \sigma_p \sqrt{1 - \frac{2}{M-1}\left(\frac{\Gamma\left(\frac{M}{2}\right)}{\Gamma\left(\frac{M-1}{2}\right)}\right)^2} \tag{27}$$

where

Σ_p is the standard deviation of the calculated standard deviation
σ_p is the calculated standard deviation (see 5.9.1.1 and 5.9.1.2)
Γ is the gamma function

This formula can be approximated by:

$$\Sigma_p \cong \frac{\sigma_p}{\sqrt{2(M-1)}} \tag{28}$$

The ratio of Σ_p calculated using Equation (27) to that calculated using Equation (28) is shown in Table 1.

Table 1—Comparison of the results from the exact and approximate formulas for computing the standard deviation of the calculated standard deviations

M	Σ_p calculated using Equation (27)	Σ_p calculated using Equation (28)	Ratio
5	$0.341063\sigma_p$	$0.353553\sigma_p$	0.965
10	$0.232197\sigma_p$	$0.235702\sigma_p$	0.985
20	$0.161225\sigma_p$	$0.162221\sigma_p$	0.994
50	$0.100756\sigma_p$	$0.101015\sigma_p$	0.997
100	$0.070943\sigma_p$	$0.071067\sigma_p$	0.998

5.9.1.4 Correcting the standard deviation

Often the measured standard deviation for the *parameter* of interest will have a contribution due to interfering sources. Examples will be given in 5.9.1.5. This subclause gives the standard method for correcting for the interference. If σ_{obs} is the observed standard deviation and σ_I is the contribution to the standard deviation from the interfering source, then the estimate for the true standard deviation is:

$$\sigma_p = \sqrt{\sigma_{\text{obs}}^2 - \sigma_I^2} \tag{29}$$

where

σ_p is the estimated standard deviation
σ_I is the contribution to the standard deviation from the interfering source
σ_{obs} is the observed standard deviation

If the values of σ_{obs} and σ_I are close to each other, then one should assure that the error in each is sufficiently small, as described in 5.9.1.5. If there are *n* different interfering sources, each with standard deviation σ_j, then the value for σ_I is given by the square root of the sum of their squares:

$$\sigma_I = \sqrt{\sum_{j=1}^{n} \sigma_j^2} \tag{30}$$

where

σ_j is the standard deviation from each *j*th interfering source
n is the number of interfering sources

5.9.1.5 Errors in the corrected standard deviation

The standard deviation of the corrected standard deviation is given:

$$\frac{\Sigma_p}{\sigma_p} = \frac{\sqrt{\sigma_{\text{obs}}^2 \Sigma_{\text{obs}}^2 + \sigma_I^2 \Sigma_I^2}}{\sigma_p^2} \tag{31}$$

where

σ_p is the calculated standard deviation
Σ_I is the standard deviation of the standard deviation of the interfering sources
Σ_{obs} is the standard deviation of the observed standard deviation of the parameter

If there are *n* different interfering sources contributing to σ_I, each with standard deviation σ_j that has standard deviation Σ_j, then the value for Σ_I is given by:

$$\Sigma_I = \frac{\sqrt{\sum_{j=1}^{n} \sigma_j^2 \Sigma_j^2}}{\sigma_I} \tag{32}$$

If the ratio, Σ_p/σ_p, is not small, then there is significant error in the calculated value of σ_p. In the case that both of the standard deviations on the right-hand side of Equation (31) were determined with the same number of measurements, *M,* this reduces to a simpler relation, namely,

$$\frac{\Sigma_p}{\sigma_p} \leq \frac{\alpha}{\sqrt{M}} \tag{33}$$

where *M* is the number of measurements

$$\alpha = \max\left(\frac{\sigma_{\text{obs}}}{\sigma_p}, \frac{\sigma_I}{\sigma_p}\right)$$

where max{..} returns the maximum value of its argument.

5.9.2 Measuring fluctuation and jitter of an instrument

Before using an instrument to measure the *fluctuation* and *jitter* of a *signal* source, one should determine the *fluctuation* and *jitter* of the instrument. The instrument will typically be some form of digital oscilloscope. It is most convenient to measure *fluctuation* first.

5.9.2.1 Measuring fluctuation of an instrument

The measurement of the *fluctuation* of the instrument depends on the *level parameter* of interest and on the algorithm that will be used to determine the *level parameter*. The *parameter* calculations performed in the instrument *fluctuation* measurements shall be made with essentially the same algorithm as will be used for the *parameter* calculations in the *signal* source *fluctuation* measurements. Two approaches are presented in 5.9.2.1.1 and 5.9.2.1.2, respectively.

5.9.2.1.1 Measuring fluctuation of an instrument—Simulation approach

This approach requires an input *signal* that is similar to the *signal* source to be tested and is known to have a *fluctuation* that is less than one-quarter of the *fluctuation* of the *signal* to be measured.

a) Record *M waveforms* of the input *signal*.

b) Calculate the value of the *level parameter* for each recorded *waveform* using one of the algorithms described in 5.2 and 5.3 if applicable.

c) Determine the standard deviation, σ_{obs}, of the values obtained in step b) by any of the methods described in 5.9.1.

If the input *signal* does not have negligible *fluctuation* compared to that of the instrument, and if the instrument *fluctuation* will subsequently be used to correct the measured *fluctuation* value of a device under test, then the corrected *fluctuation* of the device under test will be underestimated.

5.9.2.1.2 Measuring fluctuation of an instrument—Constant signal approach

Use of this method is valid with the assumption that the instrument's contribution to *fluctuation* is caused by additive random noise, which is often the case.

a) Record *M waveforms* of a constant *signal*.

b) Calculate the value of the *level parameter* for each record obtained in step a) using an algorithm essentially equivalent (5.2 and 5.3 if applicable) to the algorithm that will be used to determine the *level parameter* for the *signal* source.

c) Determine the standard deviation of the values obtained in step b) by any of the methods in 5.9.1.

In step b) it may not be possible to use the exact same algorithm to calculate the *level parameter* for a constant *signal* that will be used for the actual time-varying *signal*. For example, if the *level parameter* is the *amplitude* of a *transition,* the algorithm may involve taking a histogram of the entire record, separating it into two separate histograms based on the two modes and taking the difference of the means, medians, or modes of the two histograms. With the *waveform* of a constant *signal,* a bimodal histogram is not obtained. Therefore, a different method shall be supplied to obtain two separate histograms, one histogram each for the two constant-*signal waveforms*. Each of these two histograms should come from approximately the same time interval in the record, have the same histogram bin width, and have approximately the same number of total counts as the corresponding histogram for the time-varying *signal*. The calculations performed on these two histograms should be identical to those that will be performed when a time-varying *signal* is present.

5.9.2.2 Measuring jitter of an instrument

There are two distinct kinds of *jitter*: *trigger jitter* and relative *jitter*. For an instrument (as opposed to a *signal* source), *trigger jitter* refers to the variation between the *instant* the trigger *signal* occurs and the *instant* that a given *waveform* sample is taken. Relative *jitter* refers to the variation in the *interval* between two sample *instants* in the same record. Relative *jitter* may be dependent on the time *interval* between the two sample *instants*. *Trigger jitter* may depend on the *instant,* within the *waveform epoch,* of the sample used in the measurement. The shortest possible *interval* between the trigger *instant* and the sample *instant* should be selected.

5.9.2.2.1 Measuring trigger jitter of an instrument

The measurement requires a *signal* with a rapid *transition*. The *signal* is passively split into two *signals*, one to provide the trigger and one to be recorded on the instrument under test. The *signal* to be recorded may have to be *delayed* (with a passive *delay* line) in order to record, in the *waveform,* the rapid *transition* of the *signal*.

a) Record *M waveforms,* each containing the rapid *transition* of the *signal*.

b) Calculate the average, $\overline{y}_i$, of the *M waveforms* for every *instant* of the *waveform* using:

$$\overline{y}_i = \frac{1}{M}\sum_{m=1}^{M} y_{m,k} \tag{34}$$

where

$\overline{y}_i$ is the average
$y_{m,k}$ are the *waveform* values
M is the number of *waveforms*
m is the *waveform* index
k is the *waveform* sample index

c) Using $\overline{y}_i$, determine a *level,* v_0, at which the instantaneous slope, S, in the *transition* of the *signal* is large, and determine the value of S at v_0 by a method specified by the user of this standard.

d) For each of the *M waveforms,* determine the *instant* at which the *waveform* value crosses v_0 using the method in 5.3.3.

e) Determine the standard deviation, $\sigma_{\tau\text{obs}}$, of the *instants* obtained in step d).

f) Correct the result found in step d) for *fluctuation* using:

$$\sigma_{ITJ} = \sqrt{\sigma_{\tau,\text{obs}}^2 - \left(\sigma_{IF}/S\right)^2} \tag{35}$$

where

σ_{ITJ} is the corrected standard deviation (corrected *trigger jitter*)
$\sigma_{\tau,\text{ obs}}$ is the observed standard deviation of the *instants* (observed *trigger jitter*)
σ_{IF} is the *rms fluctuation* of individual values from the instrument
S is the instantaneous slope in the *transition* of the *signal*

To verify the result, the standard deviation of σ_{ITJ} should be calculated using the method in 5.9.1.5.

5.9.2.2.2 Measuring relative jitter of an instrument

This measurement requires a test *signal* with two rapid *transitions*, such as a *rectangular pulse.* The *interval* between the two *transitions* of the test *signal* should have *jitter* less than one-fourth of the *jitter* to be measured and be approximately the same as the *interval* over which the relative *jitter* is to be measured.

a) Record *M waveforms,* each containing the two rapid *transitions* of the *signal*.

b) Calculate the average, $\bar{y}_i$, of the *M waveforms* for every *instant* of the *waveform,* as described in step b) of 5.9.2.2.1.

c) Using $\bar{y}_i$, determine *levels,* v_1 and v_2, (one on each *transition*) at which the slopes, S_1 and S_2, in the *transitions* of the *signal* are large. Determine S_1 for v_1 and S_2 for v_2 by a method specified by the user of this standard.

d) Determine the *instant*, t_1, when v_1 occurs using the method described in 5.3.3.

e) Determine the *instant*, t_2, when v_2 occurs using the method described in 5.3.3.

f) For each of the *waveforms* from step a) calculate the difference, $t_2 - t_1$.

g) Determine the standard deviation, $\sigma_{\tau,\,\mathrm{obs}}$, of the time differences calculated in step f).

h) Correct the result found in step g) for *fluctuation* using:

$$\sigma_{\tau,IJ,\mathrm{rel}} = \sqrt{\sigma_{\tau,\mathrm{obs}}^2 - \left(\sigma_{IF}/S_1\right)^2 - \left(\sigma_{IF}/S_2\right)^2} \tag{36}$$

where

$\sigma_{\tau,\,IJ,\,\mathrm{rel}}$ is the relative *jitter* of the instrument
S_1 and S_2 are the instantaneous slopes of the two *transitions* of the *signal* used in step c)

To verify the result, the standard deviation of σ_τ should be calculated using the method in 5.9.1.5.

5.9.3 Measuring fluctuation and jitter of a signal source

The measurements for a *signal* source are identical to those for an instrument, except that the *signal* source is used instead of a test *signal*. The *signal* source measurements have an additional *correction* for the *fluctuation* and *jitter* of the instrument.

5.9.3.1 Measuring fluctuation of a signal source

Measure the *fluctuation* a *signal* source using the following steps:

a) Perform step a) through step c) in 5.9.2.1.1.

b) Determine the corrected standard deviation, $\sigma_p = \sqrt{\sigma_{\mathrm{obs}}^2 - \sigma_I^2}$, where σ_I is the *fluctuation* of the instrument as determined by one of the methods in 5.9.2.1. To verify the result, the standard deviation of σ_p should be calculated using the method in 5.9.1.5.

5.9.3.2 Measuring the trigger jitter of a signal source

This requires triggering the oscilloscope with the trigger generated by the *signal* source and recording a rapid transition of the *signal* source on the oscilloscope.

a) Perform step a) through step e) in 5.9.2.2.1.

b) Correct the result found in step a) for *fluctuation* of the *signal* source and *jitter* and *fluctuation* of the instrument using:

$$\sigma_{\tau,STJ} = \sqrt{\sigma_{\tau,\mathrm{obs}}^2 - \sigma_{ITJ}^2 - \left(\sigma_{IF}/S\right)^2 - \left(\sigma_F/S\right)^2} \tag{37}$$

where

$\sigma_{\tau,STJ}$ is the *trigger jitter* of the *signal* source
σ_F is the *fluctuation* of the instrument *signal* source

To verify the result, the standard deviation of $\sigma_{\tau,STJ}$ should be calculated using the method of 5.9.1.5.

5.9.3.3 Measuring a relative jitter of a signal source

There are several *jitter* values that involve the *interval* between two *instants*: *cycle-to-cycle jitter*, *period jitter*, and *pulse duration jitter*. The measurement method is the same for all of them.

a) Record *M waveforms* containing the two relevant *instants*.

b) Perform step b) through step e) in 5.9.2.2.2 for the *parameter* of interest.

c) Correct the result of step b) for *fluctuation* and the relative *jitter* in the instrument using:

$$\sigma_{\tau,SJ,\mathrm{rel}} = \sqrt{\sigma^2{}_{\tau,\mathrm{obs}} - \sigma_{ITJ} - \left(\sigma_{IF}/S_1\right)^2 - \left(\sigma_{IF}/S_2\right)^2} \tag{38}$$

where $\sigma_{\tau,SJ,\mathrm{rel}}$ is the relative *trigger jitter* of the *signal* source.

To verify the result, the standard deviation of $\sigma_{\tau,SJ,\mathrm{rel}}$ should be calculated using the method in 5.9.1.5.

6. Figures

This clause contains numerous figures depicting different types of waveform examples, with the associated expressions used to generate them.

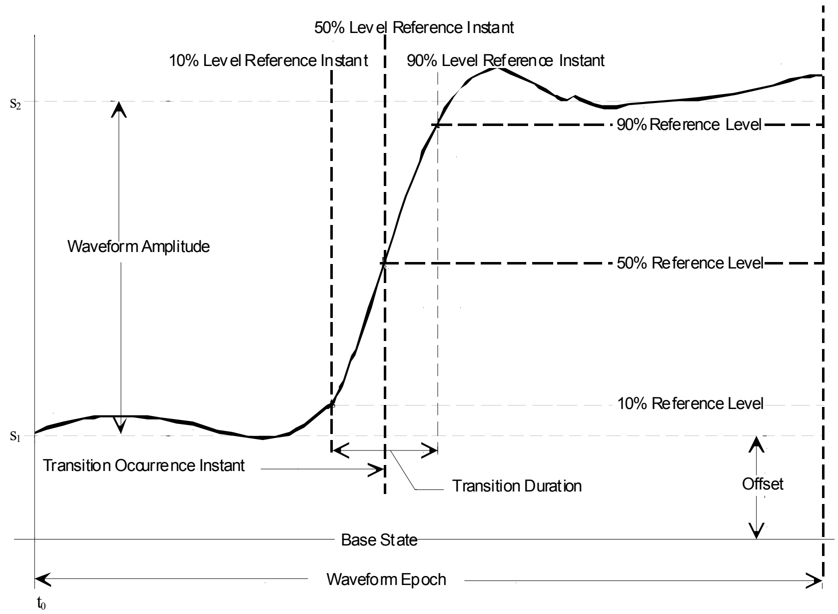


Figure 2—Single positive-going transition

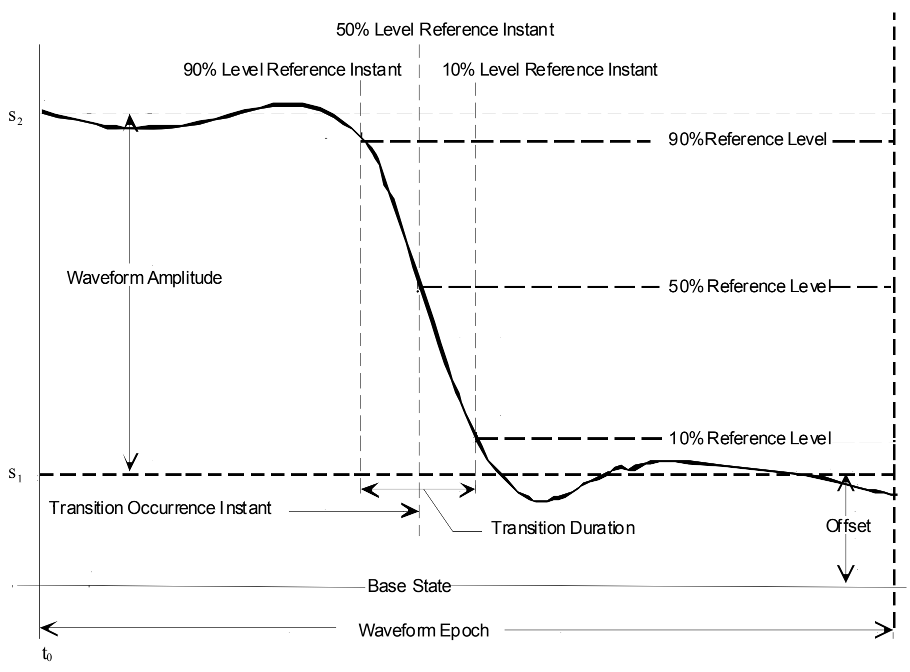


Figure 3—Single negative-going transition

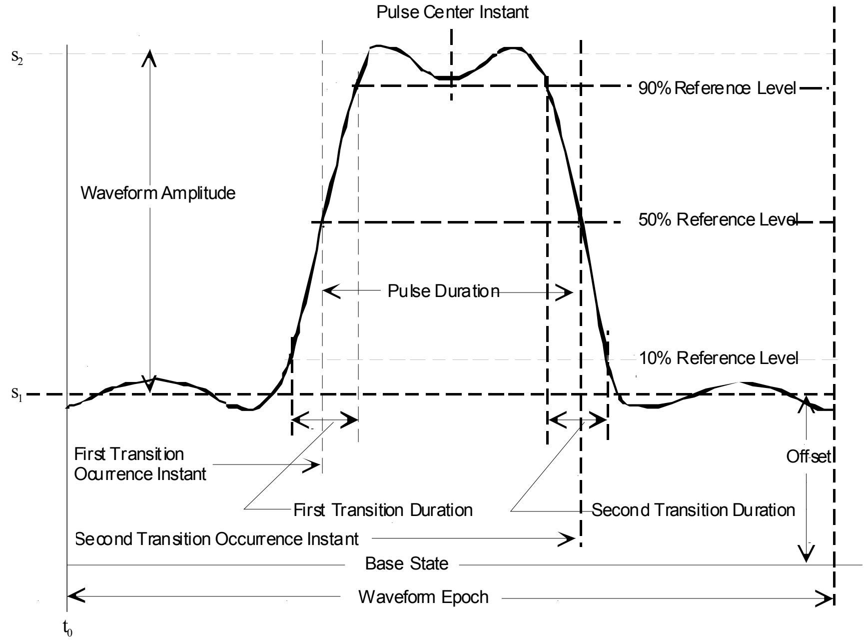


Figure 4—Single positive pulse waveform

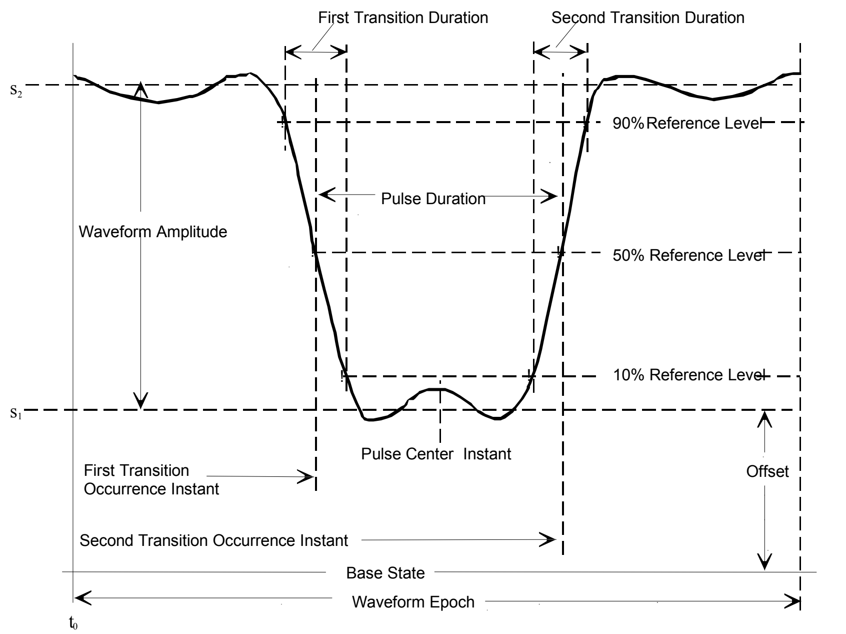
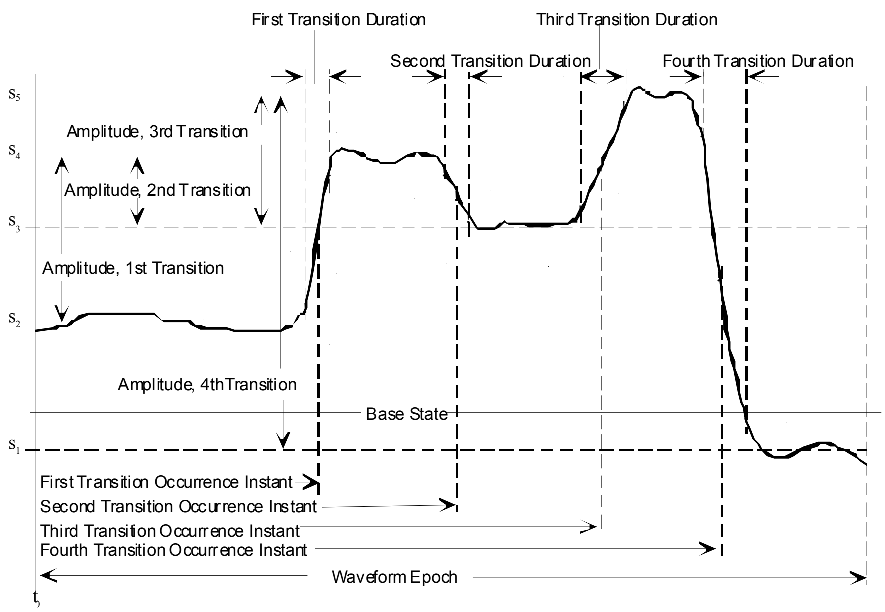


Figure 5—Single negative pulse waveform



NOTE—The dots indicate the intersection of the *waveform* with the 10%, 50%, and 90% *reference levels*. The term *amplitude* is used in place of the defined term *waveform amplitude* because of space constraints. References to *transition durations* and *transition occurrence instants* for the *transitions* are abbreviated by, for example, "second *transition duration,*" instead of the more accurate reference, "*transition duration*, second *transition*."

Figure 6—Compound waveform

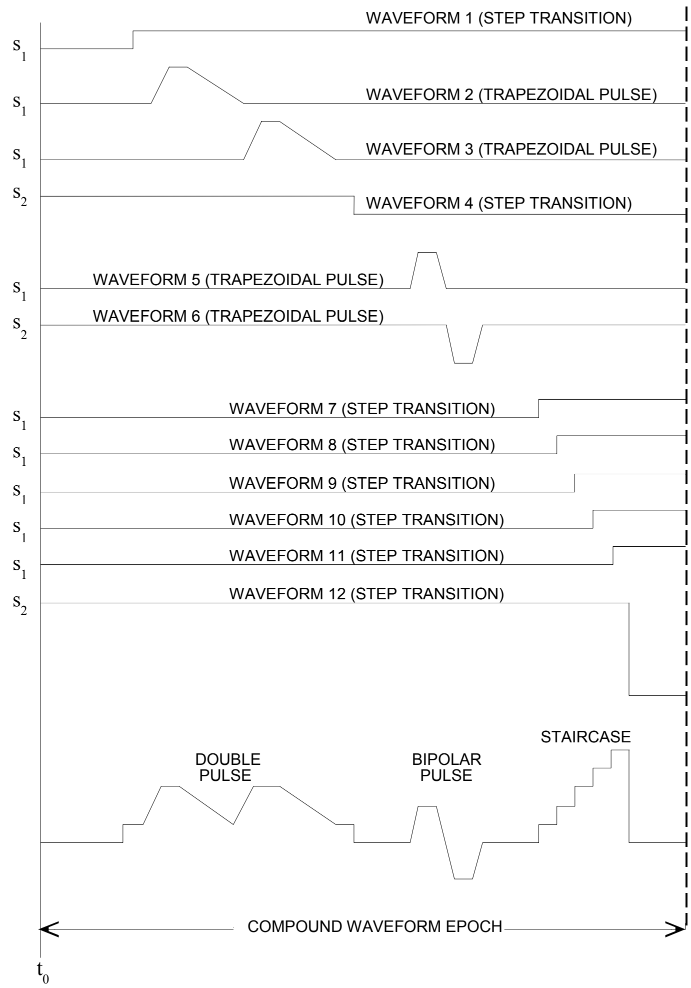


Figure 7—Generation of a compound waveform

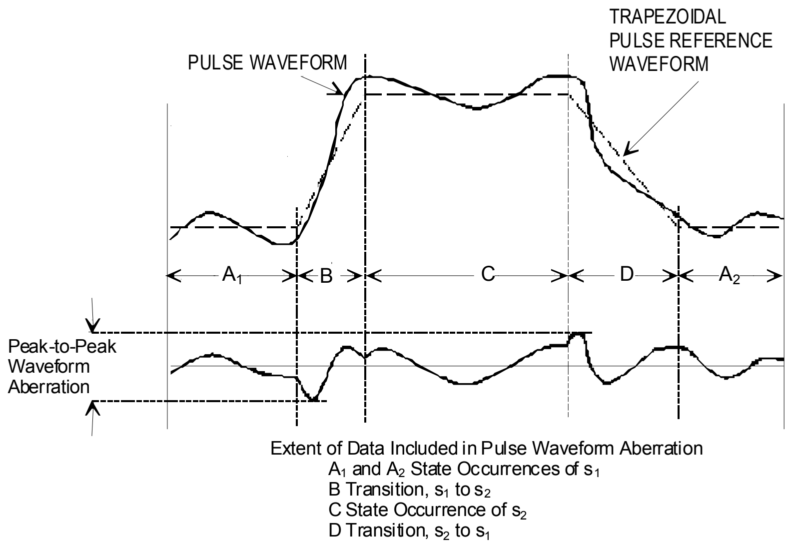


Figure 8—Calculation of waveform aberration

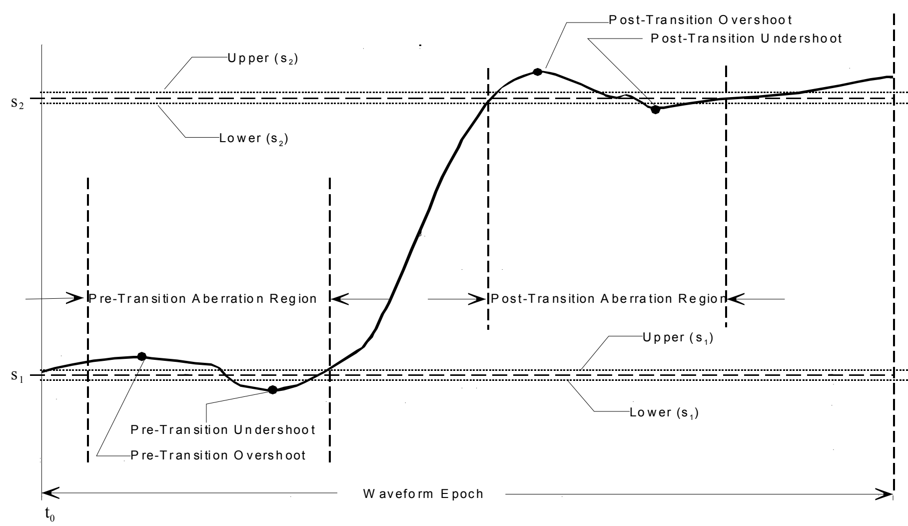


Figure 9—Overshoot and undershoot in single positive-going transition

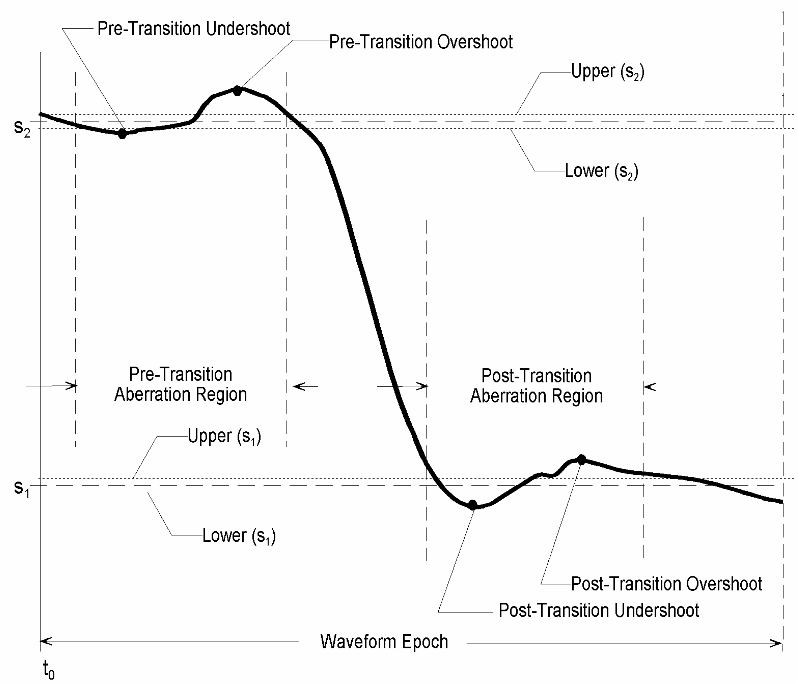


Figure 10 —Overshoot and undershoot in a single negative-going transition

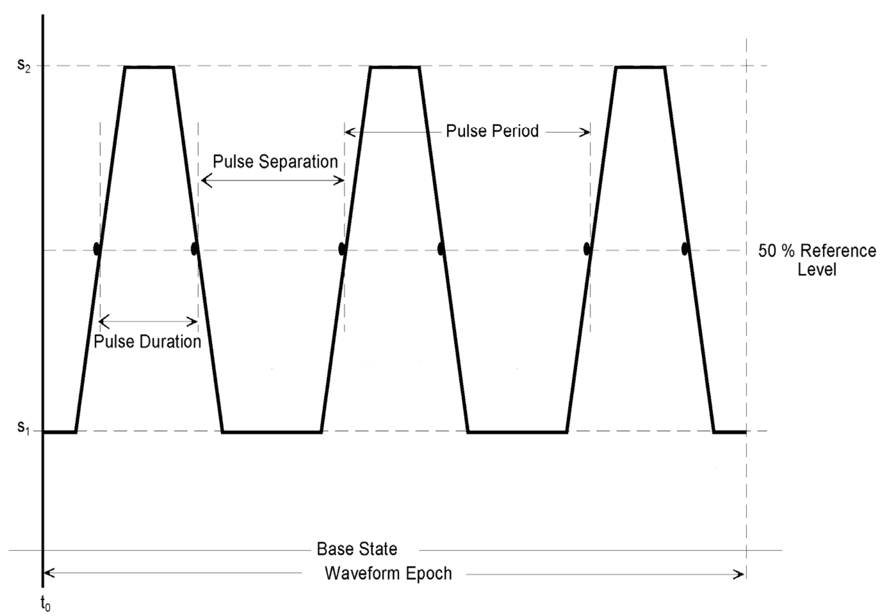


Figure 11 —Pulse train

Annex A

(informative)

Waveform examples

A.1 Reference waveform examples

A reference *waveform* is a *waveform* that is used for comparison (quantitatively or qualitatively) with, or in evaluation of, other *waveforms*. A reference *step-like waveform* may, or may not, be a *step waveform*. Some *waveforms* that are commonly used as reference *waveforms* are defined below.

A.1.1 Step-like waveform

A *waveform* defined by:

$$y(t) = \begin{cases} s_1 & t < t_1 \\ s_2 & t \geq t_1 \end{cases} \tag{A.1}$$

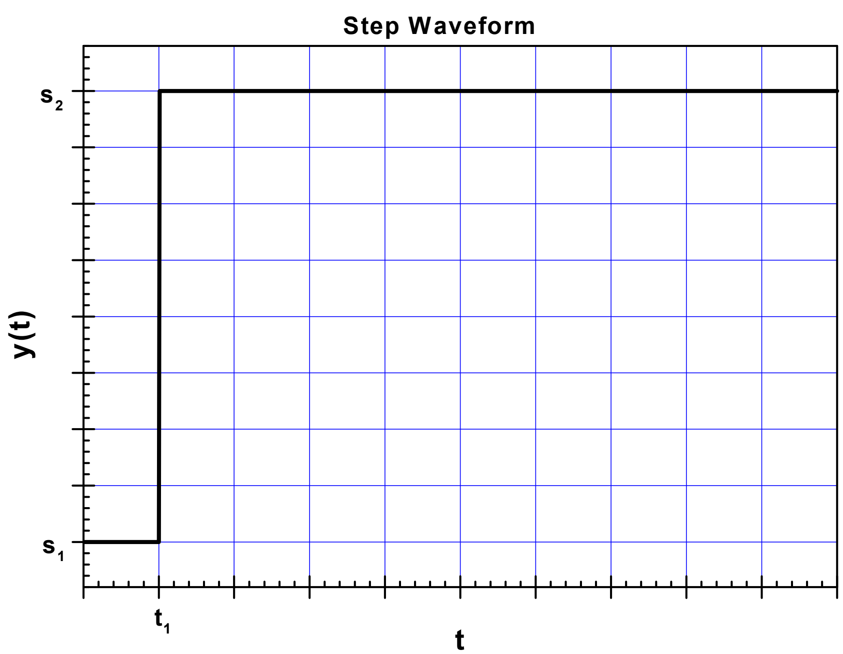


Figure A.1—Step-like waveform

A.1.2 Linear transition waveform

A *waveform* defined by:

$$y(t)=\begin{cases} s_1 & t < t_1 \\ s_1+\dfrac{s_2-s_1}{t_2-t_1}(t-t_1) & t_1 \le t \le t_2 \\ s_2 & t > t_2 \end{cases} \tag{A.2}$$

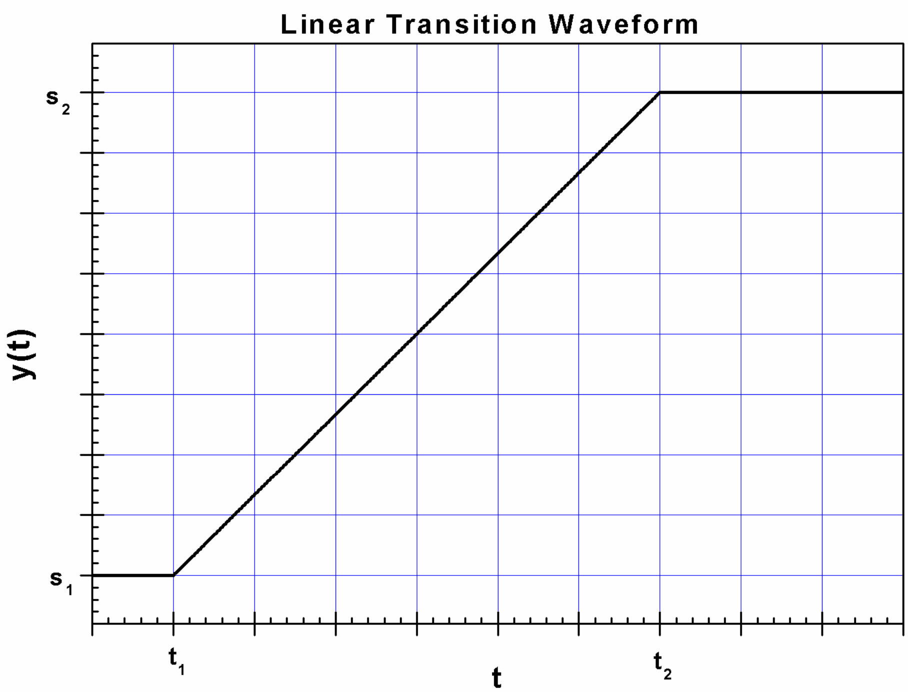


Figure A.2—Linear transition waveform

A.1.3 Exponential waveform

A *transition waveform* defined by:

$$y(t) = \begin{cases} s_1 & t < t_1 \\ s_1 + (s_2 - s_1)\left[1 - e^{-(t-t_1)/b}\right] & t \geq t_1 \end{cases} \tag{A.3}$$

where b is the exponential time constant.

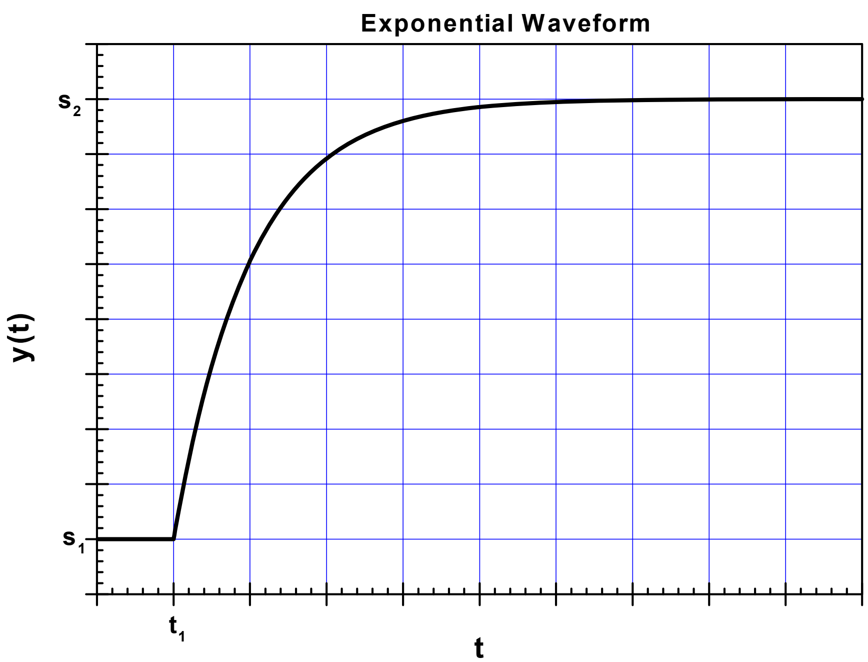


Figure A.3—Exponential waveform

A.1.4 Impulse-like waveform

A *pulse waveform* defined as:

$$y(t) = \begin{cases} s_1 & t \neq t_1 \\ s_2 & t = t_1 \end{cases} \tag{A.4}$$

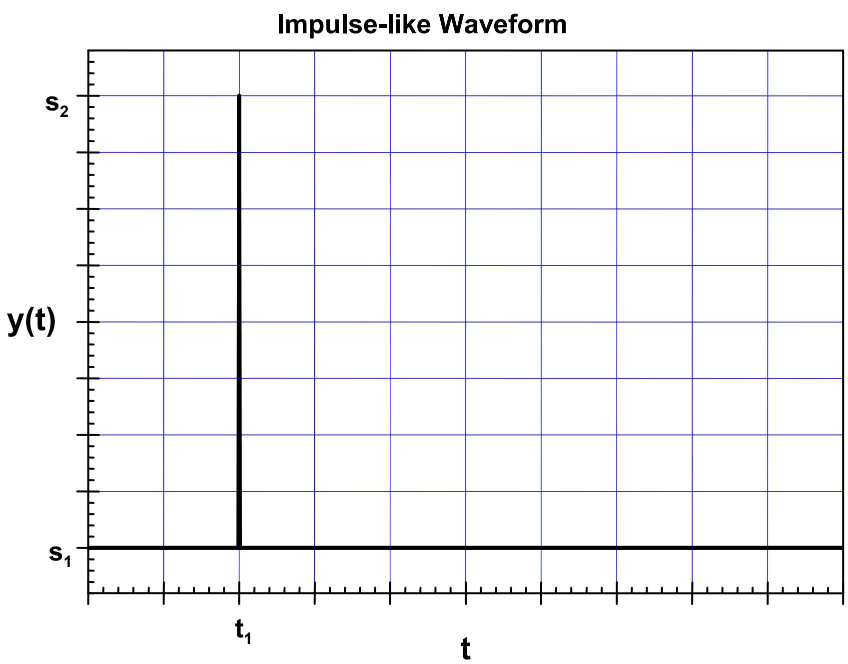


Figure A.4—Impulse-like waveform

A.1.5 Rectangular pulse waveform

A *pulse waveform* defined as:

$$y(t) = \begin{cases} s_1 & t < t_1 \\ s_2 & t_1 \le t \le t_2 \\ s_1 & t > t_2 \end{cases} \tag{A.5}$$

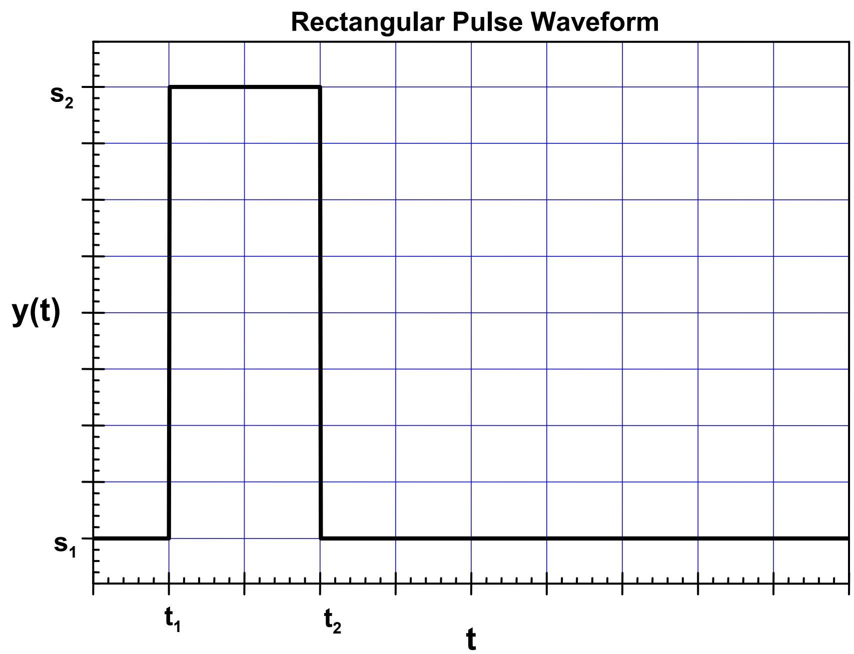


Figure A.5—Rectangular pulse waveform

A.1.6 Trapezoidal pulse waveform

A *pulse waveform* defined as:

$$y(t) = \begin{cases} s_1 & t < t_1 \\ s_1 + (s_2 - s_1)\dfrac{t - t_1}{t_2 - t_1} & t_1 \le t \le t_2 \\ s_2 & t_2 < t < t_3 \\ s_1 - (s_2 - s_1)\dfrac{t - t_4}{t_4 - t_3} & t_3 \le t \le t_4 \\ s_1 & t > t_4 \end{cases} \tag{A.6}$$

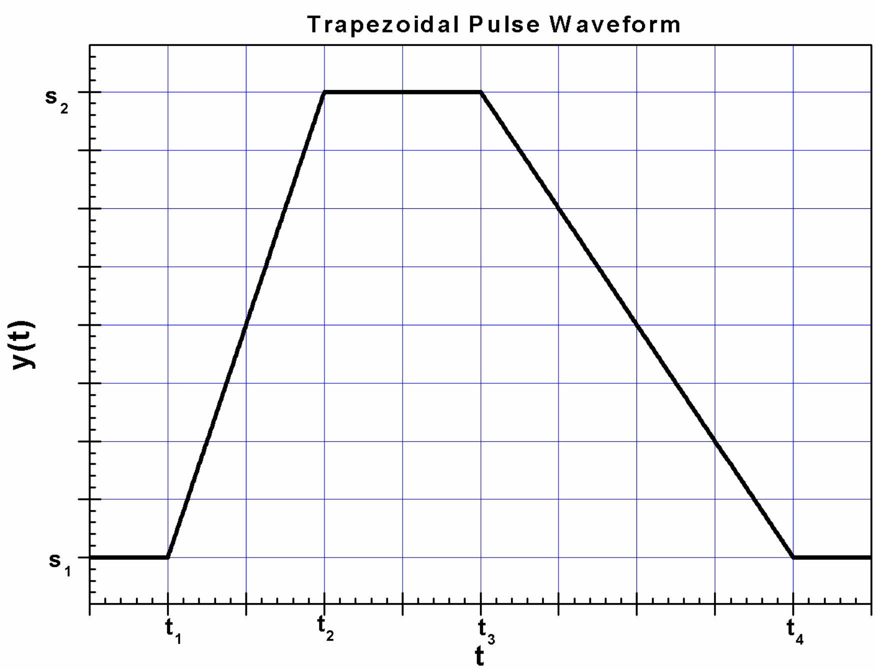


Figure A.6—Trapezoidal pulse waveform

A.1.7 Triangular pulse waveform

A *pulse waveform* defined as:

$$y(t) = \begin{cases} s_1 & t < t_1 \\ s_1 + (s_2 - s_1)\dfrac{t - t_1}{t_2 - t_1} & t_1 \le t < t_2 \\ s_2 & t = t_2 \\ s_1 - (s_2 - s_1)\dfrac{t - t_3}{t_3 - t_2} & t_2 < t \le t_3 \\ s_1 & t > t_3 \end{cases} \tag{A.7}$$

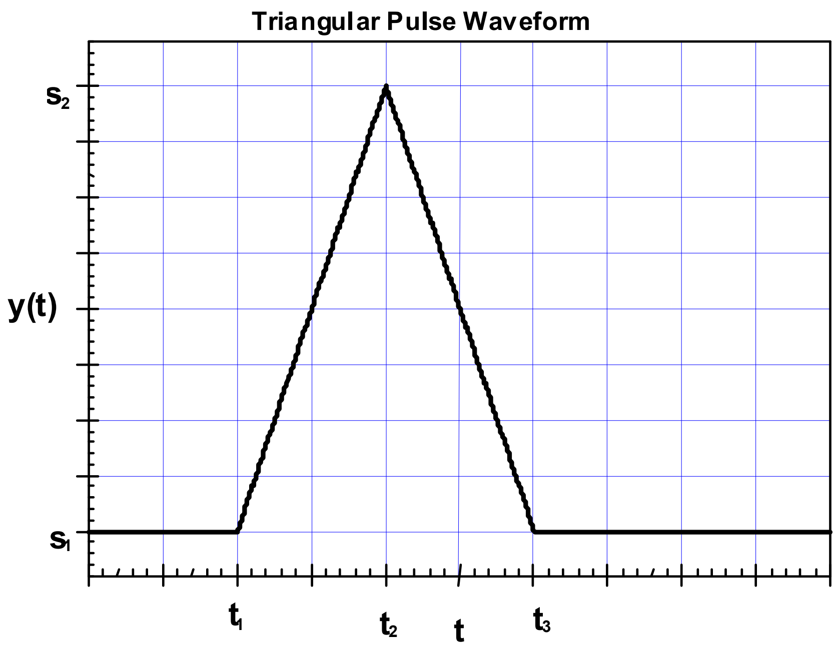


Figure A.7—Triangular pulse waveform

A.1.8 Exponential pulse waveform

A *pulse waveform* defined as:

$$y(t) = \begin{cases} s_1 & t < t_1 \\ s_1 + (s_2 - s_1)\left[1 - e^{-(t-t_1)/b}\right] & t_1 \le t \le t_2 \\ s_1 + (s_2 - s_1)\left[1 - e^{-(t-t_1)/b}\right]e^{-(t-t_2)/c} & t > t_2 \end{cases} \quad (A.8)$$

where

b is the time constant of first *transition*
c is the time constant of second *transition*

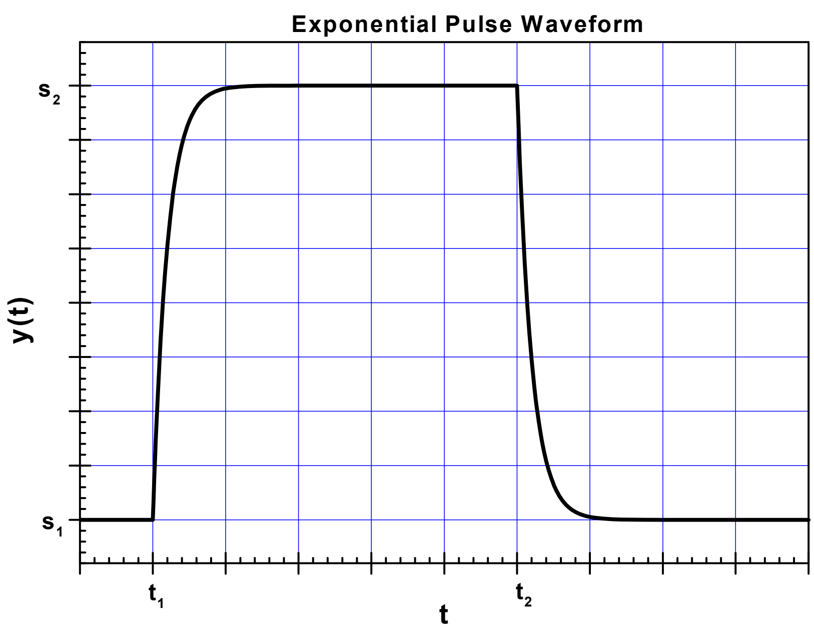


Figure A.8—Exponential pulse waveform

A.2 Compound waveform examples

A *compound waveform* can be generated by concatenating or summing a finite number of single *step-like waveforms*, each of which is defined over an appropriate part of the *waveform epoch*. Examples of some *waveforms* of this type are defined below.

A.2.1 Double pulse waveform

a) The summation of two *pulse waveforms* of the same polarity that are adjacent in time and that are considered or treated as a single *waveform*.

b) Two pulses with the same polarity, *waveform amplitude,* and *base level* that are not overlapping and are treated as a single *waveform*. A c*ompound waveform* with two *states* and four *transitions*.

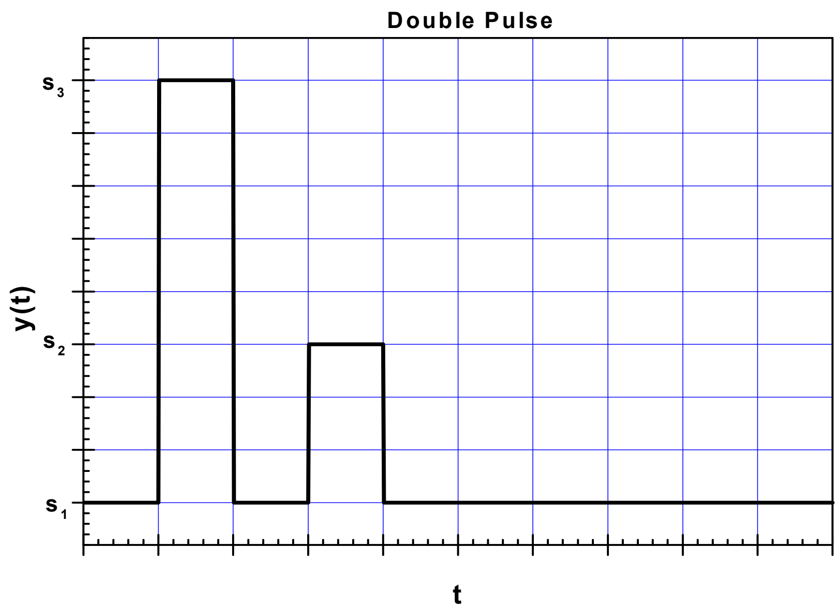


Figure A.9—Double pulse waveform

A.2.2 Bipolar pulse waveform

a) The summation of two *pulse waveforms* of opposite polarity that are adjacent in time and that are considered or treated as a single *waveform*.

b) Use a figure that stresses the order of the *states*. As an example, the order of the *states* for the figure below is s_2, s_3, s_2, s_1, s_2. The *states* of the tristate *waveform* in this example have the ordering (s_2, 1) (s_3, 1) (s_2, 2) (s_1, 1) (s_2, 3).

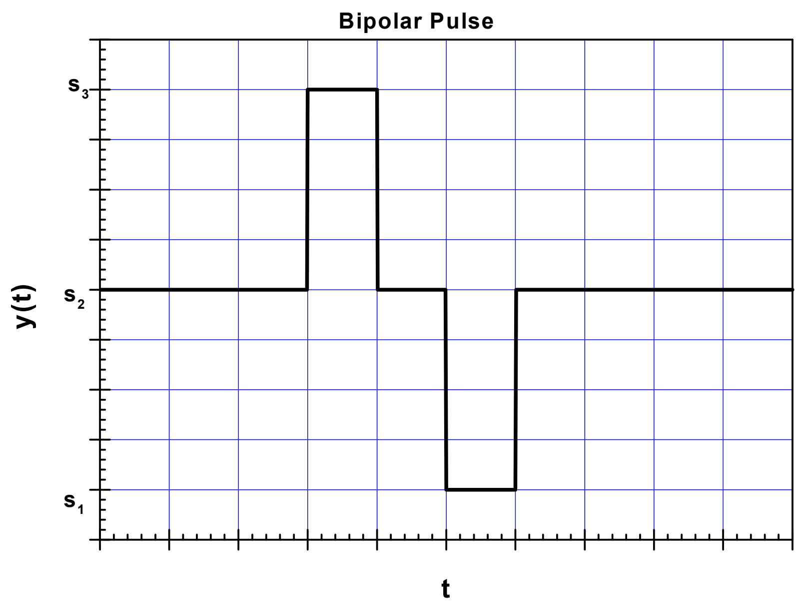
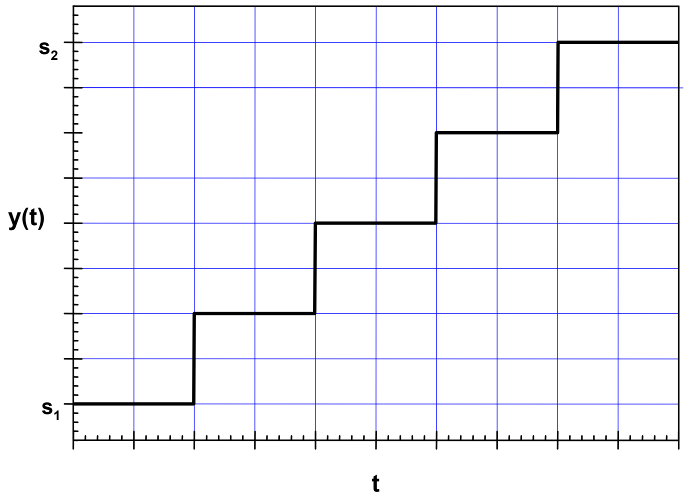


Figure A.10—Bipolar pulse waveform

A.2.3 Staircase waveform

A staircase waveform is the summation of a finite sequence of *step-like waveforms* of the same polarity.

Figure A.11—Staircase waveform



A.2.4 Pulse train

A pulse train is a repetitive sequence of *pulse waveforms*. Unless otherwise specified, all of the *pulse waveforms* in the sequence are assumed to be identical.

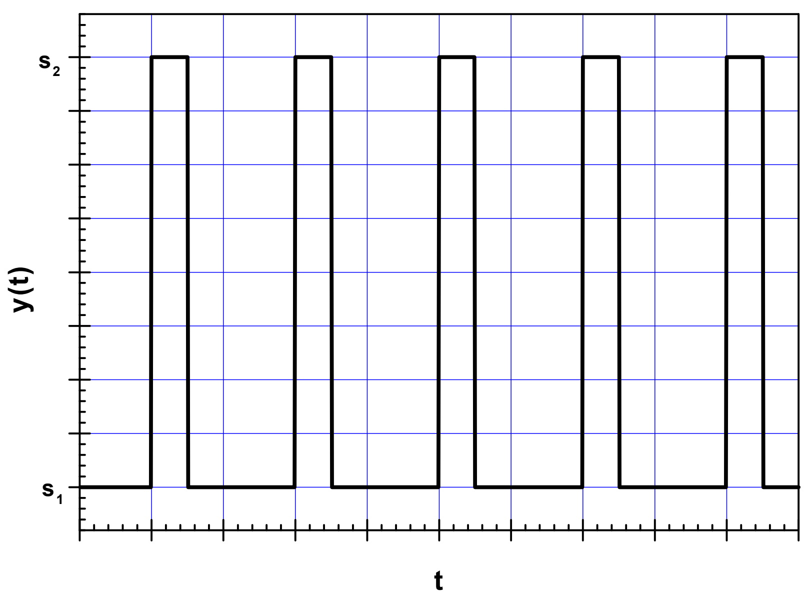


Figure A.12—Pulse train

Annex B

(informative)

Bibliography

Bibliographical references are resources that provide additional or helpful material but do not need to be understood or used to implement this standard. Reference to these resources is made for informational use only.

[B1] Hale, P. D. and C. M. Wang, "Calculation of pulse parameters and propagation of uncertainty," *IEEE Transactions on Instrumentation and Measurement,* vol. 58, no. 3, pp. 639–648, March 2009.[5]

[B2] Hartigan, J. A. *Clustering Algorithms: Probability & Mathematical Statistics,* New Jersey: John Wiley & Sons, Inc., p. 84, 1975.

[B3] NIST Special Publication 811, "Guide for the Use of the International System of Units (SI)," Ambler Thompson and Barry N. Taylor, March 2008.[6]

[B4] Paulter, N. G. "The effect of histogram size on histogram-derived pulse parameters," *IEEE Transaction on Instrumentation and Measurement,* vol. 47, no. 3, pp. 609–612, June 1998.

[B5] Rousseeuw, Peter J. and Annick M. Leroy, *Robust Regression and Outlier Detection,* New Jersey: John Wiley & Sons, Inc., p. 164, 2003.

[B6] Solomon O. M., D. R. Larson, and N. G. Paulter, "Comparison of Some Algorithms to Estimate the Low and High State Level of Pulses," *IEEE Instrumentation and Measurement Technology Conference,* Budapest, Hungary, pp. 21–23, May 2001.[7]

[5]This publication is available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854, USA (http://standards.ieee.org/).
[6]NIST publications are available from the National Institute of Standards and Technology, 100 Bureau Drive, Stop 2300, Gaithersburg, MD 20899-2300, USA (http://www.nist.gov/index.html).
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