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IEEE Std 181™-2003
(Revision of
IEEE Std 181-1977 and
IEEE Std 194™-1977)

181™

IEEE Standard on Transitions, Pulses, and Related Waveforms

IEEE Instrumentation and Measurement (I&M) Society

Sponsored by the
Subcommittee on Pulse Techniques

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Subcommittee on Pulse Techniques
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IEEE Instrumentation and Measurement (I&M) Society

Approved 20 March 2003

IEEE-SA Standards Board

Abstract: This standard presents approximately 100 terms, and their definitions, for accurately and precisely describing the waveforms of pulse signals and the process of measuring pulse signals. 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, 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 181-2003, IEEE Standard on Transitions, Pulses, and Related Waveforms.)

History

The Subcommittee on Pulse Techniques (SCOPT) is a subcommittee of the Waveform Generation, Measurement, and Analysis Committee (TC-10) of the IEEE Instrumentation and Measurement (I&M) Society. Since 1996, the SCOPT has been writing a revision to the now withdrawn IEEE Std 181-1977, IEEE Standard on Pulse Measurement and Analysis by Objective Techniques, and withdrawn IEEE Std 194-1977, IEEE Standard Pulse Terms and Definitions.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. The revised standard combines information from both of these withdrawn IEEE standards.

The SCOPT is comprised of an international group of electronics engineers, mathematicians, and physicists with representatives from national metrology laboratories, national science laboratories, the test instrumentation industry, and academia.

This standard combines the information of and supersedes IEEE Std 181-1977 and IEEE Std 194-1977. IEEE Std 181-1977 superseded IEEE Std 181-1955, Methods of Measurement of Pulse Quantities. Information on IEEE Std 181-1955 and the history of the development of IEEE Std 181-1977 can be found in the Foreword to IEEE Std 181-1977, which is found following this introduction. IEEE Std 194-1977 superseded IEEE Std 194-1951, Standards on Pulses: Definition of Terms—Part 1, 1951. Information on IEEE Std 194-1951 and the history of development of IEEE Std 194-1977 can be found in the Foreword to IEEE Std 194-1977, which is found following this introduction.

The SCOPT submitted a Project Authorization Request (PAR) to the IEEE Standards Board in September 1996 for combining IEEE Std 181-1977 and IEEE Std 194-1977 into a single document and revising the subsequently merged document. The PAR was approved on 11 December 1996, and work on the revised and combined draft started in February 1997. The PAR expiration date was December 2002. SCOPT and TC-10 have applied for a one-year extension to enable balloting and revision as required. The draft went through several major revisions that resulted in the changes to the standard, relative to the withdrawn standards, that will be discussed later. The SCOPT revised the draft several times. These revisions resulted in eliminating previously-proposed suggestions to add frequency-domain terms, which is consistent with the original intent of the SCOPT not to introduce these terms (see forewords to the withdrawn standards), and eliminating the discussion of and terms for pulse modulated radio frequency signals. These revisions also resulted in the development of algorithms for computing the values of certain waveform parameters for which a value is appropriate. The intent of the SCOPT to add 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 draft revisions developed by the SCOPT also resulted in significant changes to terms and their definitions. 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. In the end, however, the importance of unambiguously and accurately defined terms prevailed. Consequently, many terms were deleted and many others added. Most definitions were modified. This work finally ended in September 2002 with a draft agreed upon by the SCOPT.

Purpose

The purpose of the standard is to facilitate 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 to ensure that the definitions and methods of computation for pulse parameters are consistent.

Changes

The most significant change to the IEEE Std 181-1977 and IEEE Std 194-1977 was to merge these two documents. The next major changes were in three areas of information content: definitions, algorithms, and waveform examples. Changes to the definitions included adding 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 IEEE 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 is not within the scope of the standard as determined by SCOPT.

The withdrawn standards did not contain algorithms for calculating the value (number plus unit of measure) of a waveform parameter. The SCOPT introduced into this standard algorithms for calculating the values for all defined terms that describe a measurable parameter. Examples of defined terms that describe a measurable parameter are *pulse amplitude*, *transition duration*, and *state level*. Not all defined terms have an associated algorithm because these terms do not describe a measurable parameter. Examples of defined terms that do not describe a measurable waveform parameter are *spike*, *sampling*, and *sampled waveform representation*. The algorithms are provided as a reference, and the user is advised to specify any departures from the algorithm procedures. Furthermore, the algorithms provide default values for variables used in the computation of certain parameters, such as the transition duration of a waveform where the default values for the variables may be the 10% and 90% reference levels. The user is instructed to specify the values for these variables if other than the default values are used.

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 jitter of waveforms were also introduced into the standard. These algorithms describe the computation of the mean and standard deviation of jitter and fluctuation. Methods to estimate the accuracy of and correcting the value of the standard deviation are also given.

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

Foreword to IEEE Std 194-1977

This standard supersedes IEEE Std 194-1951, Standards on Pulses: Definition of Terms—Part 1, 1951. It should be used in conjunction with IEEE Std 181-1977, IEEE Standard on Pulse Measurement and Analysis by Objective Techniques.

The previous editions of the IEEE standards on pulses were published in 1951–1955, a period when pulse measuring instruments (principally, the cathode ray oscilloscope) were completing their evolution from qualitative indicators to quantitative instruments. These previous standards reflected this evolutionary stage in nomenclature, definitions, and methods of measurement which relied heavily on visual observation and subjective evaluation. No review of the growth of pulse technology in the intervening years is needed here; by 1966, when the IEEE Subcommittee on Pulse Techniques was formed, the previous edition of this standard was obsolete.

The greatest challenge the subcommittee faced was the development of a standard which would satisfy the needs of a wide range of users, users whose measurement practices ranged from the casual and inexact to the most careful and exact. Since a standard which covers exact work can, by degradation or omission, also cover inexact work, the subcommittee developed a standard which satisfies the needs of the user and manufacturer of sophisticated pulse apparatus. Nonetheless, study of Figure 2 will show that, barring changes in nomenclature, nothing has changed and the previous practices of the casual user are preserved.

The subcommittee also made the following decisions relative to the content of this standard:

1) No frequency domain terms (for example, bandwidth) would be used or defined.
2) No terms which link the time and frequency domains (for example, pulse bandwidth) would be used or defined.
3) No acronyms or coined words would be used or defined.
4) No synonyms would be used or defined. (For example, pulse is defined and impulse is neither used nor defined.)
5) The introduction of new concepts would be minimized. The only new concepts that are introduced are found in the definitions of epochs, feature, and quadrant.

The presentation of definitions in this standard, and within its sections, starts with the most general terms and proceeds to the definition of terms which are more specific in terms of terms that have been defined previously. This arrangement, while sacrificing alphabetical listing, yields a logical presentation of significant tutorial value. Terms that are adjectives are defined separately from terms that are nouns with the expectation that, as the need arises, adjective and noun terms will be combined to provide the required term.

Since its formation in 1966, the IEEE Subcommittee on Pulse Techniques has been broadly based. Collectively, its members represented or provided liaison with seven IEEE societies or groups (Circuits and Systems, Computer, Electron Devices, Engineering in Medicine and Biology, Instrumentation and Measurement, Magnetics, and Nuclear and Plasma Sciences), six technical associations (American Society for Testing and Materials, Electronic Industries Association, Instrument Society of America, National Conference of Standards Laboratories, Precision Measurement Association, and Scientific Apparatus Makers Association), and three technical committees of the International Electrotechnical Commission (Electron Tubes and Valves, Electronic Measuring Equipment, and Magnetic Materials and Components). Nine members of the subcommittee were from six countries other than the U.S. (France, Germany, Hungary, Japan, the Netherlands, and the United Kingdom). Subcommittee members who represented users of pulse apparatus outnumbered members who represented manufacturers.

Beginning in 1970 the liaison between the subcommittee and Technical Committee 66, Electronic Measuring Equipment, of the International Electrotechnical Commission (IEC) became progressively closer and culminated in an informal mutual understanding that both groups would attempt to provide their parent organizations with pulse standards which were the same. This goal was achieved; IEC Publication 469-1, 1974, Pulse Techniques and Apparatus, Part 1: Pulse Terms and Definitions, is technically (and, otherwise, substantially) identical to this standard.

Foreword to IEEE Std 181-1977

This standard supersedes IEEE Std 181-1955, Methods of Measurement of Pulse Quantities. It should be used in conjunction with IEEE Std 194-1977, Pulse Terms and Definitions.

The previous editions of the IEEE standards on pulses were published in 1951–1955, a period when pulse measuring instruments (principally, the cathode ray oscilloscope) were completing their evolution from qualitative indicators to quantitative instruments. These previous standards reflected this evolutionary stage in nomenclature, definitions, and methods of measurement which relied heavily on visual observation and subjective evaluation, or where more exact results were desired, on planimeters techniques. No review of the growth of pulse technology in the intervening years is needed here; by 1966 when the IEEE Subcommittee on Pulse Techniques was formed, the previous edition of this standard was obsolete.

The greatest challenge the Subcommittee faced was the development of a standard which would satisfy the needs of a wide range of users whose measurement practices ranged from the casual and inexact to the most careful and exact. Since a standard which covers exact work can, by degradation or omission, also cover inexact work, the Subcommittee developed a standard which satisfies the needs of the user and manufacturer of sophisticated pulse apparatus. In doing this the Subcommittee found it necessary to define or describe in a rigorous manner a number of well-established terms and techniques. Nonetheless, careful study of this standard will show that the techniques and practices of the more casual user have been preserved.

The Subcommittee also made the following decisions relative to the content of this standard: (1) No frequency domain terms (e.g., bandwidth) would be used or defined. (2) No terms which link the time and frequency domains (e.g., pulse bandwidth) would be used or defined. (3) No acronyms or coined words would be used or defined.

The Subcommittee minimized the introduction of new concepts. At the first reading it may appear that there is a significant amount of new material; this is not the case. Section 2, Definitions, merely defines terms and techniques, some, perhaps, for the first time, more completely, or to a finer level of distinction. Section 3 [of Std 181-1977], Measurement of Pulse Characteristics, presents a model of the pulse measurement process. Sections 5 through 9 [of Std 181-1977] merely extend analysis of the single pulse waveform to encompass both simpler and more complex waveforms. Only in Section 4 [of Std 181-1977] is new material found as follows:

1) Section 4.2, Waveform Epoch Determination. This material is not really new, but a new emphasis is put on the choice of data. Sections 4.3.1, and 4.3.2 do present new techniques for the determination of base magnitude, top magnitude, and pulse amplitude.
2) The presentation of material in this standard, and within its sections, starts with the most general concepts and proceeds to the presentation of concepts which are more specific in terms of concepts which have been presented previously. This arrangement, while sacrificing alphabetical listing, yields a logical presentation of significant tutorial value.

Since its formation in 1966 the IEEE Subcommittee on Pulse Techniques has been broadly based. Collectively, its members represented or provided liaison with seven IEEE Societies or Groups (Circuits and Systems, Computer, Electron Devices, Engineering in Medicine and Biology, Instrumentation and Measurement, Magnetics, and Nuclear and Plasma Sciences), six technical associations (American Society for Testing and Materials, Electronic Industries Association, Instrument Society of America, National Conference of Standards Laboratories, Precision Measurement Association, and Scientific Apparatus Makers Association), and three Technical Committees of the International Electrotechnical Commission (Electron Tubes and Valves, Electronic Measuring Equipment, and Magnetic Materials and Components). Nine members of the Subcommittee were from six countries other than the U.S. (France, Germany, Hungary, Japan, the Netherlands and the United Kingdom).

Beginning in 1970 the liaison between the Subcommittee and Technical Committee 66, Electronic Measuring Equipment, of the International Electrotechnical Commission (IEC), became progressively closer and culminated in an informal mutual understanding that both groups would attempt to provide their parent organizations with pulse standards which were the same. This goal was achieved; IEC Publication 469-2, 1974, Pulse Techniques and Apparatus, Part 2: Pulse Measurement and Analysis, General Considerations, is technically (and, otherwise, substantially) identical to this standard.

Participants

At the time this standard was completed, the Subcommittee on Pulse Techniques had the following membership:

Nicholas G. Paulter, Jr., *Chair*
Otis M. Solomon, *Previous Chair*

Pasquale Arpaia
Jerome J. Blair
Pasquale Daponte
Chris Duff
Robert M. Graham
Daniel J. Kien
Dan Knierim
Donald R. Larson
Yeou-Song Lee
James M. Lewis
Thomas E. Linnenbrink
Solomon Max
Martin T. Miller
Alan G. Roddie
Joseph M. Schachner
Andrew J.A. Smith
Steven J. Tilden

The following members of the balloting committee voted on this standard. Balloters may have voted for approval, disapproval, or abstention.

Jacob Ben Ary
Jerome J. Blair
Keith Chow
Robert M. Graham
Erich Gunther
Donald R. Larson
Yeou-Song Lee
James Lewis
Art Light
Thomas E. Linnenbrink
Gergory Luri
Andrea Mariscotti
Solomon Max
Gary Michel
Charles Kamithi Ng'ethe
Nicholas G. Paulter, Jr.
Joseph Schachner
Steven J. Tilden

When the IEEE-SA Standards Board approved this standard on 20 March 2003, it had the following membership:

Don Wright, *Chair*
Howard M. Frazier, *Vice Chair*
Judith Gorman, *Secretary*

H. Stephen Berger
Joe Bruder
Bob Davis
Richard DeBlasio
Julian Forster*
Toshio Fukuda
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Laura Hitchcock
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Anant Jain
Lowell G. Johnson
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Tom McGean
Steve Mills
Daleep C. Mohla
William J. Moylan
Paul Nikolich
Gary Robinson
Malcolm V. Thaden
Geoffrey O. Thompson
Doug Topping
Howard L. Wolfman

*Member Emeritus

Also included are the following nonvoting IEEE-SA Standards Board liaisons:

Alan Cookson, *NIST Representative*
Satish K. Aggarwal, *NRC Representative*

Catherine Berger
IEEE Standards Project Editor

Contents

IEEE Standard on Transitions, Pulses, and Related Waveforms

1. Overview

1.1 Scope

This standard provides definitions of terms pertaining to transitions, pulses, and related waveforms, and provides definitions and descriptions of techniques and procedures for measuring their parameters. The waveforms considered in this standard are those that make a number of transitions and that remain relatively constant in the time intervals between transitions.

1.2 Object

The object of this standard is to facilitate accurate and precise communication concerning parameters of transitions, pulses, and related waveforms and the techniques and procedures for measuring them.

1.3 Deprecated terms

Along with the recommended terms and their definitions, Clause 3 of this standard also contains a number of deprecated but widely used terms. These deprecated terms and the reason for their deprecation are given after the definition of the recommended term.

1.4 Representations and conventions

Throughout this standard, time is taken to be 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.

2. References

This standard shall be used in conjunction with the following publications. When the following specifications are superseded by an approved revision, the revision shall apply.

ISO Guide to the Expression of Uncertainty in Measurement, rev. 1993, ISBN 92-67-10188-9.[1]

[1]ISO 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 publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).

ISO International Vocabulary of Basic and General Terms in Metrology, rev. 1993, ISBN 92-67-01075-1.

ISO 9000, Quality Management Systems—Fundamentals and Vocabulary, rev. 2000.

ISO 10012-1, Quality Assurance Requirements for Measuring Equipment—Part 1. Metrological Confirmation System for Measuring Equipment.

NIST Special Publication 811, Guide for the Use of the International System of Units (SI), Barry N. Taylor, April 1995.[2]

3. Definitions and symbols

3.1 Definitions

All defined terms are italicized in this document.

3.1.1 aberration region

3.1.1.1 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* when the *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*.

3.1.1.2 aberration region, post-transition: The *interval* between a user-specified *instant* and a fixed *instant*, where the fixed *instant* is the first sampling *instant* succeeding the 50% *reference level instant* when the *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*.

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

3.1.3 amplitude

3.1.3.1 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*.

3.1.3.2 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 must be clearly identified. The two definitions are as follows:

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

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

[2]NIST publications are available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402-9325 (http://www.gpo.gov).

3.1.4 correction: The correction operation combines the results of the conversion operation (see 4.2) with the transfer function information to yield a waveform that is a more accurate representation of the signal. Correction may be effected by a manual process by an operator, a computational process, or a compensating device or apparatus. Correction must be performed to an accuracy that is consistent with the overall accuracy desired in the waveform measurement process.

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

3.1.6 delaying: A process in which a *signal* is delayed in time.

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

3.1.8 duration: The difference between two specified *instants*.

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

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

3.1.10 fluctuation: Variation (dispersion) of a *level* parameter of a set of repetitive *waveforms* with respect to a *reference amplitude* or a *reference level*. Unless otherwise specified by a mathematical adjective, root-mean-square (rms) *fluctuation* is assumed.

3.1.11 frequency: The reciprocal of *waveform period*.

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

3.1.13 instant: Unless otherwise specified, a time specified with respect to the *initial instant*, t_0, of a *waveform epoch*.

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

3.1.13.2 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.

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

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

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

3.1.13.6 instant, transition occurrence: The first 50% *reference level instant* (see 5.3.3.1), unless otherwise specified, on the *transition* of a *step-like waveform*.

NOTE—See Figure 2, Figure 3, Figure 4, Figure 5, and Figure 6.

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

3.1.15 interval: The set of all values of time between an *instant* and a second *instant*, where the second *instant* is later in time than the first. The *instants* referred to are called the endpoints of the interval. The endpoints, unless otherwise specified, are assumed to be part of the interval.

3.1.16 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 instant* or *duration*. Unless otherwise specified by a mathematical adjective, rms *jitter* is assumed.

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

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

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

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

3.1.17 level: Constant value, such as a dc voltage.

3.1.17.1 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:

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

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

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

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.

3.1.17.2 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:

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

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

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

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.

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

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

where

$0\% < x < 100\%$

$y_{0\%}$ = level of *low state*,

$y_{100\%}$ = level of *high state*,

$y_{0\%}$, $y_{100\%}$, and $y_{x\%}$ are all in the same unit of measurement.

Commonly used *reference levels* are 0%, 10%, 50%, 90%, and 100%.

NOTE—See Figure 2, Figure 3, Figure 4, and Figure 5.

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

NOTE—The following are deprecated terms: *mesial*, *proximal*, and *distal*. *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) the terms *mesial*, *proximal*, and *distal* refer to user-defined *reference levels*, and it is not necessary to have redundant definitions for these *reference levels*; (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, for (3), 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*.

3.1.17.5 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.

3.1.17.6 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:

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

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

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

The summation or the integral extends over the *waveform epoch* for which the rss *level* is desired.

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

3.1.19 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, Figure 3, Figure 4, and Figure 5.

3.1.20 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*.

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

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

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

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

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

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

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

NOTES

1—See Figure 4 and Figure 5.

2—The following is a deprecated term: *pulse width*. *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 desired 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.

3.1.26 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*.

3.1.27 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.

3.1.28 pulse waveform: A *waveform* whose *level* departs from one *state*, attains another *state*, and ultimately returns to the original *state*. As defined here, a *pulse waveform* consists of two *transitions* and two *states* (see Clause 4). 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—See Figure 4 and Figure 5.

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

NOTE—See Figure 5.

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

NOTE—See Figure 4.

3.1.29 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*. A reference entity may or may not be an ideal entity.

3.1.30 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.

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

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

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

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

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

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

3.1.37 state: A particular *level* or, when applicable, a *level* with an associated *upper* and *lower state boundary*. 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, ..., 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 $lower(s_1)$, $lower(s_2)$, …, $lower(s_n)$.

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.

3.1.37.1 state, base: The *base state* of a *step-like waveform* is a user-specified state that, unless otherwise specified, is the *state* that possesses a *level* closest to zero.

NOTE—See Figure 2, Figure 3, Figure 4, Figure 5, and Figure 6.

3.1.37.2 state, high: Unless otherwise specified, the *high state* of a *waveform* is the most *positive state* within the *waveform epoch*.

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.

3.1.37.3 state, low: Unless otherwise specified, the *low state* of a *waveform* is the most *negative state* within the *waveform epoch*.

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.

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

3.1.38 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*. The *state boundaries* are defined by the user.

3.1.39 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. 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_i,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. 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).

NOTE—The *state occurrences* for a single *pulse*, as shown in Figure 4 and Figure 6, are (s_1, 1), (s_2, 1), (s_1, 2). The *state occurrences* for the *compound waveform* shown in Figure 6 are (s_2, 1), (s_4, 1), (s_3, 1), (s_5, 1), (s_1, 1).

3.1.40 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* must be integer multiples of one another.

3.1.41 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*.

3.1.42 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. Tilt may be of either *polarity.*

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

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

3.1.44 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*.

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

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

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

3.1.45 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*.

NOTES

1—See Figure 2 and Figure 3.

2—The following are deprecated terms: *risetime*, *falltime*, *leading edge*, *rising edge*, *trailing edge*, *falling edge*, and *transition time*. 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 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*.

3.1.46 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 following is a deprecated term: *settling time*. The term *settling time* is a deprecated term because the word *time* in this standard refers exclusively to an *instant* and not an *interval*.

3.1.47 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*.

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

3.1.49 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*.

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

NOTE—See Figure 2, Figure 3, Figure 4, Figure 5, Figure 6, and the figures of Annex A.

3.1.50.1 waveform, compound: A waveform that may be completely represented by m states and n transitions where $(m + n) \geq 4$. Any compound waveform can be parsed (see 5.5) into n two-state waveforms.

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

NOTE—See Figure 6.

3.1.50.3 waveform, reference: A *waveform* against which other *waveforms* are compared. A.1 contains figures that depict different *reference waveforms*.

3.1.50.4 waveform, step-like: A *waveform* whose *level* departs from one *state* and attains another *state*. Unless otherwise specified, multiple *transitions* are ordered from the earliest *transition occurrence instant* to the latest occurrence in time.

NOTE—See Figure 2 and Figure 3.

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

NOTE—The following is a deprecated term: *preshoot*. *Preshoot* is a deprecated term because "pre" is a temporal prefix, and "shoot," in this context, refers to a *level parameter*.

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

NOTE—See Figure 8.

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

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

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

NOTE—See Figure 2, Figure 3, Figure 4, and Figure 5.

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

3.1.55 waveform measurement process: A realization of a method of *waveform* 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*.

3.1.56 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*.

3.1.57 waveform representaton: (See 3.1.47.1 through 3.1.47.4.)

3.1.57.1 waveform representation, pictorial: A graph, plot, or display in which a *waveform* is presented for observation or analysis. Any of the *waveform* formats defined in this clause may be presented in the pictorial format.

3.1.57.2 waveform representation, sampled: 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 *aperiodically sampled waveform representation* and the *periodically sampled waveform representation*.

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

3.1.57.2.2 waveform representation, sampled, periodically: A finite sequence of *levels* $y_0, y_1, y_2, \ldots, y_n$ each of which represents the value of the waveform at times $t_0, t_0 + \Delta t, t_0 + 2\Delta t, \ldots, t_0 + n\Delta t$, 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* (see 3.1.17.5)
y_{rss}	rss *level* (see 3.1.17.6)
$y_{x\%}$	*x% reference level*
$\bar{\boldsymbol{y}}$	*average level* (see 3.1.17.1)
$\bar{\boldsymbol{y}}_{\boldsymbol{i}}$	mean over a collection of *waveforms* $y_{k,i}$, where k is the *waveform* index
$\boldsymbol{\Sigma}_{\boldsymbol{i}}$	the standard deviation of a set of standard deviations

3.3 Deprecated terms

The terms listed on the left are the deprecated terms in alphabetical order, and the terms on the right are the accepted terms

droop	*tilt*
duty cycle	*duty factor*
preshoot	*overshoot* or *undershoot* in the *pre-transition aberration region*
pulse width	*pulse duration*
fall time	*transition duration*
falling edge	*transition duration*
leading edge	*transition duration*
risetime	*transition duration*
rising edge	*transition duration*
settling time	*transition settling duration*
trailing edge	*transition duration*
transition time	*transition duration*

4. Measurement and analysis techniques

This clause 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

4.1 Method of *waveform* measurement

A method of making a *waveform* measurement comprises

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

4.2 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*. Figure 1 shows the constituent steps of any *waveform measurement process* where, as indicated, the process involves two distinct sequential subprocesses: *signal*-to-*waveform* conversion and *waveform* analysis. Thus, the *waveform measurement process* involves the following:

a) The conversion of a *signal* into its transform (*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*

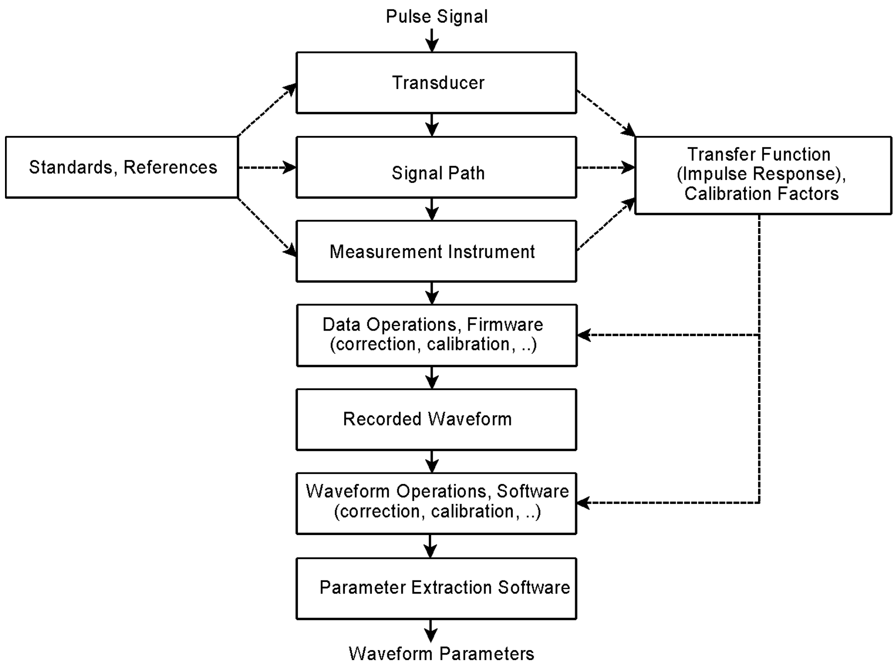

Figure 1—Waveform acquisition and measurement process

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 that 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.

4.3 *Waveform epoch* determination

4.3.1 Selection of *waveform epoch*

A *waveform epoch* must contain the *waveform* features under analysis. The *waveform epoch* must 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*.

4.3.2 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 must 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 level* 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

5.2 Selecting *state levels*

In the following clauses, algorithms for determining *state levels* are described. 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 Histogram methods

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 must be divided into *M* unique, but not necessarily equal, amplitude intervals. For simplicity, however, only the equal-amplitude-interval case will be considered. 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

a) Determine the maximum and minimum amplitude values, $y_{\max}$ and $y_{\min}$, of the *waveform* or data using (a.1) or (a.2).
   1) Search the *waveform* or data for $y_{\min}$ and $y_{\max}$.
   2) Set $y_{\min}$ and $y_{\max}$ from user-specified criteria or knowledge of the *waveform* or data.
b) Calculate the amplitude range, y_R, of the *waveform* or data using: $y_R = y_{max} - y_{min}$.
c) Calculate the bin width:
   1) For equal-sized bins, Δy is found by dividing y_R by *M* (selection of *M* is discussed in 5.2.1.2):

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

where
Δy is the histogram bin size,
M is the number of histogram bins,
$y_{\max}$ 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 specificces an array of bin sizes Δy_i.

d) Sort through the *waveform* or data values, y_i, and if the value lies within the range of a bin, that is if: $y_{\min} + (i-1)\Delta y < y_i < y_{\min} + i\Delta y$, for $1 \le i \le M$, for equal-sized bins, or $y_{\min} + \Delta y_i < y_i < y_{\min} + \Delta y_{i+1}$, for $1 \le i \le M$, for unequal-sized bins, then $B_i = B_i + 1$, where B_i is the count in the i^{th} histogram bin. If a data value equals the value of a bin boundary, that data value must be assigned to one of the bins located on either side (below or above) of that bin boundary. The side that is selected must be consistently applied to all such data values and specified by the user.

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

Three 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 compromised. 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 signal 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 must 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 bins, where n is an integer and x is less than 1, then each histogram bin will actually have a width of either n or $n + 1$. 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 sizes, 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 criteria is attained. One criteria 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 must 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 Paulter [B1],[3] which also shows the effects of varying bin size 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 user-defined *parameters*, f_1 and f_2, where $f_1 \le f_2$. 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_i, for $i = 1...M$, be the bin counts in a histogram as defined in 5.2.1. Let i_{low} be the smallest value of i for which $B_i > 0$, and let i_{high} be the largest value of i for which $B_i > 0$. The range of the lower histogram is $i_{low} \le i \le f_1(i_{high} - i_{low})$. The range of the upper histogram is $i_{low} + f_2(i_{high} - i_{low}) \le i \le i_{high}$.

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 [B2] examine the effect of different histogram methods on the values of the *state levels*.

5.2.2 Other methods

5.2.2.1 Peak magnitude

Determine the positive peak and negative 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*.

5.2.2.2 Initial (final) instant

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

[3]The numbers in brackets correspond to those of the bibliography in Annex B.

5.2.2.3 User defined

This method is based on assumptions made by, or expectations of, the user (operator) 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 states what the values are for the *low* and *high states* of the *waveform*.

5.2.2.4 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*.

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

5.2.2.5 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 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* must 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 user-specified method; 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 user-specified method; this is the *high state* of the *waveform*.

5.2.3 Algorithm switching

The previous 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 criteria 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 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 must be specified.

5.3.1 Algorithm for calculating *signed waveform amplitude*

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*

a) Calculate the *waveform amplitude*, A, as described in 5.3.1.
b) Calculate the value for the *reference level*, $y_{x\%}$, using Equation (4):

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

where
$y_{x\%}$ is the value of the *reference level*,
x represents the percentage for the user-specified *percent reference level*,
$level(s_1)$ is the *state level* of s_1.

5.3.3 Algorithms for calculating *reference level instants*

If the values of the *reference levels*, $y_{x\%-}$ and $y_{x\%+}$, are quantized, then the set of possible *reference level instants* between two consecutive sampling *instants* is finite. This limits the precision of the *reference level instant* computed by linear interpolation. If this limitation is significant, 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 must be specified.

5.3.3.1 Algorithm for calculating the 50% *reference level instant*

a) Calculate the 50% *reference level* as described in 5.3.2.
b) Calculate the 50% *reference level instant* for $y_{50\%}$ using linear interpolation:

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

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 $y_{50\%-} \le y_{50\%} \le y_{50\%+}$,
$y_{50\%-}$ and $y_{50\%+}$ are the two consecutive *waveform* values corresponding to $t_{50\%-}$ and $t_{50\%+}$.

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*

a) Calculate the *reference levels* as described in 5.3.2.
b) Calculate the *reference level instant* for $y_{x\%}$ using linear interpolation:

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

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

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*

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*, $t_{x1\% - x2\%}$:

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

where
$t_{x1\% - x2\%}$ 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*

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

c) 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*.

d) 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 c).

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

f) 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 $t_{pre} - 3t_{10\% - 90\%}$ and t_{pre} (or as determined by the user).

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

   4) If $y_{max,pre}$ 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 Equation (8):

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

where

O_{pre} is the *overshoot* value in the *pre-transition aberration region*,

$y_{max,pre}$ is the maximum *waveform* value in the *pre-transition aberration region*,

A is the *waveform amplitude*,

level(s_k) is the *state level* of the k^{th} *state*. *Level*(s_k)=*level*(s_1) for a *positive-going transition*, and *level*(s_k)=*level*(s_2) for a *negative-going transition*.

   5) If $y_{min,pre}$ 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 Equation (9):

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

where

U_{pre} is the *undershoot* value in the *pre-transition aberration region*,

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

A is the *waveform amplitude*,

level(s_k) is the *state level* of the k^{th} *state*. *Level*(s_k)=*level*(s_1) for a *positive-going transition*, and *level*(s_k)=*level*(s_2) for a *negative-going transition*.

g) 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 $t_{\text{post}} + 3t_{10\% - 90\%}$ (or as determined by the user).
3) Search the *post-transition aberration* region for the maximum value, $y_{\text{max,post}}$, and the minimum value, $y_{\text{min,post}}$. $y_{\text{max,post}}$ is the maximum y_i in the *post-transition aberration region*, and $y_{\text{min,post}}$ is the minimum y_i in the *post-transition aberration region*.
4) If $y_{\text{max,post}}$ 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 Equation (10):

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

where
O_{post} is the *overshoot* value in the *post-transition aberration region*,
$y_{\text{max,post}}$ is the maximum *waveform* value in the *post-transition aberration region*,
A is the *waveform amplitude*,
level(s_k) is the *state level* of the k^{th} *state*. *Level*(s_k)=*level*(s_1) for a *positive-going transition* and *level*(s_k)=*level*(s_2) for a *negative-going transition*.

5) If $y_{\text{min,post}}$ 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 Equation (11):

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

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*,
A is the *waveform amplitude*,
level(s_k) is the *state level* of the k^{th} *state*. *Level*(s_k)=*level*(s_1) for a *positive-going transition*, and *level*(s_k)=*level*(s_2) for a *negative-going transition*.

5.3.6 Algorithm for calculating *waveform aberrations*

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 trapezoidal *reference waveform*, *r(t)*, unless otherwise specified, as the *reference waveform* for calculating *waveform aberrations*.
   1) Calculate the slope through the *reference levels* and *reference level instants* of the waveform using Equation (12):

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

2) Calculate the *reference level instants*, $t_{0\%}$ and $t_{100\%}$, that will be used to generate $r(t)$ in step e).
   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 Equation (13):

$$t_{100\%} = t_{x2\%} + \frac{level(s_2) - y_{x2\%}}{S} \quad (13)$$

   iii) Compute the $t_{0\%}$ *reference level instant* using Equation (14):

$$t_{0\%} = t_{x1\%} + \frac{level(s_1) - y_{x1\%}}{S} \quad (14)$$

e) Generate the trapezoidal *reference waveform*, $r(t)$, using Equation (15):

$$r(t_n) = \begin{cases} y_{0\%}, & \text{for } t_{0\%} \\ S(t_n - t_{0\%}) + y_{0\%}, & \text{for } t_{0\%} \le t_n \le t_{100\%} \\ y_{100\%}, & \text{for } t_n > t_{100\%} \end{cases} \quad (15)$$

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 Equation (16):

$$W_a = \begin{cases} \left(\dfrac{\max\{y_n - r(t_n)\}_{T_{ab}}}{y_{100\%} - y_{0\%}}\right)100\% \\ \left(\dfrac{\min\{y_n - r(t_n)\}_{T_{ab}}}{y_{100\%} - y_{0\%}}\right)100\% \end{cases} \quad (16)$$

where
W_a is the *waveform aberration*,
max{...} returns the maximum value of its argument,
min{…} 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*

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*

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, and 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, and 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 Equation (17):

$$E_{\text{settling}} = \max\left\{\left|\frac{y_i - level(s_k)}{|level(s_2) - level(s_1)|}\right|\right\}, i_s \le i \le i_f \tag{17}$$

where
E_{settling} is the *transition settling error*,
max{...} returns the maximum value of its argument,
level(s_k) is the *state level* of the k^{th} *state*,
$k = 1$ 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 clause assume the *repetitive pulse waveform* is a *compound waveform* comprised of either *positive pulse waveforms* or *negative pulse waveforms*. In either case, the user must 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*

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

$$T_P = |t_{2,\,x\%} - t_{1,\,x\%}| \tag{18}$$

where

T_P is the *pulse duration*,

$t_{1,x\%}$ and $t_{2,x\%}$ are the *reference level instants*.

5.4.2 Algorithm for calculating *waveform period*

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* on a *pulse* immediately following or preceding the *pulse* used in step d).
f) The *period*, *T*, is the difference between the *reference level instants* found in steps d) and e):

$$T = |t_{2,x\%} - t_{1,x\%}| \tag{19}$$

where

T is the *period*,

$t_{1,x\%}$ and $t_{2,x\%}$ are the *reference level instants*.

5.4.3 Algorithm for calculating *pulse separation*

There are two methods given here for calculating *pulse separation*.

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

$$T_S = |t_{2,x\%} - t_{1,x\%}| \tag{20}$$

where

T_S is the *pulse separation*,

$t_{1,x\%}$ and $t_{2,x\%}$ are the *reference level instants*.

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*:

$$T_S = T - T_P \tag{21}$$

where
T_S is the *pulse separation*,
T is *waveform period* determined in 5.4.2,
T_P is *pulse duration* determined in 5.4.1.

5.4.4 Algorithm for calculating *duty factor*

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*:

$$d_f = \frac{T_P}{T} \tag{22}$$

where
d_f is the duty factor,
T is *waveform period* determined in 5.4.2,
T_P is *pulse duration* determined in 5.4.1.

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. 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 either *transitions*, *transients*, *terminal features*, or *state levels*. 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 user-defined values for the upper *boundary* for each *state* in the *waveform*.
e) *state_lower*[] is the array containing the user-defined values of the lower *boundary* for each *state* in the *waveform*.
f) j is the *state* index, $j = 1, \ldots, N\_states$. $j = 1$ is the *base state* (see 3.1.37.1).
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*.

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, etc. 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 (as described later). 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 following algorithm:

```
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 j^{th} and $(j+1)^{th}$ 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 either *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 either *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 3.1.37, 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
for $k = 2 .. N\_sub - 1$
    if $((sub\_type[k] = 0)$ and $(sub\_type[k+1] \neq sub\_type[k-1]))$ then $sub\_class[k]$ = transition
        else $sub\_class[k]$ = transient
        endif
if $(sub\_type[k] \neq 0) sub\_class[k] = sub\_type[k]$
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 must be selected for calculating the desired *waveform parameters*. These sequential subepochs create a new *waveform*, which is a subset of the original *waveform* and has a *duration* shorter than the original *waveform*. For example, if the first *transition duration* of the n^{th} *pulse* in a *pulse train* of *positive pulses* is desired, where this *transition* is located in the j^{th} subepoch, then the $(j\text{-}1)^{th}$, j^{th}, 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*

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 user-specified function) to five (or a user-specified number) 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*

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) Applying the methods described earlier in the analysis of the different *waveforms*
b) Determining the time relationships between different *waveforms* as computed *intervals* or *durations* as described earlier

5.7.1 Algorithm for calculating *delay* between different *waveforms*

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* as the difference between $t_{50\%}$ for the different *waveforms*:

$$T_D = t_{\mathrm{mid,W1}} - t_{\mathrm{mid,W2}} \tag{23}$$

where
T_D is the delay,
$t_{\mathrm{mid,W1}}$ is the 50% *reference level instant* for one of the *waveforms*,
$t_{\mathrm{mid,W2}}$ 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* entails the determination of the differences between a *waveform* and a *reference waveform* (see 5.3.6). In any *aberration* determination, the type of *reference waveform* shall be specified.

The *reference waveform* must 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 must 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 using the following formula:

$$\bar{p} = \frac{1}{M}\sum_{i=1}^{M} p_i \tag{24}$$

where
$\bar{p}$ is the mean value,
M is the number of independent measurements,
p_i is the value of the i^{th} parameter.

b) Calculate the standard deviation using the following formula:

$$\sigma_p = \sqrt{\frac{1}{M-1}\sum_{i=1}^{M}(p_i - \bar{p})^2} \tag{25}$$

where

σ_p is the standard deviation,

all other variables defined for Equation (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 of 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 k^{th} histogram bin is denoted by v_k, and the count in the k^{th} bin is denoted by c_k. The standard deviation is calculated as follows:

a) Determine the mean of the *parameter* value using Equation (26):

$$\bar{p} = \frac{1}{M}\sum_{k=1}^{B} c_k v_k \tag{26}$$

where

$\bar{p}$ is the mean value,

c_k is the count in the i^{th} bin,

v_k is the center of the i^{th} bin,

M is the number of independent measurements,

B is the number of histogram bins.

b) Calculate the standard deviation of the parameter value using:

$$\sigma_p = \sqrt{\left(\frac{1}{M-1}\sum_{k=1}^{B} v_k^2 c_k\right) - \bar{p}^2} \tag{27}$$

where

σ_p is the standard deviation,

all other variables defined for Equation (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 previous 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 Equation (28):

$$\Sigma_p = \frac{\sigma_p}{\sqrt{2M}} \tag{28}$$

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),
M is the number of independent measurments.

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 later. This clause 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:

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

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 assure that the error in each is sufficiently small, as described in the next clause. 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_I is net standard deviation caused by all the interfering sources,
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 by Equation (31):

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

where
σ_{obs} is the observed standard deviation,
σ_p is the calculated standard deviation,

σ_I is the contribution to the standard deviation from the interfering source (see 5.9.1.4),

Σ_p is the standard deviation of the calculated standard deviation (see 5.9.1.3),

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 in the right hand side of Equation (31) were determined with the same number of measurements, M, this reduces to a simpler relation:

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

where
M is the number of measurements.

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

where
max(..) returns the maximum value of its argument,
all other variables have been defined for Equation (31).

5.9.2 Measuring *fluctuation* and *jitter* of an instrument

Before using an instrument to measure the *fluctuation* and *jitter* of a *signal* source, a user must 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 must 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.

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* 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

a) Record M records of a constant (dc) *signal*.
b) Calculate the value of the *level parameter* for each record obtained in step a) using an algorithm essentially equivalent (see below) 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 using any of the methods in 5.9.1.

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.

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 must 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 done on these two histograms should be identical to those that will be done 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 interval between the trigger *instant* and the sample *instant* should be chosen to be as short as possible.

5.9.2.2.1 Measuring *trigger jitter* of an instrument

The measurement requires a *signal* with a rapid *transition*. How rapid will be discussed later. 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, $\bar{y}_i$, of the M *waveforms* for every *instant* of the *waveform* using Equation (34):

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

where
$\bar{y}_i$ 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 $\bar{y}_i$, 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 user-specified method.
d) For each of the M *waveforms*, determine the *instant* at which the *waveform* value crosses v_0 using the method of 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 Equation (35):

$$\sigma_\tau = \sqrt{\sigma_{\tau\text{obs}}^2 - \left(\frac{\sigma_F}{S}\right)^2} \tag{35}$$

where
σ_τ is the corrected standard deviation,
$\sigma_{\tau\text{obs}}$ is the observed standard deviation of the *instants*,
σ_F 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_τ should be calculated using the method of 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* must 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 slope, S, in the *transition* of the *signal* is large. Determine S_1 for v_1 and S_2 for v_2 by a user-specified method.
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, $\sigma_{\tau\text{obs}}$, of the time differences calculated in step f).
h) Correct the result found in step g) for *fluctuation* using Equation (36):

$$\sigma_\tau = \sqrt{\sigma_{\tau\text{obs}}^2 - \left(\frac{\sigma_F}{S_1}\right)^2 - \left(\frac{\sigma_F}{S_2}\right)^2} \tag{36}$$

where
σ_τ is the corrected standard deviation,

$\sigma_{\tau\text{obs}}$ is the observed standard deviation of the *instants*,

σ_F is the rms *fluctuation* of the instrument,

S_1 and S_2 are the instantaneous slopes in the *transitions* of the *signal*.

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

a) Perform steps a) through c) of 5.9.2.1.1.
b) Determine the corrected standard deviation, $\sigma_p = \sqrt{\sigma_{\text{obs}}^2 - \sigma_I^2}$, where σ_I is the *fluctuation* of the instrument as determined by one of the methods of 5.9.2.1. To verify the result, the standard deviation of σ_p should be calculated using the method of 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 steps a) through e) of 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 Equation (37):

$$\sigma_\tau = \sqrt{\sigma_{\tau\text{obs}}^2 - \sigma_{ITJ}^2 - \left(\frac{\sigma_{IF}}{S}\right)^2 - \left(\frac{\sigma_F}{S}\right)^2} \tag{37}$$

where

σ_τ is the *trigger jitter* of the *signal* source,

σ_{ITJ} is the *trigger jitter* of the instrument,

σ_{IF} is the *fluctuation* of the instrument,

σ_F is the *fluctuation* of the instrument *signal* source,

$\sigma_{\tau\text{obs}}$ is the observed *jitter*,

S is the instantaneous slope in the *transition* of the *signal*.

To verify the result, the standard deviation of σ_τ 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 steps b) through e) of 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 Equation (38) as follows:

$$\sigma_\tau = \sqrt{\sigma_{\tau\mathrm{obs}}^2 - \sigma_{I\tau}^2 - \left(\frac{\sigma_F}{S_1}\right)^2 - \left(\frac{\sigma_F}{S_2}\right)^2} \tag{38}$$

where

σ_τ is the *relative jitter* of the *signal* source,

$\sigma_{I\tau}$ is the *relative jitter* of the instrument,

σ_F is the *fluctuation* of the instrument,

$\sigma_{\tau\mathrm{obs}}$ is the observed *jitter*,

S_1 and S_2 are the instantaneous slopes in the *transitions* of the *signal*.

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

6. Figures

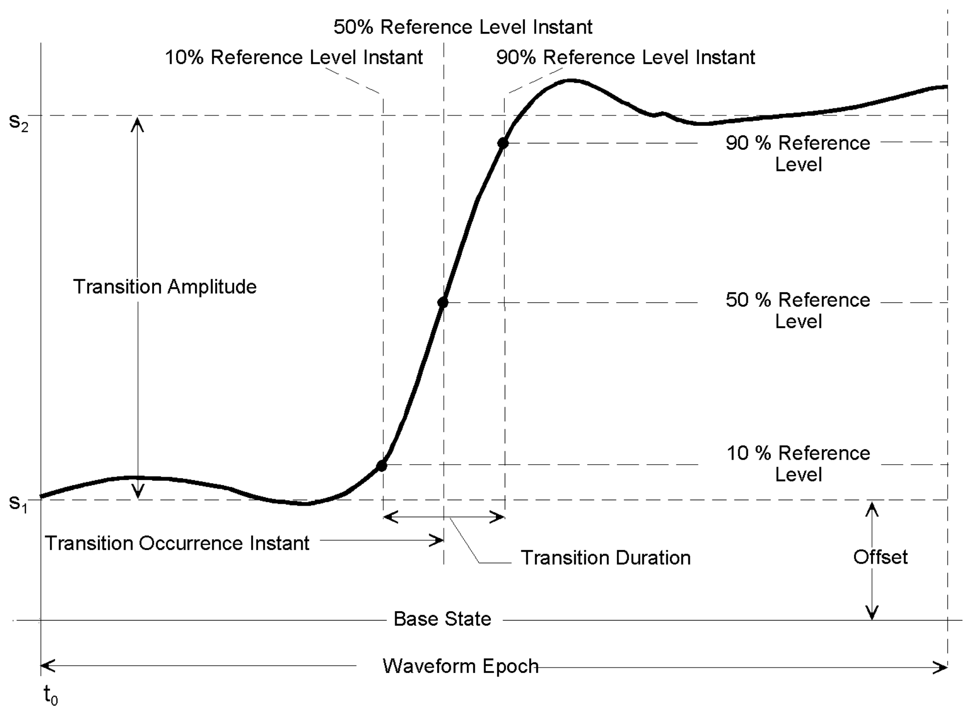

Figure 2—Positive single transition

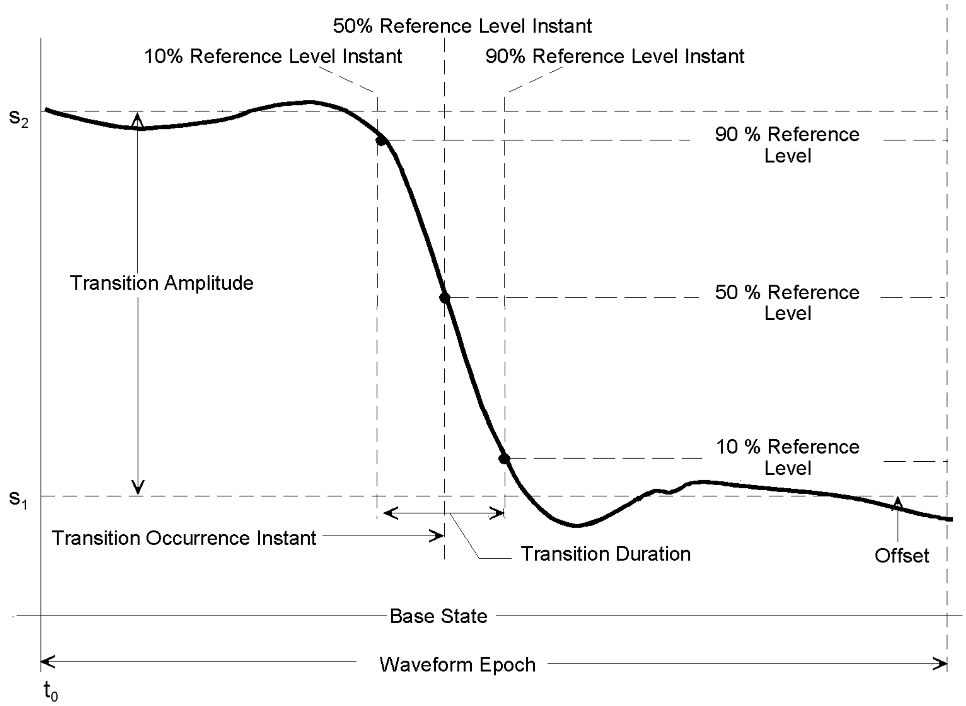

Figure 3—Negative single transition

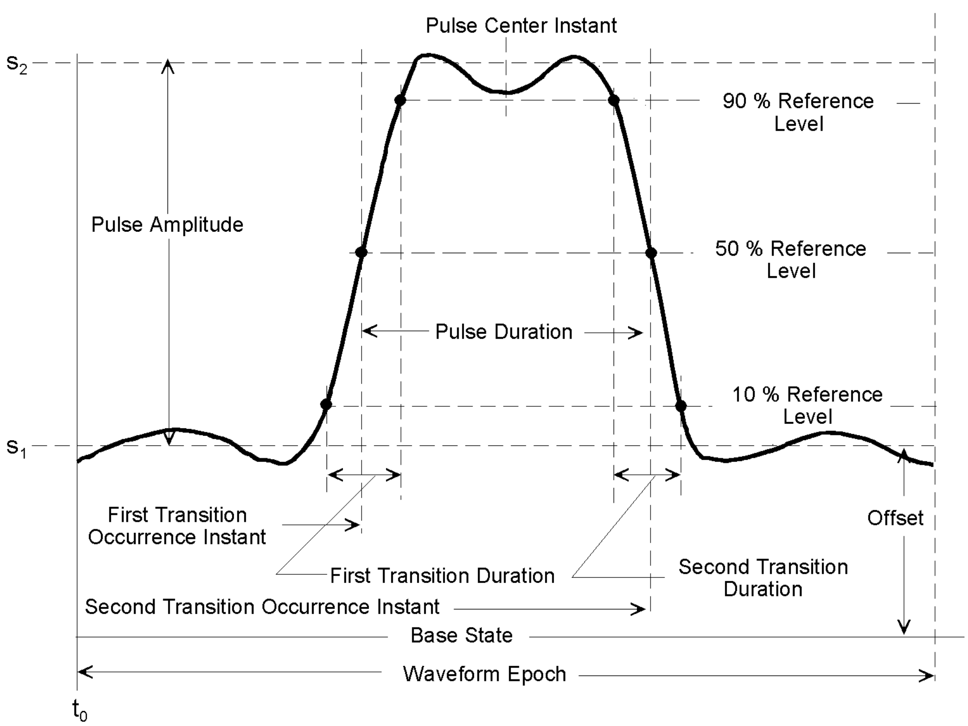

Figure 4—Positive single pulse

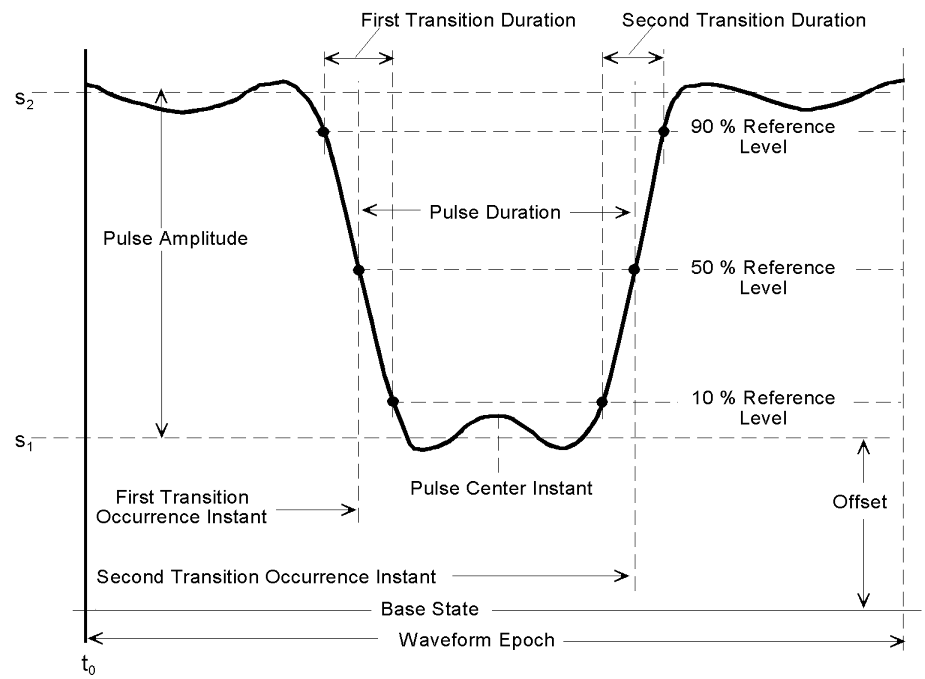

Figure 5—Negative single pulse

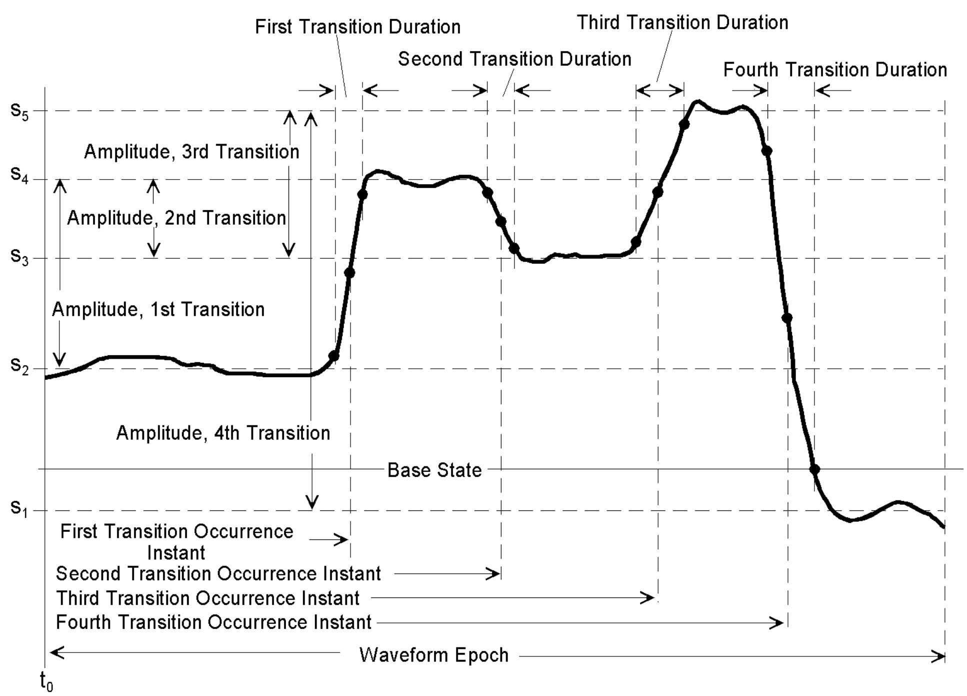

Figure 6—Compound waveform

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*."

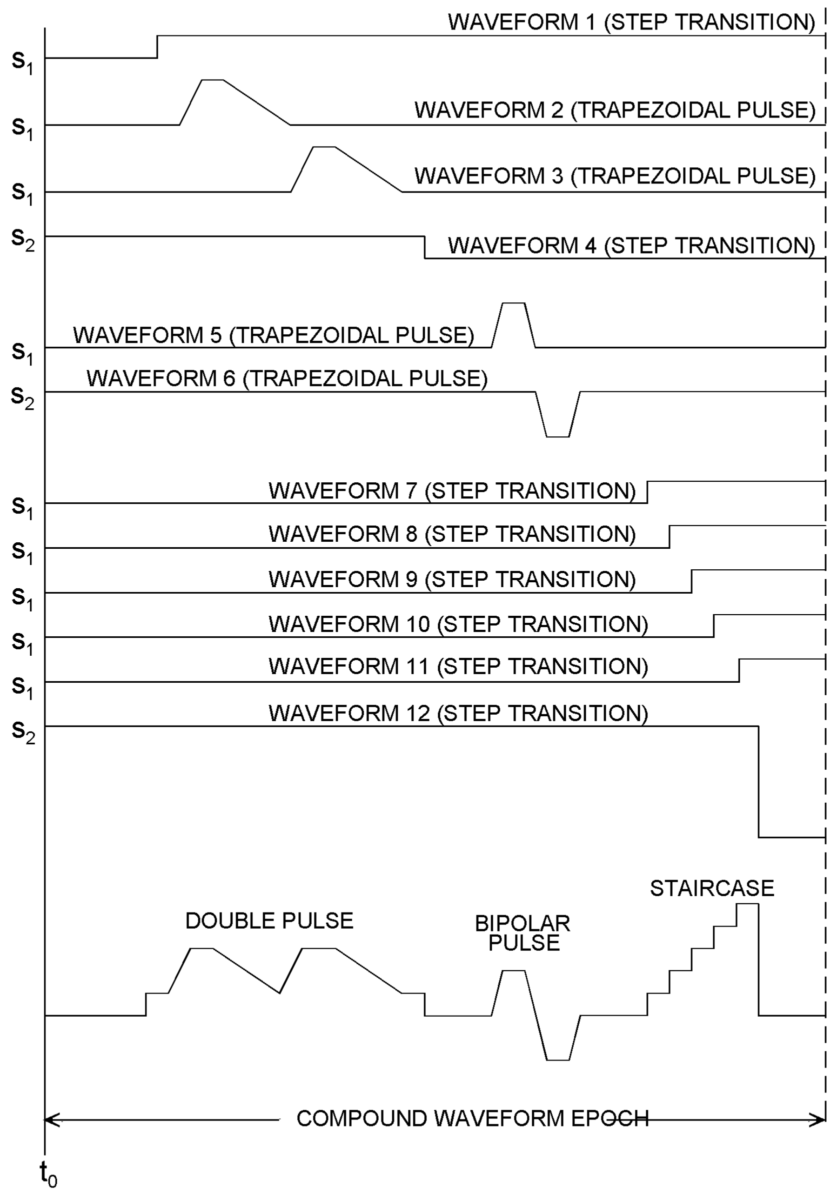

Figure 7—Generation of a compound waveform

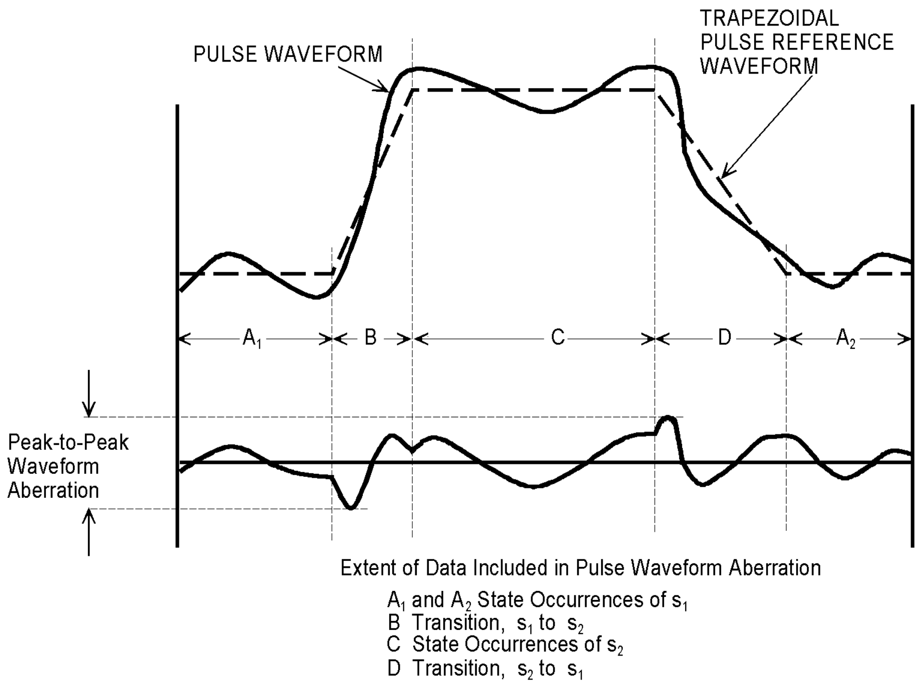

Figure 8—Calculation of waveform aberration

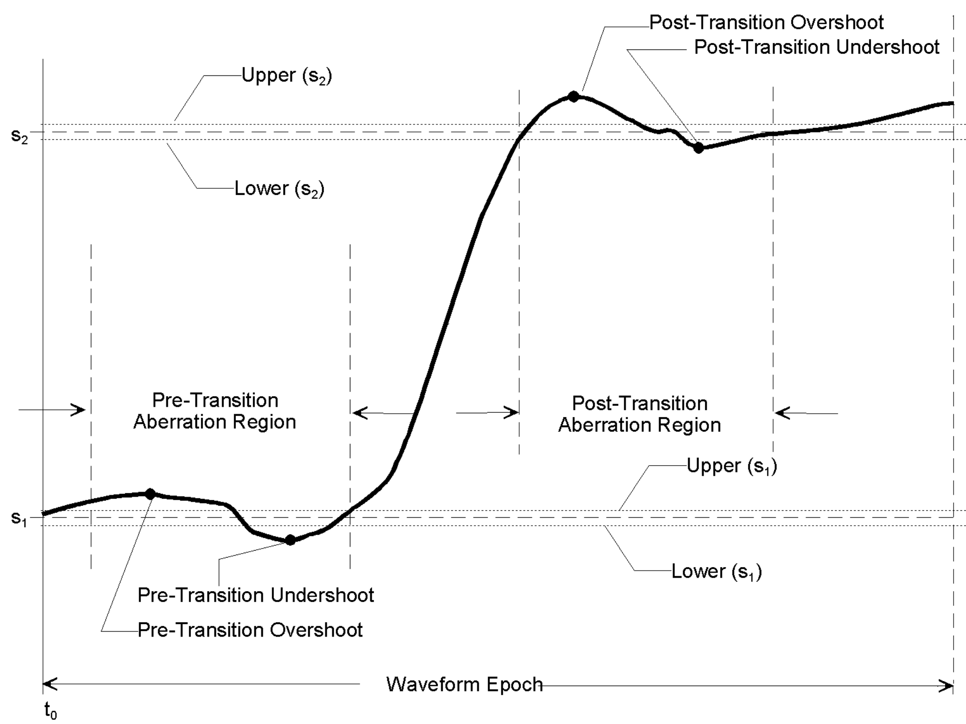

Figure 9—Overshoot and undershoot in a positive single transition

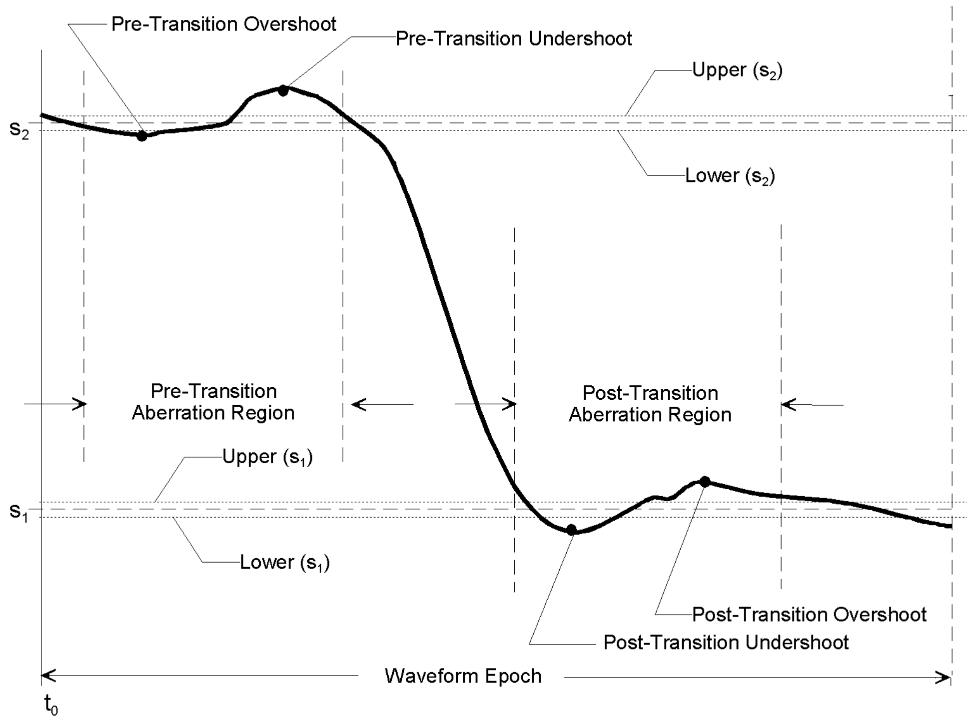

Figure 10—Overshoot and undershoot in a negative single transi-

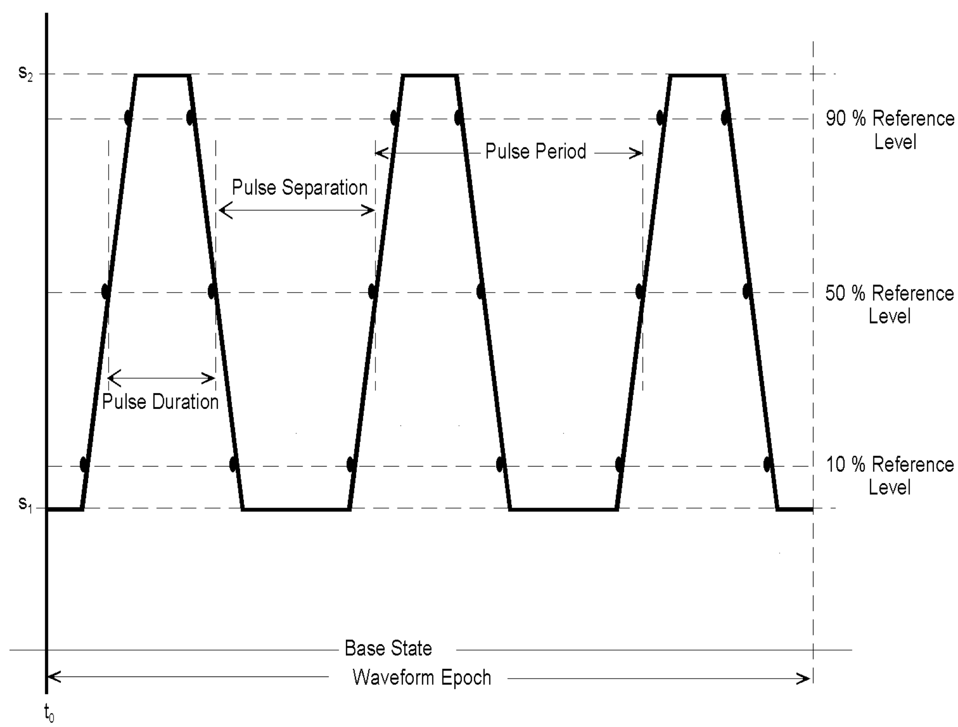

Figure 11—Pulse train

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 as follows.

A.1.1 Step waveform

A *waveform* defined by:

$$W_{\text{step}}(t) = \begin{cases} s_1 & t < t_1 \\ s_2 & t \geq t_1 \end{cases}$$

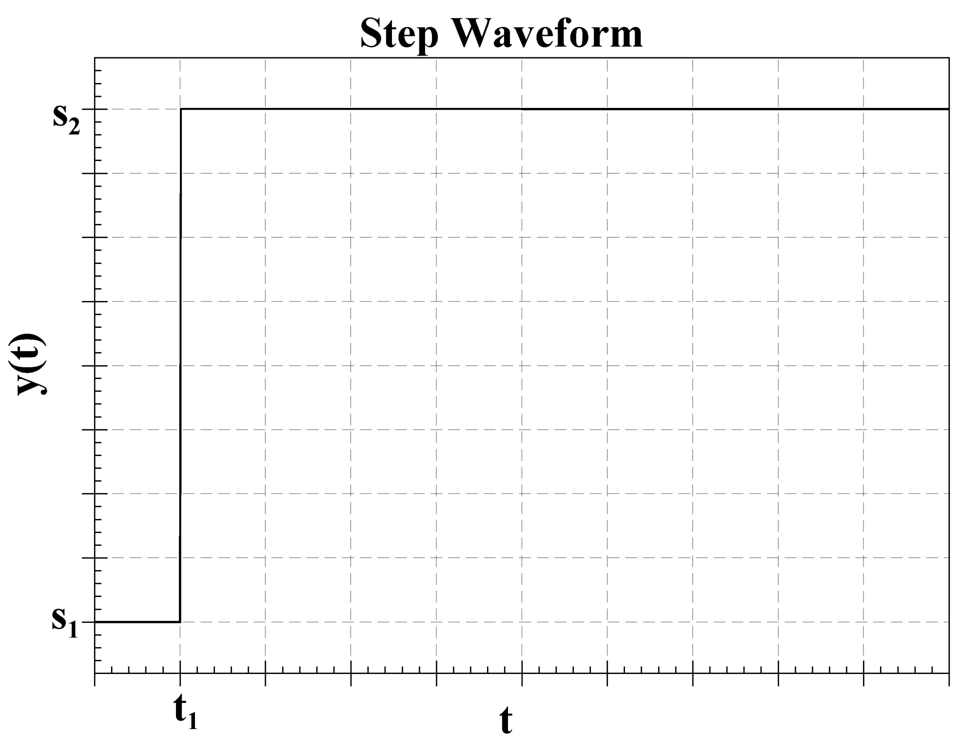

Figure A.1—Step waveform

A.1.2 Linear *transition waveform*

A *waveform* defined by:

$$W_{\text{trap}}(t) = \begin{cases} s_1 & t < t_1 \\ \dfrac{s_2 - s_1}{t_2 - t_1}(t - t_1) & t_1 \le t \le t_2 \\ s_2 & t > t_2 \end{cases}$$

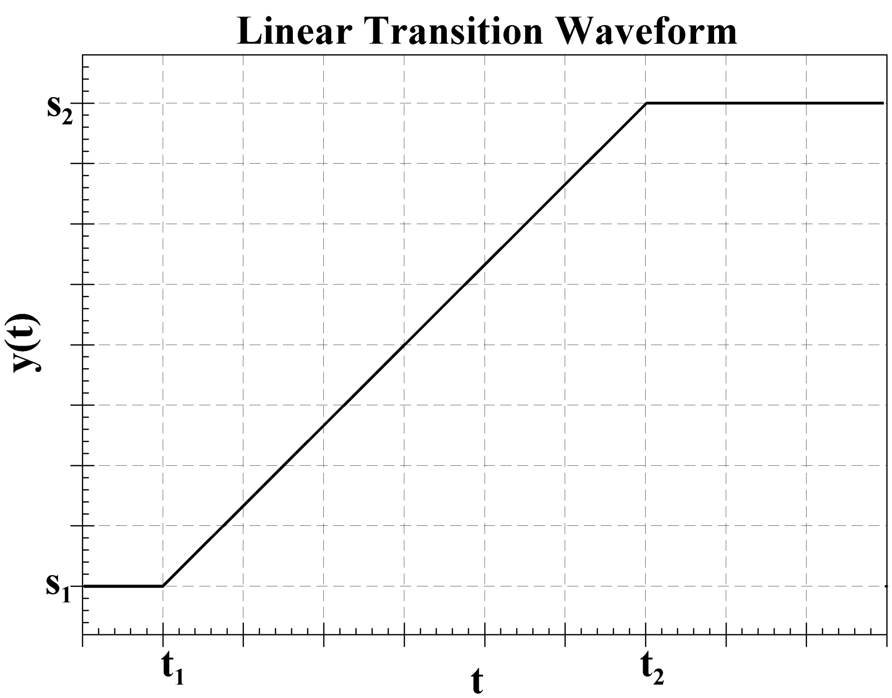

Figure A.2—Linear transition waveform

A.1.3 Exponential *waveforms*

A *transition waveform* defined by:

$$W_{\exp}(t) = \begin{cases} s_1 & t < t_1 \\ (s_2 - s_1)\left[1 - e^{-(t-t_1)/b}\right] & t \geq t_1 \end{cases}$$

where
b = exponential time constant.

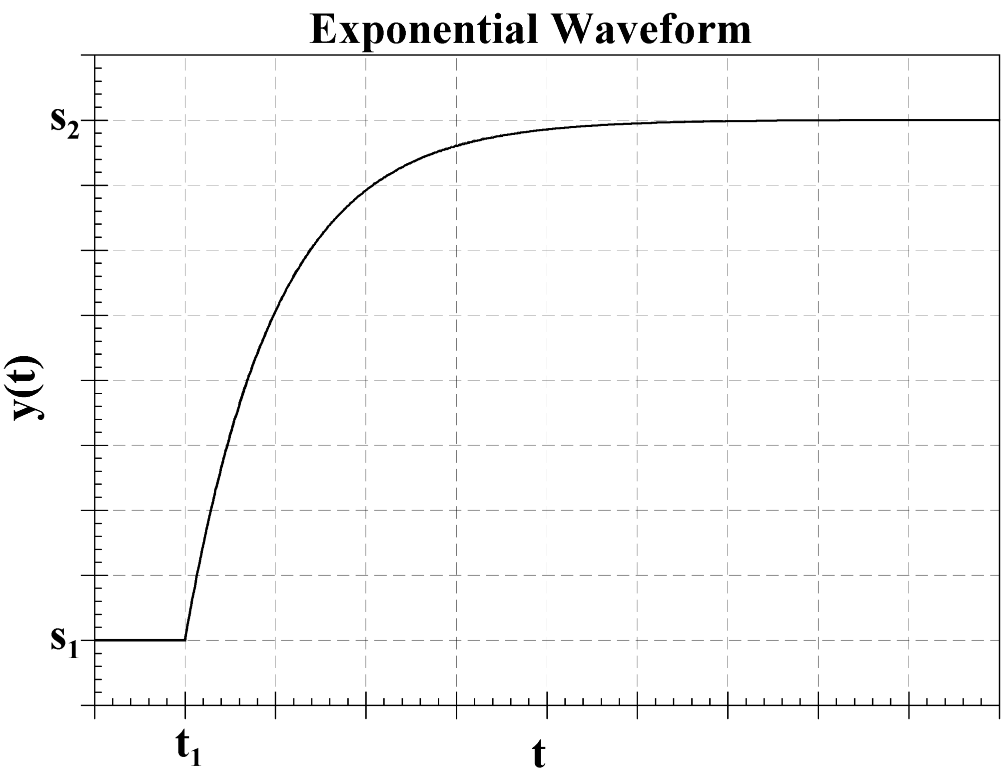

Figure A.3—Exponential waveform

A.1.4 Impulse

A *pulse waveform* defined as:

$$W_{\mathrm{imp}}(t) = \begin{cases} s_1 & t \neq t_1 \\ s_2 & t = t_1 \end{cases}$$

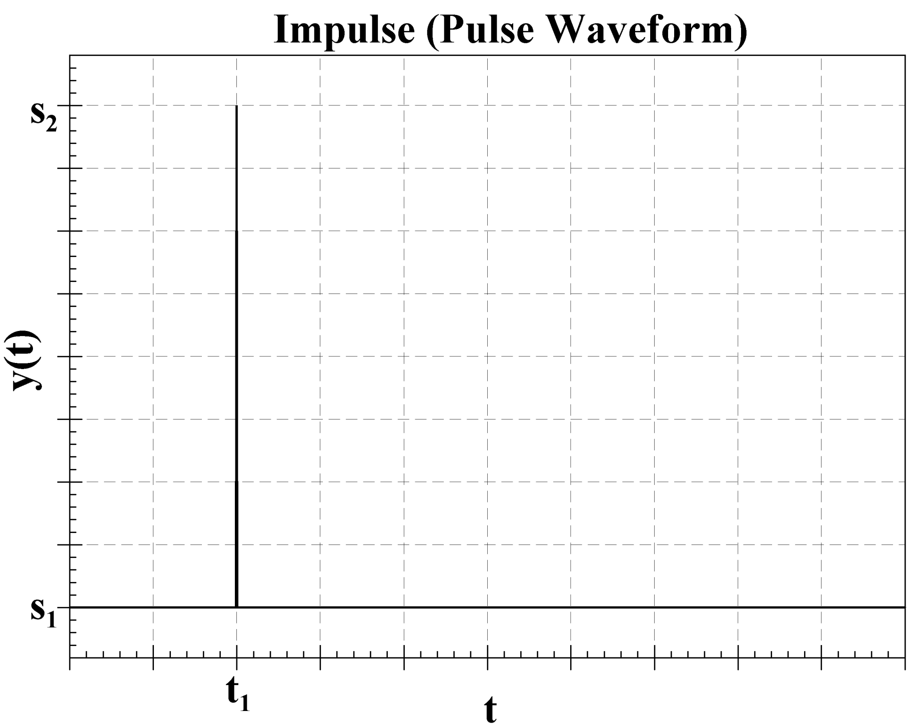

Figure A.4—Impulse

A.1.5 Rectangular *pulse waveform*

A *pulse waveform* defined as:

$$W_{\text{rect}}(t) = \begin{cases} s_1 & t < t_1 \\ s_2 & t_1 \le t \le t_2 \\ s_1 & t > t_2 \end{cases}$$

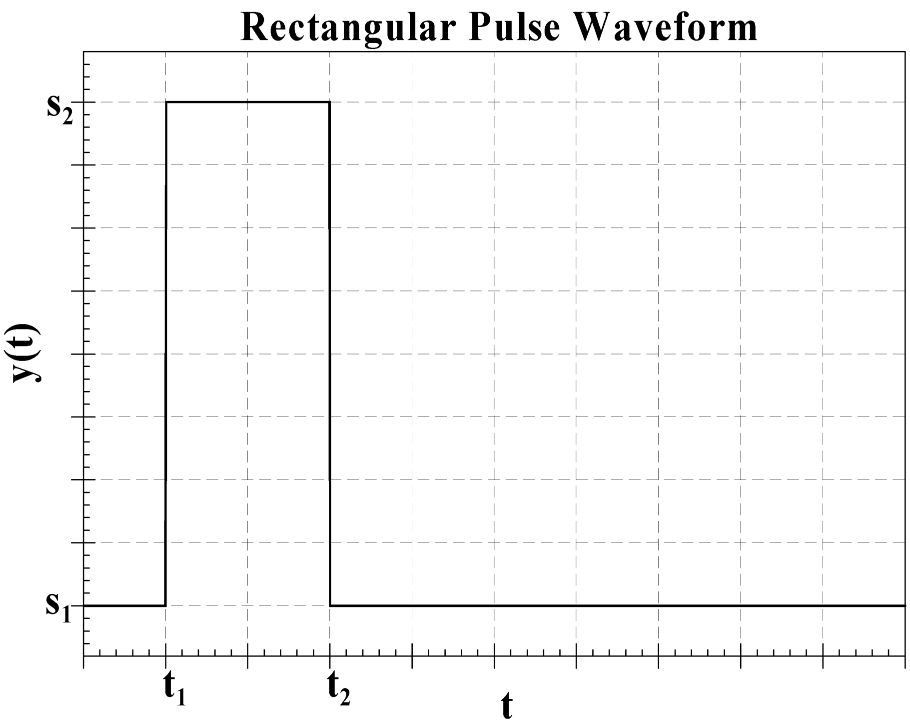

Figure A.5—Rectangular pulse waveform

A.1.6 Trapezoidal *pulse waveform*

A *pulse waveform* defined as:

$$W_{\mathrm{trap\_p}}(t) = \begin{cases} s_1 & t < t_1 \\ (s_2 - s_1)\dfrac{t - t_1}{t_2 - t_1} & t_1 \le t \le t_2 \\ s_2 & t_2 < t < t_3 \\ -(s_2 - s_1)\dfrac{t - t_4}{t_4 - t_3} & t_3 \le t \le t_4 \\ s_1 & t > t_4 \end{cases}$$

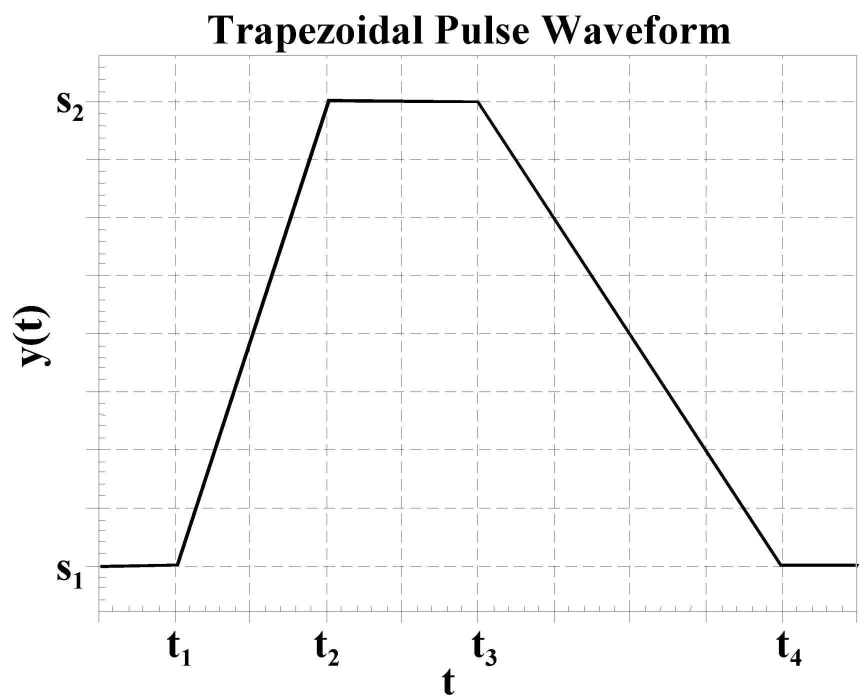

Figure A.6—Trapezoidal pulse waveform

A.1.7 Triangular *pulse waveform*

A *pulse waveform* defined as:

$$W_{\mathrm{tri}}(t) = \begin{cases} s_1 & t < t_1 \\ (s_2 - s_1)\dfrac{t - t_1}{t_2 - t_1} & t_1 \le t < t_2 \\ s_2 & t = t_2 \\ -(s_2 - s_1)\dfrac{t - t_3}{t_3 - t_2} & t_2 < t \le t_3 \\ s_1 & t > t_3 \end{cases}$$

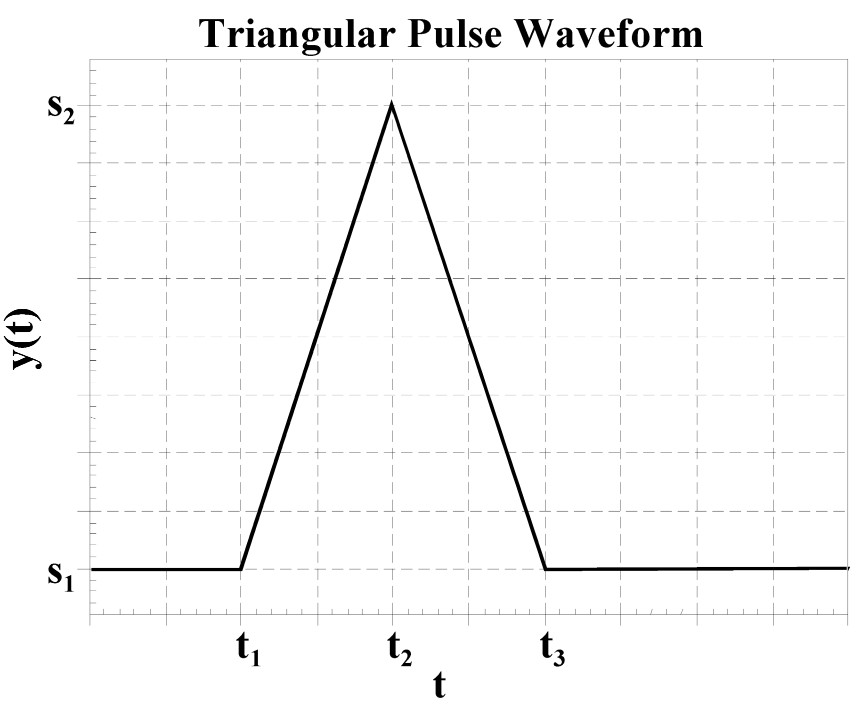

Figure A.7—Triangular pulse waveform

A.1.8 Exponential *pulse waveform*

A *pulse waveform* defined as:

$$W_{\mathrm{exp\_p}}(t) = \begin{cases} s_1 & t < t_1 \\ (s_2 - s_1)\left[1 - e^{-(t - t_1)/b}\right] & t_1 \le t \le t_2 \\ (s_2 - s_1)\left[e^{-(t - t_2)/c} - e^{-(t - t_1)/b}\right] & t > t_2 \end{cases}$$

where
b = time constant of first *transition*,
c = time constant of second *transition*.

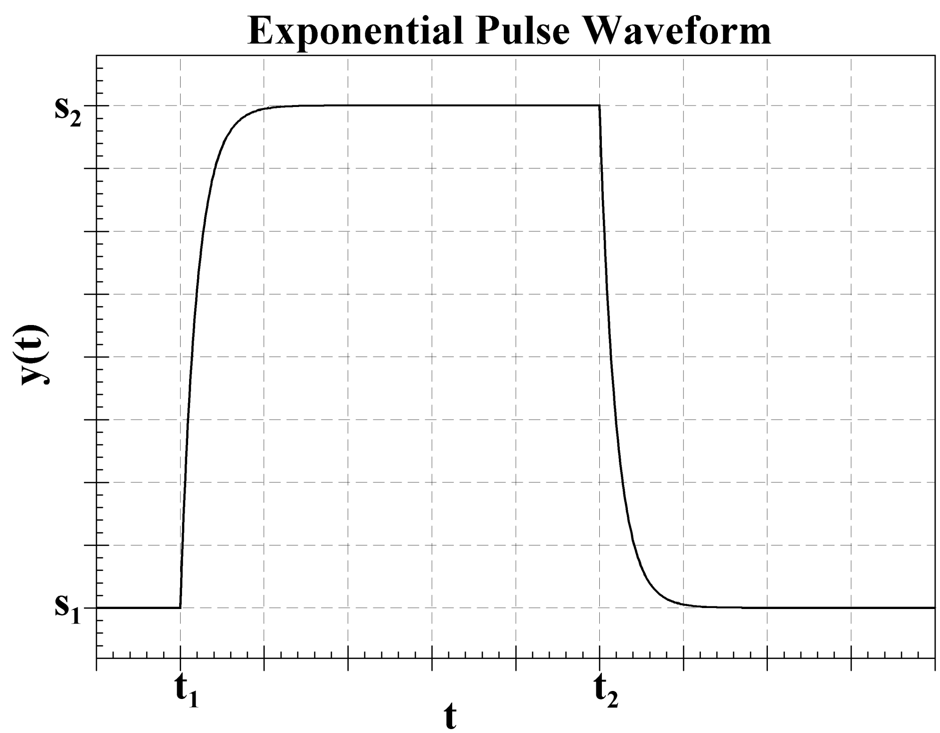

Figure A.8—Exponential pulse waveform

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 here.

A.2.1 Double pulse

1) The summation of two *pulse waveforms* of the same *polarity* that are adjacent in time and are considered or treated as a single *waveform*.
2) Two pulses with the same polarity, *waveform amplitude,* and *base level* that are not overlapping and are treated as a single *waveform*. A *compound waveform* with two *states* and four *transitions*.

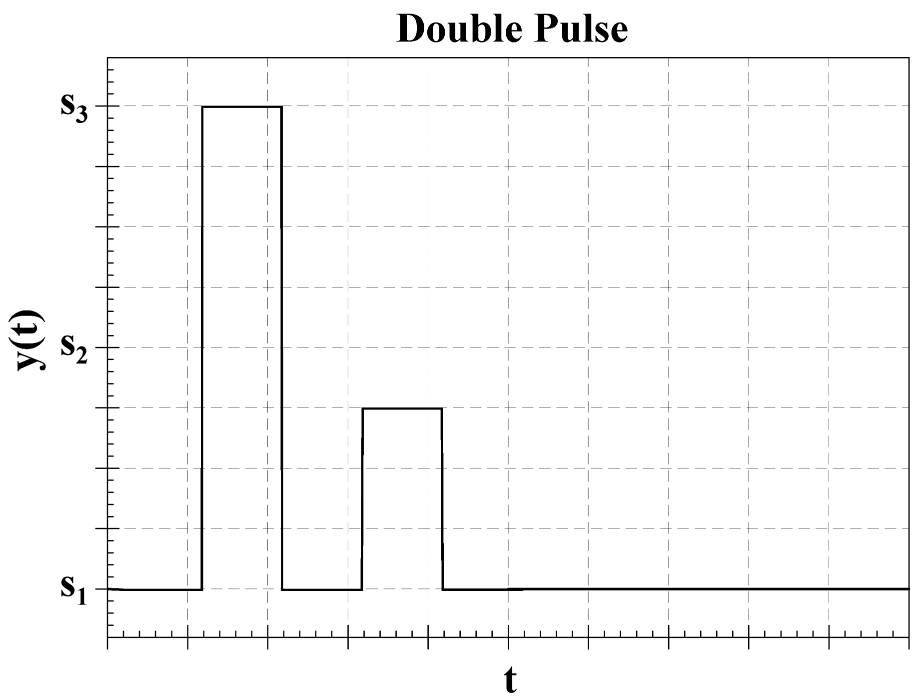

Figure A.9—Double pulse

A.2.2 Bipolar pulse

1) The summation of two *pulse waveforms* of opposite *polarity* that are adjacent in time and are considered or treated as a single *waveform*.
2) Use a figure that stresses the order of the *states*. As an example, the order of the *states* for the following figure is s_2, s_3, s_2, s_1, s_2. The *states* of the tri-state *waveform* in this example have the ordering $(s_2, 1)$ $(s_3, 1)$ $(s_2, 2)$ $(s_1, 1)$ $(s_2, 3)$.

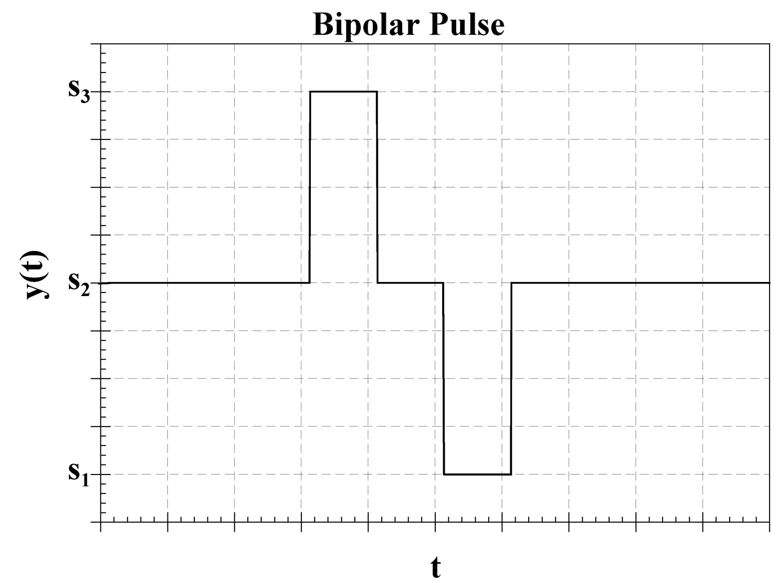

Figure A.10—Bipolar pulse

A.2.3 Staircase

The summation of a finite sequence of *step-like waveforms* of the same polarity.

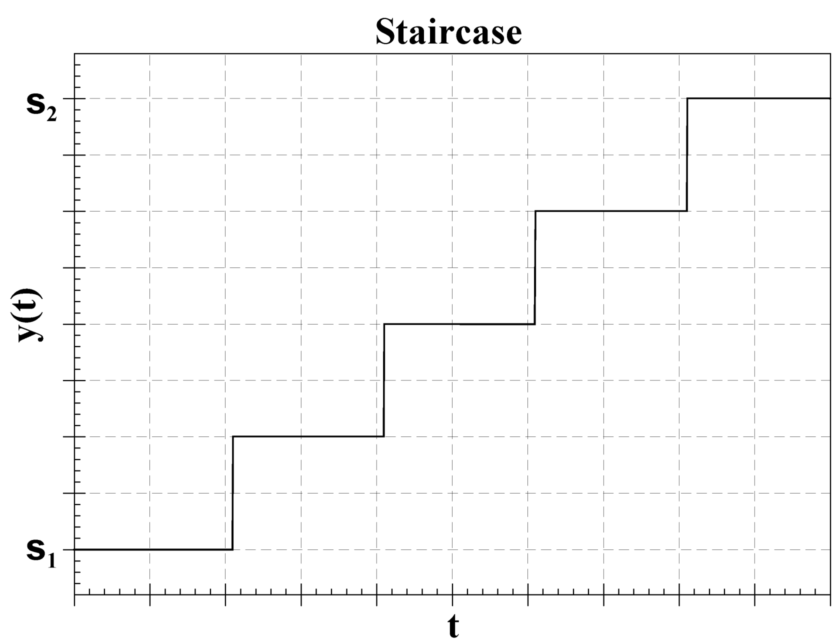

Figure A.11—Staircase

A.2.4 Pulse train

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

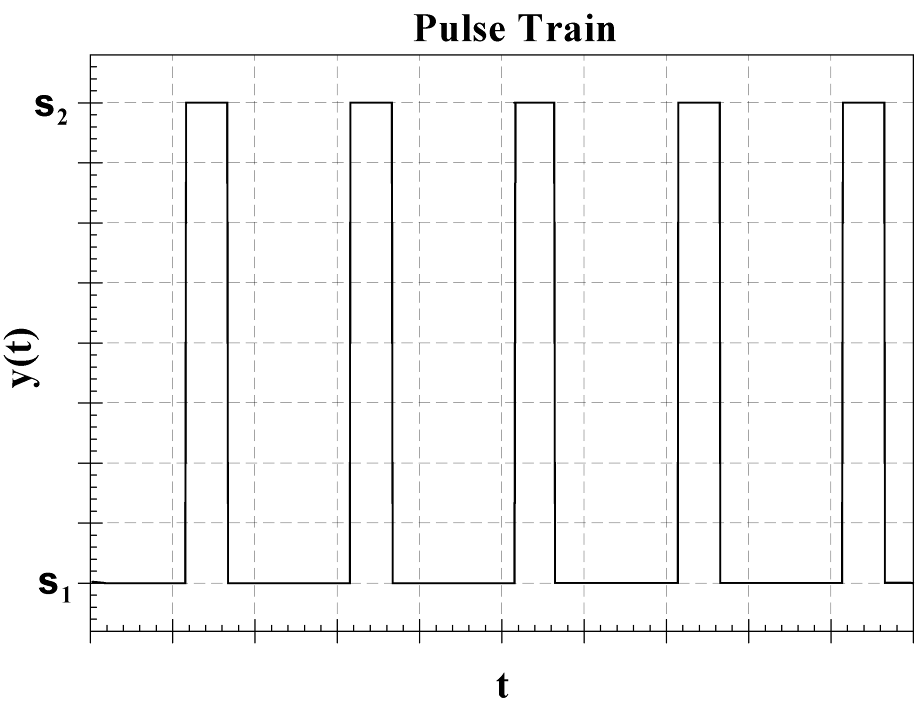

Figure A.12—Pulse train

Annex B

(informative)

Bibliography

[B1] Paulter, N.G., “The effect of histogram size on histogram-derived pulse parameters,” *IEEE Transaction on Instrumentation and Measurement,* Volume 47, June 1998, pp. 609-612.

[B2] Solomon, O.M., Larson, D.R., and Paulter, N.G., “Comparison of Some Algorithms to Estimate the Low and High State Level of Pulses,” *IEEE Instrumentation and Measurement Technology Conference,* Budapest, Hungary, May 2001.

