The Documentary Standards of the IEEE Technical Committee 10

*Sergio Rapuano, John Jendzurski, Luca De Vito, Steven J. Tilden,
William B. Boyer, and Nicholas G. Paulter, Jr.*

Global trade relies on the ability to reproducibly and accurately communicate the performance of products and to support these attestations. This standardization is essential for accurate, reproducible, reliable, and communicable characterization of the performance of these devices, to support technology and product advancement, product comparison and performance tracking, and device calibration and traceability. Standard terms and definitions, reproducible test methods, and accurate computational procedures are necessary for this communication and facilitate economic growth and technology evolution through the common understanding of technology. The IEEE Technical Committee 10 (TC-10), the Waveform Generation, Measurement, and Analysis Committee of the IEEE Instrumentation and Measurement Society (IMS), fulfills the global need for standardized terms and test and computational methods for describing and/or measuring the parameters that describe the performance of signal generators and waveform recorders and analyzers. The TC-10 has developed and maintains the following documentary standards: IEEE Std 181-2011, "Standard on Transitions, Pulses, and Related Waveforms" [1]; IEEE Std 1057-2017, "Standard for Digitizing Waveform Recorders" [2]; IEEE Std 1241-2010, "Standard for Terminology and Test Methods for Analog-to-Digital Converters" [3]; IEEE Std 1658-2011, "Standard for Terminology and Test Methods for Digital-to-Analog Converters" [4]; and the IEEE Std 1696-2013, "Standard for Terminology and Test Methods for Circuit Probes" [5]. In development is the IEEE Draft Std P2414 "Draft Standard for Jitter and Phase Noise." The TC-10 comprises an international group of electronics engineers, mathematicians, professors and physicists with representatives from national metrology laboratories, national science laboratories, component manufacturers, the test instrumentation industry, academia, and end users. The status of the TC-10 standards is described herein.

The TC-10's progress has been reported periodically at IEEE and IMEKO conferences [6]–[10]. This paper emphasizes activity since around 2011 through the third quarter of 2020. The title and scope of each of the TC-10's projects and the current activities of the associated subcommittees is presented.

TC-10 Documentary Standards Activities

TC-10 is currently engaged in six projects, one for each of the documentary standards promulgated by the IEEE TC-10.

IEEE Std 181-2011: "Standard on Transitions, Pulses, and Related Waveforms" [1] and the Subcommittee on Pulse Technology (SCOPT)

The IEEE Std 181 defines the parameters that describe the basic characteristics of transitions, pulses, and related signals and defines the computational procedures for estimating the value of these parameters. Because of the broad applicability of electrical pulse technology in the electronics industries (such as computer, telecommunication, entertainment, and test instrumentation industries), the development of unambiguous definitions and computation methods for these parameters is important for communication between manufacturers and consumers and promotes product comparison and improvement and technology advancement.

The SCOPT published the latest revision to the IEEE Std 181 in January 2011 [1], a discussion of which can be found in [11]. The largest single change to the IEEE Std 181 was the introduction of the shorth method [12] for computing state levels, where the states are shown as s_1 and s_2 in Fig. 1. The state level, $level(s_i)$, is the value associated with s_i. The primary method for computing $level(s_i)$ has historically been, and still is, the histogram mode method [13]. The shorth method is more computationally intensive than the histogram-mode method. Comparative studies on the performance of the shorth method and the histogram-mode method for estimating $level(s_i)$ has shown that the shorth method typically provides smaller estimation errors and measurement uncertainties than the histogram-mode method [14], [15]. However, these estimation errors and measurement uncertainties are typically much less than the signal noise and, consequently, have minimal influence on the measurement uncertainties of $level(s_i)$.

1094-6969/20/$25.00©2020IEEE

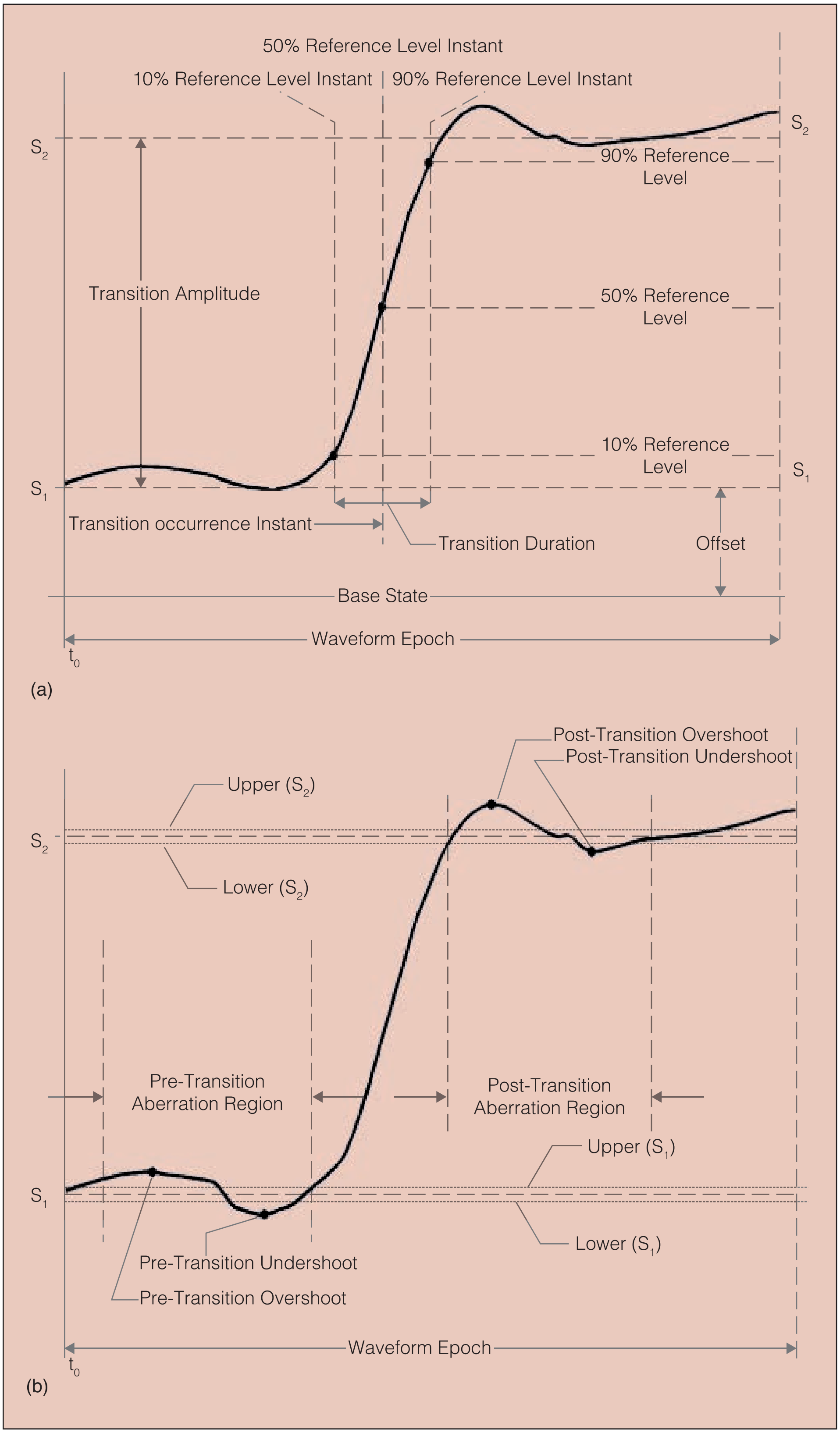

Fig. 1. Two figures displaying various parameters used to describe the characteristics of a waveform. (a) The fundamental waveform parameters on which all other parameters are derived. (b) The parameters that are used to describe aberrations of a waveform.

SCOPT members participated in the revision of the IEC 60469: Transitions, pulses and related waveforms—Terms, definitions and algorithms [16]. The SCOPT is now soliciting inputs, and interested participants, for a new revision or a reaffirmation of the Std 181.

IEEE Std 1057-2017: "Standard for Digitizing Waveform Recorders" [2] and the Subcommittee on Digital Waveform Recorders (Std 1057)

The IEEE Std 1057 defines specifications and describes test methods for measuring the performance of electronic digitizing waveform recorders, waveform analyzers, and digitizing oscilloscopes with digital outputs. The standard is directed toward, but not restricted to, general-purpose waveform recorders and analyzers.

An updated version of IEEE Std 1057 on waveform recorders was published in 2018. The 1057 Subcommittee spent approximately five years modifying the previous version, which was published in 2007. The latest revision of the Std 1057 reflects a few new general information clauses that were added to match those in IEEE Std 1241. Also, a number of new and revised test methods were added based on information in 1241: total harmonic distortion, monotonicity, hysteresis, static and dynamic gain, frequency response and dynamic gain, and aperture duration. Several parameter definitions were also changed to match those in the IEEE Std 1241: aperture, aperture duration, common-mode signal, differential input recorder, dynamic range, full-scale signal, harmonic distortion, and transfer curve.

IEEE Std 1241-2010: "Standard for Terminology and Test Methods for Analog-to-Digital Converters" [3] and the Subcommittee on Analog-to-Digital Converters (ADCs) (Std 1241)

The IEEE Std 1241 provides common terminology and test methods for the testing and evaluation of analog-to-digital converters (ADCs). It considers only those ADCs whose output values have discrete values at discrete times, i.e., they are quantized and sampled. In general, this quantization is assumed to be nominally uniform (the input-output transfer curve is approximately a straight line), and the sampling is assumed to be at a nominally uniform rate. Some, but not all, of the test methods presented in the IEEE Std 1241 can be used for ADCs that are designed for non-uniform quantization. The current revision of the IEEE Std 1241 was published in 2010 and reflects revisions and improvements in comparison to the previous 2000 revision. The Subcommittee on ADCs also led the development of a complementary IEC standard, the IEC 60748-4-3: Semiconductor devices–Integrated circuits–Part 4-3; Interface integrated circuits–Dynamic criteria for analogue-digital converters (ADC) that was published in 2006 [17].

The next challenge that was identified by the Subcommittee on ADCs was regarding standardization for embedded ADCs. The challenge here is in measuring and verifying the advertised performance of embedded circuits in which the ADC is surrounded by hostile system-on-a-chip (SOC) environments, which makes accurate and reliable measurements difficult due to interference. This task has not been advanced because of the lack of sufficient stakeholder interest.

A work effort to revise and update the content of the IEEE Std 1241 was started in 2018 and is planned to complete by the end of 2021.

IEEE Std 1658-2011: "Standard for Terminology and Test Methods for Digital-to-Analog Converters" [4] and the Subcommittee on Digital-to-Analog Converters (DACs) (1658)

The IEEE Std 1658 defines the terminology to clearly document the prevalent world-wide terms used to describe digital-to-analog converters (DACs) and the methods that are used to test the performance of DACs. It is restricted to monolithic, hybrid, and modular DACs and does not cover systems that incorporate DACs. DACs serve an important and ever-increasing role in signal processing today. The Subcommittee on DACs set about to resolve the disparities among DAC terms and definitions with a body of international experts from universities, government agencies, test laboratories and industry with extensive and diverse experience in data converter design, modelling and test.

DACs and ADCs perform complementary functions. However, there are subtle but important differences in the behavior of ADCs and DACs. As an example, consider the difference in their transfer functions illustrated in Fig. 2. For a DAC, each digital input corresponds to single average analog output amplitude. For an ADC, each digital output corresponds to an interval of analog input values.

ADCs and DACs also differ in their quantization processes, in their time-domain and frequency-domain responses, and in aliasing and image frequency generation. Aliasing is a phenomenon usually associated with ADCs, while the generation of image frequencies is usually associated with DACs.

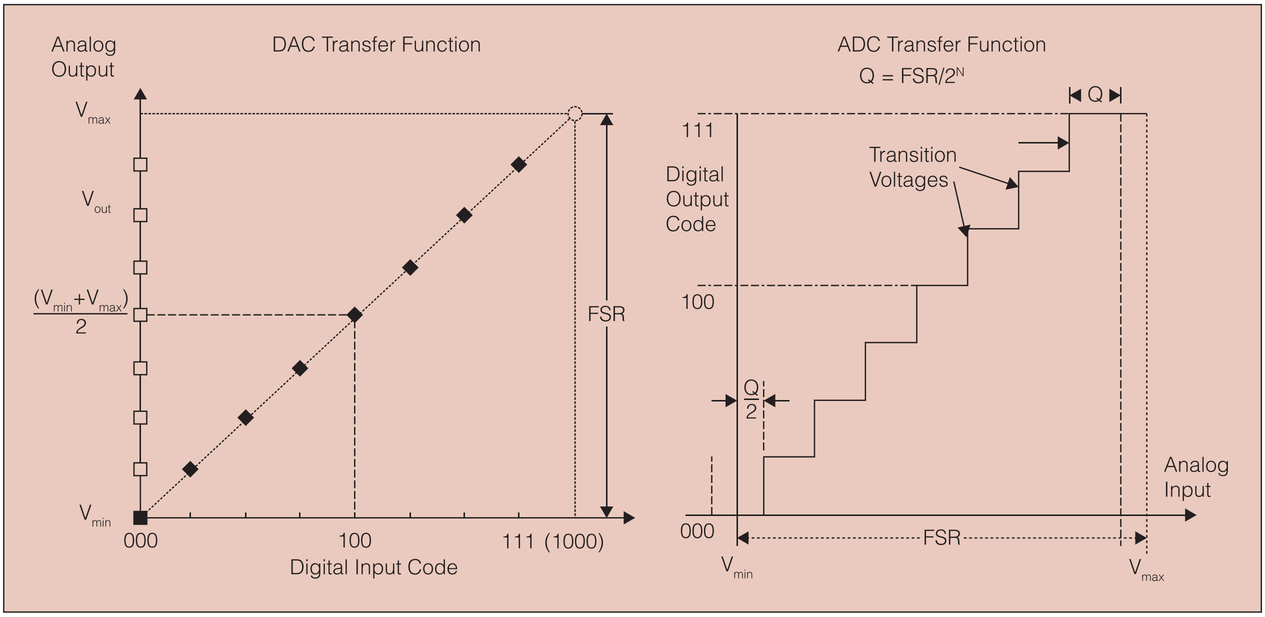

Fig. 2. Transfer functions of ideal 3-bit unipolar DAC and ADC.

The 1658 Subcommittee is currently involved in the revision of the Standard, after 10 years from the first publication.

IEEE Std 1696-2013: "Standard for Terminology and Test Methods for Circuit Probes" [5] and the Subcommittee on Probe Standards (SCOPS) (Std 1696)

The IEEE Std 1696 describes test methods and transfer (artifact) standards for characterizing electrical circuit probes and probes systems. The systems may include waveform acquisition hardware and software and signal/waveform analysis software. The probe will include the mechanism by which the circuit is contacted. This method and standard will be applicable to all individual probes having one signal conductor and one ground conductor, or two signal conductors, and having input impedance greater than the impedance of the circuit under test.

The IEEE Std 1696-2013 describes methods to measure 20 different performance parameters of a circuit probe, such as input resistance, output resistance, gain, frequency response, step response, and many others. These measurements are based on the use of a probe-characterization test fixture (artifact standard). Furthermore, the standard describes test methods to perform these measurements for single-ended or differential probes as well as probe-only and probe-system techniques. Fig. 3 shows an example from the standard of the test setup for measuring the input impedance of a single-ended stand-alone probe.

The ability to accurately characterize circuit probes enables probe users to fully understand a circuit probe's effect on their circuits. Circuit probe characterization can support the systematic removal of the probe effects from the measured data, resulting in a more accurate and complete representation of a measurement system's electrical performance than if the probe effects were not removed.

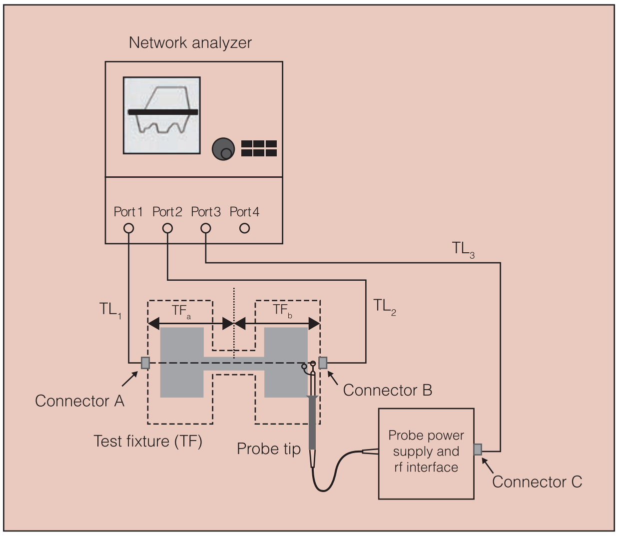

Fig. 3. Test setup for measuring the input impedance of single-ended stand-alone probe.

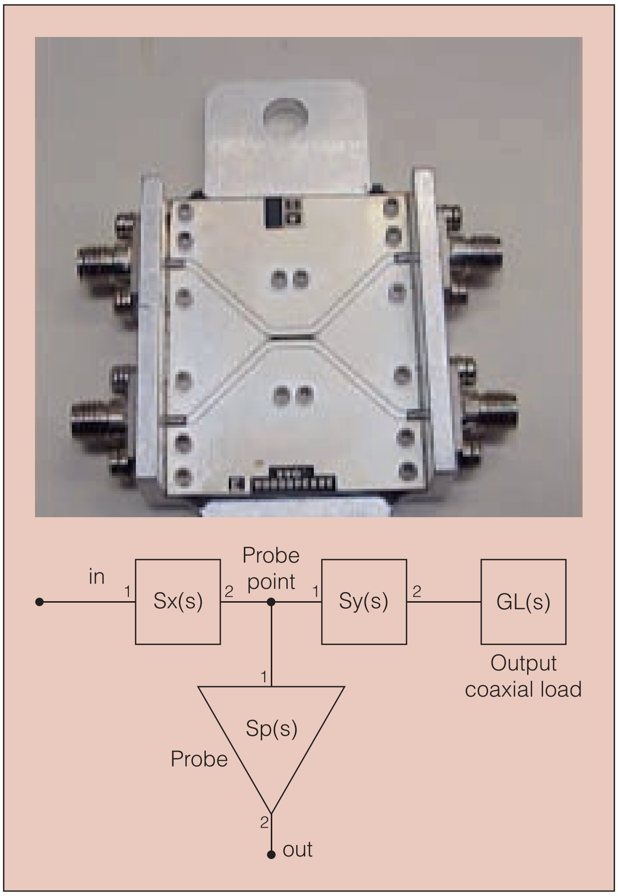

Fig. 4. Example fixture (differential fixture shown) and block diagram for probe measurement.

Circuit probe characterization starts with a carefully designed and accurately characterized probe-characterization test fixture. Fig. 4 shows an example of a probe-characterization test fixture and its electrical block diagram.

Once an accurate probe-characterization test fixture is obtained, the probe plus the test fixture must be accurately measured to get their joint electrical characteristics. The block diagram shows the S21-through-measurement approach. These joint electrical response characteristics can subsequently be converted to a probe-only response using data available on the probe-characterization test fixture. Once the probe's frequency-response characteristics are known, the probe's effects on the circuit can then be accurately quantified and/or removed from subsequent electrical measurements of the response of a measurement instrument, such as a waveform recorder.

IEEE Draft Std P2414: "Draft Standard for Jitter and Phase Noise" and the Subcommittee on Jitter (P2414)

The IEEE Std 2414 is being written to define specifications, models and terminology that describe the dispersion of specified instants of repetitive and/or periodic signals in electronics, telecommunications and measurement, which are referred to as jitter and phase noise. Jitter occurs in many different parts of digital systems such as the jitter of data with respect to clock in synchronous protocols or the jitter of the clock signal in clock data recovery applications. Every circuit element generating, conveying and receiving signals can introduce jitter.

There are many misconceptions about what exactly jitter is, and its definition is often strictly dependent on the specific application. This situation is not the best possible pre-requisite for a correct measurement. An unambiguous definition of a quantity is also the first step to design reference standards to create a calibration chain to the main measurement units. The purpose of the standard is to facilitate accurate and precise communication concerning jitter and phase noise.

When considering jitter, it is quite clear that there is not a single, comprehensive, universally accepted definition for all applications. Most often, the term jitter expresses the deviation from the ideal timing of an event. The exact meaning of ideal timing, as well as the meaning of actual timing, and the type of event may change depending on the application.

Because of the ubiquity of jitter, a number of application-specific documentary standards have been developed by the IEEE and other standardizing bodies [18]–[27]. The Subcommittee on Jitter addresses the need for a harmonized, unitary approach to terminology and models for jitter. This effort was started in 2011, and after a long study phase to analyze the existing world-wide literature, including standards, a Project Authorization Request was submitted to and approved by the IEEE in 2013. Several draft documents have been discussed and continuously improved during recent years. The draft has been completed and a first ballot has conducted in 2019. The first ballot resulted in amendments to the draft standard and reballoting in July 2020. The final approval is expected in the last quarter of 2020 and publication in early 2021.

The current version of the draft includes definitions and models for the most common types of jitter that are classified as random or deterministic ones. The deterministic jitter class is further divided into data-dependent jitter, periodic jitter and bounded-uncorrelated jitter. A general model for jitter is also provided, considering it as a random variable and modeling it with its probability density function. A model is also provided, for each type of jitter, to facilitate the construction of a complete jitter model from the contributions of all the different types of jitter.

Conclusion

The IEEE's TC-10 continually updates and improves its existing standards and develops new ones as needed by its stakeholders. The TC-10 encourages fresh ideas and new perspectives. If you are interested in the TC-10's work and would like to join one or more of its subcommittees, please visit our home page at http://tc10.ieee-ims.org/tc10-home. Contact information for the Subcommittee Chairs can be found at this home page. We welcome your interest and participation.

Acknowledgment

The TC-10 is grateful for the many years of dedicated volunteer service provided by its past chair Thomas E. Linnenbrink. His vision and guidance forged the TC10 into an effective and productive technical committee. Tom's commitment to the TC-10, the Instrumentation and Measurement Society, and his profession were inspirational and motivating. He was the quintessential gentleman engineer.

References

[1] *IEEE Standard for Transitions, Pulses, and Related Waveforms,* IEEE Std. 181-2011, Institute of Electrical and Electronics Engineers, 2011.

[2] *IEEE Standard for Digitizing Waveform Recorders,* IEEE Std. 1057-2017, Institute of Electrical and Electronics Engineers, 2017.

[3] *IEEE Standard for Terminology and Test Methods for Analog-to-Digital Converters,* IEEE Std. 1241-2010, Institute of Electrical and Electronics Engineers, 2010.

[4] *IEEE Standard for Terminology and Test Methods of Digital-to-Analog Converter Devices,* IEEE Std. 1658-2011, Institute of Electrical and Electronics Engineers, 2011.

[5] *IEEE Standard for Terminology and Test Methods for Circuit Probes,* IEEE Std. 1696-2013, Institute of Electrical and Electronics Engineers, 2017.

[6] T. E. Linnenbrink, W. B. Boyer, N. G. Paulter, and S. J. Tilden, "IEEE TC-10: What's it all about?" in *Proc. IEEE Instrum. Meas. Technol. Conf.* (*IMTC 2003*), 2003.

[7] T. E. Linnenbrink, W. B. Boyer, N. G. Paulter, and S. J. Tilden, "IEEE TC-10: Update 2006," in *Proc. IEEE Instrum. Meas. Technol. Conf.* (*IMTC 2006*), 2006.

[8] T. E. Linnenbrink, W. B. Boyer, R. N. Graham, N. G. Paulter, and S. J. Tilden, "IEEE TC-10: Update 2008," in Proc. *16th IMEKO TC4 Symp. And 13th Workshop on ADC Modeling and Testing*, 2008.

[9] T. E. Linnenbrink, W. B. Boyer, T. Ellis, N. G. Paulter Jr., and S. J. Tilden, "IEEE TC-10: Update 2011," in *Proc. IMEKO Int. Workshop on ADC Modelling, Testing and Data Converter Analysis and Design* (*IWADC 2011*), 2011.

[10] S. Rapuano, L. De Vito, J. Jendzurski, W. B. Boyer, S. J. Tilden, and N. G. Paulter Jr., "The IEEE TC-10 standards: update 2019," in *Proc. 24th IMEKO TC4 Int. Symp.*, 2019.

[11] N. G. Paulter, D. R. Larson, and J. J. Blair, "The IEEE standard on transitions, pulses, and related waveforms, Std-181," in *Proc. Instrum. Meas. Technol. Conf. (IMTC 2003)*, pp. 110-112, 2003.

[12] D. F. Andrews, P. J. Bickel, F. R. Hampel, P. J. Huber, W. H. Rogers, and J. W. Tukey, *Robust Estimates of Location*. Princeton, NJ, USA: Princeton University Press, 1972.

[13] O. M. Solomon, D. R. Larson, and N. G. Paulter, "Comparison of some algorithms to estimate the low and high state level of pulses," in *Proc. Instrum. Meas. Technol. Conf. (IMTC 2001)*, pp. 96-101, 2001.

[14] M. Bieler M and N. G. Paulter, "Estimation of waveform state levels and uncertainties using the histogram and shorth methods," in *Proc. Conf. Precision Electromagnetic Meas. (CPEM 2016)*, pp. 10-15, 2016.

[15] N. G. Paulter Jr., "NIST Technical Note 2036, Comparison of the Measurement Uncertainties and Errors for the Waveform State Levels Estimated Using the Histogram Mode and Shorth Methods," National Institute for Standards and Technology, 2019.

[16] *IEC Transitions, Pulses and Related Waveforms–Terms, Definitions and Algorithms,* IEC 60469, Edition 1.0 2013-04, International Electrotechnical Commission, Geneva, Switzerland, 1st Ed., 2013.

[17] IEC *Semiconductor Devices - Integrated Circuits - Part 4-3: Interface Integrated Circuits— Dynamic Criteria for Analogue-Digital Converters (ADC),* IEC 60748-4-3:2006, International Electrotechnical Commission, Geneva, Switzerland, 2006.
[18] *IEC Fiber Optic Communication Subsystem Test Procedures - Part 2-3: Digital Systems— Jitter and Wander Measurements,* IEC 61280-2-3:2009, International Electrotechnical Commission, Geneva, Switzerland, 2009.
[19] *IEEE Standard on Jitter in Methods and Equipment for Measuring the Transmission Characteristics of Pulse-Code Modulation (PCM) Telecommunications Circuits and Systems,* Std 1007-1991, Institute of Electrical and Electronics Engineers, 1991.
[20] *IEEE Standard on Jitter in a High-Performance Serial Bus,* Std 1394-2008, Institute of Electrical and Electronics Engineers, 2008.
[21] *IEEE Standard on Measurement of Video Jitter and Wander,* IEEE Std 1521-2003 (R2010), Institute of Electrical and Electronics Engineers, 2010.
[22] *IEEE Standard on Jitter for Low-Voltage Differential Signals (LVDS) for Scalable Coherent Interface (SCI),* IEEE Std 1596.3-1996, Institute of Electrical and Electronics Engineers, 1996.
[23] *IEEE Standard on Jitter in Radar Definitions*, IEEE Std 686-1997, Institute of Electrical and Electronics Engineers, 1997.
[24] *IEEE Standard on Jitter in the Equipment Requirements and Measurement Techniques for Analog Transmission Parameters for Telecommunications,* IEEE Std 743-1995, Institute of Electrical and Electronics Engineers, 1995.
[25] *IEEE Standard for Jitter in Information technology— Telecommunications and information exchange between systems — Local and metropolitan area networks—Specific requirements. Part 3: Carrier sense multiple access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications,* IEEE Std 802.3-2008, Institute of Electrical and Electronics Engineers, 2008.
[26] *ITU-R Jitter Specifications and Methods for Jitter Measurements of Bit-Serial Signals Conforming to Recommendations ITU-R BT.656, BT.656, ITU-R BT.799 AND ITU-R BT.1120*, Recommendation BT.1363, International Telecommunications Union,1998.
[27] *ITU-T Transmission Systems and Media Digital Transmission Systems, Digital networks - Design objectives for digital networks - Definitions and terminology for synchronization networks.* ITU-T G.810, SERIES G, International Telecommunications Union, 1996.

Sergio Rapuano (M ‘00, SM ‘10), Ph.D., is an Associate Professor of Electrical and Electronic Measurement at the Department of Engineering of the University of Sannio, Italy. He is Member-at-Large of the Administrative Committee, Vice President for Education and Past Vice President for Membership of the IEEE Instrumentation and Measurement Society (IMS), Treasurer of the IEEE Italy Section, Secretary of the IMS TC-25 Medical and Biological Measurements and Subcommittee Chair of TC-10. He participated in the realization of three IEEE standards and is currently coordinating the working group developing the new jitter standard. His research interests include ADC and DAC modelling and testing, digital signal processing, distributed measurement systems, and medical measurement.

John Jendzurski is an Electrical Engineer at National Institute of Standards and Technology (NIST) in Gaithersburg, MD where he conducts research and standards development in through-barrier and traffic enforcement radar. He is currently the chair of TC-41, Traffic Enforcement Technologies, responsible for performance standards in down-the-road radar and lidar used in traffic enforcement.

Luca De Vito (M’10–SM’12) is an Associate Professor of Electrical and Electronic Measurement at the Department of Engineering of the University of Sannio, Italy. Since 2015, he has collaborated on research related to magnetic measurement, control and electricity and the hadron synchrotron collective effects sections of CERN, Switzerland. He is Editor of *Measurement* (Elsevier), Subcommittee Chair of the IMS TC-10 and Chapter Chair Liaison of the IEEE IMS. His research interests include measurements for the telecommunications, data converter testing and biomedical instrumentation.

Steven Tilden is with Raytheon Company in Tucson, AZ. He is a Senior Principal Systems Engineer there, working on state-of-the-art semiconductor factory for large pin count digital and mixed-signal packaged devices. He is an IEEE Senior Member and Past Chair of TC-10, the DAC standard, and is acting ADC standard Chairman.

William Boyer is retired from Sandia National Laboratories in Albuquerque, NM. For most of his career at Sandia, he was responsible for the development of large high-speed data acquisition systems. He is currently the Chairman of the TC-10 subcommittee responsible for the IEEE 1057 Waveform Recorder standard.

Nicholas Paulter is with the National Institute of Standards and Technology (NIST) in Gaithersburg, MD. He develops and oversees metrology programs related to a variety of threat-detection and trauma-mitigation technologies. He is an IEEE Fellow.