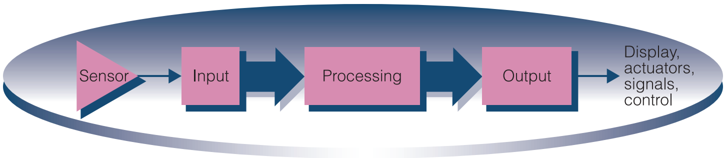

Pulse Metrology: Part 1

Part 32 in a series of tutorials on instrumentation and measurement

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This tutorial is the first part of a two-part series on pulse metrology. Part one provides a brief introduction to the field of metrology in general and to pulse metrology. Metrology involves the important concepts of traceability to fundamental units, measurement uncertainty, and reproducibility and repeatability of measurement. These aspects are not automatically included in measurements.

Introduction

Pulse metrology is the science of the measurement of pulses. It is the ability to measure pulse signals in a repeatable and reproducible manner and to do this with defensible measurement uncertainties. Measurement uncertainty, as defined in [1], is the "non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, 'a quantity intended to be measured', based on the information used." Many scientists and engineers perform pulse measurements, but very few actually know their measurement uncertainties or even know how to perform a measurement uncertainty analysis. One of the very useful outcomes of an uncertainty analysis (also known as a sensitivity analysis) is a set of coefficients that describes the sensitivity of the measurand to various parameters and effects. An accurate uncertainty analysis shows the path to improve your measurements!

Pulse metrology affects a plethora of industries. Obvious industries are the ubiquitous telecommunications, data communications, and computing industries. And, of course, all the 'information' we receive on our digital entertainment devices (radios, televisions) is encoded in pulse signals. The spark that drives our vehicles is an impulse. Many phenomena in nature are pulses – pulsar emissions, solar flares, earthquakes, nerve impulses, heartbeats, etc. Pulses and their measurement are important to our lives in many different and diverse ways.

However, pulse metrology is primarily directed to the measurement of high-speed electrical and optical signals because of the commercial importance of our communications, computing, and entertainment

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industries. Consequently, the bias in this article is towards high-speed pulse metrology, although the concepts apply equally well from ultra-fast pulse signals to ultra-slow pulse signals. Here the words "ultra-fast" and "ultra-slow" refer to the rate of the amplitude transition in the pulse and not pulse propagation velocity.

The pulses we use in our communication and entertainment devices are either impulse-like or step-like. Impulse-like signals are used, for example, in optical links in data communications and telecommunications equipment, whereas step-like signals are used in electrical links. The accurate measurement of pulse parameters is critical for the viability of these industries. That is, the amplitude levels, amount of aberration, and transient characteristics must be known to achieve the design and performance goals of the electronics and photonics devices, systems, and instruments.

In digital systems, the parameters that describe a pulse (amplitude, transition duration, etc.) at its point-of-use (transistor gate, optical detector, etc.) can vary by a few percent from the nominal values and still be useful. However, the verification of the design and performance of devices and circuits that generate or use these pulses requires much more accuracy and less uncertainty than do the measurements for their point-of-use application. Furthermore, the characterization of measurement systems that do the verification requires even more accuracy and smaller uncertainties than does the design verification measurement. Finally, the national metrology institute (NMI) that supports these industries requires the greatest accuracy, smallest uncertainties, and best measurement repeatability and reproducibility. The perspective of this paper is that of an NMI.

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Metrology in General

Metrology is the science of measurement and its application [1]. Metrology is multi-disciplinary. The measurement process is studied for the purpose of having a better understanding of the limits of the measurement process and of the sensitivity of the measurand to measurement variables. The measurement process includes instruments, components, analyses, human operation, and anything else required to obtain a value for the measurand. Improving the understanding of the measurement process increases the accuracy of the measurand. Metrology can include considerations of any or all of test methods, test systems, data analyses, calibration procedures, calibration artifacts, design of measurement, and traceability.

Metrology is a science pursued by very few scientists and engineers for several reasons. One of the biggest reasons is that very few institutions support metrology because of its high cost and uncertain return on investment. There is rarely any product to sell except for calibration or measurement services that provide traceability to fundamental or derived units and reference materials, devices, and data, and the revenue from these services rarely covers the cost of the research. Consequently, most metrology is performed at NMIs. NMIs offer or provide reference materials and data freely available to the public to promote commerce. Another reason metrology is not typically pursued is that it is not considered (except by the authors) very glamorous or flashy. As a result, most laboratories do not engage in metrology programs unless it is absolutely essential to a product line and accredited calibration service providers are not readily available. Last, metrology is often an arduous endeavor, requiring very dedicated individuals who are willing to spend long hours, days, weeks, or years (many of these) to glean fractional improvements in accuracy and uncertainties. Metrology, however, is one of the few sciences where one can determine whether one's laboratory is world-class or not.

In metrology, all possible and identifiable physical processes involved in a measurement process are studied to know how each affects the measurand. These processes may include the responses of sensors and instrumentation, background effects (temperature, humidity, electromagnetic interference), data extraction algorithms, and human variability for manually-operated systems. Few researchers actually take the time to identify all these relationships and to try to understand their effect on the measurand. Typically a simple root-sum-of-squares approach of some of the important measurement variables is used to estimate measurement uncertainty. Although this is an acceptable approach, it does not help the researchers understand their measurement system and process. In the worst case, measurement uncertainty is simply estimated by the standard deviation of the values of the measurand. This approach is simply not acceptable, because there are so many other contributors to measurement uncertainty.

Understanding a measurement process means a person can write down the functional relationships that describe the effect of measurement variables on the measurand and on intermediate and calibration factors. Intermediate and calibration factors are the factors obtained from any and all auxiliary measurements necessary to provide uncertainties for the measurand. From these functional relationships and associated measurements, the uncertainty in the measurand can be determined. These functional relationships provide the path and formulas for propagating uncertainties from the measurement variables and intermediate factors to the uncertainty in the measurand. If the measurement process includes a traceability path to fundamental units, then the functional relationships will allow the measurand to be traceable to fundamental units. For an NMI, uncertainty analyses are paramount for providing traceability. In other words, there can be no traceability without considering the measurement uncertainties of the entire calibration chain back to the NMI.

What is Traceability?

Metrological traceability is the "property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty" [1]. Consequently, traceability is not a path to a scientific discipline, such as physics, but to a reference, such as a measurement system or to a fundamental unit (kilogram, candela, ampere, Kelvin, meter, second, and mole). This may seem like an obvious statement and not worth saying, but it is, because the authors have often heard and read the phrase "traceable to fundamental physics" made by colleagues. This statement provides no useful information. For example, consider the operation of the fuel level indicator in a car. It may use a float connected to a variable resistor. The operation of the float is based on physics, and the operation of the variable resistor is based on physics. Ergo, the fuel indicator in your car is "traceable to fundamental physics," but so what? You still do not know the uncertainty in fuel level indication. Traceability to fundamental units and derived units is provided by NMIs to other laboratories via transfer artifacts (standard test objects) and calibration services.

Uncertainties in Measurement

The number of uncertainty contributors in a measurement sometimes appears limitless (which may explain the authors' obsession with uncertainty analyses). This is because the metrologist must constantly be searching for potential weaknesses in previously developed uncertainty analyses: looking for overlooked measurement effects, inaccurate or erroneous simplifying assumptions, and errors in computational steps. Uncertainty is not the same as measurement variation or variability, as mentioned before, and a couple of simple examples can illustrate this point.

Example 1: A voltage measured with a voltmeter: The measured voltage V_{meas} is the result of an input voltage V_{in} applied to the terminals of the imperfect voltmeter:

$$V_{meas} = V_{in}g + V_{off},$$

where g describes the transfer ratio of applied voltage to observed voltage (this is, in effect, a gain coefficient) and V_{off} is the offset of the voltmeter. The estimate of the input voltage V_{est}, is given by:

$$V_{est} = \frac{V_{meas} - V_{off}}{g}.$$

Using this formula, the uncertainty in V_{est} can be obtained:

$$\begin{aligned} u_{V_{est}} &= \sqrt{\frac{1}{g^2}\left(\sigma^2_{V_{meas}} + \sigma^2_{V_{off}}\right) + \frac{\left(V_{meas} - V_{off}\right)^2}{g^4}u_g^2} \\ &= \frac{\left(V_{meas} - V_{off}\right)}{g}\sqrt{\frac{\left(\sigma^2_{V_{meas}} + \sigma^2_{V_{off}}\right)}{\left(V_{meas} - V_{off}\right)^2} + \frac{u_g^2}{g^2}} \\ &= V_{est}\sqrt{\frac{\left(\sigma^2_{V_{meas}} + \sigma^2_{V_{off}}\right)}{\left(V_{meas} - V_{off}\right)^2} + \frac{u_g^2}{g^2}}, \end{aligned}$$

where σ represents the standard deviation of a measurement, a Type A uncertainty, and u represents the uncertainty in a measurand or intermediate value, which will contain both Type A and Type B uncertainties. Type A uncertainties are defined as "those which are evaluated by statistical methods" and Type B uncertainties are defined as "those which are evaluated by other means" [2]. The other terms are the sensitivity coefficients (partial derivatives). This simple formula does not consider environmental effects and connector repeatability. Even with this simple example, and letting $\sigma_{V_{meas}} = \sigma_{V_{off}} = \sigma_V$, $V_{est} = V_{meas} - V_{off}$, $g = 1$, and $u_g = 0$, we see that $u_{V_{est}} \approx \sqrt{2}\sigma_V$. That is, the uncertainty in V_{est} is at least $\sqrt{2}$ times the standard deviation of the measured voltage. Clearly, the uncertainty is not equivalent to the measurement variation or variability in this example.

Example 2: Permittivity of a capacitor: It is worth examining another simple example where uncertainty in the measurand can far exceed that of the measurement standard deviation. An example is determining the static relative permittivity ε_r of the insulator used in a capacitor. The capacitance C of a simple parallel plate capacitor (neglecting edge effects) is described by:

$$C = \varepsilon_r \frac{A}{d},$$

where A is the area of the capacitor plates (both plates of equal area) and d is the distance between the plates. Since we want to solve for ε_r, we rearrange the previous equation to get:

$$\varepsilon_r = C\frac{d}{A}.$$

We perform separate sets of measurements to get values of C, A, and d (which will represent the means of the appropriate measurement set). Each mean value will have an associated standard deviation, σ_C, σ_A, and σ_d. Each measurement system will also have additional uncertainties, u_C, u_A, and u_d, due to the calibration process, calibration artifacts, environmental variations, etc. The uncertainty, u_ε, in ε_r, assuming the number in each set of measurements is large (>> 100), is:

$$\begin{aligned} u_\varepsilon &= \sqrt{\left(\frac{d}{A}\right)^2\left(u_C^2 + \sigma_C^2\right) + \left(\frac{C}{A}\right)^2\left(u_d^2 + \sigma_d^2\right) + \left(\frac{Cd}{A^2}\right)^2\left(u_A^2 + \sigma_A^2\right)} \\ &= \varepsilon_r\sqrt{\frac{\left(u_C^2 + \sigma_C^2\right)}{C^2} + \frac{\left(u_d^2 + \sigma_d^2\right)}{d^2} + \frac{\left(u_A^2 + \sigma_A^2\right)}{A^2}}. \end{aligned}$$

The advantage of writing u_ε in the bottom form is that the metrologist can get an immediate idea of the importance that the uncertainty of any parameter has on the uncertainty of the measurand. For example, because d is usually small, σ_d/d will usually dominate u_ε. And if σ_d/d is on the order of a few percent, u_ε will be at least that same percentage of ε_r. Using values to highlight this point, if $d = 50$ µm and $\sigma_d = 10$ µm, then u_ε can be no less than 20% of ε_r. This situation was actually encountered in determining the uncertainty in the measurement of the real part of the permittivity of thin dielectrics used in high-performance printed wiring boards [3].

Pulse Metrology

Pulse metrology is the science of the measurement of pulses. Pulse measurement is not necessarily pulse metrology although, as should be obvious, pulse metrology comprises pulse measurement. Potentially anyone with an oscilloscope or any other waveform recorder can perform pulse measurements. However, this does not automatically imply that anyone doing pulse measurement knows what has been measured and to what accuracy and with what uncertainty.

When you speak to researchers engaged in any metrology, they are often pushing the limits of measurement. This should be expected, because as measurements improve through metrology, metrology must advance to support the newly developed measurement capability, which in turn promotes advancement of the technology being measured. Accordingly, pulse metrology as it relates to the commercially-important industries mentioned earlier, is concerned with improving the ability to measure the amplitude and temporal characteristics of pulses, specifically, high-speed electrical and optical pulses and the responses of instruments that measure these pulses. We have written several papers describing the development of uncertainty analyses for different high-speed pulse metrology topics that show the detail necessary for pulse metrology [4-7]; however, these specific subjects will not be discussed in detail here. Examples of the detailed studies performed to elucidate the parameters affecting pulse measurement accuracy and reproducibility can be found in references [8-16].

Often it is necessary to remove the effect of the measurement instrument's response from the acquired waveform through a process called deconvolution [17], [18]. Consequently, pulse metrology must also be concerned with attributing uncertainty to the deconvolution process and artifacts used to determine the instrument's response.

Issues that are important to pulse metrology include standards (terms and definitions, measurement methods), traceability, and measurement uncertainty, as will be discussed in the following sections.

Standards

It has been said many times, and we'll reiterate it here, "Standards mean different things to different people." For our purposes, we'll focus on standards appropriate for pulse metrology, and these are standards for terms and definitions, standards for computing parameters, test method standards, and artifact or transfer standards. All of these standards, except for the last, are documentary standards. Documentary standards are defined in [19] as "Standards that specify:

- common and repeated use of rules, conditions, guidelines or characteristics for products or related processes and production methods, and related management system practices; and
- definition of terms; classifications of components; delineation of procedures; specification of dimensions, materials, processes, products, systems, services or practices; test methods and sampling procedures; or descriptions of fit and measurements of size or strength."

Minimum performance standards for equipment can also contribute to pulse metrology but are more typically *a product* of pulse metrology, so these types of standards won't be considered here.

***Terms and definitions*:** Pulse metrology must start with a defined set of terms to describe observed pulse phenomena. The IEEE Standard 181-2003 [20, 21], "IEEE Standard on Transitions, Pulses, and Related Waveforms," in its "Purpose" describes quite well the purpose of such a standard:

> The purpose of the standard is to facilitate accurate and precise communication concerning parameters of transition, pulse, and related waveforms and the techniques and

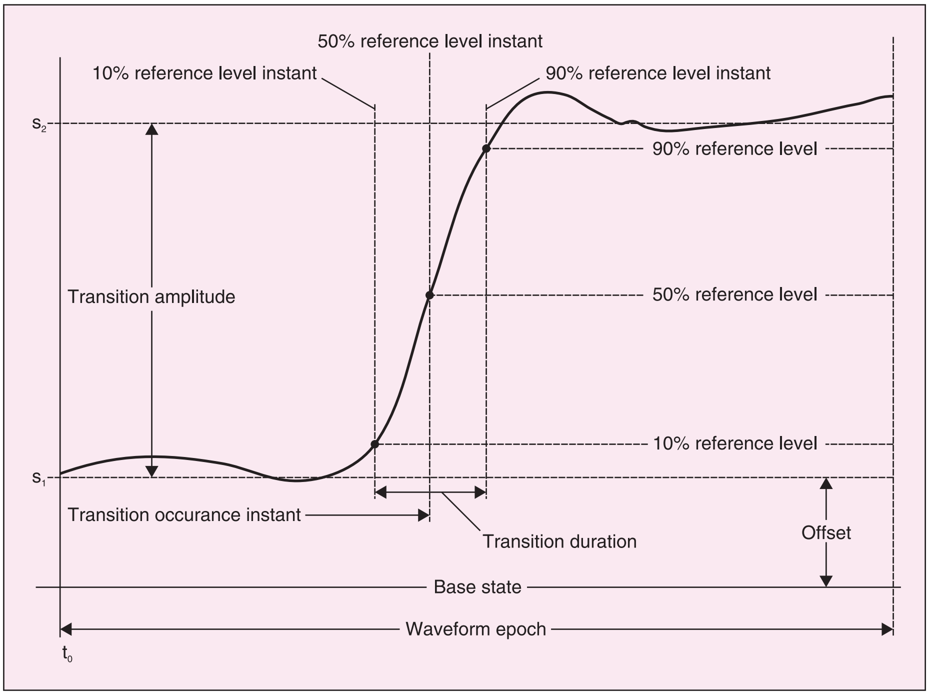

Fig. 1. Positive step-like waveform showing amplitude, transition duration, reference levels, reference level instants, and state levels. This figure displays the fundamental characteristics of a waveform, namely, its state levels and reference level instants from which all other pulse parameters are computed.

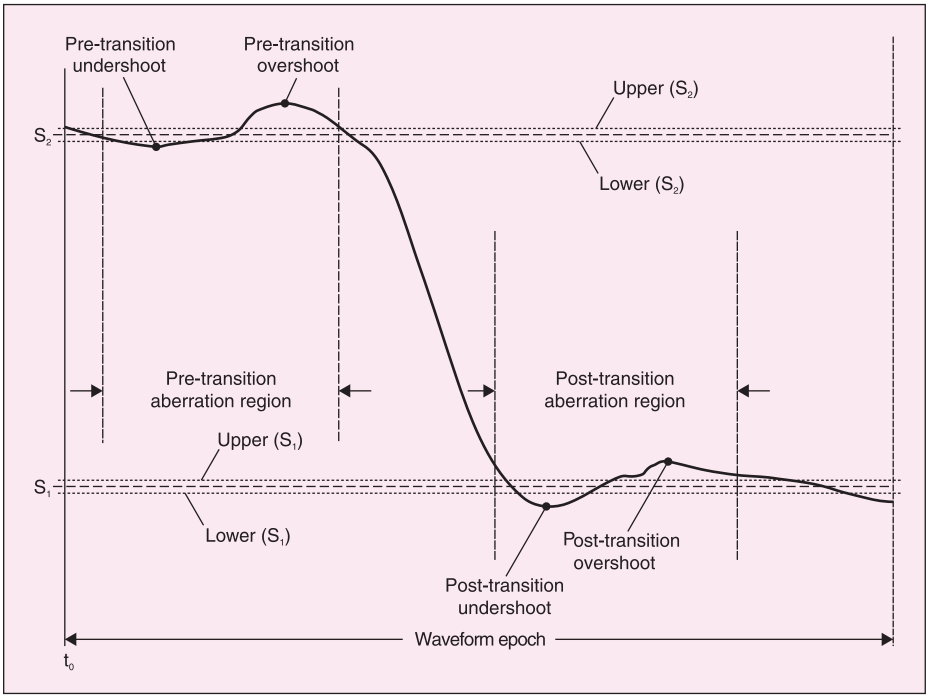

Fig. 2. A negative transition waveform showing undershoot and overshoot aberrations and upper and lower bounds for states. This figure depicts the waveform parameters necessary to clearly describe pulse overshoot and undershoot, which are the most commonly cited waveform aberrations.

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.

The ability to communicate with a common language regarding a technology is fundamental. And this is one of the key topics in the international dissemination of the International System of Units (SI). For pulse metrology, there is no mandatory or governmental oversight of terms and definitions. Instead, pulse metrology terms and definitions were developed by a group of engineers and scientists through a standards activity of the Institute of Electrical and Electronics Engineers' (IEEE's) Technical Committee 10 (TC-10, Waveform Generation, Measurement, and Analysis Committee). The Subcommittee on Pulse Techniques (SCOPT) developed the original two standards in 1977. These standards were adopted almost verbatim ten years later (in 1987) by the International Electrotechnical Commission (IEC) Technical Committee 85 (TC 85, the Committee on Measuring Equipment for Electrical and Electromagnetic Quantities).

The 1977 IEEE standards, although a good start, were not entirely clear and unambiguous. Moreover, they did not prescribe methods for computing pulse parameters. Consequently, the SCOPT modified the standards to address these issues and combined them for technical continuity. This revised standard was published in 2003. It contains about 100 terms that have a unique meaning in pulse metrology and their definitions. Terms that were confusing are listed as being deprecated, and the rationale for that deprecation is also given.

It is useful to introduce common pulse terms. Common pulse terms promote and facilitate discussion and understanding. Figs.1 and 2 provide examples of the most commonly-used pulse terms. Definitions for these terms can be found in the IEEE Std 181-2003. However, for clarification, the nomenclature used in Figs. 1 and 2 is described here:

- s_i = waveform state. There are at least two states. States are numbered starting at the most negative.
- *level*(s_i) = level of the i^{th} state.
- *upper*(s_i) = upper boundary of the i^{th} state. There is also a *lower*(s_i). If the waveform values do not stay between *upper*(s_i) and *lower*(s_i), the waveform value is not in the i^{th} state.

Summary

Pulse metrology is a measurement science that provides reproducible and repeatable measurements of pulse signals with defensible uncertainties. These uncertainties describe the sensitivity of the measurand (the thing for which you want to find a number) to various parameters and effects. Pulse metrology affects the commercially-important telecommunications, data communications, and computing industries.

Although this Part 1 and the upcoming Part 2 are only a partial introduction to pulse metrology, they demonstrate the importance of this work and the challenge to continuously provide the manufacturing and user communities with measurement capability exceeding their present and future requirements. Part 2 will address parameter computation, test methods and test objects (artifacts), traceability, and measurement uncertainty.

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