NIST Impulse Spectrum Amplitude Measurement Service

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Abstract: The NIST service for measuring the impulse spectrum amplitude of the output of impulse generators is described. The calibration procedures used in this measurement service were recently modified, and this reduced both the time for measurement and the published uncertainties. Using this new calibration method and associated uncertainty analysis, the published uncertainties for the bandwidth of 10 MHz to 4 GHz have been reduced from ± 0.5 dB to less than ± 0.1 dB for the parameter of impulse spectrum amplitude. Furthermore, the new calibration method allows this NIST measurement service to be extended to higher frequencies to support the measurement of the spectrum amplitude of ultra-wideband (UWB) signals.

Keywords: calibration, electromagnetic interference emission, electromagnetic interference immunity, impulse spectral intensity, impulse spectrum amplitude, impulse strength, spectral density, spectrum amplitude, ultra-wideband, UWB

1. Introduction
The National Institute of Standards and Technology (NIST) has a service [1] for measurement of the output of high-speed (pulse durations < 1 ns) impulse generators. This service, service ID number 65100S, provides an estimate of the parameter of impulse spectrum amplitude [2]. Other names for this term that have been used are: spectrum amplitude, voltage spectrum, impulse strength, spectral intensity, impulse spectral intensity, impulse area, and spectral density. The primary application of this service has been in the measurement of impulse spectrum amplitude for impulse generators used in electromagnetic interference emission and immunity tests. However, with the improvements in the calibration procedures, 65100S can now support the ultra-wideband electronics community by providing measurement of the parameters of spectrum amplitude of ultra-wideband (UWB) signals. Time-domain pulse parameters of the UWB signal, such as the pulse width, transition duration, etc. of the modulation envelope, can be measured using NIST’s 65200S and 65250S pulse measurement services.

Impulse spectrum amplitude, or one of its synonyms or equivalents, is specified in several international and national standards. For example, one characteristic of receivers (quasi-peak,
peak, rms, and average measuring) is its response to pulses of a given impulse area (units of μVs or dB(μVs)), see CISPR-22 [3] and CISPR-16 [4]. In ETSI EN 300-328 [5], several related terms (peak power density, spectral power density) are defined, and limits (in units of dBm/Hz or in dBm if a 100 kHz bandwidth is assumed) for spurious emissions from transmitters used in data transmission are given. The IEEE guide C62-41 [6], describes spectral density (in units of dB(μVs)) as a parameter for characterizing ac power circuits, and a standard for measuring impulse strength is given in [7]. For certain low-frequency applications, the U.S. Federal Communication Commission (FCC) puts a limit on the power emitted, in units of mV/m or μV/m for a given frequency range, for intentional radiators and in units of μV/m/Hz for certain automotive applications (Subpart C - Intentional Radiators of [8])). For personal communication devices and national information infrastructure devices, the FCC expresses limits in terms of power spectral density (given either in units of mW for a specified bandwidth, or dBm/MHz) (Subpart D - Unlicensed Personal Communications Service Devices of [8], and Subpart E - Unlicensed National Information Infrastructure Devices of [8]). More recently, the FCC has defined emission limits for ultra-wideband devices and expresses this limit in terms of EIRP (equivalent isotropically radiated power - defined in [8]) in units of dBm for a given resolution bandwidth (Subpart F - Ultra-Wideband Operation of [8]).

The NIST measurement service presently uses commercially available, high-bandwidth sampling oscilloscopes (3 dB attenuation bandwidths = 80 GHz) to acquire waveforms of the pulses generated by high-speed baseband impulse generators or pulsed radio frequency (rf) sources. The NIST system can measure both the response of receivers to a known impulse or the output of an impulse or ultra-wideband generator.

2. Measurement System

A typical instrument set up used to acquire \( V(t_n) \) is shown in Figure 1. The signal produced by the generator or source, \( V(t) \), is acquired by the 65100 measurement instrument to yield a discretized replica, \( V(t_n) \) \((n = 1, 2, ..., N, \text{where} \ N \text{is the number of samples, and} \ t_n \text{are the sample instants}), \) of \( V(t) \). This measurement system is similar to the conceptual arrangement shown in Fig. 3 of [9]. The measurement system can be readily modified to accommodate different device under test (DUT) characteristics by removing unnecessary components. For example, if the DUT has a low repetition rate, low duty factor, no output trigger, and provides a large amplitude signal, then the system shown in Figure 1 is used where the trigger is derived from the delay/splitter (depicted by the thick solid line). If, on the other hand, the DUT is similar to that just described except that it provides a trigger, then the measurement system shown in Fig. 1 can be used where the trigger is supplied by the DUT (dotted line in Fig. 1). If the signal amplitude is small, the attenuator is unnecessary. If the DUT has an external trigger input, then the delay line is not necessary because the DUT can be synchronized to the sampler by a low-jitter trigger system[10]. In this case, however, the combined jitter of the sampler and the pulse generator, not only the jitter of the sampler, must be measured and its effect removed from the measured data. Jitter must be taken into account because it effectively acts as a low-pass filter[11].

2.1 Measurement Process

The measurement process consists of a set of measurements of the DUT and a set of calibration measurements. A set of data consists of \( M_i \) sampler-acquired DUT waveforms and one
measurement of the timebase accuracy[12,13]. The DUT measurement sequence is as follows:

1. Measure timebase error one independent measurement
2. Acquire waveforms $M_i$ independent measurements of DUT output

The spectra of the acquired waveforms are obtained using Fourier transforms. Measurement of the system frequency response is done periodically and a control chart of that response, with uncertainties, maintained. Corrections are applied to these spectra, if necessary. Only the magnitude of the spectra are reported to the customer.

2.2 Calibration
The magnitude of the frequency response of the measurement system is calibrated using a swept frequency technique. The frequency intervals are calibrated using sine fit methods[13]. The calibration measurements include timebase errors, trigger jitter, and system frequency response. The arrangement for performing the system frequency response calibration is shown in Figure 2.

2.3 Computation of Impulse Spectrum Amplitude
The parameter reported to customers for their DUT is the impulse spectrum amplitude, $S_R[f_k]$, in logarithmic units referenced to $1 \text{ } \mu\text{V/MHz}$. $S_R[f_k]$ is given by:

$$S_R[f_k] = 20 \log \left( \frac{S[f_k]}{S_0} \right),$$

Figure 1. Diagram of measurement system, generator or source without an output trigger.
Figure 2. Diagram of measurement system during calibration.

where $k$ is the discrete frequency index, $S_0 = 1 \, \mu V/\text{MHz}$, and

$$S[f_k] = 2|V[f_k]|,$$  \hspace{1cm} (2)

where $V[f_k]$ is the Fourier transform of the output of the impulse generator. The uncertainty, $u_S$, in $S$ is:

$$u_S = 2u_V,$$ \hspace{1cm} (3)

where $u_V$ is described in Section 4.1. The $V[f_k]$ is obtained by deconvolving the effect the measurement instrument has had on the measured output of the DUT. Time-domain deconvolution is achieved by a division of appropriate spectra in the frequency domain. For $V[f_k]$, this is:

$$V[f_k] = \frac{V_m[f_k]}{H_{sys}[f_k]}f[f_k],$$ \hspace{1cm} (4)

where $V_m$ is the discrete spectrum of the measured output of the DUT, $J[f_k]$ is the discrete spectrum of the trigger jitter, $H_{sys}$ is the transfer function (Fourier transform of the impulse response) of the measurement system, and the explicit reference to the discrete frequency, $f_k$, has been dropped for brevity. $H_{sys}$ includes both the sampling instrument transfer function, $H_s$, and that of the auxiliary electronics, $H_{aux}$, required to measure the output of the impulse generator:

$$H_{sys} = H_{aux}H_s.$$ \hspace{1cm} (5)

In this measurement process, $H_{aux}$ and $H_s$ are obtained with the same measurement.
3. Measurement Results

Figure 3 shows the impulse spectrum amplitude (curve labeled “S” in Fig. 3) and the expanded uncertainty (curve labeled “U” in Fig. 3) for an impulse generator using the 65100 measurement system. The impulse generator produced pulses with a peak amplitude of approximately 5.5 V at a repetition rate of approximately 100 Hz. The primary difference between the results from the present 65100 measurement system and the new system are in the expanded uncertainty values. And this difference is the result of using a swept-frequency calibration method of the entire measurement system, as compared to a piecemeal calibration of each component (delay line/splitter, attenuators, sampler) using time-domain techniques. The time-domain calibration method required deconvolving the response of each component to a step input from that step input. Using the older system, the expanded uncertainty is 0.5 dB. As can be seen from Fig. 3, the expanded uncertainty using the new calibration method and associated uncertainty analysis produces an expanded uncertainty much lower than 0.5 dB. Although analysis and other tests confirm the large reduction in expanded uncertainty compared to the present calibration method, further tests will be performed to corroborate these results. The new uncertainty analysis includes more variables than does the existing analysis (see Sec. 4.2).

Figure 3. Impulse spectrum amplitude (S) and expanded uncertainty (U) obtained from an impulse generator using the new calibration method and associated uncertainty analysis.
4. Measurement Uncertainties

4.1 General
The reported impulse spectrum amplitude is the result of the average of \( M \) spectra, one spectra from each of the \( M \) acquired wavefonms. The averaging is done on a frequency-by-frequency basis:

\[
\bar{S}[f_k] = \frac{1}{M} \sum_{i=1}^{M} S_i[f_k](\alpha_j),
\]

where \( \bar{S} \) is the impulse spectrum amplitude reported to the customer, which is dependent on a number of measurement variables, the \( \alpha_j \) (see Sec. 4.2 for a partial list). The uncertainty reported for each frequency component is the maximum uncertainty computed over the reported frequency range. The uncertainty for \( \bar{S} \) is given by:

\[
\begin{align*}
\sigma_S &= k_{eff} \sum_{i=1}^{M} \frac{1}{M} \left[ \frac{\partial \bar{S}}{\partial \alpha_j} \right]^2 \left( \frac{1}{M} \sum_{i=1}^{M} \left( \frac{\partial S_i(\alpha_j)}{\partial \alpha_j} \right)^2 \right)^{1/2} \left( \frac{1}{\sum_{i=1}^{M} u_i^2} \right)^{1/2} \\
&= k_{eff} \sum_{i=1}^{M} \frac{1}{M^2} \left[ \frac{\partial \bar{S}}{\partial \alpha_j} \right]^2 u_j^2 \\
&= k_{eff} \sum_{i=1}^{M} \left( \frac{\partial \bar{S}}{\partial \alpha_j} \right)^2 u_j^2
\end{align*}
\]

where it is assumed in (7a) that the \( \alpha_j \) are uncorrelated, which is the reason there are no cross terms in the partial derivatives with respect to the \( \alpha_j \). In (7b) it is further assumed that the \( u_i \) are the same for every \( S_i \); that is, the uncertainties in the variables for a given parameter are the same for every \( S_i \) at a given frequency. The \( k_{eff} \) is the statistical weight[14] applied to the uncertainties of variables obtained from a limited number of trials. For a number of variables with different degrees of freedom, \( k_{eff} \) is found by first calculating the effective degrees of freedom using [14]:

\[
\nu_{eff} = \sum_{i=1}^{M} \left( \frac{\partial S_i(\alpha_1, \alpha_2, \ldots \alpha_M)}{\partial \alpha_i} \right)^4 u_i^4 \sum_{i=1}^{M} \frac{c_i^4 u_i^4}{\nu_i},
\]

where \( \nu_i \) is the degrees of freedom for the parameters and
\[ c_i = \frac{\partial s}{\partial x_i}. \]

The \( k_{\text{eff}} \) is then found from \( v_{\text{eff}} \) using the t-distribution \([14]\).

### 4.2 Contributors to uncertainty

There are many parameters that can affect the total uncertainty in the values provided by this measurement service. A partial list of the parameters contributing to uncertainty in impulse spectrum amplitude are:

- \( B \) 3 dB attenuation bandwidth of oscilloscope
- \( f_c \) frequency used in timebase calibration
- \( R_0 \) resistance of terminations (nominally 50 Ω)
- \( R_1 \) resistance value of the resistors in the power divider
- \( P_{ps} \) power at power sensor during measurement system calibration
- \( P_{src} \) power provided by source
- \( T_{\text{meas}} \) temperature at which a particular waveform was recorded
- \( T_{\text{avg}} \) average temperature over which a set of waveforms was recorded
- \( V_{\text{sys}} \) amplitude of signal measured by measurement system during calibration
- \( X \) number of cycles of \( f_c \) observed in waveform epoch
- \( Z_{ps} \) input impedance of power sensor (nominally 50 Ω)
- \( Z_s \) synthesizer output impedance (nominally 50 Ω)
- \( \alpha_{ps} \) efficiency and responsivity of power sensor

### 5. Summary

The calibration method and uncertainty analysis for the 65100 measurement system, which provides the parameter of impulse spectrum amplitude, has been modified. This modification has resulted in a decrease in the expanded uncertainty of 0.5 dB to less than 0.1 dB.

### References


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Metrology - The Process of Providing Good Measurements

The definition of metrology, from the simplest - The science of measurement, to The science of measurement for determination of conformance to technical requirements including the development of standards and systems for absolute and relative measurement, may need to be reconsidered in light of increased responsibilities for calibration laboratories.

Over the last decade, there has been a dramatic increase in the requirements applied at various levels of the international measurement system. Thanks, in large part, to national and international standards, standards and calibration laboratories in particular have come to consider becoming both registered [ISO 9000] and accredited [ISO 17025]. Even metrology institutes must implement a full quality program. No longer is it enough to concentrate on providing a good, traceable measurement; metrologists must also consider the legal aspects of metrology, with training, documentation, metrics, customers, complaints, etc., as well as the legal aspects of metrology.