NIST Impulse Spectrum Amplitude Measurement Service

Speaker: D.R. Larson,
National Institute of Standards and Technology
100 Bureau Drive, Gaithersburg, MD
phone: 301-975-2437; FAX: 301-926-3972; e-mail:donald.larson@nist.gov

Authors: N.G. Paulter, Jr.[1], D.R. Larson[1]
Quantum Electrical Metrology Division
National Institute of Standards and Technology

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 $\approx$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, $V[t_n]$ ($n = 1, 2, ..., N$, where N is the number of samples, and t_n 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_1 sampler-acquired DUT waveforms and one
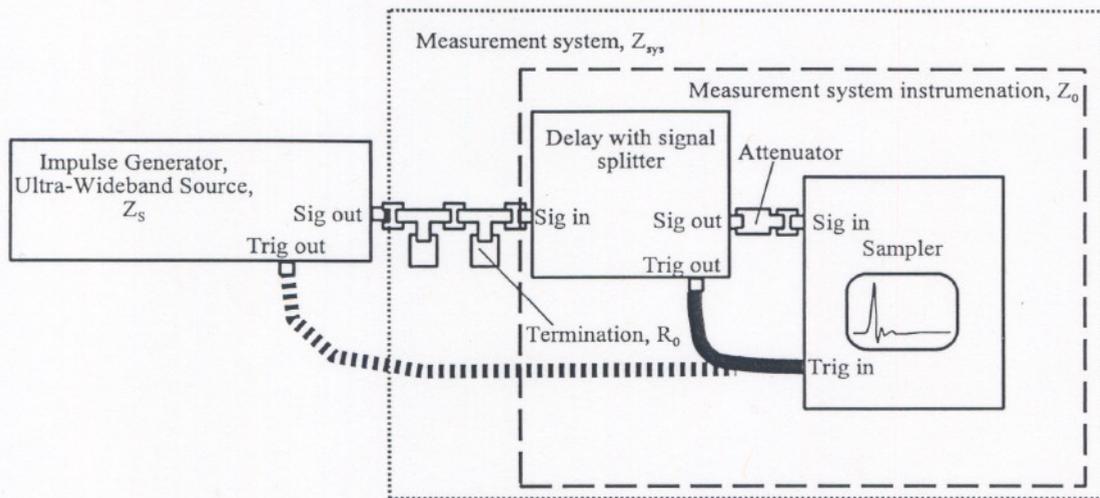
Figure 1. Diagram of measurement system, generator or source without an output trigger.

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_1 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 μV/MHz. $S_R[f_k]$ is given by:

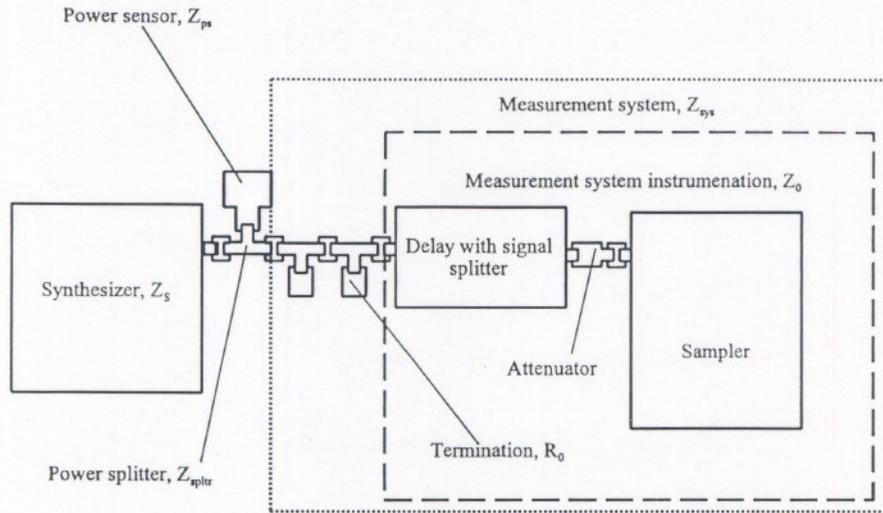$$S_R[f_k] = 20\log\left(\frac{S[f_k]}{S_0}\right),$$

(1)

Figure 2. Diagram of measurement system during calibration.

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

$$S[f_k] = 2\left|V[f_k]\right|,\tag{2}$$

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

$$u_S = 2u_V,\tag{3}$$

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:

$$V[f_k] = \frac{V_m[f_k]}{H_{sys}[f_k]J[f_k]},\tag{4}$$

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:

$$H_{sys} = H_{aux}H_s.\tag{5}$$

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
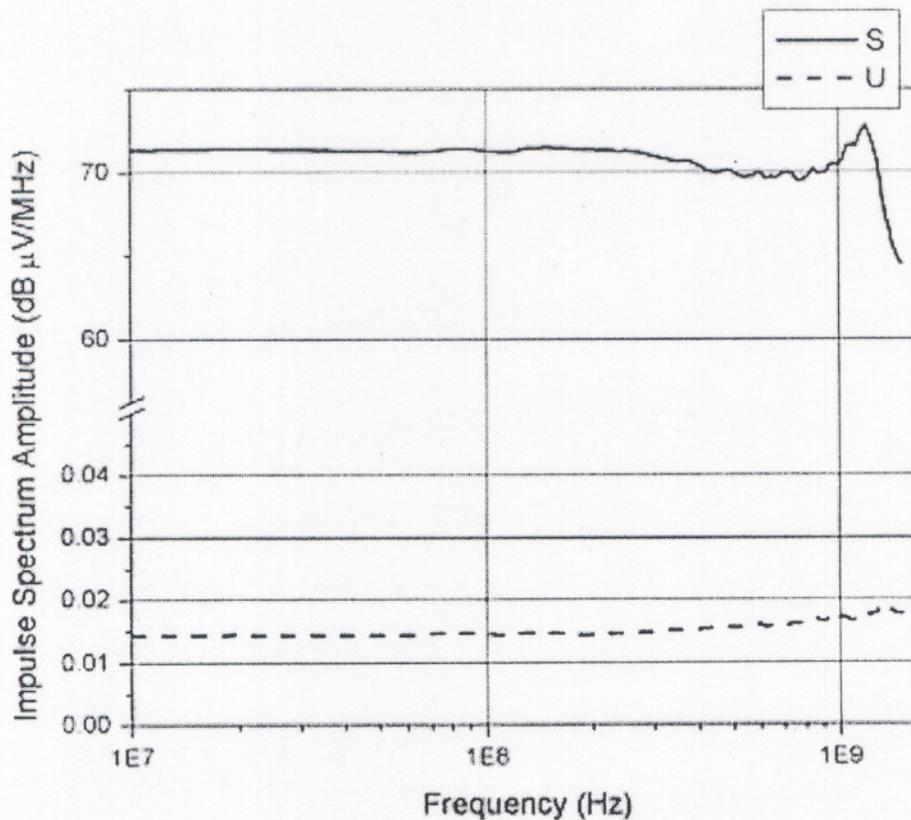

Figure 3. Impulse spectrum amplitude (S) and expanded uncertainty (U) obtained from an impulse generator using the new calibration method and associated uncertainty analysis.

includes more variables than does the existing analysis (see Sec. 4.2).

4. Measurement Uncertainties

4.1 General

The reported impulse spectrum amplitude is the result of the average of M_1 spectra, one spectra from each of the M_1 acquired waveforms. The averaging is done on a frequency-by-frequency basis:

$$\bar{S}[f_k] = \frac{1}{M_1} \sum_{i=1}^{M_1} S_i[f_k](\alpha_j), \tag{6}$$

where $\bar{S}$ is the impulse spectrum amplitude reported to the customer, which is dependent on a number of measurement variables, the α_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:

$$
\begin{aligned}
u_{\bar{S}} &= k_{eff} \sqrt{\sum_{i=1}^{M_1}\left[\left(\frac{\partial \bar{S}}{\partial S_i}\right)^2 \left\{\sum_j \left(\frac{\partial S_i(\alpha_j)}{\partial \alpha_j}\right)^2 u_j^2\right\}\right]} \\
&= k_{eff} \sqrt{\sum_{i=1}^{M_1}\left[\frac{1}{M_1^2}\sum_j \left\{\left(\frac{\partial S_i(\alpha_j)}{\partial \alpha_j}\right)^2 u_j^2\right\}\right]} \quad (a) \\
&= k_{eff} \sqrt{\frac{1}{M_1^2}\sum_j \left(\frac{\partial S(\alpha_j)}{\partial \alpha_j}\right)^2 u_j^2} \quad (b)
\end{aligned}
\tag{7}
$$

where it is assumed in (7a) that the α_j are uncorrelated, which is the reason there are no cross terms in the partial derivatives with respect to the α_j. In (7b) it is further assumed that the u_j 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]:

$$\nu_{eff} = \frac{\left[\sum_{i=1}^{M}\left(\frac{\partial S(\alpha_1, \alpha_2, \dots \alpha_M)}{\partial \alpha_i}\right)u_i^2\right]^2}{\sum_{i=1}^{M} \frac{c_i^4 u_i^4}{\nu_i}}, \tag{8}$$

where ν_i is the degrees of freedom for the parameters and

$$c_i = \frac{\partial S}{\partial \alpha_i}.$$

The k_{eff} is then found from v_{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_s	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_{meas}	temperature at which a particular waveform was recorded
T_{ref}	average temperature over which a set of waveforms was recorded
V_{sys}	amplitude of signal measured by measurement system during calibration
X	number of cycles of f_s observed in waveform epoch
Z_{ps}	input impedance of power sensor (nominally 50 Ω)
Z_S	synthesizer output impedance (nominally 50 Ω)
α_{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

1. NIST Calibration Services Users Guide, NIST Special Publication, SP250, U.S. Department of Commerce, Washington, DC, pp. 189 to 193, January 1998.
2. J.R. Andrews and M.G. Arthur, NIST Technical Note 699, "Spectrum Amplitude - Definition, Generation and Measurement," U.S. Department of Commerce, October 1977.
3. CISPR 22, Third Edition, 1997-11, Information Technology Equipment - Radio Disturbance Characteristics - Limits and Methods of Measurement, Comité International Spécial des Perturbatinos Radioélectriques, Geneva, Switzerland.
4. CISPR 16-1-1, First Edition, 2003-11, Specification for Radio Disturbance and Immunity Measuring Apparatus and Methods - Part 1-1: Radio Disturbance and Immunity Measuring Apparatus - Measuring Apparatus, Comité International Spécial des Perturbatinos Radioélectriques, Geneva, Switzerland.

5.   ETSI EN 300 328-1, V1.3.1 (2001-12), Electromagnetic Compatibility and Radio Spectrum Matters (ERM); Wideband Transmission Systems; Data Transmission Equipment Operating in the 2,4 Ghz ISM band and Using Spread Spectrum Modulation Techniques; Part 1: Technical Characteristics and Test Conditions, European Telecommunications Standards Institute, Sophia Anitpolis, France.

6.   IEEE C62/41-1991, IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits, October, 1991, The Institute of Electrical and Electronic Engineers, Piscataway, NJ, USA.

7.   ANSI/IEEE Std 376-1975, IEEE Standard for the Measurement of Impulse Strength and Impulse Bandwidth, August 1993, The Institute of Electrical and Electronic Engineers, Piscataway, NJ, USA.

8.   Code of Federal Regulations, Title 47, Part 15, 1 October 2002.

9.   ANSI/IEEE Std 376-1975, IEEE Standard for the Measurement of Impulse Strength and Impulse Bandwidth, Corrected Edition June 1992, The Institute of Electrical and Electronic Engineers, Piscataway, NJ, USA.

10.   N.G. Paulter, "Low-jitter trigger system for pulse calibration and intercomparison of high-speed samplers," IEEE Trans. Instrum. Meas., Vol. 47, pp. 606 to 608, June 1998.

11.   W.L.Gans, "The measurement and deconvolution of time jitter in equivalent-time waveform samplers," IEEE Trans. Instrum. Meas., Vol. IM-32, pp. 126 to 133, March 1983.

12.   J. Verspecht, "Accurate spectral estimation based on measurements with a distorted-timebase digitizer," IEEE Trans. Instrum. Meas., Vol. 43, pp. 210 to 215, April 1994.

13.   G.N. Stenbakken and J.P. Deyst, "Time-base nonlinearity determination using iterated sine-fit analysis," IEEE Trans. Instrum. Meas., Vol. 47, pp. 1056 to 1061, October 1998.

14.   B.N. Taylor and C.E. Kuyatt, NIST Technical Note 1297, "Guidelines for evaluating and expressing the uncertainty of NIST measurement results," U.S. Dept. of Commerce, 1994.

2004 Ncsli International Workshop & Symposium
Metrology - The Process Of Providing A Good Measurement

Home

Program

Search Proceedings

Author Index

About NCSLI

Contact NCSLI

CD Tech Support

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 requi
including the development of standards and systems for absolute and relative me
may need to be reconsidered in light of increased responsibilities for calibration la

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