Measurement of Impulse Spectrum Amplitude for Use in EMI Susceptibility Tests

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Abstract: A system for measuring the impulse spectrum amplitude of the output of impulse generators and the response of receivers is described. The calibration procedures used in this measurement system were recently modified, which resulted in a reduction in the time for measurement and in the magnitude of the published uncertainties. The uncertainties for the bandwidth of 10 MHz to 4 GHz have been reduced from 0.5 dB to less than 0.02 dB for the parameter of impulse spectrum amplitude.

1. Introduction

The National Institute of Standards and Technology (NIST) has a service [1] for measurement of the parameter of impulse spectrum amplitude [2] for the output of high-speed (pulse durations < 1 ns) impulse generators. Other names for impulse spectrum amplitude 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. The impulse spectrum amplitude data provided to customers start as time-domain waveforms of impulse-like signals that are transformed into the frequency domain where they are corrected and appropriately processed (see Sec. 2.1).

Impulse spectrum amplitude, or one of its synonyms or equivalents, is specified in several international and national standards. For example, one characteristic of a receiver (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]).

The impulse spectrum amplitude (ISA) measurement system described herein 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 measurement system can measure both the output of an impulse or ultra-wideband generator.

2. Measurement System

Three examples of instrument setups used to acquire the impulse signal, $V[t_n]$, are shown in Figures 1-3. The nature of the available trigger and the repetition rate of the pulse generator dictate which instrument setup should be used, as described in the figure captions. The signal produced by the generator or source, $V(t)$, is acquired by the ISA measurement system to yield a discretized replica, $V[t_n]$ ($n = 1, 2, \ldots, N$, 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. 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 Fig. 1 is used where the trigger is derived from the delay/splitter. If, on the other hand, the DUT is similar to that just described except that it provides a trigger output, then the measurement system shown in Fig. 2 can be used where the trigger is supplied by the DUT (labeled by "Ref Out" in Fig. 2). If the signal amplitude is small, the attenuator is unnecessary. If the DUT has an external trigger input, then the

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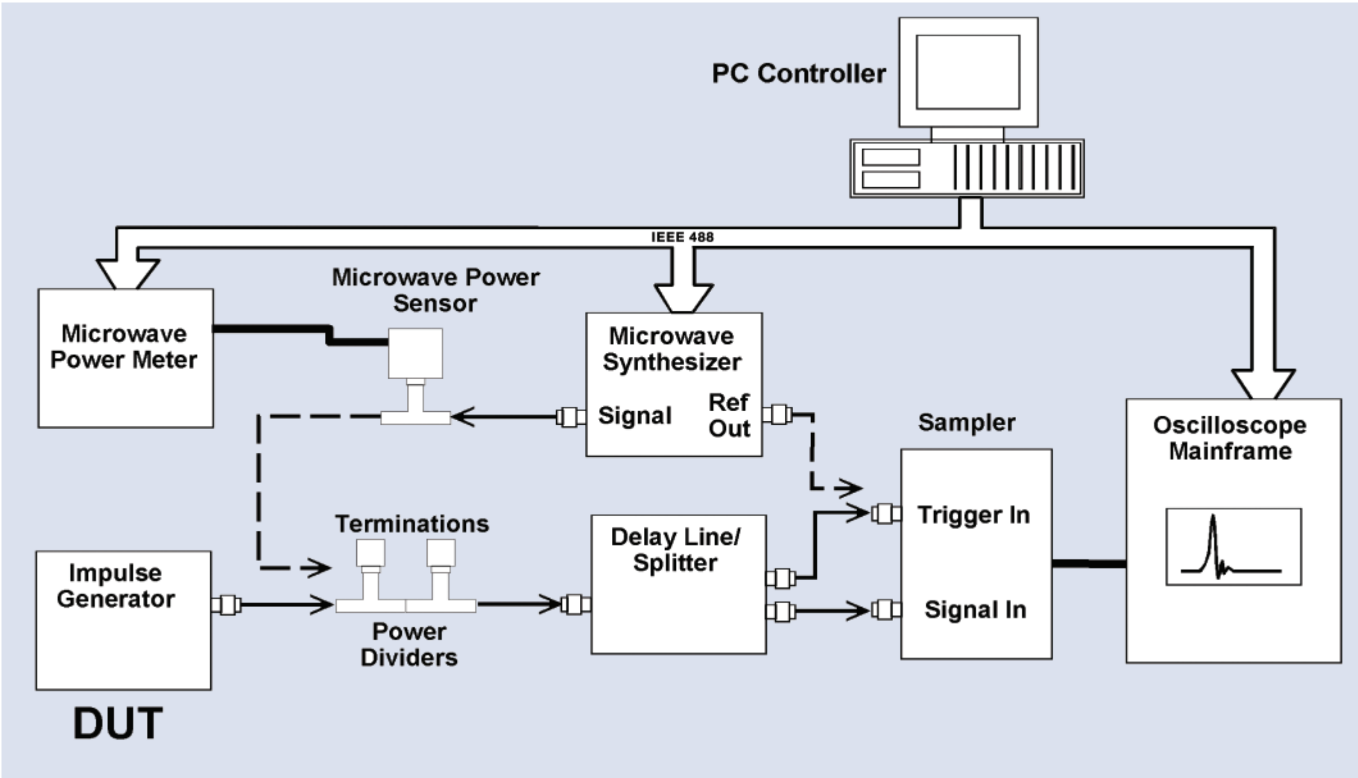

Figure 1. Diagrammatic depiction of calibration and measurement arrangement for the DUT (in this case a pulse generator) having no trigger reference output and a large magnitude output signal. The dotted lines represent the alternate connection path for the calibration arrangement.

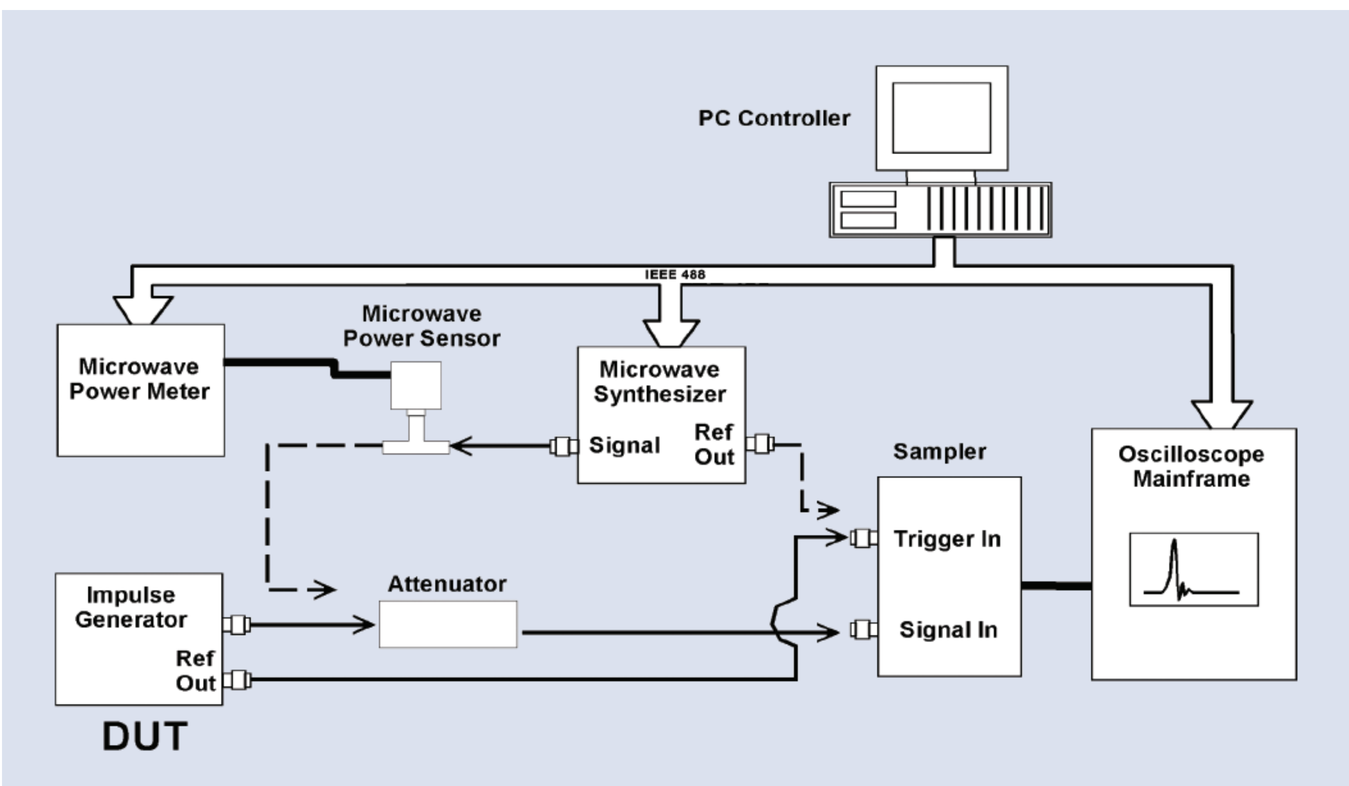

Figure 2. Measurement arrangement optimized for pulse generator providing a reference trigger output. The dotted lines represent the alternate connection path for the calibration arrangement.

delay line is not necessary because the DUT can be synchronized to the sampler by a low-jitter trigger system [10] (see Fig. 3). 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 measurement of the timebase accuracy [12,13]. The DUT measurement sequence is as follows:

1. Measure timebase error: One independent measurement
2. Acquire waveforms: M1 independent measurements of DUT output

The spectra of the acquired waveforms are obtained using Fourier transforms. Measurement of the ISA measurement system frequency-dependent magnitude response is done periodically with the microwave synthesizer (shown in Figs. 1–3) and a control chart of that response, with uncertainties, maintained. Corrections are applied to these spectra.

2.2 Instrumentation

The instrumentation that has operating characteristics relevant to the performance of the ISA measurement system are the trigger generator, the sampler, the impulse generator, and the microwave synthesizer.

The trigger generator must exhibit a fast transition to minimize the introduction of jitter caused by noise on the trigger signal. It also must have sufficient amplitude to drive both the oscilloscope trigger and the pulse generator trigger after passing through the delay line/splitter. Performance requirements for the present embodiment of the measurement system are:

Output pulse transition duration:	$\leq$150 ps
Output pulse amplitude:	$\geq$ 2 V
Output impedance:	50 Ω ± 1 Ω.

The performance requirements for the microwave synthesizer are:

Frequency Range:	0.01 GHz to 26.5 GHz
Spectral Purity (Harmonics):	< –55 dBc, 0.05 GHz to 40 GHz
(Subharmonics):	< –55 dBc
Leveled Output:	> +10 dBm.

The performance requirements for the pulse generators are:

Impulse duration:	$\geq$ 100 ps typically, but is DUT dependent
Amplitude:	$\geq$ 0.2 V typically, but is DUT dependent
Trigger jitter:	$\leq$ 1 ps.

The performance requirements for the samplers are:

Step response transition duration:	$\geq$ 7 ps
Amplitude range, A_{in}:	$-400 \text{ mV} \leq A_{in} \leq 400 \text{ mV}$
Trigger jitter:	$\leq$ 1 ps.

2.3 Calibration

2.3.1 Timebase Characterization

The ISA measurement system timebase is calibrated using nominally single-frequency sinusoidal signals provided by a microwave synthesized frequency source. Waveforms of these signals are acquired and errors in the timebase are derived from sinewave curve fitting techniques [13]. The synthesizer is the artifact standard and the manufacturer claimed uncertainty in frequency (10 ppm of set value) is used. However, we are introducing global-positioning-system (GPS)-based calibration of the microwave synthesizer, which will reduce the frequency uncertainty to around 0.1 ppm. The frequency uncertainty may be mapped to the time-domain using the following formula:

$$T = N\Delta t = X\frac{1}{f_s}, \tag{1}$$

where T is the duration of the waveform epoch, N is the number of samples (data elements) in the waveform, Δt is the interval between sample instants, f_s is the input frequency provided by the source, and X is the number of cycles of f_s observed in the waveform epoch. To determine the uncertainty in T caused by uncertainty in f_s , we take the appropriate partial derivative and analyze the result. The effect of u_{f_s} on the measurement is given by:

$$u_T(f_s) = \left|\frac{\partial T}{\partial f_s}\right| u_{fs} = X\frac{1}{f_s^2}u_{fs} = T\frac{u_{fs}}{f_s}. \tag{2}$$

The uncertainty in f_s relative to f_s is about 10^{-5}, which is based on manufacturer specification, as mentioned earlier. Therefore, the uncertainty in the duration of the waveform epoch due to uncertainties in the reference frequency is currently about 10 ppm. Since the waveform epoch contains between about 1000 and 4000 elements, this epoch error corresponds to about 0.04 of a sample interval, which is within the noise limit of our ability to measure timebase error.

2.3.2 Vertical Axis Calibration (System Transfer Function)

The magnitude of the transfer function of the ISA measurement system as a function of frequency is determined by comparing measurements of a microwave signal (from a microwave synthesizer) taken with the ISA measurement system to those made using a calibrated power sensor. The power sensor calibration is traceable to NIST through the manufacturer. This calibration is performed at discrete frequencies (typically customer specified) over the desired frequency range (typically customer specified). To calibrate the transfer function over the necessary frequency range, the output of the synthesizer is incremented and measure-

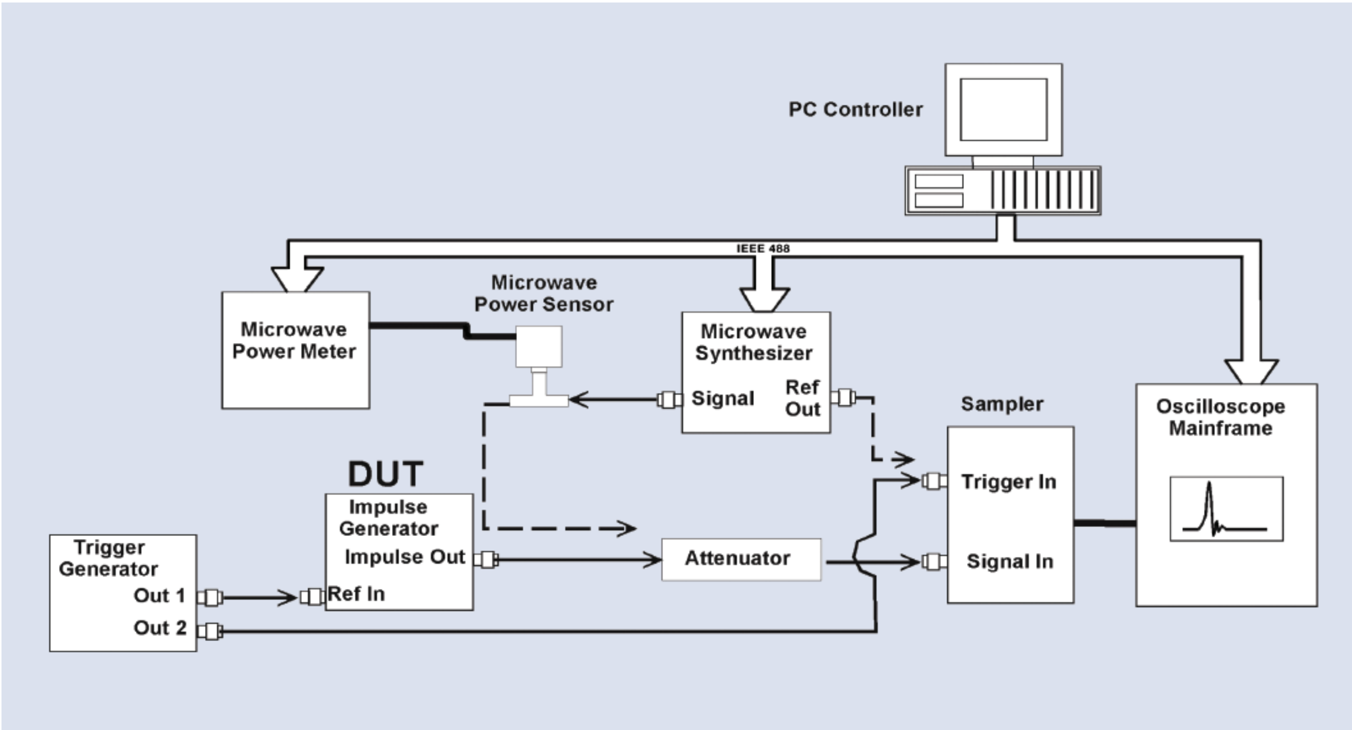

Figure 3. Measurement arrangement optimized for pulse generator providing a reference trigger input. The dotted lines represent the alternate connection path for the calibration arrangement.

ments made with the ISA measurement system and the power sensor. The uncertainties in the power readings from the power sensor are approximately 20 times less than that reported in the measurement reports. The transfer function of the ISA measurement system is used to correct the magnitude of the measured spectrum amplitude obtained from the customer's device.

2.4 Computation of Impulse Spectrum Amplitude

The parameter reported to customers for their DUT is the impulse spectrum amplitude, S_k, in logarithmic units referenced to 1 µV/MHz. $S_{R,k}$ is given by:

$$S_{R,k} = 20\log\left(\frac{S_k}{S_0}\right), \tag{3}$$

where k is the discrete frequency index, S_0 = 1 µV/MHz, and

$$S_k = 2\left|V_k\right|, \tag{4}$$

where V_k is the Fourier transform of the output of the impulse generator. The uncertainty, u_S, in S is:

$$u_S = 2u_V, \tag{5}$$

where u_V is described in Section 4.1. The V_k is obtained by deconvolving the effect the ISA measurement system 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_k, this is:

$$V_k = \frac{V_{m,k}}{H_{sys,k}J_k}, \tag{6}$$

where $V_{m,k}$ is the discrete spectrum of the measured output of the DUT, J_k is the discrete spectrum of the trigger jitter, and $H_{sys,k}$ is the transfer function (Fourier transform of the impulse response) of the measurement system. J_k is the Fourier transform of a normal distribution that represents the measured trigger jitter. $H_{sys,k}$ includes both the sampling instrument transfer function, $H_{s,k}$, and that of the auxiliary electronics, $H_{aux,k}$, required to measure the output of the impulse generator:

$$H_{sys,k} = H_{aux,k}H_{s,k}. \tag{7}$$

In this measurement process, $H_{aux,k}$ and $H_{s,k}$ are obtained in a single measurement.

3. Measurement Results

Figure 4 shows the impulse spectrum amplitude (curve labeled "S") and the expanded uncertainty (curve labeled "U" in Fig. 4) for an impulse generator using the ISA 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 ISA measurement system and the previous system are in the expanded uncertainty values. And this difference is the result of using a swept-frequency calibration method of the entire ISA 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 step response of each component to a known step pulse excitation. Using the previous calibration method, the expanded uncertainty was about 0.5 dB. As can be seen from Fig. 4, the expanded uncertainty using the new calibration method and associated uncertainty analysis is much lower than 0.05 dB. Moreover, the new 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:

$$\bar{S}_k = \frac{1}{M_1}\sum_{i=1}^{M_1} S_{i,k}\left(\alpha_j\right), \qquad (8)$$

where $\bar{S}_k$ 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 $\bar{S}_k$ is given by:

$$U_{\bar{S}_k} = k_{eff}\sqrt{\sum_{i=1}^{M_1}\left[\left(\frac{\partial \bar{S}_k}{\partial S_i}\right)^2\left\{\sum_j\left(\frac{\partial S_{i,k}(\alpha_{i,j})}{\partial \alpha_{i,j}}\right)^2 u^2_{\alpha_{i,j}}\right\}\right]}$$

$$= k_{eff}\sqrt{\sum_{i=1}^{M_1}\left[\frac{1}{M_1^2}\sum_j\left\{\left(\frac{\partial S_{i,k}(\alpha_{i,j})}{\partial \alpha_{i,j}}\right)^2 u^2_{\alpha_{i,j}}\right\}\right]} \qquad (a) \qquad (9)$$

$$= k_{eff}\sqrt{\frac{1}{M_1}\sum_j\left(\frac{\partial S_k(\alpha_j)}{\partial \alpha_j}\right)^2 u_j^2} \qquad (b)$$

where it is assumed in (9a) that the α_{ij} are uncorrelated, which is the reason there are no cross terms in the partial derivatives with respect to the α_{ij}; α_{ij} are independent of i (that is, $\alpha_j = \alpha_{ij}$); and for brevity, we set $u_{\alpha_j} = u_j$.

In (9b) it is further assumed that the u_j are the same for every S_k; that is, the uncertainties in the variables for a given parameter are the same for every S_k at a given frequency. The k_{eff} is the statistical weight (coverage factor) applied to the uncertainties of variables obtained from a limited number of trials and that is calculated by using the t-distribution with an effective degrees of freedom determined using the Welch-Satterthwaite formula [14].

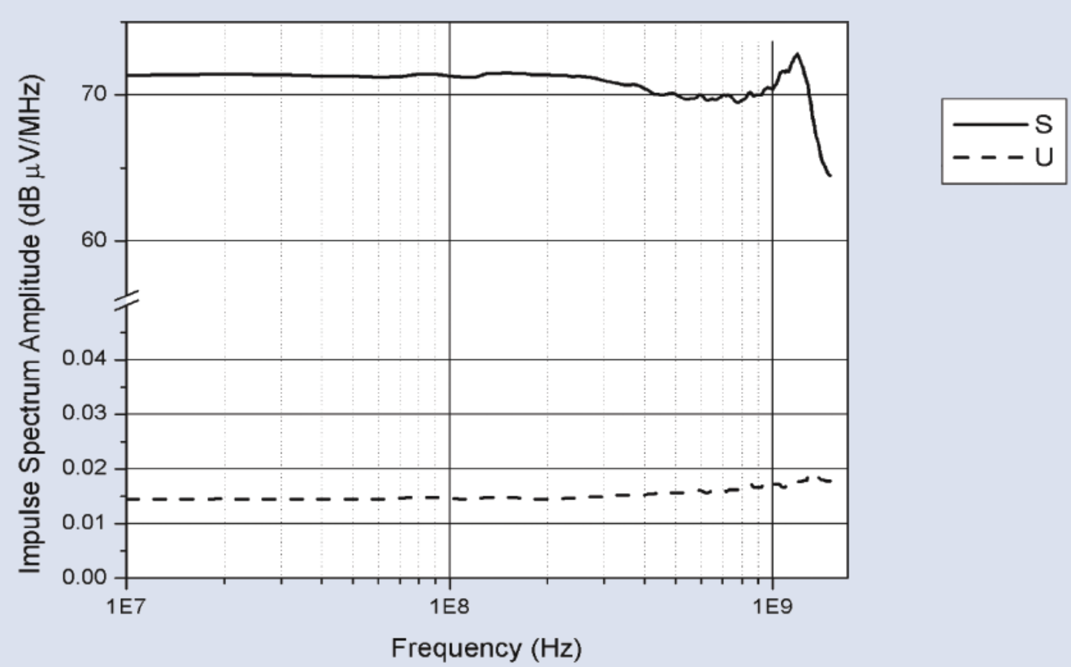

Figure 4. Impulse spectrum amplitude (S) and expanded uncertainty (U) obtained from an impulse generator using the new calibration method and associated uncertainty analysis.

4.2 Contributors to uncertainty

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

1. 3 dB attenuation bandwidth of oscilloscope.
2. Frequency used in timebase calibration.
3. Resistance of terminations (nominally 50 Ω).
4. Resistance value of the resistors in the power divider.
5. Power at power sensor during measurement system calibration.
6. Power provided by source.
7. Temperature at which a particular waveform was recorded.
8. Average temperature over which a set of waveforms was recorded.
9. Amplitude of signal measured by measurement system during calibration.
10. Number of cycles of f_s observed in waveform epoch.
11. Input impedance of power sensor (nominally 50 Ω).
12. Synthesizer output impedance (nominally 50 Ω).
13. Efficiency and responsivity of power sensor.

5. Summary

The calibration method and uncertainty analysis for the ISA 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 0.02 dB.

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