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An alternative to the geometric addition method for calculating the rise time of fast oscilloscopes and pulse generators

Eine Alternative zu der geometrischen Additionsmethode für die Berechnung der Anstiegszeit von schnellen Oszilloskopen und Impulsgeneratoren

DOI 10.1515/teme-2016-0046
Received October 28, 2016; revised December 6, 2016; accepted December 6, 2016

Abstract: In this paper, we propose a new method for calculating the rise time of pulse generators and oscilloscopes using a correction factor. This new method is advantageous over the well known geometric rule, also known as the root-sum-of-squares (RSS) rule, because its corresponding uncertainty contribution can be estimated, whereas the uncertainty assigned to the RSS method due to systematic error is typically unknown in any given measurement scenario. In our method, the correction factor is estimated from a large set of representative classical response functions. Furthermore, the systematic error caused by the time base distortion of sampling oscilloscopes is corrected in order to reduce the uncertainty of the calibration process.

Keywords: Rise time, correction factor, oscilloscopes, pulse generators, root-sum-of-squares rule.

Zusammenfassung: In diesem Artikel schlagen wir eine neue Methode zur Berechnung der Anstiegszeit von Impulsgeneratoren und Oszilloskopen mit Hilfe eines Korrekturfaktors vor. Diese neue Methode ist vorteilhaft gegenüber der bekannten geometrischen Rechenvorschrift, auch als Geometrische Additionsmethode bekannt, da ihr zugehöriger Unsicherheitsbeitrag geschätzt werden kann, wohingegen die Unsicherheit, die der Methode der geometrischen Addition bei einer beliebigen Messung zugeordnet wird, auf Grund eines systematischen Fehlers typischerweise unbekannt ist. Bei unserer Methode wird der Korrekturfaktor aus einer großen Anzahl von repräsentativen, klassischen Übertragungsfunktionen geschätzt. Weiterhin wird der systematische Fehler, der durch die Zeitbasis von Sampling Oszilloskopen hervorgerufen wird, korrigiert, um die Gesamtunsicherheit der Kalibrierprozedur zu verringern.

Schlüsselwörter: Anstiegszeit, Korrekturfaktor, Oszilloskop, Impulsgenerator, geometrische Additionsmethode.

Article Note: Work partially supported by the U. S. government, not protected by U. S. copyright.

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1 Introduction

The geometric addition rule, also known as the root-sum-of-squares rule, is commonly used for calibrating the step-response transition duration of fast oscilloscopes and step-like pulse generators. This well-known method applies the geometric addition of the two response transition durations (of the signal and of the measurement device) to obtain the square of the transition duration of the measurement [1]. For example, if the transition duration of a step-like pulse generator is t_{gen} and the transition duration of the response of an oscilloscope to a step-like pulse with infinitesimal duration (the *step response*) is t_{osc}, the RSS rule states that if the output of the of the pulse generator is measured with the oscilloscope, the (raw) measured transition duration is given by

$$t_{\mathrm{meas}} = \sqrt{t_{\mathrm{gen}}^2 + t_{\mathrm{osc}}^2} \tag{1}$$

Usually, one of t_{gen} or t_{osc} is known and the other is the desired quantity and can be found by solving the above equation. However, this “rule” is only rigorously correct when both of the step-like response functions involved have a shape of the form [2]

$$y(t) \propto \operatorname{erf}\left(\frac{t-\mu}{\sigma\sqrt{2}}\right). \tag{2}$$

In practice both the generated pulse and the oscilloscope response deviate significantly from this form [3]. As a result, the RSS rule can be in error, particularly as the characteristic time scales of the two response functions become commensurate. When the exact response functions are known, the error associated with the use of the RSS rule can be quantified by use of convolution of these impulse response functions [2, 4]. However, when the exact response functions of the pulse generator *or* oscilloscope are unknown the magnitude of this error cannot be quantified, thus leading to an unquantified systematic error.

2 Present calibration procedure

Ideally, electrical step-like pulse generators should be calibrated with an oscilloscope whose response to a step-like pulse of infinitesimal duration has a duration that is no greater than one third of the duration of the generated pulse. However, with the present state of the art in oscilloscopes and calibration-grade pulse generators, this is not usually possible. Therefore, a sampling oscilloscope with a bandwidth of more than 70 GHz is utilized. The step response of the oscilloscope is calibrated by use of electro-optic sampling (EOS) [5, 7]. An EOS system comprises a femtosecond laser which is focused to a coplanar waveguide with a photoconductive semiconductor and excites approximately 1 ps long voltage pulses. With the use of a microwave probe the pulses are coupled into the oscilloscope.

The traceability chain is depicted in Figure 1. This sampling oscilloscope with a known transition duration can now be used as a transfer standard for the calibration of an electrical pulse generator. This pulse generator can then be either the device under calibration (DUC) or can be used in a further step as a secondary standard for the calibration of a (third tier) oscilloscope with a bandwidth up to 50 GHz. In this case the transition duration of the generated pulse should be significantly shorter than the transition duration of the secondary oscilloscope’s response function. A typical setup is shown in Figure 2.

Operationally, the calibration of the transition duration of the pulse generator and the calibration of the step response transition duration of the secondary oscilloscope are similar. The procedures are divided into two steps. In

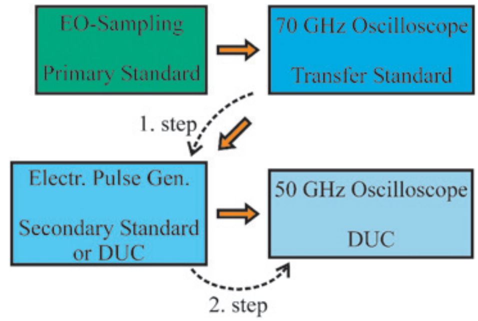

Figure 1: Traceability chain for rise time calibration.

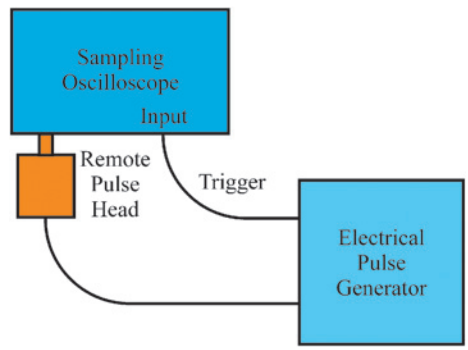

Figure 2: An electrical pulse generator with a remote pulse head connected directly to a sampling oscilloscope for rise time calibration.

the first step, many oscilloscope traces (of 4000 samples per trace) are measured and averaged in a time window covering a length of approximately 1000 times the transition duration of the measured pulse. The top and base reference level (0% and 100%) of the measured step impulse must reach a constant level at the edge and outside the measured time epoch. We can then determine the reference levels precisely from the corresponding medians of the histograms of the two levels [7]. From the knowledge of the 0% and 100% reference levels (as depicted in Figure 3 with red lines) the 10% and 90% level (Figure 3, green lines) used for the rise time determination can be calculated. Due to the fact that the measured traces are affected by jitter, the temporal distribution of the sampled data points at the absolute 10% and 90% voltage levels have to be known (see Figure 3). To get a sufficient number of sampled data points for the histogram, an amplitude window of ±1% of the pulse amplitude around the calculated level is chosen. The resulting histograms are shown as an inset in Figure 4. We need to consider non-averaged traces because an averaging of the traces would function as a low pass filter resulting in a slower rise time. From the temporal distance between the medians of the 10% and 90% histogram, we obtain the measured rise time $t_{\mathrm{r,meas}}$.

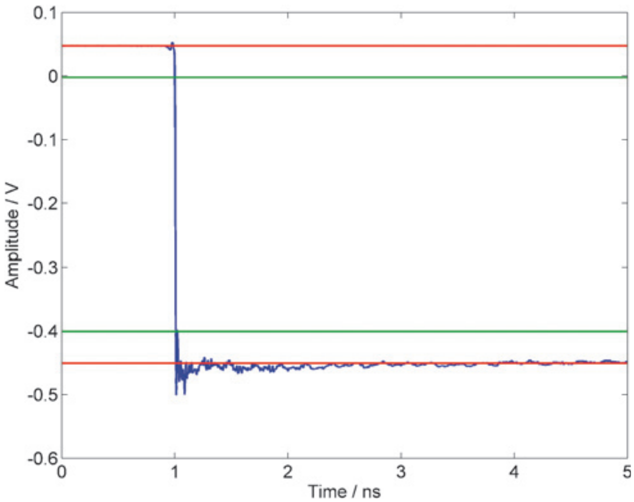

Figure 3: The average of 100 single traces of the measured step-like pulse. The 0% and 100% reference level are shown as red lines whereas the 10% and 90% level are indicated by green lines.

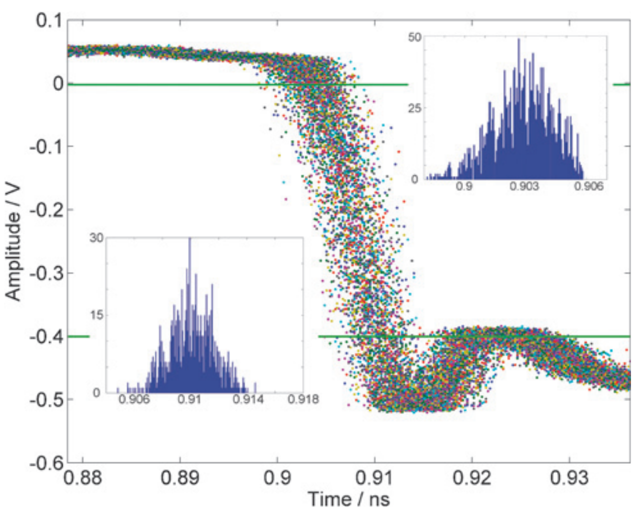

Figure 4: The histograms show the temporal distribution of the samples at the 10% and 90% instants of 100 single traces of an electrical step pulse generator. The vertical slice width along the green lines for calculating the histograms is chosen to be 1% of the full amplitude.

Previously, the measured transition duration and the transition duration of the standard would be inserted into the RSS equation to calculate the transition duration of the unknown device (pulse generator or secondary oscilloscope). However, because the ratio of the transition durations of the DUC to that of the standards used here is only about 1.5, this would lead to a significant uncharacterized error. Therefore, an improved method is required. Furthermore, the above method does not correct for deterministic timing error in the oscilloscope timebase. In the following sections we describe improvements upon the above procedure to account for both of these effects.

3 Time base correction

The time base of a sampling oscilloscope suffers from a significant deterministic non-linearity in its internal time base circuits in particular in the trigger circuit. In principle the trigger circuit consists of an oscillator and a ramp generator and the time at which a sample is taken is shifted for each consecutive trigger event. Due to systematic imperfections of the circuitry, the samples are not taken at equally spaced times as it is estimated by the oscilloscope. This distortion causes timing errors in the measured signal which results in an inaccurate determination of the rise time. To correct the time base distortion (TBD), additional measurements of reference sine wave signals with orthogonal phases at one or a few different frequencies are required. This can be done by the use of two signal generators. One is set to the trigger frequency and the other one which is phase coupled to the first one, provides a higher harmonic frequency of the trigger frequency with a 0° phase compared to the trigger frequency. After the acquisition of a sufficiently number of traces the phase of the generator providing the higher frequency is shifted by 90° and the same number of traces has to be sampled. The measured sine and cosine wave traces are fitted by an orthogonal distance regression (ODR) to a distorted sinusoidal model [8, 9]. The result of this procedure delivers the amount of time which each sample point deviates from its true temporal position along the time window set at the oscilloscope. To achieve a good quality correction, a sine wave signal source with low jitter and noise must be cho-

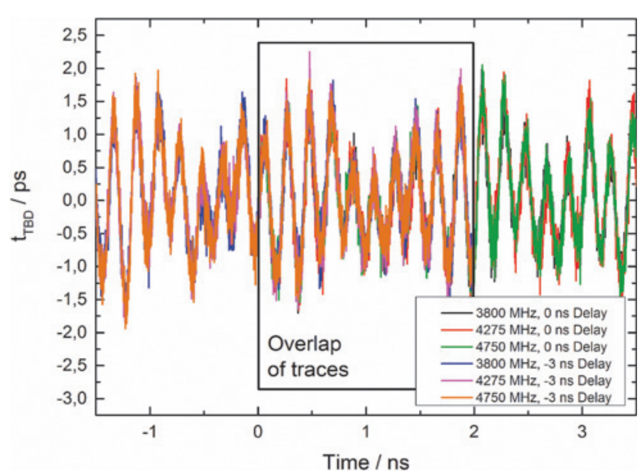

Figure 5: Time base distortion (t_{TBD}) as a function of the temporal position acquired at three different sine wave frequencies. Three traces with no time base delay starting at 0 ns (black, red and green line) and three shifted by −3 ns (blue, magenta and orange line). Between 0 ns and 2 ns all traces overlap. This clarifies the systematic characteristic of the time base error.

sen. In [8] is stated that the standard deviation of the jitter σ_τ should be smaller than the standard deviation of the noise σ_ε of the signal so that this equation applies

$$1/2 \gg f\sigma_\tau > \sigma_\varepsilon/(2\pi A) \tag{3}$$

where f is the frequency and A the amplitude of the sinusoidal wave. Furthermore the slew rate of that signal must be high enough to get satisfactory results with the ODR routine because the influence of the jitter becomes the dominant error compared to noise. A more in-depth discussion can be found in [8].

Figure 5 shows measurements of such a source at three different frequencies. As an example, a value of $t_{\mathrm{TBD}} = -0.9$ ps at the displayed time of -1 ns means that the time of this particular sample point in the step pulse signal has to be corrected by t_{TBD}. Correction for the timebase error is performed in post processing. After this correction, the data points are unevenly spaced in time, and so must be interpolated back to an equally spaced time grid for averaging and further analysis. We use linear interpolation. Finally, the standard deviation of the voltage (pooled over all times from Figure 5) is regarded as the uncertainty contribution for the time base correction in the uncertainty budget, although a more detailed analysis is possible [10].

4 Correction factor

For the determination of the transition duration of the response of a DUC we need to distinguish between two cases.

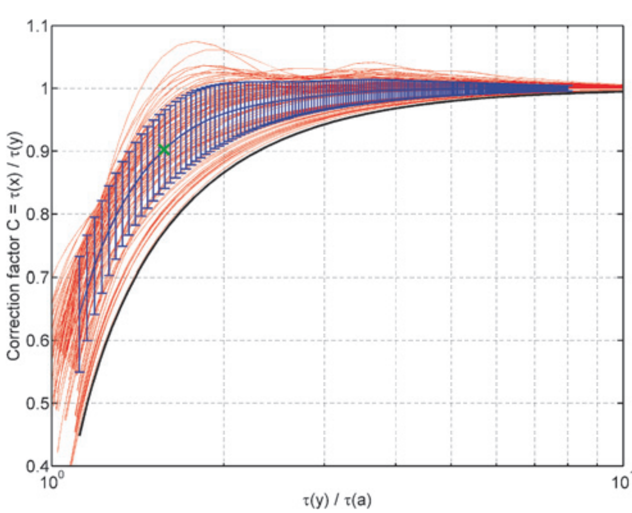

Figure 6: The correction factor calculated from a set of different input and system response function combinations (red lines). The blue line depicts the mean of the set of curves and the corresponding standard deviation as error bars. The black curve is the result of the convolution of two Gaussian response functions.

In the first case, the rise time of the DUC is more than 3 times longer than the rise time of the standard so the indicated rise time on the oscilloscope can be used without any correction. In the other case, the ratio of the rise times of the DUC and the standard (DUC / std) is below 3, so that the uncertainty of the calibration result increases significantly with decreasing ratio, therefore a correction must be applied. This can be done by a multiplication of the rise time measurement with a correction factor. As shown in [4] and [2], the RSS rule can significantly overcorrect for the smearing effect of convolution. In order to estimate the magnitude of this bias we modelled the impulse response of a pulse generator and an oscilloscope as classical filter impulse response functions: Butterworth, Chebychev and Bessel-Thompson filters of order 2, 4, and 6. These functions are convolved in all possible different combinations to get a set of measured waveforms y(t) as an estimation of the spread of the influence of typical oscilloscope and pulse generator response functions. The correction factor C can be calculated by the ratio of the DUC and measured transition durations $\tau(x)$ and $\tau(y)$:

$$C = \tau(x)/\tau(y). \tag{4}$$

In Figure 6, the correction factors as a function of the ratio of the measured and standard transition times $(\tau(y)/\tau(a))$ is shown as a set of red lines for each of the response function combinations. The thick black line is the convolution of a Gaussian shaped DUC and standard response functions. This is the curve that would be followed if the RSS method were accurate. To estimate the correction factor and its spread for a given rise time ratio (x-axis) we calculate the mean (blue line) and standard deviation (length of the error bars) of the complete set of correction factors. During post processing the previously calculated rise time is used together with the known rise time of the oscilloscope to calculate the specific rise time ratio. This is done offline with PC software which calculates the corrected mean value and standard deviation for that specific rise time ratio.

We note that the classical filters are only used as example functions and may not span the entire space of possible functions. The distribution of the example functions should in no way be understood to represent the true underlying distribution of possible functions. However, by the functionals described in [2] we see that our functions span a similar range to that spanned by commercially available oscilloscopes [3]. In addition we have plotted in Figure 7 the calculated convolutions of the measured impulse response of our 70 GHz oscilloscope with its own impulse response. For that the width of one of the functions is mathematically varied in time. For this

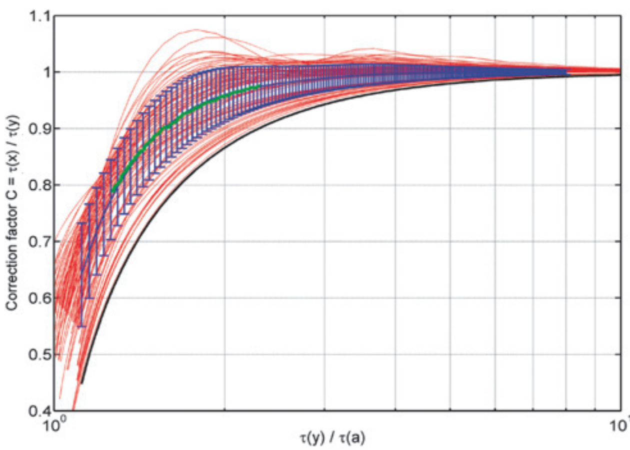

Figure 7: Convoluted response functions of the used 70 GHz oscilloscope (green line).

particular device we can see that the tabulated values coincide well with the mean of all response functions.

We therefore argue that the uncertainty we obtain here is our best engineering judgement, and the uncertainty is therefore a Type B uncertainty. The calculated standard deviation (length of the error bars) is used as a type B uncertainty with a rectangular distribution in the uncertainty budget, as prescribed by [11] because it is not based on a statistical process. Furthermore, we see from Figure 6 that the rise time calculated from the RSS method which is equal to the slope of the black curve overestimates the rise time of typical DUCs. As stated in the introduction the RSS method is only accurate for pure Gaussian response functions but most of the real response functions are somewhat non-Gaussian and normally unknown so the correction factor approach is, for these cases, less biased than the RSS method. This error is significant for a ratio $\tau(y)/\tau(a) < 3$.

5 Result of pulse generator calibration

On the basis of the procedure from the previous section the calculation of a correction factor for a specific rise time ratio is a straight forward process. The known rise time of the transfer standard (sampling oscilloscope) of $t_{\mathrm{r,std}} = 4.56\,\mathrm{ps} \pm 0.7\,\mathrm{ps}$ ($k = 2$) and the measured (and corrected for TBD) rise time $t_{\mathrm{r,meas}} = 7.17\,\mathrm{ps}$ of a pulse generator result in a ratio $t_{\mathrm{r,meas}}/t_{\mathrm{r,std}} = 1.57$. The corresponding correction factor from Figure 6 is 0.90 ± 0.06, where the uncertainty corresponds to the length of the uncertainty bars for that specific mean value. The intrinsic rise time of the pulse generator can then be calculated as

$$t_{\mathrm{r,gen}} = C \cdot t_{\mathrm{r,meas}} = 6.47\,\mathrm{ps} \pm 1.8\,\mathrm{ps} \tag{5}$$

From the uncertainty budget the final expanded uncertainty of 1.8 ps can be determined.

6 Result of oscilloscope calibration

The presented result of the rise time of the pulse generator could not be verified by an independent measurement. Therefore this calibration result is used in a second step to calibrate a sampling oscilloscope (DUC) with a bandwidth of 50 GHz. The procedure is exactly the same as used in Section 5 but in this case the previously calibrated pulse generator is used as a secondary rise time standard. The measured and TBD corrected rise time $t_{\mathrm{r,meas}} = 8.7\,\mathrm{ps}$ of the oscilloscope (DUC) results in a rise time ratio of $t_{\mathrm{r,meas}}/t_{\mathrm{r,std}} = 1.34$. From Figure 6 we then obtain the correction factor $C = 0.82 \pm 0.07$. This results in an intrinsic rise time of the oscilloscope of

$$t_{\mathrm{r,osc}} = C \cdot t_{\mathrm{r,meas}} = 7.16\,\mathrm{ps} \pm 2.0\,\mathrm{ps} \tag{6}$$

After this second step, we can verify the calibration result by calibrating this sampling oscilloscope directly at the electro optic sampling system which is the primary standard of the traceability chain. From this independent calibration a rise time of $t_{\mathrm{r,osc,EOS}} = 7.03\,\mathrm{ps} \pm 0.7\,\mathrm{ps}$ ($k = 2$) results. The E_{n} criterion as a compatibility check for both calibration results gives

$$E_n = \frac{\left|t_{\mathrm{r,osc}} - t_{\mathrm{r,osc,EOS}}\right|}{\sqrt{U^2_{\mathrm{osc}} + U^2_{\mathrm{osc,EOS}}}} = 0.06 \tag{7}$$

Table 1: Comparison of calibration results with expanded uncertainties ($k = 2$).

DUC	RSS method	Correction factor method	EOS system
Pulse generator (after first step)	5.33 ps ± 1.8 ps	6.47 ps ± 1.8 ps	–
50 GHz oscilloscope (after second step)	5.81 ps ± 2 ps	7.16 ps ± 2 ps	7.03 ps ± 0.7 ps

where U_{osc} and $U_{\mathrm{osc,EOS}}$ are the expanded uncertainties of the associated calibration values.

In Table 1 the results achieved are compared to the outcome of the RSS method. It is clearly noticeable that in this particular case of the 50 GHz oscilloscope the RSS method has a larger bias than the correction factor method. In general this is not necessarily the case especially if the response functions have an almost Gaussian shape. However the uncertainties of the correction factor method are based on the presumed space of low-pass filter models while the uncertainties from the RSS method are unknown.

7 Conclusion and further work

For the calculation of the intrinsic rise time of a device under test, it is common practice to use the well-known RSS method, but the uncertainty contribution of the method itself is, at best, an estimation and cannot be verified. We have proposed a new method based on a large set of standard response functions. Out of this set of functions a correction factor is found. This factor, multiplied with the measured rise time gives the estimated transition duration of the DUC. From the spread of the response functions a rectangular distributed type B uncertainty is proposed. Additionally, the new method is less biased, when pooled over a certain class of non-Gaussian response functions, than is the RSS method. As verification of our new method, we have compared the calibration result of a 50 GHz sampling oscilloscope at the end of the traceability chain to the result when calibrating the same device directly at the primary rise time standard. The E_{n} criterion applied to these values shows excellent compatibility. Additionally, we applied the known time base correction procedure to correct the systematic distortion of the time base of a sampling oscilloscope. This can reduce the corresponding uncertainty contribution of the oscilloscope.

We note that the estimated transition duration of the generator's output is still unverified and we must be careful to not equate good agreement in the second tier calibration with correct calibration of the pulse generator. Comparison with another laboratory would be useful in this regard. Also, the correction factor worked with our particular oscilloscope. Further tests must be performed to demonstrate viability with other makes and models of oscilloscopes.

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