Systematic Error of the Nose-to-Nose Sampling-Oscilloscope Calibration

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***Abstract*—We use traceable swept-sine and electrooptic-sampling-system-based sampling-oscilloscope calibrations to measure the systematic error of the nose-to-nose calibration, and compare the results to simulations. Our results show that the errors in the nose-to-nose calibration are small at low frequencies, but significant at high frequencies.**

***Index Terms*—Calibration, electrooptic sampling, impedance mismatch, mismatch correction, nose-to-nose calibration, sampling oscilloscope, swept-sine calibration.**

I. INTRODUCTION

THE "nose-to-nose" sampling-oscilloscope calibration determines the impulse response of the oscilloscope's sampler by using that sampler to measure the "kickout" or "kickback" pulses [1] generated by a similar sampler. The calibration is based upon the assumption that the impulse response of the first sampler and the kickout pulse of the second sampler are the same to within a constant multiplicative factor. This allows the impulse response of the oscilloscope to be estimated form the measured convolution of the oscilloscope's impulse response and kickout pulses. In this paper, we present experimental evidence showing that, while errors in the nose-to-nose calibration are small below 15 GHz, differences in the kickout pulses and impulse response of our 50-GHz oscilloscopes lead to readily measurable systematic errors in the nose-to-nose calibration above 25 GHz.

Over a decade ago, Rush *et al.* [1] noticed that when they applied a charge to the hold capacitor of their oscilloscopes' balanced sampling circuits, the sampler generated an electrical pulse each time the sampling gate was closed. They observed that these kickout pulses were generated by charge flowing from the hold capacitor through the sampling gate to the oscilloscope's output when the sampling gate was closed. Fig. 1, which was derived from our earlier simulation study [2], compares SPICE simulations of the temporal impulse response and kickout pulses of a balanced 20-GHz sampling circuit.

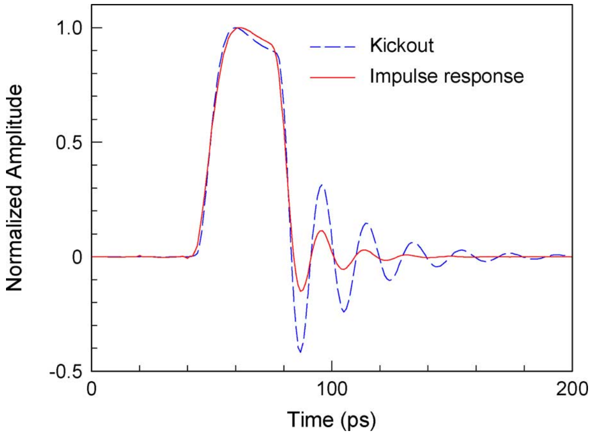

Fig. 1. Temporal impulse response and kickout pulses calculated from SPICE simulations. Data from [2].

Based on the notion that the oscilloscope's impulse response is determined by the flow of charge through the same sampling gate, Rush *et al.* [1] hypothesized that the sampling gate's conductance, kickout pulses, and oscilloscope impulse response should all have approximately the same duration and shape. Based on the assumption that the kickout pulses and impulse response of the samplers are proportional to each other, they then proposed the nose-to-nose sampling-oscilloscope calibration in [1].

The nose-to-nose oscilloscope calibration has become quite popular, in part because it is relatively easy to perform. A constant voltage is applied to the hold capacitor of one sampler, usually by adjusting the offset voltage of the sampler in oscilloscopes with that option [1]. This generates a kickout pulse each time the sampler's sampling gate closes. In its simplest implementation, a second nearly identical sampler is then used to measure these kickout pulses.

The second sampler measures the convolution of the kickout pulse from the first sampler and its own impulse response. While the shape of the kickout pulse is not known *a priori*, if the kickout pulses and impulse response are the same to within a constant multiplicative factor, the impulse response of the oscilloscope can be determined to within a constant multiplicative factor from the measurement of their convolution.

The frequency-domain representation of the impulse response of the oscilloscope's sampling circuit is typically determined by calculating the Fourier transform of the measured temporal convolution and taking the square root of the result. The square root of the Fourier transform of the convolution is proportional to the Fourier transform of the

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impulse response of the sampler when the kickout pulses and impulse response of the two samplers are proportional. Once the frequency response of the sampler has been determined in this fashion, it can be used directly to calibrate the oscilloscope in the frequency domain, or it can be transformed back into the time domain by means of an inverse Fourier transform.

Even before the early study of [3], which investigated the nose-to-nose calibration, the National Physical Laboratory (NPL), Middlesex, U.K., began developing alternative oscilloscope calibrations. NPL developed both oscilloscope calibrations [4]–[8] and direct on-wafer measurement systems [9]–[11] based on electrooptic phenomena.

A number of experiments on the nose-to-nose calibration were also performed at the National Institute of Standards and Technology (NIST), Boulder, CO, and Gaithersburg, MD, over the same time period to examine and improve its stability and accuracy [12]–[17]. In 2003, NIST and NPL conducted a measurement comparison of the parameters of pulses with a roughly 15-ps transition duration time measured with 20-GHz oscilloscopes and found agreement within their stated uncertainties [18]. While the NIST oscilloscopes were calibrated with the nose-to-nose calibration and NPL oscilloscopes were calibrated by electrooptic means, the speeds of the 20-GHz oscilloscopes and roughly 15-ps transition-duration pulses used in these comparisons were quite low, and potential systematic errors in the nose-to-nose calibration were not investigated. NIST also performed a preliminary uncertainty analysis of the nose-to-nose calibration in 2003 that did not consider systematic error [13].

Verspecht and Rush suggested in [19] and [20] that sampler asymmetry and nonlinear capacitance in the sampler diodes may lead to differences in the shapes of the kickout pulses and impulse response of sampling oscilloscopes. The studies of [3] and [21] observed discrepancies of 0.5 dB or greater in the magnitude response of the nose-to-nose calibrations and calibrations traceable to fundamental power measurements. The authors concluded, considering other uncertainties involved in the measurements, that the swept-sine and nose-to-nose calibration were in good agreement, but did not include uncertainty analyses upon which to base firm conclusions.

Our parametric studies [22], which summarize the SPICE-based results of [23] and [24], and the analytic model of [25], also indicated that the nonlinear capacitance of the sampling diodes used in the sampling circuits could cause differences between the kickout pulses and the impulse response of the oscilloscope's sampling circuit. These numerical studies predicted that the nonlinear capacitance of the sampling diodes should give rise to measurable systematic error in the nose-to-nose calibrations at high frequencies. Due to a lack of intimate knowledge of the internal circuitry of the sampling oscilloscopes, we were unable to make definitive statements concerning the accuracy of the nose-to-nose calibration when applied to oscilloscopes with a bandwidth greater than 20 GHz. Nevertheless, these numerical studies encouraged us to also develop alternatives to the nose-to-nose calibration at NIST based on electrooptic sampling [26]–[33].

Despite a move away from the nose-to-nose calibration at NIST and NPL, the nose-to-nose calibration is still used in other settings. Furthermore, the electrical engineering community has not yet reached a consensus on the accuracy of the nose-to-nose calibration, in large part due to a lack of definitive experimental results in the literature. This paper fills this gap. We present new experimental evidence of systematic error in the nose-to-nose sampling-oscilloscope calibrations obtained by comparing the nose-to-nose oscilloscope calibration to two other oscilloscope calibrations, both traceable to fundamental units. Furthermore, we use a rigorous uncertainty analysis to show that the nose-to-nose calibration exhibits statistically significant and easily measurable systematic error, at least with our 50-GHz oscilloscopes. We then repeat the experiments in a second laboratory to confirm our experimental results. Finally, we compare our experimental results to systematic errors we predicted earlier with SPICE models, adding further insight and weight to our conclusions.

II. MAGNITUDE CALIBRATION

The swept-sine calibration measures the magnitude response of a sampler by applying sine waves of known amplitude to the input of the oscilloscope's sampler. The swept-sine calibration can be made traceable by determining the amplitude of the sine waves with a traceable power meter, as was done in [3], [16], [19], [21], and [34].

Henderson *et al.* [3] first compared the swept-sine calibration (called a "stepped frequency measurement" in [3]) to an oscilloscope calibration based on electrooptic sampling and to the nose-to-nose calibration in 1992. They observed deviations of up to 0.5 dB in their magnitude comparisons. Nevertheless, these observations were consistent with the ±0.7 dB uncertainties Henderson *et al.* estimated for their swept-sine calibration to 30 GHz, and they reported good agreement between the methods. It is important to keep in mind that, at this early stage, corrections for impedance mismatch and for differences between the samplers were not available. We have found these necessary to reduce the frequency-domain uncertainties to a level where definitive statements can be made regarding the significance of the discrepancies in the nose-to-nose calibration.

Henderson *et al.* also compared temporal aspects of measurements performed with an oscilloscope calibrated with the nose-to-nose calibration to measurements performed by an electrooptic sampling system in [3]. While they found reasonable agreement between the two temporal measurements, it is difficult to draw conclusions regarding the responses in the frequency domain.

The magnitude of the nose-to-nose calibration was later compared to swept-sine measurements in [19]. These authors also observed differences of up to 0.5 dB in the nose-to-nose and swept-sine calibrations. However, they also were unable to draw firm conclusions regarding the significance of these discrepancies because they had not corrected for mismatch, time-base distortion, or jitter and because they did not develop an uncertainty analysis.

Later experiments performed at NIST [16] did include the oscilloscope time-base distortion, jitter, and mismatch corrections unavailable in [3] and [19], but also lacked an uncertainty analysis. These results also show deviations in the magnitude of the

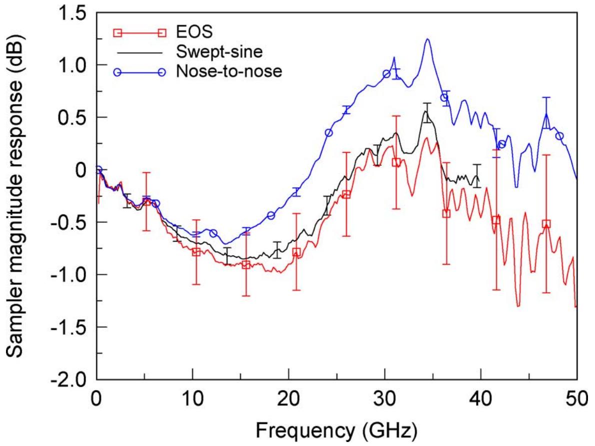

Fig. 2. Comparison of the sampler's measured magnitude response determined by the swept-sine calibration, the electrooptic sampling system calibration (labeled "EOS calibration" in this figure), and the nose-to-nose calibration performed at NIST. The "error bars" in the figure correspond to 95% confidence intervals.

two calibrations of 0.5 dB or greater above 20 GHz, but did not allow the authors to draw statistically based conclusions.

Recently, Scott reported comparisons in [21] of swept-sine and nose-to-nose calibrations that used an improved time base that dramatically reduces time-base distortion and jitter. Scott also observed deviations of roughly 0.5–1 dB in the two calibrations. Scott reported good agreement in light of the uncertainties in his measurements. Scott attributed much of this uncertainty to impedance mismatches in the system and was unable to make definitive statements about the sources of the discrepancies he observed because he did not perform a full uncertainty analysis.

More recently, we performed new experiments at NIST to assess the agreement of the nose-to-nose and swept-sine calibrations. We performed the nose-to-nose calibration with the approach described in [15] and [16], correcting for distortion and jitter in the oscilloscope time base using the methods described in [16] and [35]–[37] and correcting for mismatch using the method of [15]. We also used three samplers in our nose-to-nose calibration to account for differences between them, as explained in [16] and [19].

When performing the swept-sine calibration, we corrected for impedance mismatches using the method of [15]; we also performed an uncertainty analysis of our results. Fig. 2 compares the response of a commercial 50-GHz sampling oscilloscope determined with the nose-to-nose calibration performed at NIST with a traceable swept-sine calibration.

To generate the third curve, labeled "EOS calibration" in Fig. 2, we calibrated the oscilloscope with photodiodes characterized by the traceable NIST electrooptic sampling system [26]–[29] using the procedures outlined in [31]. The photodiode was calibrated to 110 GHz, and has significant energy at that frequency. We also corrected for impedance mismatch and for distortion and jitter in the oscilloscope time base, and performed an uncertainty analysis.

Fig. 2 shows very good agreement between all of the calibrations below 15 GHz, and agreement on the order of 0.1 dB between the swept-sine and electrooptic sampling system calibrations up to 40 GHz. While the 3-dB bandwidth estimates derived from the three calibrations are quite close (not shown), this figure also shows a smooth, but significant deviation of as much as 1 dB between the nose-to-nose calibration and both the traceable swept-sine and the traceable electrooptic-sampling-system-based oscilloscope calibrations above 15 GHz.

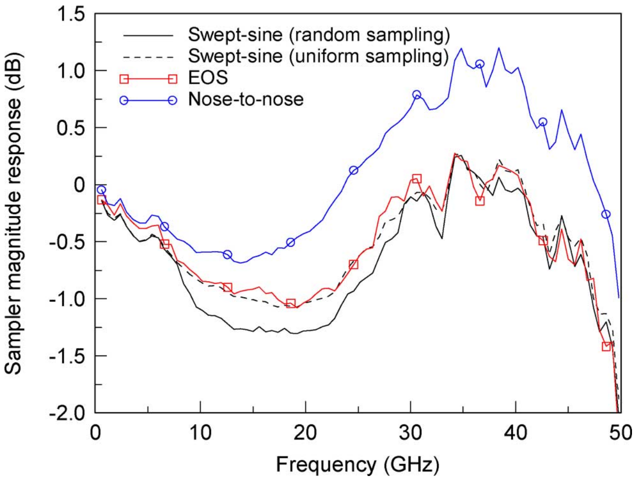

Fig. 3. Comparison of the sampler's measured magnitude response determined by the swept-sine calibration, the electrooptic sampling system calibration (labeled "EOS calibration" in this figure), and the nose-to-nose calibration performed at NMDG Engineering BVBA, Bornem, Belgium. No uncertainties were available for these data, which were also presented in [34].

Finally, we note that the impact of the frequency-domain deviations shown in Figs. 2 and 3 on the temporal impulse response of these oscilloscopes are difficult to assess because the impulse responses of these oscilloscopes have significant energy above 50 GHz, the highest frequency at which we performed comparisons.

To better quantify our comparison, we plot 95% confidence intervals in Fig. 2. We derived the confidence intervals for the electrooptic-sampling-system-based oscilloscope calibration from [31] and our uncertainty in the swept-sine calibration from [16] and [38]. We did not account for potential additional uncertainty in the swept-sine calibration due to the discrepancies in results obtained with the random sampling technique we used and the uniform sampling method noted in [34]. If we treated those discrepancies as a source of error in the analysis, the uncertainties in the swept-sine calibration increase to approximately $+/-0.3$ dB over most of the band.

The nose-to-nose results plotted in Fig. 2 were derived from the mean of 18 measurements (as opposed to the five measurements employed in [16]), allowing us to greatly reduce our uncertainty due to repeatability. Our estimate of the uncertainty in the nose-to-nose calibration also only included those components of uncertainty unrelated to systematic error in the assumption that the kickout pulses and impulse response are proportional to each other, which is the hypothesis we are studying here. This is in contrast to the electrooptic-sampling-system-based and swept-sine calibrations, whose uncertainties contain significant systematic components. Thus, the uncertainty in the mean of the 18 nose-to-nose calibrations plotted in Fig. 2 is quite low compared to the uncertainties of the EOS-system-based and the swept-sine calibrations.

As we stated earlier, we used three samplers in our nose-to-nose calibrations, allowing us to form several nose-to-nose estimates of the response of our sampler from each experiment. We included these variations in our statistical analysis of the uncertainty due to repeatability. Thus, our repeatability estimate includes not only the repeatability in the measurements, but perhaps some other errors in the nose-to-nose calibration that manifest themselves as differences between calibrations based on using different combinations of oscilloscopes. To this we added our estimate of the uncertainty in the nose-to-nose calibration due to the uncertainty in the NIST Measurement Service Test 61263S reflection coefficient measurements we employed to perform the mismatch corrections. While the 95% uncertainty intervals we estimate for the nose-to-nose calibration do not include contributions due to the time-base distortion and jitter corrections we applied, these missing components of the overall uncertainty are small and do not greatly affect the confidence intervals plotted in Fig. 2.

In the case of the swept-sine measurement, traceability is achieved via careful calorimetric measurements, while in the electrooptic sampling system, traceability is achieved via the very fast response time of the opto-electronic crystals that translate voltages to optical polarization changes [26]–[29]. The swept-sine and electrooptic-sampling-system-based calibrations agree reasonably well and are within the 95% confidence intervals for the two calibrations over the entire frequency range. This is expected, as these two calibrations are traceable to fundamental physical phenomena.

However, Fig. 2 also shows that the 95% confidence intervals for the nose-to-nose and swept-sine calibrations do not overlap, an indication that the differences in the two calibrations are statistically significant. As we discussed earlier, both SPICE simulations and analytic models identify significant potential sources of systematic error in the nose-to-nose calibration [2], [22]–[25], [39], while no such systematic error sources have been identified in the swept-sine or electrooptic sampling system calibrations. Thus, our statistical uncertainty analysis leads us to conclude that this deviation is due to systematic error in the nose-to-nose calibration.

To further confirm our results, NMDG Engineering BVBA repeated the comparison of the nose-to-nose and swept-sine calibrations in Belgium following the approach outlined in [34]. Results of the measurements performed at NMDG Engineering BVBA are shown in Fig. 3. The oscilloscope and plug-in were of the same model. However, none of the equipment or the methods used in the nose-to-nose and swept-sine calibrations performed at NMDG Engineering BVBA were the same as those performed at NIST, including the vector network analyzers used for the mismatch corrections, the power meters to which the swept-sine calibrations were traceable, and the algorithms used to correct for mismatch and time-base distortion and jitter.

Finally, the oscilloscope plug-in used at NMDG Engineering BVBA was also calibrated with a photodiode calibrated on the NIST electrooptic sampling system. While the measurements of the photodiode were performed at NIST, the oscilloscope was calibrated with NMDG software and algorithms.

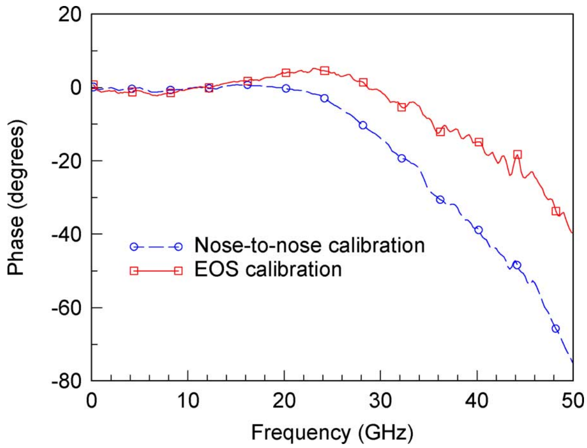

Fig. 4. Measured phase response as determined by the nose-to-nose and electrooptic-sampling-system calibrations. Measurements performed at NIST.

Fig. 3 shows the results of the comparison performed at NMDG Engineering BVBA. Two swept-sine calibrations are shown. The oscilloscope's magnitude response determined with a swept-sine calibration performed by taking random samples and building up a histogram of the sinusoids are indicated by a solid line in Fig. 3. This same approach was used at NIST to perform the swept-sine calibration shown in Fig. 2. Reference [34] outlines several disadvantages of this approach: ensuring that the time axis is sampled with a uniform probability density function is difficult, it is difficult to identify harmonic and subharmonic content when samples are taken randomly, and the noise added by the sampling oscilloscope must be measured with no signal present and assumed to be independent of the signal level. In addition, no time-base corrections are applied when taking random samples, while time-base corrections must be applied when performing other measurements with the oscilloscope.

The magnitude response indicated by a dashed line in Fig. 3 was determined with the swept-sine calibration was determined from equally spaced measurements of the sine wave. This approach circumvents the disadvantages listed in the previous paragraph [34]. This may explain the better agreement between this variation of the swept-sine calibration and the electrooptic-sampling-system-based oscilloscope calibration.

While the measurements performed at NMDG Engineering BVBA did not include an uncertainty analysis, this experiment does further confirm our previous results. These measurements not only indicate that the differences between the nose-to-nose and the traceable swept-sine calibration are repeatable, even within different oscilloscope plug-ins, but confirm the accuracy of the magnitude of the electrooptic-sampling-system-based oscilloscope calibration.

III. PHASE CALIBRATION

We are unaware of any experimental work comparing the phases of nose-to-nose and electrooptic-sampling-system-based oscilloscope calibrations with a statistical analysis. Fig. 4 plots the phase responses of the NIST 50-GHz oscilloscope determined with NIST's nose-to-nose calibration and our traceable calibration based on the NIST electrooptic sampling system.

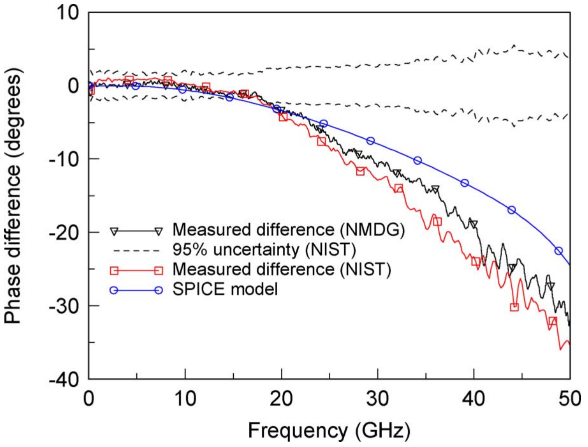

Fig. 5. Measured difference between the sampler's phase response as determined by the nose-to-nose and electrooptic-sampling-system calibrations. The uncertainties apply only to the NIST measurements. The measurement performed at NMDG Engineering BVBA was also presented in [34].

The differences in these phases are small below 15 GHz, but begin to grow significantly at approximately 20 GHz.

Fig. 5 plots the differences in the phases determined by these two calibrations alongside the uncertainty in that difference. Here we temporally aligned the calibrations by subtracting a linear phase that minimizes deviations below 15 GHz. A comparison of the measured differences of the nose-to-nose and electrooptic-sampling-system-based calibrations to our estimated 95% uncertainty interval for this difference leads us to conclude that the differences between the two calibrations are indeed statistically significant at higher frequencies. Again, because we have not been able to identify any significant systematic sources of measurement error in the traceable electrooptic-sampling-system-based calibration, our statistical analysis leads us to conclude that the measured differences are due to high-frequency systematic errors in the nose-to-nose calibration.

To help confirm our results, we also plot in Fig. 5 the differences in the phase of the nose-to-nose and electrooptic-sampling-system-based oscilloscope calibrations measured at NMDG Engineering BVBA, and label them with triangles. Here again, we subtract a linear phase from the result so as to minimize deviations below 15 GHz. This allows the NIST and NMDG Engineering BVBA deviations to grow at the high frequencies. Nevertheless, the differences in the phase response of the nose-to-nose and electrooptic-sampling-system-based oscilloscope calibrations determined in the two laboratories are quite similar, despite the differences in algorithms and equipment used at NIST and at NMDG Engineering BVBA to perform the nose-to-nose calibrations.

Also plotted in Fig. 5 is the error in the phase of the nose-to-nose calibration predicted with SPICE models in the parametric study of [22]. As explained in [22], the SPICE models were based on the equivalent circuit of [40] modified to better correspond to the circuitry used in the 50-GHz samplers we employed in our experiments. The agreement seems reasonable considering the approximations that had to be employed in the SPICE models. In particular, the SPICE simulations show the error to be of the same sign and the same order of magnitude. We noted similar agreement for the magnitudes of the responses (not shown). This indicates that at least the principal systematic errors in the nose-to-nose calibration due to the nonlinear capacitance of the sampling diodes were identified correctly by the SPICE simulations.

IV. CONCLUSION

We used a rigorous uncertainty analysis to compare the nose-to-nose, swept-sine, and electrooptic-sampling-system-based calibrations. While our magnitude measurements were generally consistent with previous measurements, our uncertainty analysis allowed us to state that the differences we observed were statistically significant, and indicate the presence of systematic error in the magnitude of the nose-to-nose oscilloscope calibration.

We also compared the phase response of the nose-to-nose and electrooptic-sampling-system-based calibrations for the first time, allowing us to further characterize the systematic error in the nose-to-nose calibration. Our analysis showed that nose-to-nose calibrations of our 50-GHz oscilloscopes are accurate to at least 15 GHz: this suggests the possibility of using nose-to-nose calibrations to extend to lower frequencies electrooptic-sampling-system-based oscilloscope calibrations, which are currently limited in the NIST system to approximately 600 MHz and higher. Our analysis also showed that the nose-to-nose calibration has statistically significant and easily measurable high-frequency systematic errors.

We further verified our results by performing them in two different laboratories with different oscilloscopes and with different oscilloscope calibration algorithms. We also compared our experimental results with simulations we performed previously, and showed that the systematic errors in the nose-to-nose phase calibration we measured were consistent with errors due to the nonlinear capacitance of the sampling diodes predicted from SPICE models.

Finally, all of our results were limited to oscilloscopes with a 50-GHz bandwidth. Our SPICE simulations do not indicate that the systematic error of the nose-to-nose calibration necessarily grows smaller as the bandwidth of the oscilloscope is increased. Thus, we are unable to extrapolate these results to other oscilloscopes with a greater bandwidth.

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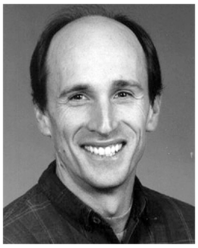

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