

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

Dylan F. Williams, *Fellow, IEEE*, Tracy S. Clement, *Senior Member, IEEE*, Kate A. Remley, *Senior Member, IEEE*, Paul D. Hale, *Senior Member, IEEE*, and Frans Verbeyst, *Member, IEEE*

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 from 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.

Manuscript received February 8, 2007; revised May 31, 2007.

D. F. Williams, T. S. Clement, K. A. Remley, and P. D. Hale are with the National Institute of Standards and Technology, Boulder, CO 80305 USA (e-mail: dylan@boulder.nist.gov; tracy.clement@boulder.nist.gov; remley@boulder.nist.gov; hale@boulder.nist.gov).

F. Verbeyst was with the Vakgroep ELEC, Faculteit Ingenieurswetenschappen, Vrije Universiteit Brussel, Brussels B-1050, Belgium. He is now with NMDG Engineering BVBA, Bornem B-2880, Belgium (e-mail: frans.verbeyst@nmdg.be).

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TMTT.2007.904333

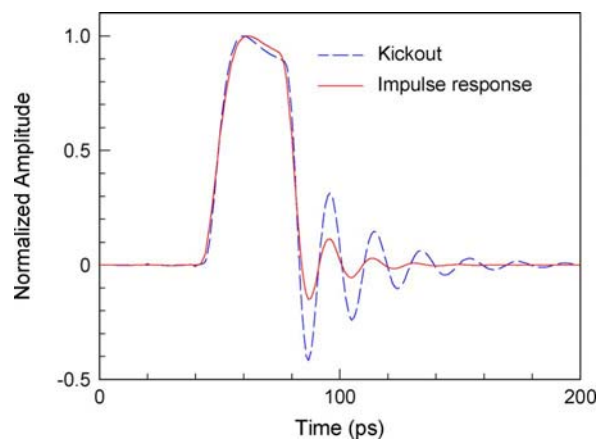


Fig. 1. Temporal impulse response and kickout pulses calculated from SPICE simulations. Data from [2].

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

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

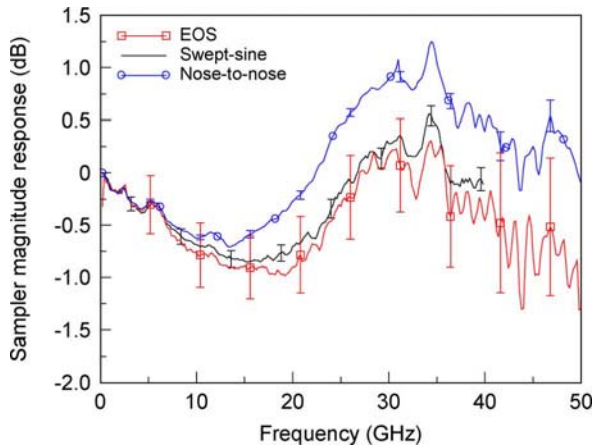


Fig. 2. Comparison of the sampler's measured magnitude response determined by the swept-sine calibration, the electrooptic sampling system calibration (labeled "EOS calibration" in this figure), and the nose-to-nose calibration performed at NIST. The "error bars" in the figure correspond to 95% confidence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

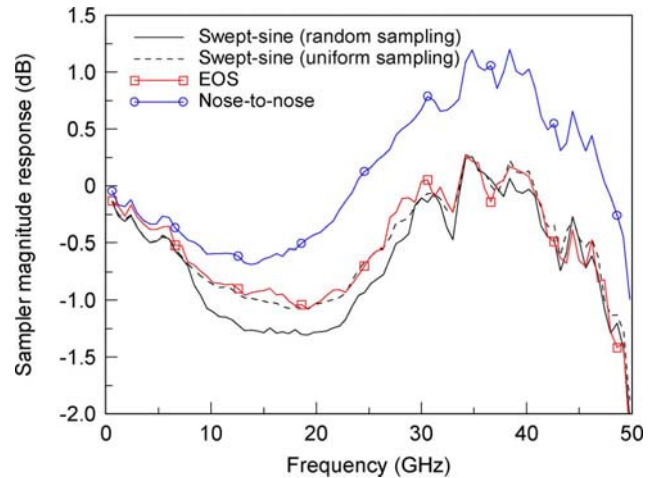


Fig. 3. Comparison of the sampler's measured magnitude response determined by the swept-sine calibration, the electrooptic sampling system calibration (labeled "EOS calibration" in this figure), and the nose-to-nose calibration performed at NMDG Engineering BVBA, Bornem, Belgium. No uncertainties were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

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.

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.

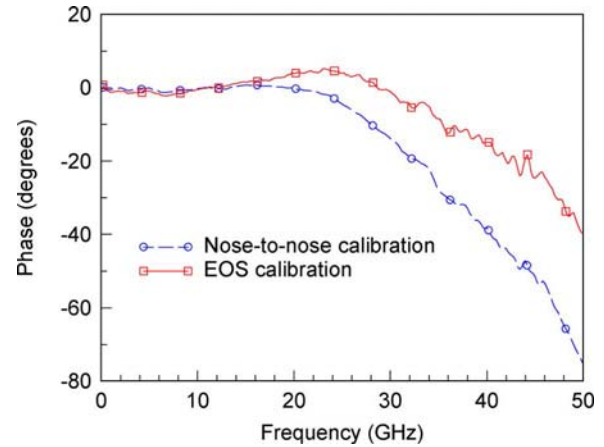


Fig. 4. Measured phase response as determined by the nose-to-nose and electrooptic-sampling-system calibrations. Measurements performed at NIST.

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.

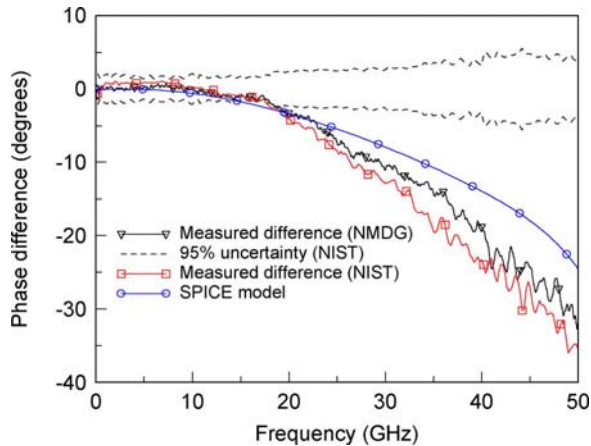


Fig. 5. Measured difference between the sampler's phase response as determined by the nose-to-nose and electrooptic-sampling-system calibrations. The uncertainties apply only to the NIST measurements. The measurement performed at NMDG Engineering BVBA was also presented in [34].

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.

REFERENCES

- [1] K. Rush, S. Draving, and J. Kerley, "Characterizing high-speed oscilloscopes," *IEEE Spectr.*, pp. 38–39, Jan. 1990.
- [2] D. F. Williams, K. A. Remley, and D. C. DeGroot, "Nose-to-nose response of a 20-GHz sampling circuit," in *Automat. RF Tech. Group Conf. Dig.*, Dec. 1999, vol. 54, pp. 64–70.
- [3] D. Henderson, A. G. Roddie, and A. J. A. Smith, "Recent developments in the calibration of fast sampling oscilloscopes," *Proc. Inst. Elect. Eng.*, vol. 139, no. 5, pt. A, pp. 254–260, Sep. 1992.
- [4] D. Henderson and A. G. Roddie, "Calibration of fast sampling oscilloscopes," *Meas. Sci. Technol.*, pp. 673–679, Jan. 1990.
- [5] A. J. A. Smith, A. G. Roddie, and D. Henderson, "Electro-optic sampling of low temperature GaAs pulse generators for oscilloscope calibration," *Opt. Quantum Electron.*, vol. 28, pp. 933–943, Jul. 1996.
- [6] A. J. A. Smith, A. G. Roddie, and P. D. Woolliams, "Electro-optic sampling of coplanar to coaxial transitions to enhance the calibration of fast oscilloscopes," in *Automat. RF Tech. Group Dig.*, Nov. 2000, vol. 56, pp. 190–195.

- [7] A. J. A. Smith, A. G. Roddie, and P. D. Woolliams, "Optoelectronic techniques for improved high speed electrical risetime," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2002, vol. 3, pp. 1501–1504.
- [8] A. J. A. Smith, M. R. Harper, and A. Basu, "Progress in high-speed time domain metrology at NPL," in *Automat. RF Tech. Conf. Dig.*, Dec. 2003, vol. 26, pp. 35–43.
- [9] R. A. Dudley, A. G. Roddie, D. Bannister, F. Facon, and T. Krems, "Electro-optic probing of microwave circuits," in *Proc. Precision Electromagn. Metrol. Conf.*, Jul. 1998, p. 489.
- [10] R. A. Dudley, F. Rodriguez-Llorente, and A. G. Roddie, "Non-invasive measurement of MMICs using electro-optic techniques from 100 MHz–60 GHz," *IEE Colloq. Microw. Meas.*, pp. 4–1–4–6, Feb. 1999.
- [11] R. A. Dudley, A. G. Roddie, D. Bannister, A. D. Gifford, T. Krems, and P. Facon, "Electro-optic S -parameter and electric-field profiling measurement of microwave integrated circuits," *Proc. Inst. Elect. Eng.—Sci., Meas., Technol.*, vol. 146, no. 3, pp. 117–122, Jul. 1999.
- [12] N. G. Paulter and D. R. Larson, "An examination of the spectra of the 'kick-out' pulses for a proposed sampling oscilloscope calibration method," *IEEE Trans. Instrum. Meas.*, vol. 51, no. 5, pp. 1221–1223, Oct. 2001.
- [13] N. G. Paulter and D. R. Larson, "Sources of uncertainty in the nose-to-nose sampler calibration method," *IEEE Trans. Instrum. Meas.*, vol. 52, no. 4, pp. 1618–1626, Aug. 2003.
- [14] D. R. Larson and N. G. Paulter, "The effects of offset voltage on the amplitude and bandwidth of kick-out pulses used in the nose-to-nose sampler impulse response characterization method," *IEEE Trans. Instrum. Meas.*, vol. 50, no. 4, pp. 872–876, Aug. 2001.
- [15] D. C. DeGroot, P. D. Hale, M. Vanden Bossche, F. Verbeyst, and J. Verspecht, "Analysis of interconnection networks and mismatch in the nose-to-nose calibration," in *Automat. RF Tech. Group Conf. Dig.*, Jun. 2000, vol. 55, pp. 116–121.
- [16] P. D. Hale, T. S. Clement, K. J. Coakley, C. M. Wang, D. C. DeGroot, and A. P. Verdoni, "Estimating the magnitude and phase response of a 50 GHz sampling oscilloscope using the 'nose-to-nose' method," in *Automat. RF Tech. Group Conf. Dig.*, Jun. 2000, vol. 55, pp. 35–42.
- [17] N. G. Paulter and D. R. Larson, "Improving the uncertainty analysis of NIST's pulse parameter measurement service," in *Automat. RF Tech. Group Dig.*, Nov. 2000, vol. 56, pp. 16–24.
- [18] N. G. Paulter, A. J. A. Smith, D. R. Larson, T. M. Souders, and A. G. Roddie, "NIST–NPL interlaboratory pulse measurement comparison," *IEEE Trans. Instrum. Meas.*, vol. 52, no. 6, pp. 1825–1833, Dec. 2003.
- [19] J. Verspecht and K. Rush, "Individual characterization of broadband sampling oscilloscopes with a nose-to-nose calibration procedure," *IEEE Trans. Instrum. Meas.*, vol. 43, no. 2, pp. 347–354, Apr. 1994.
- [20] J. Verspecht, "Calibration of a measurement system for high frequency nonlinear devices," Ph.D. dissertation, Dept. ELEC., Free Univ. Brussels, Brussels, Belgium, 1995.
- [21] J. B. Scott, "Rapid millimetre-wave response characterization to well beyond 120 GHz using an improved nose-to-nose method," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2003, vol. 3, pp. 1511–1514.
- [22] K. A. Remley, "Nose-to-nose oscilloscope calibration phase error inherent in the sampling circuitry," in *Automat. RF Tech. Group Conf. Dig.*, Dec. 2002, vol. 60, pp. 85–97.
- [23] K. A. Remley, D. F. Williams, D. C. DeGroot, J. Verspecht, and J. Kerley, "Effects of nonlinear diode junction capacitance on the nose-to-nose calibration," *IEEE Microw. Wireless Compon. Lett.*, vol. 11, no. 6, pp. 196–198, Jun. 2001.
- [24] K. A. Remley, "The impact of internal sampling circuitry on the phase error of the nose-to-nose oscilloscope calibration," NIST, Boulder, CO, NIST Tech. Note 1528, Aug. 2003.
- [25] D. F. Williams and K. A. Remley, "Analytic sampling-circuit model," *IEEE Trans. Microw. Theory Tech.*, vol. 49, no. 6, pp. 1013–1019, Jun. 2001.
- [26] D. F. Williams, P. D. Hale, T. S. Clement, and J. M. Morgan, "Mismatch corrections for electro-optic sampling systems," in *Automat. RF Tech. Group Conf. Dig.*, Nov. 2000, vol. 56, pp. 141–145.
- [27] D. F. Williams, P. D. Hale, T. S. Clement, and J. M. Morgan, "Calibrating electro-optic sampling systems," in *IEEE MTT-S Int. Microw. Symp. Dig.*, May 2001, vol. 3, pp. 1527–1530.
- [28] T. S. Clement, P. D. Hale, D. F. Williams, and J. M. Morgan, "Calibrating photoreceiver response to 110 GHz," in *15th Annu. Meeting IEEE LEOS Conf. Dig.*, Nov. 2002, pp. 877–878.
- [29] D. F. Williams, P. D. Hale, T. S. Clement, and C. M. Wang, "Uncertainty of the NIST electrooptic sampling system," NIST, Boulder, CO, NIST Tech. Note 1535, Dec. 2004.
- [30] D. F. Williams, P. D. Hale, T. S. Clement, and J. M. Morgan, "Calibrated 200 GHz waveform measurement," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 4, pp. 1384–1389, Apr. 2005.
- [31] T. S. Clement, P. D. Hale, D. F. Williams, C. M. Wang, A. Dienstfrey, and D. A. Keenan, "Calibration of sampling oscilloscopes with high-speed photodiodes," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 8, pp. 3173–3181, Aug. 2006.
- [32] D. F. Williams, A. Lewandowski, T. S. Clement, C. M. Wang, P. D. Hale, J. M. Morgan, D. A. Keenan, and A. Dienstfrey, "Covariance-based uncertainty analysis of the NIST electro-optic sampling system," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 1, pp. 481–491, Jan. 2006.
- [33] D. F. Williams, T. S. Clement, P. D. Hale, and A. Dienstfrey, "Terminology for high-speed sampling-oscilloscope calibration," in *Automat. RF Tech. Group Conf. Dig.*, Dec. 2006, vol. 68, pp. 9–14.
- [34] F. Verbeyst, "Contributions to large-signal network analysis," Ph.D. dissertation, Vakgroep ELEC, Vrije Univ. Brussel, Brussels, Belgium, 2006.
- [35] C. M. Wang, P. D. Hale, and K. J. Coakley, "Least-squares estimation of time-base distortion of sampling oscilloscopes," *IEEE Trans. Instrum. Meas.*, vol. 48, no. 6, pp. 1324–1332, Dec. 1999.
- [36] C. M. Wang, P. D. Hale, K. J. Coakley, and T. S. Clement, "Uncertainty of oscilloscope timebase distortion estimate," *IEEE Trans. Instrum. Meas.*, vol. 51, no. 1, pp. 53–58, Feb. 2002.
- [37] K. J. Coakley, C. M. Wang, P. D. Hale, and T. S. Clement, "Adaptive characterization of jitter noise in sampled high-speed signals," *IEEE Trans. Instrum. Meas.*, vol. 52, no. 5, pp. 1537–1547, Oct. 2003.
- [38] A. Dienstfrey, P. D. Hale, D. A. Keenan, T. S. Clement, and D. F. Williams, "Minimum-phase calibration of sampling oscilloscopes," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 8, pp. 3197–3208, Aug. 2006.
- [39] K. A. Remley, D. F. Williams, and D. C. DeGroot, "Realistic sampling-circuit model for a nose-to-nose calibration," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2000, vol. 3, pp. 1473–1476.
- [40] S. Riad, "Modeling of the HP-1430A feedthrough wideband (28-ps) sampling head," *IEEE Trans. Instrum. Meas.*, vol. IM-31, no. 3, pp. 110–115, Jun. 1982.



Dylan F. Williams (M'80–SM'90–F'02) received the Ph.D. degree in electrical engineering from the University of California at Berkeley in 1986.

In 1989, he joined the Electromagnetic Fields Division, National Institute of Standards and Technology (NIST), Boulder, CO, where he develops metrology for the characterization of monolithic microwave integrated circuits and electronic interconnects. He has authored or coauthored over 80 technical papers.

Dr. Williams is co-editor-in-chief of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES. He was the recipient of the Department of Commerce Bronze and Silver Medals, two Electrical Engineering Laboratory's Outstanding Paper Awards, two Automatic RF Techniques Group (ARFTG) Best Paper Awards, the ARFTG Automated Measurements Technology Award, and the IEEE Morris E. Leeds Award.



Tracy S. Clement (S'89–M'92–SM'05) received the Ph.D. degree in electrical engineering from Rice University, Houston, TX, in 1993. Her doctoral research involved the development and study of a variety of ultrashort pulse and very short wavelength lasers.

Since 1998, she has been with the Optoelectronics Division, National Institute of Standards and Technology (NIST), Boulder, CO. Her current research interests include the development of measurement systems for high-speed electrooptic components, as well as ultrashort pulse laser measurements. Prior to joining the Optoelectronics Division, she was an Associate Fellow of the Joint Institute for Laboratory Astrophysics (JILA), the Quantum Physics Division, NIST, and was an Assistant Professor Adjunct with the Department of Physics, University of Colorado at Boulder. From 1993 to 1995, she was a Director's Post-Doctoral Fellow with the Los Alamos National Laboratory, Los Alamos, NM.



Kate A. Remley (S'92–M'99–SM'06) was born in Ann Arbor, MI, in 1959. She received the Ph.D. degree in electrical and computer engineering from Oregon State University, Corvallis, in 1999.

From 1983 to 1992, she was a Broadcast Engineer in Eugene, OR. From 1989 to 1991, she was Chief Engineer of an AM/FM broadcast station. In 1999, she joined the Radio-Frequency Technology Division (now the Electromagnetics Division), National Institute of Standards and Technology (NIST), Boulder, CO, as an Electronics Engineer. Her research activities include metrology for wireless systems, characterizing the link between nonlinear circuits and system performance, and developing methods for improved radio communications for the public safety community.

Dr. Remley was the recipient of the Department of Commerce Bronze and Silver Medals and the Automatic RF Techniques Group (ARFTG) Best Paper Award.



Paul D. Hale (M'01–SM'01) received the Ph.D. degree in applied physics from the Colorado School of Mines, Golden, CO, in 1989.

Since 1989, he has been with the Optoelectronics Division, National Institute of Standards and Technology (NIST), Boulder, CO, where he conducts research on broadband opto-electronic device and signal metrology. He has been Leader of the High-Speed Measurements Project of the Sources and Detectors Group since 1996. He has authored or coauthored over 50 technical publications. His

current technical research focuses on extending both time- and frequency-domain opto-electronic measurements to beyond 110 GHz, implementing a novel covariance-based uncertainty analysis that can be used for both time- and

frequency-domain quantities, and disseminating NIST traceability through high-speed electronic and opto-electronic measurement services.

Dr. Hale was an associate editor of optoelectronics/integrated optics for the *IEEE JOURNAL OF LIGHTWAVE TECHNOLOGY* from June 2001 to March 2007. He was the recipient of the Department of Commerce Bronze, Silver, and Gold Awards, two ARFTG Best Paper Awards, and the NIST Electrical Engineering Laboratory's Outstanding Paper Award.



Frans Verbeyst (M'07) was born in Merchtem, Belgium, in 1963. He received the Electrotechnical-Mechanical Engineer degree from the Vrije Universiteit Brussel (VUB), Brussels, Belgium, in 1986, and the Werktuigkundig Elektrotechnisch Burgerlijk Ingenieur and Doctor in Engineering Sciences degrees from the Vrije Universiteit Brussel, Brussels, Belgium, in 1986 and 2007, respectively.

After four years with Philips (1990–2003), he joined the Network Measurement and Description Group (NMDG), Agilent Technologies (Hewlett-Packard). Since he joined Hewlett-Packard/Agilent Technologies, he has been involved in large-signal RF and microwave measurements and behavioral modeling. He has also been involved with a streamlined implementation of the “nose-to-nose” calibration procedure as an essential part of the phase calibration of large-signal network analyzers and its transfer into other groups within Agilent Technologies and into the National Institute of Standards and Technology (NIST). Since 2003, he has been with NMDG Engineering BVBA, Bornem, Belgium. From July 2004 to June 2006, he worked part-time with the Vakgroep ELEC, Faculteit Ingenieurswetenschappen, Vrije Universiteit Brussel, Brussels, Belgium, during completion of his doctoral dissertation “Contributions to Large-Signal Network Analysis.”

Dr. Verbeyst was a corecipient of the 2002 ARFTG Technology Award. He was the recipient of two ARFTG Best Paper Awards.