A Pulse Measurement Intercomparison

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***Abstract*—A pulse measurement intercomparison, organized by the National Institute of Standards and Technology (NIST) and conducted by the authors in their respective labs, is described. The purpose was to assess the state of the art for time-domain pulse waveform measurements in the nanosecond regime, and to find problem areas in need of better metrology support. The experiment was conducted by circulating two stable pulse generators among the five labs; participants recorded the waveforms over two different time epochs: 10.24 ns with 10 ps sampling period and 102.4 ns with 100 ps sampling period. The data records were sent to NIST for analysis and comparison. The pulse generators that were used produce a step-like waveform with nominal high and low states of 0.5 and 0 V, respectively, transition duration of approximately 200 ps, and significant frequency components out to almost 10 GHz. The settling behavior was purposely spoiled. Some significant measurement differences were found among the five labs. The overall experiment is described, along with measurement results and conclusions.**

***Index Terms*—Laboratory intercomparison, measurement, oscilloscopes, pulse measurements, time-domain measurements.**

I. Introduction

Time-domain waveform metrology is a discipline that is becoming increasingly important because of the reliance on higher speed signals in commercial electronic products. The nanosecond time scale, with subnanosecond transitions, is of particular commercial interest, and new oscilloscope calibrators covering this time scale have recently been introduced on the market [1], [2]. This intercomparison is one of the first attempts to compare measurements among different laboratories active in this area of metrology. Earlier work, notably by J. Andrews, reported on performance comparisons of commercial high-speed sampling oscilloscopes [3].

The pulse measurement intercomparison (round-robin) was organized in 1993 by the National Institute of Standards and Technology (NIST) to assess the state of the art for time-domain pulse waveform measurements in the nanosecond regime, and to find problem areas in need of better metrology support. The plan was to circulate a reference pulse generator (with 200 ps transition duration) among the participating labs, which would each measure its waveform over two time epochs (10.24 and 102.4 ns), and report the results to NIST for processing and comparison. The measurement phase of the intercomparison was carried out in 1994 and 1995. Not including NIST, four labs out of seven which had originally agreed to participate returned useful data for comparison purposes: Picosecond Pulse Labs (J. Andrews), Tektronix (A. Caravone), LeCroy (S. Naboicheck), and Hewlett-Packard, Colorado Springs (C. Duff). In addition to these labs, NIST (M. Souders, W. Gans, and J. Deyst) also made several measurements on the generators, and that measurement data is used for reference purposes in the analysis.

Explicit directions were given on what time epochs to record, what sampling rates to use, where in the time epoch to position the 50% point on the step transition, and how the data files were to be formatted. Otherwise, the measurement procedure used was up to the individual participants. Thus, each was instructed to "...deliver the best discrete-time estimate you can realize for the test waveform, regardless of the method you choose to obtain it. The choices of measurement approach, test equipment, and data processing techniques are up to you." The measurements were performed blind: while the nominal pulse parameters were known to the participants *a priori*, detailed knowledge of the signal was not, and no data was shared during the course of the measurements. As an incentive to participate, it was agreed that, unless there was a unanimous negative vote, anonymity would be maintained, i.e., each lab would be identified with its data via a code designation known only to two parties: NIST and the individual lab. However, it was understood in the beginning that NIST would waive its own anonymity. Consequently, while the round-robin participants are identified in this report, the reported test results are tied to the participants only by arbitrarily assigned code letters.

II. Reference Generator

The actual pulse generator package that was circulated was designed and fabricated by NIST. It included two virtually identical pulse heads (in case one failed along the way) and a control/rate generator box. Sets of measurement data were provided for both of these pulse heads by the participating labs. The generators produce a step-like signal from a 50 Ω source impedance, with nominal high and low state levels of 0.5 and 0 V, respectively, and a transition duration (TD) of approximately 200 ps. The generator has excellent offset and amplitude stability, but its settling behavior was purposely spoiled. Despite its 200 ps TD, the generator has significant frequency components out to almost 10 GHz. The repetition rate and duty cycle were fixed at 100 kHz and 10%, respectively. A separate trigger signal that leads the pulse transition

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by about 200 ns is provided. A front-panel switch can cause the generator to output its high and low state levels as dc signals as well as to produce the 100-kHz pulse signal that toggles between the two levels. The participants were asked to record and report both of the static levels, before and after the pulse waveform was recorded. This feature was used to normalize the data to correct for any static offset and gain differences that might be present. For example, gain differences among the labs resulting from *static* impedance mismatches are minimized with this approach. Differences that remain are those that could not have been removed by simple static calibration procedures.

Each lab was also asked to include estimates of the random and systematic uncertainties of their measurements, in the form of two uncertainty vectors indexed by sample time, for each data file. This data has not yet been processed.

III. Test Equipment and Procedures

A. NIST

Two systems are used at NIST for time-domain pulse measurement services [4]: 1) the automatic waveform analysis and measurement system (AWAMS) that consists of a commercial (HP 54 121) 20-GHz digitizing oscilloscope,[1] with ancillary hardware and software for calibration and error correction [5] and 2) the sampling comparator system (SCS), that uses an NIST-developed strobed comparator as the sampling and decision element in a 2.3-GHz BW measurement system optimized for high accuracy and fast settling [6]. NIST typically measures step-like signals with either the AWAMS or the SCS, depending on the signal frequency content and the required accuracy (the two usually being inversely related). For many reference signals, a clear choice can be made. However, in this exercise, both high accuracy and wide bandwidth were required because of the rich frequency content of the round-robin waveforms. Consequently, the output signals from the round-robin pulse generators were measured at NIST using both measurement systems.

The final NIST waveform estimate of the round-robin signal for the 10-ns epoch was derived by combining the measurements from both of these systems in a way intended to capitalize on their individual strengths. Basically, the estimate for the 10-ns epoch consists of dc and low frequency ($\leq$1.6 GHz) information from the SCS and high frequency ($\geq$1.6 GHz) features measured by the AWAMS—an attempt to combine the accurate high speed performance of the AWAMS with the superior settling performance of the SCS. The NIST waveform estimate was developed prior to any evaluations of the waveforms from the other labs. For the 102.4-ns epoch, the NIST waveform estimate is based solely on the measurements made with the SCS.

Fig. 1 shows the NIST estimate for the 10.24-ns epoch for generator A. Fig. 2 shows the equivalent frequency response of generator A derived from the data of Fig. 1 (this is the frequency response of the network whose step response is that of Fig. 1). Note the significant frequency components out to almost 10 GHz.

[1] Certain commercial products are identified to describe the experimental setup. This does not imply that NIST recommends the products as necessarily the best available for the purpose.

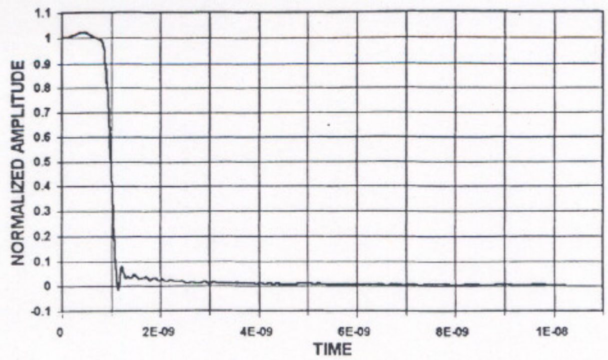

Fig. 1. NIST waveform, generator A, 10.24-ns epoch.

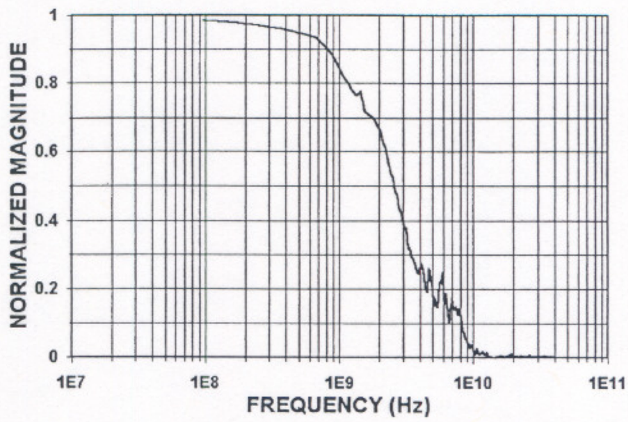

Fig. 2. Equivalent frequency response for generator A (from data of Fig. 1).

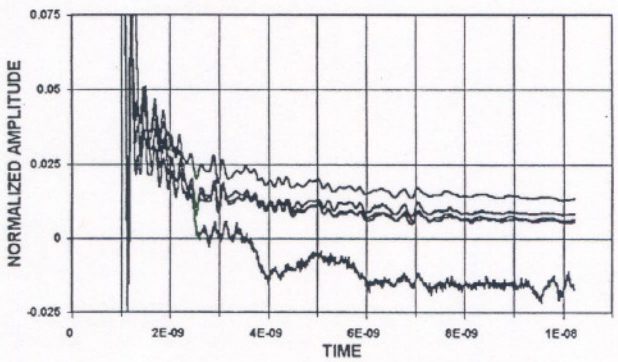

Fig. 3. Low state regions of all five waveforms for generator A.

B. Picosecond Pulse Labs

These measurements were made with a Hewlett-Packard model 54 124A oscilloscope, used in the *low bandwidth* (nominally 18 GHz) and *signal averaging* modes. A special calibration procedure was used by PSPL to correct for known settling errors in the oscilloscope [3]. In this correction process, another step generator with known fast settling performance (Picosecond Pulse Labs model 6110 *reference flat pulse generator*) was set up with the same amplitude, polarity, pulse rate, duty cycle and delay as the round-robin generator, and

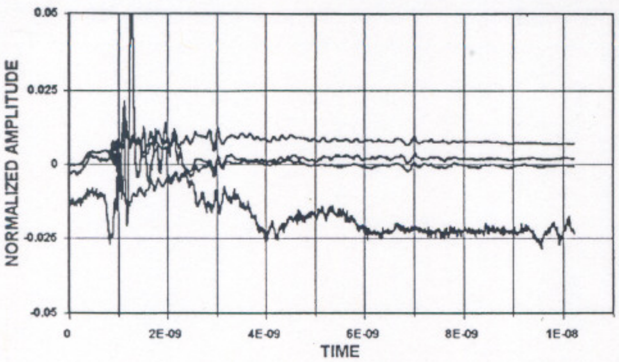

Fig. 4. Difference waveforms (Lab X—NIST) in the low state region (Generator A).

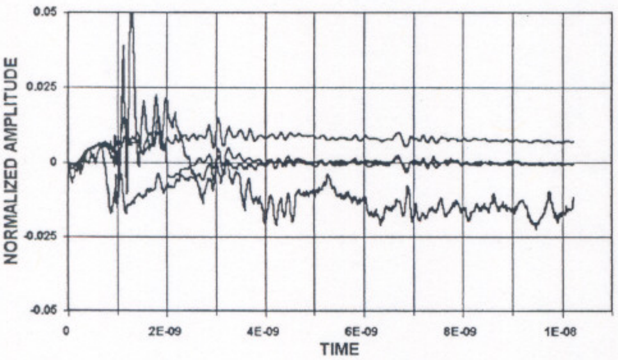

Fig. 5. Difference waveforms (Lab X—NIST) in the low state region (Generator B).

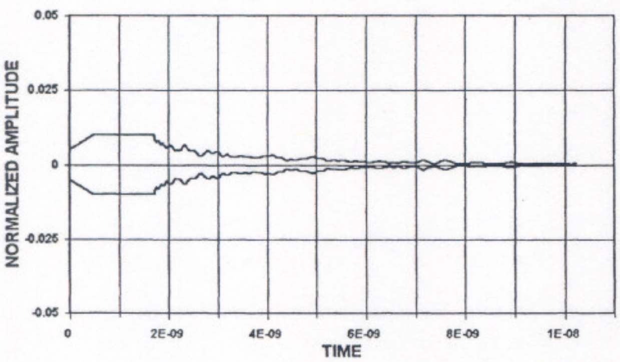

Fig. 6. NIST expanded uncertainty (95% confidence) for waveform measurement of Generator A.

its waveform was also recorded. This calibration waveform was numerically subtracted from the recorded round-robin waveform, producing a difference waveform. For the 10.24-ns epoch, the reported waveform for the round-robin generator is the concatenation of the raw measurement data up to 1 ns following the 50% point on the transition, with the difference waveform starting 1 ns after the 50% point and lasting to the end of the record. For the 102.4-ns epoch, the reported waveform is a similar concatenation with the break point at 2 ns after the 50% point.

C. Tektronix

These measurements were made using a Tektronix model CSA803A oscilloscope with model SD-22 sampling head with

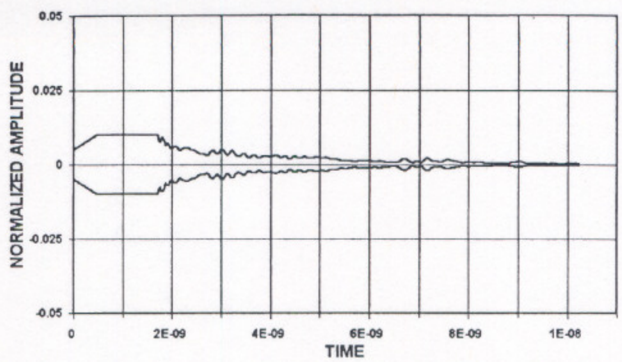

Fig. 7. NIST expanded uncertainty (95% confidence) for waveform measurement of Generator B.

a nominal bandwidth of 12.5 GHz. The oscilloscope was set up for the *high precision waveform* and *high precision time-base* modes. *Offset and loop gain* adjustments were performed prior to making the measurements, using the instrument's internal calibration features. No external dc calibrations were performed, and no external signal processing was applied to the data.

D. Hewlett-Packard

These measurements were made using a Hewlett-Packard model 54 750A sampling oscilloscope, with a nominal bandwidth of 50 GHz. It was operated in the *high bandwidth* and *averaging–best flatness* modes. Prior to making the measurements, its dc offset, gain, and time-base were calibrated using its internal calibration features. No external signal processing was applied.

E. LeCroy

These measurements were made using a LeCroy model 7262 sampling oscilloscope with a nominal bandwidth of 4 GHz. Prior to making the measurements, the dc offset and gain and the time-base were calibrated using the standard internal calibration features of the oscilloscope. No external signal processing was used.

IV. Waveform Comparisons

As explained previously, measured waveforms were acquired for two nearly identical pulse generator signals. The resulting waveforms are generally very similar, but the *relative* responses among the labs are different in some small respects for the two sets of data. In most of the comparisons, waveform measurements on both of the pulse heads will be shown.

For the plots that follow, the waveforms from each lab were first normalized to their measured static high and low state levels to remove any differences caused by static offset and gain errors. Therefore, *in these normalized units, a value of 0.000 represents the static low state level, and a value of 1.000 represents the static high state level.* The waveforms from the 10-ns epochs were then time aligned so that direct comparisons could be made (see *signal processing,* below, for details). The 50% points of the time-aligned waveforms occur at 1.00 ns after the start of the records. No time-alignment was performed

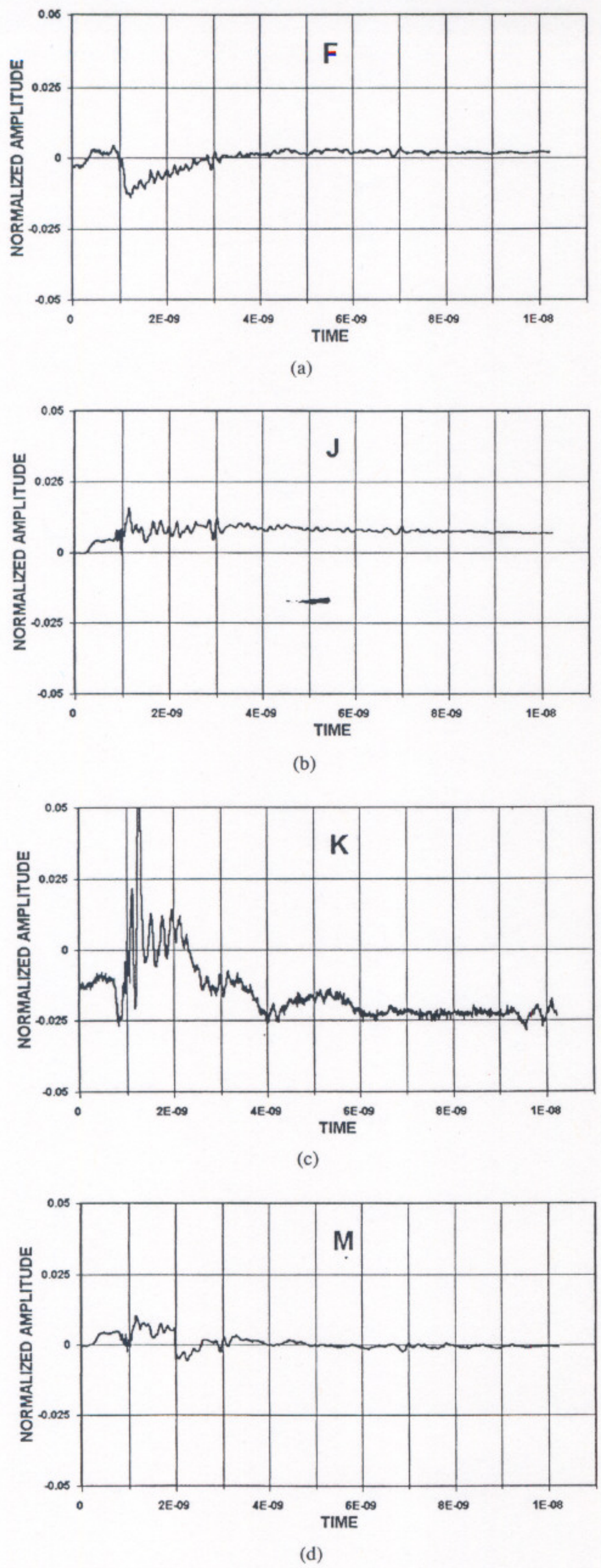

Fig. 8. Difference waveforms (Lab X—NIST), 10.24-ns epoch, Generator A. (Lab F) (Lab J) (Lab K) (Lab M).

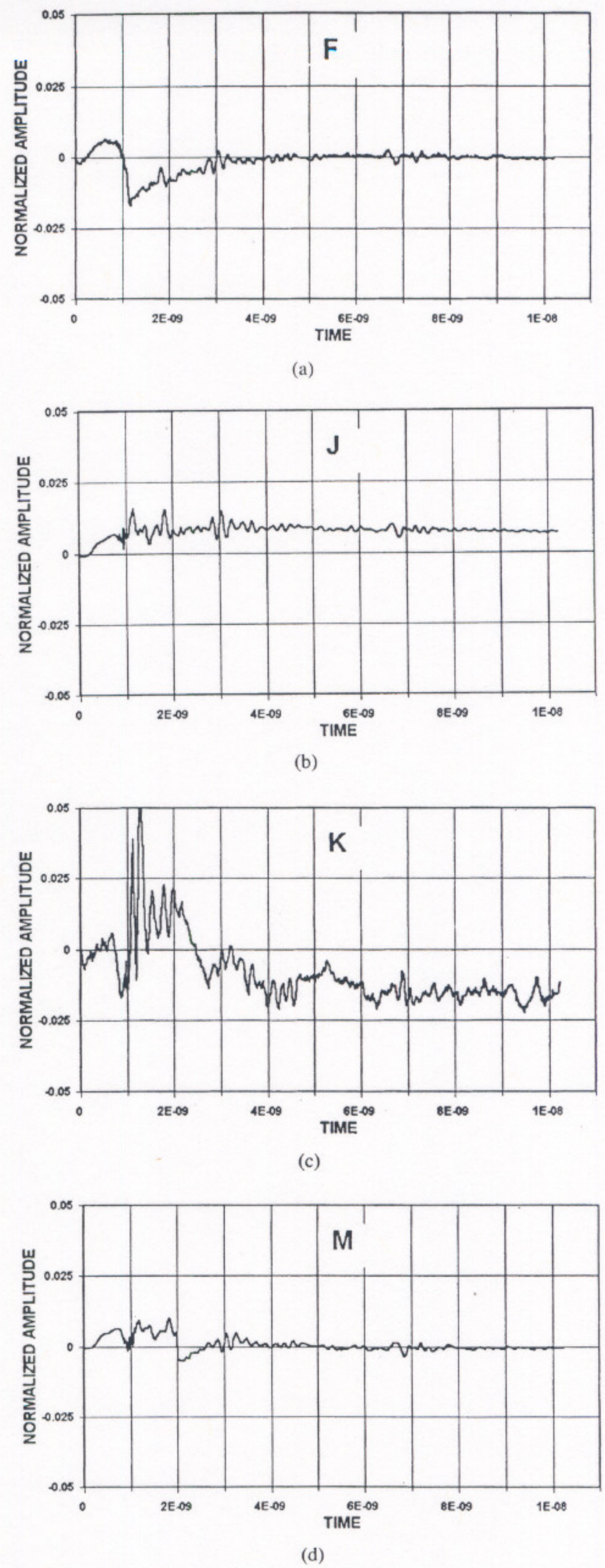

Fig. 9. Difference waveforms (Lab X—NIST), 10.24-ns epoch, Generator B. (Lab F) (Lab J) (Lab K) (Lab M).

on the 102.4-ns records since they were already reasonably well aligned, and their time-derivatives are very small after 10.24 ns or so.

In many of the comparisons, the NIST waveform is used as a reference, and the *difference* waveforms (Lab X minus NIST) are plotted. This is not to suggest that the NIST waveform

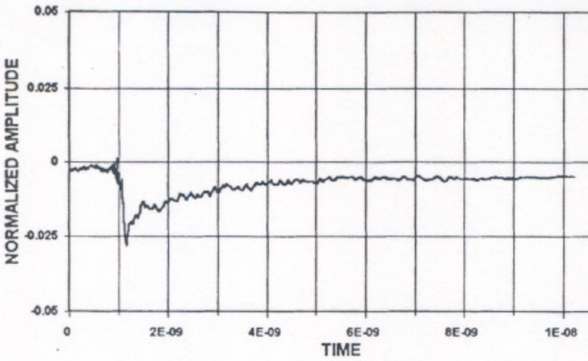

Fig. 10. Difference: Lab F—Lab J; 10.24-ns epoch, Generator A.

is necessarily a better estimate than those of the other labs; instead, it is used so that similarities and differences among the estimates will become more apparent, and so that all regions of the waveforms can be displayed at higher resolution on the same graphs.

A. Signal Processing

After normalizing, the waveforms were end-padded to minimize end effects caused by subsequent signal processing routines, i.e., extrapolated data was added to each end. After processing, these ends were removed from the displayed results. Next, the waveforms were time-aligned by fitting each in turn to the NIST waveform using an algorithm that adjusts offset, scale factor and time displacement to achieve the minimum mean squared difference between them. However, the final waveforms are only time-aligned; the offset and scaling factors are calculated but not applied.

B. Comparisons: 10-ns Epoch

The low state regions of all five waveforms for generator A are plotted together in Fig. 3. In Figs. 4 and 5, the NIST waveforms have been subtracted from the waveforms from each of the other four labs, and the differences are plotted together. These plots show the overall level of agreement among the labs, while Figs. 6 and 7 give the estimated expanded uncertainties (at a 95% level of confidence) for the NIST waveforms [7]. In Figs. 8 and 9, the difference waveforms (from Figs. 4 and 5) are plotted individually for more clarity. Finally, Fig. 10 shows a comparison between Labs F and J results, illustrating some short-term settling discrepancies.

C. Comparisons: 100-ns Epoch

As with the 10-ns epoch data, the differences (Lab X minus NIST) are plotted individually (Fig. 11). For this epoch, the NIST expanded uncertainties are ±0.0003 in the interval from 20 ns (10 ns beyond the transition) through the end of the record, for both generators.

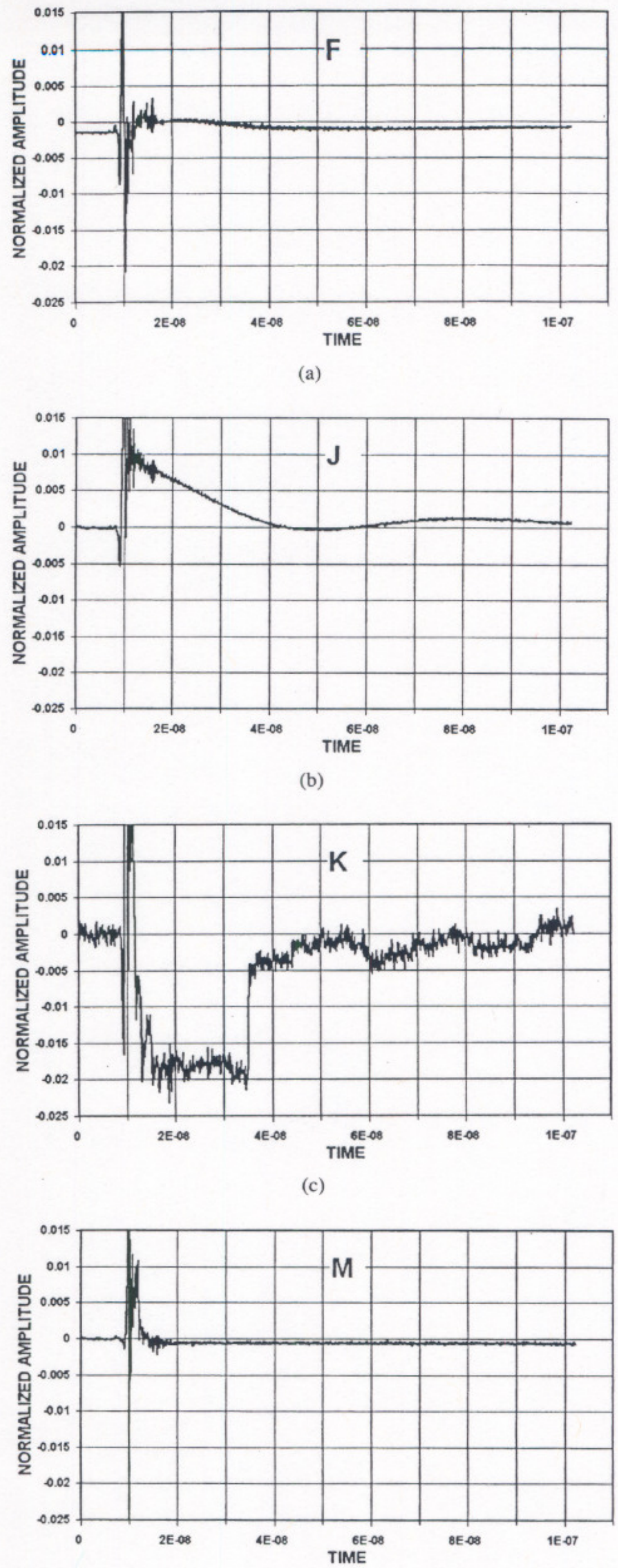

Fig. 11. Difference waveforms (Lab X—NIST), 102.4-ns epoch, Generator A. (Lab F) (Lab J) (Lab K) (Lab M)

V. General Observations and Conclusions

Based on comparisons of the data from the five labs, a few general observations can be made about the overall levels of agreement and areas that can be identified as requiring further work.

The results from Lab K appear to include more noise than those from the other labs, and there is a substantial jump occurring about 25 ns after the transition.

Referring to the pretransition data for the 10.24-ns epoch (see Fig. 4), the NIST results seem to estimate the $\sim$2.5% precursor (the positive "hump" that precedes the transition) with about 0.6% error for Gen. B (less for Gen A), based on the mutual agreement in this region among the other four labs.

Further analysis of the data shows that over all points within $\pm$1 ns of the 50% point, the five waveforms show a maximum difference of almost 8%, dropping to about 4% after 2 ns, and to 1% after about 27 ns. In contrast, among four of the five labs (excluding Lab K), the agreement is about 3.0% within 1 ns, and after 5 ns, it is within 1.0%. Furthermore, three out of four of the commercial labs show agreement with NIST to 1.6% or better in the first nanosecond. The short term settling disparities in the 2-ns region following the transition need to be resolved; there is no clear consensus here.

Most of the labs tend to report the same major waveform features, but local variations in relative feature position as well as size cause differences of as much as 50% of the aberration amplitude. (Here, aberrations refers to bumps and wiggles out past the transition region of the waveform.) These apparent disparities in measurements of the aberrations occurring in the settling region warrant further investigation.

Finally, Labs J and K show significant disparities with respect to the other three labs in their reported settling behavior over the 102.4-ns epoch.

It should be noted that some of the anomalous behavior represented in the data was anticipated by the participants. For example, Lab K was aware that a discontinuity might occur in their waveforms at 25 ns, and Lab J expected the settling behavior that was found with their measurements. However, it is one thing to realize that measurement problems exist, and another to correct them.

We hope that this exercise will provide impetus to make more accurate measurements possible in the future, with hardware and/or software improvements. It particularly illustrates the need for better measurement support in the 2-ns region following the transition, where discrepancies are in the 1–3% range.

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T. Michael Souders (M'75–SM'90–F'94), photograph and biography not available at the time of publication.

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A. Caravone, photograph and biography not available at the time of publication.

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C. Duff, photograph and biography not available at the time of publication.

S. Naboicheck, photograph and biography not available at the time of publication.