Characterization of a Sampling Voltage Tracker for Measuring Fast, Repetitive Signals

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Abstract—**An equivalent-time sampling and digitizing system is described, together with test methods for characterizing its dynamic performance. Time-base errors, linearity errors, step response parameters, harmonic distortion, and frequency response are considered, and typical measurement results are included. The system is capable of state of the art measurements for signal frequencies up to 200 MHz.**

I. INTRODUCTION

MANY applications arise in waveform metrology in which accurate measurements of repetitive waveforms are required. These include the characterization of precision reference waveforms such as voltage steps, ramps and the like, the measurement of settling times for D/A converters, S/H amplifiers, operational amplifiers, etc., and characterization of the many new arbitrary waveform generators now being marketed. For these applications, accurate measurements are required in the nanosecond time domain. Often however, real-time sampling instruments, i.e, waveform recorders, lack the requisite accuracy, sampling rate, or bandwidth. An equivalent-time sampling approach, based on the so-called sampling voltage tracker (SVT), has shown considerable promise for making such measurements [1], [2]. However, little published data exist to indicate the performance limits of SVT's. In this paper, techniques for characterizing the performance of SVT's will be presented, along with typical performance data.

The SVT is an equivalent-time sampling and digitizing system which uses a high speed latched IC comparator as the sampler. In one implementation, illustrated in Fig. 1, the latched comparator is operated in a feedback loop to repetitively sample the input signal at a given instant on the waveform and generate a dc level equal to the average sampled voltage. (As noted later, other implementations are also possible for the feedback loop.) Digitization is accomplished simply by measuring the dc level with a precision DVM. The process is repeated at sucessive delays determined by a precision time delay generator, until the entire waveform has been characterized. A complete SVT system based on the IEEE-488 bus, is shown in Fig. 2.

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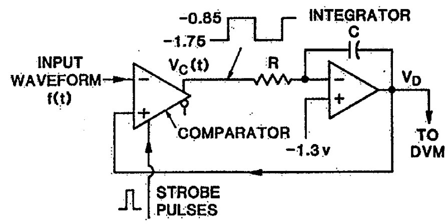

Fig. 1. Basic circuit of the sampling voltage tracker.

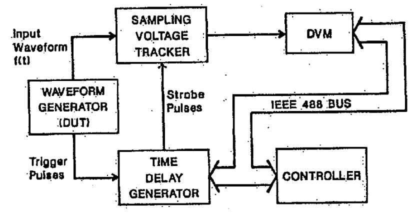

Fig. 2. Block diagram of a complete SVT system.

The performance of the SVT itself is difficult to characterize because it is capable of state of the art accuracy at radio frequencies (to 200 MHz). Furthermore, SVT's share many of the difficult characterization problems that are associated with transient waveform recorders. These include the following.

1) Time-base errors, i.e., fixed errors due to nonlinearities in the time base used to generate the sample commands (strobe pulses), and time-varying errors due to phase noise between the signal and the time base which generates the sample delays.
2) Static linearity errors and harmonic distortion (i.e. dynamic linearity errors), associated primarily with the comparator.
3) Step-response parameters, including transition duration and long- and short-term settling time.
4) Bandwidth and frequency response.

Techniques for measuring these parameters are described in the following sections, together with typical measurement results. All tests were performed with input signals within the range of ± 1 V, with a 50-Ω terminating impedance. The measurement results confirm that the SVT can satisfy some difficult measurement requirements which are otherwise difficult or impossible to fulfill.

II. Linearity

Static Linearity

Static linearity measurements are made by inputing known, programmable dc voltages to the SVT, recording the SVT readings and performing a linear regression of the form $Y = ax + b$ on the results. The residuals of the fit are the static linearity errors. Typical results are given in Fig. 3. The estimates $\hat{b}$ and $\hat{a}$ give the actual static offset and gain of the SVT.

Dynamic Linearity

Dynamic linearity errors (or harmonic distortion) are measured by sampling and recording high purity sine waves, and fitting an ideal sine wave to the records. The residuals of the fit in this case include not only the amplitude linearity errors but also errors due to nonlinearities in the time base. (The errors due to the time base are minimized by an averaging technique which is explained later in the section on the time base errors.) The algorithm used for the nonlinear curve fitting is based on Taylor's series linearization, sometimes referred to as Newton's method. Fig. 4 shows typical plots of the linearity errors thus measured at two input signal amplitudes (at a frequency of 50 MHz). The rms linearity error or total harmonic distortion versus frequency, expressed as a percentage of the rms value of the fitted sine wave, can be found in the performance summary, Table I. Note that the errors generally decrease as a percentage of the applied signal, at lower signal levels. The total harmonic distortion of the input signal, which was minimized by heavily filtering the output of a commercial generator, contributed an insignificant amount to these errors.

III. Time-Base Errors

Fixed Errors (Nonlinearity)

Nonlinearities in the time base cause displacements of the sampling instants, which in turn cause apparent amplitude errors proportional to the derivative of the signal being meaured. To the extent that the nonlinearities can be reduced over the time interval of interest with a moving average digital filter of reasonable window length, their effects can be minimized, and their values estimated, by employing the following signal averaging technique. A high purity sinewave signal is input to the SVT, digitized and stored. The input is then advanced (or delayed) incrementally with respect to the trigger signal, and another record is taken. This process is continued m times. The result is m records of the same signal; however, the time-base errors are phase shifted from record to record with respect to the phase of the sinewave itself. The records are then realigned in phase and averaged point-by-point. If the incremental phase shift equals the sampling period, then the resulting averaged record will have residual errors (due to time base) that are equivalent to those which would remain after filtering the time base errors with a moving average digital filter of window length m. (If the incremental phase shift is n times the sampling period, the window will span $n \times m$ sample periods, but will include only m samples.) On the other hand, the true amplitude errors remain unchanged by this averaging process. Therefore, the time-base errors can be estimated by subtracting the averaged data record in which the time-base errors have been filtered out, from the nonaveraged records, and dividing the results by the derivative of the signal. (Regions near the cusps of the sinewaves where the derivative approaches zero must, of course, be avoided.)

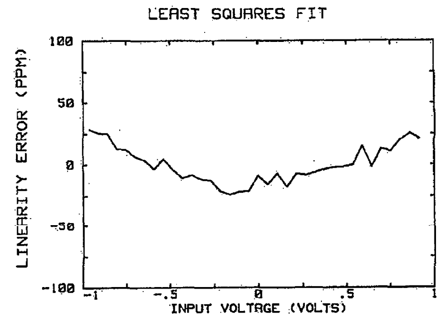

Fig. 3. Typical plot of static linearity errors.

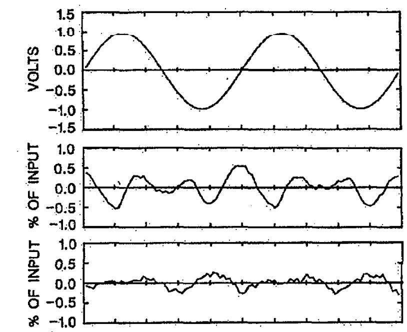

Fig. 4. Typical plot of digitized 50-MHz sinewave (top) and dynamic linearity errors derived from curve fitting for 1-V peak input (middle), and 50-mV peak input (bottom). *Horizontal scale is 4 ns per division.*

TABLE I

	dc	1	10	20	50	100	200	300	MHz
Linearity Error									
1 V (peak)	0.002	0.03	0.06	0.08	0.39	1.4	4.2	9	%
50 mV (peak)			0.06	0.12	0.20	0.2	0.7	1.3	%
Gain Error	0	--	0.004	0.02	0.30	0.7	-0.3	-4.5	%
Bandwidth (3 dB)					600				MHz
Step Response									
• Transition Duration (10-90 %)					600				ps
• Settling Time (-1 to +1 V step)									
0.1 %					4				ns
0.02 %					20				ns
• Long Term Settling Error (0-1 μs) -1 to +1 V Step					± 0.4				mV
Time Base Linearity Error 100 ns epoch					<2				ps rms
Time Base Phase Noise, > 1 Hz					<10				ps peak

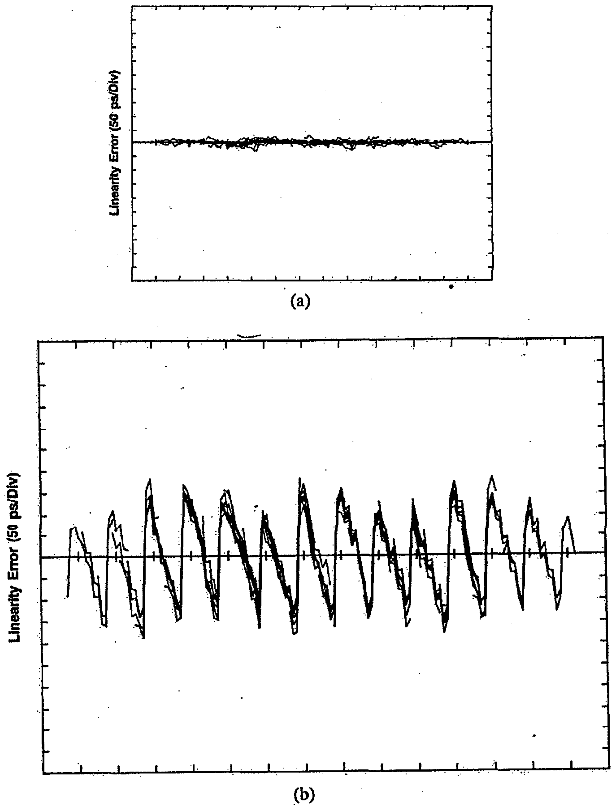

Fig. 5. Time-base linearity errors for (a) and (b): two different time bases. (a) Results from ten different data sets are overlaid in each plot. In (a), the linearity errors are buried in noise. The rms value of the average of the ten data sets for this time base is 1.7 ps. Horizontal scale is 10 ns per division.

The results of such measurements are given in Fig. 5 for two different time bases. In both cases, the period of each record was 100 ns (two cycles of the 20-MHz test signal), the sampling interval was 1 ns, and in notation used above, $m = 9$ and $n = 4$. Therefore, the total time epoch spanned by the 10, i.e., $m + 1$, shifted records is 100 ns $+ m \times n \times 1$ ns $= 136$ ns. The error data obtained from all 10 records are overlaid in the plots, giving up to 10 estimates per sample point for times in the middle of the range. The errors shown in Fig. 5(a) have an rms value of 7 ps over the 136-ns epoch and appear to be essentially random, indicating the limits of repeatability from run to run. These random errors can be reduced by averaging the ten plots. For the data plotted in Fig. 5(a), the rms value of the average is 1.7 ps, however, clear patterns are still not observable in the averaged data. The data for the poorer time base given in Fig. 5(b) is included as an example of results when the linearity errors are more evident.

B. Time-Varying Errors

Another significant source of time base errors results from phase noise between the sample commands and the input signal. The high frequency phase noise components produce jitter in consecutive samples; however, the large time constant and integration period of the feedback loop tend to filter out the amplitude noise resulting from these components. On the other hand, the low-frequency components of phase noise can cause relatively slow variations in the sampled amplitude which is actually tracked by the feedback loop, requiring excessively long integration periods for adequate filtering. Phase noise in the signal being measured, the trigger signal, and the delay generator can all contribute to the overall error. Errors due to phase noise are readily determined, however, by observing the integrator's output signal on an oscilloscope. With the delay set to sample the input waveform at a point where the rate of change is high, amplitude fluctuations resulting from phase noise are easily observed with the oscilloscope set for high sensitivity and ac coupling. The observed peak amplitude is the product of the peak phase displacement expressed in units of time, and the time rate of change of the input signal at the nominal sample instant. The equivalent timing uncertainty measured in this way is less than 10 ps (peak) when low phase noise input signals are used.

IV. Step-Response Parameters

A. Transition Duration (Rise Time)

Transition duration is measured by determining the duration between the 10- and 90-percent points of the recorded response to a step of much faster rise time. The measured transition duration for the SVT is approximately 600 ps.

B. Settling Time

The measurement of fast settling performance at high accuracy is especially difficult because of the lack of reference waveforms having the requisite characteristics. The best reference waveform sources available for much of this work appear to be those developed by one of the authors for use in characterizing the transient response of waveform recorders [3], [4]. From these two generators, fully programmable steps are available having settling times of <4 ns to 0.2 percent (full-scale range) accuracy, <6 ns to 0.1 percent, and <25 ns to 0.02 percent. These values, although not ideal, are nevertheless suitable for establishing rather tight bounds on the settling performance of the SVT. Figs. 6–8 present plots of the waveforms from these generators as measured with the SVT. The short and long term settling performance derived from these plots is summarized in Table I.

V. Bandwidth and Frequency Response

The accurate measurement of frequency response, i.e., gain versus frequency, is also difficult in this case due to the lack of adequate reference waveforms. A direct measurement of frequency response requires sinewave sources of resonable spectral purity and accurately known amplitude. Commercially available sources are not adequate in these respects at the frequencies of most interest, say, from 10 to 200 MHz. On the other hand, indirect measurements based on time-domain data [5] require very high performance step generators, preferably with transition durations on the order of 300 ps or less. Measurements based on the latter method have been made using an NBS step generator with 600-ps transition duration [6]. The frequency response was computed from the discrete-time impulse response which was in turn calculated from the step response [5]. The results are given in Fig. 9. In Fig. 9(a), the dashed plot is of the frequency response of the composite step generator-SVT system. The solid plot is an estimate of the actual frequency response of the SVT itself, obtained by deconvolving the equivalent response of the input step. For this computation, the input step was modeled in terms of an ideal single-pole response whose bandwidth was estimated from independent risetime measurements. The bandwidth of the SVT response thus estimated by deconvolution is 640 MHz, and some peaking is present. This is more evident in Fig. 9(b) in which the gain errors, i.e., the deviations from unity gain, are plotted. In this graph, the vertical axis has a split logarithmic scale to enable the representation of sign information. The dashed curve in Fig. 9(b) represents the gain error of an ideal single pole filter with a bandwidth of 640 MHz. Note that the peaking holds the gain errors to within 1 percent up to about 250 MHz.

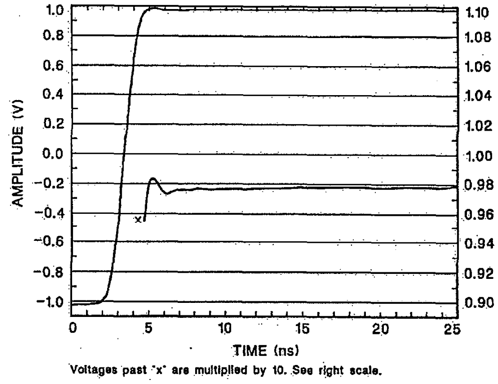

Fig. 6. Response to 2-V step from precision step generator [4], showing settling to 0.1 percent FSR in 4 ns. Note lower curve is magnified version of final settling, with scale shown on right side of plot.

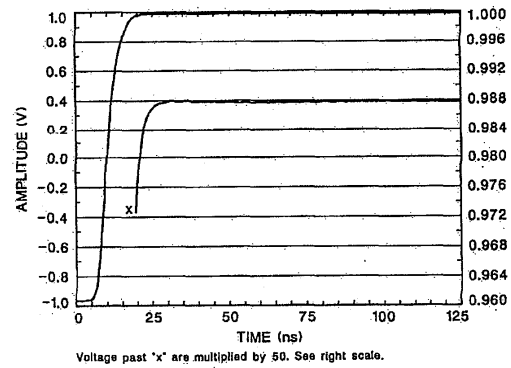

Fig. 7. Response to 2-V step from second (slower, more accurate) generator [3], showing settling to 0.02 percent FSR in 20 ns.

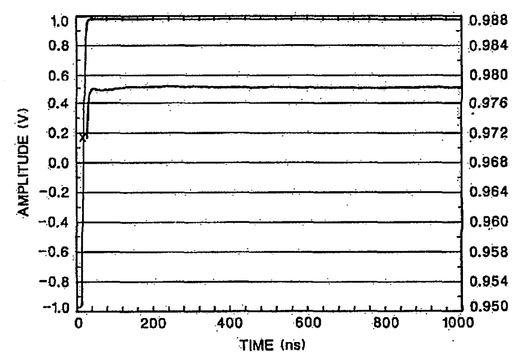

Fig. 8. Long term response to step from second generator, showing aberations less than 0.4 mV (0.02 % FSR) out to 1 μs.

VI. Conclusions

The results of the measurements described in this paper indicate that the SVT is capable of state-of-the-art time-domain measurements of repetitive RF signals. In addition

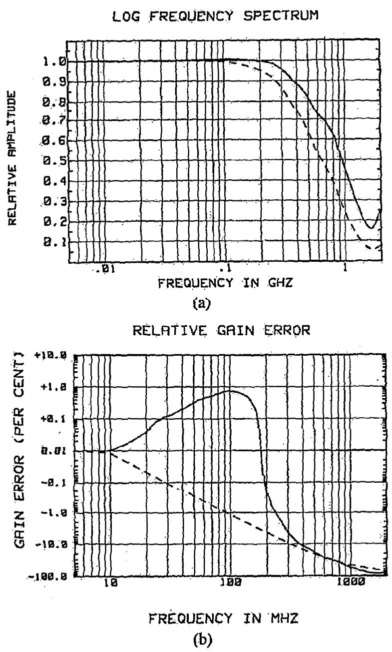

Fig. 9. (a) Frequency response derived from measured step response [5], based on equivalent time sampling rate of 10 GHz. The dashed plot is for the composite step generator-SVT system. The remaining plot is the response of the SVT itself, estimated using deconvolution. (b) Gain error of the SVT, computed from the estimated frequency response. Dashed line represents ideal gain error from single pole filter with 640-MHz cutoff frequency.

to the applications noted earlier, the system should also prove useful for accurate rms voltage measurements in the 1–100 MHz region, since the gain errors are small and repeatable, and the linearity errors are low. Accuracies approaching those of ac–dc thermal transfer instruments should be attainable.

With the exception of time base errors, the performance specifications listed in Table I are limited primarily by the SVT's comparator. As improved comparators become available, the overall performance of the SVT can be expected to improve as well. In addition, other circuit configurations can be used to minimize some of the comparator's limitations. For example, the comparator can be operated in a single ended configuration rather than the differential input configuration shown in Fig. 1. While this introduces some other complications, it relieves the comparator of common mode voltages, and leads to shorter transition duration, and possibly other improvements as well. Finally, a more compact system can be realized by substituting an up-down counter and D/A converter for the integrator in the feedback loop. This configuration would produce an equivalent time tracking A/D converter, eliminating the need for the DVM, and increasing the system's operating speed.

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