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Some effects of temperature variation on sampling oscilloscopes and pulse generators

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Abstract

The effects of temperature variation on the timebase errors and impulse responses of two 50 GHz bandwidth sampling oscilloscopes and on the pulse parameters of two pulse generators commonly used for oscilloscope calibrations are reported. The observed variations are significant for high accuracy measurements and contribute to the uncertainty of any measurements performed.

1. Introduction

Equivalent time, sampling oscilloscopes are now commercially available with 3 dB attenuation bandwidths exceeding 50 GHz. Pulse generators with transition durations of less than 16 ps are also commercially available. These high speed sampling oscilloscopes and pulse generators are used to make measurements needed to characterize high speed communications networks and components. These measurements are often made in locations where the temperature may change by several degrees Celsius between measurements. We have observed that the sampling heads and pulse generators may show differences due to changes in the ambient temperature. Furthermore, the uncertainties in the measurements may mean the difference between meeting specifications and failing an expensive network component.

2. Measurement set-up

We tested two different manufacturers' oscilloscope mainframes together with four different sampling heads and two different step generators. One sampling oscilloscope mainframe is identified as SM1 and the two sampling heads used with it are identified as SH1 and SH2. SH1 is a 50 GHz (3 dB attenuation bandwidth) sampling head and SH2 is a 20 GHz bandwidth sampling head. Similarly, the other sampling oscilloscope mainframe is identified as SM2 and the sampling heads used with it are identified as SH3 and SH4. SH3 and SH4 are, respectively, a 50 GHz (3 dB attenuation bandwidth) sampling head and a 20 GHz bandwidth sampling head. Each of these oscilloscopes was tested with two different manufacturers' step generators having a nominal bandwidth of 20 GHz. The step generators are identified as SG1 and SG2.

Before making any measurements, all instruments were allowed to warm up for at least two hours after applying power. This warm-up period was determined by attaching a temperature sensor to the cases of several instruments and observing the temperature of the instruments as a function of time. The measurements were performed by placing the instrument under test (oscilloscope mainframe, step generator or sampling head) inside an environmental chamber. This environmental chamber is located inside a shielded room where the temperature is controlled to within 1 °C over the measurement period. Only the temperature of the instrument under test was intentionally varied. The other components were kept at room temperature, 23.0 °C ± 1 °C. The sampling heads were connected to the oscilloscope mainframes using cabled extender modules purchased from the manufacturers. The step generator was connected to the sampling head using a high bandwidth (approximately 26 GHz) coaxial cable approximately 0.5 m long. When the step generators were being evaluated, a 50 GHz bandwidth sampling head was used. The trigger signal source was also kept at room temperature. The trigger signal input was located in the mainframe of one oscilloscope model and in the sampling heads of the other model. The temperature sensor was

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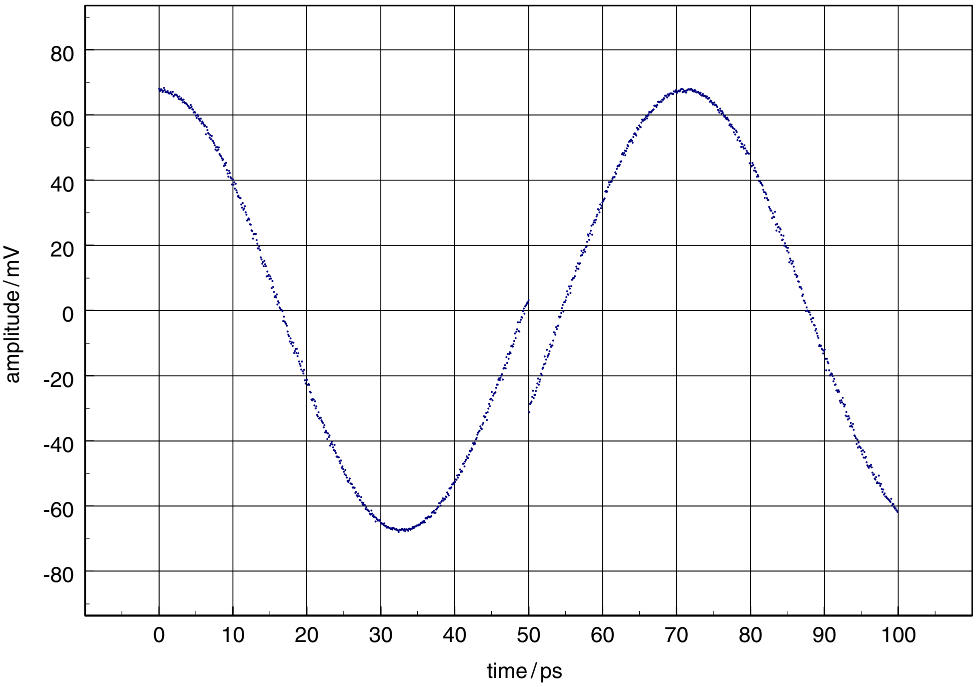

Figure 1. Waveform distortion caused by timebase error, 15 GHz sine wave.

a J type thermocouple and attached to the case of the instrument under test. The temperatures used in this work represent the manufacturers' narrowest specified operating temperature range (15 °C to 35 °C). The temperature was incremented in 5 °C steps. The instrument under test was kept at the target temperature for at least 30 min before measurements were made. In all cases, the temperature of the instrument varied by less than 0.2 °C during the measurements. At each set temperature, multiple waveforms were acquired, the parameters of interest determined and the mean and standard deviations of the parameters were calculated.

3. Sampling oscilloscope timebase errors

The timebase of a sampling oscilloscope generates an impressive range of epochs that can be varied from picoseconds to seconds, nine to eleven orders of magnitude. For the oscilloscope mainframes examined, the timebase consists of a startable oscillator and a time interpolator vernier (fine delay ramp) that has a delay range equal to one period of the startable oscillator. The timebase can be viewed as a repeated concatenation of the time interpolator vernier at every cycle of the startable oscillator until the desired epoch is achieved [1]. Unless the range of the time interpolator vernier is exactly one period of the startable oscillator, the sampling instant immediately after the concatenation occurs may differ from the intended sampling instant by several picoseconds. This timing error may produce a visible error in the waveform (figure 1). The time interpolator vernier, which has a range of several nanoseconds, is not perfectly linear and timing errors are also seen in that range. The non-linearity of the time interpolator vernier will also distort the waveform but this distortion is usually not obvious when observing an acquired waveform. The timing errors due to the non-linearity of the time interpolator vernier can be separated into two components, a fixed error in the reported sampling interval and a variable timing error that varies throughout the range of the time interpolator vernier. This first error component leads to the overall slope seen in the timebase error (figure 2). Although the second error component varies over the range of the time interpolator vernier, it varies the same way in each concatenation and can be seen as the repeating pattern in figure 2.

NIST has developed a method to characterize these timing errors [2] which has been used to obtain the results presented here. To summarize this technique, the single-frequency output from a synthesized sine-wave source is connected to the sampling oscilloscope and two or more unique waveforms are acquired. Each acquired waveform has a different phase relative to the trigger. The acquired waveforms are then compared to a theoretical sine wave and the residuals, divided by the derivative of the theoretical sine wave, yield the timebase error. The timebase error is the deviation of the actual time from the sampler reported time (intended time) as a function of the sampler reported time. It is evident from figures 1 and 2 that these timebase errors may impact measured pulse parameters [3].

To characterize the temperature dependence of the timebase error, an oscilloscope mainframe was placed in the environmental chamber while the 50 GHz bandwidth sampling head remained outside the environmental chamber at room temperature. The oscilloscope mainframe was allowed to come to thermal equilibrium by waiting 45 min before acquiring timebase data. A set of sine waves were acquired (two frequencies and multiple phases) and then the temperature was set to the next target temperature. This procedure was followed for both the mainframes tested. A subset of the results obtained is depicted in figures 3 and 4. The measurement

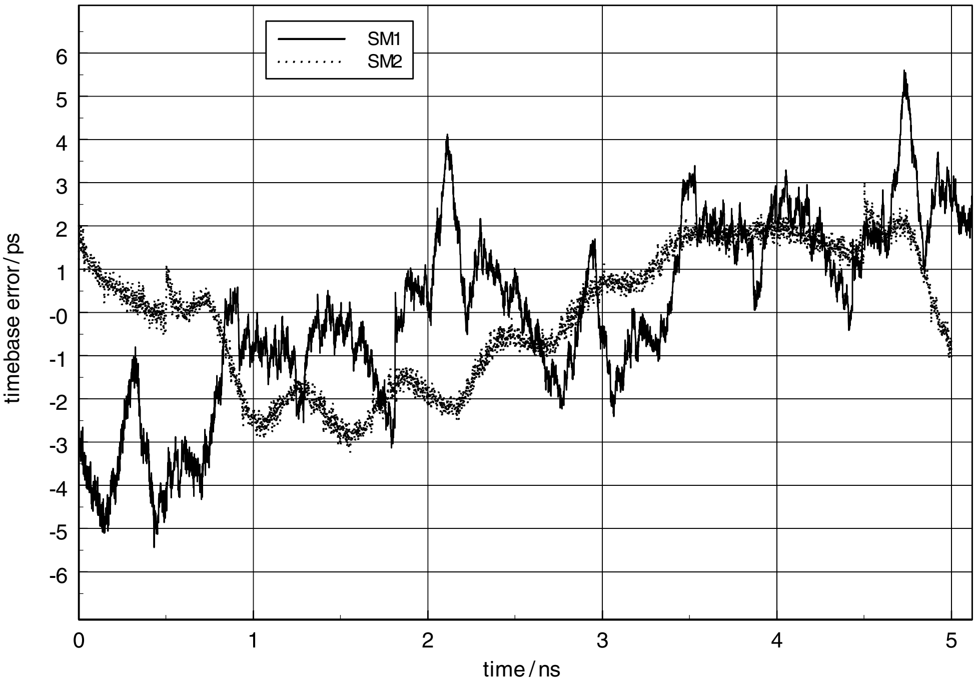

Figure 2. Timebase errors for SM1 and SM2 sampling oscilloscopes.

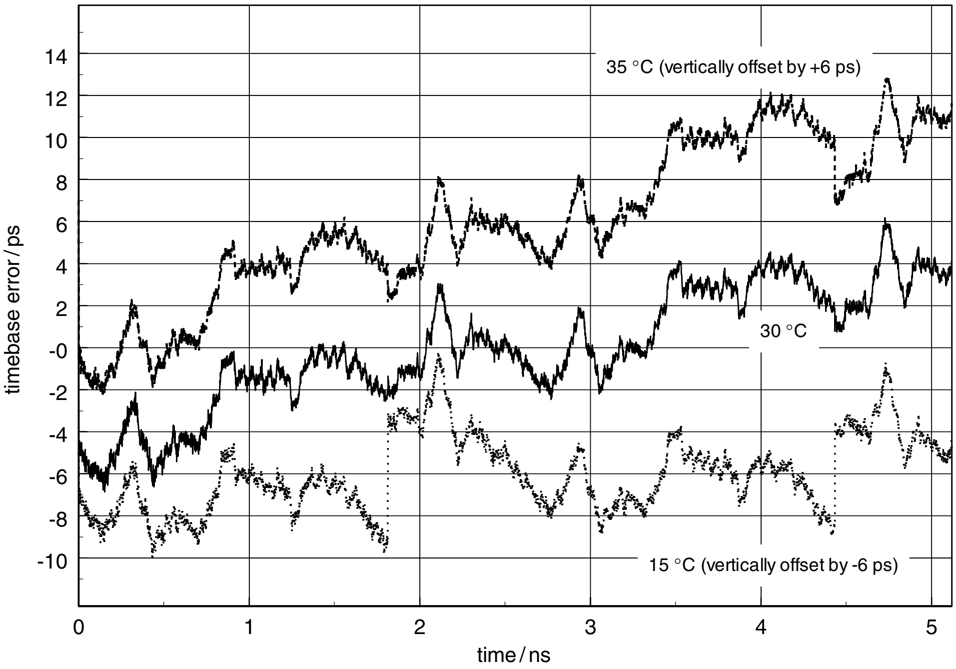

Figure 3. Timebase error for SM1 oscilloscope at three temperatures.

uncertainty corresponding to a 95% confidence interval is ±0.08 ps. The concatenation error for SM1 (see figure 3) is seen to go through a minimum and change sign near 30 °C. Over the range of temperatures used, the timebase error for SM2 (see figure 4) did not go through a similar minimum but decreased monotonically. The error in the reported sampling interval changes for both mainframes as indicated by the tilt of the graph of the error estimate. The variation of the non-linearity appears to be nearly constant with temperature for both mainframes.

4. Pulse parameters

The pulse amplitude, high state, low state and transition durations (10% to 90% and 20% to 80%) were determined according to the procedures outlined in IEEE Standard 181-2003 [4]. A histogram of the data is first created and the two maxima of the resulting bimodal distribution define the high state and the low state. The number of histogram bins used for the data presented here was 4096. The amplitude is the difference between the high state and the low state.

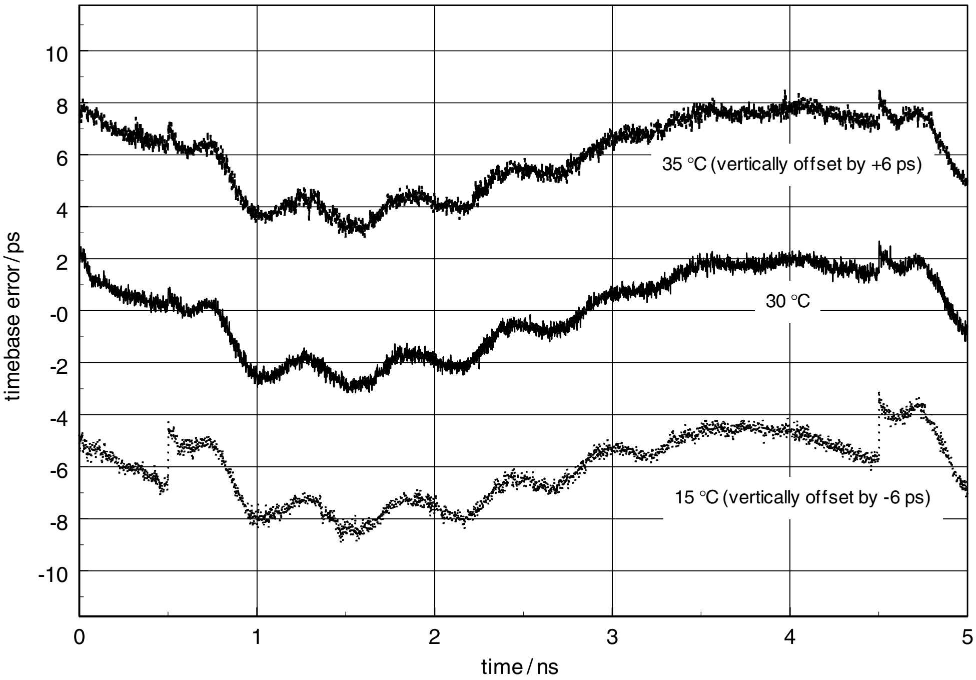

Figure 4. Timebase error for SM2 oscilloscope at three temperatures.

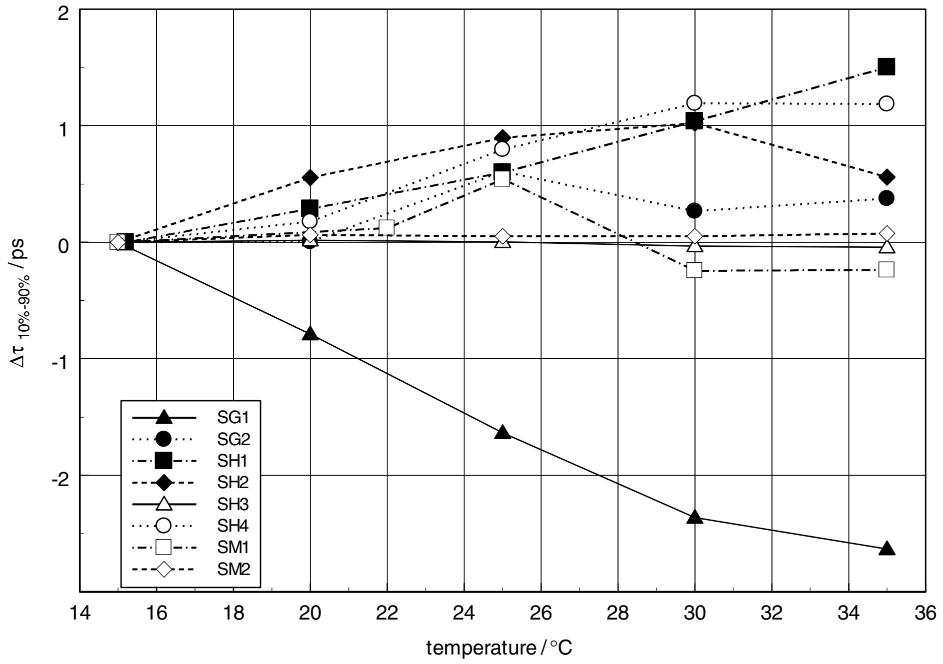

Figure 5. Change in transition duration (10% to 90%) as a function of temperature.

The 10%, 20%, 80% and 90% reference levels are calculated and their occurrence instants found by linear interpolation. The transition duration is the difference between the occurrence instants of the appropriate percentage reference levels.

The change in transition duration (10% to 90%) of all eight devices as a function of temperature is depicted in figure 5. Sampling heads SH1, SH2 and SH4 exhibited a small increase in transition duration (decrease in bandwidth) with increasing temperature. The transition duration of the waveform from step generator SG1 decreased significantly with temperature. Step generator SG2 exhibited only a small increase in transition duration with increasing temperatures. As previously mentioned, a set of data was obtained at each temperature; the maximum standard deviation observed in these sets of data was 0.206 ps.

Although the 10% to 90% transition duration is the most quoted pulse parameter, the 20% to 80% transition duration is included here and in the calibrations we perform. The 20% to 80% transition duration is affected less by aberrations than the 10% to 90% transition duration and, consequently,

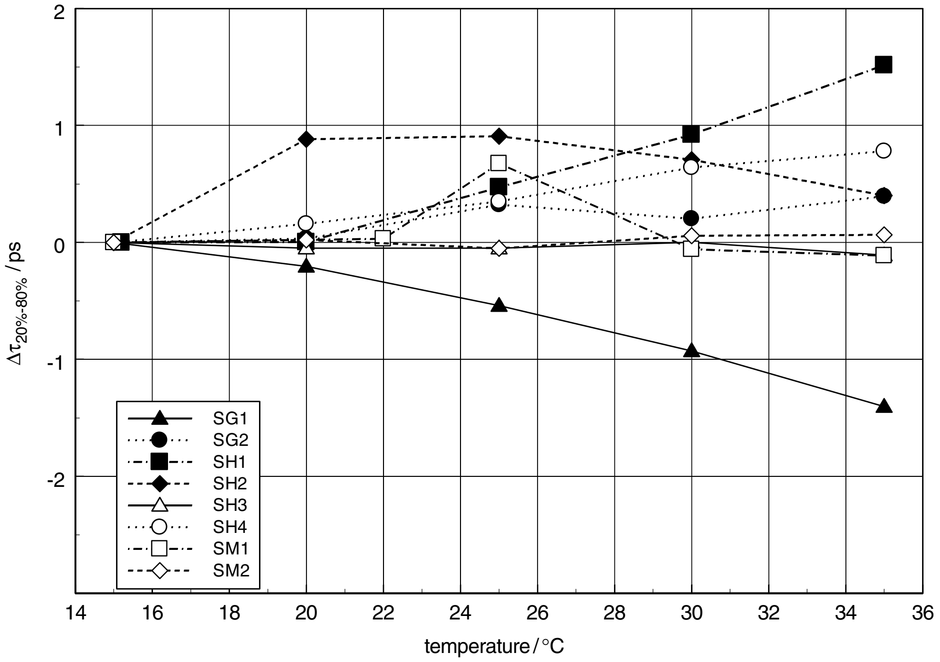

Figure 6. Change in transition duration (20% to 80%) as a function of temperature.

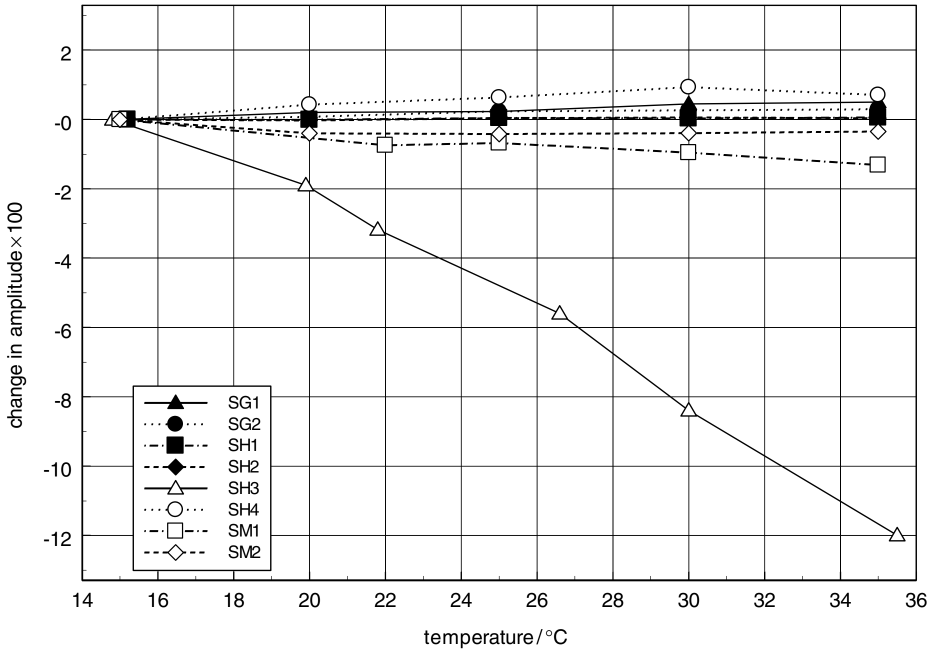

Figure 7. Change in amplitude (percentage) as a function of temperature.

often exhibits a smaller standard deviation. Figure 6 depicts the temperature dependence of the transition duration (20% to 80%) for all devices tested. These results were similar to the results for the 10% to 90% transition duration. The maximum standard deviation observed in any of the (20% to 80%) transition duration data sets is 0.130 ps.

Another parameter used to describe a pulse is the pulse amplitude. When the temperature is varied, both sampler gain and offset can vary. Figure 7 displays the amplitude changes we measured. SH3 displayed an unusually large decrease in amplitude with increasing temperature. To confirm this behaviour, a second sampling head of the same make and model was also tested with similar results. The other sampling heads and step generators exhibited increasing step amplitudes with increasing temperature. SH1 and SH2 (from the same manufacturer) were almost temperature invariant. For all the amplitude data reported here, the maximum standard deviation of a data set was 0.455 mV for a nominal pulse amplitude of 245 mV.

The changes in the voltage level associated with the high state and the voltage level associated with the low state were also examined and are depicted in figures 8 and 9. For sampling

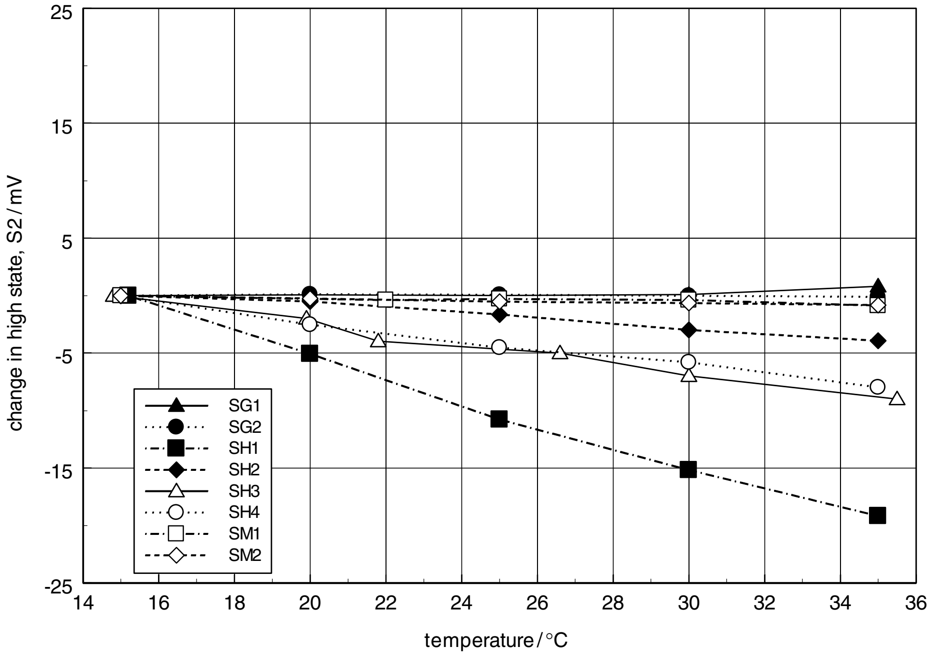

Figure 8. Changes in the high state, S2, as a function of temperature.

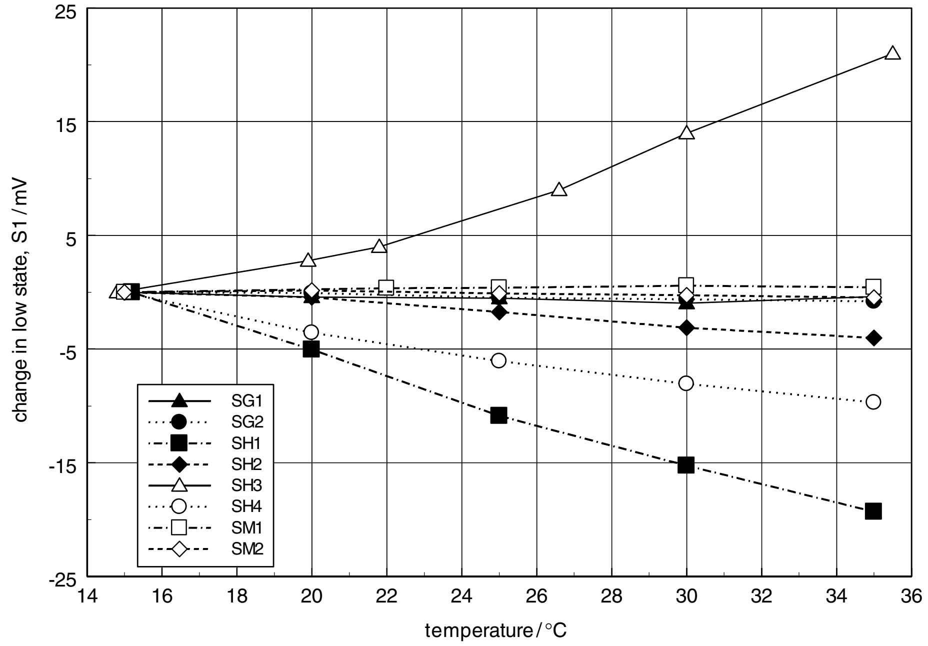

Figure 9. Changes in the low state, S1, as a function of temperature.

heads SH1, SH2 and SH4, the low states shifted to lower values as the temperature increased. However, because the high states exhibited a shift nearly equal to the low state shift and in the same direction, the change in amplitude (figure 7) for waveforms measured with these sampling heads is small. SH3, on the other hand, exhibited both a relatively large change in amplitude and offset. A waveform measured with this sampling head exhibited a decrease in amplitude and offset magnitude as the temperature increased.

The change in pulse parameters as a function of temperature for each device tested is summarized in table 1. Each entry is the slope of a straight line fit to the data for that particular step generator, sampling head or oscilloscope mainframe.

5. Transition occurrence instant

The position of the pulse in the epoch was also observed to change with temperature when the sampling oscilloscope mainframe, sampling head or pulse generator temperature varied. Figure 10 depicts the change in the transition occurrence instant (50% reference level instant) as a function

Table 1. Change in pulse parameters as a function of temperature, linear fit to data.

	High state slope/ (mV/°C)	Low state slope/ (mV/°C)	Amplitude slope/ (mV/°C)	10% to 90% transition duration slope/(ps/°C)	20% to 80% transition duration slope/(ps/°C)
SG1	0.033	−0.026	0.059	−0.137	−0.071
SG2	−0.006	−0.043	0.037	0.020	0.019
SH1	−0.976	−0.983	0.007	0.076	0.080
SH2	−0.206	−0.214	0.008	0.032	0.016
SH3	−0.435	1.043	−1.478	−0.003	−0.003
SH4	−0.385	−0.477	0.093	0.068	0.041
SM1	−0.037	0.024	−0.061	−0.017	−0.007
SM2	−0.040	−0.027	−0.014	0.003	0.003

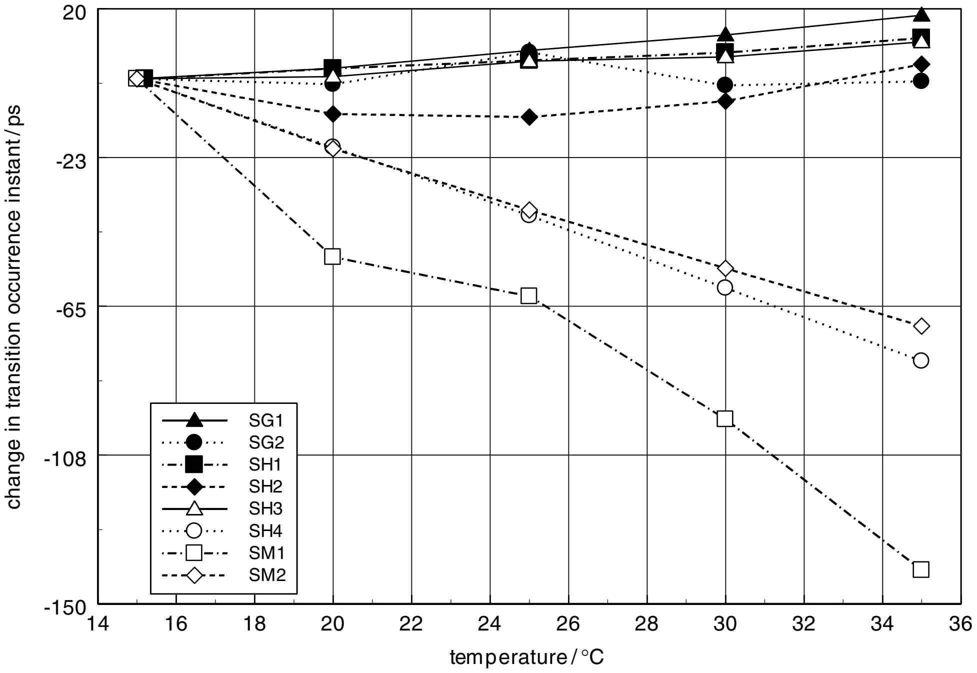

Figure 10. Change in transition occurrence instant (50% reference level instant) as a function of temperature.

of temperature. The maximum observed standard deviation for all instruments was 0.44 ps. For the sampling heads and pulse generators, this is independent of the temperature dependence of the timebase error or trigger signal since the oscilloscope mainframe temperature was held constant for those measurements. However, the large change in transition occurrence instant observed for SH4 is probably due to the trigger signal being routed through the sampling head. The changes observed for SM1 and SM2 are much too large to be the result of the change in the timebase error. Under certain conditions, the observed change in transition occurrence instant will have a significant effect on the transition duration. For example, if the temperature changes while a pulse waveform is being acquired and further, if the embedded waveform averaging routine is being used, the transition duration will increase as a result of this temperature-induced change in transition occurrence instant. It should be noted that the transition duration results presented previously were obtained at set temperatures and the small standard deviation of the measurements indicates that the change in transition occurrence instant was not a significant factor. This is indicative of a well-controlled environment, a necessity for a metrology facility involved in calibrating pulse generators and samplers.

6. Jitter

When making pulse waveform measurements, the acquired waveforms are impacted by the presence of trigger or system jitter. As with drift of the transition occurrence instant, averaging waveforms acquired in the presence of jitter will increase the transition duration. The effect on transition duration may be removed by measuring the jitter, modelling it with a Gaussian distribution and deconvolving the Gaussian distribution model from the acquired waveforms before determining the pulse parameters [5]. Because the measurements reported here are comparative, we did not remove jitter from any of the waveforms used. Consequently, the transition duration values will exhibit effects of the temperature dependence of jitter. However, the observed changes in jitter were much less than the uncertainty in our transition duration values. For SM1, the average jitter was less than 1.5 ps with a maximum standard deviation of 0.06 ps and varied less than 0.2 ps over the range of temperatures examined. For SM2, the average jitter was less than 1.0 ps with a maximum standard deviation of 0.02 ps and varied less than 0.03 ps over the temperature range used.

7. Summary

Changes in the error of the oscilloscope timebase have been characterized for two manufacturers' sampling oscilloscopes, both commonly used to characterize high speed digital communications networks and components. The changes in pulse parameters with temperature have been determined for two step generators, four sampling heads and two sampling oscilloscope mainframes. The transition duration measured by each sampling head increased (a bandwidth decrease) as the temperature increased except SH3 which displayed almost no change. Step generator SG1 produced a pulse with a faster transition duration (bandwidth increase) with increasing temperature. The step amplitudes for SG1, SG2, SH1, SH2, SH4, SM1 and SM2 were nearly insensitive to temperature changes, although level shifts were observed. This indicates a change in offset with temperature. No statistically significant changes in trigger or system jitter were observed. Changes in the pulse aberrations of overshoot and undershoot were also observed but are not reported here. Temperature-induced changes in pulse parameters and transition occurrence instant can contribute significantly to the uncertainty estimate [6, 7]. The results indicate a need for a well-controlled environment, typical of good metrology facilities, for pulse parameter measurements with low uncertainties. Although the results from the two sampling heads of the same model were similar, they were sufficiently different that each instrument had to be individually characterized. We note that when comparing measurement results from different laboratories using identical equipment or from the same laboratory but at different temperatures, the relative temperature differences must be known in order to explain the differences in results. Both sampling oscilloscopes examined here incorporated an embedded sampling head calibration routine. These routines were executed only once, before any measurements were made.

Acknowledgments

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