# Temperature Effects on the High Speed Response of Digitizing Sampling Oscilloscopes

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## ABSTRACT

We describe the effects of temperature on the performance of 20 GHz and 50 GHz digital sampling oscilloscopes and high speed pulse generators. The temperature of the sampling heads is varied through the manufacturer's specified minimum operating temperature range (15 °C to 35 °C) and the corresponding changes in the measured pulse amplitude, top level, base level, and transition duration (rise time) of a step-like pulse are presented. We also describe the effects of temperature on the pulses produced by two reference step generators commonly used to perform oscilloscope calibrations. Some of the measured changes with temperature are quite large.

## INTRODUCTION

One of the calibration services that we perform at NIST provides the pulse parameters for the step generators that are used by our customers as transfer standards for calibrating their oscilloscopes. The uncertainty analysis of measurements using digital sampling oscilloscopes should include the uncertainty due to the temperature fluctuations that occurred during the measurement. To calculate the magnitude of this uncertainty, the temperature dependence of the measured parameters must be known and the temperature of the equipment environment must be monitored. We have focused on the pulse amplitude and transition duration since these are parameters reported in our calibrations.

We tested four different sampling heads and two different step generators. SH1 and SH3 are 50 GHz (-3 dB attenuation bandwidth) sampling heads from different manufacturers. SH2 and SH4 are 20 GHz bandwidth sampling heads from the same manufacturers as SH1 and SH3, respectively. SG1 and SG2 are nominally 20 GHz bandwidth step generators from two different manufacturers.

## MEASUREMENT SETUP

The measurements were performed by placing the step generator or sampling head inside a bench top environmental chamber. This environmental chamber is located inside a shielded room that is temperature controlled to better than ± 1 °C over several hours. Only the temperature of

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the sampling head or the step generator head was intentionally varied. The temperature of the oscilloscope mainframe and step generator drive electronics was 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. 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 for the other models. A J type thermocouple was attached to the sampling head or step generator case. The temperatures used in this work represent the manufacturer's narrowest specified operating temperature range (15 °C to 35 °C). The temperature was incremented in 5 °C steps. The sampling head or step generator was kept near the target temperature for at least 30 minutes before measurements were made. In all cases, the device temperature varied less than 0.2 °C during the measurements. Multiple waveforms were acquired at each temperature and the mean and standard deviations of the measurement results were calculated.

The pulse amplitude, top level, base level and transition durations (10%-90% and 20%-80%) were determined according to the procedure outlined in IEEE Standard 181. A histogram of the data is first created and the two maximums of the resulting bimodal distribution define the top level and base level. The number of histogram bins used for the data presented here was 4096. The amplitude is the difference between the top level and base level. The 10%, 20%, 80% and 90% levels are calculated and their occurrence times found by linear interpolation. The transition duration is the time difference between the appropriate percent levels.

## RESULTS

The change in transition duration (10%-90%) as a function of temperature is depicted in Figure 1. Sampling heads SH1, SH2, and SH4 exhibited a small decrease in bandwidth (increase in transition duration) 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 at increased temperature. The repeatability of the results shown in figure 1 is indicated by the standard deviation; the maximum standard deviation from these measured data was calculated to be 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, often exhibits a smaller standard deviation. Figure 2 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 of all the (20%-80%) transition duration data reported is 0.130 ps.

Another parameter used to describe a pulse is the base level to top level amplitude. When the temperature is varied, both sampler gain and offset can vary. Figure 3 displays the amplitude changes we measured. SH3 displayed an unusually large decrease in amplitude with increasing temperature. To confirm this behavior, 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 (same manufacturer) were almost temperature invariant. For all the amplitude data reported here, the maximum standard deviation was 0.455 mV for a nominal pulse amplitude of 245 mV.

The changes in top level and base level were also examined and are depicted in Figures 4 and 5. For sampling heads SH1, SH2 and SH4, the base levels shifted to lower values as the temperature increased. However, because the top level exhibited a shift nearly equal to the base level shift, the change in amplitude (figure 3) 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 decreased in amplitude and shifted to lower voltages 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 line fit to the data for that particular sampling head or step generator.

TABLE 1.

| | top level slope (mV/°C) | base level slope (mV/°C) | amplitude slope (mV/°C) | 10%-90% transition duration slope (ps/°C) | 20%-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 |

## UNCERTAINTY

Commonly in a standards lab an unknown pulse generator is calibrated by a well characterized oscilloscope. During a measurement, the temperature variation exhibits both random fluctuations and a low frequency oscillation. The low frequency oscillation results in a linear temperature change during the course of a measurement. Considering only the effects due to this temperature variation, the error in the measured amplitude, for a given reference oscilloscope (or signal generator), can be approximated using the following equation,

$$A = A_{obs} + \Delta T \times dV/dT \qquad (1)$$

where $A_{obs}$ is the observed step amplitude, $dV/dT$ is the change in amplitude with temperature from Table 1, and $\Delta T$ is the temperature difference between a reference temperature and the device temperature when the measurements were made. After correcting the measurement results using equation 1, the Type B combined standard uncertainty[1] of the amplitude due to temperature effects is given by the root sum of squares of the product of the partial derivatives with respect to the terms that are uncertain, $\Delta T$ and $dV/dT$ and the uncertainty of those values, $U_{\Delta T}$ and $U_{dV/dT}$ (equation 2).

$$U_{A,T} = [(U_{\Delta T}\, dV/dT)^2 + (U_{dV/dT}\, \Delta T)^2]^{1/2}\,, \tag{2}$$

where $U_{\Delta T}$ is the one sigma equivalent temperature variation observed during the measurements and $U_{dV/dT}$ is the standard deviation in the amplitude versus temperature data. Following a similar development, the uncertainty due to temperature effects for the transition duration is given by

$$U_{\tau,T} = [(U_{\Delta T}\, d\tau/dT)^2 + (U_{d\tau/dT}\, \Delta T)^2]^{1/2}\,, \tag{3}$$

where $d\tau/dT$ is the change in transition duration with temperature from Table 1 and $U_{d\tau/dT}$ is the standard deviation in the transition duration versus temperature data. For a temperature range of 2 °C centered around an arbitrary reference temperature ($\Delta T = 0$), the amplitude uncertainty for SH4 would be 0.186 mV and the 10% to 90% transition duration uncertainty would be 0.136 ps.

## CONCLUSIONS

The change in pulse parameters with temperature have been determined for two step generators and four sampling heads. 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 shorter transition duration (bandwidth increase) with increasing temperature. The step amplitude was stable for SH1, SH2, SH4, SG1, and SG2, although level shifts were noted. Changes in pulse aberrations were also observed and are being investigated.

Temperature-induced changes in pulse parameters can contribute significantly to the uncertainty estimate. The results indicate a need for a well controlled environment for pulse parameter measurements. Although the results from two sampling heads of the same model were similar, they were sufficiently different that each device must be individually characterized. We may note that when comparing measurement results from different laboratories or the same lab at different temperatures, the relative temperature differences must be known to explain differences in results.

## Acknowledgements

We wish to thank T. M. Souders for his technical comments and B. A. Bell for administrative support. This work was partially funded by the U.S. Air Force Coordinated Calibration Group.

## Reference:

[1] Taylor, Barry N. and Kuyatt, Chris E., *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, NIST Special Publication 1297, 1994 Edition (U.S. Government Printing Office, Washington, DC, September 1994).

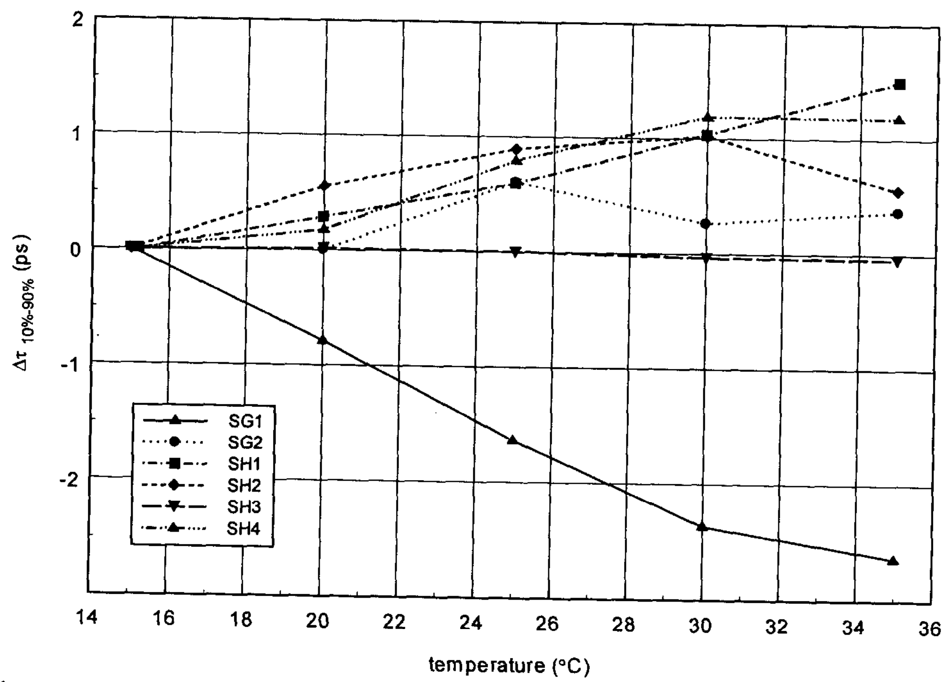

Figure 1. The change in 10% to 90% transition duration with temperature relative to 15 °C.

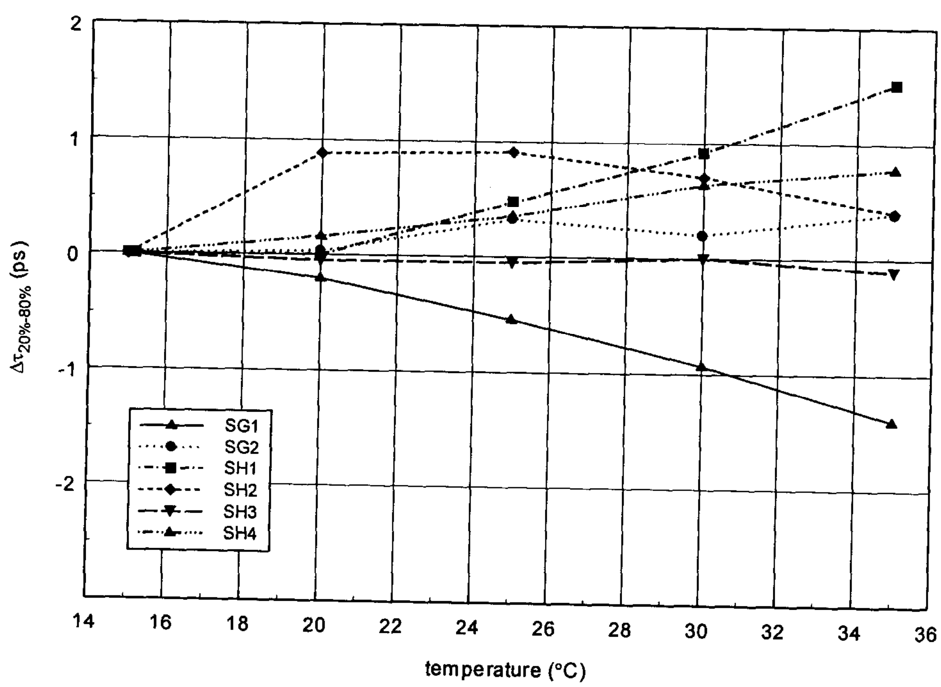


Figure 2. The change in 20% to 80% transition duration with temperature relative to 15 °C.

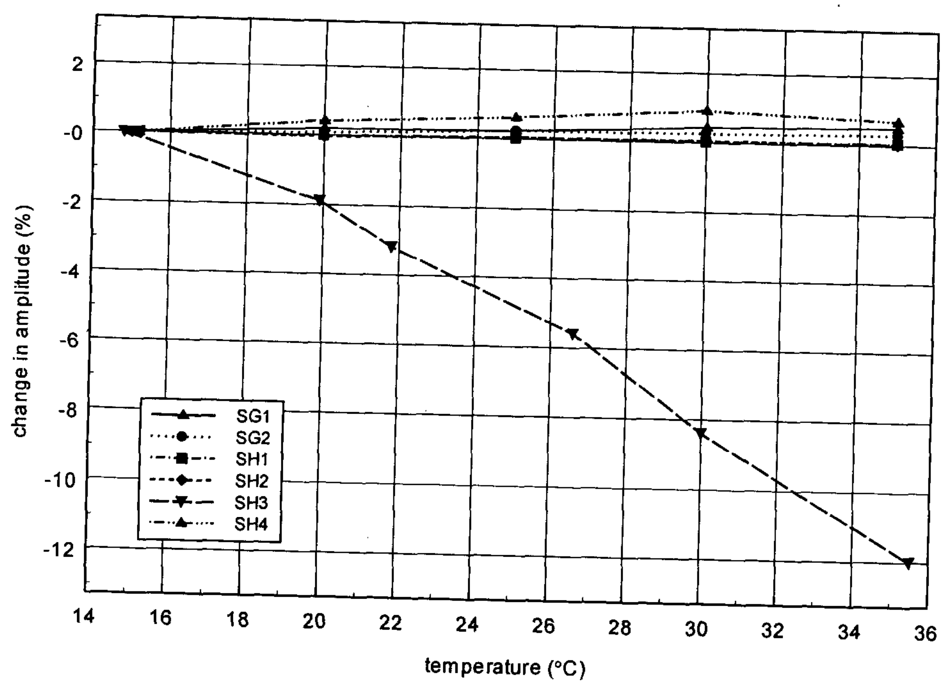


Figure 3. The percent change in pulse amplitude with temperature relative to 15 °C.

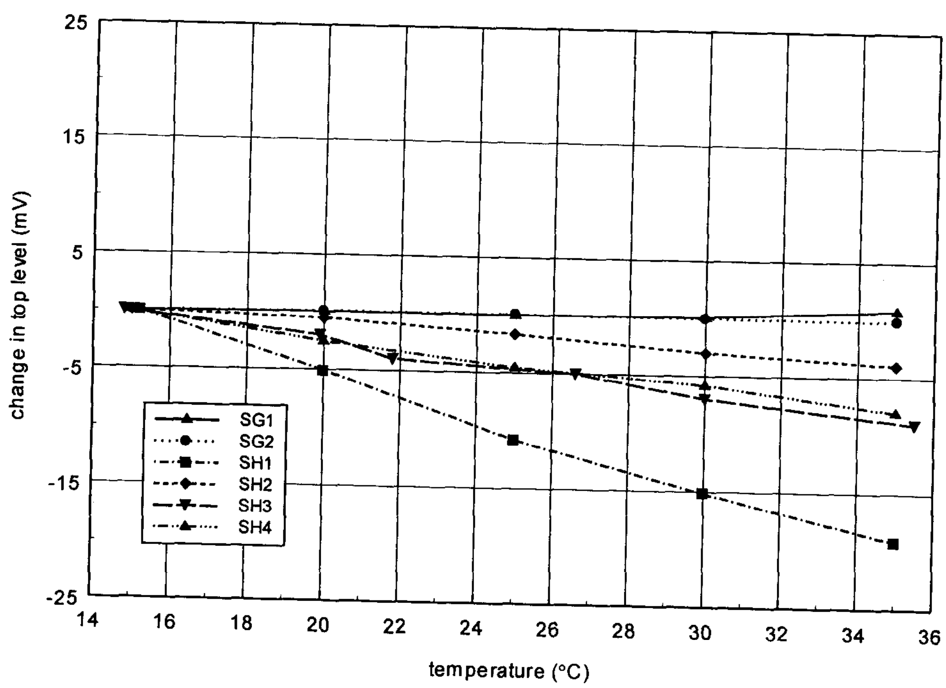


Figure 4. The change in pulse top level with temperature relative to 15 °C.

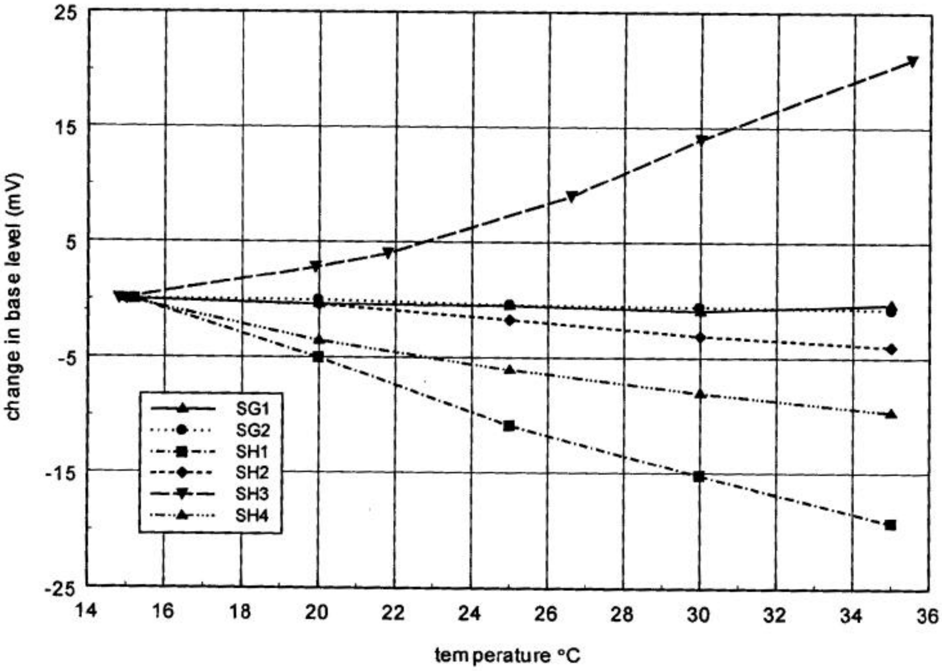

Figure 5. The change in pulse base level with temperature relative to 15 °C.