PICTIC Interpolator Linearity

W.J. Riley
Hamilton Technical Services
Beaufort, SC 29907 USA

Introduction

This document shows the results of a linearity test performed on a 1 PPS clock measuring system [1] using a PICTIC interpolating time interval counter [2]. Note that these tests used the original Rev. 1.0 Simple PICTIC design of 12/17/2008 and not the newer PICTIC II.

Test Setup

The linearity test was performed on the complete 1 PPS clock measuring system shown in Figure 1 by driving the A input from a rubidium oscillator and the B channel from a high-resolution 48-bit DDS synthesizer coherently referenced to the same Rb source. The DDS was programmed for a frequency offset of $5\text{x}10^{-13}$ to cause a linear phase change of 20 ns (the TIC clock period) in 40,000 seconds. The PICTIC coarse counter and scaled interpolator data were captured over a period of about 14 hours at a 1/s rate and averaged by a factor of 100 to correspond to about 1 ½ cycles of the 400 count TIC analog interpolator span.

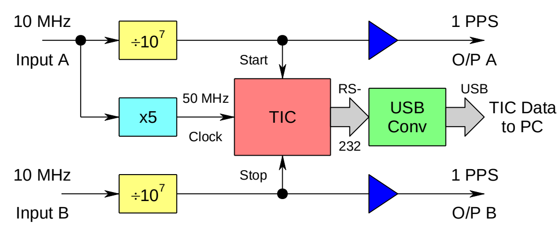

Figure 1. 1 PPS Clock Measuring System

Test Methodology

There are several ways to assess the linearity of a time interval interpolator [3], including observing the uniformity of the distribution of interpolator reading when measuring random time intervals, which can be used to calculate the differential and integral nonlinearity [4]. The method used here is particularly simple and direct, requiring no special test setup or analysis tools. It simply drives the measuring system from a coherent source having a small frequency offset that results in a slow linear phase change that exercises the full span of the analog interpolator under test. In the case of the system described here, the interpolator has a span of 400 counts corresponding to a range of 20 ns, and, in order to reduce the measurement noise, 100 samples are averaged for each interpolator state. The test was conducted after a normal automatic calibration. It should be noted that this test methodology observes the net readings of the two start and stop interpolators in the same way that they are used in an actual TIC measurement.

Test Results

The results of this TIC interpolator linearity test are shown in the figures below. Figure 3 shows the normalized phase data extending over a range of about ±13.5 ns, a bit more than one 20 ns clock period. The average phase slope corresponds to a frequency offset of $-5.07\text{x}10^{-13}$, close to the expected value. Variations around this line represent the interpolator nonlinearity, which have maximum excursions of about ±1 ns. There are both short and long term quasi-periodic variations along with a small amount of noise. The two horizontal lines at ±10 ns shown one 20 ns relative clock period. Figure 3 shows the interpolator readings, along with lines having unity slope corresponding to ideal performance for a 400 count span from 50 to -350. The maximum deviation from linearity is about 24 counts, 1.2 ns or 6% of full scale.

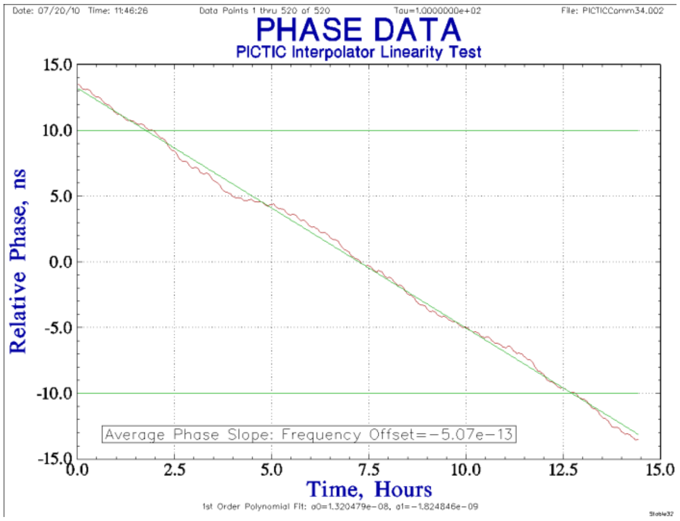

Figure 2. Normalized Phase Record

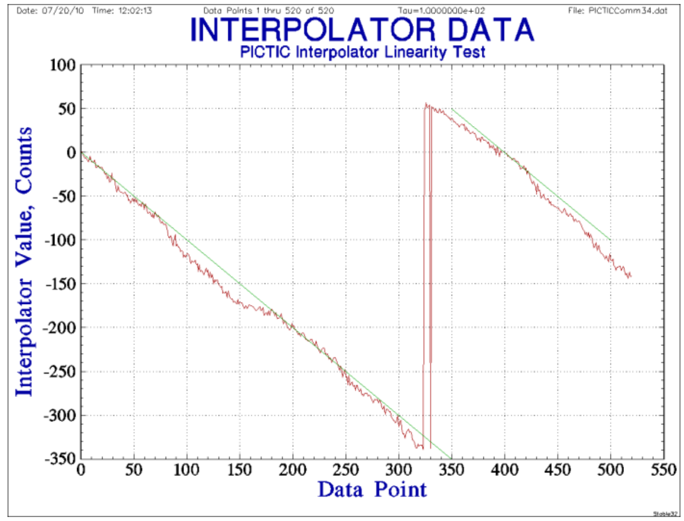

Figure 3. Interpolator Record

- Other Tests

A similar test was conducted over multiple interpolator cycles without averaging the 1-second data and with a larger frequency offset of 5×10^{-11} corresponding to 1 measurement per interpolator count. That test verified that the general behavior of the interpolators was quite repeatable over every cycle, establishing the possibility of error compensation. The interpolator data was unevenly distributed however, as shown in the histogram of Figure 5.

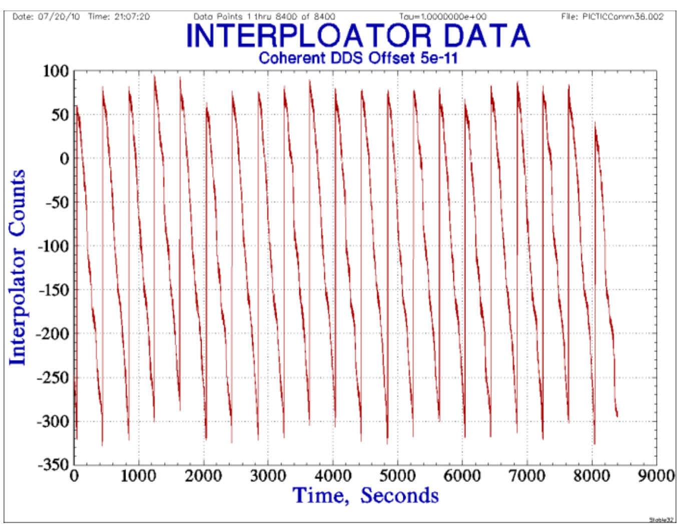

Figure 4. Interpolator Data

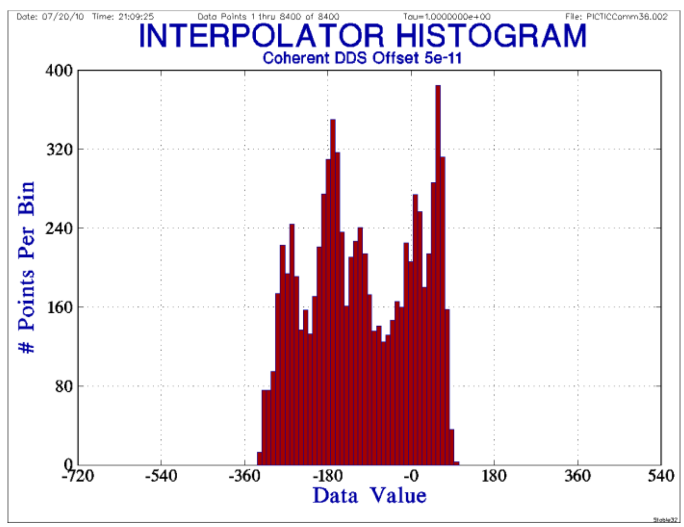

Figure 5. Interpolator Histogram

Analysis of a larger ≈ 35,000 point data set of this type produced the histogram of Figure 6, and, using the methodology of Equations (17) and (18) of Reference 3, resulted in a maximum integral nonlinearity (INL) of -8.7%.

Other fully-coherent tests have shown a p-p noise level of about ±4 interpolator counts without averaging.

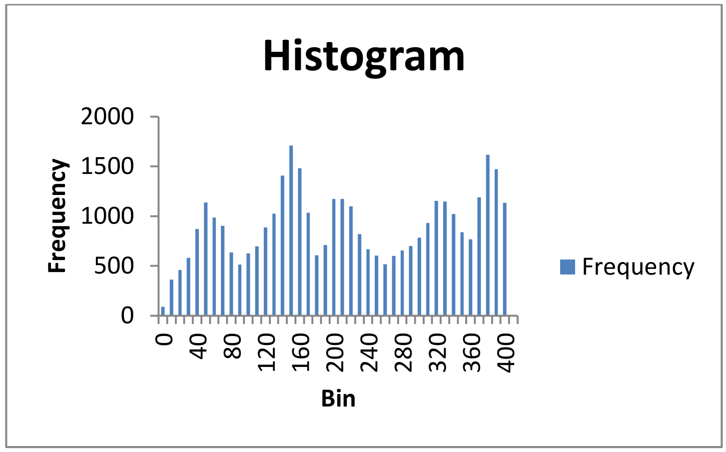

Figure 6. Interpolator Histogram

Discussion

The PICTIC analog interpolators have both short and long range nonlinearity plus noise that together limits their effective resolution. The short range variations are quasi-periodic, and appear to be related to coherent interference between the clock and interpolator logic. Changes in the clock source (a free-running crystal oscillator, a phase-locked crystal oscillator, a synthesizer with adjustable frequency offset, and a harmonically multiplied source) affect the character of this interference but do not eliminate it. One wonders if a multilayer board with full ground and power planes would improve this situation. The longer range variations in the interpolator characteristic appear to be intrinsic to the interpolator design and implementation. The PICTIC interpolators used for this test had 470 pF silver mica integrating capacitors and used a 5 mA nominal current source. The effect of interpolator configuration and such parameters as charging current and integrating capacitor type and value are variables that could be usefully explored.

Conclusion

The PICTIC analog interpolator has about 6-9% maximum nonlinearity that limits its accuracy, but it nevertheless provides a very useful resolution enhancement midway between that of the clock period (20 ns) and the interpolator increment (50 ps).

References:

1. W.J. Riley, "Examples of 1 PPS Clock Measuring Systems", Hamilton Technical Services, July 14, 2010.
2. R. McCorkle, PICTIC Time Interval Counter.
3. J. Kalisz, "Review of Methods for Time Interval Measurements with Picosecond Resolution", *Metrologia* **41** (2004), 17-32.
4. J. Kalisz, et al, "Error Analysis and Design of the Nutt Time Interval Digitizer with Picosecond Resolution", *J. Phys. E. Sci. Instrum.*, **20**, 1330-1341.

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W.J. Riley
Hamilton Technical Services
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