Temperature Coefficient of the PicoPak Clock Measurement Module

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- **Introduction**

This report describes the results of tests and analysis of the phase temperature coefficient of several PicoPak clock measurement modules.

- **PicoPak TC Measurements**

PicoPak S/N 103 was placed in an insulated Igloo box containing a Variac-controlled incandescent lamp as a heater. The module reference and signal inputs were driven coherently from the same stable 10 MHz source, and its temperature was measured by a thermocouple probe attached to the top of its enclosure. The heater was set to establish a significant rise while recording its phase response as shown in Figure 1.

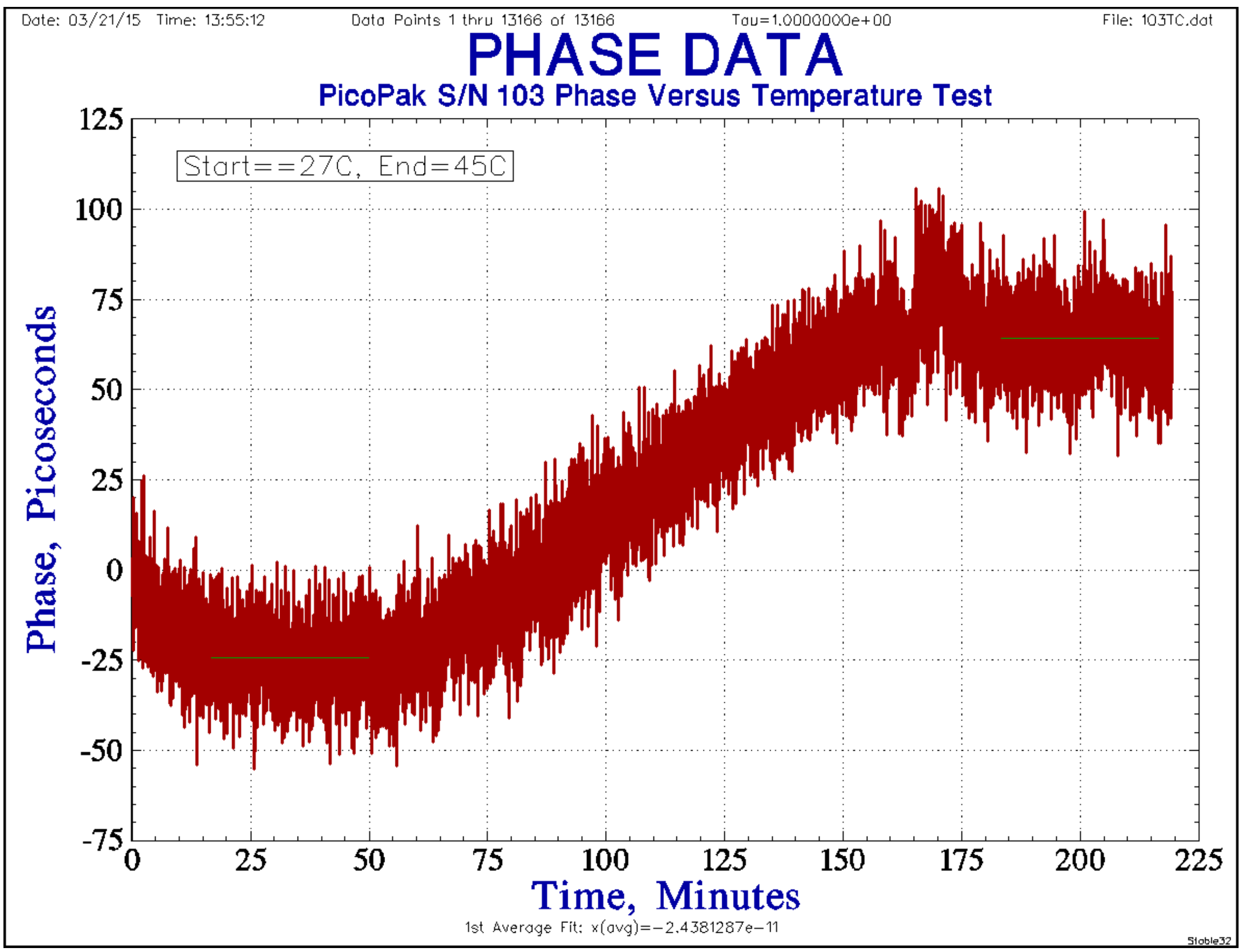

Figure 1. PicoPak S/N 103 Phase Vversus Temperature

The PicoPak phase increased smoothly from -24 ps to +64 ps, an increase of 88 ps, as its temperature increased from +27°C to +45°C, an increase of 18°C, resulting in a measured temperature coefficient of +4.9 ps / °C.

A similar test was conducted with PicoPak S/N 105, as shown in Figure 2

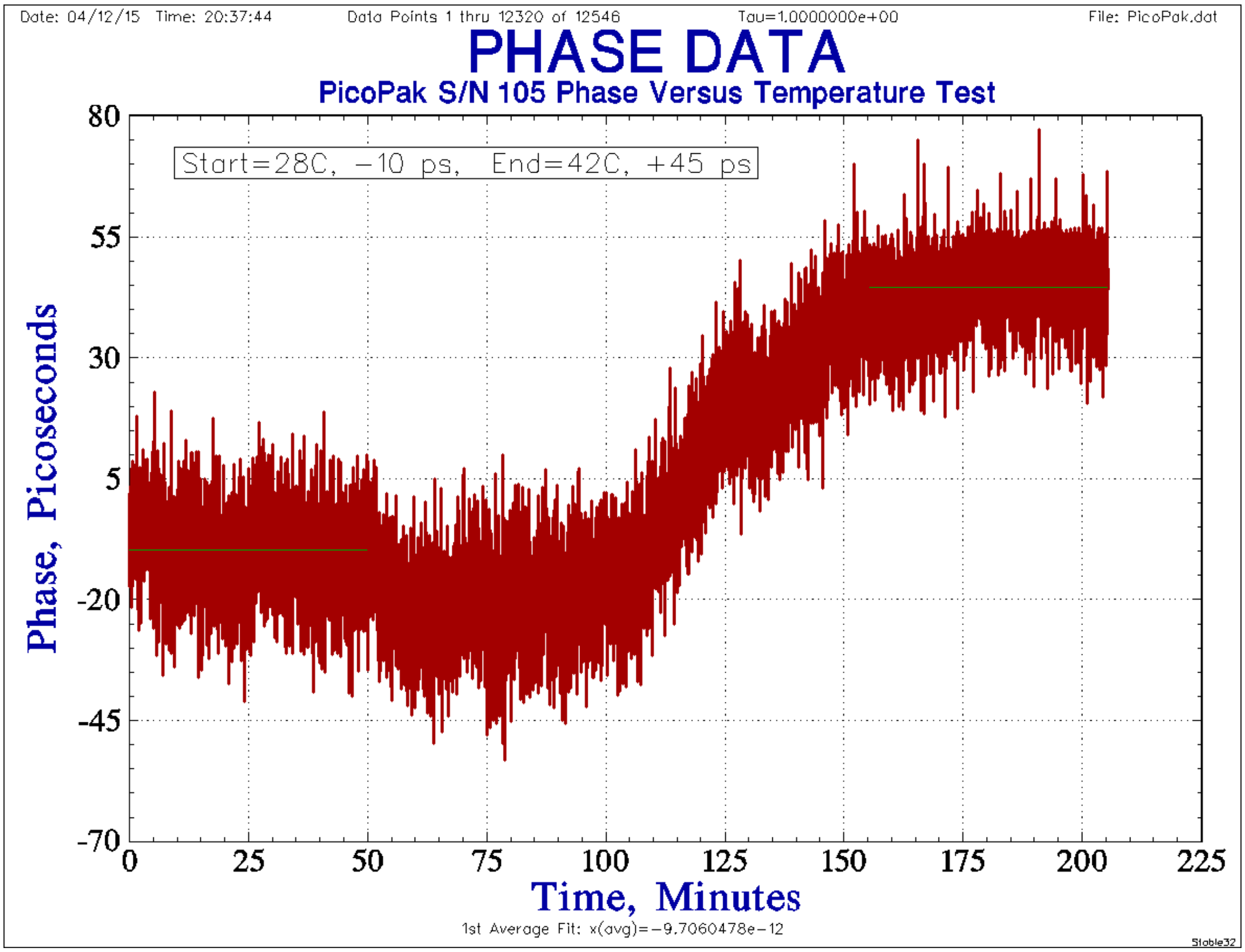

Figure 2. PicoPak S/N 105 Phase Versus Temperature

The PicoPak S/N 105 phase increased smoothly from -10 ps to +45 ps, an increase of 55 ps, as its temperature increased from +28°C to +42°C, an increase of 14°C, resulting in a measured temperature coefficient of +3.9 ps / °C.

- **TC Contributors**

There are several possible factors that could contribute toward the PicoPak phase temperature coefficient, including (a) phase detector DC offset voltage TC, (b) RF buffer amplifier phase TC, (c) DDS clock balun transformer phase TC, (d) DDS output balun transformer phase TC, (e) DDS reconstruction low pass filter phase TC, (f) DC amplifier offset voltage and/or gain TC, and (g) PIC comparator threshold voltage TC.

- **TC of Phase Detector DC Offset Voltage**

The PicoPak clock measurement module [1] uses a Mini-Circuits SYPD-1+ diode ring phase detector [2], which has a specified DC offset voltage of 0.2 mV typical and 1 mV maximum.

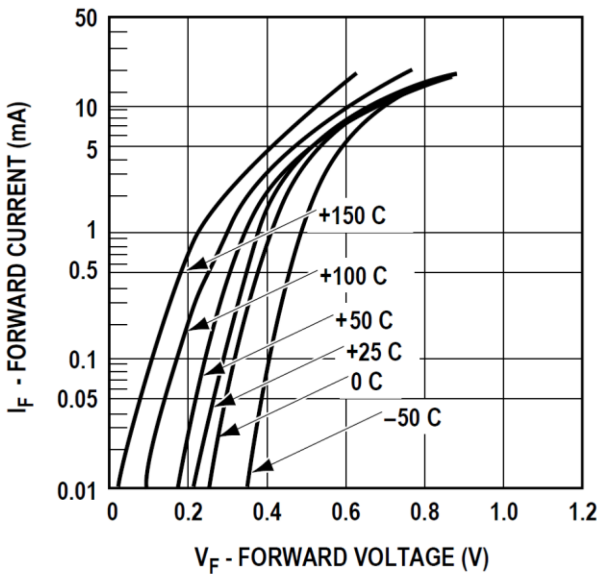

Figure 2. V-I Characteristics of 1N5711 Schottky Diode versus Temperature

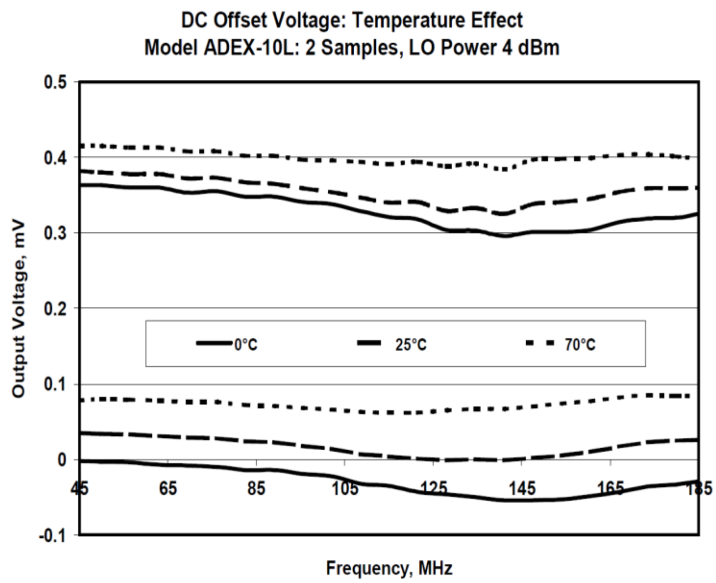

Figure 3. DC Offset Voltage versus Temperature for Mini-Circuits ADEX-10L Phase Detector

Figure 2 [3] shows that the forward voltage of a 1N5711 small signal Schottky diode is about 0.4 volts at a current of 1 mA and that it varies by about -1.2 mV per °C (both about half that of a Si diode). These diodes are available as matched pairs and quads with $\Delta V_F \le 10$ mV. Since the SYPD-1+ DC offset is specified as one-tenth that, Mini-Circuits must do an exceptionally good job of matching.

Figure 3 [4] shows the DC offset voltage versus temperature of a typical Mini-Circuits diode ring phase detector (private communication [5] indicates that the SYPD-1+ is similar).

If we say that the SYPD-1+ DC offset match is 1 mV compared with a forward drop of 400 mV, then it is reasonable to assume that a diode TC of -1.2 mV/°C is reduced by a similar factor to about -3 µV/°C or -0.21 mV over 70°C. Thus the Figure 3 TC value of about 0.1 mV over 70°C seems credible.

In the PicoPak application, at 10 MHz, the SYPD-1+ phase detector has a sensitivity of about 35 ps per mV [1] so ans offset voltage TC of about 1.5 µV/°C per Figure 3 corresponds to a negligible phase TC of only 0.05 ps/°C.
Additional information about double-balanced diode ring mixers as phase detectors and their DC offset and its temperature coefficient can be found in Reference [5].

- **PicoPak Component Phase TC Measurements**

A PicoPak module can be used to measure the phase stability versus temperature of a two-port device such as an RF transformer, RF amplifier or filter by splitting the output of an RF source, applying one as the reference input and the other, via the device under test (DUT), as the signal input. The DUT (only) is exposed to varying temperature and the PicoPak inputs are otherwise coherent except for the effect of temperature on the DUT. This test setup is shown in Figure 4. This is an excellent PicoPak application.

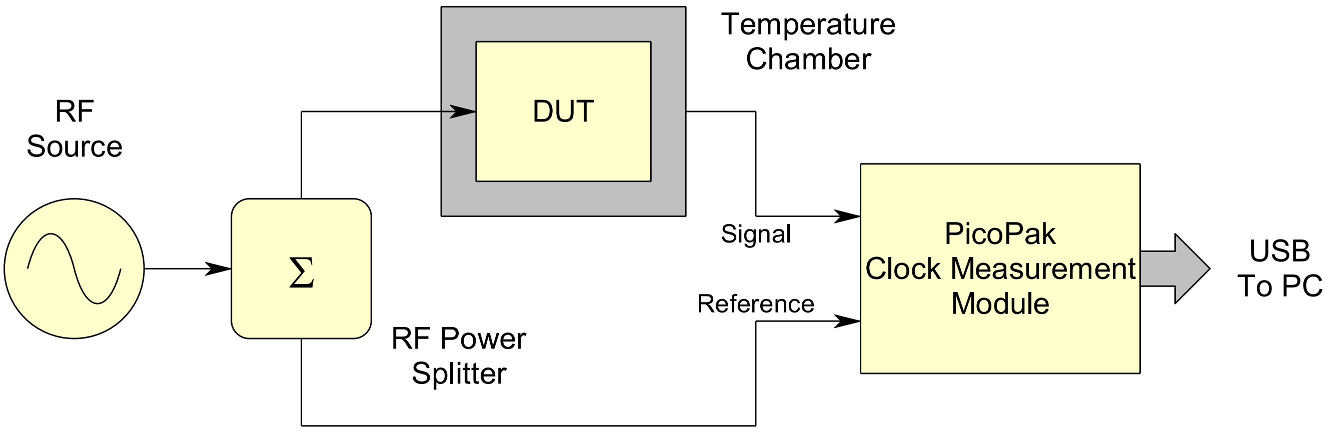

Figure 4. Device Phase TC Test Setup

- **TC of RF Balun Transformer Phase**

A Mini-Circuits TC1-1TG2+ balun transformer (with the secondary CT unconnected) was tested at 10 MHz for its phase stability versus temperature using the setup shown in Figure 4. The temperature was varied from 26.6°C to 40.0° over a period of 2 ¾ hours and the phase of the signal was observed to change by +22 ps, a phase TC of +1.6 ps/°C. This is about one-third of the TC observed for the complete PicoPak module, and could therefore be considered a significant but not dominant contributor. There are, however, two such transformers in the PicoPak design, at the DDS clock input and its RF output, which could potentially double, or even cancel, the balun transformer's contribution. It would be interesting to try reversing the phase of one on these transformers and re-measuring the overall PicoPak phase TC. In practice, however, the sense of the balun transformer phase TC may not be consistent unit-to-unit.

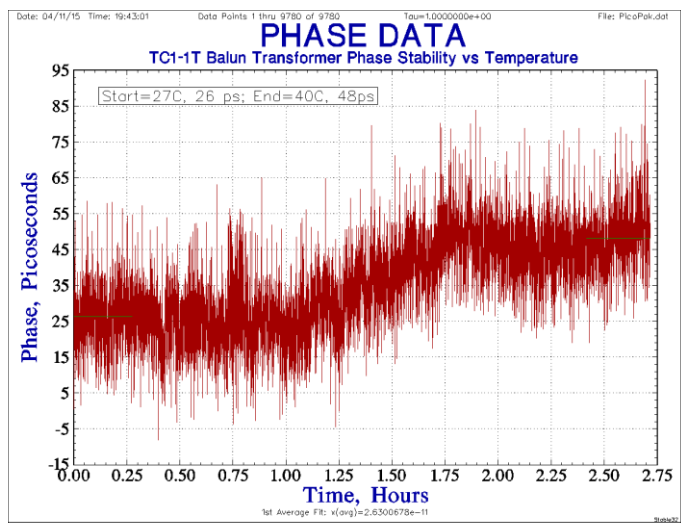

Figure 5 Phase TC of TC1-1T Balun Transformer

- **TC of RF Buffer Amplifier Phase**

The phase stability versus temperature of a PicoPak LMH6609 3 dB RF buffer amplifier (see Figure 6) was tested with the same Figure 4 setup at 10 MHz as shown in Figure 7.

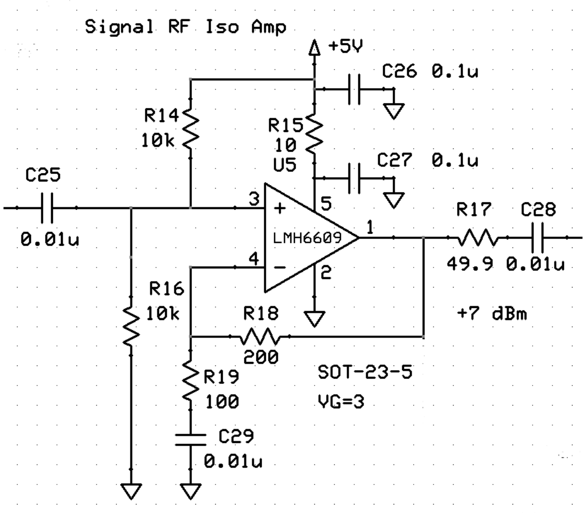

Figure 6. RF Buffer Amplifier Schematic

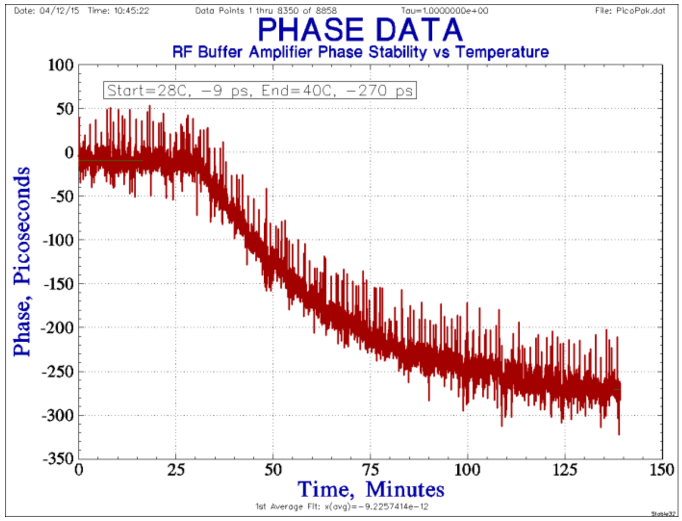

Figure 7. Phase TC of RF Buffer Amplifier

This amplifier on an early developmental board had a very significant phase TC of about -21.9 ps/°C. The C28 0.01 µF output series capacitor has a nominal reactance of –j1.6Ω and a phase shift of about 500 ps at 10 MHz. It has X7R dielectric which has a typical capacitance change of about -3% from +25°C to +50°C, so one would expect this component to cause a phase change of about 15 ps over that temperature range. The C3 input capacitor has little effect but C29 in the feedback network could also be significant. Changing C28 and C29 to 0.1 µF might be a good idea. The PicoPak signal and reference (DDS output) channels driving the phase detector both have identical RF buffer amplifiers of this type and apparently there is a high degree of cancellation of their individual phase TCs.

A similar test on another "identical" amplifier showed much less phase TC: -1.6 ps/°C.

- **TC of DDS Reconstruction Low Pass Filter Phase**

The phase stability versus temperature of a PicoPak DDS LPF (see Figure 8) was also measured at 10 MHz with the Figure 4 test setup as shown in Figure 9.

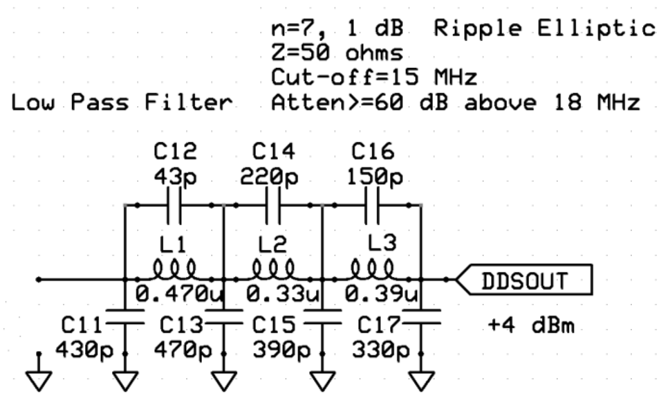

Figure 8. DDS Low Pass Filter Schematic

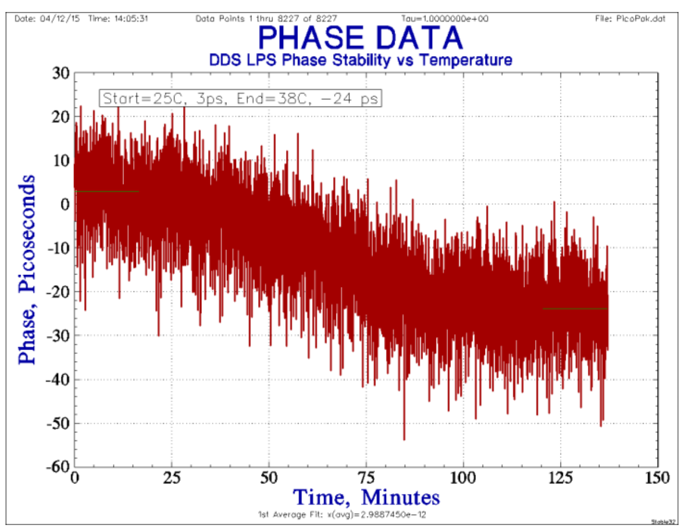

Figure 9. Phase TC of DDS LPF

The DDS LPF has a nominal phase response of -190° at 10 MHz that varies about -25°/MHz, and it has a fairly small phase TC of about -2.0 ps/°C.

- **TC of DC Amplifier Offset Voltage**

The DC amplifier is referenced to the regulated 3.3V supply via a resistive voltage divider. These 0603 1% metal film resistors have a nominal TC of ±100 ppm/°C, a maximum differential TC of 200 ppm/°C, and can therefore cause up to a 0.33 mV/°C TC of the 1.65 VDC reference voltage. The phase detector has a nominal sensitivity of 35 ps/mV at 10 MHz, so the resulting worst case TC is about 12 ps/°C. However the typical TC would be expected to be much less than that. The TC effect pf the LMV772 op amp offset voltage is negligible since it has a typical offset voltage TC of only 0.35 µV/°C.

- **TC of PIC Comparator Offset Voltage**

The PIC comparator is referenced to its internal stable fixed voltage reference (FVR) and should therefore have a negligible TC effect. It is specified to have a typical TC of -114 ppm/°C, is set at a nominal value of 1.66 VDC, and therefore has a nominal TC of 0.19 mV/°C. After amplification by x11, the phase sensitivity at the comparator input is 3.2 ps/mV, so the net TC caused by the FVR is only about 0.6 ps/°C. The TC of the comparator offset voltage is not specified.

- **TC of PC Board**

The FR4 PC board material could contribute a TC because of its transmission line capacitance and phase/length change. The TC of ε_r for FR4 is quite high (+600 ppm/°C), and the line phase varies as its square root, so that TC is +300 ppm/°C. For a 6" line length (0.5 ns), the phase change would be only about 0.15 ps/°C. But this effect has the observed sense, and deserves further consideration. A 2 foot length of solid polyethylene dielectric coax cable was measured as having negligible phase TC.

- **Additional Temperature Tests**

Additional temperature tests were performed on PicoPak S/Ns 103 and 108 using a small thermoelectric heater/cooler box [7] as shown in Figure 10. The signal and reference inputs of the PicoPak under test were driven at +4 dBm nominal by splitting the RF power from an LPRO rubidium oscillator. The RF power splitter was outside the box so that its temperature sensitivity, if any, was not a factor. The PicoPak made ordinary coherent phase measurements using its standard Windows® user interface. The temperature measurements were made with an Extech EasyView11A thermometer. The two RF, thermocouple and USB connections were brought out of the box with relatively long cables to provide some thermal guarding. This setup provided temperatures from about +10°C to +45°C.

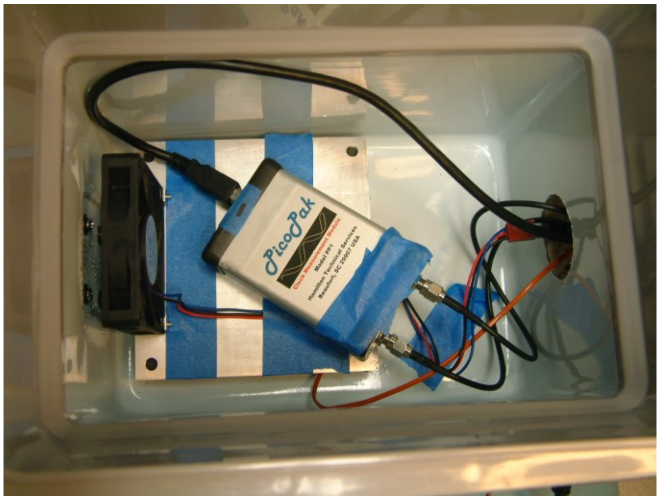

Figure 10. PicoPak in TEM Heater/Cooler Box, showing interior of box with fan, fan wiring, aluminum plate, PicoPak module, USB cable, thermocouple, and RF coax cables.

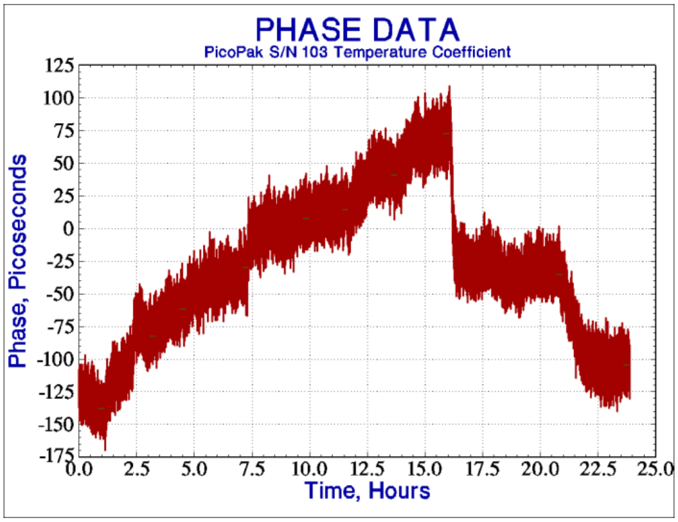

Figure 11. PicoPak S/N 103 Phase Record

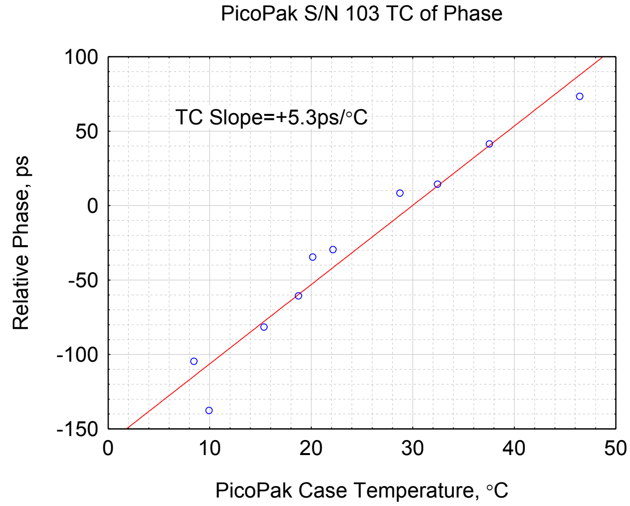

Figure 12. PicoPak S/N 103 Phase TC

The results for PicoPak S/N 103 are shown in Figures 11 and 12, and tabulated at the right. The module had an average phase TC value of about +5.3 ps/°C over the whole +8.5°C to +46.5°C range. The phase versus characteristic was smooth and quite uniform throughout although hard to quantify exactly within the noise.

The green lines in Figure 11 are the 1000-point averages at the various temperatures (left to right in the plot, top to bottom in the table).

°C	ps
10.0	-138
15.4	-82
18.8	-61
22.2	-30
28.8	+8
32.5	+14
37.6	+41
46.5	+73
20.2	-35
8.5	-105

A short 3-point run was done first for PicoPak S/N 108 as shown in Figure 13 and the adjacent table. The green lines in the plot are the following 1000-point averages at the various temperatures (left to right corresponding to top to bottom in the table). The end-to-end TC slope is only +2.0 ps/°C.

°C	ps
7.5	-124
22.0	-79
42.3	-53

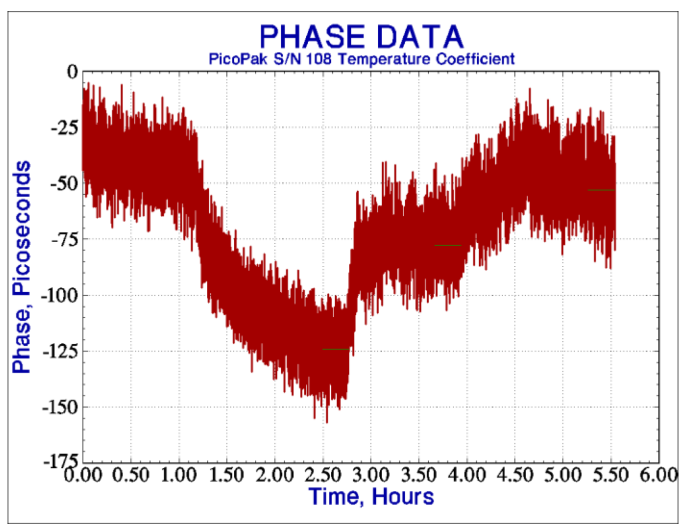

Figure 13. PicoPak S/N 108 Phase Record

A more detailed run for PicoPak S/N 108 is shown in Figures 14 and 15.

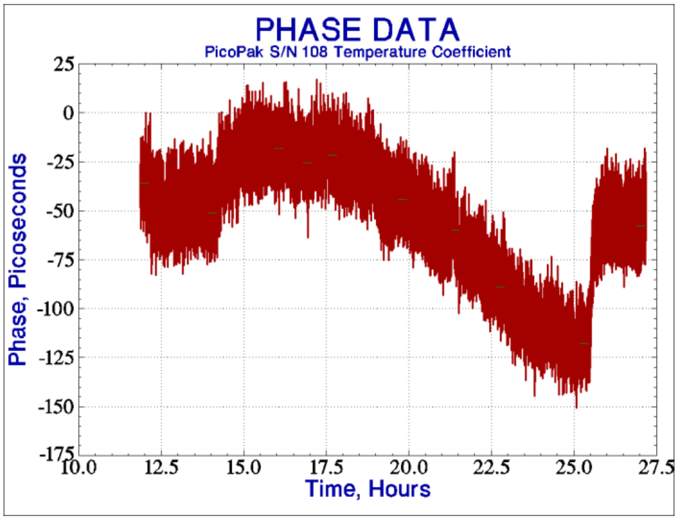

Figure 14. PicoPak S/N 108 Phase Record

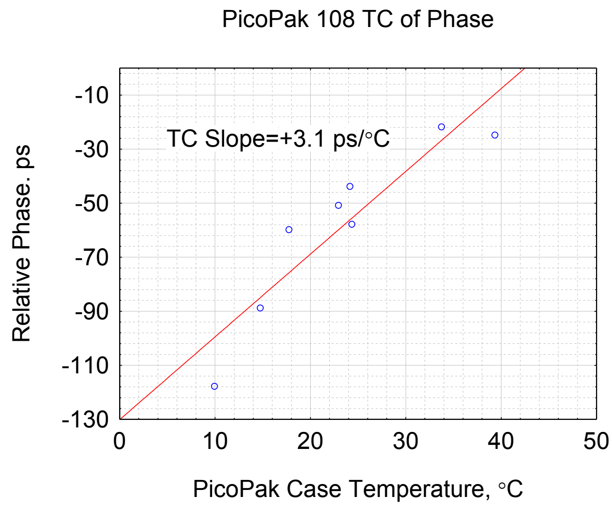

Figure 15. PicoPak S/N 108 Phase TC

The results are tabulated at the right. The temperatures (top to bottom) correcpond to the 1000-point green phase average lines in plot (left to right).

Note that in all cases the RF power splitter used to produce the coherent PicoPak inputs is located outside the box and therefore does not contribute to the measured phase TC. The short coax cables for the PicoPak RF inputs have relatively stable polyethylene dielectric that should not contribute appreciable phase TC.

°C	ps
44.3	-36
23.0	-51
44.9	-18
39.4	-25
33.8	-22
24.2	-44
17.8	-60
14.8	-89
10.0	-118
24.4	-58

Another run for S/N 105 is shown below. The TC slope is very close to that measured previously.

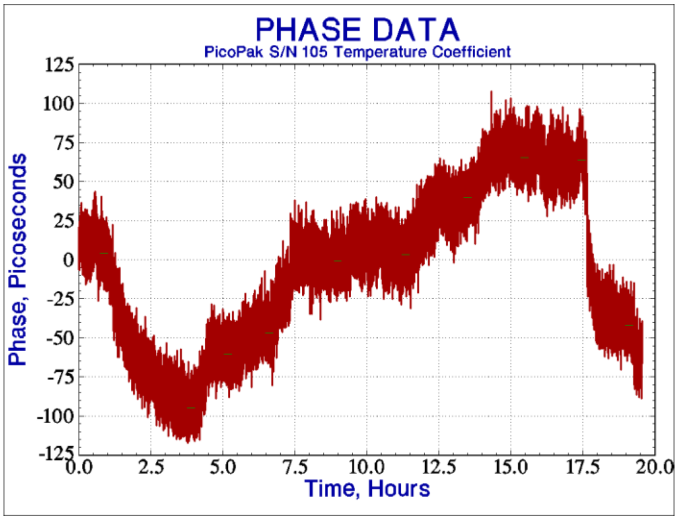

Figure 16. PicoPak S/N 105 Phase Record

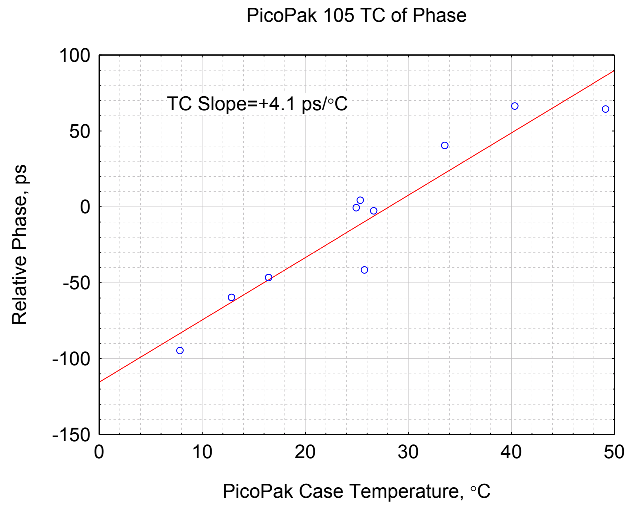

Figure 15. PicoPak S/N 105 Phase TC

°C	25.4	7.9	12.9	16.5	25.0	26.7	33.6	40.4	49.2	25.8
ps	+4	-95	-60	-47	-1	-3	+40	+66	+64	-42

- **Summary of PicoPak Phase Stability versus Temperature**

Estimates of the typical phase TC for various contributors are shown in the table below along with the methodologies used and their overall algebraic and RSS values.

Contributor	TC of Phase, ps/°C	Methodology	Remarks	Improvement
Phase Detector	0.05	Calculated value	Negligible	OK as is
Balun Transformer	1.6	Measured value. 1 of 2. May add or cancel.	Small	Unknown. Improvement unlikely.
RF Buffer Amplifier	4.4	Measured value with x5 pair cancellation	Dominant. Results depend on good cancellation.	Unknown. Worth further investigation.

DDS LPF	2.0	Measured value	Small	Not bad as is.
DC Amp Offset	3.0	25% of worst case	Moderate	Lower TC or matched resistors
Comparator Offset	3.2		Moderate	Not too bad as is. Could change circuit to use a common reference voltage.
Total	Sum: 14.3 RSS: 6.7	Measured: +4.9 ps/°C for S/N 103	Measured: +3.9 ps/°C for S/N 105	Measured: +2.0 and +3.1 ps/°C for S/N 108

These values are simply estimates of what typically might be expected and do not represent the worst case. The actual overall module TCs are considerably less than the estimates based on the individual contributors, perhaps indicating some sort of fairly consistent cancellation.

- **Conclusions**

Phase stability versus temperature is an important aspect of a clock measuring device like the PicoPak module. Even in a well-controlled laboratory environment it can introduce pseudo-frequency offsets and determine the ultimate noise floor of stability measurements. Many items can contribute phase TC including coaxial cables, distribution amplifiers, etc. Sensitivity on the order of 5 ps/°C is typical for such devices, and the PicoPak is no exception. Its phase TC is reasonably consistent with its resolution and noise limits, and is quite acceptable for its intended purposes.

- **References**

1. W.J. Riley, "The PicoPak Clock Measurement Module", Hamilton Technical Services, April 2015.
2. Data Sheet, "SYPD-1+ Phase Detector", Mini-Circuits, M112207 Rev. A, July 2010.
3. Data Sheet, "1N5711, 1N5712, 5082-2800 Series Schottky Barrier Diodes for General Purpose Applications", Avago Technologies, Limited, AV02-0429EN, June 2007.
4. Application Note, "Frequently Asked Questions about Phase Detectors", Mini-Circuits, AN-41-001, M119925, October 2008.
5. Andrew Baczynsky/Mini-Circuits E-Mail, 04/08/15.
6. S.R. Kurtz, "Mixers as Phase Detectors", Watkins-Johnson Technical Note, 1978.
7. W.J. Riley, "A Low Cost Temperature Chamber Using a Small Thermoelectric/Heater/Cooler", Hamilton Technical Services, November 2015.

File: PicoPak TC.doc
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March 21, 2015.
Rev A. April 13, 2015
Rev B. August 14, 2015
Rev C. November 13, 2015
Rev D. November 19, 2015

Appendix I

Temperature Test Data Sheet

PicoPak TC of Phase Data Sheet   Remarks____
PicoPak S/N _________ Date___________ Operator__________ File Name______________________

Time	Point #	Mode	Box Cover	Voltage VDC	Current ADC	Ambient °C	UUT °C	Remarks