Technical Topics

Match the Z3801A crystal Turning Point

In this article Graham Baxter, G8OAD and Steve Smith, G8LMX explain some fundamentals of quartz crystal temperature turning points and describe how they fine tuned their Z3801A oven oscillators. They adjusted the oven operating temperature to closely match the inherent temperature turning point of the quartz oscillator. Careful measurements and patience can pay off in improved crystal oscillator characteristics.

Graham was fortunate with his Z3801A. It was one of the comparatively few units whose clock oscillator was well behaved, and was eventually able to settle with a predicted uncertainty of around 300 ns.

However, Steve had one which seemed less stable. As was reported previously, the problem moved with the oscillator, so it was determined that there was a fundamental difference between them. To explore this without damaging his good oscillator, Graham bought a second Z3801A which was known to be less stable. Steve had dismantled his and examined it several times but had reached no firm conclusions.

Since the problems seemed to be temperature related, we wondered if the inner oven temperature was not correctly set to the turning point of the system.

For an explanation we need to look at the graph of Figure 1 which is frequency versus temperature for an SC cut crystal. It is in the form of a cubic with two points of inflection. The lower temperature, or "lower turning point" is a frequency maximum. The upper turning point is a frequency minimum. If the temperature can be placed exactly on a turning point, then the temperature coefficient of frequency will be zero. This means that for very small perturbations of temperature, there will be no change in frequency. This is an ideal that cannot be completely realized, since the crystal is also sensitive to temperature gradients, and it also exhibits some hysteresis. However, these effects are minimized in the case of the SC cut crystal compared to the AT cut.

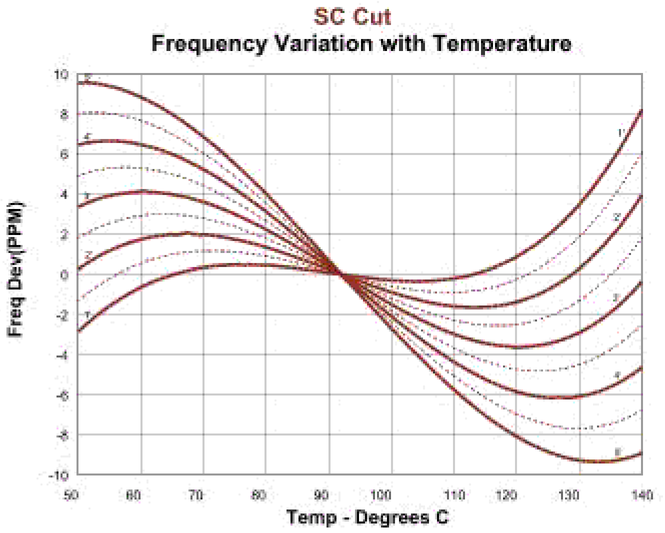

Figure 1

The upper turning point is most commonly used for an AT cut crystal, where it can be typically arranged to occur at 65 - 85 degrees. However, the upper turning point for an SC cut crystal often is too hot for reliable use in an oven, so the lower turning point is usually chosen. To find the correct temperature, one simply has to adjust it for a frequency maximum. It sounds easy, but keep in mind that we are aiming for a precision of a few milli-degrees.

Z3801A inner oven temperature bridge

The temperature controller of the 10811 has a bridge, which comprises three precision resistors and a thermistor that changes resistance according to temperature. The thermistor is embedded within the inner oven, but the component wire leads are accessible. There is a 'select on test' resistor, whose value is chosen in accordance with the temperature that is marked on the crystal. However, this assumes that the crystal was correctly marked when new, that the turning temperature has not changed, and that the turning temperature of the assembled oscillator is identical to that of the crystal alone. We decided to ignore the markings on the crystals and start from scratch.

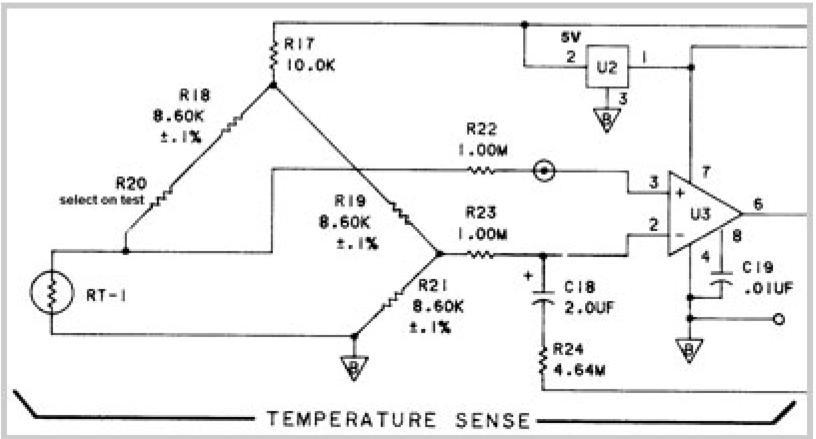

Figure 2
Z3801A inner oven temperature bridge

Measurement Procedure

The first step must be to accurately measure the bridge resistors. If any resistors have drifted from their marked values they must be replaced, otherwise they will continue to drift. Fortunately, our resistors seemed beyond reproach.

Our procedure was to bring test leads to the outside of the double oven so that the bridge temperature could be varied at will. This had to be done with some care. We decided to use a length of the very lightweight twin screened cable of the kind used for tape head connections.

The 'lower' end of the thermistor, and the lower resistor on the opposing side of the bridge were disconnected and carefully connected to the two inner wires of the screened cable. The braid was connected to the original common point of the thermistor and the resistor as shown in Figure 3.

A note was made regarding which color conductor was connected to the thermistor. A small hole was drilled in the oven casing and the lead was passed through. The inner oven was then reassembled.

The reasons for doing this were:

- We did not know in advance which way the temperature needed to be moved.

- By introducing identical wiring into both halves of the bridge, the effects of the cable resistance, temperature coefficient, and any thermal e.m.f. would tend to cancel.
- The braid would be connected to the negative supply, which is at RF ground.

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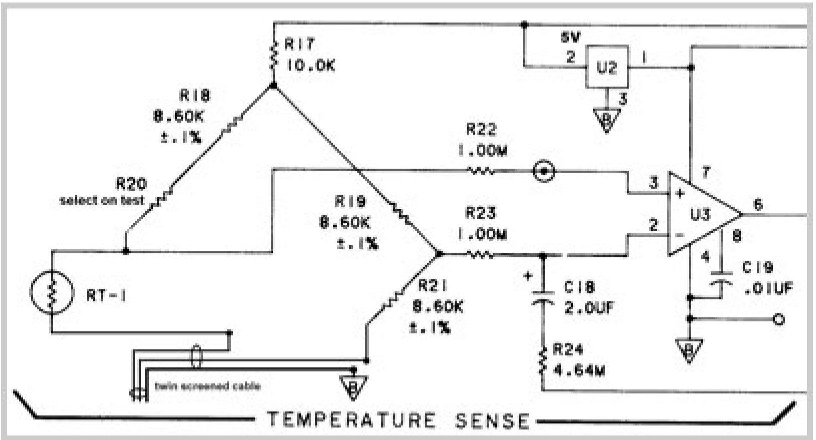


Figure 3
Z3801A oven temperature bridge with external wiring

During manufacture the connecting leads to the inner oven are passed twice around the inner oven. They are then routed through the outer oven and twice around that as well. This was done to minimize the effect of thermal shocks traveling down the copper. We considered it was important to replicate this technique with the routing of the screened lead, so it was dressed to follow a similar path.

The outer oven was reassembled so we now had clock assemblies with just an extra twin screened wire. If the two inner wires are connected to the braid, the system will work as before. For the next stage you need a resistor substitution box, or a precision low-value multi-turn pot and a selection of high stability resistors. Arbitrarily choose an inner core and connect it to the resistor substitution system. Connect the braid and the unused inner wire to the other end of the resistor system. Start with the resistor set to zero and allow the system to stabilize for a few days.

The task of finding the turning point is made much easier if you have a second frequency standard with good short-term stability. It is possible without one, but it is a very tedious task.

The procedure we followed was:

- Put the Z3801A into holdover and let it recover from the initial disturbance for about 20 minutes.
- Compare the frequency of the Z3801A with that of your secondary standard. One way is to externally trigger your oscilloscope from the standard oscillator and watch the Z3801A signal drift. We used a phase meter and a data logging system to plot graphs.
- Introduce some resistance of about 100 ohms. You might see a small transient disturbance, but wait two minutes and note the effect on the frequency. If the frequency has fallen, add a further increment to make absolutely sure. If it continues to

fall, then you are moving away from the turning point. This means that you chose to start with the wrong wire! Correct it and allow it to stabilize again.

- Continue moving the temperature until the frequency reaches a maximum and starts to fall.

Make plenty of notes, since one change every ten minutes is adequate and you may get distracted from your adjustment procedure. When you have a rough idea of the amount of resistance to be added, fit a high quality fixed resistor of a value a little less than the needed value, and then explore again in smaller increments. The reason for fitting the fixed resistor in series with the variable one is to avoid having the temperature coefficient of the resistor box involved in the measurements.

We found that Graham's Z3801A needed to go cooler by the equivalent of an extra 1750 ohms in the resistive side of the bridge. On the other hand, Steve's oscillator needed to go hotter by 1880 ohms in series with the thermistor. In both cases they were in error by several degrees. It is well worth spending a few weeks tuning the temperature, ultimately in one-ohm steps. The Z3801A can still be in normal use apart from the short spells of holdover.

Explore in both directions. Hopefully you will find a value where an ohm either way makes no difference. In the absence of a second standard it is just about possible to perform the adjustments while observing the TI during holdover. However, there is limited resolution available, and the GPS signal is not really stable enough in the short term.

Once you are absolutely convinced that you have found a frequency maximum, you will need to dismantle the oscillator once more and carefully fit a fixed resistor of the exact measured value into the appropriate position at the lower end of the bridge. There is no need to allow for the resistance of the cable since it affected both sides of the bridge equally. Seal the hole with solder and reassemble. The performance should further improve once the selected resistor is in the oven.

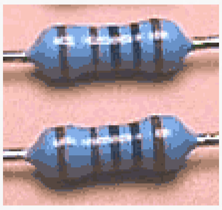
Notes

(a) Be wary of making too large a change of temperature in one step. The Z3801A monitors the oven health signal, and if it sees the heater turn full on it flags this as an error and resets.

(b) Keep your cell phone away from the resistor substitution wiring.

(c) We paid a lot of attention to C18. We measured the leakage current vs temperature for a selection of brand new film capacitors. We never found one to outperform the original C18.

OK, I need an 1880 ohm resistor. Now what?



Rather than try to use a high tolerance precision resistor of .1 per cent or better, you are likely to achieve results closer to your target value by simply selecting a resistor from a low tolerance batch. Assuming you have a reasonable digital ohmmeter, finding your specific resistor should not be too difficult.

Searching from a group of five per cent resistors is probably easier than limiting your search to a batch of one per cent resistors because the 5 per cent batch will have a tendency to have distributed values. Also, if you need to add a total of 1880 ohms to the circuit, using a resistor within plus or minus ten ohms is going to make a very big improvement to the circuit.

A little patience sorting through some low cost high stability (carbon or metal film) resistors should yield a value nearly at your target, and at a cost much less than using a high tolerance precision value resistor.

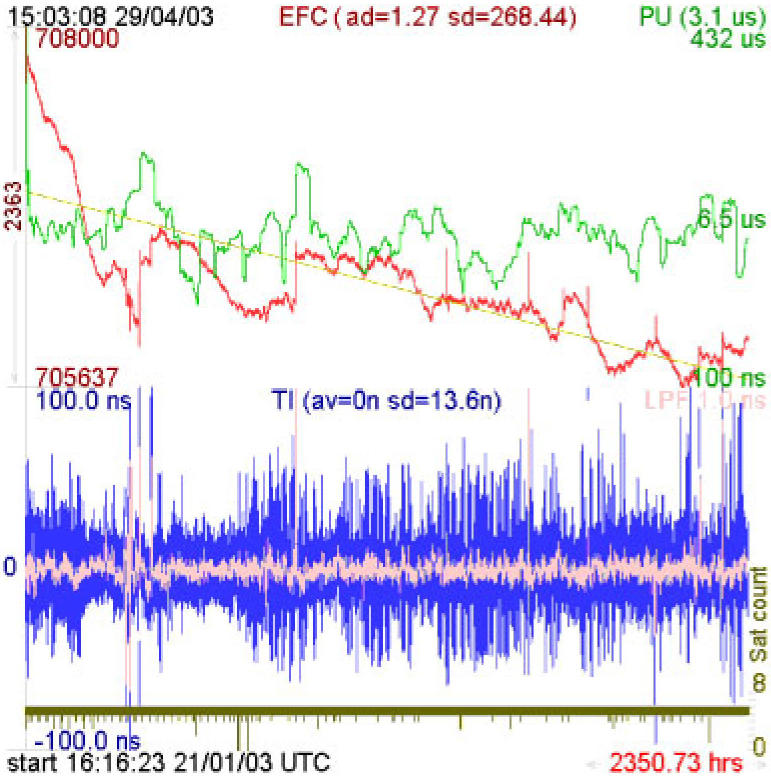
*Steve Smith reported that he and Graham were able to find their **exact** values amongst their 5% high stability resistors at a cost of only a few pennies each. With care, there is room to allow the use of two resistors.*

Results

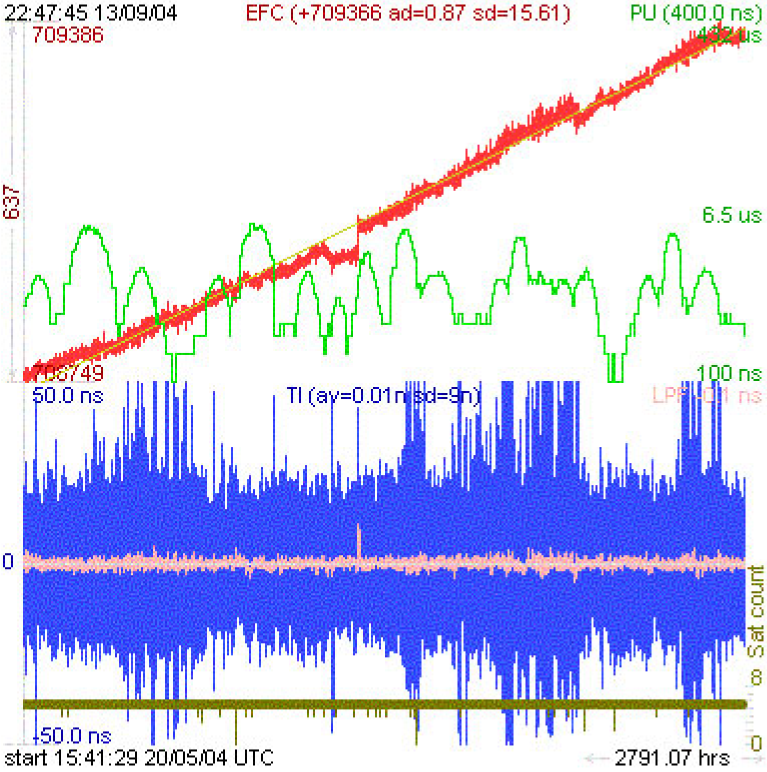
Before and after [GPSCon](#) performance charts illustrate the benefits of fine tuning the oven temperature to closely match the turning point of the quartz oscillator. Obvious improvements in EFC stability (red trace) and lower overall predicted uncertainty values (green trace) are shown. On both charts the TI (blue trace) is the same scale. The reduction in 'noise' is significant when both charts are compared.

The apparent high aging rate of the "after" plot is due to the receiver being inactive for over four weeks because of an unrelated fault and not as a consequence of the temperature tweak. This is why the early aging rate is so steep in the "after" plot.

Oscillator performance before adjustment



Oscillator performance after adjustment



How the measurements were made

The phase measurement of the rubidium to GPS is done with a HP 3575A phase meter with its recorder output connected to a Solartron 7150 GP-IB multimeter. This in turn is logged by Graham's customized Viewer program which he has modified to read from an IEEE-488 card in the PC. This gives a resolution of less than 10 pico seconds.

The temperature plots are done with Steve's custom designed serial interface PIC board, also logged by Graham's Viewer program, with 10 bits of resolution. Some of the equipment below is home constructed. Notice Steve's use of a recycled HP equipment cabinet (bottom in the photograph) for his rubidium oscillator.

The logger is plotting the air temperature of the part of the room where the frequency standards are located. It is also plotting the output of a phase meter which is scaled to display nanoseconds of time difference between the 10 MHz outputs. The time trace is also differentiated, filtered and scaled to produce an instantaneous fractional frequency error.