Is The Machine “On-Frequency” ? (Part 1)

By Arch, KT4AT
Engineering Chairman

A few months back, a discussion was going on over the repeater. Somebody made the claim that he could “see” that the repeater was “off-frequency by 40 Hz”. Let’s look into that.

There are two different problems involved: if the machine is not on frequency today, has it ever been in the past ? The first issue we will review this month is “initial setting”. The second issue we will review next month is the phenomenon of “drift”, after a good and accurate initial setting.

Let’s start by establishing how oscillators are measured for accuracy, frequency-wise. The measurement unit for this is the PPM (parts per million), PPB (parts per billion), or PPT (parts per trillion). Easy to use. Example: a 2 PPM oscillator at 1 MHz can be:

2 / 1000000 x 1000000 = 2 Hz
(ppm x frequency = error)

Measuring (or even worse, ...setting) an oscillator will depend greatly on which equipment you use. Table 1 provides a quick summary of the performance of several devices that could be used to adjust the machine. The first category, which is not really used for that purpose, rather just an example, is the class of cheap computer or CPU clocks (XO’s in short, for Xtal Oscillators). If such a device was used as a reference to set 145.15, or 442.875, those machines could be off by as much as 7.3 kHz at VHF, and 22 kHz at UHF. You are invading the next channel. Plainly unacceptable.

The second class of devices is “low end instrumentation”, like cheap frequency counters, older service monitors, cheap frequency generators, etc... (average cost of such things is a few thousands of dollars). Those devices generally use TCXO’s (Temperature Compensated Xtal Oscillators). You could still end up 725 Hz off at VHF, and over 2 kHz off at UHF. Equally unacceptable (although used often in the amateur community).

The next category is high end instrumentation. We start being serious only here. Are in this category high performance frequency counters, spectrum analyzers, and top of the line service monitors (average cost of such instruments is around $15000 to $25000, including precision timebase options). Even so, at VHF you could still have an error of 30 Hz, and at UHF up to 90 Hz. Those instruments use OCXO’s (Oven Controlled Xtal Oscillators). Acceptable this time, but you need to maintain them well calibrated at all times (at least once a year - cost to do that for my HP-8594 spectrum analyzer: $1500 per calibration).

Let’s jump to the last category on Table 1, lab frequency standards. Frequency standards use atomic clock references (mostly Cesium tubes), and will provide accuracy on steroids. They have a price tag on steroids too (around $90000, and the tube has limited lifetime).

Equipment	Oscillator Type	Accuracy PPM	Error @ 145.15 MHz	Error @ 442.875 MHz
Computer/CPU oscillator	XO	+/- 50 ppm	+/- 7258 Hz	+/- 22144 Hz
Low end instrumentation	TCXO	+/- 5 ppm	+/- 725 Hz	+/- 2214 Hz
High end instrumentation	OCXO	+/- 0.2 ppm	+/- 30 Hz	+/- 90 Hz
WWV	Rubidium	+/- 10 ppb	+/- 1.5 Hz	+/- 4.4 Hz
GPS	Cesium	+/- 0.1 ppb	+/- 0.015 Hz	+/- 0.044 Hz
Lab frequency standard	Cesium	+/- 1 ppt	+/- 0.0002 Hz	+/- 0.0004 Hz

Table 1 - Common Oscillator Accuracies, and equivalent error at VHF and UHF

This is an overkill for two-way radios and repeaters.

Wouldn't it be neat if there was some frequency standard out there which would be (a) very accurate, (b) available all the time, and (c) free of charge to use ? Well, actually there are several. The WWV frequency standard broadcast in Boulder, CO, is one of them. It provides 2.5, 5, 10 and 15 MHz references suitable for our application. The problem is that reception is limited here to a couple of hours per day, with a lot of QRM which degrades accuracy quite a bit.

The other one is GPS, the Global Positioning System. Although GPS is a position determination system, its inner workings are based on TOA (Time Of Arrival) of coded sequences. This implies that a GPS receiver has very precise knowledge of time. And, if you know time, then you can in turn extract frequency. There are several systems, which are commercially available, which will extract timing from GPS and deliver a super-accurate 10 MHz reference. They cost several thousands of dollars, and you need to set them up with outside antenna to have a predictable frequency reference, 100% of the time, accurate at VHF and UHF at less than a fraction of a Hz.

Another piece of gear was released to the market recently. Made by EndRun Technologies in California, the Praecis CF frequency reference (see Figure 1) does not synchronize directly on GPS, but on the pilot channel of 800 MHz CDMA (Code Division Multiple Access, developed by Qualcomm) telephone cell base stations. This is quite clever because those CDMA carriers need to be themselves locked to GPS to function properly, and therefore are almost identical in accuracy to the original GPS timing. The advantage is double. First, there is much better territory coverage by CDMA signals than by GPS ones, with much higher levels, which require only a little 800 MHz rubber-duckie (especially at the repeater site !...). Second, it is easier to acquire and decode a CDMA pilot carrier than a full GPS three or four satellite set. This allows for a very small and cheap solution ($1300), which truly delivers the same accuracy performance than a full size GPS synchronizer.

It will provide a frequency reference at 10 MHz, accurate to around +/- 0.1 part per billion. Then, you can use that 10 MHz reference with pretty much any instrument which uses a 10 MHz reference (that is practically all of them). Since it is small, and works everywhere there is CDMA cell phone service, you just take it with you, and synchronize it wherever you need it. It virtually eliminates instrument variations with temperature, aging, etc. (bye-bye calibrations at $1500 every year...).

The last interesting thing is that it allows to use the more mediocre devices of the "low end instrument" category (if they have a 10 MHz external reference input). One of those is my 9 digit Heathkit frequency counter, which I had retired a long time ago (+/- 2 ppm). This thing is usable again, counting frequencies at less than one Hz of error up to 700 MHz.

Now that we can precisely adjust things, next month we will review where the repeater drifts come from.

Figure 1 - EndRun Technologies Praecis CF CDMA Reference

Is The Machine “On-Frequency” ? (Part 2)

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Last time, in Part 1, we saw that we had now the capability to adjust both VHF and UHF machines with a frequency error of only a fraction of a Hz, thanks to CDMA base stations and EndRun Technologies. The question now is, are those machines going to stay there ?

The answer is a resounding “Heck No !...”. The Mastr2 is equipped with two master oscillators, one to generate the LO (Local Oscillator) in the receiver, the other for transmit in the exciter. They are called ICOM’s (for Integrated Circuit Oscillator Module - nothing to do with the brand of same name). Depicted on Figure 1, they are little plug-in modules containing a TCXO (Temperature Compensated Xtal Oscillator). They operate between 12 and 18 MHz, because at those frequencies, the crystal disk is not too thin, and can be cut very precisely (“AT” cut). Figure 2 shows the Mastr2 frequency generation strategy, for both VHF and UHF machines, receive and transmit, with the values applicable to the 145.15 and 442.875 MHz repeaters. The receive sides are similar, with the TCXO followed by multiplying stages. On transmit, the TCXO is followed on UHF by a multiplying-type exciter, but for sideband noise reasons, on VHF a PLL (Phase-Locked-Loop) is used.

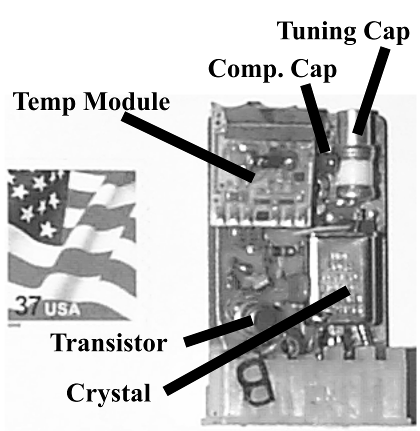

Figure 1 - Mastr2 ICOM

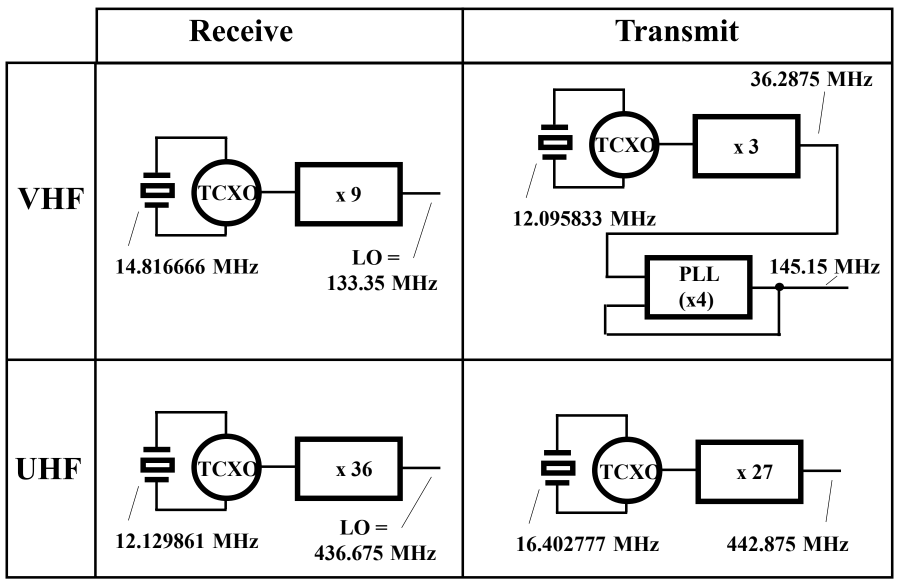

Figure 2 - Mastr2 Frequency Generation

There are three sources of drift for the TCXO: (a) crystal aging, (b) temperature, and (c) power supply variations. The last one is orders of magnitude lower than the other two if the supply voltage applied to the TCXO is well regulated. This is the case in the Mastr2, so we will not worry about this one any longer.

Crystal aging creates frequency drifts because of two different phenomenons: (1) contamination, and (b) assembly stress. Contamination occurs during the manufacturing of the crystal, when particles of various substances may enter the crystal enclosure. Those particles may include soldering or welding residues. Those particles redeposit on the crystal overtime, and reduce its frequency of resonance through mass loading. It is the manufacturer duty to ensure the cleanliness of his assembly process to minimize contamination. The second problem, stress, creates an increase in frequency when, overtime, that stress is relieved. This can be accelerated by application of heat, by storing the brand new crystal in an oven for sometime. The manufacturer does some of that. I also submit every new complete ICOM to a one week bake at 75 degrees Celsius (stress also happens when soldering the crystal to the ICOM board). Figure 3 shows the typical aggregate effects of both contamination and stress. The crystal will typically drift around 1 ppm during each of the first two years (creating an error around +/- 300 Hz at VHF, and up to 900 Hz at UHF). Then, the drift slows down, to reach a cumulative value of 2.5 to 3 ppm after ten years. What can be done to minimize those effects ? In addition to the bake mentioned above, the other action is to retune frequently, particularly during the first two years. It is a good policy, for a machine with a new crystal, to retune after one month, three months, six months, a year, a year and a half, and after that once a year. Both GARA UHF machines have new ICM crystals (International Crystal Manufacturing) on receive and transmit. Both VHF machines are equipped with older crystals, of unknown origin, on receive, and one on transmit. The last VHF transmit has a 4 year old ICM crystal on transmit.

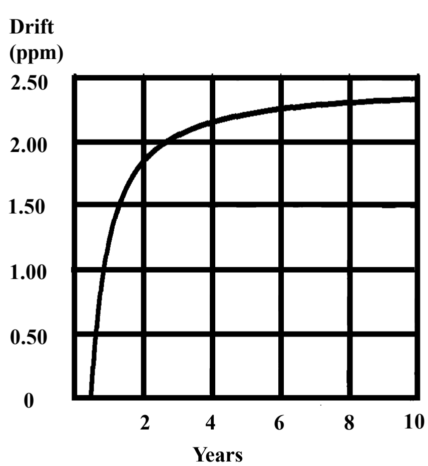

Figure 3 - Cumulative Aging

The last source of drift is the most difficult to deal with: temperature. As shown on Figure 4, AT-cut crystals exhibit an inverted S-shape drift curve as a function of temperature. Drift is zero at 25 degrees C, and frequency increases below, and decreases above. The magnitude of the drift is directly linked to the precision of the AT-cut angle. On Figure 4, Curves A and B would be typical of cheap crystals for computer use. Curve C would be typical of a more precisely cut crystal (and more expensive), without compensation. Curve D would apply to a partially compensated crystal, and Curve E to an ideally compensated crystal. The compensation is generally done by a capacitor in the oscillator circuit, which shows a drift opposite to the crystal drift. Uncompensated ICM crystals will generally have a drift of +/- 1.5 to 2 ppm between 0 and +50 degrees C. In the Mastr2 ICOM, this will generally decrease to less than +/- 1 ppm, without adjusting the compensation capacitor. The GARA machines are subjected to approximately +10 to +40 degrees C, so we should see a drift on them of +/- 0.6 to 0.8 ppm. This translates to roughly +/- 100 Hz for VHF, and +/- 300 Hz for UHF. Frequency will increase in winter, and decrease in summer, and we should be able to maintain the limits above. The last thing to do for that is to center the tuning point around 25 degrees C. This involves calibrating each ICOM drift, and tuning them with a correction depending on the ambient temperature at tuning time. This has not been done yet, but will be for all eight ICOM's by next summer. And, maybe one day, I will redesign those ICOM's to use an OCXO (Oven Controlled Xtal Oscillator), and a synthesizer.

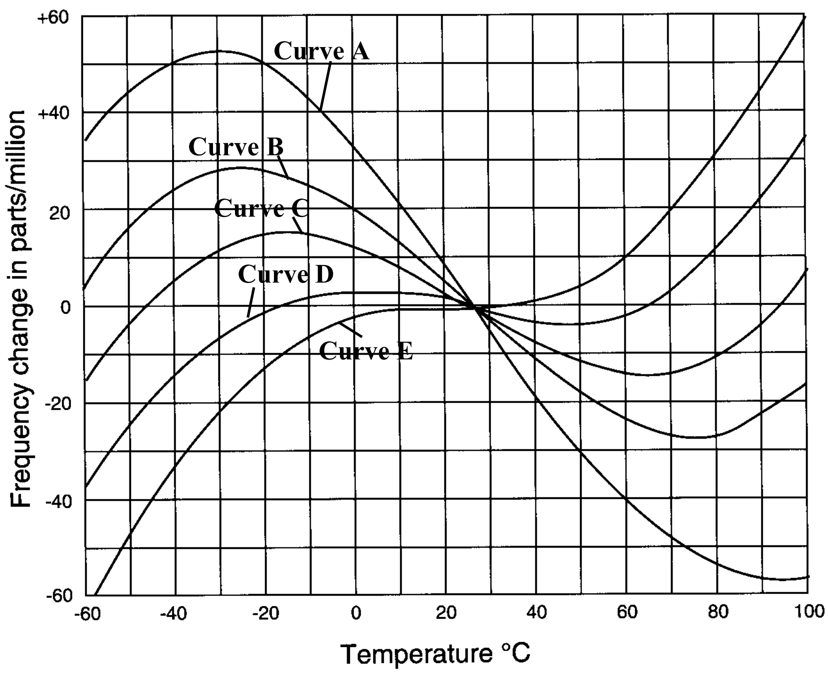

Figure 4 - Xtal Temperature Drift