MEASUREMENTS OF THE SHORT-TERM STABILITY OF QUARTZ CRYSTAL RESONATORS - A WINDOW ON FUTURE DEVELOPMENTS IN CRYSTAL OSCILLATORS

F. L. Walls and A. E. Wainwright

TIME AND FREQUENCY DIVISION
NATIONAL BUREAU OF STANDARDS

ABSTRACT

Recent measurements of the inherent short-term stability of quartz crystal resonators will be presented. These measurements show that quartz resonators are much more stable for times less than 1s than the best available commercial quartz oscillators. A simple model appears to explain the noise mechanism in crystal controlled oscillators and points the way to design changes which should permit more than 2 orders of magnitude improvement in their short-term stability. Stabilities of order 1 part in 10^{12} at .001 s appear obtainable. The achievement of short-term stabilities of this level would in many cases greatly reduce the time necessary to achieve a given level of accuracy in frequency measurements. Calculations show that a reference signal at 1 THz, derived from frequency multiplying a 5 MHz source with the above measured crystal stability, should have an instantaneous or fast linewidth of order 1 Hz. These calculations explicitly include the noise contributuion of our present multiplier chains and will be briefly outlined.

INTRODUCTION

Quartz crystal controlled oscillators play a key roll in frequency metrology in that they are used in nearly all precision frequency measurement and generation devices. Indeed, the short-term frequency stability of virtually every precision frequency source is determined by a quartz crystal controlled oscillator. The short-term frequency stability sets a fundamental limit on the minimum amount of time necessary to reach a specified level of accuracy in frequency measurements, limits the spectral purity, and limits the highest frequency to which an oscillator can be multiplied and still be used as a precision source.

In the following we will show experimental results which indicate that the inherent short-term stability of some quartz crystal resonators is at least 100 times better than the best commercially available crystal controlled oscillators. Next we will briefly outline the reasons for the decrease in stability of the crystal controlled oscillators relative to the quartz crystals and indicate how the short-term stability is related to spectral purity and how these limit the maximum frequency to which the frequency of an oscillator may be multiplied and still be used as a precision source.

EXPERIMENTAL RESULTS

Figure 1 shows a schematic diagram of the phase bridge used to measure the inherent short-term stability of the quartz crystal resonators. Two crystal resonators which are as identical as possible are driven by the same low noise source. By careful adjustment of crystal tuning and the balancing of the relative Q's, the output from the double balanced mixer, which is used as a phase detector, is independent of both residual amplitude and frequency modulation in the source. This reduction of noise from the source is crucial to being able to measure small time varying frequency deviations of the crystals [1]. At balance the mixer output is directly proportional to the difference in the resonance frequency of the two crystal resonators. This voltage can now be processed to yield both the spectral density of fractional frequency fluctuations, $S_y(f)$, or the time domain stability, $\sigma_y(\tau)$, per the recommendation of the IEEE subcommittee on frequency stability [2].

Figure 2 shows a typical example of frequency domain data. $S_y(f)$ for a pair of 5 MHz crystal resonators is plotted versus Fourier frequency offset, f, assuming equal contribution from each crystal. Note the change from flicker of frequency to random walk frequency modulation at a Fourier frequency equal to one half of the crystal bandwidth. Crystal drive was approximately 200 microwatts. Figure 3 shows a similar plot for a pair of very high quality 5 MHz crystals. The change from flicker of frequency to random walk of frequency modulation should occur at a Fourier frequency of 1 Hz, which was the lower limit of our spectrum analyzer.

Figure 4 shows the time domain data for the same pair of 5 MHz quartz crystal resonators. The solid dots are the actual time domain measurements. The lower heavy solid lines show the frequency domain data translated to time domain [2], where h_{-1} and h_{-2} are the intensity coefficients for the assumed power law spectral densities f^{-1} and f^{-2} respectively. These data show that the inherent time domain stability of the quartz crystals improves as the sample time, τ, becomes short compared to the inverse half angular bandwidth γ, of the crystal. The functional dependence is $\sigma_y(\tau) = \kappa\tau^{\frac{1}{2}}$. As one goes to shorter and shorter times the stability becomes worse again due to noise in the isolation amplifier and the measurement system. This noise causes an uncertainty in the measurement of the position of the zero crossing. If the noise is white then the frequency fluctuations will have a white phase modulation character and $\sigma_y(\tau)$ will go as τ^{-1} for times larger than the inverse bandwidth of the measurement system, which in this case was $\sim 4 \times 10^{-6}$ seconds.

The line labelled "Johnson noise from amplifier" indicates the estimated contribution of our measurement system to $\sigma_y(\tau)$. Calculations of the Johnson noise in the series loss resistance of the crystal, R_s, show that this contribution to $\sigma_y(\tau)$ is very small compared to that of most active circuits [1].

For comparison, the stability of these same two crystals in a high performance crystal oscillator at 65° C is also indicated in Figure 4. Note the dramatic difference in stability for times less than 1s. This difference is just the noise contribution due to the electronics in the crystal controlled oscillators. The difference for measurement times greater than 1s is primarily due to the decrease in the stability of this crystal pair at 65° C.

The character of the oscillator stability for times less than 1s is very similar to that of the crystal measurements below 10ms, only the level is different. Our measurements show that the noise in the buffer amplifier fully explains the short-term stability of the oscillator.

The above confirms the widely held belief (see e.g.[3,4]), that Johnson noise sources in the amplifier and oscillator stages that are not filtered by the crystal are the cause of the observed noise in this and most low drive crystal oscillators. Short-term stability could be greatly improved merely by increasing crystal drive. A factor of 100 increase in crystal drive should produce a factor of 10 improvement in the short-term stability of the oscillator. Recent measurements [5] by J. Groslambert, G. Marianneau, M. Oliver and J. Uebersfeld on a crystal controlled oscillator with 50μW of crystal drive, yield a factor of 10 improvement in the short-term stability as compared to the oscillator of of Figure 4 which has approximately 1μW of drive. In both oscillators multiplicative phase modulation was reduced by local negative feedback as originally suggested by D. Halford [6]. Additional improvements in short-term stability can be obtained by using a high input impedance buffer amplifier and driving it with a series resonant circuit from a point in the oscillator where the noise is bandwidth limited by the crystal. This can increase the signal level to the buffer amplifier by a factor of 10 without changing the level of Johnson noise in the buffer amplifier. This should improve the short-term stability by a factor of 10. Moreover, most buffer amplifiers are designed for isolation and not low noise. With a little more care in the design of the buffer amplifier, the noise level could be reduced by approximately a factor of 4. The net result should be a crystal controlled oscillator with a short-term stability at least 100 times better than present state-of-the-art commercial 5 MHz crystal controlled oscillators. Stabilities approaching one part in 10^{12} at .001 seconds appear feasible. Even at this level the short-term stability will be limited by the electronics and not the crystal resonators, if the best available crystals are used.

The medium term stability of a crystal controlled oscillator is determined by the flicker of frequency level in the crystal. Measurements on a number of crystal pairs show that the flicker of frequency level or stability floor is approximately given by $\sigma_y(\tau) = \frac{10^{-6}}{2Q}$. This has been verified for crystals ranging in frequency from 5MHz to 125MHz and crystal Q's from 10^4 to 2×10^6. Individual crystals with identical Q's sometimes vary as much as a factor of 10 in their stability floor, indicating that fabrication techniques have a considerable influence on stability beyond just considerations of obtainable crystal Q's. The departure of solid line derived from h_{-1} from the experimental time domain data is probably due to the limited amount of frequency domain data that could be taken to cover this region.

Figure 5 illustrates the effect of white phase modulation or additive Johnson noise on the spectral purity of the signal and how this limits the maximum frequency to which an oscillator can be multiplied and still be used as a precision signal source.

Curve a shows the rf spectrum of a precision 5MHz crystal controlled oscillator after multiplication to 9 GHz (x-band). The broad base is called the noise pedestal while the central peak is called the carrier. The noise pedestal determines the short-term fractional frequency stability of the oscillator. In this case $\sigma_y(\tau) = (2 \times 10^{-13})/\tau$. The carrier width is determined by the flicker of frequency level of the oscillator. The width is approximately

$$\Delta\nu = 2\nu \left(\sigma_y(\tau)_{flicker}\right) = .006\text{Hz}$$

at 9.2GHz for the present oscillator. The narrow peaks of a and b have a width of 10 KHz which is the bandwidth of the spectrum analyzer. Curve b shows the rf spectrum at 9.2GHz when the additive noise level has been increased by a factor of 50 over its initial value. This corresponds to a short term stability of $\sigma_y(\tau) = 10^{-11}/\tau$. Note that the relative power in the carrier has dropped 8dB and that the height of the noise pedestal has risen 34dB. The power in the carrier is now -8dB or 16% of the total available power. Curve C shows the rf spectrum at 9.2 GHz when the additive noise has been increased by a factor of 150 over its initial value. This corresponds to a short term stability of $\sigma_y(\tau) = 3 \times 10^{-11}$. The carrier has now totally disappeared!

Although there still is power available, the line width has increased a factor of 10^8 from .006 Hz to 600 KHz. Clearly Curve c can no longer be used as a precision reference signal. These results are of significance for the design of both precision frequency oscillators and of the total system in which they are used. For, as Figure 5 illustrates, the addition of even relatively small amounts of noise can seriously degrade the short-term stability, the spectral purity, and the useful operating range of a precision frequency source.

These results can be generalized and summarized by the following. The relative power in the carrier, P_c, and the relative power in the pedestal, P_p, are given by[7]:

$$P_c(\nu) = e^{-\Phi_p(\nu)}, \text{ and}$$

$$P_p = 1 - P_c = 1 - e^{-\Phi_p(\nu)}$$

where $$\Phi_p(\nu) = \int_{pedestal} S_y(f) \left(\frac{\nu^2}{f^2}\right) df$$

Recall that $S_y(f)$ is the spectral density of fractional frequency fluctuations, ν is the carrier frequency, and f is the fourier frequency offset from the carrier. The short-term fractional frequency fluctuations for white phase noise or additive Johnson noise is given by:

$$\sigma_y(\tau) = \left(\frac{1}{\tau}\right)\left(\frac{1}{2\pi}\right)\sqrt{\left(3\ S_y(f)B_o\right)\Big/ f^2}$$

where B_o is the bandwidth of the noise.

CONCLUSIONS

It has been shown: (1) that the inherent short-term stability of the resonators is vastly superior to the best available commercial crystal controlled oscillators, (2) that the short-term stability of a crystal controlled oscillator is dominated by noise processes in the buffer amplifier, (3) that the adoption of several design changes should produce crystal controlled oscillators with short-term fractional frequency stabilities approaching $\sigma_y(\tau) = \frac{10^{-15}}{\tau}$ and (4) that the short-term stability or, alternately, the spectral purity limits the maximum frequency to which an oscillator can be used as a precision source.

ACKNOWLEDGEMENT

The authors are grateful to H. Hellwig, S. Jarvis Jr., D. W. Allan, and A. DeMarchi for many helpful discussions.

REFERENCES

[1] A. E. Wainwright and F. L. Walls, "Direct measurements of the inherent frequency stability of quartz crystal resonators," Proc. 28th Annual Symp. on Frequency Control,Fort Monmouth, NJ, pp. 177-180, May 1974. See also "Measurement of the short-term stability of quartz crystal resonators and the implications for crystal oscillator design and applications," IEEE Trans. Instrum. Meas., IM-24, March 1975. To be published.

[2] J. A. Barnes, A. R. Chi, L. S. Cutler, D. J. Healey, D. B. Leeson, T. E. McGunigal, J. A. Mullen, Jr., W. L. Smith, R. L. Sydnor, R. F. C. Vessot and G. M. R. Winkler, "Characterization of frequency stability," IEEE Trans. Instrum. Meas., vol. IM-20 pp. 105-120, May 1971.

[3] L. S. Cutler and C. L. Searle, "Some aspects of the theory and measurement of frequency fluctuations in frequency standards," Proc. IEEE, vol. 54, pp. 136-154, Feb. 1966.

[4] Erich Hafner, "The effects of noise in oscillators," Proc. IEEE, vol. 54, pp. 179-198, Feb. 1966. See also the IEEE-NASA Symposium on Short-term Frequency Stability, 1964.

[5] J. Groslambert, G. Marianneau, M. Oliver, J. Uebersfeld, "Design and performance of a crystal oscillator exhibiting improved short-term frequency stability, "Proc. 28th Annual Symp. on Frequency Control, Fort Monmouth, NJ, pp. 181-183, May 1974.

[6] D. Halford, A. E. Wainwright, and J. A. Barnes, "Flicker noise of phase in RF amplifiers and frequency multipliers: Characterization, cause and cure," Proc. of the 22nd Annual Symp. on Frequency Control, Fort Monmouth, NJ, pp. 340-341, April 1968.

[7] The contribution of the multiplier chains to the noise pedestal is absorbed in $S_y(f)$. Our present 5 MHz to 9.26 GHz multiplier chains increase $S_y(f)$ by less than .1 dB over the value of $S_y(f)$ for the 5 MHz crystal controlled oscillator by itself.

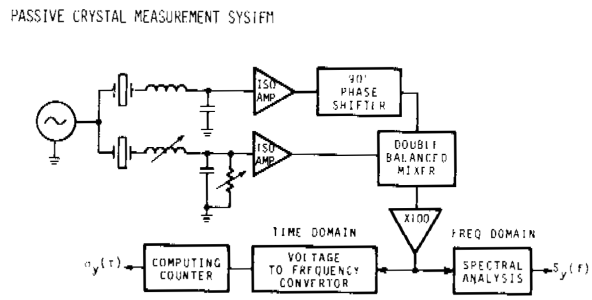

FIGURE 1 Passive system used to measure the inherent frequency stability of pairs of similar quartz crystal resonators.

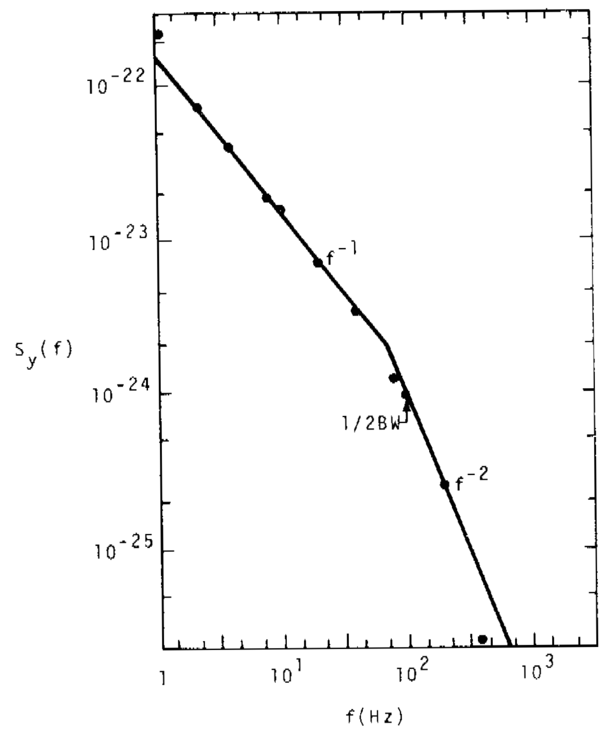

FIGURE 2 Frequency domain measurements on crystal pair 5A-200 at 28° C. These are 5 MHz crystals with a bandwidth of 200 Hz. $S_y(f)$ is shown for a single crystal.

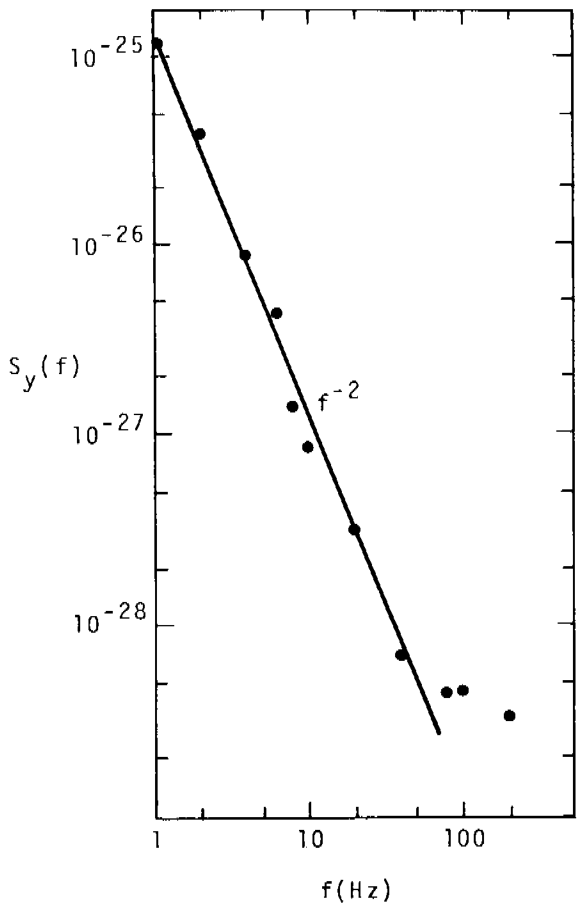

FIGURE 3 Frequency domain measurements on crystal pair 5B-2 at 28° C. These are 5 MHz crystals with a bandwidth of 2 Hz. $S_y(f)$ is shown for a single crystal.

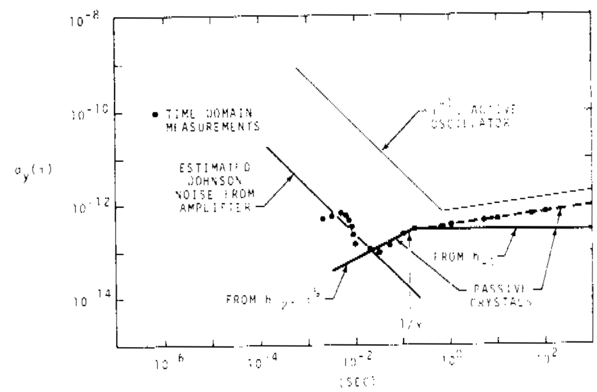

FIGURE 4 Time domain measurements as a function of sample time τ, for crystal pair 5B-2 at 28° C. Also shown are the frequency domain results of Figure 3 converted to time domain, and the stability of a high quality oscillator controlled by one 5B-2 crystal at + 65° C. $\gamma = \pi BW$; here the bandwidth is BW = 2 Hz

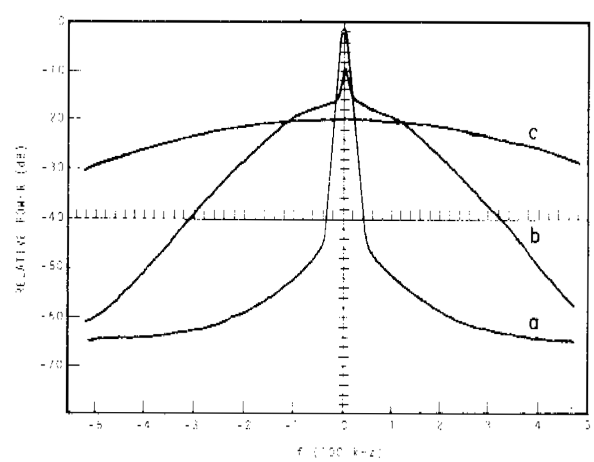

FIGURE 5 rf spectrum of 5 MHz crystal controlled oscillators after multiplication to 9.2 GHz for 3 different short-term stabilities. Curves a, b and c are for oscillators having a short-term fractional frequency stability of

$$\sigma_y(\tau) = \frac{2 \times 10^{-13}}{\tau}, \quad \frac{10^{-11}}{\tau} \quad \text{and} \quad \frac{3 \times 10^{-11}}{\tau}$$

respectively.

QUESTION AND ANSWER PERIOD

DR. WINKLER:

Winkler, Naval Observatory.

You have mentioned the role of buffer amplifiers as contributors to noise. I think probably for practical applications the most important example of that is the buffer amplifiers in the cesium standards which we have.

The 5 megahertz crystal oscillators which provides the output at 5 megacycles has to be buffered very extensively in order to prevent reflective power and side bands getting back into the oscillator and into the multiplier which would shift the frequency of the cesium resonance.

But on the other hand, that severe buffering deteriorates somewhat the performance of that crystal for very short integration times. One second or shorter.

Now there are two possibilities. If people have a requirement, and I know of some such requirements, to use the output of that 5 megahertz source not only for time keeping but at the same time also for generation of microwave signals, where spectral purity is required there are two ways to go about that. One would be to take out part of the buffering in the output circuits, to increase it directly which is dangerous.

The other one would be to phase lock a second crystal oscillator which could be designed according to your recipe and so to provide that spectral purity from a secondary oscillator.

Now, would you like to comment on these two possibilities, particularly what is your estimate on the required quality of that second oscillator? If you really do not need any stability, any inherent stability, beyond one second integration time, which would be provided by the phase-lock loop on the cesium, what would be the requirement for such a second crystal?

DR. WALLS:

I'm not sure I understand exactly where you want the requirements—on the crystal or on the crystal oscillator?

DR. WINKLER:

On the crystal and the crystal oscillator. It is clear that you need still a high Q crystal for that.

DR. WALLS:

Yes. You would want to have as high a Q crystal as you could which is about 2-1/2 million at 5 megahertz and you would want to drive it rather hard, you're not interested in stability at 10 seconds or 100 seconds, for example. And you would want very few stages of buffering, not 10 or 15 stages.

DR. WINKLER:

But am I correct in assuming that actually that design could be extremely simple? You wouldn't even need temperature control, maybe.

DR. WALLS:

That's true.

DR. WINKLER:

So it's not an expensive substance.

DR. WALLS:

It shouldn't be.

DR. WINKLER:

It would not cost $15,000 per unit?

DR. WALLS:

No. I agree. It could be a much simplified design.

DR. HELLWIG:

I'd also like to comment on your question. If one substitutes higher performance crystal oscillators in existing cesium standards, but still goes through the buffer amplifiers of the existing cesium amplifiers, you will not realize the better short-term stability. So be careful in doing that. That is my advice.

The other comment is, as I said yesterday, you have to get away from the one second time constant of the cesium if you replacc the internal oscillator.

DR. WINKLER:

What you just said is one should not go about replacing the internal workings but put a makeshift externally to that oscillator.

DR. WALLS:

I would prefer that.

DR. WINKLER:

Yes. It's much cheaper and much more direct and much more reliable.

DR. WALLS:

Yes, one should really think in terms of systems, right? And you can, if you use two components, sometimes have the best of both worlds rather than having one device be everything to all people.

MR. PHILLIPS:

The Naval Research Lab has taken some of these items into account and developed a system called a disciplined time and frequency oscillator.

That wasn't the system we developed. And we have noticed very large improvements when multiplied to X band so that these are very real effects and this is a very powerful approach for the person who needs the long-terms stability of a cesium and then must require the short-term stability so that he can have a pure signal at microwave frequency. So this is a very real thing and we have been addressing it. I wondered if you have, in commercial oscillators, looked at this particular system?

DR. WALLS:

Well, we have commercial 5 megahertz oscillators that we have multiplied to X band and the measurements you saw there were on some commercial 5 megahertz oscillators. They weren't laboratory designed oscillators. We have not tried to change the internal power or the buffer amplifiers yet. That is something that we hope to do.

DR. KARTASCHOFF:

In this context of crystal oscillators, I just remembered that about 15 years ago the Marconi Company in England developed a crystal oscillator system where they had a high Q crystal in the bridge and they servoed the frequency of a half driven second crystal oscillator to that bridge. Of course that was done with tube technology about 15 years ago, but it might be that this scheme, in view of the results of the measurements of Dr. Walls, might be well worth looking at again.

DR. HELLWIG:

I think it is a concept worth pursuing. I claim the concept, which I call the dual crystal concept, would be superior if that second crystal is not used in an oscillator but passively.

I think that is even superior. Replacing tubes by transistors will help too.