Revisiting the Measurement of Phase Noise in Test Oscillators

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Sometime back I was interested in making measurements of close in receiver IMD and other items pertaining to some controversy over published (and unpublished) numbers for my various transceivers used in CW contesting. (Note, I do not subscribe to the buzz that close in dynamic range tells the whole story about close in CW operation. I believe linearity of the front end of a receiver is too often left out of the discussion as well as the IMDR potential from crystal filters.)

My interest was (and still is) in making measurements of useful dynamic range of the receiver for close in CW use during contests. This has some accepted practice in meaning 2 kHz signal spacing. This is much less than the typical 10, 15 or 20 kHz spacing often used when referring to voice mode use of a transceiver.

Before providing much resolution to the phase noise problem, I had heeded a comment from a notable RF person chum who indicated that the using the venerable HP8640's might be a problem for these measurements due to reciprocal mixing with the source phase noise. That lead me to construct a pair of crystal oscillators that had a good pedigree for noise. My last article in the series showed how I started down the path of phase noise measurements, acquiring a better grade spectrum analyzer and coming to the conclusion that the crystal oscillators might have decent phase noise measurements. The method I used also indicated similar or better noise measurements for both my HP8640 signal generators, and I let the whole issue drop. I knew I would have to revisit the measurements someday and add some 'depth' to the method.

That day has arrived. Dallas Lankford   (*the dallasfiles2 at Yahoo Groups*) pointed out to me that I probably had some errors in my measurements and between his correspondence and looking up references from Wes Hayward , W7ZOI, and others I realized I had to dig a little deeper into the measuring of phase noise.

During my investigations I discovered that there are plenty of issues with oscillators used to simulate the close signal conditions to make these measurements. Normally strong signals in the +5 dBm range are used. These are strong signals for any receiver. A weak signal next to as strong signal has to contend with whatever is at the base of the signal in the receiver pass band. If we inject a synthetic signal into the pass band, there is plenty of opportunity to create mixing products with the weak signal and the phase noise from the strong signal. Therefore, it is a very good idea to get very low phase noise signals if you want to achieve a reasonably accurate receiver dynamic range measurement.

I have two HP8640 signal generators which I use regularly for RF testing, in my shop. At the time I was doing the original measurements it had been suggested to me that these HP generators were not suitable because of the possibility of close in phase noise problems. That lead me to find some suitable low phase noise oscillators for this testing and to figure out how to determine the magnitude of the phase noise problem.

Back then I did not own a spectrum analyzer of any merit, but could borrow one occasionally from a laboratory I worked with. This phase noise problem triggered a search and eventual acquisition of a decent spectrum analyzer. I wound up with a surplus HP3589A instrument which was more than suitable for the task. Owning this instrument has forced me to relearn some facts about spectrum analyzers .

Figure 1: My HP3589 Vector Network Analyzer

One of the more interesting spectrum measurements involves phase noise. My quick read of phase noise of my test generators in the articles on the IC7700 IMD and dynamic range were cursory at best.

This article addresses these concerns.

Let's start off with the fact that the phase noise of a suitable test signal of +10 dBm is going to be a small number, and right away we have a problem with most spectrum analyzers not having enough dynamic input range to provide resolution at the small energies involved. My numbers from the previous article are too big and are buried in the apparent noise floor of the analyzer. To dig them out, we have to find a way to zoom in on the basement of the signal. Wes Hayward, Doug DeMaw, Rick Cambell, Dallas Lankford and others found in internet searches use a method which incorporates a steep sloped bandpass filter in series with the signal source plus a little math to correct the readings. So long as the filter has deep enough skirts and is sufficiently narrow, one puts the source signal frequency outside of the filter pass band and reads the noise within the pass band, effectively providing a zoom window within the filter passband to read the noise energy levels. To make this work, it is mandatory to have a filter that is close to the frequency of your test oscillators. This can be a problem, unless you are willing to build or buy special filters for any particular signal. Ultimately, I want to measure the phase noise of my two 9 MHz crystal signal sources. Wes Hayward has an excellent description of this method in RF Design [1]. Dallas Lankford has descriptions of his method that can be found in the DallasFiles2 on Yahoo Groups. They are described in his notes on his recently aquired Rigol spectrum analyzer.

Here is my application of the method:

<u>Numbering:</u> Since we want to wind up with dBc/ Hz, it is convenient to reference everything to a 0 dBm source (for calculation) and to a root Hz. The phase noise can be summarized as the ratio of oscillator power to the noise power at a different frequency normalized to 1 Hz. When using a typical spectrum analyzers, the oscillator source is read in dBm, the noise power is read at a difference of some KHz, the analyzer resolution bandwidth (RBW) is noted and any corrections that have to be made are noted. Some math produces the phase noise at the specified distance from the source in dBc/Hz. This is decibels below the test signal level, or carrier, per Hz.

<u>Filter</u>: select a filter in suitable fixture to provide very high isolation between input and output, with a center frequency that is close to your needed test frequency. Since I have 9 MHz test oscillators, and the HP8640's can go anywhere, a 9 MHz filter is highly suitable. Characterize the filter with a swept analyzer and determine it's skirt depth and the attenuation within the filters pass band. The attenuation is added to the reading. The first filter I selected was an Icom Fl-232, 9.0155 MHz IF filter with 2.4 KHz pass band and -90 db+ skirts. This filter has a 2:1 shape factor. This allows parking the signal generator to 3 KHz away, and still be outside of the filter passband. All of the spectrum analyzer readings are made within the pass band. This method effectively adds the filter skirt depth to the input dynamic range of your analyzer, allowing measurements right down to the 'real' noise floor of the analyzer. This filter had an attenuation of 5.2 dB.

Some of my assorted filters, mounted in shielded enclosures with internal matching networks and maximum isolation between input and output. The top one has a socket for various Icom filters. They all have 50 ohm matching networks. Not terribly neat, but quite effective.

Figure 2: Typical filters, mounted in RF tight housings with internal matching networks or transformers

<u>Source:</u> an accurate reading of the output power is needed. The filter is hooked between the signal generator and the spectrum analyzer and the generator is moved to center of the filter pass band. The signal on the spectrum analyzer is adjusted until there is a decent signal of 5 to 10 dBm. The filter attenuation is added to this to make an adjustment to get the proper ratio of carrier power to noise power output is then 10 * log (output milliwatts) giving the power in dBm. A value of 20 dBm is a good number, but I found anything over 5 seems to be useable.

For the <u>spectrum analyzer</u>, in my case an HP3589A, I spent more time familiarizing myself with what it can do, how it calibrates and how some of its functions work. This is still a fairly high end analyzer even though it is 20 years old. In wideband swept spectrum mode, it can go to 1.1 Hz resolution bandwidth and in narrow band FFT mode it can zoom in easily to .01 Hz. I don't need anything like this for phase noise so I elected to use 150 Hz in wide band mode and 90 Hz in narrow band mode. This machine also has a built in noise marker function which calculates the noise in dBc in the swept mode, based on the settings for RBW, saving you some calculations. I picked these numbers as I didn't mind making corrections to the readings based on the resolutions.

<u>Corrections:</u>

- **RBW**: The readings have noise introduced by the analyzer as 10*log (RBW). For 150 Hz this is 21.8 dBm, and for 90 Hz it is 19.5 dBm. These are subtracted. If the HP3589A noise function is used, the function does an internal calculation for this reading plus adjusts the bandwidth slightly for a correction for noise vs sinusoidal type sources. The most accurate reading on this machine will come from the noise function.
- **Non sinusoid factor**: nearly all analyzers are calibrated against sinusoidal sources. Noise is not a sinusoid and I found several spectrum analyzer application notes that offered up 2.5 dB as being the proper correction. Normally this is added but on the HP3589 there is internal compensation if the noise function is used. The manual also states that the peak detector and over sweep should be turned off when measuring noise. If you set the machine up this way, you do not have to make the non sinusoid correction, but you do have to remember to turn the peak detector and over sweep (if needed) back on when measuring the power of the oscillator source.
- **Gaussian window**: My analyzer in FFT narrow band mode has a built in Gaussian window algorithm, as compared to some units that allow Hanning, Haming or other corrections. The required correction is .8 dB and is applied internally on my HP3589. The swept spectrum and nosie marker function do not need this correction.

Marker Noise function and method:

HP8640's: It was easy to make measurements at 4,10 and 50 KHz away from the filter passband. The output attenuator is set to deliver approx. 10 dBm when the generator is set in the filter passband. This value plus the filter attenuation is used to make the correction to the source level to noise level ratio correction.

Test oscillator: These are fixed frequency and less than 0 dBm out. The range to the filter passband is therefore fixed. The source was measured at 3.42 dBm, which just allowed a measurement to be made. (Spoiler alert: as it turns out, these oscillators are not as good as I had hoped, so they would require engineering and revisions if I intend to make use of them for further IMDR tests) The measurement method is slightly different for these devices, as I must measure their source levels independent of the filter attenuation, and then be sure to apply the proper corrections in the calculations.

On my HP3589 analyzer, the following settings are used, per recommendations from HP manuals:

Table 1: Analyzer settings

Over sweep	Off
Auto range	On
Peak detector, source reading	On
Peak detector, noise reading	Off
Swept spectrum	On
Averages	10
RBW	150
VBW	21
Noise marker function	On
Input impedance ohms	50
Auto Cal	On

And here are the readings, with the correction for the dBc/Hz made:

Table 2: 9 MHz results for two HP8640's and one 9 MHz crystal oscillator.

KHz-mode 9 MHz filter Icom FL-232 Atten. 5.2 dB, source 15.2 dBm	HP8640-a	HP8640-b	8.998 oscillator
4 swept 150 RBW, NF	-151.9	-150.6	tbd
8 swept 150 RBW, NF	-150.2	-153.9	tbd
50 swept 150 RBW,NF	-150.7	-153.8	tbd
100 swept 150 RBW,NF	-151	-154.1	tbd
Floor	-154.4	-155.6	tbd
All corrections made through noise function(NF) All readings dBc/Hz, within filter BW, except analyzer noise floor reading, outside of filter band			

Here is a screen shot of the typical sweep of noise in the filter pass band, and you can see the oscillator signal to the right.

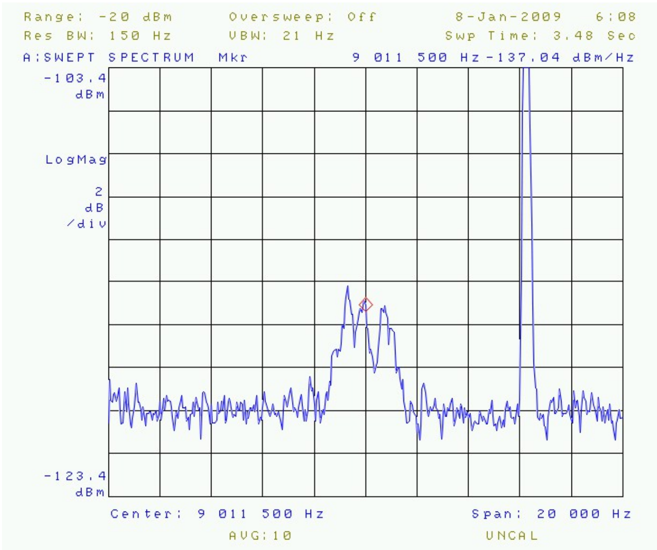

Figure 3: Swept noise, 9.0115 MHz, 4 Khz spacing, HP8640a

To exercise the readings on the HP8640's a little more, I also setup the test at 453 KHz and used a Collins filter, I had lying around.

Table 3: 455 Khz results for one HP8640

KHz-mode 455 KHz filter Collins 526-8536-010, Atten. 5 dB, Source 15 dBm	HP8640-a	HP8640-b
4 swept 150 RBW, NF	-148.9	-147.3
8 swept 150 RBW,NF	-149.6	-147.8
50 swept 150 RBW,NF	-151	-149
100 swept 150 RBW,NF	-152	-150.2
Floor	-156.3	-151.4
All corrections made All readings dBc/Hz, within filter BW, except analyzer noise floor reading, outside of filter band		

Noise in filter pass band for 455 KHz setup:

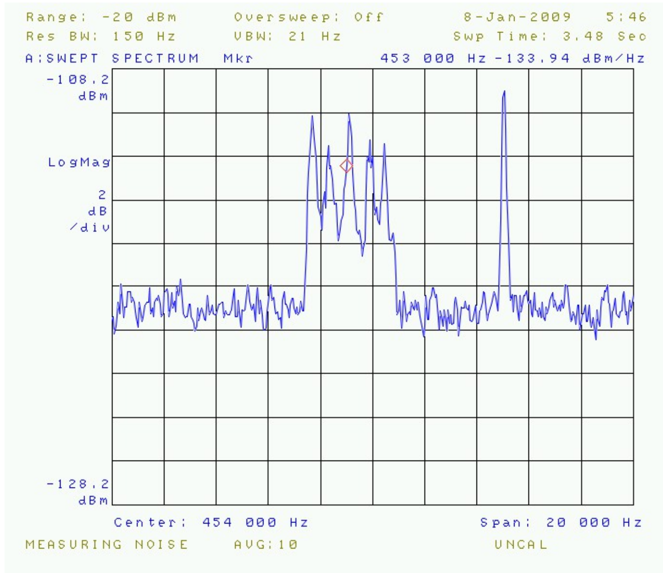

Figure 4: Swept noise, 453 KHz, 4 Khz spacing, HP8640a

Further work: I intend to repeat some of these tests with the notch method and maybe with a phase lock loop to see how they compare.

My preliminary conclusions:

<u>Math:</u> It looks like my analyzer provides some reassurances that the math is going in the right direction. The two HP8640's are not the same, which is to be expected for two long running instruments of different pedigrees.

<u>Accuracy:</u> The observed readings were not that simple. There was noise on the screen in all marker read areas. Still, with averaging and being confident I was looking at the approx. midpoint of any ripple, the readings are consistent and provide a full scale 1% reading accuracy. The analyzer was calibrated by its internal routine. The instrument was used continuously to make all 4 tests. That is, it was not shut down and restarted in between tests.. My numbers are probably +-1 dB in absolute accuracy, at best. I can't vouch for the absolute accuracy of the readings without at least getting a hold of either a calibrated source or another spectrum analyzer that has been recently calibrated by reputable calibration lab. (This is a hobby, after all.)

<u>My test Oscillator:</u> *These measurements are not conclude yet..coming soon*

<u>The HP8640's</u>: Not surprising, there is a slight difference in the noise between the units. That seems reasonable.

I did find a graph for typical HP8640 phase noise:

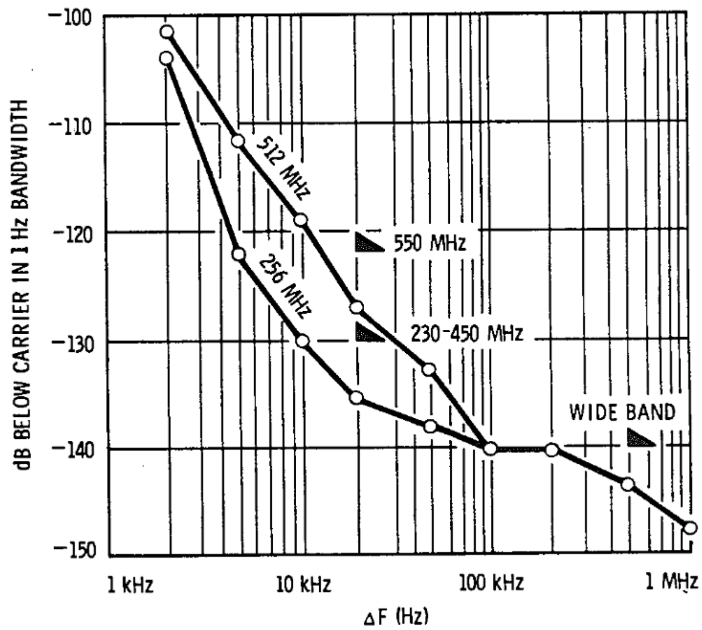

Figure 5: HP8640 phase noise

There is a statement with this graph that *"…the phase noise decreases with lower frequencies at approx. 6 dB per frequency division down to the noise floor.*"

There is also a graph for typical measurements made that show 5 dB lower at 20 KHz offset, from the published specs, but at the higher frequency range of the generator.

How do my HP8640's compare ? Here is a plot of a 9 MHz signal at .6 dBm output (20 dBm through an attenuator, to prevent overloading the front end of the analyzer)

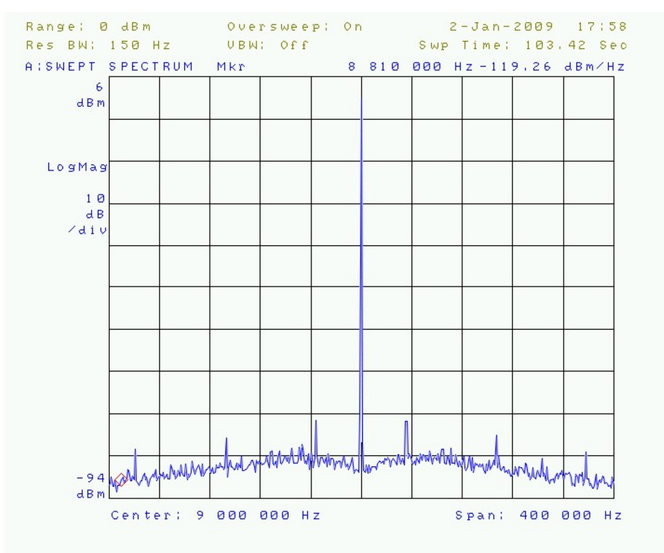

Figure 6: HP8640 9 MHz scan

You can see the noise level increases about 7 dB or so as you get within 100 KHz of signal. The peak detector is on here, and the noise marker is being used. These readings are limited by the input dynamic range.

Here is the same view of a 500 KHz signal, same setup, and you can see the same thing going on.

In both cases, the marker is parked off to the left in the floor. The noise function is turned on. Since it is reading directly from the signal generator through an external attenuator, the range is limited by the dynamic range of the analyzer input.

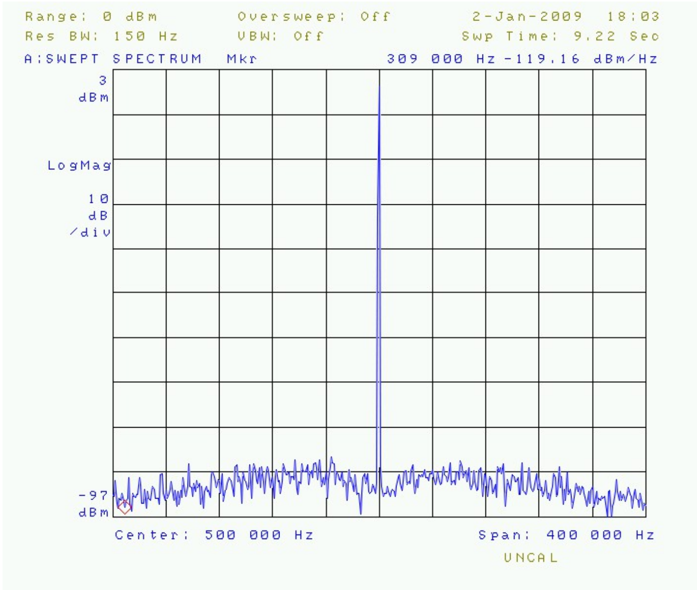

Figure 7: HP8640 500KHz scan

This measurement does not go through the filters used in the actual phase noise measurements.

Frankly, these look perfectly normal. I don't think there is anything untoward happening with HP8640 signal generators. For now, it looks like the HP generators have very good phase noise characteristic's.

When using these units for IMDR tests with a receiver, the outputs should be coupled through a capacitor to block DC and a small attenuator of 10 dB or so, to aid in linearity in the output amplifier of the HP8640.

<u>References</u> on the front end crystal filter method to measure oscillator noise:

1) Introduction to Radio Frequency Design Wes Hayward, 1994, ARRL Press, Pages 298,299 (This is the method I followed, which pretty much matches the information provided by Dallas Lankford)

2) Experimental Methods in RF Design, Wes Hayward, Rick Campbell, Bob Larkin, 2003, ARRL Press, Pages 6.52, 7.40

3) Solid State Design for the Radio Amateur, Wes Hayward, Doug DeMaw, 1986, ARRL, Page 127

4) Comments on my phase noise by Dallas Lankford (who does not believe that I have good numbers yet. I defer to his expertise)

<u>On spectrum analyzer noise measurements</u>:

5) Phase Noise Webcast 19Jul12, a presentation by Kay Gheen, Agilent Technologies, on Phase Noise Measurement Methods and Techniques

6) Hewlett Packard Application Note AN-270-2, Automated Nosie Sideband Measurements Using the HP

8568A Spectrum Analyzer

ACRONYMS (tbd)