Phase-noise by Jens Koefoed SM7OVK

This article will try to explain some things about phase-noise. There will not be any theories with mathematical explanations. If you are interested in this subject there are plenty of books available. Phase-noise isn't anything new and much has already been written in a popular way as is this article. There are still too many amateurs, and also radio-constructors for that matter, who are acting like ostriches.
(This article has also been presented in Swedish in QTC, the SSA periodical, no. 2009-01.)

"Radio pollution"

If letting out CO_2 is a big threat to the environment, phase-noise is in many ways the same thing for our radio-world! If Mr. Marconi had attempted his early trans-Atlantic communication experiments today, with the same equipment, it would most probably not have worked. Noise is created in many ways in our world, not only from space where a background noise is always present, but also from disturbances caused by electric motors and other equipment which could be seen as noise at some frequencies. Phase-noise is very common in radio-transceivers and since high output powers and also high-gain antennas are used especially on VHF and above, this energy can travel far away. Phase-noise is created in all oscillators and can not be completely filtered away later. A more simple oscillator often has a higher phase-noise than a more complicated circuit, but it doesn't have to be that way. A crystal oscillator has often a very low phase-noise.
Phase-noise can often be reduced with a good PLL-circuit, i.e. the system for frequency-control of the oscillator. Unfortunately it can be quite expensive to develop a good oscillator-solution and that explains why many manufacturers of modern equipment are often unwilling to solve these problems, despite the solutions sometimes being quite simple. Consumers may also have more interest in a wider frequency-range for the receiver, forcing the manufacturers to compromise by implementing a wideband solution.

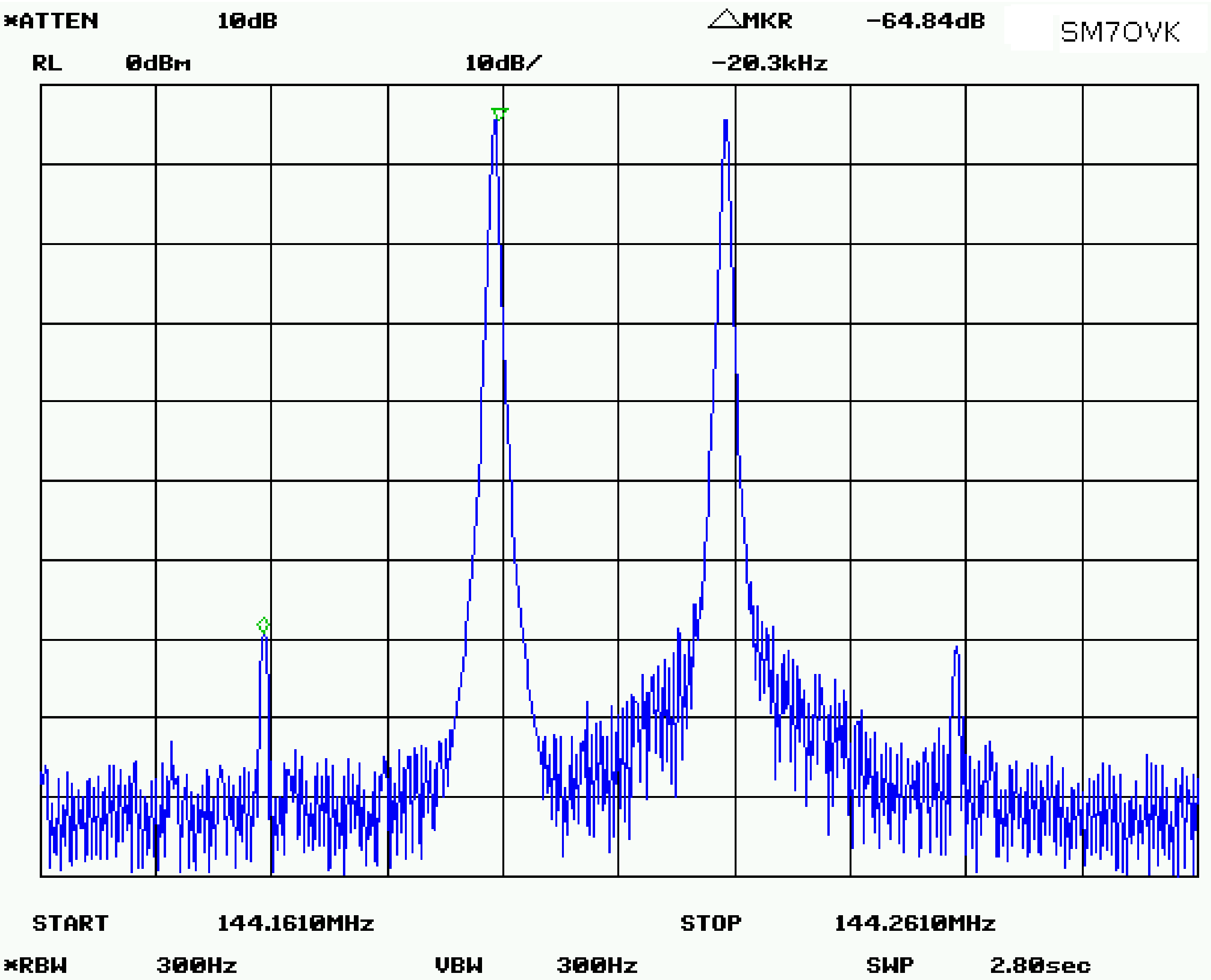
By the mid seventies, Leif, SM5BSZ, amongst others, was very active in trying to make us and the manufacturers aware of these problems by publishing modifications for radios to increase their performance. Such performance is sadly rare to find in new ham-radio transceivers. Unfortunately the manufacturers use oscillator-solutions from HF-radios in the VHF- and UHF-bands, where much higher antenna-gain results in much higher field-strength bringing new problems. Few HF-radios are therefore suited to be used together with transverters for higher bands, this situation is even worse if a power-amplifier is added!

About noise

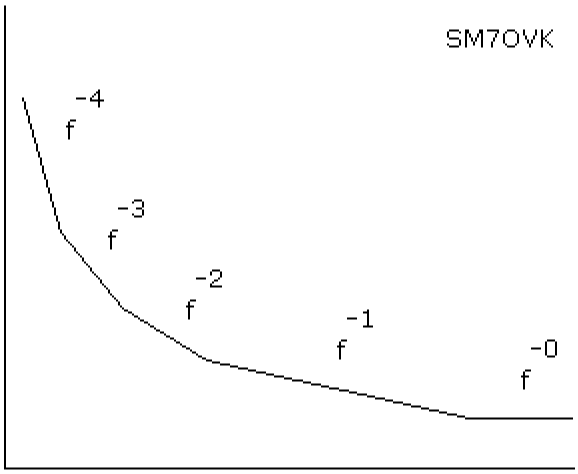
Noise is additive, i.e. all types of noise add together with the wanted signal. Noise in the local-oscillator will mix with the wanted signal, but also with the transmitted since the same oscillator is normally used. Phase-noise in the transmitted signal attenuates in exactly the same way as the wanted signal. If you amplify the signal, the phase-noise will also be amplified in the same way.

What does phase-noise look like? Figure1 shows two signals with much higher amplitude than the smaller on the sides. These are from two different signal-generators where the right trace is from a much cheaper machine than the left. The right one is a Fluke 6061A with a clear phase-noise, i.e. raised noise on the sides of the carrier compared to the spectrum-analyser background-noise. The left signal is from a Rohde&Schwarz SMIQ where we hardly see any phase-noise. There is of course phase-noise on the R&S-generator too, but with this setting of the spectrum-analyser we can hardly see it.
Since all oscillators contain phase-noise it's important to know how much and how quickly it decays from the carrier. The faster the phase-noise decay, the cleaner signal, and we can also say that we can hear weaker signals - if the background-noise isn't stronger. You don't want to suffer

interference from your neighbours, and you wouldn't like to cause them interference either. Would you?



Drawing 1: Oscillators with phasenoise

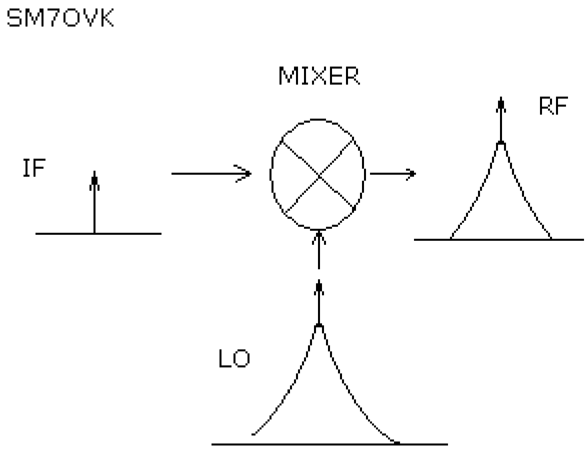


Drawing 2: Characterization of noise sideband in the frequency domain.

Phase-noise can be characterised according to figure2, where the different areas in the curve originates from different physical processes in the oscillator and the PLL. The part to the right, f-0, is white noise. f-1 is called 1/f-noise or flicker noise, i.e. a noise that increases with decreasing frequency and often mentioned together with transistors and so on. We can clearly see that the different components are increasing faster, the closer we get to the carrier. Selection of both the active oscillator component and the Q-values in its circuit is of great importance.

What happens when transmitting?

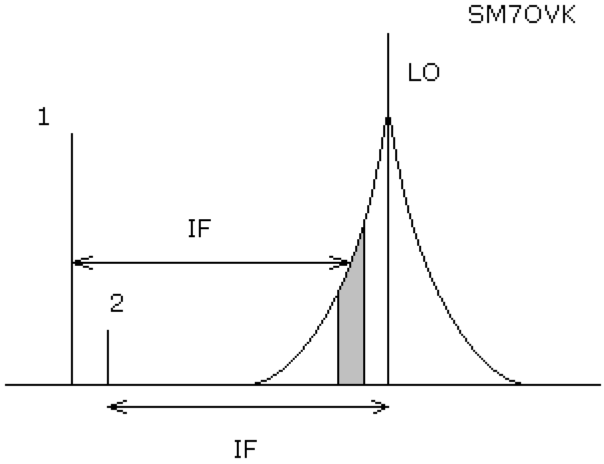
The modulated signal, let's say a keyed carrier, is often made in the radio with a crystal-oscillator on the intermediate frequency, IF. (Often the same oscillator is used as BFO at reception.) This signal is normally very clean, since it's usually a crystal-oscillator. When it mixes with the local-oscillator it will pick up that oscillator's noise, see figure3.
Exactly the same thing happens in a transverter for the higher frequency bands. Then the local-oscillator in the transverter is a crystal-oscillator and is then characterised by the IF-signal in figure3. The HF-transceiver is sadly often the noisy signal marked LO in figure3!
This can work if you don't have any radio-neighbours, but if the signal is amplified the noise will increase as much as the wanted signal. Noise is attenuated in the same manner as the wanted signal and also reaches as far as the wanted signal, until it's killed by the background-noise. The result on the higher frequency-bands is of course that nearby stations find it impossible to receive signals that are weaker than your broadband noise. It's simply impossible to remove it with filters if they want to receive the wanted signal at the same time.
The transmitted noise is most often as wide-band as the amplifier output circuits. This also indicates that it's often reaching far outside the amateur-radio bands!



Drawing 3: TX mixer

What happens at reception?

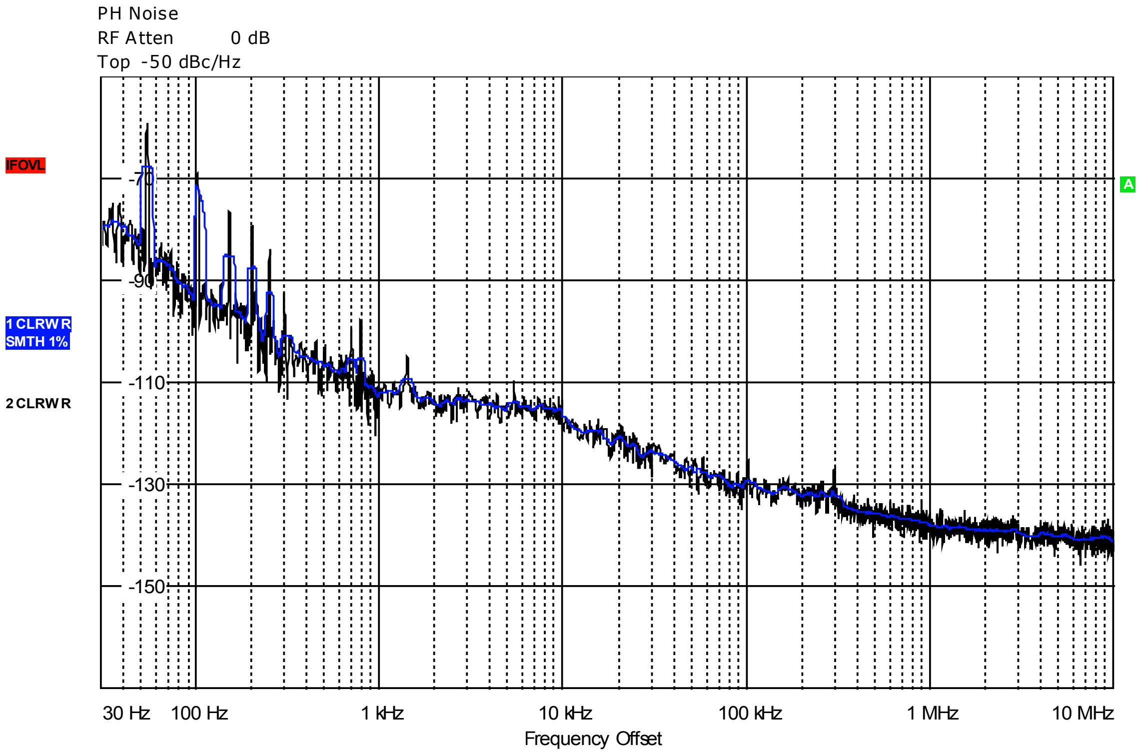
This is more tricky, since you could have a both disturbing signal nearby transmitting with high phase-noise level, ***or*** that your own receiver is overloaded by the received signal and is then affected by your own noise in the local-oscillator. The latter is called reciprocal mixing, see figure4.
In a superheterodyne-receiver, in other words the type of receiver that still is the most common type, the received signal is mixed with a local-oscillator and the result is the IF, intermediate frequency.



Drawing 4: Reciprocal mixing.

It's easy to see that this will work over the total IF-filter bandwidth if the phase-noise in the LO is high enough and if there are one or several high level signals in your surroundings, the IF-filter bandwidth is grey-marked in figure4. This effect is most often noticed during contests since the

PHASE NOISE					
Settings		**Residual Noise**		**Spot Noise [T1]**	
Signal Freq:	144.298879 MHz	Evaluation from 30 Hz	to 10 MHz	1 kHz	-112.31 dBc/Hz
Signal Level:	2.82 dBm	Residual PM	0.12 °	10 kHz	-116.56 dBc/Hz
Signal Freq ?:	793.39 mHz	Residual FM	2.478 kHz	100 kHz	-129.12 dBc/Hz
Signal Level ?:	-0.01 dBm	RMS Jitter	2.3124 ps	1 MHz	-138.18 dBc/Hz



□□L¼Z Measurement

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Drawing 5: FT225RD phase-noise measurement.

received signal level is then higher when there are more stations active. (All received signals are added in the receiver, as noise. The more signals that are on air, the more power the receiver must be able to handle, and at the same time the oscillators must be cleaner with less phase-noise.)
Since the phase-noise from the local-oscillator is mixed with the transmitted signal it's easy, but unfortunately quite expensive, to measure the phase-noise. There are several different manufacturers producing equipment for this and a measurement can look like in figure5. This picture gives us even more information than the noise-level at different distances from the carrier. The spikes at the left side of the curve are with very high probability from the power-supply. If the supply voltages are not filtered it'll show up nicely on a phase-noise measurement like this. You can see that the first spike is at 50Hz from the carrier, in the US this would be at 60Hz. If we did this measurement when the radio was new and the capacitors were fresh these spikes would be much lower – yet another reason to exchange the electrolytic-capacitors in the old rig! This measurement was made at full output power, 25W, so the capacitors are working full time.
Nowadays, phase noise measurements are made by ARRL when they are doing tests of transceivers and receivers. It doesn't prove that your rig is as good or bad however, and we can only hope that the manufacturer succeeded to maintain an even quality in the factory. The phase-noise can also be worse when the radio gets old, especially as shown when the electrolytic-capacitors dry out.
(It doesn't matter if the local-oscillator is higher or lower than the received signal.) The wanted signal, number2 in figure4, is mixed with the local-oscillator and out we get an intermediate frequency, IF. If the local-oscillator, LO in figure4, has high phase-noise meanwhile another received signal is strong enough it'll be mixed together with the phase-noise instead and get through all the IF-stages. Even if the mixer inputs are marked RF-input, LO and IF, it'll work nearly as good if the inputs are changed. If the input signal has enough signal level the mixer will deliver an IF-output.

How do you know if your radio has a high phase-noise level?

Another way go find out if you radio suffer from high phase-noise is to have a clean station, not to far away, to listen to your transmitted signals. The reason for not being to far away is that the phase-noise is most often much lower than the wanted signal. (In figure5 we can see that at 1kHz from the carrier the noise is 110dB down!) If the receiving station is too far away it'll not be able to hear this noise.
One very important thing when this type of test is made is that there must not be any amplifier that is resonating. If an amplifier is self-oscillating on a frequency much higher or lower in frequency this can often be hear as an increased noise-level. (An oscillator is after all an amplifier with a frequency-dependant feedback with just enough feedback to keep it oscillating.) When the receiving station listens, it should listen very close but also far out from the carrier. Phase-noise can rise several hundred kHz from the carrier.

If you have a high phase-noise in your radio?

Well, first and foremost, you should never use a power amplifier! That would make things even worse and you would be interfering with your ham-neighbours. If we look again at figure5 we can see that the noise is about 110dB down at 1kHz distance. If we should feed this signal into a power amplifier with 20dB gain the result will be at least 90dB down at 1kHz and often higher since noise can be added in many ways in the transmitting system.
If you have an older radio there are often several modifications that you can do, but don't forget to verify that there is any difference on your radio. There could have been differences in the production so your modification might not have the same effect as it have had when it was first presented in a magazine or on the Internet.
If you have a new radio you should contact your distributor, but preferably you should have checked this out ***before*** you bought the radio. As when buying a car we normally want to know a little about the fuel-consumption.

The most problematic situation is probably for those with transceivers that are a little older, since the manufacturer doesn't feel any high responsibility for these units. They perhaps have a more complicated PLL-solution that can't be improved in some easy way. After all, it's always the one who presses the PTT-button who is responsible for the transmitted signal! Unfortunately many think that when they have bought an expensive radio it must be best. Something that has been achieved by Leif, SM5BSZ, with his WSE is a very pure and clean receiver with only a couple of crystal-oscillators instead of PLL-circuits. Clean oscillators together with mixers and amplifiers with high dynamic range result in a very good receiver and it can even be used as a good instrument. (You can read more about this on his homepage.) To get all transceivers as good as the WSE is of course an utopia, but we must insist on more stringent requirements when we buy new transmitters! The products must certainly be used correctly, this is of course most important for the transmitters, but also for other equipment that generate disturbances. There are only a small number of VHF-transceivers that you, with good radio-neighbour-conscience, can use together with a power amplifier - and from my knowledge none of those are in current production.

Many thanks to Rhys, GW4RWR, who have been most helpful correcting my SwEnlish!