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The harmful effects of local oscillator noise

1
Introduction

The goal of any transmission system is to transfer information from point to point. It is correctly done when the received information is identical to the original one. In practice, the information can be distorted and/or mixed with disturbing signals. Noise of all transmission stages is the main troublemaker. At the limit, they can be so high that the ratio information/noise ratio is too low to get the information available.

2
Local oscillator

A local oscillator, LO, is composed of an oscillator eventually followed by mixers and/or frequency multipliers in order to obtain the desired frequency, because it is not possible or desirable to start with a very high frequency oscillator.

As with all electronic devices, an oscillator makes noise. As long as oscillators were based on transistor and crystal arrangement, their noise was acceptable. The use of lower Q resonators and the modern devices PLL and DDS are quickly showing their weakness where more demanding performances are required.

Noise level is an important limitating parameter for weak signals communications as it decreases the RX sensitivity and TX signal quality.

More, other shortcoming can upset weak signal reception when strong signals are on adjacent channels: it is called reciprocal mixing.

Those defects are restricting for both amateur and professional equipment.

3
Electronic circuits noise

Electronic circuits are composed of active and passive components. It is well known that any conductor generates noise by thermal agitation of electrons, called white noise as it extends from DC up to the highest frequencies.

The power of thermal noise is given by:

$$P_{noise} = k\ T\ B\ \text{(watts)}$$

where:

k = Boltzmann's constant ($1.38.10^{-23}$ K/J)

T = absolute temperature (K = 273°C + ambient)

B = bandwidth (hertz)

At 27°C and one hertz of bandwidth, we have:

$$
\begin{aligned}
P_{noise} &= 1.38 \times 10^{-23} \times 300 \\
&= 4.14 \times 10^{-21} \text{ (watt)} \\
&= 4.14 \times 10^{-18} \text{ (mW)} \\
&= 10 \log (4.14 \times 10^{-18}) \\
&= -174 \text{dBm/Hz}
\end{aligned}
$$

(see Appendix)

Oscillators produce other kinds of noise. Most influential are:

- Shot noise occurs when there is a potential barrier, i.e. diodes and transistors junctions
- Flicker noise, called pink noise or 1/f noise as it is decreasing with the frequency up to a cut off frequency and remains constant after that. Metallic resistors produce the lowest and it is more prominent in FET and MOS transistors.

Powers of different noises add.

4 Oscillator noise

An oscillator is composed of an amplifier in conjunction with a high Q resonator. Oscillator behaviour survey comprises:

Whys: various noise voltages and currents are present together with normal DC and HF ones. They are due to various oscillator components, passive and active.

Wherefores: those voltages and currents modulate the normal ones by amplitude and phase modulation.

Mixer and other stages following the oscillator attenuate amplitude-modulated noise. Therefore, amplitude noise is generally treated as immeasurable and neglected. If it were not, any residual AM noise would produce a familiar effect. On the contrary, phase-modulated noise produces less intuitive effects and requires more attention to be well understood. Even after saturated stages phase modulation remains. Moreover, the phase offset is multiplied by any multiplier stage.

Usually, we use the expression: phase noise.

5 Low Noise LO design

To design a low noise oscillator, we need to follow some requirements. It is the aim of this article, to minimise the phase noise, the advice of the KA2WEU/DJ2LR, Pr. Dr Ulrich Rohde check list [5,6] and F5RCT lecture [7] is:

- Maximise the unloaded resonator Q
- Maximise the resonator reactive energy
- Avoid oscillator saturation
- Choose an active device with the lowest possible noise figure at the actual working conditions, especially for flicker noise under 10kHz
- Use low frequency negative feedback to reduce transistor flicker noise
- The energy should be coupled from the resonator rather than another part of the oscillator
- Use high stability and low noise passive components. Be careful with low Q varicap diodes.

More, external reasons can add noise:

- DC supplies from linear and switching regulators
- Vibrations (fan) and mechanical

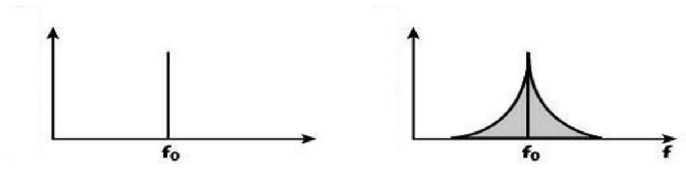

Fig 1: Frequency spectrum of an ideal and a real oscillator.

shocks (microphonic effect of resonators and some capacitors and coils)

- Digital circuits (computer).

6

Whole oscillator noise

When multipliers stages follow an oscillator the phase noise is increased by the multiplication factor. For an N factor, noise is degraded by 20 log N. In real world conditions, it is a minimum value increased by the multipliers stages own noise. Therefore, a choice should be made between:

- To start from a rather low frequency oscillator that requires a large multiplication
- To start from a high frequency oscillator.

On one hand, high stability, low retrace effect and low noise sources, such as OCXOs, caesium or rubidium generators, usually generate a 10MHz signal. A very large multiplication factor is required for the microwave bands. On the other hand, VHF OCXOs are able to give an acceptable solution if the drift and the retrace effect are cancelled by a permanent power supply [8].

A 10MHz OCXO can be used as a reference for PLL and DDS devices [9]. A microwave PLL can be based on a DRO.

Those solutions avoid a large multiplication factor, but they are more difficult to achieve.

7

Real oscillator spectrum

Fig 1 shows the frequency spectrum of an ideal and real oscillators. The spectrum spread is due to the phase noise. This is common for analogue signals, like those from an LO. Fig 2 shows the time domain. In this case, the word jitter is used in digital applications.

From the Fig 1, we can see two sidebands around the central frequency called the carrier. Fig 3 shows the complete spectrum (DSB) and the half-sideband spectrum (SSB). As the phase noise spectrum is symmetric around the carrier, it is commonly characterised by the SSB spectrum. The symbol is L_φ (f_m). It represents the ratio of the SSB noise power in a one hertz bandwidth centred at f_m hertz away from the carrier, to the carrier power. It is called SSB spectral density;

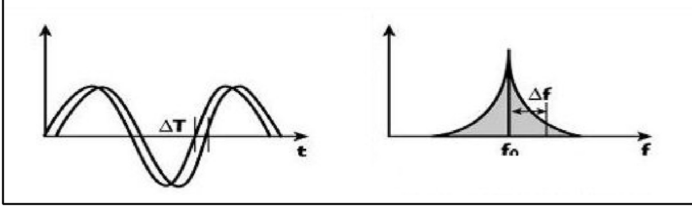

Fig 2: Phase noise in the time domain (jitter).

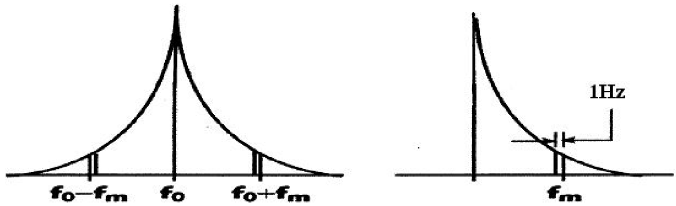

Fig 3: DSB and SSB spectrums.

the units are dBc/Hz.

If we assume that the phase noise is approximately constant over the bandwidth of interest, at a distance f_m from the carrier and for a bandwidth B, noise power is given by:

$$P_{in\ B\ hertz} = B\ L_{\varphi}(f_m)\ P_c \quad \text{(watt)}$$

where P_c is the carrier power.

It is generally more convenient to work in dBs. Then:

$$P_{in\ B\ hertz} = 10\log(B) + L_{\varphi}(f_m) + P_c \quad \text{(dBm)}$$

That offset (f_m) can be 10Hz, 100Hz, 1kHz, 10kHz or 100kHz.

Spectral density can be calculated from Leeson [1] who established a formula using the oscillator's parameters. A number of surveys [2,3,4] added corrections and complements.

Fig 4 shows the general look of a calculated curve. We can see several regions with different slopes. Near the carrier, up to a few tens of hertz, the slope is following an f^{-3} law, so a -30 dB/decade slope. Within the kilohertz region, the law is f^{-2} equals to -20 dB/decade. Then, follows the thermal noise region with a constant value.

A more detailed analysis shows other regions in f^{-4} and f^{-1}. After reading of several surveys, it is questionable, so the above is mentioned.

8

LO noise measurement

To measure an LO noise spectral density, we need equipment able to handle megahertz and even gigahertz signals. In general, its own noise near the carrier would be at the same level or even more than we want to measure.

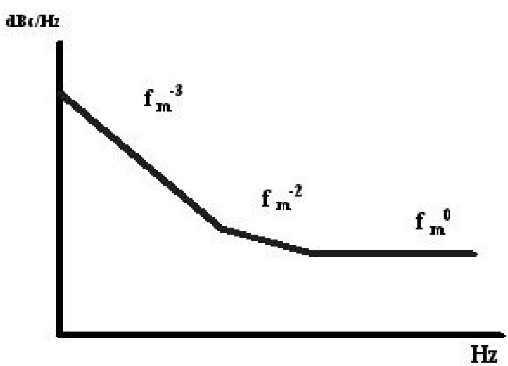

Fig 4: Simplified theoretical curve of the noise spectral density of an oscillator.

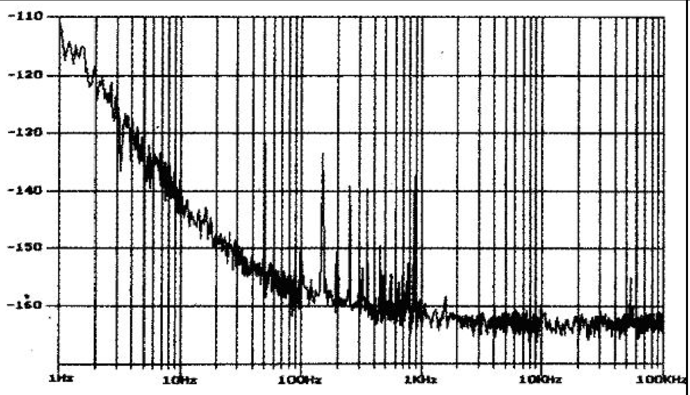

Fig 5: Spectral density of a very low noise OCXO spoiled by a poor power supply.

Specialised equipment is not common for a radio amateur. For example, the E 5052 from Agilent cost is $85,000! The Aeroflex PN 9000 is able to do the test at a quite high cost.

An affordable method is to use a very clean auxiliary signal, a detector or a phase discriminator to get a signal acceptable for use with standard equipment

Fig 5 shows the spectral density of a very low noise OCXO. Nevertheless, we can see large undesirable spurious signals between 100 and 1000Hz. They come from the power supply (main frequency harmonics and variations).

However, we can show a poor quality oscillators spectrum with a common spectrum analyser. That will be detailed later with added noise oscillators. Moreover, we can listen an oscillator signal with a receiver to "hear" its noise but not be able to quantify the noise. That is very useful for UHF and microwaves.

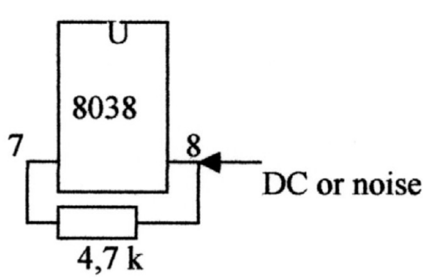

Fig 6: Narrow frequency modulation device.

9

Test of deliberately added noise oscillators

It is useful to know the effect of a noise polluting a sine wave signal.

To test amplitude modulation effect, a 1000Hz signal from an audio generator is mixed using a dual gate FET (BF 988) with noise. The noise is produced by a device comprising of a 78L09 regulator followed by two stages of amplification [11]. On an oscilloscope, we can distinctly see the noise above 1% modulation. With headphones, we can hear much lower levels.

To test phase modulation, an 8038 deliv-

Table 1: Fig 6 calibration.

F	U_8	Δf (Hz)	U_{dc} (mV)
1039	9,600	-23	50
1058	9,560	-4	10
1062	9,550	0	0
1080	9,510	18	-40
1103	9,460	41	-90

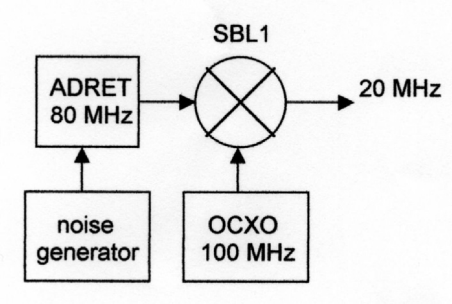

Fig 7: HF device to produce a noisy HF signal.

ers a 100Hz signal with a narrow frequency modulation (NBFM produces the same effect as phase modulation). Fig 6 shows the block diagram. First, the device is calibrated with a DC signal (see Table 1). We have:

$$\Delta_f / \Delta_{Udc} \text{ (average)} = 1\text{Hz} / 2.2 \text{ mV}_{dc}$$

NB: there is no amplitude modulation, as the amplitude remains constant.

The noise generator already described is used with this modulation. The threshold is 40mVpp that is to say about 18Hz or a 1.8% frequency variation.

NB : the audio effect is not the same when the signal is amplitude or phase modulated by the noise. It is difficult to explain this! It seems deeper and more disturbing even when the bandwidths are the same.

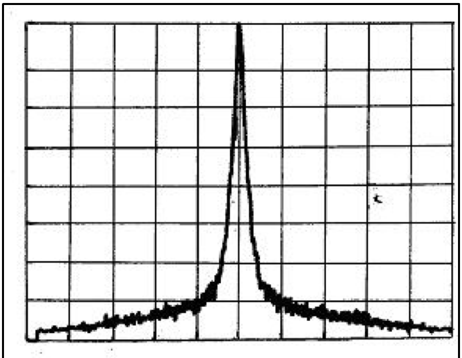

Fig 8: Original 20MHz spectrum.

10

TX signal purity versus LO noise

LO noise spoils TX signals even when there is no mixer, only frequency multipliers. The received signal spreads, as a large part of the power is lost in undesirable sidebands. The noise appears around the received carrier. It is really a jammer!

F1GHB and F5EFD "listened" to two LOs at 10GHz. One is an OCXO followed by multipliers. Its measured noise is about -90dBc/Hz. The other is a synthesiser based on a LMX 2326 having noise of about -63dBc/Hz. With the first one, nothing was wrong but audible noise was heard on the second.

Radio amateurs working the microwave bands above 76GHz know how difficult it is to obtain a pure note. SSB and CW can be upset by the phase noise. WA1ZMS has made a presentation at MUD 2004 [10]; we can "hear" noise of several oscillators at 241GHz.

11

Noisy HF TX

To known how noise upsets a HF TX, the device in Fig 7 is able to produce a noisy 20MHz signal.

This device comprises a HF generator (ADRET 6315) to deliver an 80MHz signal. The noise generator can modulate that generator. A mixer mixes the output signal and a 100MHz produced by an OCXO. A spectrum analyser shows the output at 20MHz. Scan is one kHz/division, bandwidth 100Hz and scale 10dB/division.

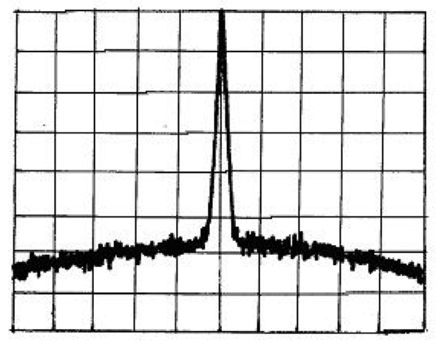

Fig 9: 20MHz spectrum with added noise.

Figs 8 and 9 show the 20MHz spectrums before and after noise is added. The floor noise, noise without signal, increases by more than 15dB. With a RX in AM mode, we can hear the noise on each side of the tuning frequency, as we hear a NBFM signal. In NBFM mode, noise is at the centre frequency. In SSB mode, we can find the noise on one side. For those three cases, listening seems not to be affected by this noise level.

12

Deliberately noisy microwave signal

Fig 10 shows the equipment. It starts with a XO at 108MHz, phase modulated by a varicap. The noise generator is as above. Several multipliers stages follow to produce a 10,368MHz signal. Because of the large multiplication factor and the heavy saturation, the output signal is easily phase modulated without noticeable AM.

With a 10GHz RX, we can hear the sound effect. In SSB mode without added noise, tuning gives the usual tone variation, low to high frequency. With an increase added noise the tone become "rougher and rougher"

My "poor mans lab" does not allow me to quantify precisely that effect. Nevertheless, my old 141T spectrum analyser with an 18GHz plug-in is able to show me the spectrum variations during the test. The floor noise of that old spectrum analyser is -110dBm for a 100Hz bandwidth in the 8.23 to 14.35GHz range. Figs 11 and 12 clearly show the noise effect. We can see that the reports by F1GHB and F5EFD are roughly confirmed. A 20dB of noise increase changes a signal from correct to unacceptable.

By interpolation, we have approximately:
Fig 11

- -50dBc at 1kHz offset; then:
- -50 -log 100 (B in Hz) = -70dBc/Hz

Fig 12

- -30dBc at 1kHz offset; then:
- -30 -log 100 = -50dBc/Hz

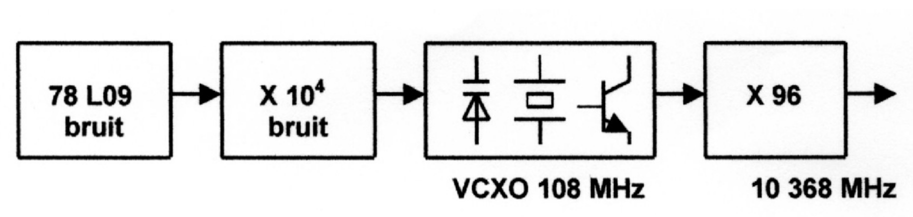

Fig 10: Equipment to produce a noisy microwave signal.

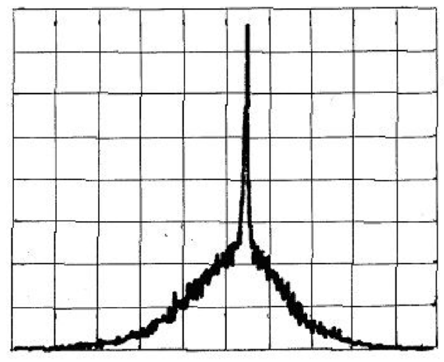

Fig 11: Correct 10,368MHz spectrum, BW=100Hz, scan=5kHz/division, scale=10dB/division.

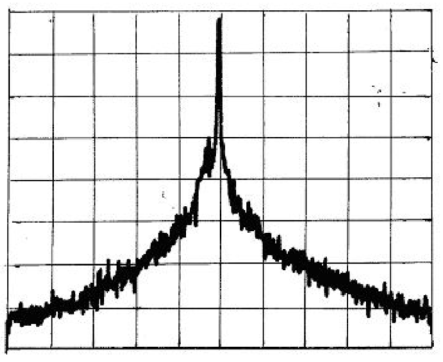

Fig 12: Noisy 10.368MHz spectrum, BW=100Hz, sacn-5kHz/division scale=10dB/division.

13

Noise LO effect on a RX sensitivity

The 144MHz transceiver [F9HX 12] is based on an IQ mixer and a zero intermediate frequency. A 24MHz VFO with a frequency variation by a varicap is followed by multipliers stages to get an LO output at 144MHz. Figs 13 and 14 show the 144MHz spectrum before and after deliberately added noise.

Those spectrums are displayed with a 100Hz bandwidth, a 1kHz/division scan and 10dB/division. We obtain approximately:

Before added noise:

- -80dBc at 1kHz offset; then:
- -80 - log 100 = -100dBc/Hz

After added noise:

- -40dBc/Hz at 1kHz offset; then:
- -40 - log 100 = -60dBc/Hz

In the last case, in SSB mode, signals are heavily spoiled. Weak signals are unintelligible.

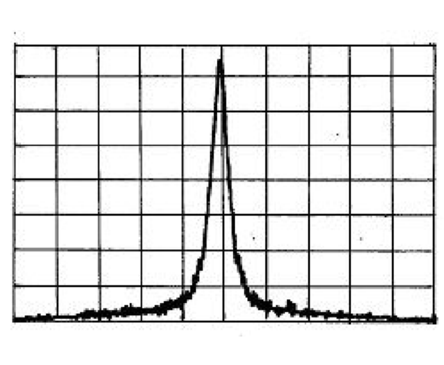

Fig 13: Correct 144.300MHz spectrum.

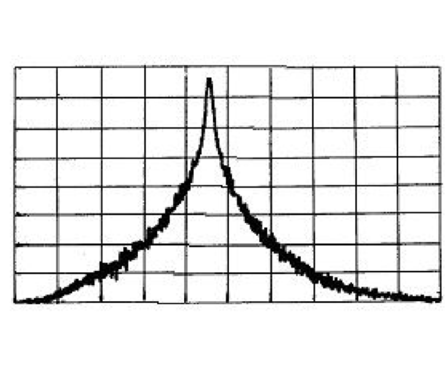

Fig 14: Noisy 144.300MHz spectrum.

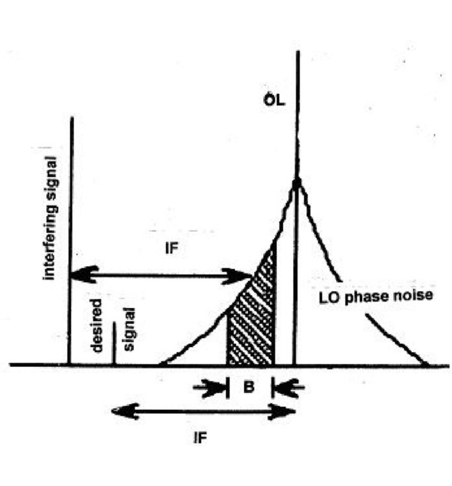

Fig 15: Reciprocal mixing.

14

Reciprocal mixing

That is the second LO noise effect. It limits the low signals reception in the presence of loud adjacent signals (Fig 15). When the LO noise mixes with an interfering signal, a signal is produced in the IF bandwidth B. It can perturb or even damps it.

This effect is very awkward on the HF and VHF bands during the contests. A loud station can be near a weak one. The RX seems to go "deaf".

From [13 and others], we can calculate the reciprocal mixing effect. For example, a 2m band RX with a 2700Hz bandwidth 9MHz IF and a -90dBc/Hz noise LO. It is tuned for a S3 = -129dBm signal. An S9+20dB = -73dBm interfering station is 10kHz away.

Approximate calculation gives:

- LO noise power in 270Hz: - 90 + 10 log 2700 = -90 + 34 = -56dBm
- Mixer output from LO noise + interfering signal = -73 - 56 = -129dBm.

We notice that the noise level produced by the interfering signal equals the desired signal.

A test verifies that calculation. Two RF generators feed simultaneously a RX while the LO is added noise or not. Without, a weak signal is audible; with, it is almost lost in noise.

15

Conclusion

As we can see, LO noise is an important parameter for communication equipments. In the HF and VHF bands, it can upset weak signals reception by loud adjacent signals; that is currently the case during contests.

For very low signals communications, it is a limiting factor. Microwaves are very demanding owing to the very large multiplication factor in LO.

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16

Appendix

Thermal noise comprises two orthogonal components not correlated: amplitude and phase. Each is half of the total. Consequently, from [18]:

$$P_{\text{phase noise}} = P_{\text{amplitude noise}} = -174 - 3 = -177\text{dBm/Hz}$$

Nevertheless, -174dBm/Hz remains the currently used value.

17

References

It is easy to find tens of references on the Internet, professional and amateur topics. Here is an extract of those I read and assimilated.

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