Analyzing the Role of Local Oscillator Phase Noise in Reciprocal Mixing

by Dale D. Henkes, ACS

Effective sensitivity and dynamic range of a receiver can be limited by LO (local oscillator) noise sidebands translated to the IF by a strong signal that is not far outside of the IF band. This undesirable process, called reciprocal mixing, is caused by the mixing of weak LO sidebands with a strong interfering signal. The process of superimposing LO noise sidebands onto signals entering the mixer is a result of the normal operation of a mixer. It is a function of how a mixer works and is not due to any fault of the mixer but, instead, is a result of a non ideal noisy LO. After the mixer, the strong interfering signal is substantially eliminated by the IF filter but the LO phase noise, imposed onto the interferer(s) by the mixing process of the mixer, cannot be removed because it extends well into the IF band.

The schematic in Figure 1 represents a receiver front end section from antenna through the IF filter (Port1). Port2 in Figure 1 provides a sample of the signal prior to passing through the IF filter (for purposes of facilitating the simulation analysis). The circuit is designed to tune the 915 MHz ISM band in steps of 30 KHz channel bandwidth. The mixer employs high side injection using a 1315 MHz LO to down-convert the 915 MHz received signal to 400 MHz IF (intermediate frequency).

In this article, the LINC2 Visual System Architect (VSA) from Applied Computational Sciences (ACS) will be used to demonstrate the effects of reciprocal mixing. The LINC2 VSA is a schematic based system level simulator. The VSA's menu of components provides quick access to both linear and nonlinear parts that can be easily arranged in any combination to represent the system on the schematic page. The LINC2 VSA system simulator is particularly suited for analyzing many component and system performance parameters.

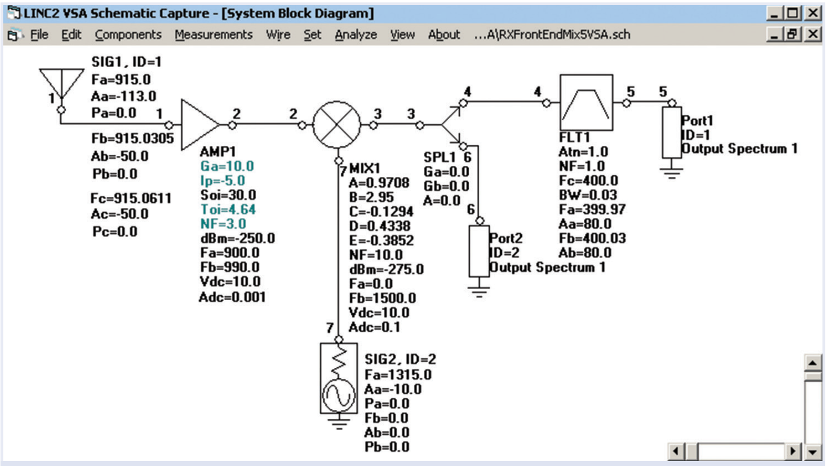
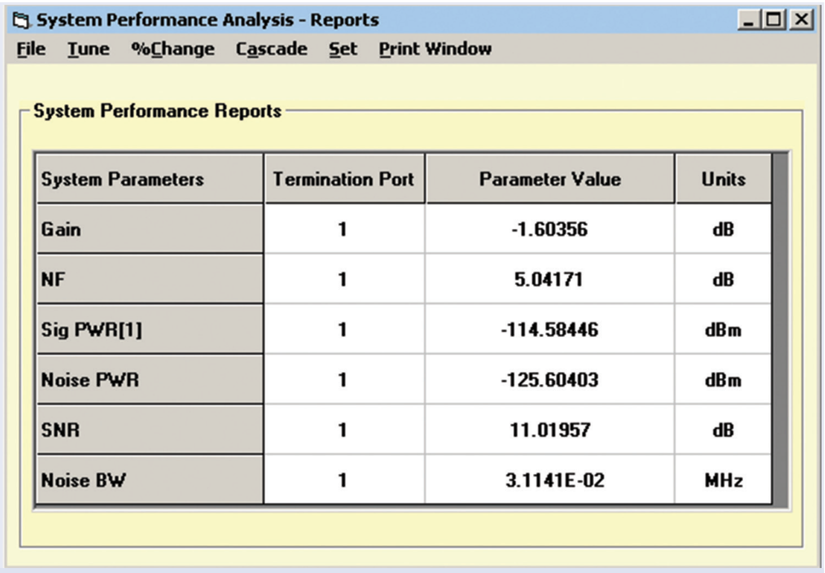


Figure 1: Receiver RF Front End (Antenna through IF)



System Parameters	Termination Port	Parameter Value	Units
Gain	1	-1.60356	dB
NF	1	5.04171	dB
Sig PWR[1]	1	-114.58446	dBm
Noise PWR	1	-125.60403	dBm
SNR	1	11.01957	dB
Noise BW	1	3.1141E-02	MHz

Figure 2: Some Receiver Front End Simulation Results (LINC2 VSA Simulation of the Circuit in Figure 1)

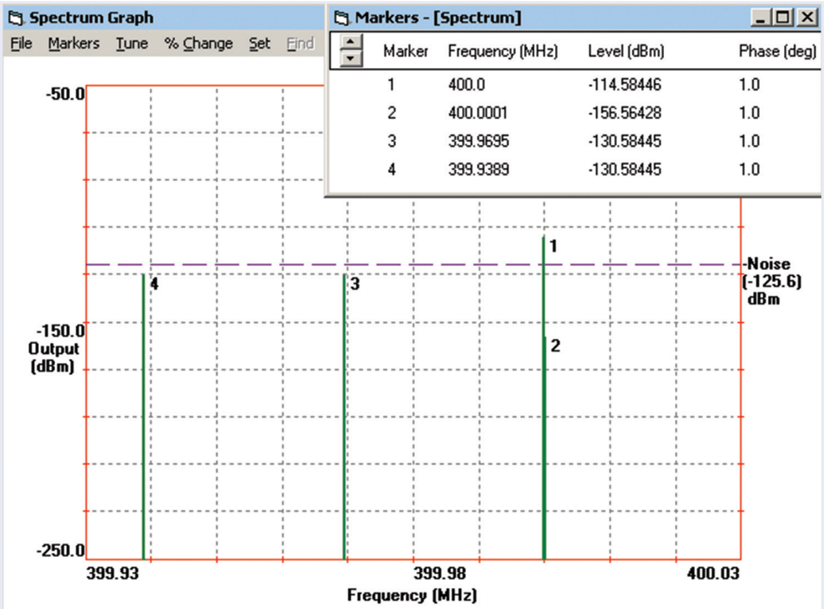


Figure 3: 400 MHz IF Spectrum with Interferers

Initially we will employ the LINC2 VSA simulator to analyze the signal to noise ratio without considering LO phase noise. Then we will introduce phase noise on the LO and show through simulation how the phase noise is transferred to the adjacent channel interfering signals and consequently spread into the IF band, effectively resulting in a reduction in the apparent signal to noise ratio.

Receiver Front End Analysis without LO Phase Noise

The antenna delivers the desired 915 MHz signal at -113 dBm in the presence of two interfering signals in the adjacent and alternate channels at approximately 30 KHz and 60 KHz offset, respectively. The adjacent channel interfering signal at 915.0305 MHz is 63 dB stronger than the desired signal. The level of the alternate interferer (at 915.0611 MHz) is also 63 dB above the desired. These signals are shown at the antenna port in Figure 1.

Referring to the VSA simulation results from Figure 2 for the following, the noise bandwidth (NBW) of the 30 KHz IF filter is 31.1412 KHz, providing an effective noise floor at the antenna port of 10Log(1000 KT) + 10Log(NBW) + NF = -173.976 + 44.93 + 5.0417 = -124 dBm. The front end gain is -1.6 dB, bringing the noise floor at the output of the IF filter to -125.6 dBm (-124 - 1.6 = -125.6 dBm) as shown in Figures 2 and 3. The 400 MHz desired IF signal is reported in Figure 3 (by marker 1) at a level of -114.58 dBm. Thus, the signal to noise ratio (SNR) = -114.58 - (-125.6) = 11.02 dB SNR as is also reported in Figure 2.

Another potential interfering signal is the third IM (intermodulation) product (marker 2 in Figure 3) resulting from intermodulation of the two interferers at the adjacent and

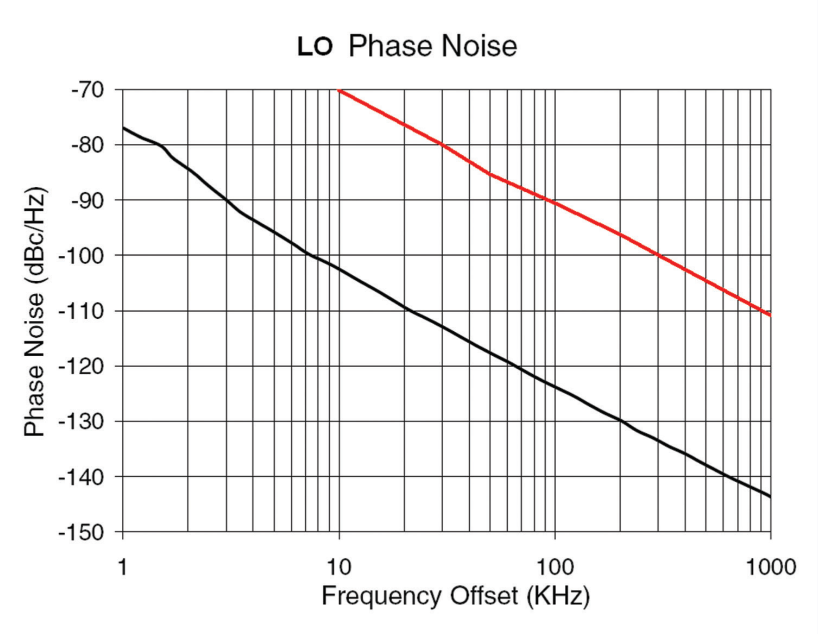


Figure 4: LO Phase Noise vs. Frequency Offset (for two different local oscillators)

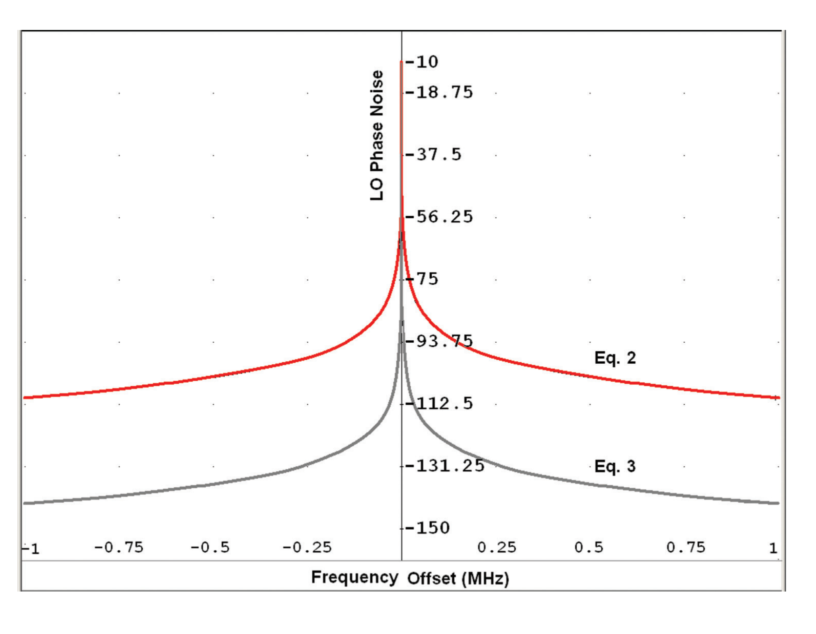


Figure 5: Double Side-Band LO Phase Noise Plots

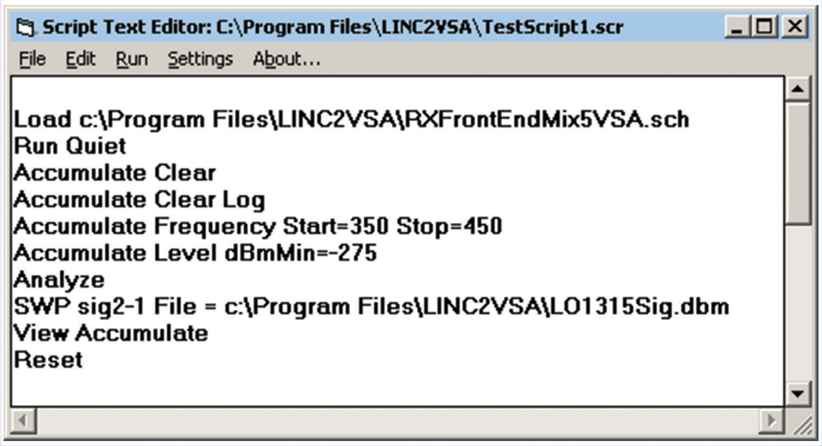


Figure 6: LINC2 VSA Script Editor

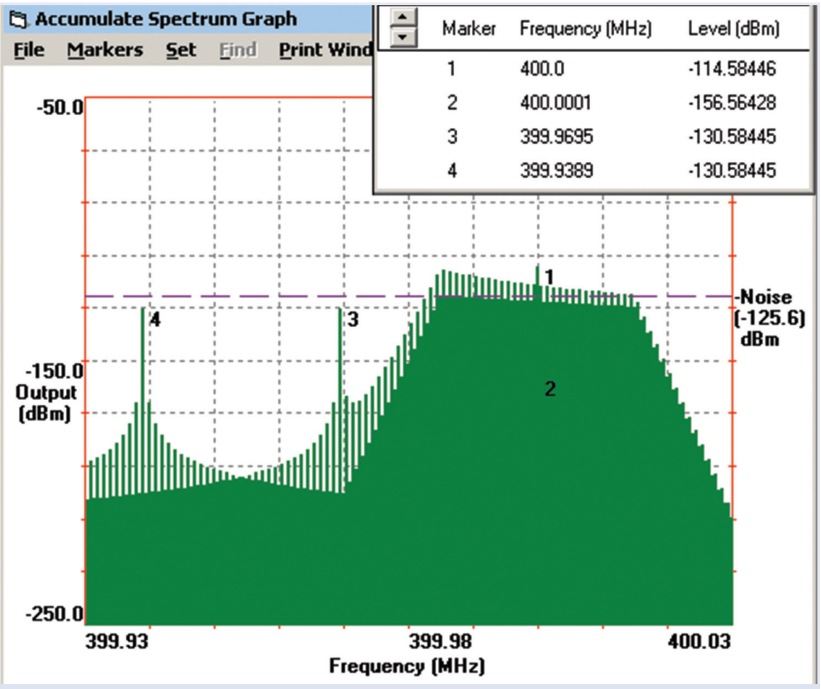


Figure 7: Spectrum Plot of Reciprocal Mixing into the IF band

alternate channels (markers 3 and 4, respectively). However, this IM interference (at 400.0001 MHz), falling near the middle of the IF band, is at a low level of only -156.56 dBm or nearly 42 dB below the desired 400 MHz signal. Thus it is of little consequence and can be ignored.

Figure 3 shows signals emerging from the IF filter. All signals are perfectly without noise. The noise free signals of Figure 3 are to be compared with Figure 7, which shows the signals and their noise sidebands that are due entirely to LO phase noise.

Receiver Front End Analysis with LO Phase Noise

To demonstrate the role of LO phase noise in reciprocal mixing (resulting in the degradation of apparent SNR), a model of an LO with poor phase noise performance will be developed and applied in a LINC2 VSA simulation similar to Figure 1 (except that phase noise will be added to the LO represented by SIG2, ID=2 in the schematic). The resulting spectrum around 400 MHz will be observed and compared to Figure 3 to determine the effect of LO phase noise on apparent SNR.

Consider the plots of LO phase noise versus frequency offset in Figure 4. The black trace represents the phase noise measured from an actual LO. The red plot is constructed such that it has about 32 dB more phase noise at 10 KHz offset. The Leeson SSB (single side-band) phase noise model is then fitted to each curve as follows:

(Equation 1) $L(fm) = 10 \text{ Log}[(1/2)\ ((f0/(2\ Ql\ fm))^2 + 1)\ (fc/fm + 1)\ (F\ K\ T/Ps)]$, where fm is the offset frequency (MHz), f0 is the LO frequency (MHz), Ql is the resonator loaded Q, fc is the flicker corner frequency (MHz), F is the noise factor, K = 1.38 (10)^-23, T = 290 deg K, and Ps is the LO power in Watts.

Red curve (poor phase noise):

Inserting into Equation 1 the following, f0 = 1315 MHz, Ql = 4.38, fc = 0.002 MHz, F = 1.99, K = 1.38 (10)^-23, T = 290 deg K, and Ps = 0.00001 W gives:

(Equation 2) $L(fm) = 10 \text{ Log}[((150/fm)^2 + 1)(1/(500\ fm) + 1)(4\ (10)^{-16})]$

Black curve (good phase noise):

Inserting into Equation 1 the following, f0 = 1315 MHz, Ql = 4.38, fc = 0.002 MHz, F = 1.26, K = 1.38 (10)^-23, T = 290 deg K, and Ps = 0.01 W yields:

(Equation 3) $L(fm) = 10 \text{ Log}[((150/fm)^2 + 1)(1/(500\ fm) + 1)(2.52\ (10)^{-19})]$

Plotting Equations 2 and 3 and folding about the zero offset axis yields the double sideband LO and phase noise plots of Figure 5. Next a LINC2 VSA signal file representing the LO from the red curve in Figure 5 was constructed. This was done by sampling the

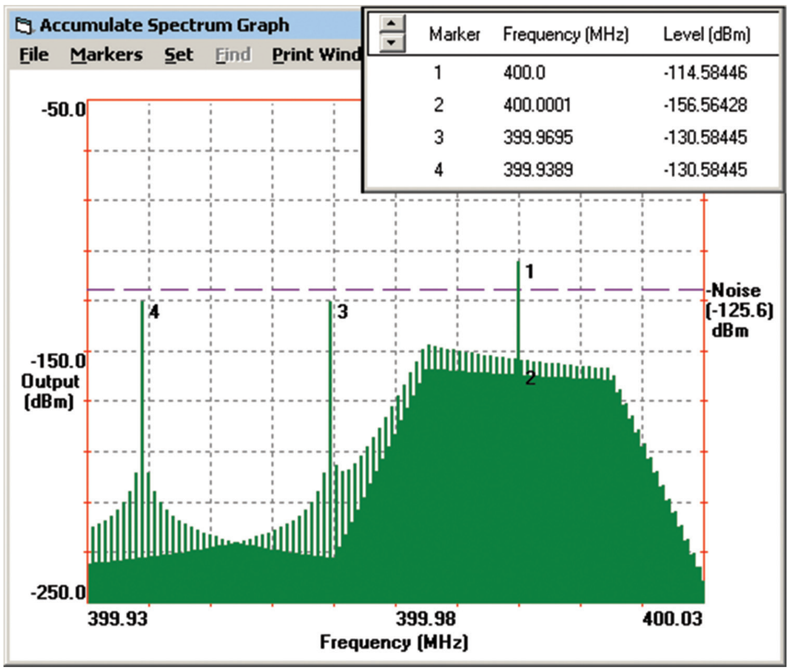


Figure 8: Improved Reciprocal Mixing Performance in IF Spectrum Resulting from Low Phase Noise LO

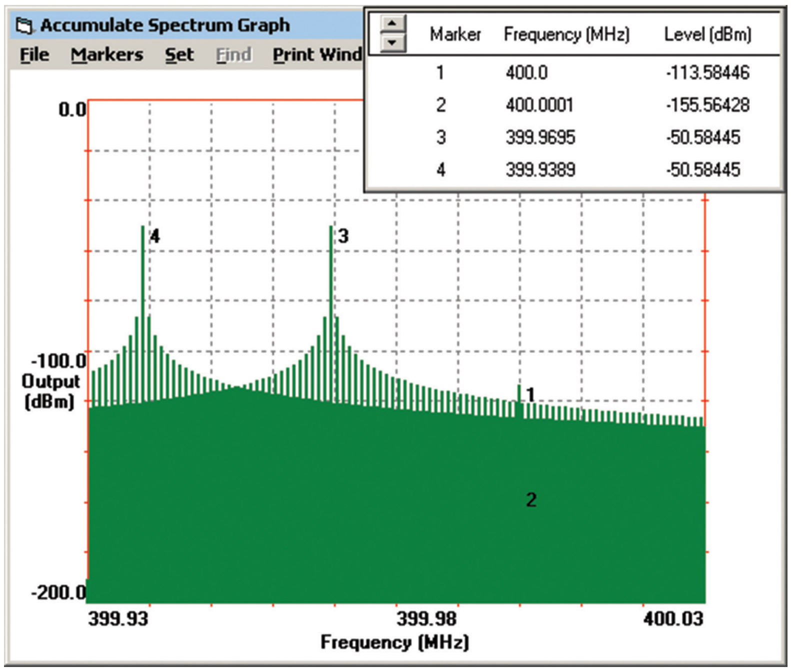


Figure 9: Spectrum Showing Phase Noise from Reciprocal Mixing Prior to IF Filtering (LO has High Phase Noise)

value of Equation 2 at 1 KHz steps up to an offset of about +/- 200 KHz.

The resulting LO phase noise file, LO1315Sig.dBm, is applied to the LO source (Sig2, ID=2 in the schematic in Figure 1) by running a script file. The script editor (invoked by selecting Edit/Run Script from the VSA schematic's File menu) allows the user to script a sequence of VSA simulation commands in any desired order.

In this case, we use the following VSA script file to set up a spectrum analysis accumulate (similar to a spectrum analyzer signal Max Hold) function (Figure 6). We follow this command with a signal file sweep (SWP) command that applies the signal file to the LO and sweeps the LO through each value, one at a time, while accumulating the resulting signals that appear in the IF spectrum. This ensures that each sampled value of LO phase noise (as recorded in the file in 1 KHz steps) is applied and analyzed.

The result is the spectrum plot of Figure 7. Signals identified by markers 1, 3 and 4 in Figure 7 are identical to signals marked 1, 3 and 4 in Figure 3. These are the desired, adjacent channel interference and second (alternate) channel interference, respectively. However, now we can clearly see the phase noise spectra spread over the entire band and beyond. The close in phase noise profile on the alternate channel interferer (marker 4) looks just like the red LO phase noise plot in Figure 5. This phase noise profile quickly changes, though, as we follow it to the right past the adjacent channel interferer (marker 3 in Figure 7). To the right of marker 3, the phase noise rapidly increases as the steep slope of the filter's lower skirt affords dramatically less attenuation between 399.97 and 399.985 MHz.

Likewise, the adjacent channel interferer at marker 3 is shrouded with phase noise, but only the left (lower) side looks like the red LO phase noise profile of Figure 5. Because the adjacent channel is so close to the filter's lower skirt, the close in phase noise on this interferer does not appear symmetrical about the signal. Instead, this interferer's phase noise rises immediately to the right, surpassing the phase noise levels of the alternate channel interferer at every point to the right. The relatively close distance between the adjacent channel and the IF pass-band is the reason why the phase noise from this interferer exhibits a pronounced negative slope throughout the IF pass-band.

The important observation here is that the LO phase noise translated to the adjacent channel interferer is, at all points throughout the IF pass-band, stronger than the thermal noise floor as indicated by the horizontal dotted line at -125.6 dBm in Figures 3 and 7 (the phase noise and thermal noise being displayed per a 31 KHz integration bandwidth). Though it has a negative slant, this interferer's phase noise exceeds the thermal noise floor by several dB on average across the IF. Thus the effective signal-to-noise ratio (SNR) has been degraded by several dB when compared to the no phase noise simulations of Figures 2 and 3. This demonstrates the mechanism (reciprocal mixing) by which LO phase noise can be transferred to strong adjacent channel interferers and then spread out over the desired signal, partially or completely masking the weak desired signal. As can be seen in Figure 7, the desired signal at marker 1 barely protrudes out of the phase noise in the IF band.

Figure 7 is to be directly compared to Figure 3 to see the effects of phase noise, particularly the way it can rise up above the thermal noise floor and mask the desired signal (marker 1) in the IF pass-band.

Improved LO Phase Noise is the Solution

One might propose that increasing the IF filter's rejection of the adjacent channel might help to reduce the in-band phase noise, arguing that if the level of the interferers are reduced then their phase noise will also be reduced. However, this will not work because the phase noise has already been added by reciprocal mixing ahead of the IF filter. Increased adjacent channel rejection can push the interferer down (as it passes through the IF filter) but it cannot reduce the strength of the phase noise already in the IF pass-band.

We will now demonstrate that the effective way to reduce in-band phase noise (due to reciprocal mixing) is to improve the phase noise performance of the LO itself. We will create a new LO signal file that will follow the lower (grey) curve in Figure 5 (black curve in Figure 4). Using Equation 3, we create the LO1315LowPhaseNoiseSig.dbm file (sampling in 1 KHz steps as before).

To run the simulation with the improved LO phase noise file, the sweep command (SWP) in the script of Figure 6 is replaced with the following (thus applying the new file):

SWP Sig2-1 File = C:\Program Files\LINC2VSA\LO1315LowPhaseNoiseSig.dbm

Clicking Run in the Script

Editor's menu bar (Figure 6) runs the simulation. When the simulation has completed, the Accumulate Spectrum Graph automatically pops up. After applying the same span and vertical axis limits (as in Figure 7) the improved spectrum of Figure 8 appears. The simulation results of Figure 8 show more than 30 dB improvement in in-band phase noise relative to what was found in Figure 7.

Conclusion

Comparing Figure 8 to Figure 7 demonstrates that for a given offset, the in-band phase noise (due to reciprocal mixing) improves dB for dB with the improvement in LO phase noise. Whereas in Figure 7 (simulation with poor phase noise LO) the in-band phase noise exceeded the thermal noise floor to become the limiting factor in SNR, in Figure 8 the in-band phase noise is more than 20 dB below the noise floor and therefore does not contribute to the SNR.

As a side note, we can look at the signals at Port2 in the schematic of Figure 1 to see what the spectrum looks like before filtering. Figure 9 should be compared to Figure 7 since they represent the phase noise spectra before and after IF filtering, respectively (when an LO with poor phase noise is used). Likewise, Figure 10 should be compared to Figure 8 since these plots represent the phase noise spectra before and after IF filtering, respectively, for a receive mixer employing a high quality LO (low phase noise).

Notice in the comparison between Figures 9 and 7 or between Figures 10 and 8 that the phase noise around the desired signal (in-band) does not improve with IF filtering — only the interferers and their close in phase noise are attenuated by the IF filter. While the IF filter cannot reduce the in-band phase noise (only the quality of the LO can), the IF filter is vital in reducing the strong interfering signals in adjacent channels to levels below the desired in-band signal.

For system level simulation, the Visual System Architect from ACS adds many built-in measurement functions for producing the stage-by-stage cumulative system budget analyses that are essential to successful system design, analysis, system performance verification, and report generation. Full spectral domain analysis provides a spectrum analyzer view of all signals and spurs at any point in the system.

At the circuit level, LINC2 provides high performance RF and microwave design and simulation. In addition to schematic based circuit simulation, optimization and statistical yield analysis, LINC2 Pro includes many value-added features for automating design tasks, including circuit synthesis.

More information about the ACS Visual System Architect and LINC2 Pro can be found on the ACS web site at www.appliedmicrowave.com.

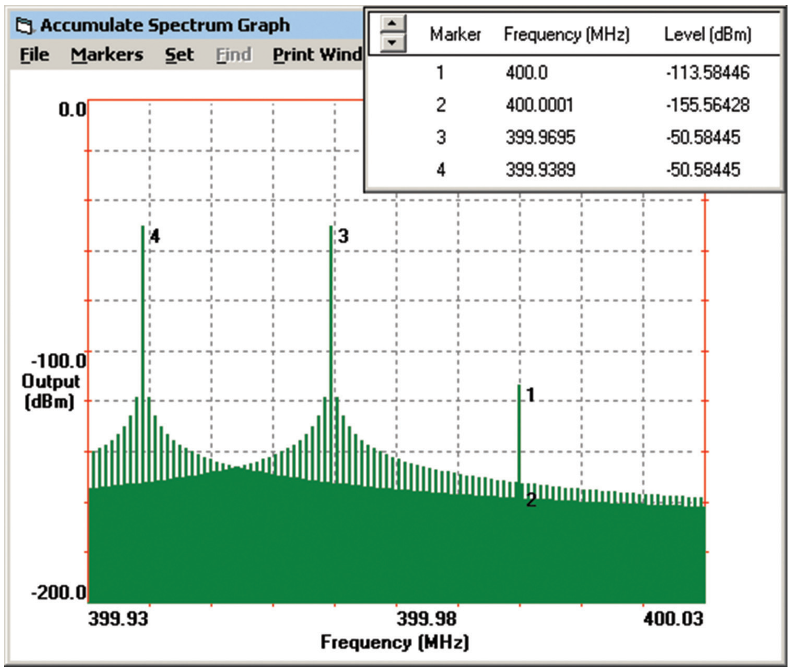


Figure 10: Spectrum Showing Phase Noise from Reciprocal Mixing Prior to IF Filtering (High Quality LO has Low Phase Noise)