enhancement at higher input voltages. Using this selection process, the LNA model perfectly provides the target P_3 value. However, it is only fortuitous that the achieved P_1 value of -22.2 dBm is close to the target value of -24.5 dBm. The final coefficient, a_5, was selected to make the output voltage stay as close as possible to "flat" for high input voltage magnitudes.

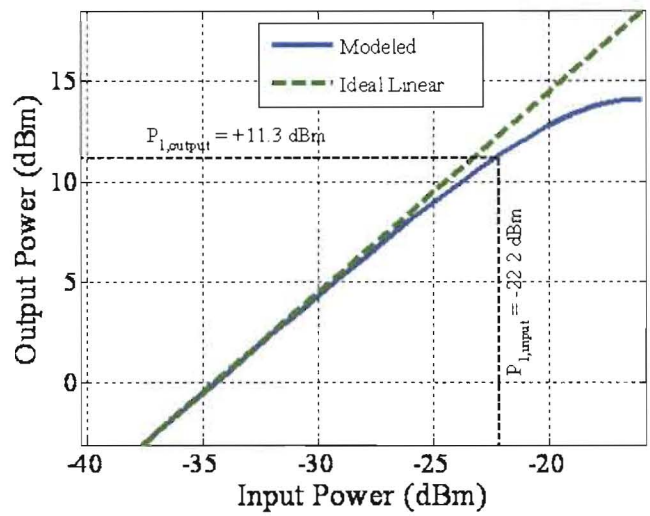

Figure 6-29. Modeled LNA Input-Output Power Characteristics

Response of LNA to LightSquared Emissions

Noting that the input-output characteristics are virtually unchanged for input power levels below -20 dBm by truncating the Taylor series to $N = 3$, here we focus on the simpler LNA input-output voltage model:

$$y = a_1 x + a_3 x^3 \tag{5}$$

with the input voltage presumed to be well-modeled as a Gaussian, wide sense stationary random process.

The output voltage autocorrelation may be determined as:

$$\begin{aligned} R_y(\tau) &\equiv E\left[y(t+\tau)y(t)\right] \\ &= E\left[\left(a_1 x(t+\tau) + a_3 x^3(t+\tau)\right)\left(a_1 x(t) + a_3 x^3(t)\right)\right] \\ &= \left(a_1^2 + 6a_1 a_3 \sigma_x^2 + 9a_3 \sigma_x^4\right) R_x(\tau) + 6a_3^2 R_x^3(\tau) \end{aligned} \tag{6}$$

where $R_x(\tau)$ is the input voltage autocorrelation and $\sigma_x^2 = R_x(0)$ is the variance of *x(t)* (i.e., input power aside from a possible scale factor for a non-unity resistance).

From equation (6), the following expression may be derived to relate the output power spectrum, $S_y(f)$, of the LNA to its input power spectrum, $S_x(f)$:

$$S_y(f) = \left(a_1^2 + 6a_1a_3\sigma_x^2 + 9a_3\sigma_x^4\right)S_x(f) + 6a_3^2 S_x(f) * S_x(f) * S_x(f) \qquad (7)$$

where * is the convolution operator.

Results with No Preselection Filtering

Figure 6-30 through Figure 6-32 show the LNA input and output power spectra for various LightSquared received power levels, presuming no filtering prior to the LNA. Phase 1 emissions are assumed, and these emissions are very simply modeled as perfectly rectangular 5-MHz blocks centered at 1528.8 MHz and 1552.7 MHz with total input power as indicated on each figure. An input noise floor of -201.5 dBW/Hz is also included[3].This truly would not fully present at the LNA input even for a receiver with this effective N_0 value, since some of the effective N_0 is due to the LNA noise figure.

In Figure 6-30, the LightSquared signal at the input of the LNA is at a power level of -45 dBm, which is much greater than the power from the thermal noise floor. This input power level is well below the LNA's 1-dB input compression point, and the LNA is operating very linearly. The output appears to be perfectly identical to the input, with the exception that the output power level is 34.5 dB (the nominal gain value) greater than the input.

In Figure 6-31 and Figure 6-32, the LightSquared input levels are increased to -35 dBm and -25 dBm, respectively. The LNA is being driven closer to its 1-dB compression point, and the output signal is seen to be increasingly distorted with a significant third-order intermodulation product clearly visible centered at 2 × 1552.7 – 1528.8 = 1576.6 MHz.

[3]This level would not truly be present at the LNA input even presuming that the overall front-end had precisely this effective N_0 value, since a good portion of the effective N_0 arises from the LNA noise figure. Nonetheless, ignoring rigor in this area does not materially affect the results presented here.

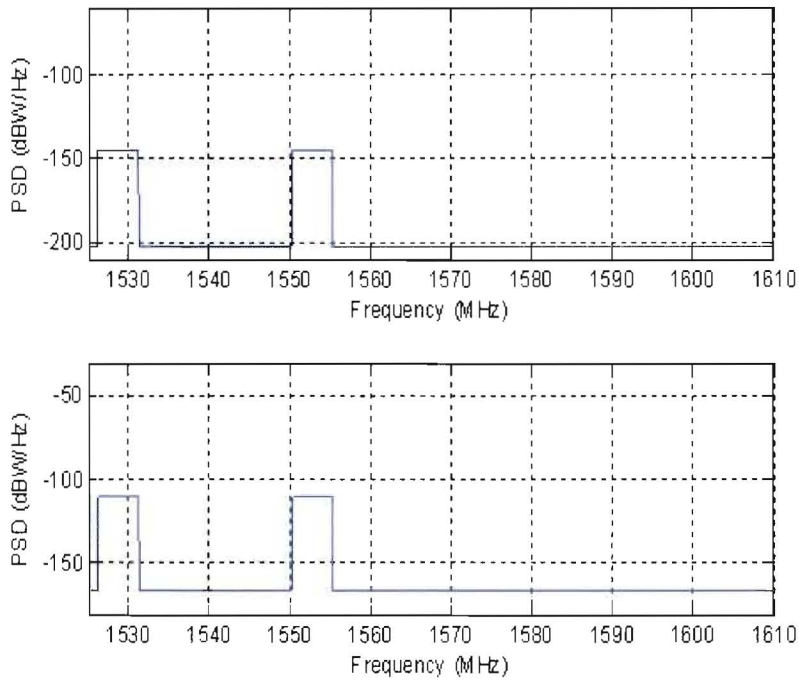

Figure 6-30. Input (top) and Output Power Spectrum of Modeled LNA, for Input Power of -45 dBm (LNA in Linear Region)

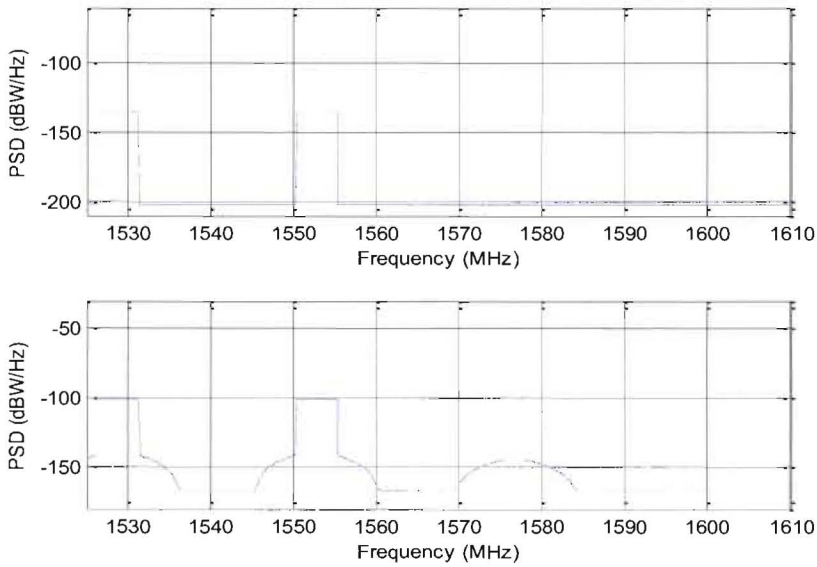

Figure 6-31. Input (top) and Output Power Spectrum of Modeled LNA, for Input Power of -35 dBm (LNA Entering into Compression)

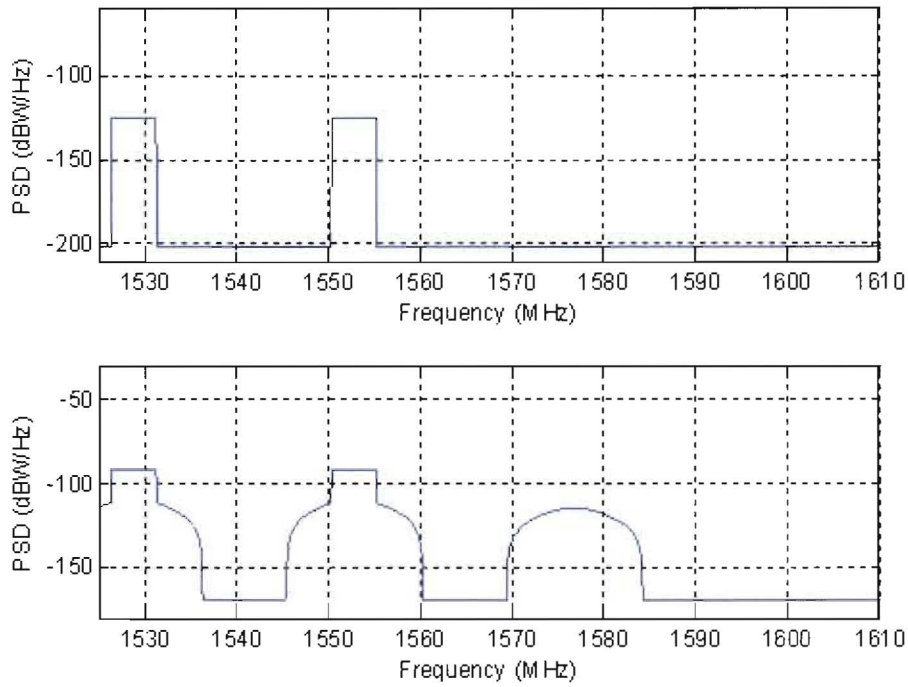

Figure 6-32. Input (top) and Output Power Spectrum of Modeled LNA, for Input Power of -25 dBm (LNA Nearly to 1-dB Compression Point)

Results with Preselection Filtering

Preselection filtering can significantly diminish the strength of the third-order intermodulation product. For example, a representative 3-pole ceramic filter provides the attenuation characteristics shown in Figure 6-33. This particular filter has an insertion loss of 2.2 dB, and for the results to follow an additional 0.5 dB insertion loss for protection circuitry is presumed to be present between the passive antenna output port and LNA input. With this configuration, Figure 6-34 through Figure 6-36 show input-output power spectra for the modeled LNA using the same remaining assumptions as were used for Figure 6-30 through Figure 6-32.

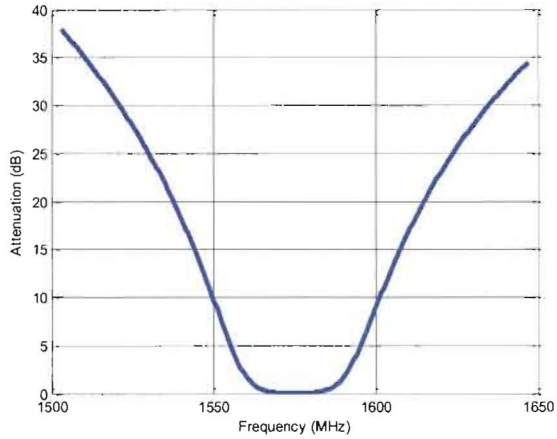

Figure 6-33. 3-Pole Ceramic Preselection Filter Attenuation (24 MHz 1-dB Bandwidth)

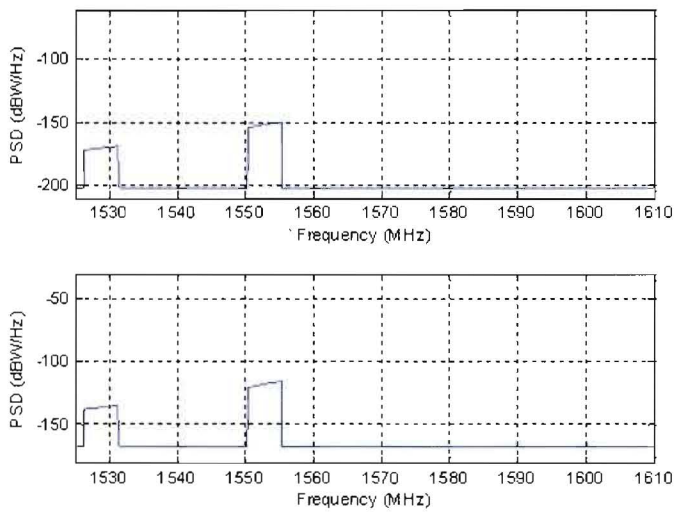

Figure 6-34. Input (top) and Output (bottom) Power Spectrum of Modeled LNA; LightSquared Signal Power at Antenna Output Port is -45 dBm, LNA Input Power is -57.5 dBm (LNA in Linear Region)

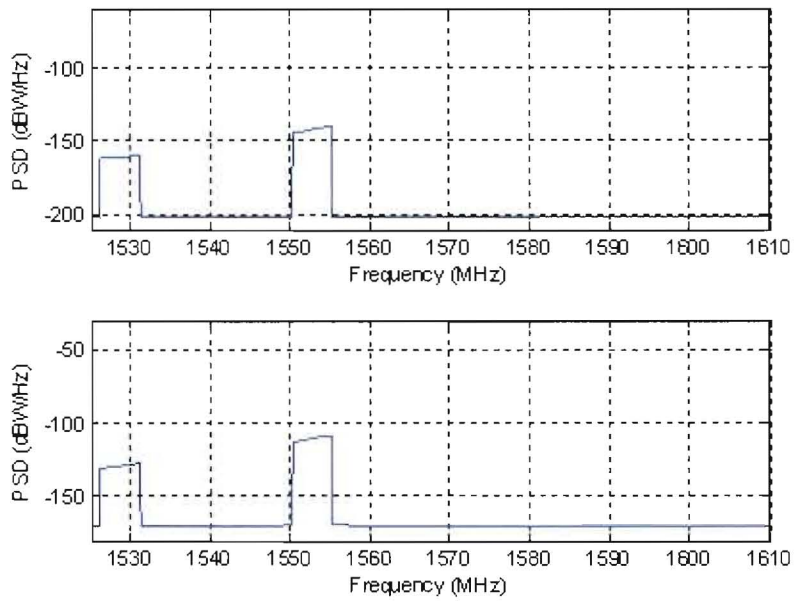

Figure 6-35. Input (top) and Output (bottom) Power Spectrum of Modeled LNA; LightSquared Signal Power at Antenna Output Port is -35 dBm, LNA Input Power is -47.6 dBm (LNA Lightly Entering into Compression)

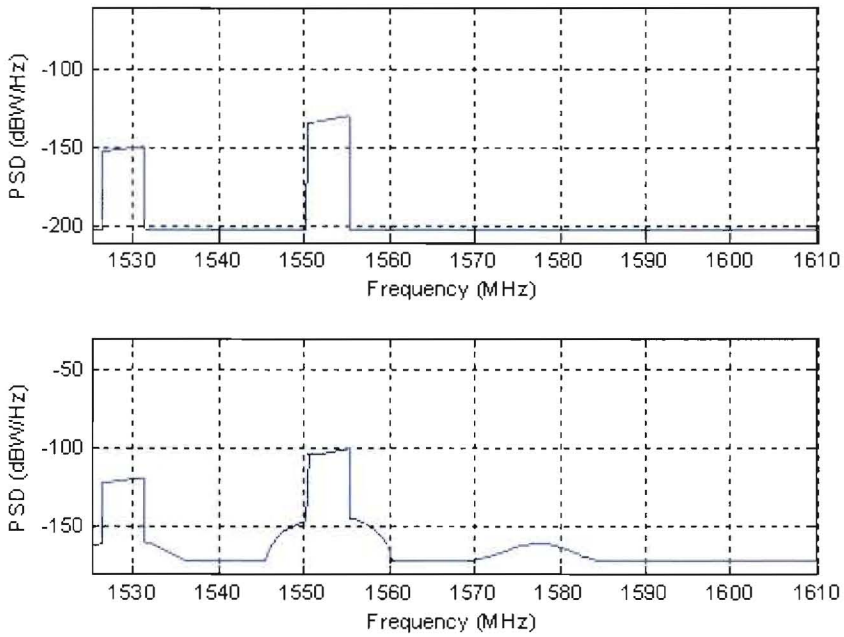

Figure 6-36. Input (top) and Output (bottom) Power Spectrum of Modeled LNA; LightSquared Signal Power at Antenna Output Port is -25 dBm, LNA Input Power is -37.6 dBm (LNA Entering Deeper into Compression)

Figure 6-37 shows the degradation to the effective N_0 for a C/A-code receiver due to the third-order intermodulation product, presuming that the remainder of the receiver front-end is perfectly linear and perfectly bandlimited to 20 MHz[4]. The plot was produced by computing the inner product of the LNA output power spectrum, referred back to the passive antenna port by scaling by the true LNA gain and assumed 2.7 dB insertion loss (for the preselector filter and protection circuitry), against the normalized power spectrum of the C/A-code. The inner product was computed over L1 +/-10 MHz under the presumption that the fundamental LightSquared emissions would be suppressed completely by later filtering within the receiver. A 0.5 dB degradation is seen at a LightSquared received power level of -31.5 dBm.

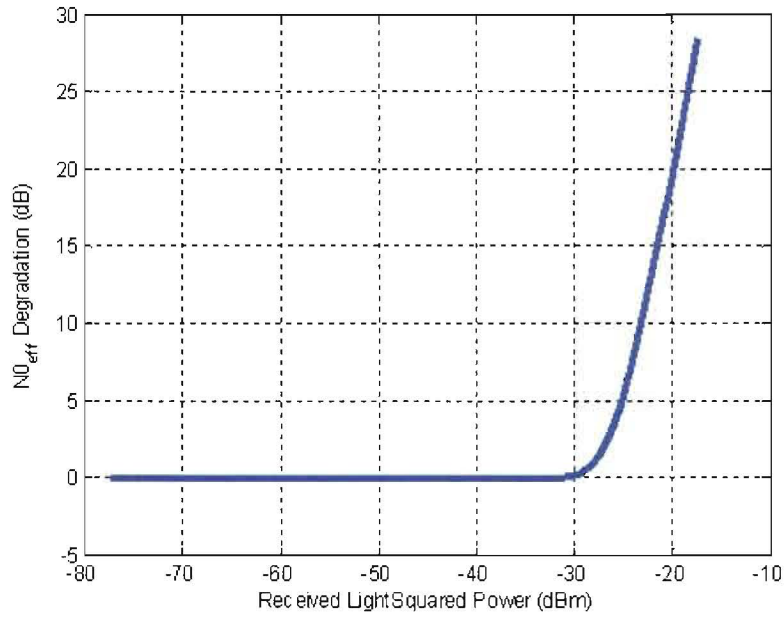

Figure 6-37. Degradation to Receiver Effective Noise Floor due to the Third Order Intermodulation Product

Comparison with Simulations and Measurements

Figure 6-36 looks very similar to a simulation result produced for the same Phase 1 emission scenario, but for a commercially available GPS receiver front-end module, see Figure 6-38 (from [2]). To produce this figure, the author of [2] created a time-domain simulation of the LightSquared Long Term Evolution (LTE) signals and fed these signals through a time-domain model of the front-end module.

[4]These are obviously big assumptions that are not likely to be true for most fielded receivers. In fact, it is the authors' view that saturation is far more likely in later receiver components such as LNAs or mixers within the receiver before appreciable attenuation of the fundamental LightSquared emissions is provided by distributed filtering (if at all).

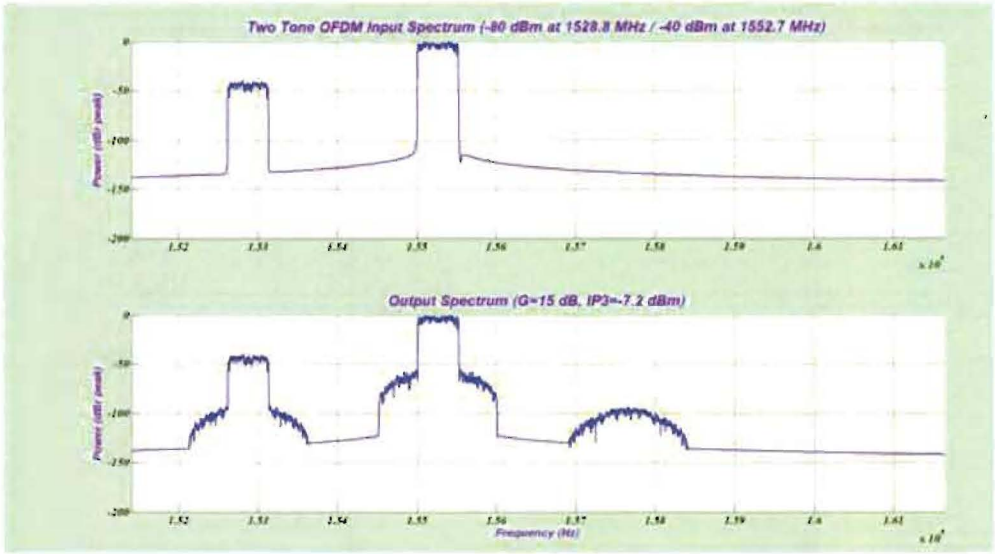

Figure 6-38. .Maxim MAX2741 Input (top) and Output (bottom) Power Spectra based Upon Simulations [2]

The model-predicted power spectra are also similar to those measured at the output of a GPS LNA from a live LightSquared base station. Figure 6-39 shows a measurement that was made by Jet Propulsion Laboratory (JPL) personnel at the Holloman Air Force Base Live Sky test event. A third-order intermodulation product is clearly visible in this spectrum analyzer screen-shot with some similar features as observed in the model results earlier in this note.

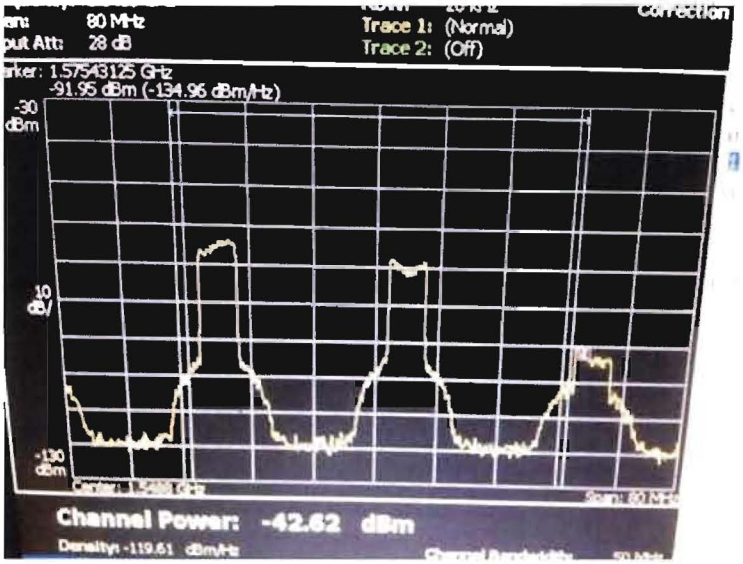

Figure 6-39. Measured Output Power Spectrum of LNA as Measured by JPL at the Holloman Live Sky Test Event