# Intermodulation Effects

## Another Perspective on LightSquared Interference to GPS

CHARLES RHODES

**Much of the research into the possible effects of the planned LightSquared cellular broadband transmissions near the GPS L1 band have focused on the saturation of the front end of GPS receivers caused by the high power of the terrestrial LightSquared base stations. In this article, an engineer with a long history in broadcast digital television takes a look at the likely effects on GPS receivers of third-order intermodulation products created by the LightSquared signals.**

As with digital television (DTV) receivers, GPS receivers have little RF selectivity to protect the receiver's mixer from out-of-band signals. The Federal Communications Commission (FCC) frequency allotment plan minimizes the possibility of such interference between DTV signals.

In the past the FCC has prohibited terrestrial transmitters in the mobile satellite services (MSS) band, and, as a result, receivers of both kinds did not need costly RF filters, which would have increased the receivers' noise figure. Modern DTV receivers generally use a tuner-on-a-chip, which is not only economical, but results in a negligible space requirement for the tuner.

Signals in adjacent bands may desensitize DTV and GPS receivers if they reach the mixer input and drive it beyond its so-called linear dynamic range. Mixers are limited in their dynamic range by the fact that they become non-linear when the total RF signal voltage approaches the voltage of the local oscillator (LO) at the LO port. This non-linearity: increases the conversion loss of the signal while it does not decrease mixer-generated thermal noise.

Desensitization may occur in various ways. A strong signal may cause a receiver's sensitivity to decrease. One example is the use of wideband RF automatic gain control (AGC) in DTVs and possibly some GPS receivers. An undesired signal, say 20 decibels above the desired signal and near its frequency, may be detected by a wideband RF power sensor that then reduces the gain of the RF amplifier.

This has been the subject of most concern arising from the terrestrial broadband cellular transmitters that LightSquared has proposed to build across the United States as part of its so-called Fourth Generation/Long Term Evolution (4G/LTE) system. The matter is currently before the FCC, which has approved LightSquared's plan pending an investigation of its potential interference to GPS receivers.

Intermodulation can also cause problems for wideband receivers, *including GPS*. This was the focus of the recently conducted research described in this article.

### Third-Order Distortion Products

Third-order intermodulation products are of the form 2Fa–Fb and 2Fb–Fa, where Fa and Fb are undesired signals. The 2Fa–Fb distortion products fall below frequencies Fa and Fb, while the 2Fb–Fa products fall above the *un*desired frequencies.

Two strong, undesired signals can generate third-order distortion that falls in the desired channel. For example, 2* 1551 MHz minus 1527 MHz = 1575 MHz. Third-order distortion products increase in amplitude by *three* decibels per each one-decibel increase of the amplitude of the undesired causative signal at the input port of the overloaded active device — in our case, the mixer in GPS receivers.

In extreme cases of mixer overload, some fifth-order products will also be generated and may fall in the desired signal frequency band.

Second-order distortion products (second harmonics and the sum of Fa + Fb) fall far from the frequencies of the causative signals; so, they are not of concern in this article.

Another third-order distortion product, called triple beat, is of the form Fa+Fb–Fc. As Fb approaches Fa, this equation turns into 2Fa–Fc. Therefore, both of these third-order products occupy the same spectrum. For three signals of equal amplitude, their triple

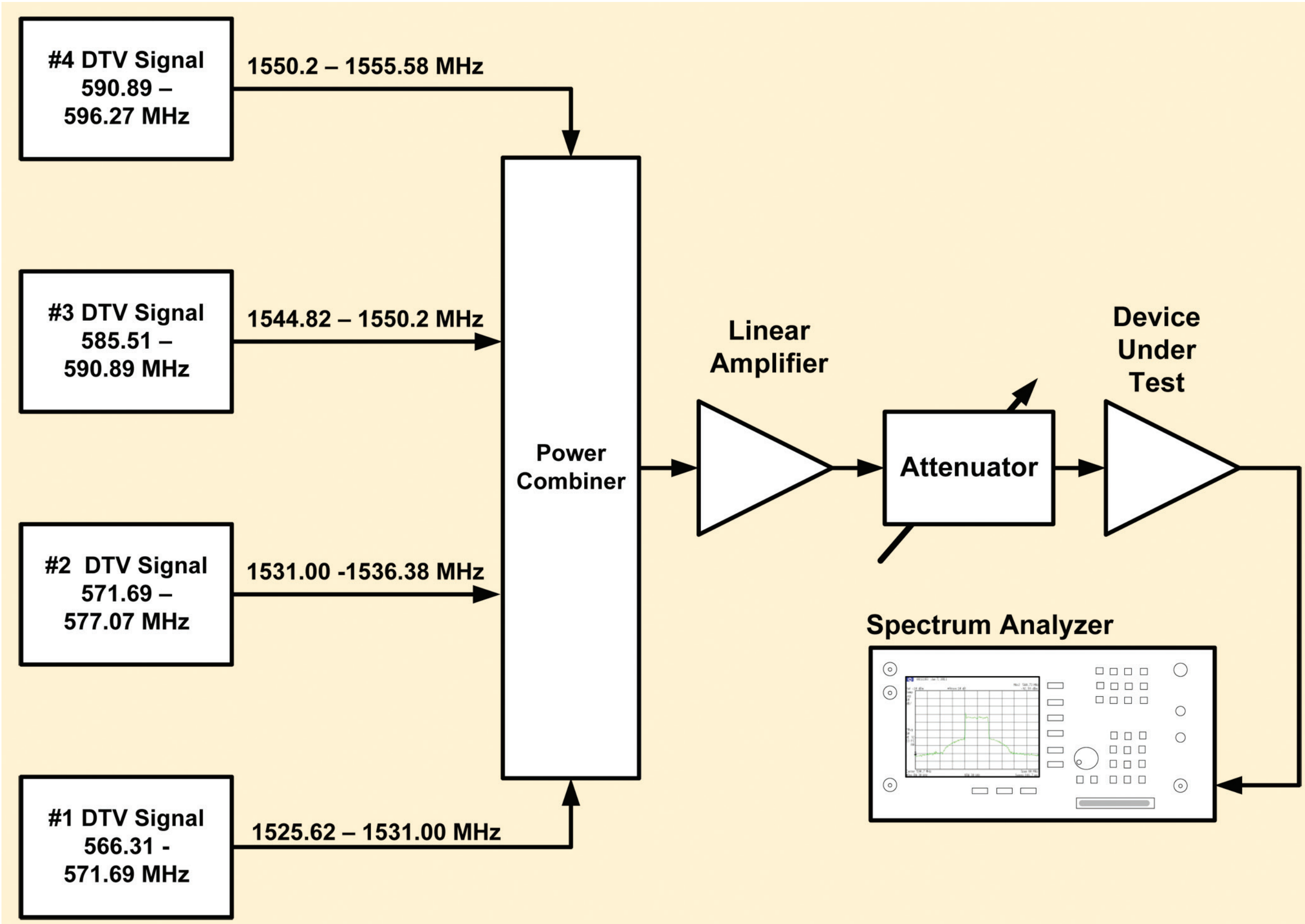


FIGURE 1 GPS interference simulator block diagram using UHF DTV signals



beats are six decibels higher in power than are their third-order intermodulation products.

The presence of a strong, nearby signal may also cause a receiver's sensitivity to decrease. One example is the use of wideband RF automatic gain control (AGC) in DTVs and possibly some GPS receivers. An undesired signal, say 20 decibels above the desired signal and near its frequency, may be detected by a wideband RF power sensor that then reduces the gain of the RF amplifier. So, undesired signals that do not produce third-order intermodulation products falling within a desired channel may still de-sensitize the receiver by overloading its mixer.

## Our Simulation Set-Up

LightSquared has a three-phase plan — designated as phases zero, one, and two — for rolling out its terrestrial transmitter network. In the initial phase of the rollout (Phase Zero), one five-megahertz–wide signal will be radiated; in Phase One, a second five-megahertz signal will be added. Phase Two will consist of two 10-megahertz–wide signals.

My colleague, Linley Gumm, and I have simulated these three phases in my laboratory using four DTV signals of 5.38-megahertz bandwidth each.

All four DTV signals are of equal power, and this power is maintained for simulations of Phase Zero and Phase One. For Phase Two the total signal power was reduced by three decibels for reasons that I will explain later. These four signals simulate Phase Two.

When we switch off the appropriate two of these 5.38-megahertz–wide DTV signals, we simulate Phase One, and the total power decreases by three decibels. When we switch off the appropriate DTV signal, we simulate Phase Zero and the total power presented to the active device under test (DUT) decreases by another *three* decibels.

A block diagram of our simulation is shown in **Figure 1**. These DTV signals will generate signal spectra very similar to those we expect of the LightSquared signals.

In our simulation, we used an off-air DTV signal received at my laboratory for the *lowest* frequency five-megahersztz signal; therefore, the frequencies of Signal #1 are fixed. The lowest frequency of this off-air signal is 566.31 MHz; so, its highest frequency is 5.38 megahertz above 566.31 MHz, or 571.69 MHz.

DTV signal #2 is generated by a commercial DTV signal generator. Its pilot frequency is set to 571.69 MHz so that the two signals blend into one signal simulating a LTE signal of 10-megahertz bandwidth. We combined two signals whose -3 dB frequencies are equal

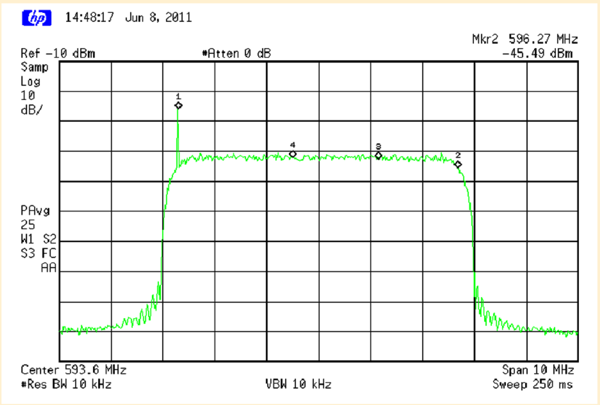


FIGURE 2 Simulation of LightSquared Phase 0 signal, undistorted

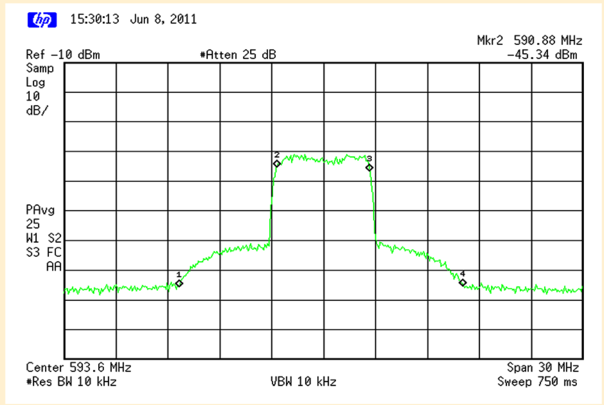


FIGURE 3 Simulation of LightSquared Phase Zero signal with third-order distortion product

so that the resulting signal is "flat" for 10.76 megahertz, thus simulating the spectrum of a 10-megahertz LTE signal.

Ideally, we would have had four LTE signals available, in which case this would not have been a simulation but rather a laboratory test of the LightSquared system. However, our simulation comes reasonably close to what could be done with actual LTE signals.

Figure 1 shows two additional DTV signals, #3 and #4. These are generated by DTV exciters developed at the University at Wuppertal, Germany, and are not commercially available. Comparing the spectrum of these with the other signals, they are seen to be very similar. These are blended to produce the second 10.76 MHz simulated LightSquared signal.

All four signals when combined in a four-way passive signal combiner are set to the same power level for simulating both Phase Zero and Phase One. For Phase Two, I reduced the signal power by three decibels. Together, the four signals simulate Phase Two.

When signals #2 and #3 are switched off, signals #1 and #4 simulate the Phase One signal. When signal ##1 is also switched off, the remaining signal, #4, simulates Phase Zero. The linear amplifier is known to remain linear with all four signals present (Phase 2).

The DUT simulates the front-end of GPS receivers. The spectrum analyzer measures the third-order distortion products, their relative power generated in the DUT in Phases Zero, One, and Two, and their absolute spectrum frequency limits above the MSS band and into the GPS L1 band centered at 1575.42 MHz..

My laboratory has the means to capture the DTV signal on channel 30 and to filter it to remove all other signals from the antenna. This DTV signal on channel 30 has a spectrum from 566.31–571.69 MHz, which simulates the lowest frequency, five-megahertz LTE signal. We chose to keep the 1531.00 MHz of the LightSquared system subtracting from it 959.31 MHz = 571.69 MHz. By subtracting the 5.38-megahertz bandwidth of our DTV signal we get the lowest frequency of our channel 30 DTV signal, 566.31 MHz.

The total power of these four signals at the input to the Active DUT is adjusted by means of a wideband attenuator to seriously overload the DUT when all four signals are present (Phase Two). The result is a large amount of third-order distortion products, many of which fall into the GPS L1 band.

With our methodology now explained, the resulting spectra captured on the spectrum analyzer in the accompanying figures can now be described.

## LightSquared Signals in MSS Band

Although LightSquared has recently indicated that it might ask to modify its rollout plan, under the current plan's Phase Zero, the signal to be radiated by terrestrial transmitters would lie between 1550.2 to 1555.2 MHz, as shown in **Figure 2**. Let Fa = 1550.2 MHz and Fb = 1555.2 MHz.

The highest third-order distortion product is 1561 MHz, well below the GPS band as shown in **Figure 3**. (In these figures, all frequencies are offset by 959.31 MHz from their locations in the L-band). In Figure 3, the third-order distortion products are at or below the noise floor of the instrumentation. This signal cannot cause interference to GPS receivers by third-order intermodulation, but the signal could still de-sensitize some GPS receivers near a LightSquared transmitter.

In the next phase of this plan, Phase One, a second five-megahertz signal will be added between 1525 to1530 MHz. In our simulation, this is 566.31 to 571.69 MHz. The simulated LightSquared Phase One signal is shown without distortion in **Figure 4**. In **Figure 5** we see the Phase One signal with third-order distortion products added. These are the beehive–shaped clusters of noise surrounding the two signals.

Two more "beehives" of third-order distortion products appear at markers #1 and #4 of Figure 5. The more important of these at marker #4 is due to 2Fb–Fa type of intermodulation. This beehive is centered quite near the GPS carrier frequency. Note that four discrete beehives are shown with the LightSquared Phase One implementation with little or no noise between them.

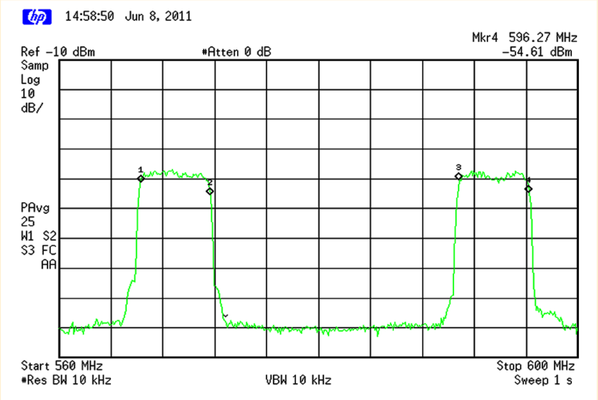


FIGURE 4 Simulation of LightSquared Phase One signal, undistorted

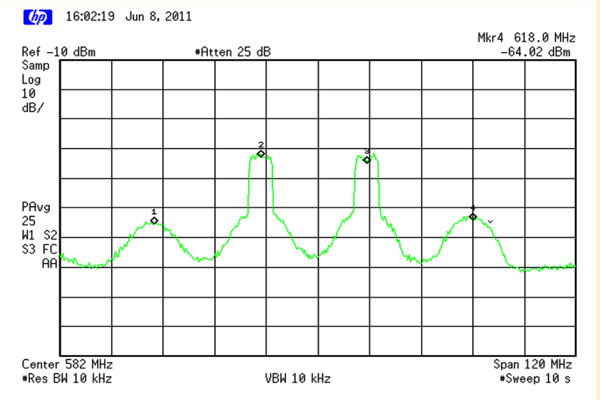


FIGURE 5 Simulation of LightSquared Phase One signal with third-order distortion products

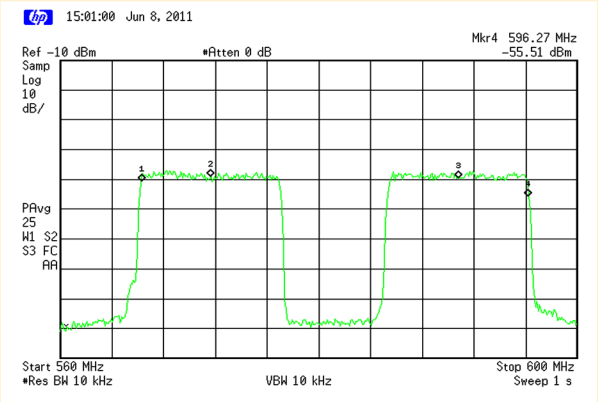


FIGURE 6 Simulation of LightSquared Phase Two signals, undistorted (each signal is 10 megahertz wide)

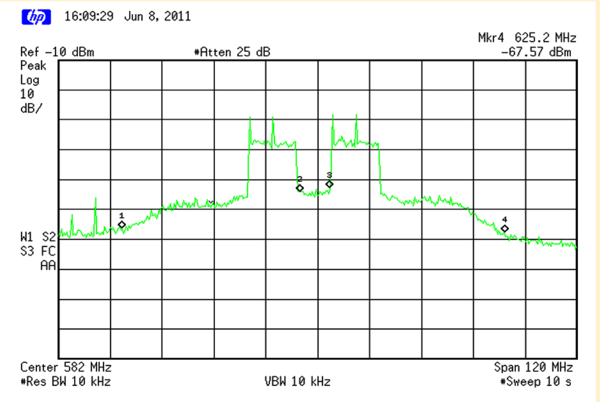


FIGURE 7 Simulation of LightSquared Phase Two signals with third-order distortion products

Phase Two of the LightSquared plan calls for two 10-megahertz–wide signals from 1526 to 1536 MHz and from 1545.2 to 1555.2 MHz, as shown in **Figure 6**. These will have to be transmitted with the same spectral *power density* as in Phases Zero and One. But the total power must be higher, as more bandwidth is involved. That would increase the amplitude of the third-order distortion products by nine decibels over that of the Phase One signal.

The simulated Phase Two signal with distortion is shown in **Figure 7**. In making this simulated spectrum capture, the signal power was reduced 3 dB because otherwise significant fifth order distortion products would have complicated the spectrum unnecessarily for my purposes. The key point shown in Figure 6 is that the distinct "beehives" of Phase One have merged into a broad band increase in the noise floor between markers #1 & # 4 which in the L Band would represent 1496 MHz and 1584 MHz.

The noise floor under both MSS and GPS bands is made extremely high by these third-order distortion products seen only in the Phase Two implementation of the LightSquared Plan. Between markers #2 and #3 of Figure 7 the noise floor is at its maximum. Those markers represent 1537–1544 MHz, which suggests that this part of the MSS band may not be suitable for space-to-earth transmissions of any kind. Because the signal power in Figure 7 was reduced by three decibels for the purposes of our simulation, this noise floor is actually nine decibels higher than the level shown.

We have now demonstrated how simulated third-order distortion products generated within the overloaded GPS receiver by the LightSquared terrestrial signals may cause interference to signals in the GPS band.

Assuming that the desired coverage by each base station of the LightSquared network requires an effective isotropic radiated power (EIRP) of 29 dBW in its initial phase with one five-megahertz signal, when they go over to Phase One- and two such signals will produce 29 dBW EIRP each or 32 dBW total interfering power. This decibel increase in total interference power with Phase One signals will generate nine decibels more third-order interference than existed during Phase Zero.

If the FCC allows the two 10-megahertz signals planned for Phase Two, the total interference power will be increased by six decibels above that radiated during Phase Zero. Each Phase Two signal will have to be radiated with 32 dBW EIRP; so, the two signals would

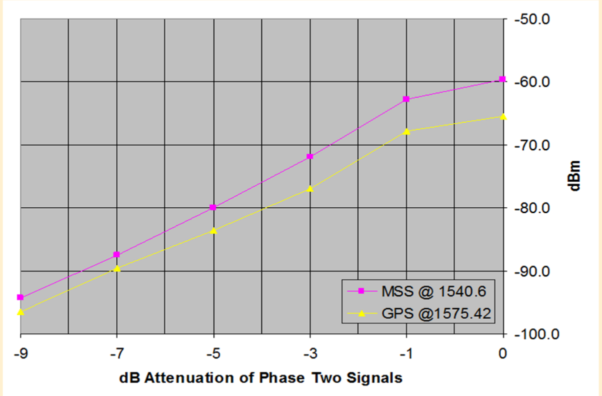


FIGURE 8 Plot of third-order distortion products (dBm) as function of attenuation of the input signal power

comprise a total radiated EIRP of 35 dBW. The third-order distortion products would then be 18 decibels above what they were during Phase Zero.

I understand that the existing FCC Permit would allow up to 42 dBW EIRP. This would be 13 decibels above the EIRP of Phase One.

## Conclusions

First, in Phase Zero, interference to GPS receivers from third-order distortion products will not occur because none fall within the GPS l1 band. However, that does not mean that near a LightSquared tower during Phase Zero, no interference will appear because the Phase Zero signal power could de-sensitize some nearby GPS receivers.

Second, in Phases One and Two third-order distortion products fall within the GPS band. These would be generated within the affected GPS receiver due to the received power of the Phase One — and even more by Phase Two — signals. In fact, the spectrum of these third-order distortion products extends to 1584.4 MHz, which is above the GPS band.

Even if well filtered at the transmitter, these Phase One and Two MSS band signals may also de-sensitize some GPS receivers. We have measured the third-order distortion products for a range of interfering signal power and confirmed that the noise in the MSS and GPS bands due to these signals does increase three decibels per each one decibel of interfering signal power. This is shown in Figure 8.

Third, when the LightSquared system commences transmitting two 10–megahertz–wide signals in the MSS band during Phase Two, our experimental results suggest that jamming will become much more prevalent. Interference due to third-order intermodulation distoritons will affect receivers in a much larger area around the tower, and some receivers near the tower that performed well while Phase One was in operation may be jammed in Phase Two.

Fourth, in Phase Two the 9.2 megahertz gap between 1536 and 1545.2 MHz discussed earlier may generate third-order distortion products uniformly distributed across this gap at a three-decibel–higher noise power density that at any GPS frequency. In Phase Two, this 9.2 megahertz of spectrum in the MSS Band may no longer be useful for space-to-earth transmissions.

Finally, the extent of interference to GPS from LightSquared Phase Two signals *should not* be inferred from the results obtained from tests of its Phase One Signal. The spectral power densities of these two signals have been shown to be significantly different.

## Acknowledgment

I wish to acknowledge the assistance of my colleagues, Linley Gumm and Stan Knight, in this investigation and in preparing this article for publication.

## Manufacturers

The commercial spectrum analyzer used in the simulations is an HP 4401B from **Hewlett-Packard Company**, Palo Alto, California, USA. The commercial DTV signal generator is an R&S SFE RF test transmitter from **Rohde & Schwarz**, Munich, Germany.

## Author

**Charles Rhodes**, of Vancouver, Washington, has been involved in broadcast television engineering since 1956. From 1988–1996 he was chief scientist of the Advanced Television Test Center Inc. He was responsible for the laboratory testing of digital TV systems, including the ATSC DTV system adopted in 1996 by the Federal Communications Commission. That work included testing interference between analog TV signals and the proposed DTV signal and testing of DTV-DTV interference. Since then, he has continued studies of interference between digital broadband signals. Recently, he devised a scheme to simulate interference from broadband signals to GPS reception.

IG