ATTACHMENT 2

HEMISPHERE TEST REPORT

Hemisphere GPS Tests at Alcatel-Lucent Labs in LightSquared Environment

Introduction

Hemisphere GPS tested several experimental antennas using Hemisphere R320 receivers at the Alcatel-Lucent Labs from 12/5/2011 ï 12/7/2011. The purpose of this test was to verify that Hemisphere's experimental antennas, when used with Hemisphere's GPS receivers, would work in the presence of the LightSquared LTE (Long Term Evolution) signal. LTE signals from both the Base Station and the Handset were tested. The experimental antennas are intended as prototypes for what will eventually become production antennas. The Hemisphere R320 receiver is a GPS receiver that we believe to be the best representation of what Hemisphere offers in the high-end positioning market. It tracks GPS L1 and L2 bands, OmniStar L-Band, as well as GLONASS L1 and L2 bands. Other Hemisphere receivers are a subset of the R320 from a signal tracking and versatility standpoint. Brad Badke and Greg Durnan of Hemisphere GPS were present for the testing. Michael Tseytlin of LightSquared was also present as well as test support personnel from Alcatel-Lucent.

Executive Summary

The results of this testing indicate that it is possible to develop external antenna solutions that allow Hemisphere GPS receivers and the LightSquared 10L signal (LTE centered at 1531MHz with 10MHz BW) to co-exist. Hemisphere's R320 receiver operating with a modified A52 antenna (A52M) and a production PA200 antenna did not begin to demonstrate C/No degradation until -22 dBm for the A52M and -14dBm for the PA200. This yields 5dB of margin for the A52M and 13dB of margin for the PA200 relative to the maximum LightSquared Base Station power of -27 dBm on the ground. The modified A52 antenna is an experimental antenna based on a production A52 antenna and is referred to as the A52M in this document. Hemisphere could have the A52M in the market in 6 months using the same technology that was used in the test setup. It may take longer if Hemisphere spends time to optimize antenna filtering and performance, perhaps taking up to a year. The Hemisphere PA200 is a production antenna that Hemisphere introduced into the market within the last several months and more than a thousand have been sold to date. In addition to GPS performance tests, there are several other things to consider going forward:

1) What should be done with existing GPS equipment that uses integrated antennas?
2) What should be done about the GPS augmentation services operating in the MSS L-band such as those services provided by OmniStar, Starfire and Veripos. Specifically, what means should be taken to allow continued use of these services within the United States and outside of the United States?
    a. Should GPS equipment be designed with different antennas to accommodate different OmniStar/Starfire/Veripos frequency plans outside of the U.S.? This

would not be optimal from a support and manufacturing standpoint and would add costs to GPS products that must incorporate these augmentation services.

b. Should the GPS augmentation service L-Band spectrum allocation be changed worldwide? It would be preferred to change all spectrum assignments to match the US so that common hardware could be used worldwide.

Test Setup Description

The tests were performed at Alcatel-Lucent labs (12/5/2011 ï 12/7/2011). The GPS transmit antenna and the LTE base and handset transmit antennas were 3 meters from the GPS receiver antennas. Additional notes on the test setup are as follows:

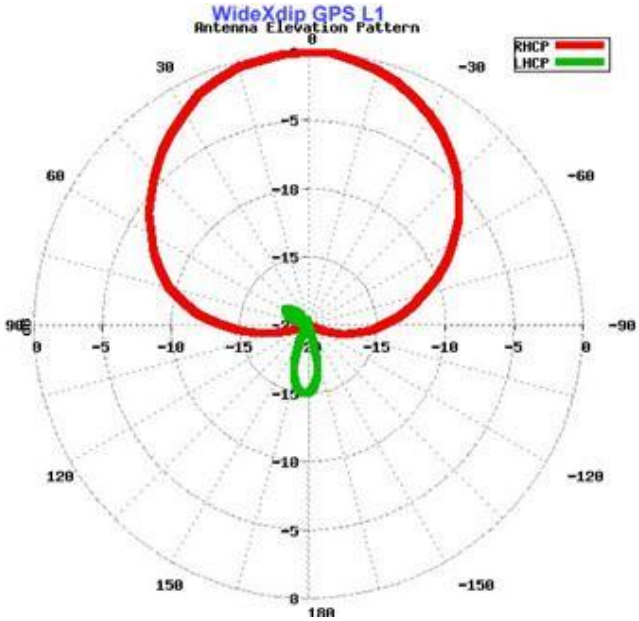
1) All GPS satellite signals generated by the Spirent were constant and equal power.
    a. Due to the single source nature of the simulated GPS signals, the conducted signal GPS receivers and the radiated signal GPS receivers appear to have a zero baseline between them since path differences appear as receiver clock biases. Solution techniques employing differencing between signals measured at two GPS receivers, such as RTK and standard differential GPS, also take on the zero baseline since both GPS receivers appear at the same location.
        i. Note: Conducted means a direct connection from the Spirent GPS signal generator to the Hemisphere R320 GPS receiver. No transmit or receive antennas are used in a conducted path and no LightSquared LTE interfering signal was introduced and so the conducted path is kept free of interference.
2) The Spirent generated L1CA, L1P, and L2P signals with pseudo-Y encryption.
    a. Using Pseudo-Y is important since some receivers will take advantage of unencrypted P-code and yield unrealistic results for L2P.
3) All testing was done using Hemisphere R320 GPS receivers (Eclipse II technology).
    a. Three R320 receivers were connected to antennas placed in the interference environment. A fourth R320 receiver was connected directly to the Spirent signal generator through a conducted channel and was thus free of broadcast interference (the non-interfering environment).
    b. Hemisphere R320 receivers support OmniStar, GPS L1CA, L1P, L2P, L2C and Glonass L1 & L2.
    c. Various multi-frequency and L1 only antennas were tested:
        i. Hemisphere A52 (multi-frequency)
        ii. Hemisphere A52M (modified multi-frequency)
        iii. Hemisphere PA200 (early production multi-frequency)
        iv. Javad (modified multi-frequency, referred to as Mod Javad in plots)
        v. Hemisphere Red Dot (modified L1 only, experimental)

vi. Hemisphere Green Dot (L1 only, experimental)
vii. Hemisphere Modified Green Dot (modified L1 only, experimental)
viii. PCTEL (modified L1 only)

d. Hemisphere GPS uses an internal SNR (dB) measurement to quantify GPS signal quality. Just add 30 dB to this number to determine C/N0.

Antenna Modifications

Hemisphere manufacturers a number of different high-precision antennas. Several of these were modified for the purpose of this test. The modifications involved changes to filters within the antenna circuit. Both modified production antennas, and non-production antennas were tested. Also tested with the Hemisphere R320 GPS receiver were antennas from Javad and PCTEL. As an example, and for future reference, gain patterns for the Hemisphere GPS A52 Antenna wide-band are shown in Figure 1. Gain patterns are shown for the GPS L1 (1575 MHz) band and also for a band (1530 MHz) in the neighborhood of the LightSquared Base Station signal.



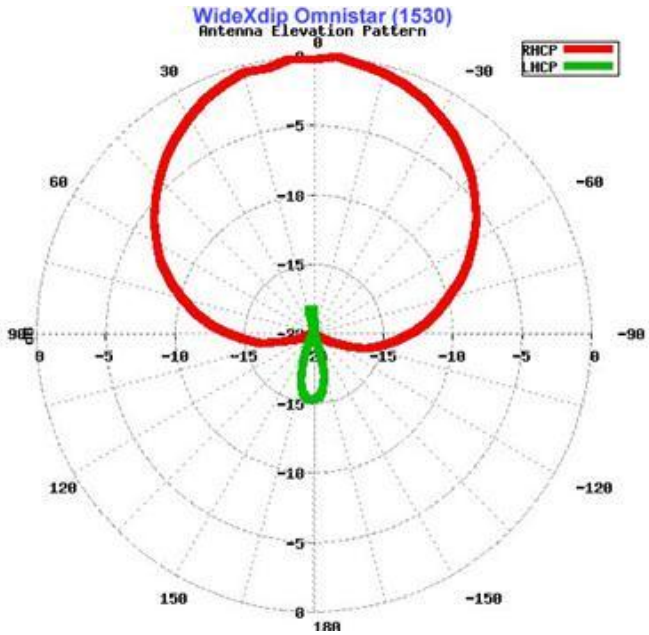


Figure 1. Plots showing LHCP vs RHCP over elevation for the A52 antenna element at 1575 and 1530 MHz

Multi-Frequency Antennas (Monday 12/5/2011)

This first test ramped the LTE 10L Base Station power from -60dBm to 0dBm as measured at the GPS receive antenna. The test began with approximately 30 minutes of ñclean airò, i.e. no LTE signal transmission. After interference testing began, the LTE power was increased in 2dB steps every two minutes and the GPS transmit power was held constant for all space vehicles. The reason for the ñclean airò transmission was so that performance in a non-interfering environment could be examined. This was done so that concerns about GPS positioning degradation could be addressed that may be introduced by the additional filtering required for compatibility with LightSquared. Positioning performance was measured using what Hemisphere GPS refers to as ñlocal differentialò (or LDif). LDif is a technique which is similar to that used in many types of systems deployed today, including the CORS network and the Coast Guardôs 300 KHz beacon system. LDif uses the same hardware set-up as RTK with a GPS base station and a rover GPS receiver. Unlike RTK, the rover is prevented from going into a pure carrier phase solution where integer ambiguities are solved. This allows examination of errors introduced while utilizing a wide-band code signal that would be masked by RTK operation utilizing narrow-band carrier phase. In all cases, the conducted path receiver (the GPS receiver that is never subject to interference) is used as the GPS base station. Note that the Rover and Base GPS receiver will actually appear to occupy the same location due to the nature of the simulated signals (signals for both receivers arrive from the same source -- the GPS simulator). When the rover and base receivers share a common location in differential GPS, this is referred to as zero-baseline. Zero baselines are good for testing because common-mode sources of errors,

that are not related to interference, cancel between rover and base. We can then concentrate on the effects of the interference alone.

Figure 2 shows the height error in meters, on a scale of +/- 0.1 meters (10cm). It is seen that maximum performance is achieved after several minutes of settling time and that the error plot then hovers between +/- 0.04 meters (+/-4 cm). Similar plots are shown in Figure 3 and Figure 4, but for Latitude error (north error) and Longitude error (east error). Similar to the height error, there is a settling time of a few minutes followed by a steady-state region where errors now hover in the +/- 2 cm neighborhood. Results are similar for both the A52 and the A52M before the interference is introduced. Thus, in this test, filtering changes are seen to have no impact on performance.

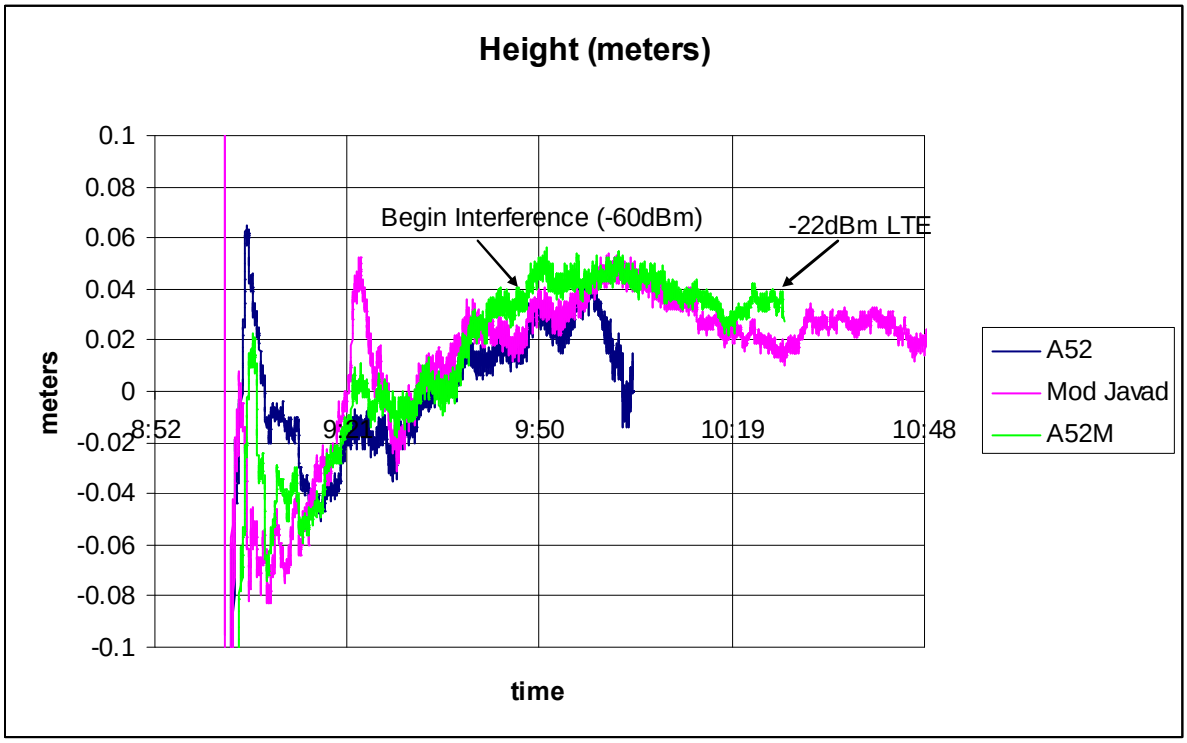


Figure 2 Local Differential Height Performance.

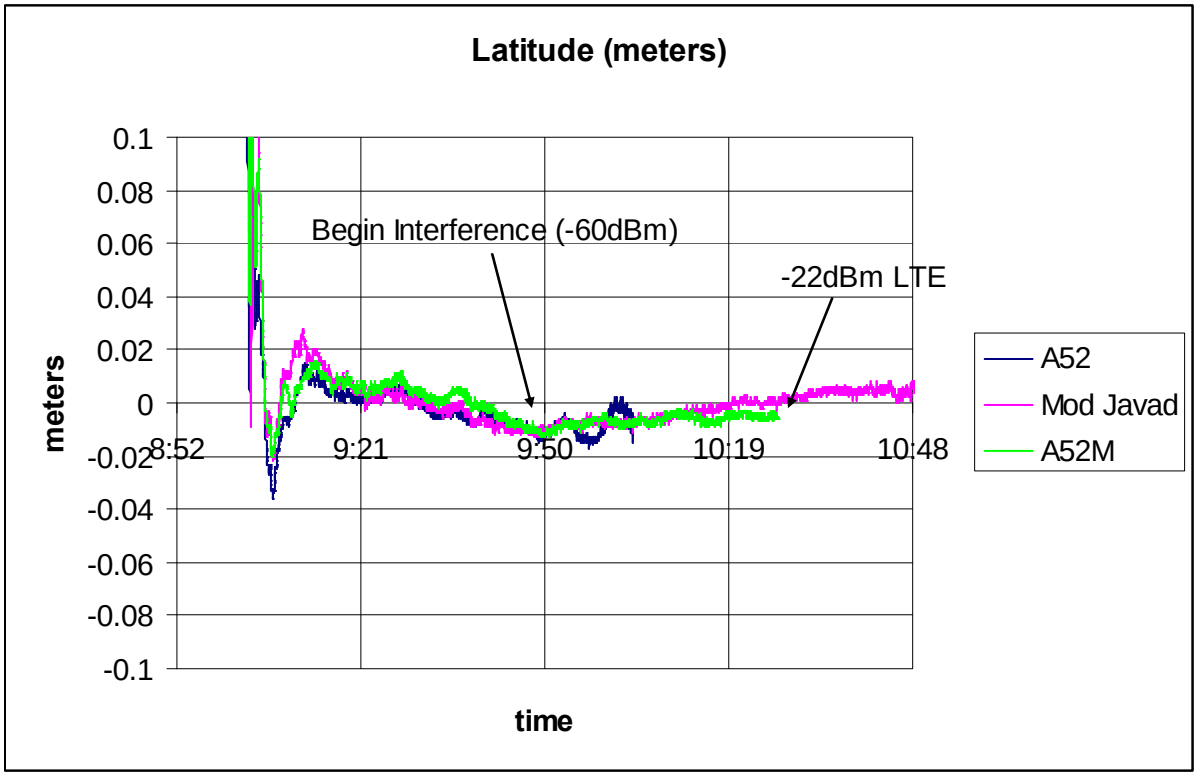


Figure 3. Local Differential Latitude Performance.

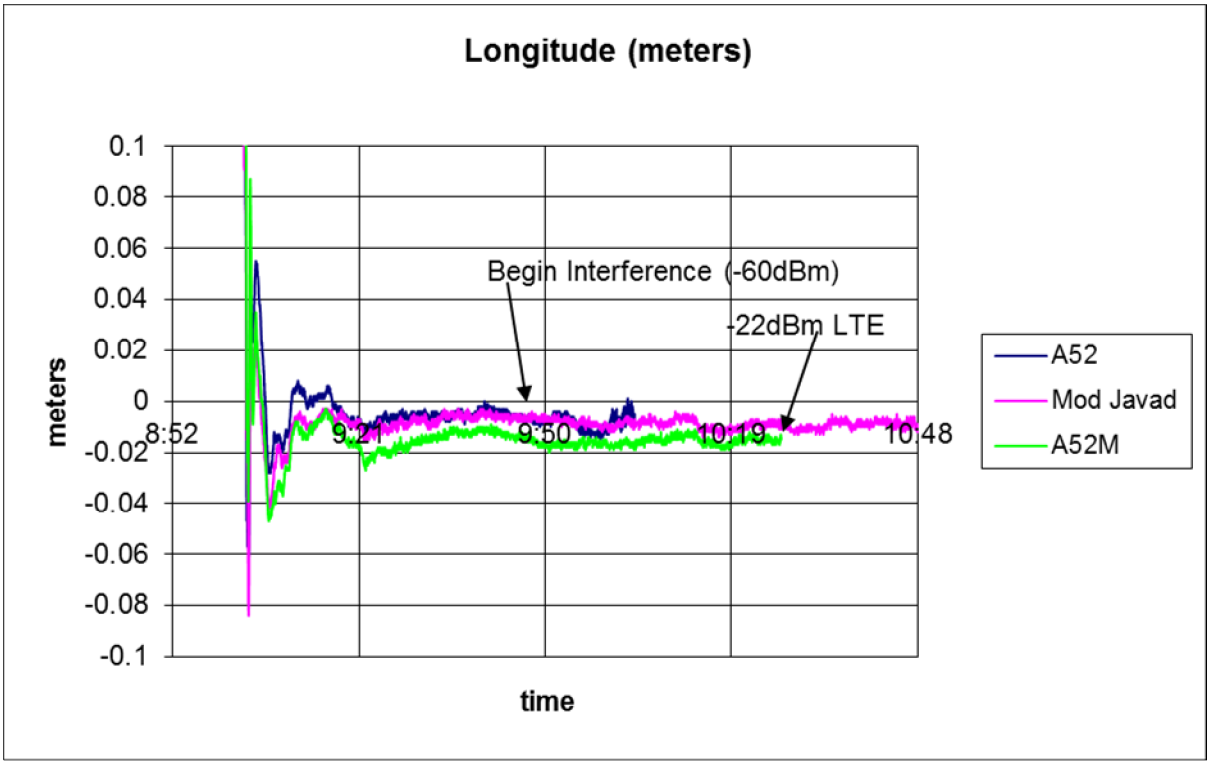


Figure 4. Local Differential Longitude Performance.

Next the performance of C/N0 (SNR+30) was examined in the presence of the LightSquared 10L base station signal.

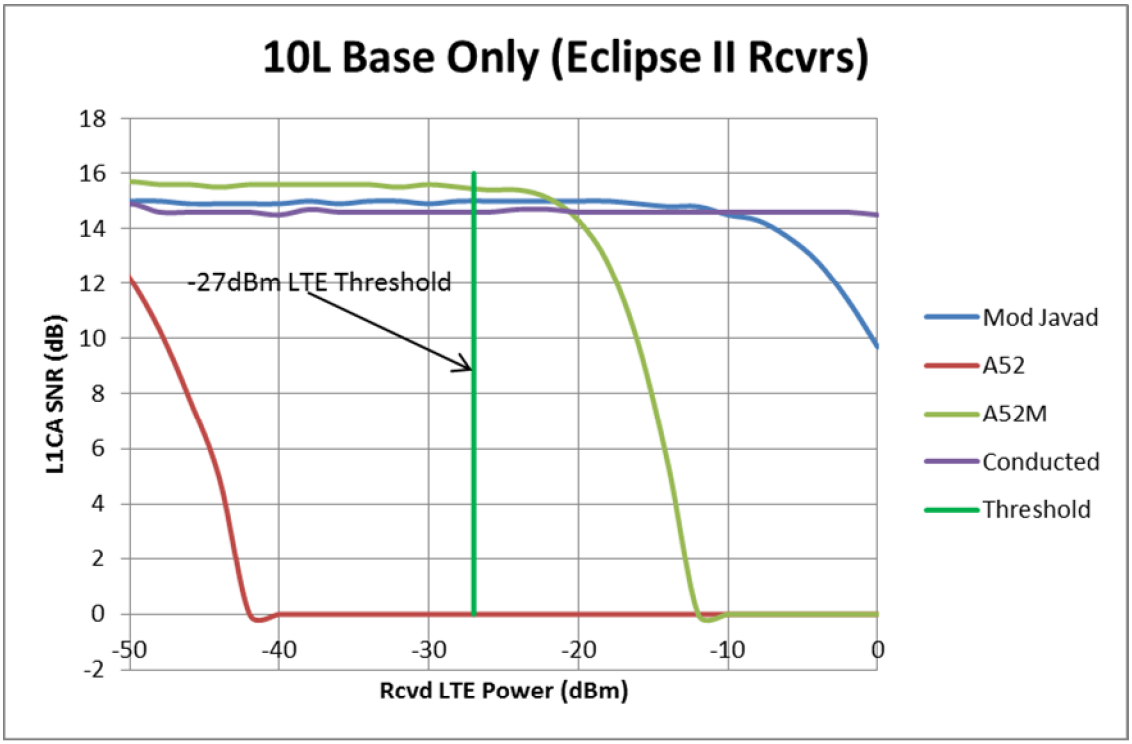


Figure 5. Interference test using 10L Base LTE signal. Note L1 C/No = L1 SNR + 30 dB

It is seen in Figure 5 that both the Modified Javad (ñMod Javadò) and the Hemisphere A52M perform acceptably with the current LightSquared proposal to not exceed -27dBm on the ground.

Multi-Frequency antennas (Tuesday 12/6/2011)

On Tuesday, again we examine position performance in a non-interfering environment using LDif. Again, recall, that this allows examination of errors introduced into code phase (which is a wide-band signal) that would be masked by RTK operation which relies on carrier phase (which is narrow band). Note that this is not exactly the same test as was done on Monday. Due to the test set up in the chamber and the supply (four total) of R320 receivers it was only possible to test three receivers in the chamber at a time. This test introduced a new antenna, the PA200. By repeating this test we are able to tie PA200 performance back to the A52 and A52M to show that antenna modification themselves, do not lead to position solution degradation. In all cases, the conducted path receiver was used as the GPS base station.

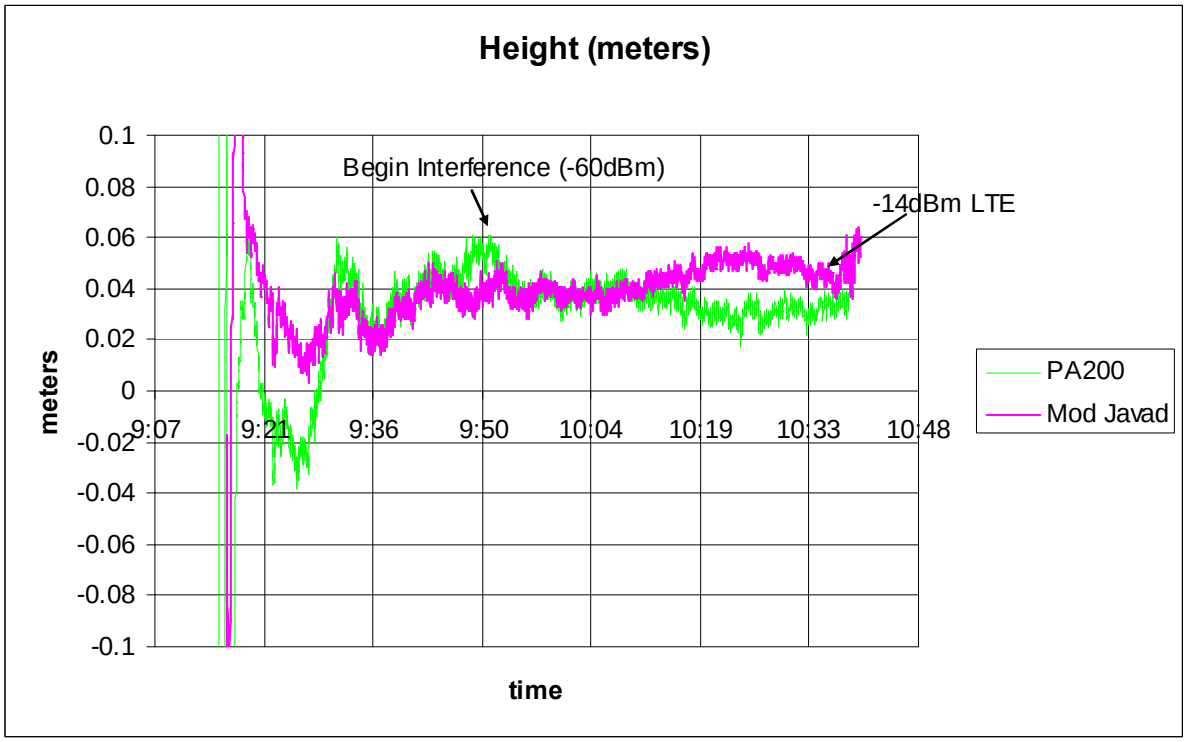


Figure 6. Local Differential Test. Conducted used as GPS Base Station.

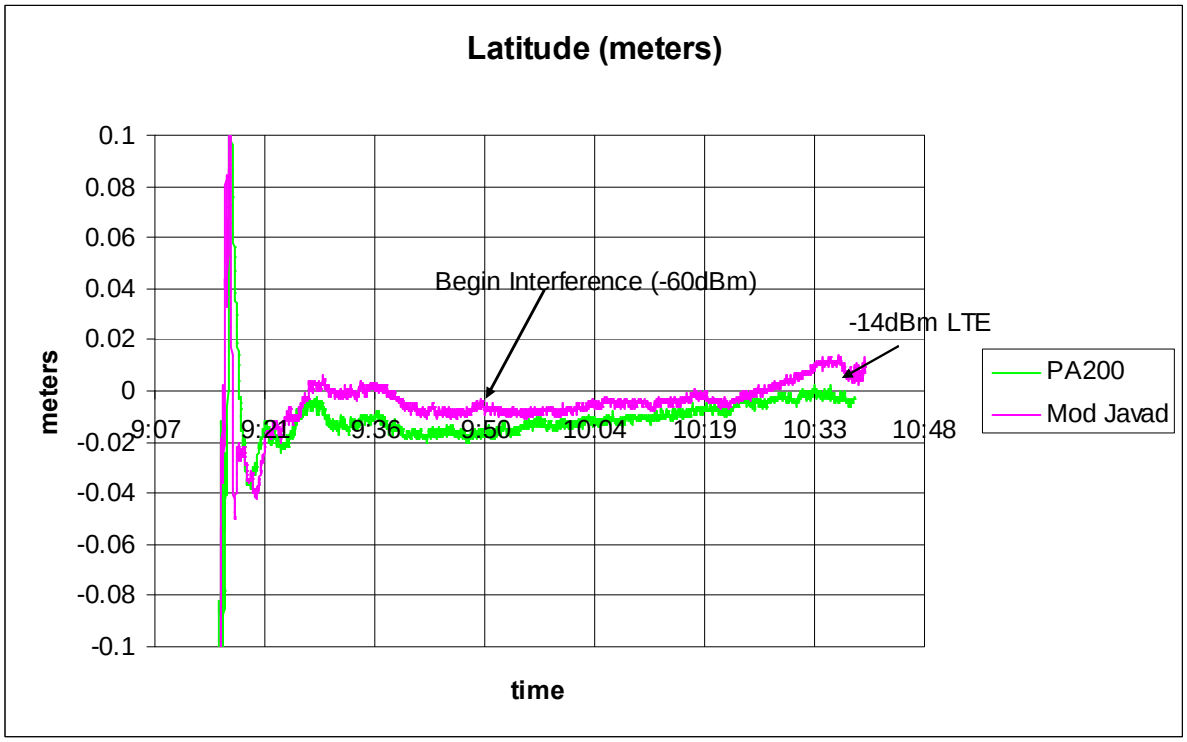


Figure 7. Local Differential Test. Conducted used as GPS Base Station.

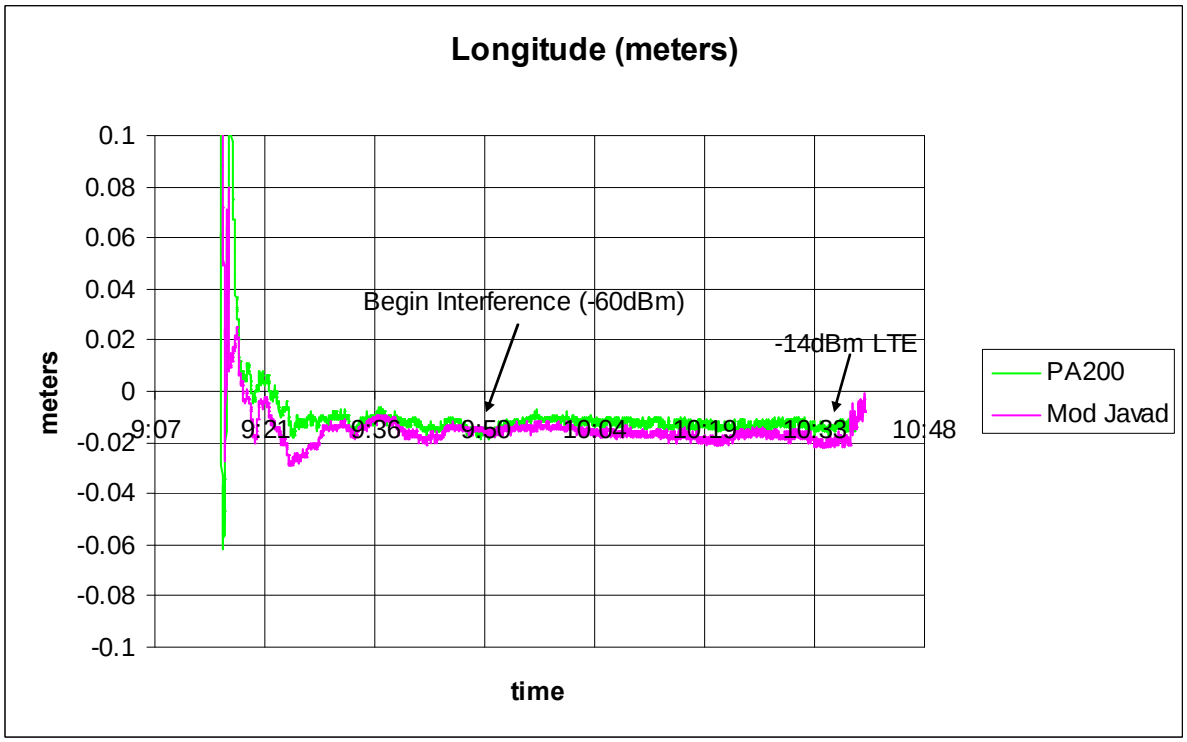


Figure 8. Local Differential Test. Conducted used as Base Station.

In the no-interference case (both Monday and Tuesday) the group delay ripple of the narrowed antenna filters shows no impact on positioning performance. This was anticipated since GPS signals share a common frequency and, hence, are all subject to essentially the same group delay effects, which fall out in the navigation solution as a common clock..

Tuesday's C/N0 Performance

The performance of C/N0 (SNR+30) was examined in the presence of the LightSquared 10L base station signal. Tests were conducted using three R320 receivers and three antennas: 1) a modified Javad antenna, 2) a pre-production Hemisphere PA200 antenna, and 3) a modified Hemisphere A52, designated as the A52M. Results are also plotted for the conducted path to a 4th GPS receiver, this path being a direct cable connection that does not require an antenna and an over-the-air broadcast. It is used as a reference for comparisons sake, since it is free of interference from the LightSquared broadcasts. Results of the 4 cases are shown below in Figure 9 -Figure 11. Note that we present results for 3 different signals tracked by GPS. L1(C/A) is the GPS standard positioning service signal broadcast at 1575 MHz that is utilized by all commercial navigation receivers, including Garmin, Tom Tom and other personal navigation devices. It is also used by aviation receivers and other general purpose receivers. L2P is a 1226.7 MHz signal intended for military use, but through innovative techniques, manufacturers of high precision receivers have found a means to track L2P, albeit it at some reduced level of performance. This signal is crucial for high-precision applications utilizing centimeter level RTK. Such applications are found in Construction, Survey, Farming, Precision Marine, used for monitoring of tectonic plates and used wherever centimeter-level performance is needed. The final signal, L1P, operating at 1575 MHz (as was the case of L1(C/A)) is similar to L2P, but broadcast at the higher frequency. It is not used as much in commercial applications since it provides essentially the same navigation capability as L1(C/A). But it is used in many academic and research applications. Of course, both L1P and L2P are heavily used by the US military.

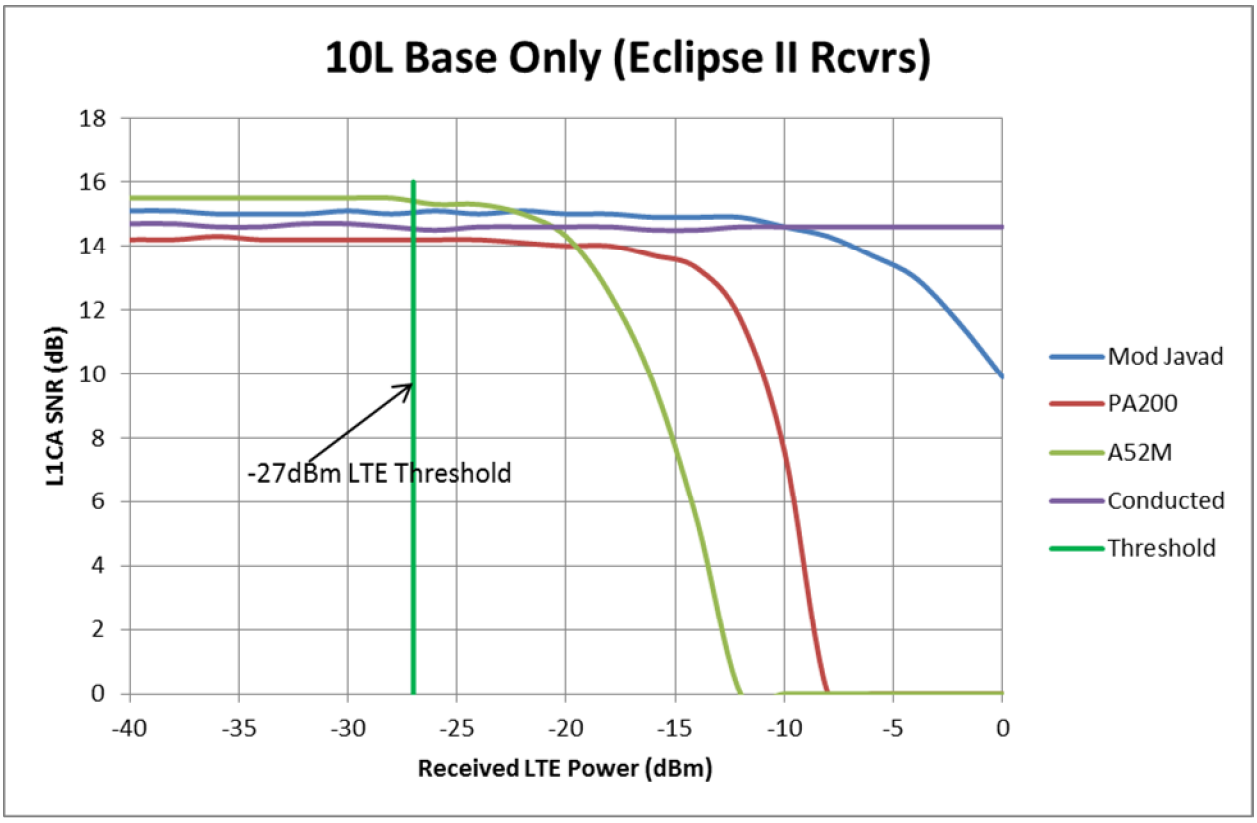


Figure 9. Tuesday 10L Base LTE Signal Only (L1CA Plot - Note L1CA C/No = SNR + 30 dB)

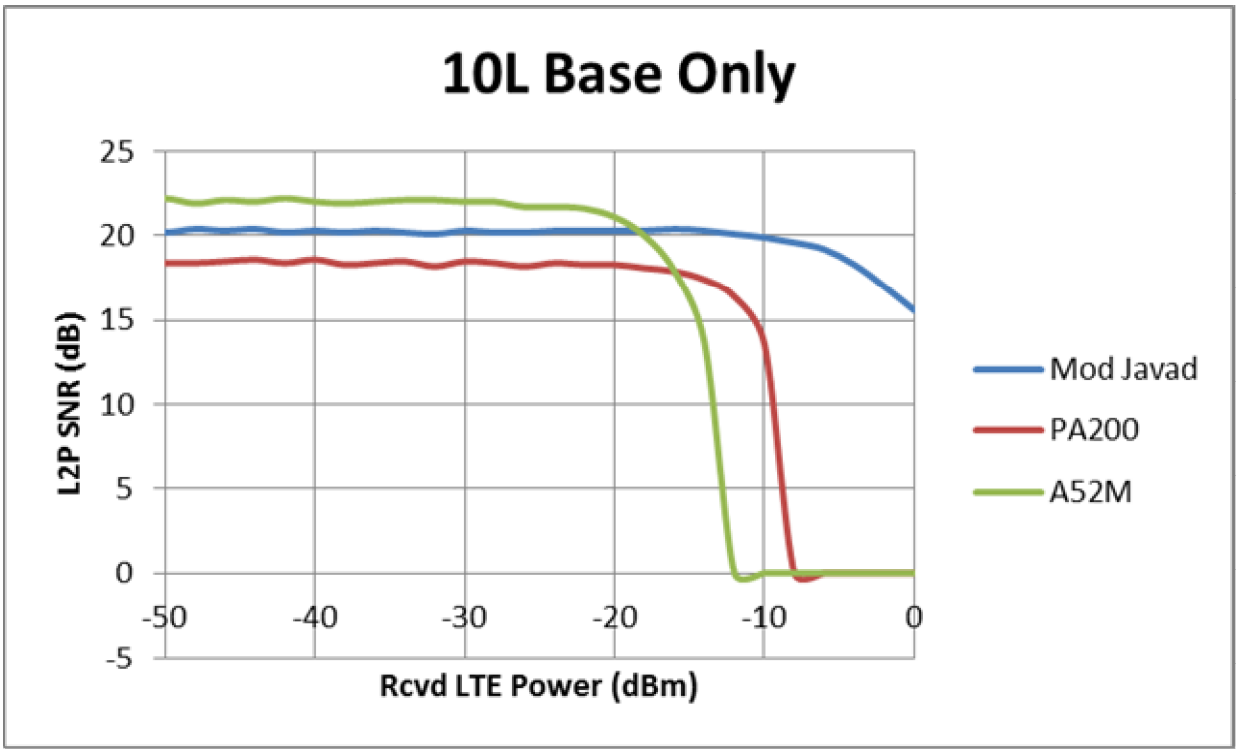


Figure 10. Tuesday 10L Base LTE Signal Only (L2P Plot)

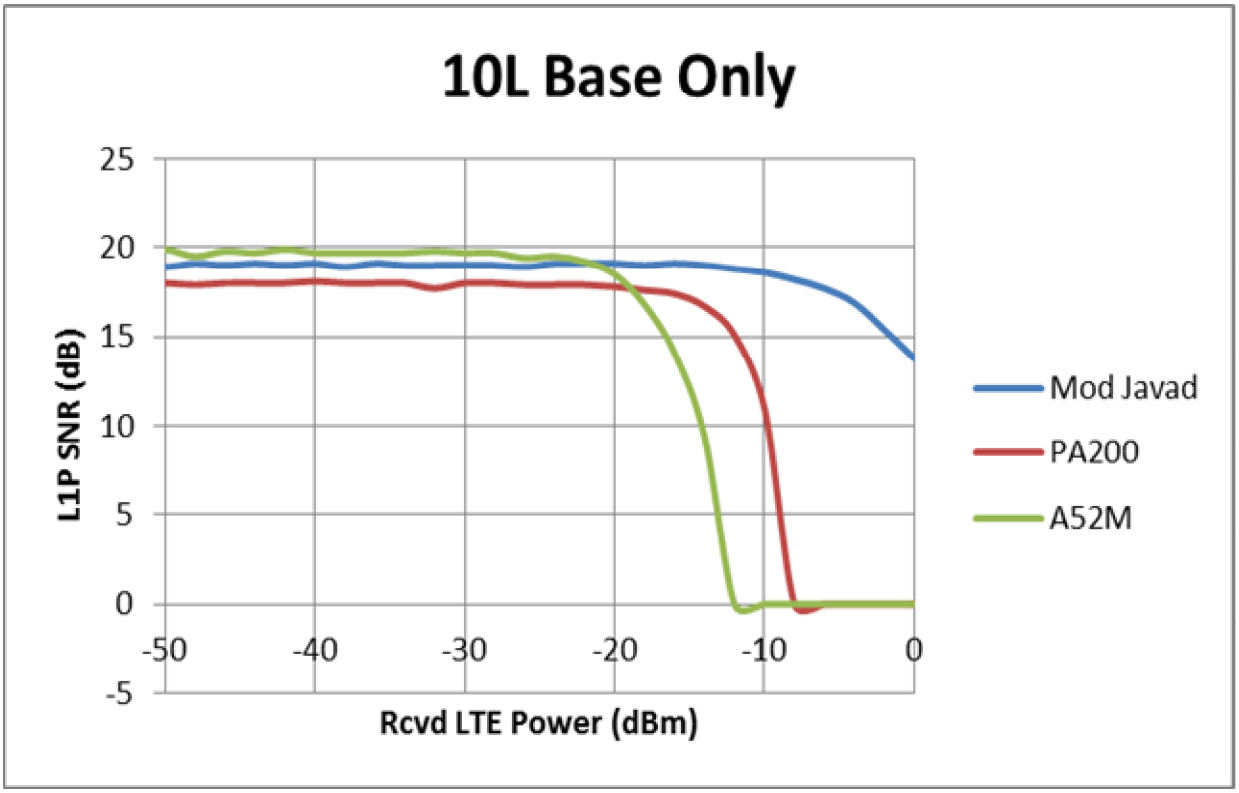


Figure 11. Tuesday 10L Base LTE Signal Only (L1P Plot)

In Figure 9 - Figure 11, it is easy to see where GPS signal strength falls off relative to the received LTE power, which is shown on the horizontal axis in dBm (decibels milliwatts). For both the PA200 and A52M we note that C/No degradation does not occur until -22 dBm or higher, providing 5 dB or greater margin relative to the maximum LightSquared power at -27 dBm. The Modified Javad antenna, when used in conjunction with the Hemisphere R320 receiver, provides an even greater margin, not falling off until -10 dBm received power, and giving a 17 dB buffer relative to the maximum LightSquared received power.

Next the LightSquared handset (HS) interference was tested. In all cases both the lower and upper handset frequencies tested a single resource block (RB). A resource block (an assigned spectral area in which the handset signal is broadcast) is approximately 180kHz wide and consists of 12 sub-carriers. Each sub-carrier is capable of QPSK up to 64 QAM modulation. It is thought that interference emanating from a single (rather than multiple) resource block is the worst case handset interference. It is possible for a handset to use more than one resource block but the power density decreases in this case (i.e. the total handset power stays constant).

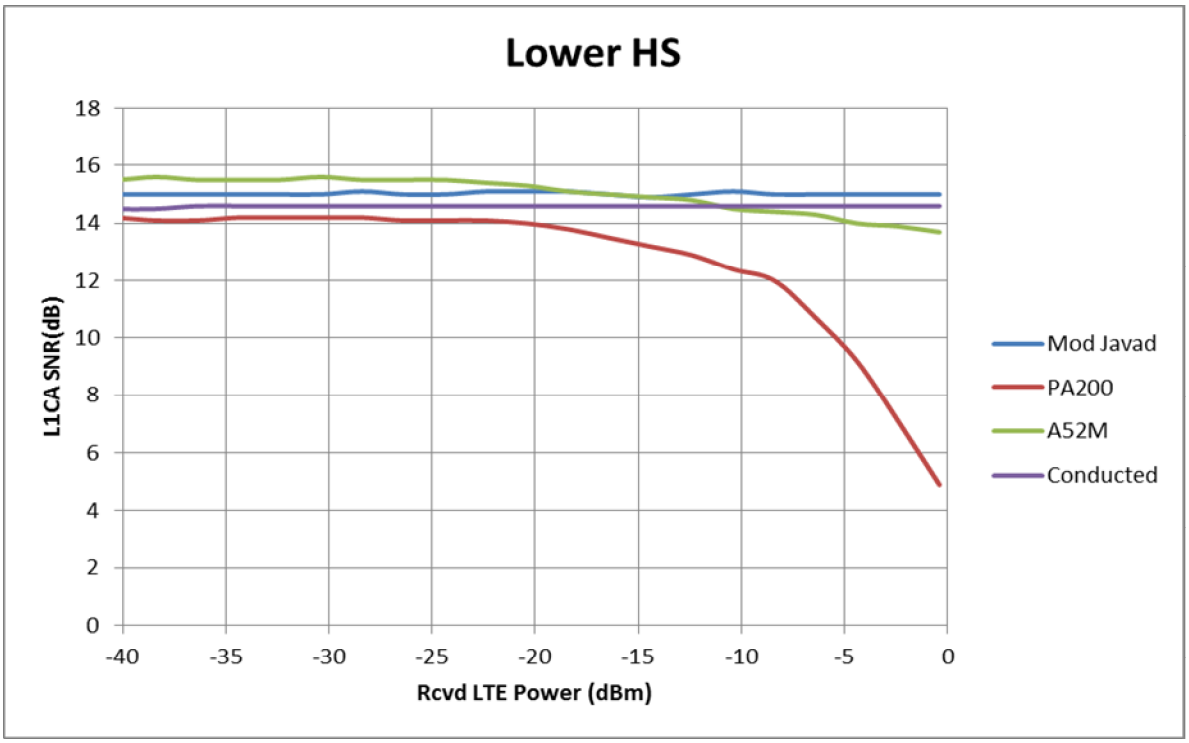


Figure 12. Tuesday Lower HS (Single RB @ 1632.5MHz) (L1CA Plot)

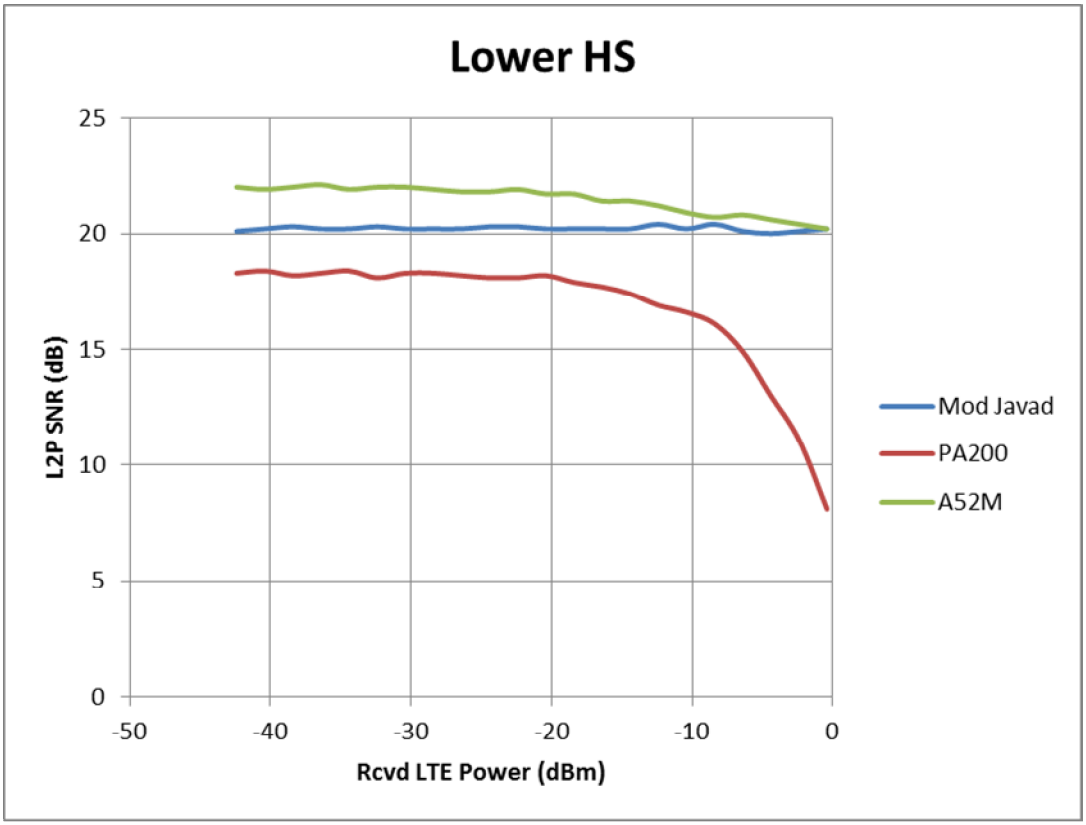


Figure 13. Tuesday Lower HS (Single RB @ 1632.5MHz) (L2P Plot)

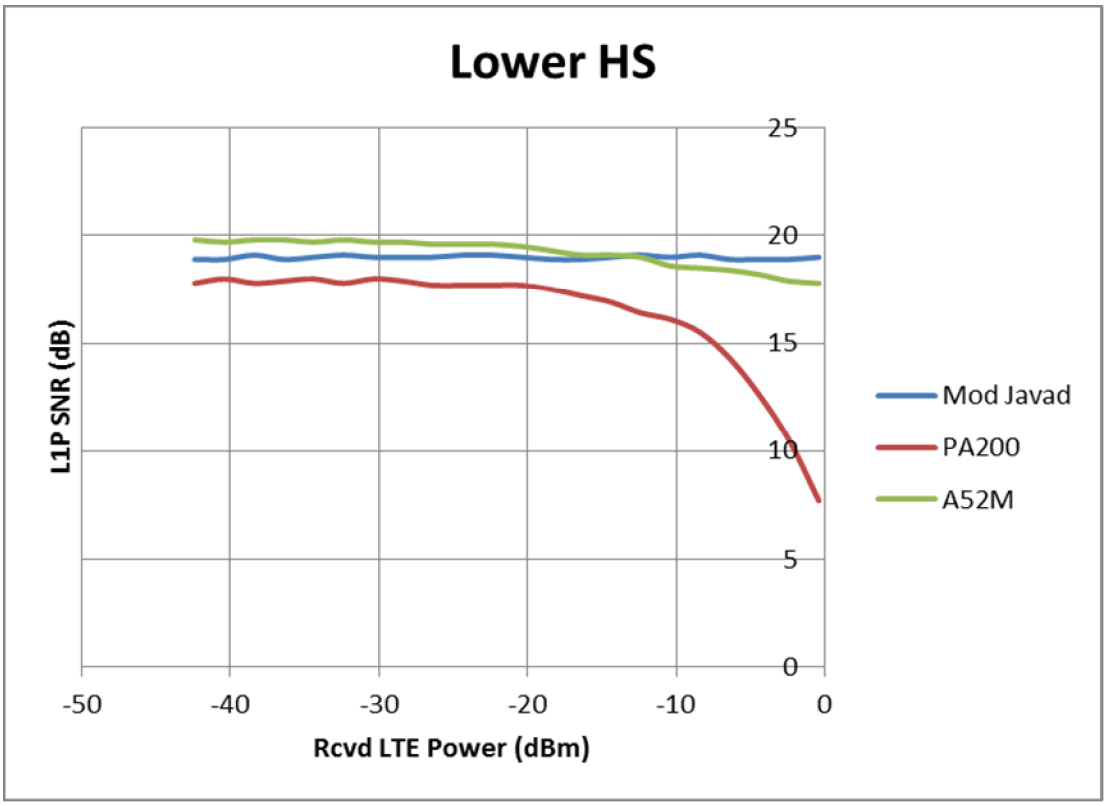


Figure 14. Tuesday Lower HS (Single RB @ 1632.5MHz) (L1P Plot)

In Figure 12 through Figure 14, the results are shown for the Lower HS signal (the Lower HS signal is the HS signal that is closest to the GPS band). As was done for the LTE base station signal, we present results for the L1(C/A), L1P and L2P signals as tracked by the three prototype antennas. As can easily be seen, below -20 dBm, there is no degradation of any of the three GPS signals (L1-C/A, L1P or L2P) while using any of the three test antennas.

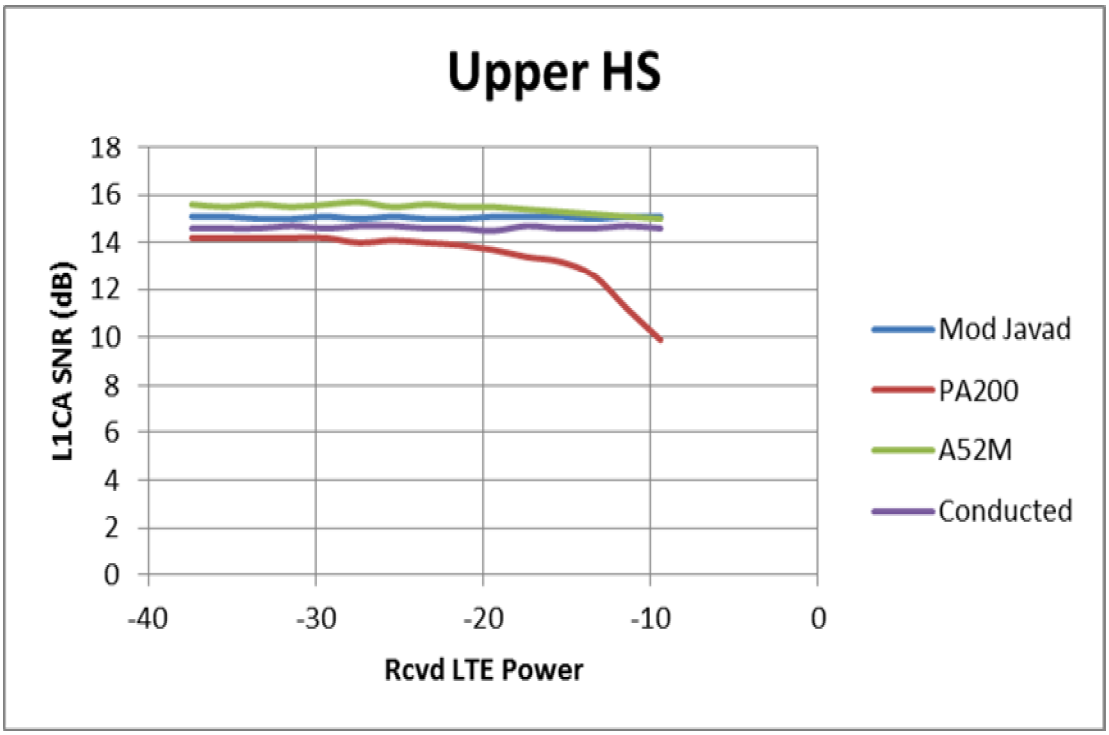


Figure 15. Tuesday Upper HS (Single RB @ 1651.7MHz) (L1CA Plot)

Next a combined case of both handset frequencies and the base station interference was tested. This is actually believed to be a quite severe case since the LTE system employs power control. So the closer you are to a base (high power base interference) the handset power should be decreased. The Base Station power was fixed at -22dBm.

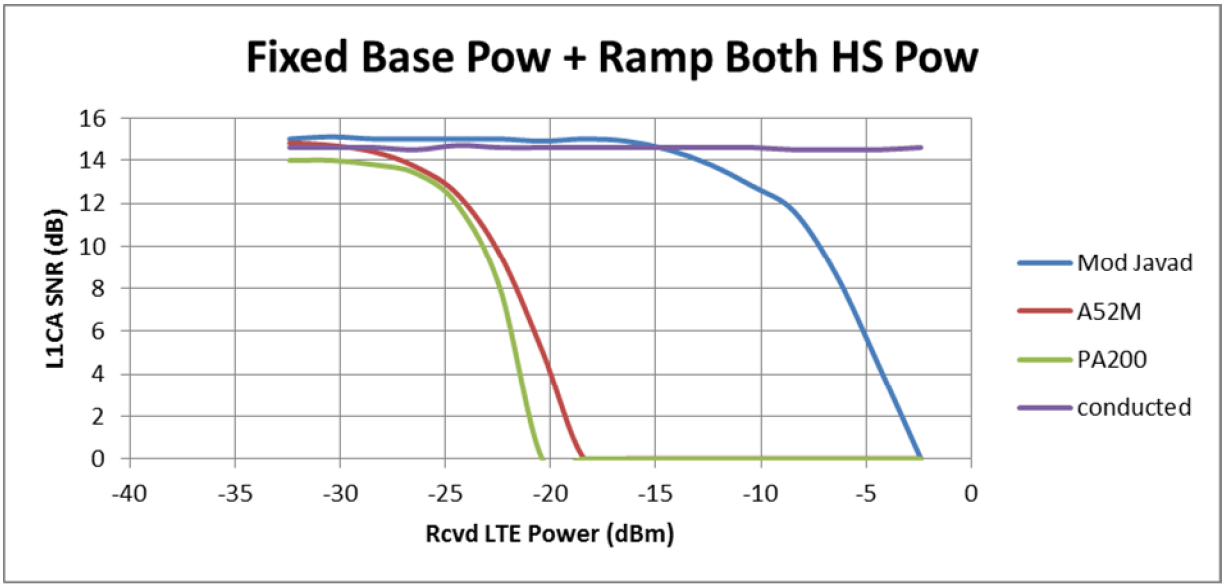


Figure 16. Fixed Base Power (-22dBm received) and Ramp Both HS Power (RB @ 1632.5MHz and 1651.7MHz) (L1CA Plot)

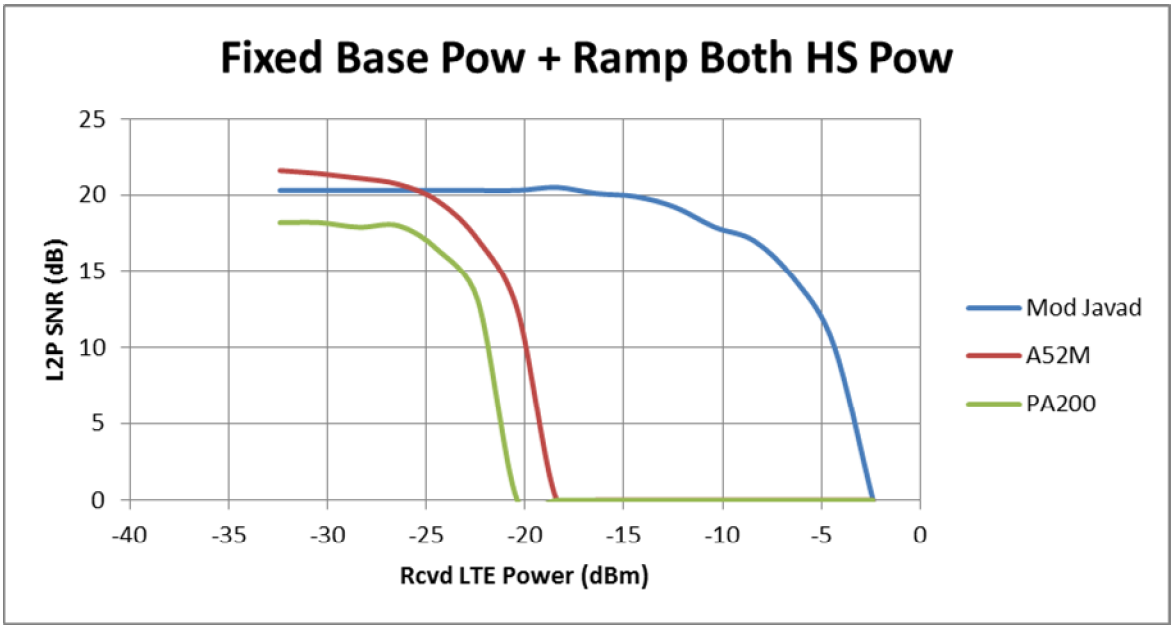


Figure 17. Fixed Base Power (-22dBm received) and Ramp Both HS Power (RB @ 1632.5MHz and 1651.7MHz) (L2P Plot)

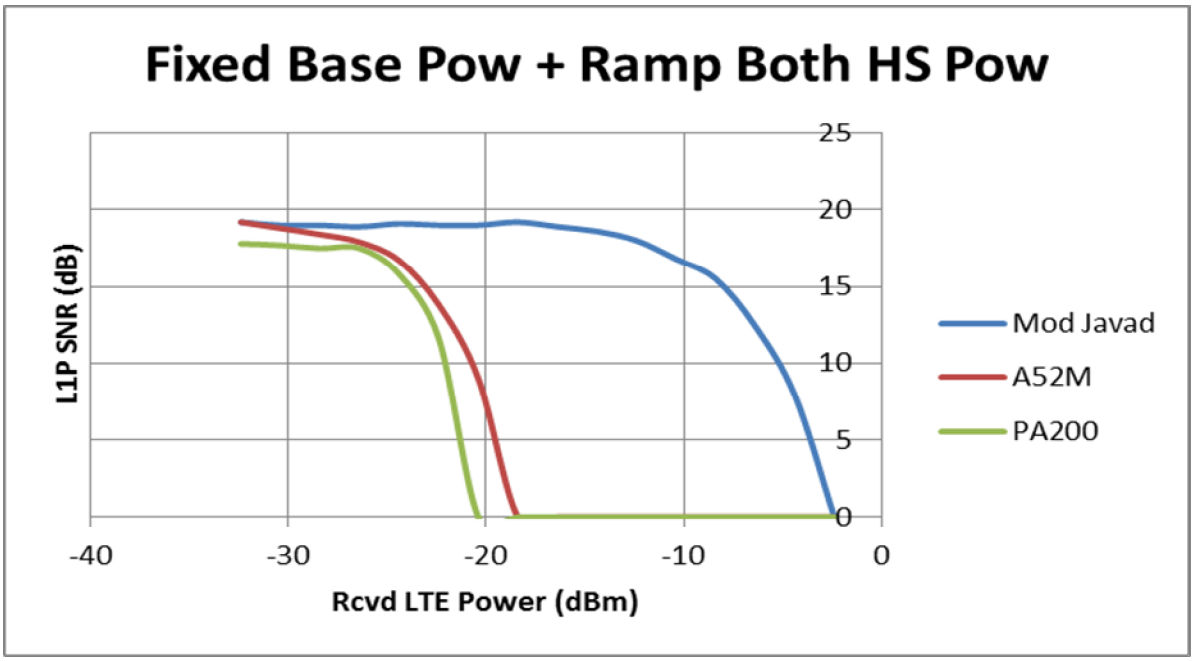


Figure 18. Fixed Base Power (-22dBm received) and Ramp Both HS Power (RB @ 1632.5MHz and 1651.7MHz) (L1P Plot)

As can be seen in Figure 16 through Figure 18, the A52M and PA200 exhibit acceptable performance with some room for improvement. They are deemed acceptable since the current LightSquared proposal limits power on the ground from the Base Station to -27dBm. Nevertheless, Hemisphere believes that interference tolerance to handsets could be improved in the A52M and the PA200.

Single Frequency Antennas (Wednesday 12/7/2011)

On the final day of testing we examined some single frequency (L1CA only) antennas.

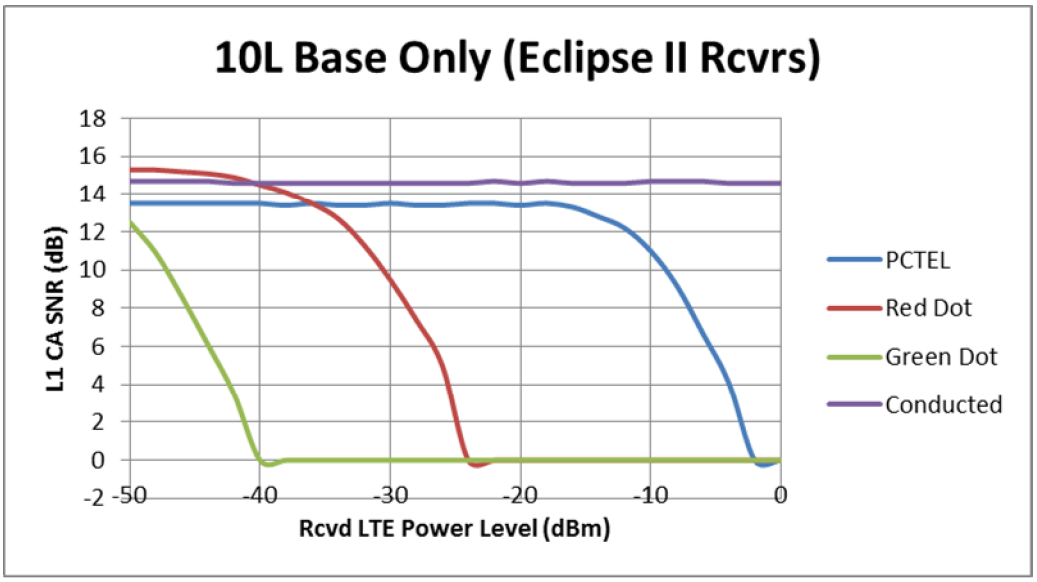


Figure 19. Wednesday 10L Base Only. Note L1CA C/No = SNR + 30 dB.

Note that Figure 20 is a similar test to Figure 19. Greg Durnan modified his green dot antenna to examine the effects of amplifier saturation on interference tolerance.

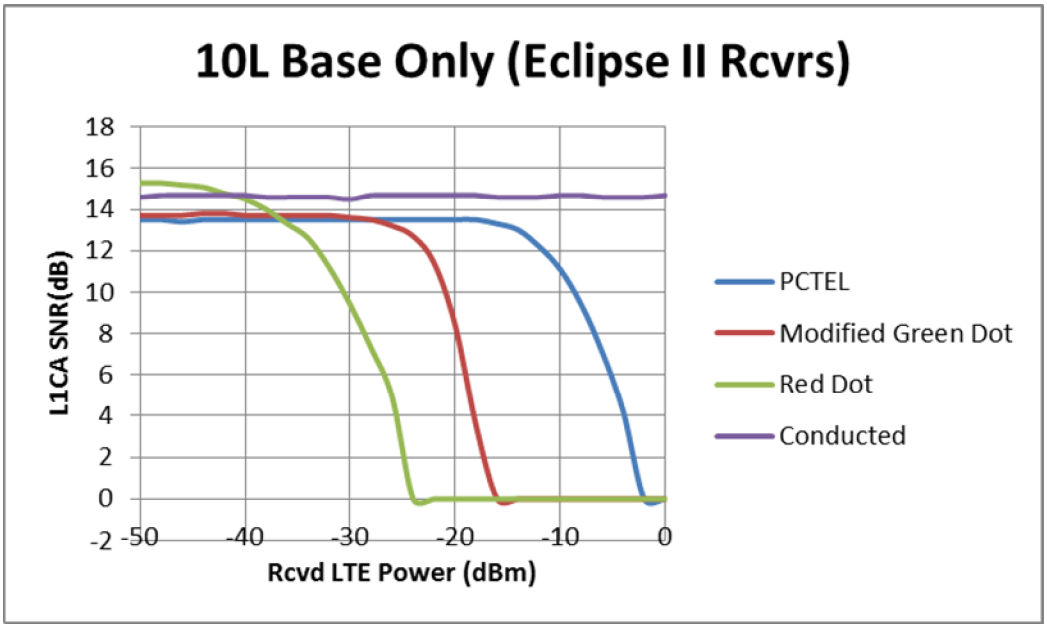


Figure 20. Wednesday 10L Base Only. Note L1CA C/No = SNR + 30 dB.

Handset interference tests were also performed on these single frequency antennas and performance was generally pretty good. The data is not being presented here since single

frequency antennas are not really of interest for this class of receiver. The data is available upon request.

Summary

In summary, the testing demonstrated that Hemisphere GPS receivers used with experimental (pre-production) antennas like the A52M and the production PA200 will not experience performance degradation in the presence of maximum LightSquared base station transmissions and severe LightSquared Handset transmissions. Hemisphere has demonstrated that, using appropriately designed antennas, margin exists relative to LightSquared maximum Base Station 10L transmission levels. With further work, Hemisphere can increase this margin for production units. Further work is planned to make the antennas tested both producible and to add robustness to the solution. Products in the field will need retro-fit solutions designed as well.

The key to the antenna solution is optimizing cascaded filtering and amplification to avoid amplifier saturation while still maintaining good noise figure. Basically, filtering prior to any amplification stages must be adequate to attenuate the out-of-band interference to the point that the down-stream amplifier will not saturate. Saturation can cause nonlinearities resulting in harmonics or inter-modulation products that fall into the passband of the GPS signals. Interestingly, in many SNR plots in this report, you can actually see that an antenna exhibiting a lower SNR without jamming performs better than an antenna with a higher no-jamming SNR as the interference increases. This is due to amplifier saturation considerations. Putting the amplifiers further down-stream and filters further up stream is the best course of action to knock out unwanted interference early before amplifier saturation can take place. But it comes at a cost of reduced gain margin and a loss in SNR under normal non-interfering operation. We will investigate methods to obtain the best compromise with regards to both interference rejection, gain margin and noise figure.

Additional rejection could be achieved with the optimal choice of polarization, i.e. using LHCP for the LightSquared signal, may provide an additional 6 dB of rejection for high precision antennas, in line of sight situations (See Figure 1).

One problem that was not explored was the impact of antenna filtering changes to GLONASS signal group delays and impacts of group delay ripple in a networked RTK solution using different manufacturerôs antennas. Hemisphere, from experience, does not believe group delay effects will impact GPS performance, but impact to GLONASS FDMA signals could possibly create difficulty in RTK solutions and other applications that make use of GLONASS. Further testing will be conducted by Hemisphere GPS in the near future. We believe it will be possible to correct for the group delay variations, and we will take care in finalizing design of the LighSquared filtering within our antennas to assure this.