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By ECFS

June 10, 2016

Ms. Marlene H. Dortch
Secretary
Federal Communications Commission
445 12th Street, SW
Washington, DC 20554

Re: Written *ex parte* presentation in IB Docket Nos. 11-109 and 12-340; IBFS File Nos. SES-MOD-20151231-00981, SAT-MOD-20151231-00090, and SAT-MOD-20151231-00091

Dear Ms. Dortch:

Enclosed is a document entitled, "Final Report: GPS and Adjacent Band Co-Existence Study," prepared by Roberson and Associates ("RAA"). This Report supplements the May 11, 2016 submission in this proceeding concerning the Roberson Test Plan and the results from RAA's testing and analysis of GPS and adjacent band co-existence.[1] Also enclosed is a certification of the RAA testing from Mark A. Sturza, who reviewed the RAA Test Plan and monitored the test campaign at the testing lab AT4 Wireless.

Please direct any questions to the undersigned.

Sincerely,

/s/ Gerard J. Waldron

Gerard J. Waldron
Counsel to Ligado Networks

Enclosures

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[1] *See* Letter from Gerard J. Waldron, counsel to Ligado, to Marlene H. Dortch, FCC Secretary, IB Docket No. 11-109 *et al.*, (filed May 11, 2016).

Final Report:
GPS and Adjacent Band Co-Existence Study

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Roberson and Associates, LLC Proprietary.

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1 EXECUTIVE SUMMARY

Ligado Networks ("Ligado") counsel, Covington and Burling, hired Roberson and Associates, LLC, ("RAA") to conduct tests to determine whether deployment of an LTE network in channels adjacent to spectrum used for GPS, using the parameters for which Ligado has applied in its license modification applications, affects the ability of GPS devices to provide accurate position information to users. This is a key question in assessing whether Ligado's proposed operations would cause any harmful interference to GPS devices.

Accordingly, RAA successfully tested 27 GPS devices, including general location and navigation ("GLN"), cellular, non-certified aviation, and high-precision devices. After analysis of the test results, we conclude that Ligado's proposed LTE deployment is clearly compatible with existing GPS operations as implemented by leading device manufacturers. Specifically, we found that the cellular and general location devices we tested were generally unaffected by Ligado's proposed operations under virtually all conditions. Together, cellular and general location devices account for more than 93 percent of all GPS devices installed as of 2015.[1] Certain other devices — primarily high-precision devices using stock antennae — showed greater effects in the proposed lower downlink and lower uplink bands. All affected devices that were able to be re-tested with a commercially available filtered antenna became compatible with Ligado's proposed operations in all bands when using the new antenna.

On May 9, 2016, RAA met with the Commission to submit and discuss the results of the aforementioned tests in the form of a summary presentation and a compendium of all the individual device results for all the frequency bands and test conditions employed. Electronic files containing the data points used to create the graphs and plots in the compendium were submitted to the Commission. The final test plan, updated to reflect changes made based on stakeholder feedback and revisions made during the period when the tests were being conducted, was also submitted.

This report completes the record for this test and the associated analysis by providing supplemental details of the specific test procedures utilized to execute the test plan. This will enable the tests to be readily replicated. The report provides further detail concerning the post-measurement analysis methods employed, including a description of the analysis of the LTE power levels that GPS devices could experience as a result of Ligado's proposed network deployment. One June 7, 2016, Ligado submitted electronic files containing all the individual device measurements (principally in the form of individual position error measurements and GPS meta-data) that were generated during the testing, in a format that allows any party to further analyze the results.[2]

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[1] *See* GPS Device Market and Supply Chain Overview, at 3, attached to Letter from Gerard J. Waldron, counsel to Ligado Networks LLC, to Marlene H. Dortch, FCC Secretary, IB Docket No. 12-340 *et al*. (filed Feb. 11, 2016) ("GPS Market Overview").

[2] *See* Letter from Gerard J. Waldron, counsel to Ligado, to Marlene H. Dortch, FCC Secretary, IB Docket No. 11-109; IBFS File Nos. SES-MOD-20151231-00981, SAT-MOD-20151231-00090, and SAT-MOD-20151231-00091 (filed June 7, 2016).

2 PURPOSE OF THE STUDY

Roberson and Associates, with the assistance of testing and technical support professionals, developed a test plan and post-measurement analysis methodology designed to rigorously assess whether Ligado's proposed terrestrial broadband operations would cause "harmful interference," which the Commission for decades has defined as follows:

"Interference which endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with [the International Telecommunication Union] Radio Regulations."[3]

Under this standard, "harmful interference" to a GPS device would be interference that endangers or seriously degrades the ability of the GPS device to measure and accurately report the data the device is designed to provide to users: principally, the device's position.

3 TECHNICAL APPROACH

We designed and conducted a testing program that has successfully measured whether Ligado's proposed operations would diminish the ability of General Location and Navigation (GLN), cellular, non-certified aviation, and high-precision GPS devices produced by leading manufacturers to report their position.

As illustrated in Figure 1 below, and in the final Test Plan submitted May 11, 2016, we first tested each device's baseline ability to accurately measure its position by comparing the device's reported position with the device's "true" position. (The true position was either the position programmed into an industry standard GPS signal simulator emulating GPS signals or, for devices tested using the Live Sky method described below, the position estimated from a long term average of the position reported when no LTE signals were present.) We then compared the device's baseline performance with the device's reported position in the presence of adjacent band LTE signals under the parameters Ligado has proposed. We determined whether a device experienced harmful interference by comparing the average position error (measured over 3 minutes) in the positions reported by the device under baseline conditions (*i.e.*, without the Ligado LTE signals) to the 3-minute average error in the positions reported by the device in the presence of the LTE signals.

[3] *See* 47 C.F.R. § 2.1(c); *Comment Sought on Ligado's Modification Applications*, Public Notice, IB Docket Nos. 11-109 & 12-340, DA 16-442, at 8 n.48 (April 22, 2016) (citing 47 C.F.R. § 2.1(c)).

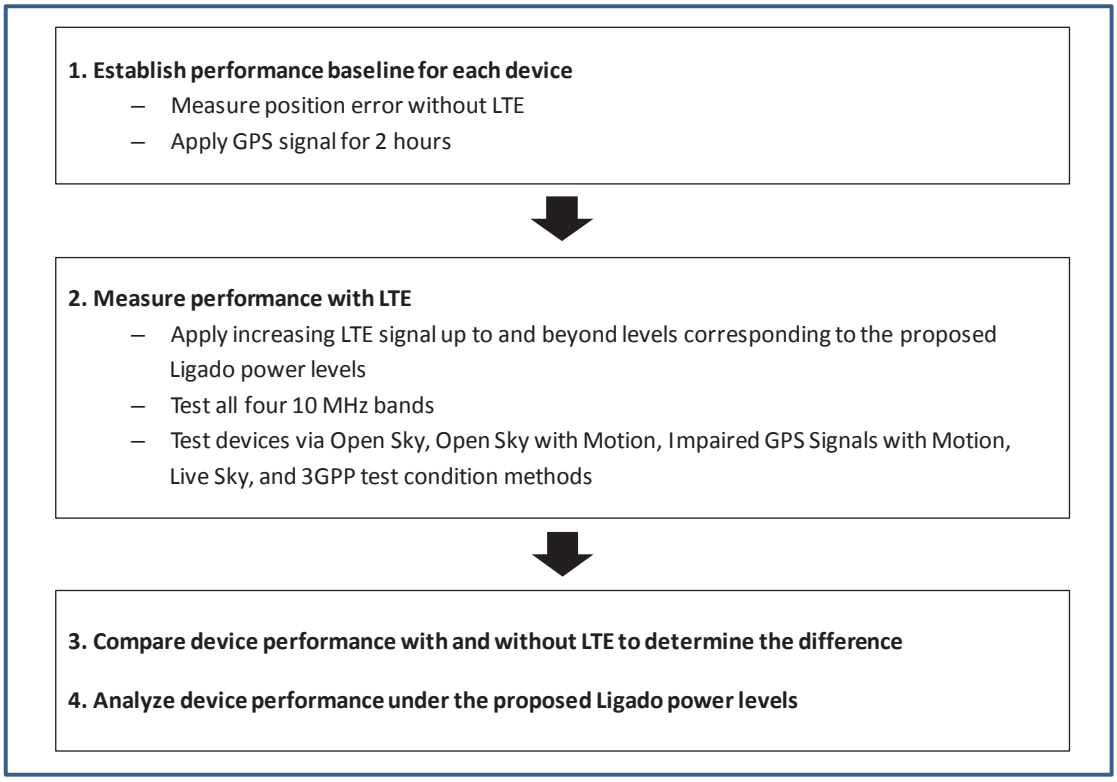


Figure 1. Measurement and Assessment Approach

Our approach thus is designed to provide the Commission and NTIA — the agencies entrusted with the management of private and federal spectrum, respectively — with actionable data on the practical effect of Ligado's proposed terrestrial broadband operations.

Comparison to Other Methods

Our testing protocol accordingly is superior to proposals that attempt to assess interference based on a proxy measurement such as carrier-to-noise power spectral density ratio (C/N_0). For instance, the Department of Transportation's ("DOT") Volpe Center has, for the past several years, been attempting to design and conduct an Adjacent Band Compatibility Study ("ABS") to measure the potential effect of terrestrial broadband operations in spectrum bands adjacent to GPS. The DOT ABS Test Plan released this past March — like earlier drafts of the plan — proposes to develop "interference tolerance masks" based on the "received interference test signal power level that causes a 1-dB [carrier-to-noise power spectral density] degradation."[4] However, there is no evidence that a change of 1 dB in the carrier-to-noise power spectral density ratio correlates to any significant error in a GPS device's reporting of position or timing data, and thus no evidence that such a change in C/N_0 is in any way indicative of the presence of harmful interference. In fact, the results of our testing show the opposite: we found no meaningful correlation between such a 1 dB change and GPS performance.

[4] Test Plan to Develop Interference Tolerance Masks for GNSS Receivers in the L1 Radiofrequency Band (1559-1610 MHz), at 3, *available at* http://ntl.bts.gov/lib/57000/57000/57046/DOT_GPS_Adjacent_Band_Test_Plan_Final_03012016.pdf.

3.1 Test Plan Development

We developed our plan for testing GPS key performance indicators based on a transparent, iterative process that both solicited input from all relevant stakeholders and took into account feedback from a wide variety of these stakeholders.

We shared the initial outline of our testing procedures with the Commission, the NTIA, the DOT and other organizations in June 2015,[5] filed a draft test plan with the Commission in August 2015,[6] conducted an open discussion regarding the test plan at DOT's October 2, 2015, workshop on adjacent band issues, and filed a revised test plan with the Commission in February 2016.[7] At each stage of the process, we and Ligado encouraged device manufacturers and other interested parties to provide feedback and any available technical data — on a confidential basis to RAA only, as needed — to make our study as robust as possible. As an example of these interactions, the National Public Safety Telecommunications Council (NPSTC) provided feedback on test parameters important to public safety GPS applications, including the range of LTE power levels that should be tested, and suggested that a unique Public Safety device be tested.

Our initial plan, like our final plan, focused on measuring what, if any, effect Ligado's proposed terrestrial broadband operations would have on the ability of what we believed to be some of the most important and highest volume GPS devices in the various market segments to accurately provide position measurements. However, we refined our test plan in several ways in response to the comments we received at the DOT workshops and through other channels. For instance:

- In response to concerns that GPS devices in motion may be more vulnerable to performance degradation than devices at rest, we added the ability to test GLN devices in simulated motion.
- We tested with LTE power levels up to -10 dBm (measured at the GPS device), even though this level is not expected to be observed with any meaningful probability in a commercially deployed system with Ligado's proposed terrestrial broadband operating parameters.

We tested with uplink signals occupying the full 10 MHz LTE bandwidth based on stakeholder feedback from the DOT workshop.

[5] *See* Letter from Gerard J. Waldron, counsel to LightSquared, to Marlene H. Dortch, FCC Secretary, IB Docket No. 12-340 *et al.*, at Attachment (filed June 24, 2015).
[6] *See* Letter from Gerard J. Waldron, counsel to LightSquared, to Marlene H. Dortch, FCC Secretary, IB Docket No. 12-340 *et al.*, at Attachment (filed Aug. 25, 2015).
[7] *See* Letter from Gerard J. Waldron, counsel to LightSquared, to Marlene H. Dortch, FCC Secretary, IB Docket No. 12-340 *et al.*, at Attachment (filed Feb. 24, 2016).

3.2 Summary of Final Test Methodology

3.2.1 Device Selection:

GPS is used in a wide variety of applications. GPS industry data set forth in the GPS Market Overview[8] identifies the various categories of the GPS receiver market. Cellular handsets represent the largest of these categories based on the number of devices installed in the market, followed by GLN devices. At the same time, although high precision devices represent a much smaller segment of the GPS market, these devices are among the most likely to be vulnerable to interference because many of these devices have relatively wide RF front end bandwidths in order to receive an MSS (Mobile Satellite Service) augmentation signal in the adjacent 1525-1559 MHz MSS band. Taking these factors into account, we selected for testing GLN, cellular, and high precision devices, as well as a non-certified aviation device, that are produced by leading manufacturers and for which it was feasible for third parties to access Key Performance Indicators reported by the device. We also took into account the fact that manufacturers in the GPS consumer device industry share a largely common supply chain and use similar or identical GPS consumer device component parts.

3.2.2 Key Performance Indicators and Other Statistics:

The purpose of our study was to collect supporting data to establish the impact on Key Performance Indicators (KPIs) that a GPS device user or application may experience in the presence of L-band LTE downlink and uplink signals within the parameters Ligado has proposed for terrestrial operations. The fundamental KPI for GPS devices used for navigation is position error, *i.e.*, how closely the position reported by the device matches the device's true position. Because of variations in the use cases for different classes of GPS devices, the precise KPI definition varies among these classes.

- GLN: The KPI for this class of device is two-dimensional position error while the device was in simulated motion.
- Cellular: Industry-standard KPIs for GPS performance in cellular devices are set by the 3GPP.[9] We performed three tests defined in 3GPP Specification TS 37.571-1, which measure device sensitivity, accuracy, and dynamic range. Success in these tests is defined by the Specification as the device limiting two-dimensional position error and maximum response time below certain thresholds under defined conditions at least 95% of the time. The 3GPP tests require the device to make phone calls and respond to requests to report position. Since the Samsung Tablet (a cellular device) could not make phone calls and perform the 3GPP tests

[8] *See* GPS Market Overview, *supra* n.1.
[9] The 3GPP (3G Partnership Project) is the internationally recognized standards organization for cellular. *See* http://www.3gpp.org/about-3gpp.

this device was tested for two-dimensional position error in the presence of LTE signals.

- High Precision: The KPI for this class of device is three-dimensional position error.
- Non-Certified Aviation: The KPI for this device is two-dimensional position error. Two-dimensional position error was chosen to be consistent with advertised specifications for the devices.

In addition to the KPIs set forth above, we recorded other information ("meta-data"), such as C/N_0 values and the number of satellites received, to the extent the tested devices reported such statistics in a format accessible to third parties.

3.2.3 Test Setup:

Each tested device was placed in an RF anechoic chamber housed at AT4 Technologies, a testing facility in Herndon, Virginia.[10] A Spirent GPS signal generator was used to produce controlled GPS signals for these tests (except for tests conducted using the Live Sky method described below).
For test and calibration procedures see Appendix A. The Final RAA test plan was filed May 11, 2016.[11]

3.2.4 GPS Signal Conditions:

Several different radiated GPS signal conditions were used, as appropriate for the typical use cases of the different classes of GPS devices. We conducted both "Live Sky" and "Simulated Signal" testing. Live Sky testing used real GPS satellite signals, and we accordingly had no control over the relative GPS signal power levels; additionally, the GPS signals were exposed to real world, non-LTE impairments, such as atmospheric delays and multipath. Chamber testing used GPS satellite signals generated by a Spirent GNSS signal generator. For these tests, we had complete control over the GPS signal power levels. No impairments were simulated other than those caused by adjacent band LTE signals and, in some tests, reduced levels of GPS signals relative to the nominal level.

Two forms of Simulated Signal testing were conducted for GLN devices: "Open Sky" and "Impaired GPS Signal." For the Open Sky tests, the Spirent signal generator was configured to provide a nominal received GPS signal level of -130 dBm for all GPS satellites in view. The GPS L1 C/A-code signal-in-space specification is a minimum -128.5 dBm signal level at the output of a 3 dBi linearly polarized antenna. The nominal maximum is -123 dBm, so the simulated clear sky signals were nominally received 1.5

[10] *See* https://www.at4wireless.com/index.html.
[11] *See* Letter from Gerard J. Waldron, counsel to Ligado, to Marlene H. Dortch, FCC Secretary, IB Docket No. 11-109; IBFS File Nos. SES-MOD-20151231-00981, SAT-MOD-20151231-00090, and SAT-MOD-20151231-00091 (filed May 11, 2016) ("May 11 Filing").

dB to 7 dB below what the receiver under test would have seen outside with an unobstructed view of the sky.

For the Impaired GPS Signal tests, the Spirent signal generator was configured to provide a nominal received GPS signal level of -142 dBm for all GPS satellites in view. This is 12 dB (a factor of 16) below the simulated Open Sky signal level. Referring to the signal-in-space specification above, -142 dBm is 13.5 to 19 dB below the GPS signal levels a GPS receiver would experience outdoors with an unobstructed view of the sky.

The different GPS signal conditions used in the testing were as follows:

- Open Sky: The Spirent simulator created a moving constellation of GPS signals representative of a static location, which were presented to the devices under test along with LTE signals. This method was predominantly used for high precision devices.
- Open Sky with Motion: The Spirent simulator created a moving constellation of GPS signals representative of a moving vehicle, which were presented to devices along with LTE signals. To simulate motion, a "golden" file of position (latitude-longitude) versus time was recorded in NMEA format while driving in a test loop. This file was then loaded into the GPS simulator, along with the date and time of the simulation's start. The simulator then calculated the relevant GPS satellite orbits and generated ideal GPS satellite signals to the device under test as if the device were moving over the test route at the simulated speed. This method was used for GLN devices and the Samsung tablet.
- Impaired GPS Signal with Motion: The Spirent simulator created a moving constellation of GPS signals representative of a moving vehicle (using the same motion-simulation procedure described above). The GPS signals' power levels were reduced as described above to simulate an impaired condition and presented to the devices along with LTE signals. This method was used for GLN devices.
- Live Sky: A rooftop antenna captured outdoor GPS signals which were conveyed into the test chamber and presented to devices along with LTE signals. Live Sky testing was used for high precision devices with MSS augmentation. This approach was utilized because the signal received by the active outdoor antenna included the augmentation signal. This made it convenient to test the device in the condition it was designed for, namely higher accuracy or precision enabled by the satellite based augmentation signal.
- Cellular A-GPS: GPS signal simulations were as defined in the application 3GPP test cases

To ensure the correct LTE signal level at the GPS receiver, the received LTE power was measured with a calibrated antenna of known gain placed in the position of the device under test and oriented toward the LTE emitter. The GPS signals from all SVs were combined and radiated towards the GPS devices as one composite signal from a separate antenna.

3.2.5 Test Sequence *(see Figure 2 below):*

- We first established a baseline for each device's performance under "no interference" conditions in each proposed Ligado band and under each of the applicable GPS signal conditions described below. This was accomplished by recording two hours of measurements for each device with only GPS signals present (*i.e.*, without any adjacent-band LTE signals). The two hour GPS-only observation period was arrived at through an extensive process of evaluating various times and observing that two hours was sufficient to collect enough sample measurements to establish a reliable performance baseline. The purpose of the observation period was to provide a representative distribution of GPS position errors so that when the adjacent band LTE power was applied, a determination could be made whether the error distribution *with LTE power* had been clearly affected relative to the distribution *without LTE power*. Furthermore, rather than comparing entire cumulative distribution functions (CDFs) with and without LTE, we chose to compare 3-minute averaged values of the distributions as their proxies, or KPIs. Choosing the mean value of the CDF as the basis of comparison was determined to be sufficient compared to other metrics such as the 95% level. An analysis of one test result comparing an LTE impact definition based on the 3-minute average versus the 95% of the CDF showed similar results (details are provided in Appendix E).
- The LTE signal (plus a fixed amount of out-of-band "white noise" simulating device Out of Band Emission (OOBE), which was applied when testing proposed uplink bands) was then applied, starting at -80 dBm, with the LTE levels incrementing until reaching -10 dBm. No OOBE noise was added to simulate the downlink OOBE as this noise, when projected to the GPS receiver, even in the most conservative use case, results in a noise PSD that is more than 20 dB below the thermal noise level of the receiver.
- We recorded data for three minutes at each LTE level, producing a sufficient number of samples to calculate reliable KPI averages and standard deviations.
- When testing of a device was complete, we reviewed the raw data for any indications that the testing deviated from the test plan (for instance, apparent inconsistencies between the GPS only data and the GPS with LTE data, C/N_0 measurements inconsistent with the test setup, or missing data points). If we observed anomalies the device was retested. During all tests a U-Blox GPS receiver was used as a monitor receive to ensure GPS signal levels and satellite counts were at expected levels.

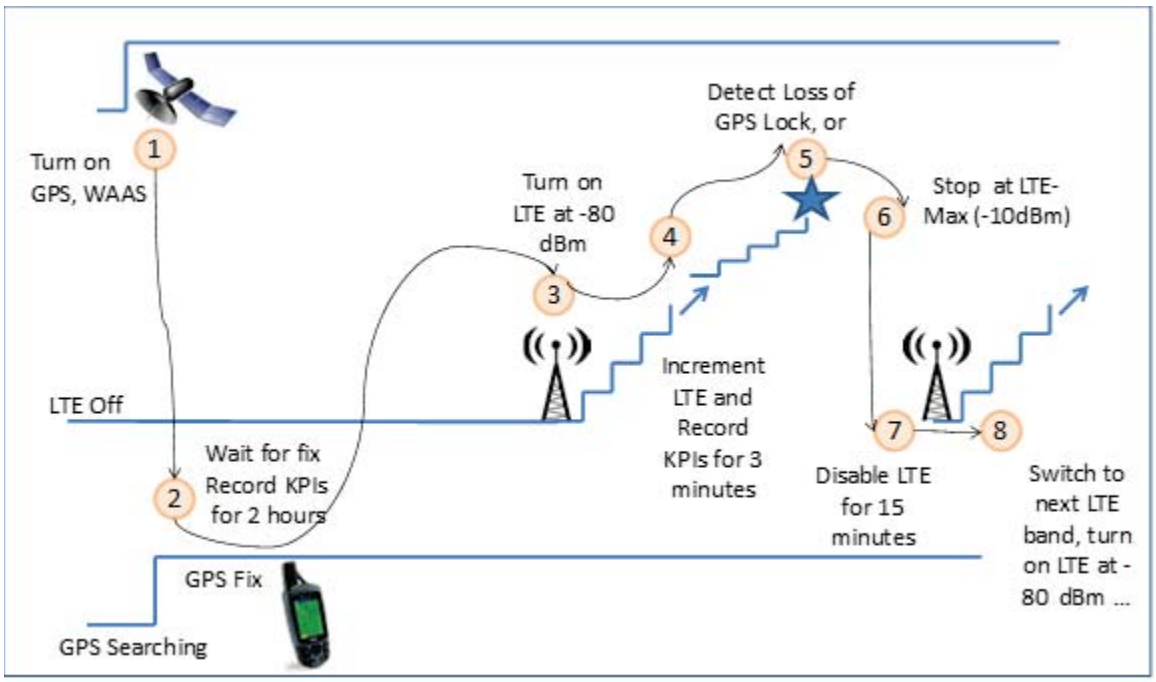


Figure 2. Basic KPI (Position Error) Measurement Sequence

3.3 Post Measurement Analysis (non-cellular devices)

3.3.1 Calculation of Position Error and Average Position Error

The post-measurement analysis of the data involved comparison of the measured received estimated positions with the true values. Depending on the capability of the device, the testing produced measurement output files for each test condition either in NMEA format, or as a file consisting as a sequence of "waypoints" consisting of at least a time-stamp of the output, and the measured latitude, longitude, altitude. As illustrated in Figure 3-I, for each position measurement output from the device, a time sequence of either 2-D position errors (for GLN devices), or 3-D position errors (for High Precision Devices), was created by software that compared the device's measured position to the true position from the Spirent GPS signal generator. As shown in Figure 3-II, the individual position error calculations, indicated as vertical black lines, were then averaged over a 3-minute window to create an average position error which was then plotted as the "device measurement result" shown in Figure 3-III. The horizontal axis for the no-LTE, GPS baseline measurements is the sequence number of the 3-minute average position error calculation (shown in Figure 3-III). The horizontal axis for the measurements with LTE is the LTE signal level.

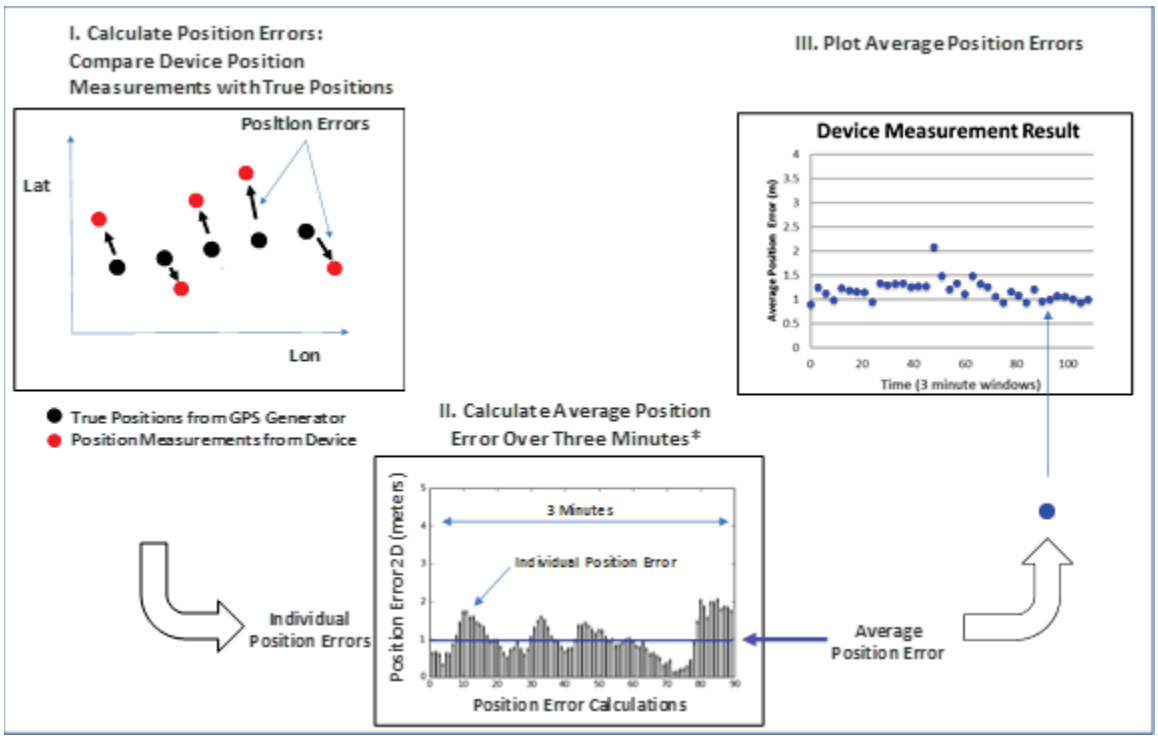


Figure 3. Post Measurement Analysis- Calculation and Plotting of Average Position Error

3.4 LTE levels assessment and LTE deployment

LTE Signal Conditions: LTE uplink and downlink signals were generated in the bands Ligado has proposed for such terrestrial broadband use, using the out-of-band emission limits proposed by Ligado, and utilizing a range of power levels including levels that exceeded the limits proposed by Ligado, such that the correct LTE signal and noise levels were present at the GPS receiver under test. A 10 MHz bandwidth LTE signal was used in the measurements.

- Downlink LTE signals were assumed to be supporting many devices and have all LTE resource blocks assigned.
- Uplink LTE signals were representative of a high data rate, with the extreme condition of all resources blocks assigned. Feedback during the DOT workshop indicated support from the community that this was a worst case. The high data rate case is the extreme worst case since this represents an entire sector of a base station dedicated to one single mobile device. Lower data rates will be experienced in the field as well as lower radiated power, since a base station will rarely if ever assign 100% of the resources to a single device located at the edge of a cell. A wideband white noise generator output combined with the LTE uplink signal was used to produce a test signal with the power spectral density (in the GPS band) matching Ligado's proposed limits for uplink OOBE projected from a Ligado device to a GPS receiver.

3.4.1 Uplink Power Calculation

When considering the receive signal levels from the Ligado Network's LTE user equipment (UE), the following analysis was considered in determining the power present at a GPS receiver at a one-meter separation distance. To arrive at the received signal under Ligado's proposed power level at the GPS receiver antenna of -19 dBm, the following calculations were used (see Table 1), which are consistent with the TWG report Section 3.2.10.2[12]:

Table 1. LTE Uplink Power Calculation

Parameter	Value	Unit	Description
Device UE TX Power	23	dBm	Maximum value per 3GPP standard (< 23 dBm 99% of time)
Path Loss at 1 meter	37	dB	Free space
GPS Device Gain towards LTE Device	-5	dBi	Combination of TX antenna gain and Rx antenna gain of the cellular devices (assumed by TWG Cellular Subgroup after reviewing empirical data submitted by cellular operators)
Received power after GPS antenna	-19	dBm	Calculated (Device TX Power – Path loss + GPS Device Gain)

3.4.2 Downlink LTE Power Calculation

For the downlink power level from the Ligado network's base stations, analysis of the field test data from the 2011 FCC TWG Las Vegas trials was used as a basis for determining the power to a GPS receiver on the ground. The TWG data shows the 99% CDF (cumulative distribution function) value for Dense Urban environment to be -35.3 dBm; -20.4 dBm for Urban and -22.5 dBm for Suburban. Specifically, for the case of Rural morphology, the distribution of measurement points in the TWG tests was not uniform over the coverage area of the base station, but clustered closer to the base station tower, improperly biasing the CDF to higher signal strengths. Therefore, in the case of the Rural scenario, a Monte Carlo model was used to generate a uniform set of measurement locations over RF coverage area of the base site using an underlying free space propagation model. The resultant Rural CDF calculations arrive at a value of -24

[12] Appendix to *Final Report, 2011*, available at http://apps.fcc.gov/ecfs/document/view?id=7021690471

dBm for 99% CDF. To set the expected downlink signal value, the largest value of -20 dBm (Urban) was selected.

3.5 Assessment of Impact of LTE

For GLN, non-certified aviation and high precision devices, we considered the LTE test condition to have "no impact" on GPS performance if there was no increase observed between the average errors in the 2-D or 3-D position errors reported by the device under typical "baseline" conditions and the average errors in the 2-D or 3-D position errors reported by the device under the LTE condition being tested.[13]

For cellular devices, we considered the LTE test condition to have "no impact" on the device if the device passed the 3GPP tests (as defined by the 3GPP specification) under both the baseline condition and the LTE test condition.

4 Summary of Results

We conclude that Ligado's proposed LTE deployment is clearly compatible with existing GPS operations as implemented by leading device manufacturers.

- GLN:
  - All 12 GLN devices tested — representing five manufacturers — maintained their baseline GPS position accuracy in the presence of Ligado's proposed operations under Open Sky conditions.
  - One GLN device — out of 12 tested — showed an impact from LTE operations in one of the four proposed LTE bands (the 1627.5 - 1637.5 MHz band). This impact to the GPS device from proposed operations in that band was observed only when the device was in motion, was receiving impaired GPS signals, and when LTE signal at the GPS device was above -30 dBm, an event that will occur with extremely low probability.
- Cellular:
  - All three cellular devices tested (one tablet and two cell phones) maintained their baseline GPS position accuracy in the presence of Ligado's proposed operations.[14] In addition, comparing the performance of the Galaxy S6 with its predecessor, the S5, shows that cellular GPS devices' performance, which already is highly robust, continues to improve. This is consistent with the fact that cellular devices include multiple transmitters and receivers

[13] The 3-minute averaged position errors in the baseline condition measured over a period of 2 hours (also referred to as the soak test) comprise a randomly fluctuating data set. The "no impact" decision is made if, for a given LTE power level, it appears that the particular position error value could have formed a typical member of the baseline data set. As the onset of overload causes a sharp increase in position error with LTE power, it was not difficult to identify cases of overload without detailed statistical analysis.

[14] We were unable to obtain useable data from the Apple iPad.

(cellular in multiple bands, Bluetooth, Wi-Fi, etc.) collocated with the GPS receiver, which necessitates a design tolerant of other signals.

- Non-Certified Aviation: This device maintained its baseline GPS position accuracy in the presence of Ligado's proposed operations.
- High Precision:
  - We completed testing on a total of 11 devices, produced by four manufacturers.[15]
  - Two manufacturers — Trimble and NavCom — offer devices that, in stock condition, maintain their baseline GPS position accuracy in the presence of Ligado's proposed operations. Four of the 11 tested devices are in this category.
  - One of these manufacturers — Trimble — also offers devices that, although they showed an impact from Ligado's proposed operations in stock condition, showed no such impact when the device's stock antenna was replaced with a filtered antenna. Three devices are in this category.
  - Another manufacturer — Topcon — offers devices that show an impact from Ligado's proposed operations only in the 1526-1536 MHz band. Three devices are in this category. Note, however, that our analysis did not consider the effect of any additional (deferential) power limits Ligado may be subject to in connection with its request that the FCC condition Ligado's licenses on power limitation requirements for the 1526-1536 MHz band necessary to achieve compatibility with current and future MOPS (Minimum Operational Performance Standards) that are incorporated into an active Technical Standard Order from the FAA at a later time.
  - RAA understands that Ligado is engaged in ongoing discussions with the remaining manufacturer — Topcon — to better understand how any potential interference with their device could be mitigated.

Finally, our testing found no meaningful correlation between 1 dB change in C/N_0 and GPS device's KPI performance. Indeed, average C/N_0 values reported by the receiver (averaged over all GPS satellites) showed random variations in excess of 1 dB in the absence of any adjacent band signals, and such variations did not accurately predict a device's position accuracy.

[15] We were unable to obtain useable data from the Deere Starfire 3000. Nonetheless, we understand that, in any case, Deere does not object to Ligado's proposed operations, subject to the license modifications Ligado has requested from the FCC.

5 Appendix A: Description of Test Procedures

5.1 Test Plan

The final Test Plan was included in the May 11 FCC filing and is incorporated here by reference.[16]

5.2 Devices

The list of GPS receivers tested was included in the May 11 FCC filing and is reproduced below for convenience. The devices tested are grouped according to the testing method used and the data output format.

Table 2: List of Devices and the Method of Testing Employed

General Location and Navigation (GLN)	High Precision	Non-Certified Aviation	Cellular
Tested via Open Sky With Motion: Devices That Output NMEA Information	**Tested via Live Sky Method**	**Tested via Open Sky with Motion**	**Tested via 3GPP Methods**
Garmin 76 Garmin Montana 650t Garmin eTrex Garmin 78sc Motorola MW810 Trimble TM3000 Furuno GP32 Wabtec	Navcom SF-3050 Trimble R9 Trimble R8s	Garmin GPSMAP 696	Samsung S5 Samsung S6
Tested via Open Sky With Motion: Devices That Do Not Output NMEA Information	**Tested via Open Sky Method**		**Tested via Open Sky***
Motorola APX 7000 Garmin nüvi 2495LMT Garmin nüvi 55 Garmin nüvi 2597LMT	Trimble AgGPS 542 Trimble SPS855 Topcon SGR-1 Topcon System 310 Trimble Geo 7x Trimble SPS985 Topcon HiPer V NovAtel SMART6-L		Samsung Tablet **Testing with 3GPP methods requires that the device can place a cellular call. The Samsung tablet provides data connectivity but did not support a phone call, therefore 3GPP testing was not possible.*

[16] *See* May 11 Filing, *supra* note 11.

5.3 Test Procedures

Five test procedures were utilized during the test campaign. The anechoic chamber environments used for each of these procedures were described in the May 11 filing and are summarized here for convenience. The testing environment, equipment used, and calibration procedures are described in detail in Section 6, Appendix B.

5.3.1 Open Sky

The Spirent GPS simulator created signals corresponding to a moving constellation of GPS signals representative of a static GPS receiver location. The GPS signals were presented to devices along with LTE signals. This method was predominantly used for High Precision Devices. Figure 4 describes the Open Sky test procedure.

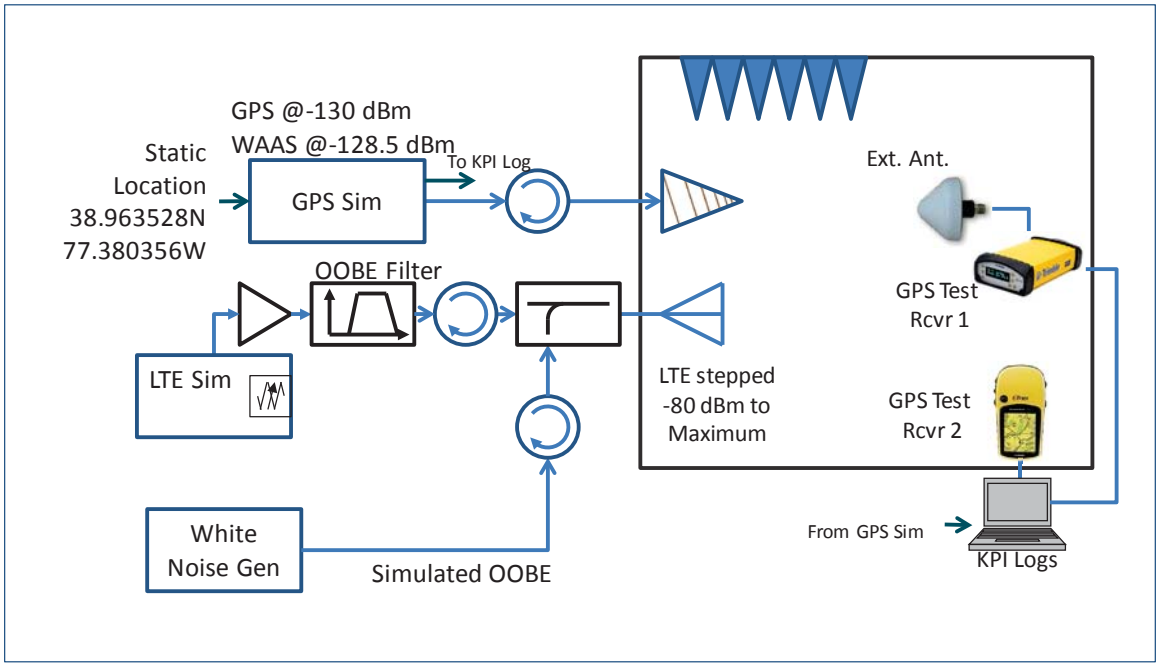


Figure 4. Environment for Open Sky Test Procedure

5.3.2 Open Sky with Motion

The Spirent GPS simulator created signals corresponding to a moving constellation of GPS signals and simulating a moving GPS receiver location. The GPS signals were presented to devices along with LTE signals. This method was used for General Location and Navigation devices and the Samsung Tablet. Figure 5 describes the Open Sky with Motion test procedure.

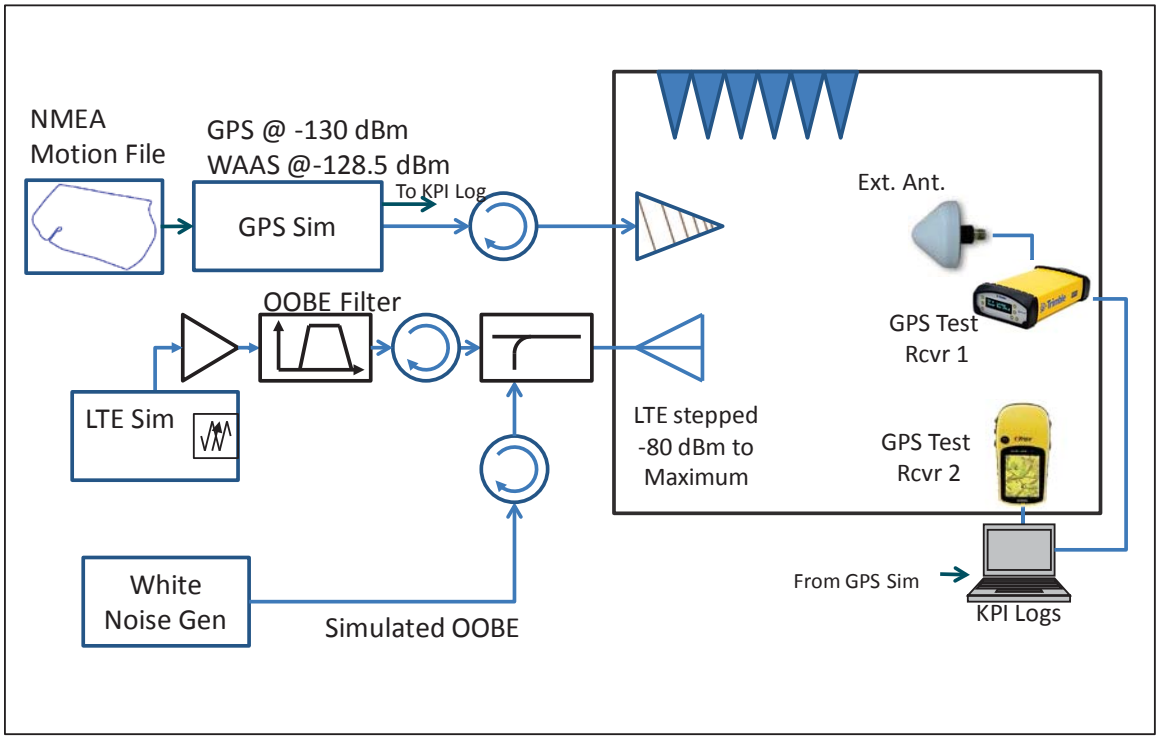


Figure 5. Environment for Open Sky with Motion Test Procedure

5.3.3 Impaired GPS Signals with Motion

The Spirent GPS simulator created a moving constellation of GPS signals at reduced GPS power levels simulating a moving vehicle. The GPS signals were presented to the devices along with LTE signals. The GPS signal levels for all the satellites were 12 dB lower than the GPS signal levels in the Open Sky Procedure, a 93% reduction in signal power compared to the Open Sky Procedure. This method was used for General Location and Navigation devices. Figure 6 describes the Impaired GPS Signals with Motion test procedure.

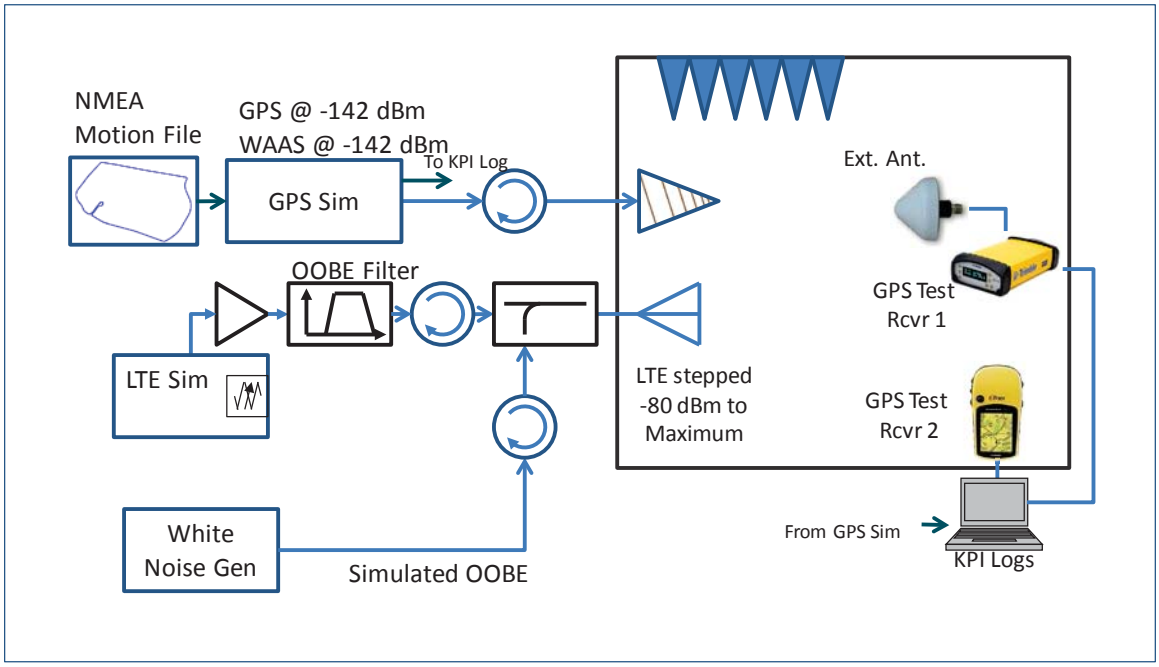


Figure 6. Environment for Impaired GPS Signals with Motion Test Condition

5.3.4 Live Sky.

Several High Precision GPS receivers required augmentation signals that could only be provided by signals received outdoors. For the Live Sky test condition, a rooftop antenna was used to receive GPS signals and MSS augmentation signals which were calibrated and presented to devices in the anechoic chamber along with the calibrated LTE signals. Figure 7 describes Live Sky test procedure.

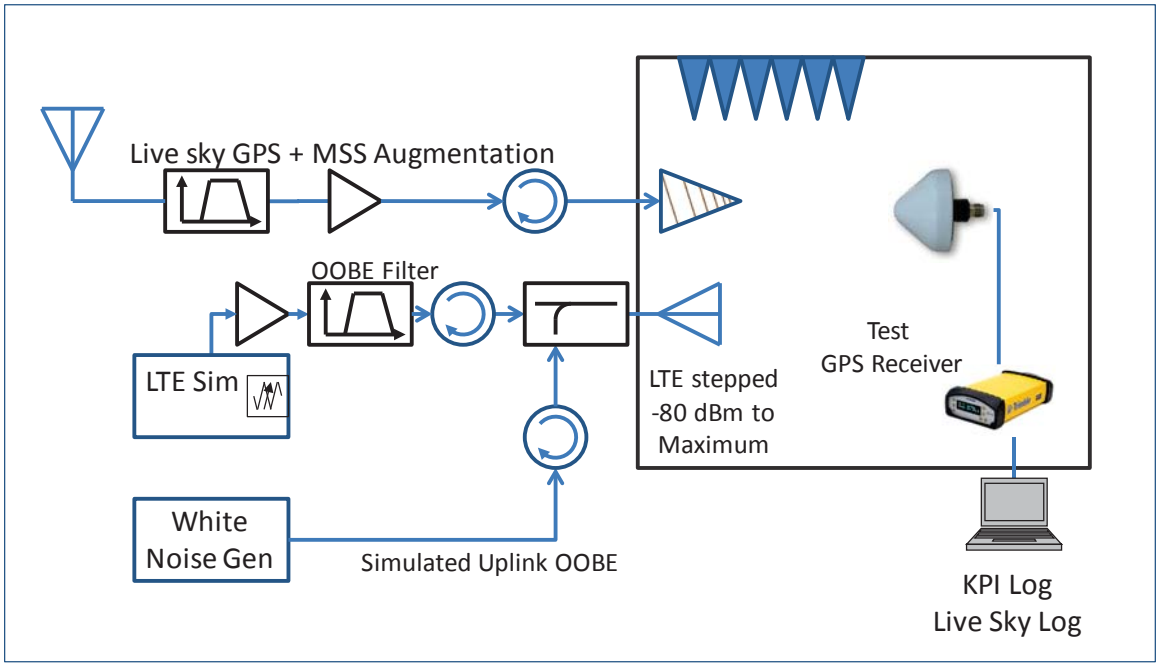


Figure 7. Environment for Live Sky Test Condition

5.3.5 3GPP A-GPS Tests.

The A-GPS (assisted-GPS) conformance tests were developed and approved by the 3GPP, the internationally recognized standards group for among other things testing cellular devices.[17] These methods were adapted to test the Samsung S5 and S6. A significant difference in the 3GPP tests and the RAA testing is that the 3GPP tests are meant to be performed using a conducted connection to a devices antenna connector the tests, while the RAA A-GPS tests were performed in an RF chamber under radiated conditions.

The controller used for 3GPP A-GPS tests was a Spirent 8100 LTE Test System. The specific test procedures were implemented in software and configuration modules provided by the controller manufacturer. The procedures involved performing many trials in order to establish statistics regarding the success rate for the different tests. Location requests and responses were sent and received by the controller over a

[17] 3GPP TS 37.571-1.

separately established 900 MHz GSM link. Test GSM SIM cards were used in the devices under test to allow them to work with the controller in GSM mode. The GPS signals were simulated using a Spirent 8000 under the control of the Spirent 8100.

Each of the devices underwent a calibration procedure individually, since the tests were performed under radiated conditions.

Two LTE levels were applied, -10 dBm and -20 dBm, to see if an impact due to LTE could be observed. Baseline performance was established by testing with no LTE signals present, i.e., GPS only.

The Spirent 8100 LTE Test System produced Excel files with details for each trial including assessment of whether each individual trial was a success or a failure.

5.3.5.1 3GPP Sensitivity Test

The goal of the 3GPP sensitivity test is to determine the GPS signal level in dBm where the device is still capable of reporting device location to within 100 meter, with a response time under 20 seconds, with a 95% success rate. The 3GPP sensitivity test is described in section 7.1 in 3GPP TS 37.571-1. One GPS satellite signal is set to -142 dBm and the remaining 7 satellite powers are adjusted down, and up in signal strength, if necessary, in 0.5 dB steps using a search procedure until a 95% success rate is achieved.

This test procedure differs from that reported in the TWG cellular device report. In that report the first satellite was also set to -142 dBm while the remaining 7 satellite powers were set to -147 dBm. During the test LTE power level was increased from a low level until impact was observed and the impact causing power level was recorded for each device.

5.3.5.2 3GPP Accuracy Test

The goal of the accuracy test is to verify that the device location reports meet the 3GPP accuracy requirements in TS 37.571-1 section 7.2. The goal is to demonstrate better than 30 meter location accuracy in under 20 seconds with a 95% success rate. All 8 GPS satellites are simulated with a power level of -130 dBm.

5.3.5.3 3GPP Dynamic Range Test

The goal of the 3GPP dynamic range test is to verify that device location reports are accurate to within 100 meters within 20 seconds with a 95% success rate. During this test, 6 satellites are simulated with satellite powers ranging from -127 dBm to -142 dBm. This test is described in section 7.3 of 3GPP TS 37.571-1. The test procedure involved alternating locations and requesting a location report for each trial.

The dynamic range test also gives an indication of re-acquisition lock time. This is because the location alternated between Melbourne, Australia and Atlanta, Georgia for each trial and the device had to re-acquire lock during each and every trial.

5.4 Motion Testing

Figure 8 describes how the test environment was configured to support simulated motion for GPS devices tested with motion. A drive route consisting of recorded latitude and longitude positions was provided as an input to the Spirent GPS simulator, which then created the GPS signals as they would be received by a moving GPS receiver.

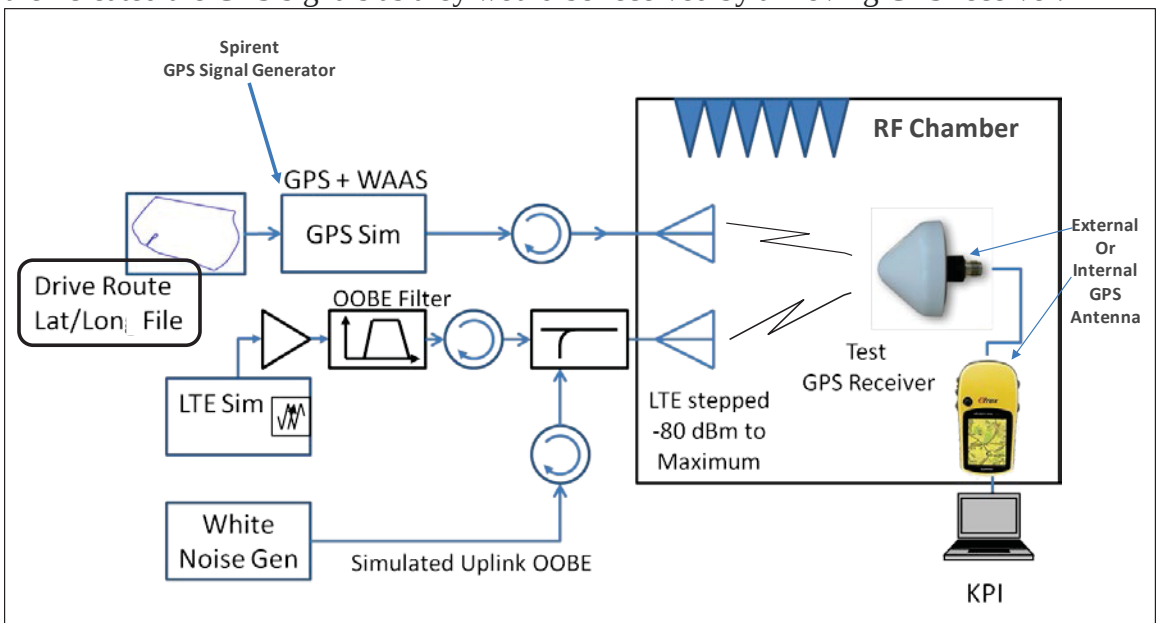


Figure 8. Environment for Motion Testing

Figure 9 describes how the drive route file was created. First, a test vehicle with a GPS receiver traversed a route as shown in the Google earth view. The latitudes and longitudes of the drive route were recorded, creating a "golden" file which was loaded into the GPS simulator. The GPS simulator then created the GPS satellite signals for the receivers under test corresponding to the signals that they would receive if they were in motion according to the golden drive route file.

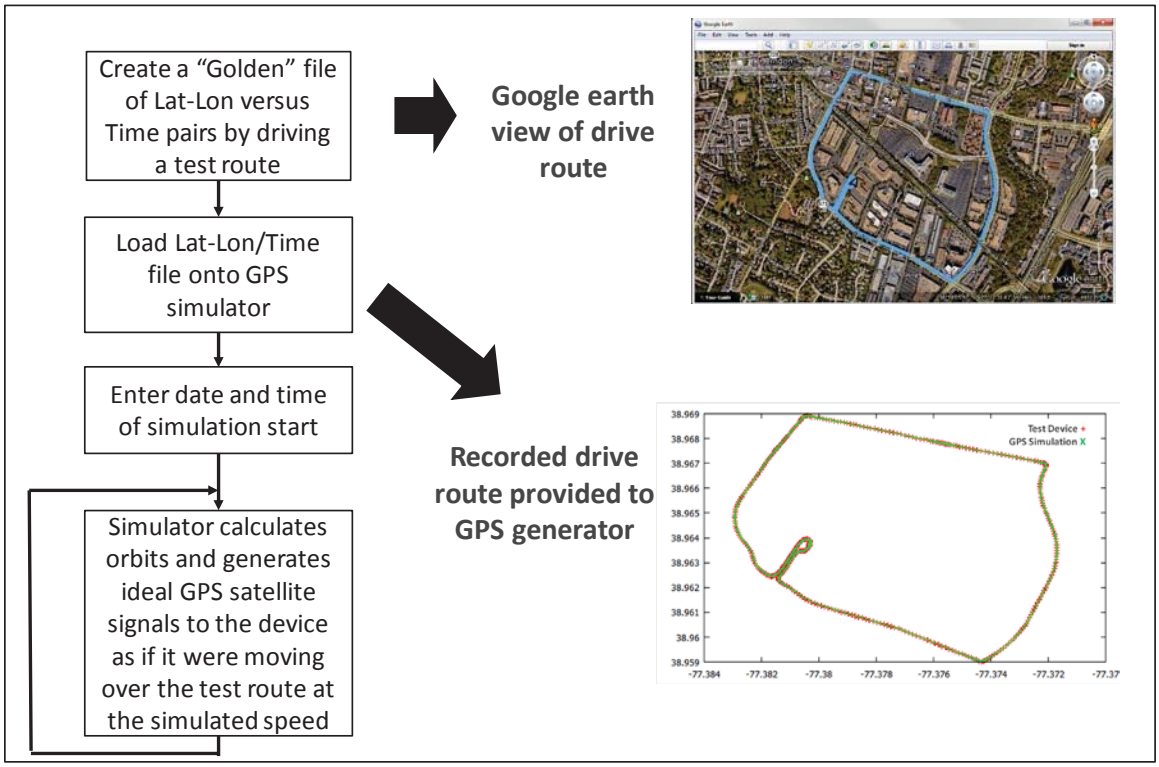


Figure 9. Generating the Drive Route for Motion Testing

6 Appendix B: Calibration and Device Interfacing

6.1 Signal Level Calibration

The four RF sources used to test GPS performance in the presence of LTE were the GPS, LTE, LTE uplink OOBE, and the GSM signals for 3GPP A-GPS tests. The levels of the GPS, LTE, and LTE OOBE signals were calibrated so that the RF power levels present at the receivers being tested was well controlled. The GSM signal's RF level was set to a level sufficient to ensure reliable communications during 3GPP A-GPS testing. The GSM signal was only present for 3GPP A-GPS testing and was transmitted on a 900 MHz channel far away from the GNSS band.

In addition, Live Sky testing used signals captured via a roof-top mounted antenna for testing high performance GPS receivers with actual satellite signals. Actual signals were essential for testing the GPS augmentation.

6.1.1 Test Environment Overview

The top view of the test chamber is shown below in Figure 10 below.

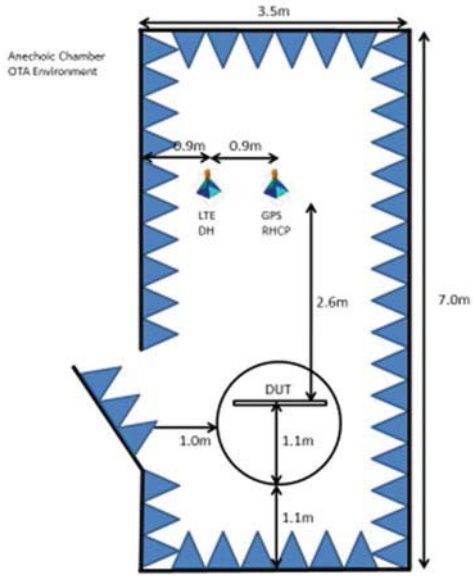


Figure 10. Top view of RF anechoic chamber

The test chamber was manufactured by ETS-Lindgren. The chamber is designed as an Antenna or Device Under Test anechoic pattern measurement chamber. During GPS performance testing the devices under test were mounted on a vertical 4ft x 4ft plywood panel attached to the turntable. The turntable was not rotated during GPS performance testing. The chamber door is located on the left side the chamber near the turntable. The photo shown below in Figure 11 of the DUT mounting area is taken through the door to the chamber. The relationship of the mounting board to the door made it convenient to mount and access the devices under test.

Figure 11. Mounting Board for GPS devices

The test equipment area was located outside the chamber at the upper right hand side of the chamber top view. A cable port in the right side wall of the chamber at the same line as the source antenna was used to connect test equipment to the source antennas and the devices under test. The USB cables were run through a port in the chamber wall and all the coaxial cables were routed through bulkhead connectors in the mounting plate in the sidewall of the chamber near the test equipment area. The cables were all run under the absorber foam on the chamber floor to minimize any interaction within the chamber.

The source antennas consist of two antennas on mounts that are spaced on a line that is 2.6 meters from the DUT mounting board. These are the GPS RHCP source antenna, and the vertically polarized dual ridge horn antenna for the combined LTE and OOBE noise signals. For the AGPS tests the GSM signal was injected using the chamber's built in Quad-ridge horn mounted in the rear wall of the chamber. The GPS antenna was centered both left to right and up-to-down in the chamber. The LTE antenna was centered vertically in relationship to the chamber and to the left of the GPS source antenna. Both antennas were mounted on dielectric support systems. The distance from the source antennas to the DUT board was chosen to ensure that the DUT's were in the far field and that the field was uniform across the test board. In addition to providing a uniform field at the device mounting board it was important to minimize the signal loss to eliminate the need for extreme power levels for the interfering LTE signals. A separation distance of 2.6 meters was a good compromise of all those concerns.

Figure 12. LTE and GPS source Antennas

Each RF cable was numbered with a unique identifying number so that every set-up could be repeated and each cable's insertion loss was measured This allowed for accurate system level pathloss calculations. All the gain stages and passive devices were also measured for path loss and/or gain. This made it easy to keep an accurate settings guide for the signal generator settings to achieve proper levels for testing.

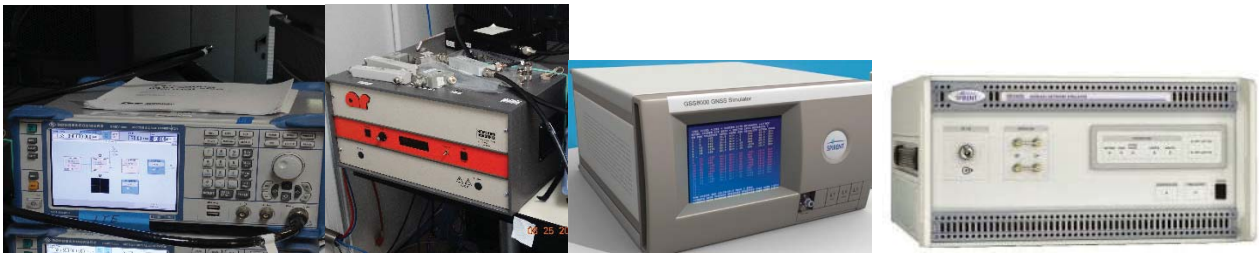


Figure 13.Test Equipment. LTE Generator, LTE Amplifier, GSS 8000, Spirent 8100 LTE Test Controller

The test bench photo above shows the test setup configuration of the test equipment area. A Spirent 8100 unit was used during 3GPP A-GPS testing. The GPS and LTE signal generators were located on the table with the OOBE wideband noise source, and spectrum monitor.

6.1.2 Calibration Methods

6.1.2.1 GPS Signals

The level of the GPS test signal was calibrated to be -130 dBm (per satellite) at the location of the Device Under Test (DUT).

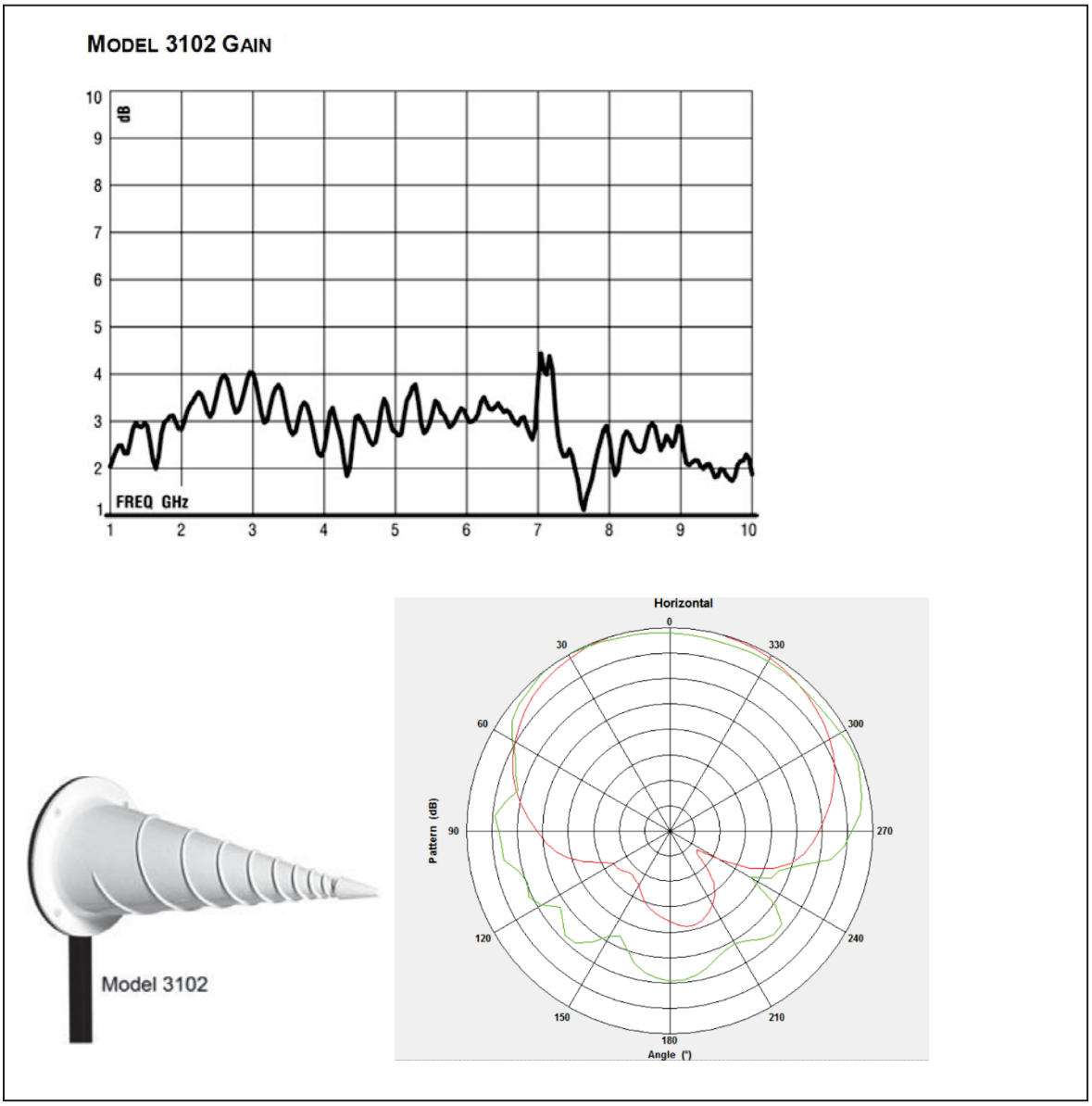


Figure 14. 3102 Conical RHCP ETS Lindgren Antenna

Calibration of the GPS signal level at the center of the device mounting board also involved both detailed calculation of the signal levels along the source path and confirmation through a monitor antenna and spectrum analyzer. Each of the cables and components (isolators) were first measured individually. Antenna gains were taken from manufacturer data sheets. The polarization loss between circularly polarized source antenna and the linearly polarized monitor antenna was included in the detailed calculation of the expected signal level. The desired GPS

signal level was -130 dBm into an ideal 0 dBic antenna at center of the plane of the mounting board.

A GPS signal generator capable of high output levels was used to during setup. Elevating the GPS signal level made measurement of the GPS signal level received by the monitor antenna possible with a spectrum analyzer. During calibration the signal was increased by a known amount so that the GPS signal was at least 15 dB above the spectrum analyzer noise floor. The expected GPS level and the measured GPS level were in agreement. Raw GPS signal power measurements took into account the simultaneous presence of multiple GPS satellite signals.

The GPS path consists of the Spirent GSS8000 GPS signal simulator, cables, and a RHCP conical antenna. The Spirent GSS8000 also generates an output on one connector that is 50 dB above the specified level. No additional external amplification was needed to generate the GPS signal since the path loss was also about 50 dB. The output level of the Spirent signal simulator was then adjusted with its internal controls to achieve the desired level at the DUT board. The GPS simulator did add small changes to the individual satellite signal levels to model the additional loss caused by changes in the satellite pseudoranges.

Table-3: GPS signal level calibration table for producing -130 dBm at the device mounting location in the chamber.

			Total	Loss to DUT	Level at DUT
Signal Source GSS 8000	-81.78		-81.78		
Cables to source	1.78	4.92	-6.53		
Conical GPS source antenna gain dBic	3.00		3.00		
Path loss 2.6m	-44.69		-44.69		
			-48.22	-48.22	-130.00

6.1.2.2 LTE signals:

Calibration of the LTE signal level at the center of the device mounting board involved both detailed calculation of the signal levels along the source path and confirmation through a monitor antenna and spectrum analyzer. Each of the cables and components (isolators, filters, amplifiers) were first measured individually. The path loss between the linearly polarized source antenna and the linearly polarized monitor antenna was also measured in order to understand the level of additional losses caused by impedance mismatches and small frequency dependent variations in the antenna gain. The Rhode & Schwarz SMBV100A generator signal level needed to provide a desired LTE signal level into a 0 dBi ideal device antenna was calculated by working backwards from the desired level to the level required at the generator.

The combined path loss of the dual ridge horn antenna and the free space propagation was found by measuring the path loss between two horn antennas (both horns were identical models, AH-SAS-571-DRH) when they were spaced 2.6 meters apart.

The expected LTE signal level and the measured LTE level were in agreement.

6.1.2.3 Antenna Patterns

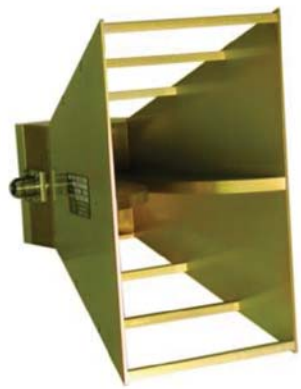
During testing the GPS devices were mounted on a common vertical plane nearly perpendicular to the direction of propagation of the LTE and GPS signals. The devices were mounted on the mounting board within a one-meter diameter circle. The minimum beamwidth needed to illuminate the devices is 22 degrees when the source antennas are 2.6 meters from the mounting board. The antennas used to radiate the LTE and GPS test signals both have beamwidths greater than 30 degrees. This ensures that the LTE and GPS signal levels were nearly equal at all test device locations.

SAS-571

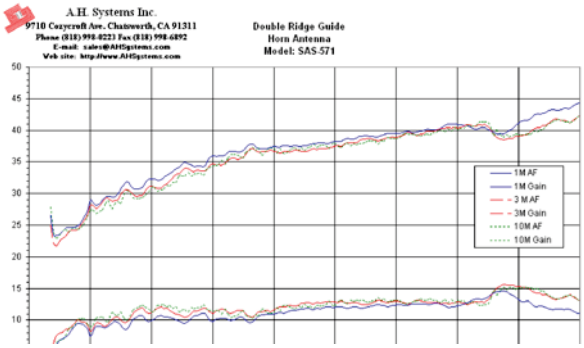
Double Ridge Guide Horn Antenna

700 MHz – 18 GHz

High gain, low VSWR, input handling capability up to 300 watts CW, and rugged design make this horn antenna excellent for both immunity and emissions testing.



Frequency Range:	700 MHz - 18 GHz
Antenna Factor:	22 to 44 dB
Gain (dBi):	1.4 to 15 dBi
Maximum Continuous Power:	300 Watts
Max Radiated Field:	200 V/m
Pattern Type:	directional
3dB Beamwidth (E-Field):	48°
3dB Beamwidth (H-Field):	30°
Impedance:	50 Ω
VSWR:	1.6:1 (3.5:1 max)
Connector:	N-Type, female
Mounting Base:	¼ - 20 Thread, female



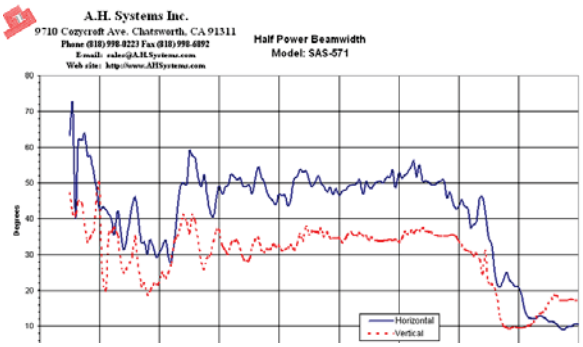


Figure 15. LTE Horn Antenna gain diagrams

The LTE source antenna is an A.H. Systems SAS-571 Double Ridge Guide Horn antenna. The 3 dB beamwidths are 48 degrees (E-Field) and 30 degrees (H-Field).

Table4 below shows the calibration table for producing -20 dBm of LTE signal at the devices under test.

Table 4: LTE Signal level calibration table, example levels for test with -20 dBm at DUT location

Path loss calc Chamber test for LTE

Desc	ID	Value	dBm Level
LTE Signal Source	SMBV100A-LTE	-33.28	
Cable s to Amplifier	L-15	-0.53	-33.81
Amplifier Gain**	AR 60S1G3	52.20	18.39
Cable to filter	L-2	-0.16	18.23
Filter Loss		-0.60	17.63
Circulator	PE 8310	-0.60	17.03
Combiner	RFDC8M4G30A	-0.30	16.73
Cable to chamber	L1	-0.34	16.39
Chamber to antenna	L3 + L6 + L8	-1.30	15.09
DRH Antenna gain*	AH SAS 571 DRH	9.60	24.69
Path loss	Theory 2.6m	-44.69	-20.00
Total level at DUT		-20.00	

6.1.2.4 OOBE for LTE devices:

Handheld LTE devices may operate close to GPS receivers. The spurious emissions from handheld devices was included during LTE uplink testing. The emissions mask for LTE handheld device OOBE (Out of Band Emissions) in the GNSS band is -105 dBW/ MHz at a 1 meter spacing. This level of OOBE was calculated to be equal to -176.5 dBm/Hz at the device under test. The combined antenna losses were assumed to be 5 dB.

A Rhode & Schwarz SMU200A signal generator was used to generate a 50 MHz wide white noise signal. During uplink testing this signal was combined with the LTE uplink signal using a directional coupler. A direction coupler was selected to ensure that LTE energy did not enter the noise generator.

The expected level of OOBE power at an ideal 0 dBi antenna (in the DUT) was calculated using the same method that was used for the LTE signal. The gains and losses of all the components in the signal path were summed to find the level required at the generator to produce -176.5 dBm/Hz at the device plane.

During LTE testing where the LTE levels were stepped from -80 dBm to -10 dBm, the OOBE power level was fixed.

The noise power density was also measured using the monitor antenna. The expected and measured levels were in agreement.

Table 5: OOBE signal level calibration table

LTE Noise Path			
Desc	**ID**	**Value**	**dBm Level**
LTE Noise Source (50 MHz BW)	SMU2000A	-29.38	-29.38
Cables to Circulator	L-15	-0.53	-29.91
Circulator	PE8310	-0.60	-30.51
30 +/- 1 dB Directional Coupler	RFDC8M4G30A	-29.30	-59.81
Cable to chamber	L1	-0.34	-60.15
Chamber to antenna	L12	-4.26	-64.41
DRH Antenna gain*	AH SAS 571 DRH	9.60	-54.81
Path loss	Theory 2.6m	-44.70	-99.51
Total level at DUT, 50 MHz		-99.51	
Convert 50 MHz to 1 Hz		-76.99	
Total Level at DUT dBm/Hz		-176.50	

6.1.2.5 3GPP A-GPS Testing Signals

For GSM 900, the ARFCN used was 62. Thus the uplink frequency (phone to base station) was 902.4 MHz and the downlink frequency (base station to phone) was 947.4 MHz. 3GPP A-GPS testing was performed on the Samsung S5 and S6 only.

6.1.2.6 Live Sky Testing

ZEPHYR GEODETIC 2 GNSS ANTENNA

Minimum tracking elevation . . . . . 0 Degrees
Practical tracking elevation . . . . . <3 Degrees
Supported positioning signal bands L1/L2/L5/G1/G2/G3/E1/E2/E5ab/E6/Compass
Supported SBAS signal bands . . . . . WAAS, EGNOS, QZSS, Gagan, MSAS, OmniStar
Phase-center accuracy . . . . . 2 mm or better
Phase-center repeatability . . . . . <1 mm
Maximum phase-center eccentricity . . . . . 2 mm
Antenna gain . . . . . 50 dB ±2 dB

A Trimble Zephyr Geodetic Antenna was mounted on the roof of the building. The Zephyr has 50+/- 2 dB of gain. A 60 Ft. LMR400 cable (3dB insertion loss) is used to connect the Zephyr to the GPS RHCP conical antenna in the chamber. The GPS signal were slightly stronger than the signals provided by the Spirent GSS 8000 generator.
Live Sky testing with augmentation was performed on Trimble R8s and Trimble R9.
Trimble R8s used a WIFI link to save KPI logs. TrimbleR9 used a USB link to save KPI logs.

6.1.2.7 Chamber Monitoring and KPI Data Collection

During the testing and especially during set-up a Rhode & Schwarz FSQ 26 spectrum analyzer was used to "see" into the chamber with a AH systems dual ridge horn antenna mounted just below the DUT board, or during set-up and calibration, it was mounted at the center of the DUT board. The path gain, including cables and an amplifier, from the horn to the spectrum analyzer was measured. The spectrum analyzer was used to confirm the GPS, LTE, and LTE OOBE signal levels. The spectrum analyzer was in operation during all tests and was used to observe the LTE signal.

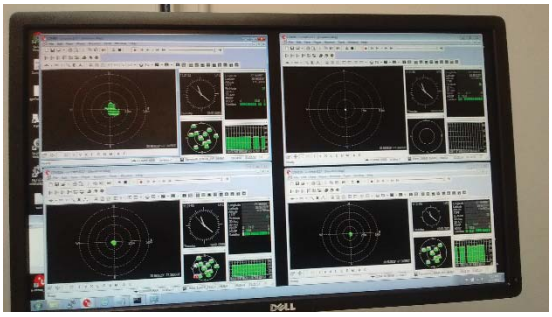


Figure 16. Photograph of U-Blox "u-center" software for 3 devices under test and the U-Blox monitor GPS receiver

During all tests a GPS monitor receiver was active in the chamber. The C/No for all satellites used for location fix and the lock status were displayed in real-time to provide visibility of the GPS levels in the chamber. These measurements were provided by a U-Blox EVK-7 evaluation receiver with a Taoglas active GPS antenna. U-Box "u-center" GNSS evaluation software for Windows was used to display NMEA data from almost all GPS data streams, plot the desired data and capture NMEA log files. The NMEA log files from the U-Blox were also captured during every test.

Most of the devices were connected to the data gathering computer via USB ports. Personal navigation devices and cellular devices stored location log files internally. The USB cables also provided power to each DUT for extended testing periods. This was accomplished by routing two sets of USB connections to the base of the mounting board. At the base of the mounting board were two multi-port powered USB hubs. These were able to supply power to all the DUT's and communications back to the test computers. One hub was a 10 port USB 3.0 powered hub connected with an active USB extension cable. The other was a four port powered hub linked with a built-in CAT5 cable USB 3.0 adapter. A matching adapter was at the data-gathering computer. Two computers were used as it was discovered that the amount of data streaming could overwhelm one computer's ability to log data over the computer's (virtual) COMM ports.

Personal navigation devices stored waypoints in an XML format in their internal memory. These devices were connected to the logging computers after each test and the waypoint files were downloaded to the logging computer.
Cellular devices stored NMEA data produced by a third party application. The files for these devices also had to be downloaded to the logging computer.

7 APPENDIX C: CHARACTERIZATION OF THE LTE ENVIRONMENT

This section is submitted as a separate document.

8 APPENDIX D: SUMMARY OF TEST PERFORMANCE UNDER THE LIGADO GPS PROPOSAL (NON-CELLULAR DEVICES)

8.1 GLN Devices with NMEA Data: Open Sky and Open Sky with Motion

Table 6: Test Performance—GLN Devices with NMEA Data, Open Sky with Motion

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
Garmin GPSMAP 76CSx	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin eTrex	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin GPSMAP 78sc	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Motorola MW810	Open Sky with Motion	External	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Trimble TM3000	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Furuno GP32	Open Sky with Motion	External	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin Montana 650t	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin Montana 650t	Open Sky (Static)	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

8.2 GLN Devices with NMEA Data: Impaired GPS Signal with Motion

Table 7: Test Performance—GLN Devices with NMEA Data, Impaired GPS Signal with Motion

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
Garmin eTrex	Impaired GPS Signal with Motion	Internal	**No Impact**	**-30 dBm***	**No Impact**	**No Impact**
Garmin GPSMAP 78sc	Impaired GPS Signal with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Motorola MW810	Impaired GPS Signal with Motion	External	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Trimble TM3000	Impaired GPS Signal with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin Montana 650t	Impaired GPS Signal with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

* The Garmin eTrex was compatible with the 1627.5-1637.5 MHz band with up to -30 dBm of LTE power when tested with an impaired GPS signal with motion.

8.3 GLN Devices with NMEA Data: Impaired GPS Signal with Various Antennae

Table 8: Test Performance—GLN Devices *without* NMEA Data, Open Sky with Motion

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
Wabtec	Impaired GPS Signal with Motion	Gilsson PCTEL	**No Impact** **No Impact**	**No Impact** **No Impact**	**No Impact** **No Impact**	**No Impact** **No Impact**

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

8.4 GLN Devices without NMEA Data: Open Sky Static and with Motion

Table 9: Test Performance—GLN Devices *without* NMEA Data, Open Sky Static and Motion

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
Motorola APX 7000	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Motorola APX 7000	Open Sky (Static)	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin nüvi 2495LMT	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin nüvi 55	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin nüvi 2597LMT	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

8.5 GLN Devices without NMEA Data: Impaired GPS Signal with Motion

Table 10: Test Performance—GLN Devices without NMEA Data, Impaired GPS Signal with Motion

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
Motorola APX 7000	Impaired GPS Signal with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin nüvi 2495LMT	Impaired GPS Signal with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Garmin nüvi 2597LMT	Impaired GPS Signal with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

8.6 High Precision Devices: Open Sky with Various Antennae

Table 11: Test Performance—High Precision Devices, Open Sky with Various Antennae

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
Trimble AgGPS 542	Open Sky	Zephyr Filtered	-34 dBm* No Impact	-38 dBm* No Impact	No Impact No Impact	No Impact No Impact
Trimble SPS855	Open Sky	GA530 Filtered	-38 dBm† No Impact	No Impact No Impact	No Impact No Impact	No Impact No Impact

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

* The Trimble AgGPS 542 with the Zephyr antenna was compatible with the 1526-1536 MHz band with up to -34 dBm of LTE power, and with the 1627.5-1637.5 MHz band with up to -38 dBm of LTE power. When retested with a filtered antenna, the Trimble AgGPS 542 was compatible with the proposed LTE emissions.

† The Trimble SPS855 with the GA530 antenna was compatible with the 1526-1536 MHz band with up to -38 dBm of LTE power. When retested with a filtered antenna, the Trimble SPS855 was compatible with the proposed LTE emissions.

8.7 High Precision Devices: Open Sky

Table 12: Test Performance—High Precision Devices, Open Sky Static

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
Topcon SGR-1	Open Sky	Internal	-24 dBm*	No Impact	No Impact	No Impact
Topcon System 310	Open Sky	Stock	-34 dBm†	No Impact	No Impact	No Impact
Trimble Geo 7X	Open Sky	Internal	No Impact	No Impact	No Impact	No Impact
Trimble SPS985	Open Sky	Internal	No Impact	No Impact	No Impact	No Impact
Topcon HiPer V	Open Sky	Internal	-32 dBm‡	No Impact	No Impact	No Impact
NovAtel SMART6-L	Open Sky	Internal	-55 dBm§	-32 dBm§	No Impact	No Impact

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

* The Topcon SGR-1 was compatible with the 1526-1536 MHz band with up to -24 dBm of LTE power.

† The Topcon System 310 was compatible with the 1526-1536 MHz band with up to -34 dBm of LTE power.

‡ The Topcon HiPer V was compatible with the 1526-1536 MHz band with up to -32 dBm of LTE power.

[§] The NovAtel SMART6-L was compatible with the 1526-1536 MHz band with up to -55 dBm of LTE power, and with the 1627.5-1637.5 MHz band with up to -32 dBm of LTE power.

8.8 High Precision Devices: Live Sky

Table 13: Test Performance—High Precision Devices, Live Sky

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
NavCom SF-3050	Live Sky	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**
Trimble R9	Live Sky	GA530 Filtered	**-55 dBm* No Impact**	**-24 dBm* No Impact**	**No Impact No Impact**	**No Impact No Impact**
Trimble R8s	Live Sky	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

[*] The Trimble R9 with the GA530 antenna was compatible with the 1526-1536 MHz band with up to -55 dBm of LTE power, and with the 1627.5-1637.5 MHz band with up to -24 dBm of LTE power. When retested with a filtered antenna, the Trimble R9 was compatible with the proposed LTE emissions.

8.9 Cellular Devices: Open Sky with Motion

Table 14: Test Performance—Cellular Devices, Open Sky with Motion

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
Samsung Tablet	Open Sky with Motion	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

8.10 Non-Certified Aviation Device: Open Sky

Table 14: Test Performance—Non-Certified Aviation, Open Sky

Device	Test	Antenna	1526-1536 MHz Downlink	1627.5-1637.5 MHz Uplink	1646.5-1656.5 MHz Uplink	1670-1680 MHz Downlink
Garmin GPSMAP 696	Open Sky	Internal	**No Impact**	**No Impact**	**No Impact**	**No Impact**

"No Impact" means that, with LTE received powers corresponding to the transmit power levels under the Ligado GPS proposal, there was no impact on the device performance compared to those KPI measurements with GPS alone.

9 APPENDIX E: 3GPP AND A-GPS RESULTS

A-GPS (Assisted GPS) is a method of sending information to a mobile device from the network to improve GPS performance. Tests for A-GPS are defined in 3GPP (Third Generation Partnership Project) Standards

- Samsung S5 and S6 were tested for A-GPS performance based on 3GPP standards
  - Industry standard tests for cellphones/smartphones
  - Based on 2011 TWG cellphone testing
  - Three tests were performed:
  - *Accuracy of Location* Provided for E911 Call
  - *Dynamic Range*: Ability to operate when large differences among GPS signal levels are present
  - *Sensitivity*: Ability to perform with low GPS signal levels
- LTE was added at -10 dBm and -20 dBm for each of the four LTE frequencies (one at a time) for each of the 3 tests
- Samsung S5 and S6 passed all tests at -10dBm LTE received level and at -20dBm LTE received level.

9.1 Summary of Test Results for Samsung Galaxy S5 and S6

All tests passed with -10 dBm and -20 dBm LTE in all four frequency bands.

Table 15: Test Performance—Samsung Galaxy S5 and S6, A-GPS

Device	Test	GPS Only	1526 - 1536 MHz Downlink	1627.5 – 1637.5 MHz Uplink	1646.5 – 1656.5 MHz Uplink	1670 – 1680 MHz Downlink
S5	Accuracy (-20 dBm)	Pass	Pass	Pass	Pass	Pass
S5	Accuracy (-10 dBm)	Pass	Pass	Pass	Pass	Pass
S5	Dynamic Range (-20 dBm)	Pass	Pass	Pass	Pass	Pass
S5	Dynamic Range (-10 dBm)	Pass	Pass	Pass	Pass	Pass
S5	Sensitivity (-20 dBm)	Pass	Pass	Pass	Pass	Pass
S5	Sensitivity (-10 dBm)	Pass	Pass	Pass	Pass	Pass
S6	Accuracy (-20 dBm)	Pass	Pass	Pass	Pass	Pass
S6	Accuracy (-10 dBm)	Pass	Pass	Pass	Pass	Pass
S6	Dynamic Range (-20 dBm)	Pass	Pass	Pass	Pass	Pass
S6	Dynamic Range (-10 dBm)	Pass	Pass	Pass	Pass	Pass
S6	Sensitivity (-20 dBm)	Pass	Pass	Pass	Pass	Pass
S6	Sensitivity (-10 dBm)	Pass	Pass	Pass	Pass	Pass

*Testing with 3GPP methods requires that the device can place a cellular call. The Samsung tablet provides data connectivity but did not support a phone call, therefore 3GPP testing was not possible.

9.2 Samsung A-GPS Sensitivity Performance

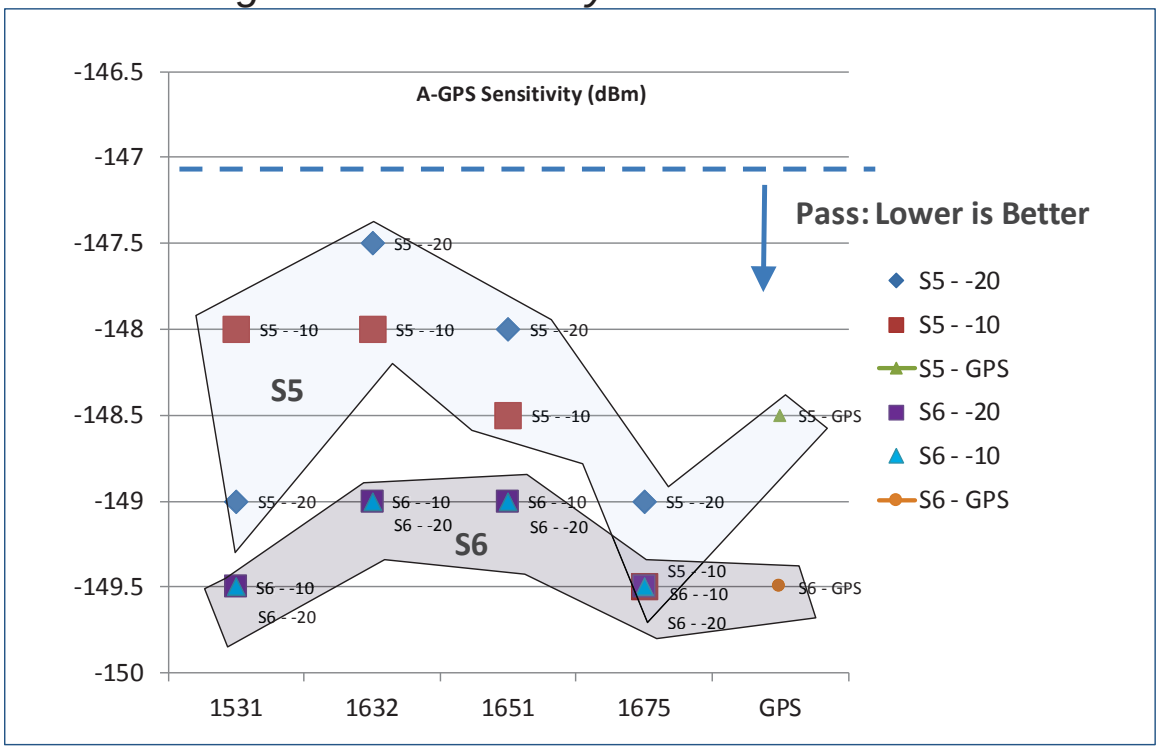


Figure 17. Samsung A-GPS Sensitivity Performance

Both Samsung S5 and S6 devices passed at -10 dBm and -20 dBm LTE received level.
Device performance is improving over time: The S6 exhibits better performance than the than S5.

10 APPENDIX F: CHOICE OF AVERAGING PERIOD IN KPI DETERMINATION

This section reports on analysis performed on raw position error data (not averaged over 3 minutes) to determine if alternate choices of KPI (other than the 3-minute mean) would show greater sensitivity to LTE power. In particular, the following were investigated: (i) movement of the entire CDF, when subjected to LTE power; (ii) the use of the 95% point of the CDF of raw data instead of the 3-minute mean value. The raw data used was recorded for the Garmin eTrex.

CDFs of the entire position error[18] data sets, taken with 2 s sampling period, are shown in Figures 11 and 12 below. Figure 11 shows the CDFs for the GPS-only testing for both the Open Sky condition (-130 dBm GPS power received by a 0 dBi reference antenna) and the impaired condition (-142 dBm GPS power received as above). The following are noteworthy:

- The CDFs of the error magnitude closely follow the theoretically expected Rayleigh distribution.[19]
- The impaired condition causes the expected right shift of the baseline CDF.

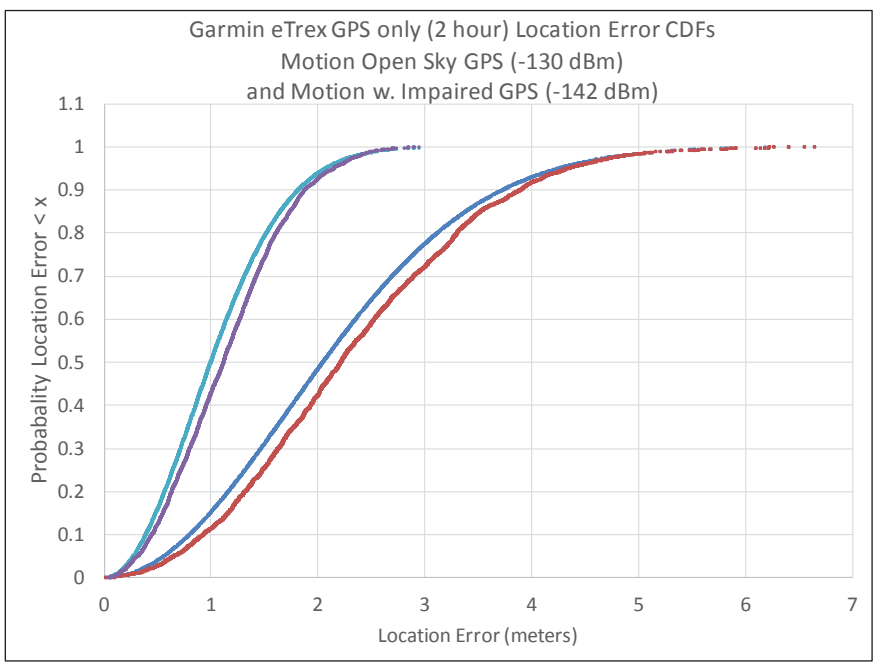


Figure 18. Baseline CDFs of Position Error (2-s sampling period) without LTE power

[18] Position Error = Magnitude of the distance of the Reported Position from the True Position. Note that time averaging is performed on this magnitude parameter, recorded at the full sampling rate of the GPS device (typically, one sample every second or 2 seconds).

[19] For 2D error, assuming that the x- and y-coordinates are zero mean Gaussian random variables, the error magnitude has Rayleigh PDF.

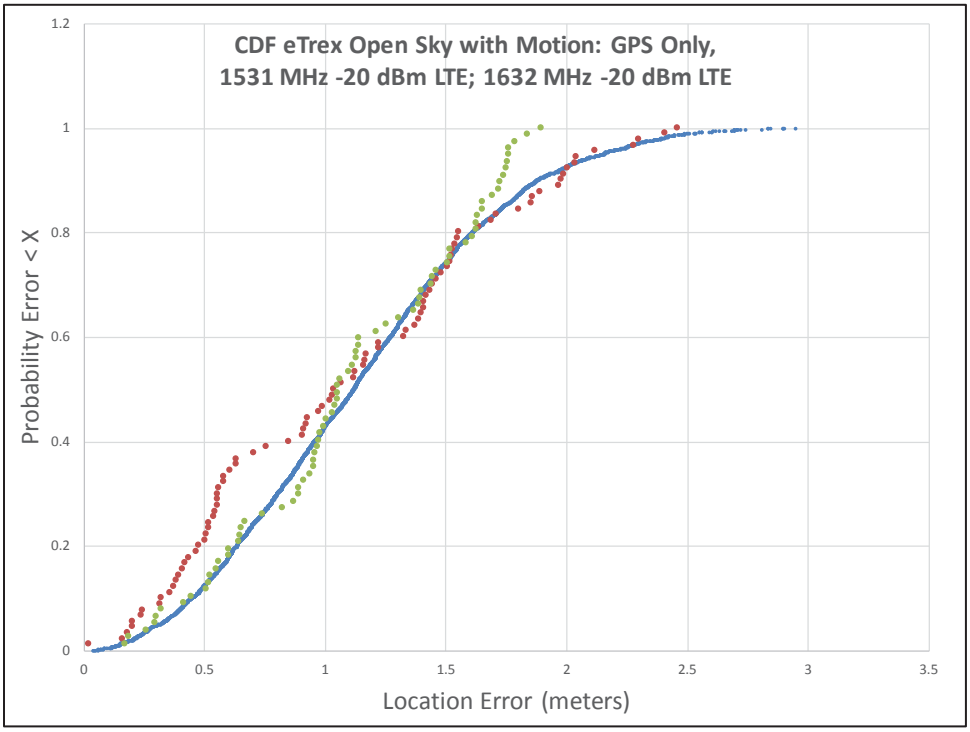


Figure 19. CDFs of Position Error (2-s sampling period) with LTE power

Figure 12 shows the CDFs for LTE tests at -20 dBm LTE for two bands. The two LTE test signal center frequencies were 1531 and 1632 MHz. No significant, systematic differences due to the addition of LTE power are observed. Impairment would be expected to cause an increase in error (a right shift of the CDF) relative to the GPS-only case.

We investigated whether our choice of *3-minute averaged position error* as the KPI was obscuring the impact of LTE on lower probability outliers on the position error CDF. This was done by comparing the 3-minute averaged position error with the 95th percentile value from the 2-s sample CDF (CDF of "raw position error data") at each LTE power. The results are shown in Figures 13 (baseline performance without LTE) and Figures 14 - 17 (performance with LTE for all four frequency bands tested).

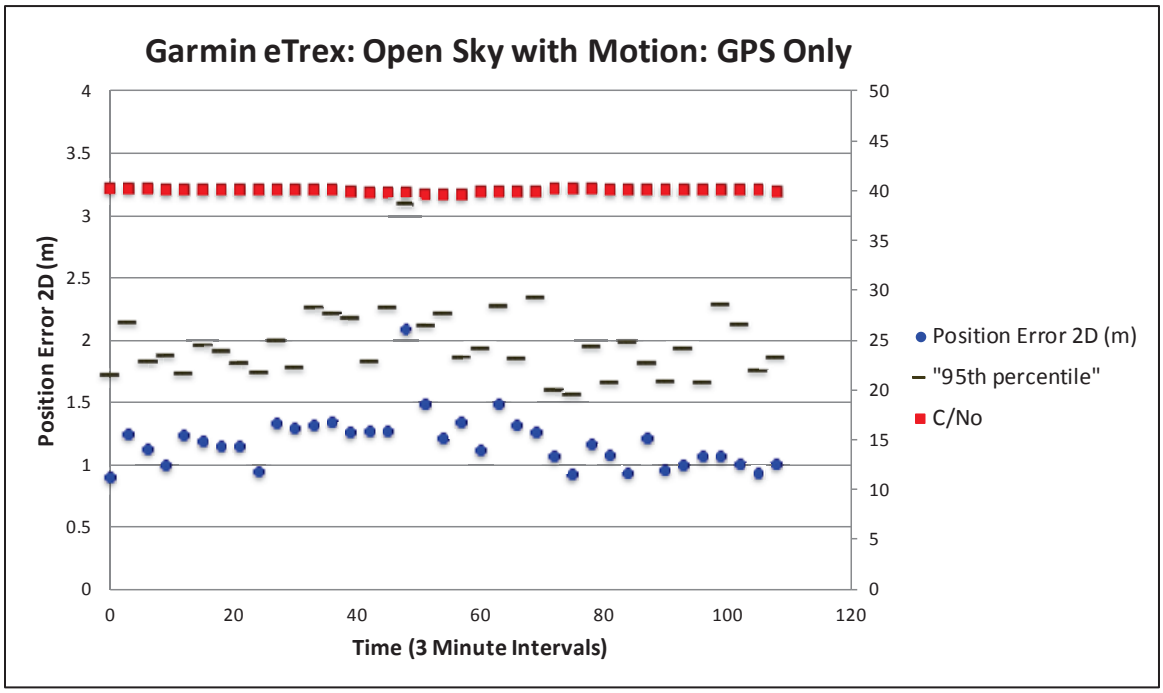


Figure 20. Baseline (GPS-only) position error for 3-min. mean and 95%-tile of raw position error CDF

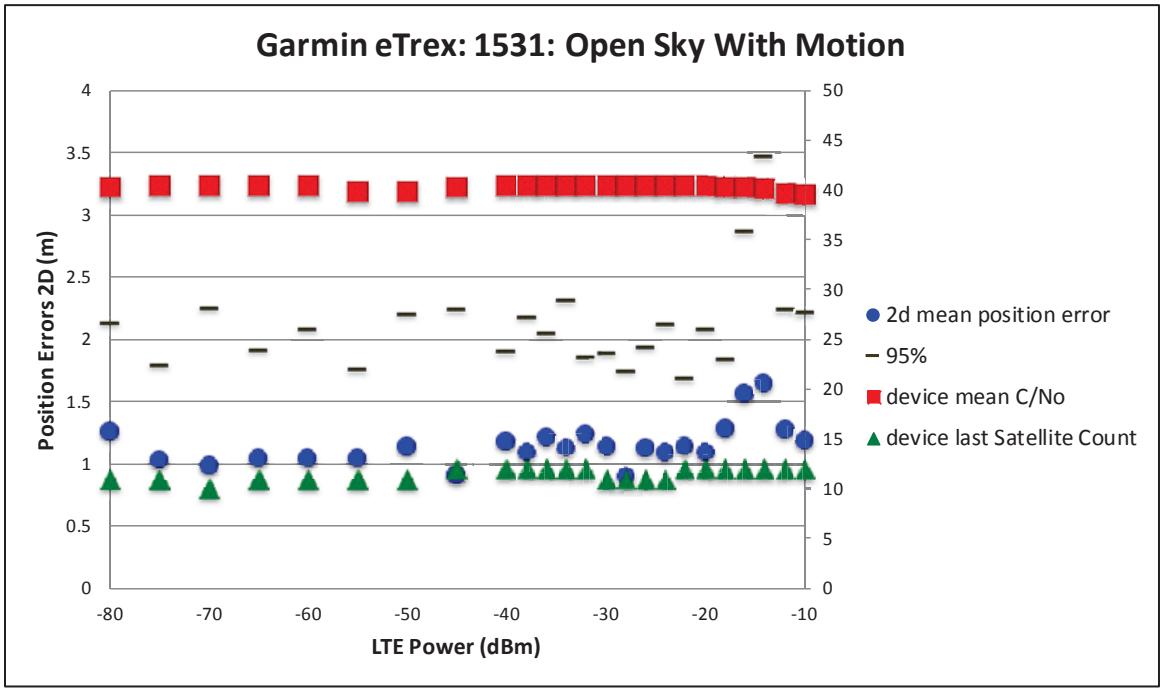


Figure 21. Position error with LTE power for 3-min. mean and 95% point of raw position error CDF for 10MHz LTE channel centered on 1531MHz

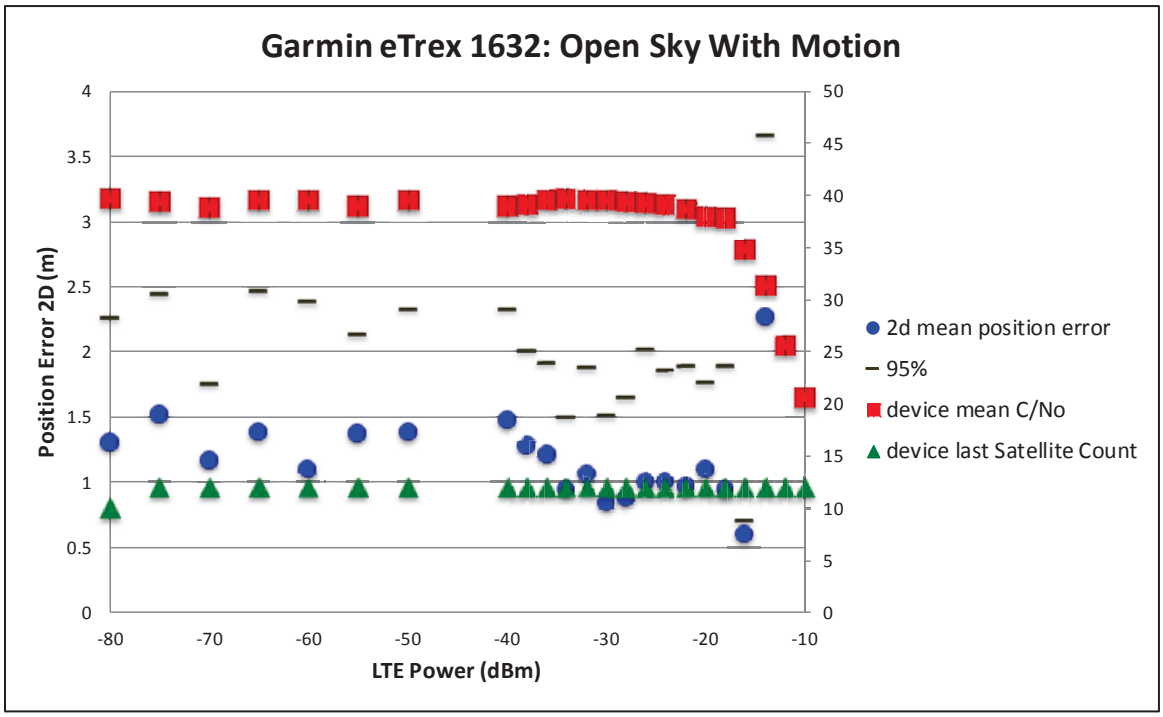


Figure 22. Position error with LTE power for 3-min. mean and 95%-tile of raw position error CDF for 10MHz LTE channel centered on 1632MHz

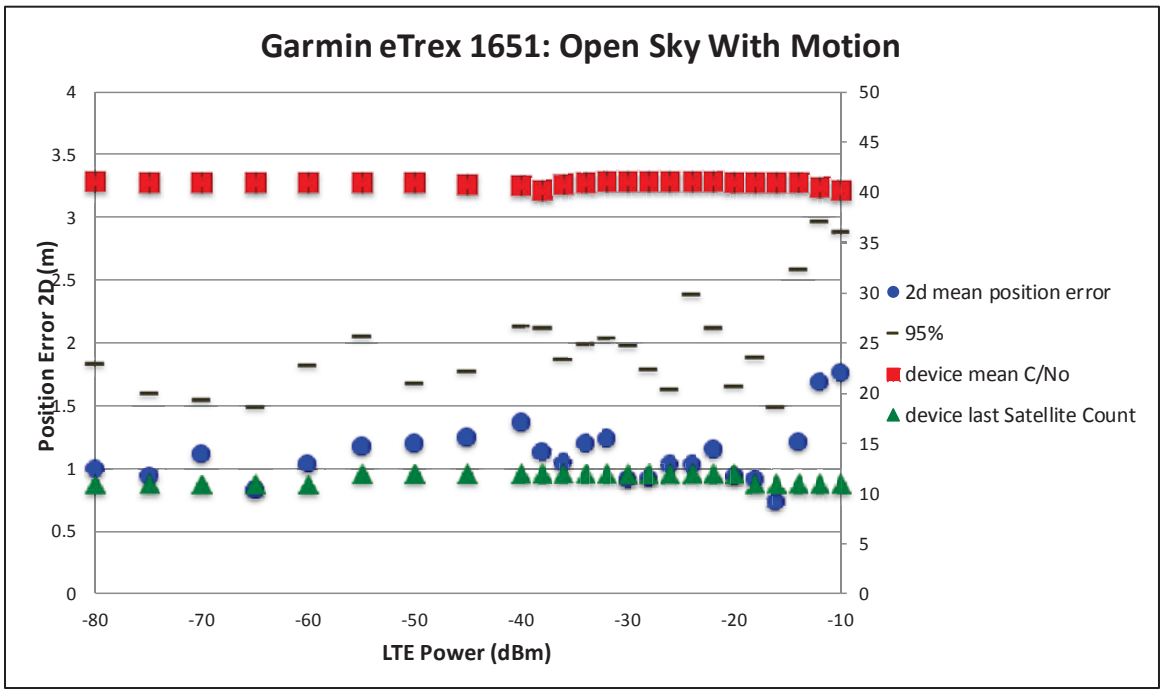


Figure 23. Position error with LTE power for 3-min. mean and 95%-tile of raw position error CDF for 10MHz LTE channel centered on 1651MHz

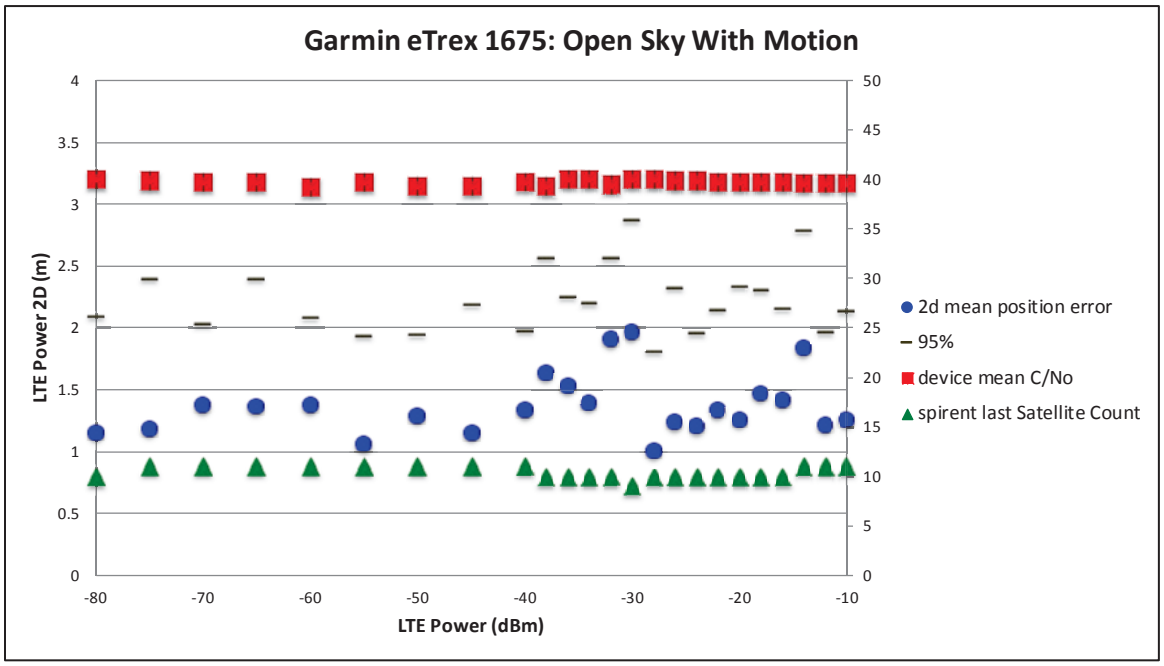


Figure 24. Position error with LTE power for 3-min. mean and 95%-tile of raw position error CDF for 10MHz LTE channel centered on 1675MHz

The above results show that the LTE power where impact on position error becomes evident (if it occurs at all within the range of applied powers) appears to be independent of whether 3-minunte mean or 95% of raw CDF is chosen as the KPI. For example, for the 1531 MHz channel (Figure 14), impairment appears to occur at approximately -18 dBm, regardless of which KPI is used.

Conclusions:

- Comparisons of full CDFs of the raw position error data showed: a received LTE power of -20 dBm caused no systematic shift of the CDF relative to the no -LTE baseline. The baseline CDF corresponded well with the theoretical Rayleigh distribution and shifted to the right, as expected, for the impaired (reduced signal strength) condition.
- A comparison of position error performances based on two choices of KPI: (i) 3-minute mean (ii) 95% point of the raw position error CDF, showed: impact due to LTE (if it occurs at all) occurs at the approximately the same received LTE power level for both KPIs.

11 APPENDIX G: ROBERSON AND ASSOCIATES, LLC PROFILE

RAA is a technology and management consulting company with extensive experience analyzing a variety of spectrum issues, including analyses involving:

- Compatibility of unlicensed Wi-Fi and licensed wireless broadband service
- Compatibility of unlicensed Wi-Fi and mobile satellite services spectrum
- Sharing of recently auctioned AWS-3 spectrum with government operations
- Coexistence of wireless broadband services with current digital television broadcast standards

Dennis Roberson is RAA's Founder, President and CEO, and also serves as the Vice Provost for Research and as a Research Professor in Computer Science at Illinois Institute of Technology. He came to these positions after having served as Motorola's Executive Vice President and Chief Technology Officer. In 2013, with Tom Wheeler's ascension to the role of FCC Chairman, Mr. Roberson was appointed to serve as Chairman of the FCC's Technological Advisory Council, a body he has served on for 18 years. He also has served as a member of the Commerce Spectrum Management Advisory Committee for the past 4 years, most recently based on an appointment by Commerce Secretary Penny Pritzker. In this role he serves as an advisor to Assistant Secretary of Commerce Larry Strickling and the NTIA leadership on various government spectrum matters.

Other members of the RAA team have similarly deep experience:

- Bill Alberth, a senior consultant for RAA, has over twenty-five years of experience in digital communications, systems engineering, digital signal processing, and new technology introductions. His prior positions include service as Vice President and Chief Technology Officer of Mobile Devices at Motorola Mobility, as an advisor to Northwestern University's Department of Electrical Engineering and Computer Science, as a member of the advisory boards for NextNav, LLC, and SiNode, and as a senior advisor for Argonne National Laboratories.
- Dr. John Grosspietsch, a Principal Engineer at RAA, has over 25 years of experience in wireless communications including transceiver and integrated circuit design for cell phones, software defined radio, spectrum compatibility, and cellular and public safety standards. Prior to joining RAA he was a Fellow of the Technical Staff at Motorola Solutions and managed the Enterprise Mobility Research group. He chaired the Software Defined Radio Forum Working Group, and has 15 U.S. patents and 25 technical publications.
- Dr. Kenneth Zdunek, Vice President and CTO for RAA, has over 35 years of experience in wireless and cellular communications, is a Fellow of the IEEE, and an Adjunct Professor at the Illinois Institute of Technology.

Prior to joining Roberson and Associates, he was Vice President of Networks Research at Motorola. He holds 17 patents in the wireless communications area, two of which received "Patent of the Year" recognition by Motorola.

Appendix C
Characterization of LTE Environment

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7 APPENDIX C: CHARACTERIZATION OF LTE ENVIRONMENT

7.1 Approach-

Figure 1 in Section 3 illustrates the overall approach to the analysis of GPS receiver performance under the LTE power levels that would be experienced by GPS receivers as a result of the Ligado's proposed LTE deployment parameters. A key element of the GPS adjacent band compatibility measurement and assessment approach is the characterization of expected LTE power levels.

LTE Downlink

Three methods were used to characterize the expected power levels for LTE signals in the frequency bands proposed by Ligado for the LTE downlink. First, an analysis of the LTE received power measurements made during the field trials that were a part of the 2011 FCC GPS Technical Working Group (TWG)[1] study was performed to determine the distributions of power levels that GPS receivers could be expected to experience within the coverage area of a single base station site for four different environment types. Second, a multi-site LTE network deployment model for the Washington DC area was created using path loss models derived from the TWG field measurements. The model was used to estimate the distribution of LTE power levels that GPS receivers would experience in the service area of a multi-site LTE downlink environment for two different deployment approaches. Third, a drive test was conducted in the Washington DC metropolitan area where LTE received signal strengths for seven commercial deployments were recorded. The received signal strength measurements were used to assess the distributions of LTE power levels that GPS receivers could experience in actual, practical LTE deployments, and to compare with the results of the TWG measurement analysis and the multi-site Washington DC deployment models. These three methods are described in the sections that follow.

LTE Uplink

Calculations consistent with the FCC TWG report Section 3.2.10.2[2] were used to establish the LTE uplink power expected to be experienced by a GPS receiver at a distance of 1 meter from an LTE handheld device. The distribution of power levels from an LTE handheld device were taken from the CSMAC WG-1 report and described in Section 7.4.

[1] Section 3.2.9.8, p. 99, Final Report, accessed at http://apps.fcc.gov/ecfs/proceeding/view?name=11-109
[2] Appendix to *Final Report, 2011*, accessed at http://apps.fcc.gov/ecfs/document/view?id=7021690471

7.2 Ligado Coexistence Plan Emission Limits

The figure below indicates the frequencies and corresponding emission power limits that Ligado has proposed for terrestrial deployment of LTE services.[3] Ligado has also established a commercial agreement with Garmin to significantly reduce uplink transmitted power in the region 1627.5-1632.5 MHz for a period of five years.

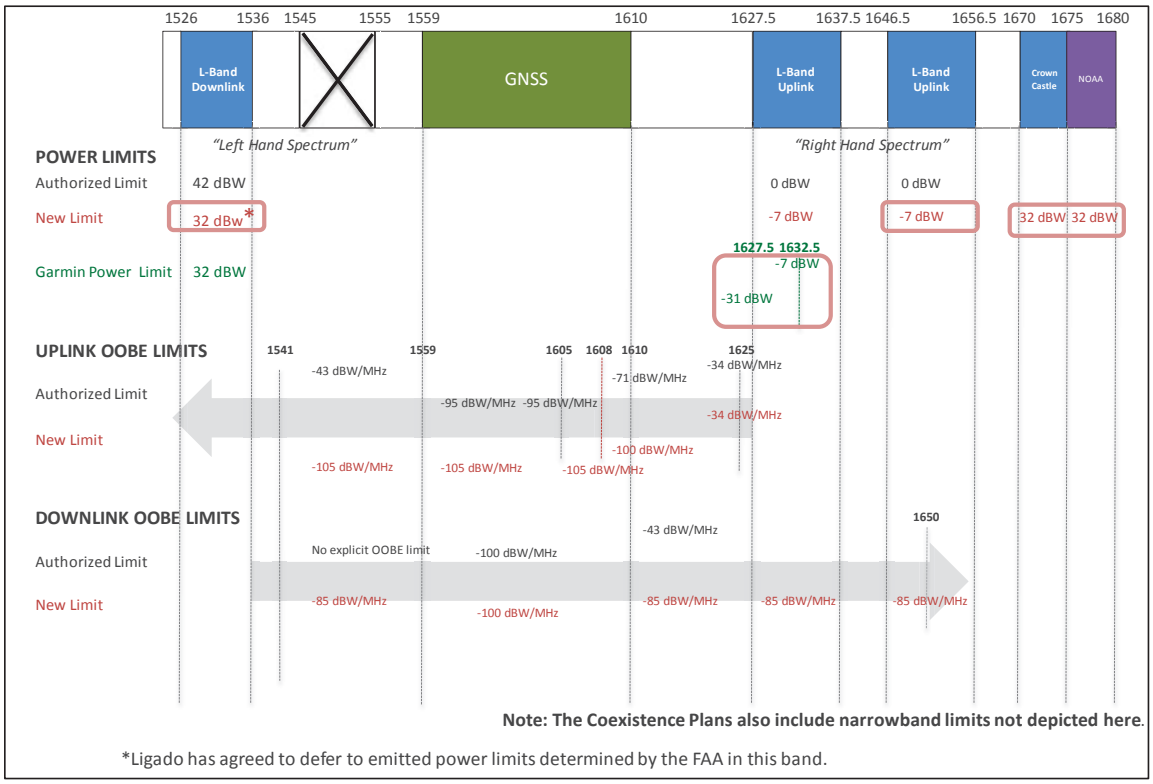

Figure 1. Ligado Coexistence Plan Emission Limits

7.3 Downlink Characterization

7.3.1 Analysis of TWG LTE Measurements

7.3.1.1 TWG Measurements

As part of the 2011 Final Report by the GPS Technical Working Group (TWG)[4], measurements of LTE received signal powers were made by Trimble Inc. for four towers deployed by LightSquared as part of the Las Vegas "Live Sky" Field Trials[5]. The four

[3] *Comment Sought on Ligado's Modification Applications*, IB Docket Nos. 11-109 & 12-340, DA 16-442 (April 22, 2016)
[4] The report is available through the FCC's Electronic Comment Filing System (ECFS) in IB Docket No. 11-
109: http://apps.fcc.gov/ecfs/proceeding/view?name=11-109
[5] Ibid, Section 3.2.9.8, p. 99

towers and their locations, designated 217, 160, 68, and 53, were selected to correspond to propagation conditions in Dense Urban, Urban, Suburban, and Rural conditions, respectively. The transmitted power levels for these tests were consistent with the power levels in the current Ligado Coexistence Plan shown in Figure 1 above.

The scatter plots shown in the four figures below, reproduced from the TWG Report, show the individual received signal level measurements as a function of range for each tower, to a distance of 2,000 meters, a typical service distance of an LTE cell tower. The colored lines on the plots show predicted median signal levels based on a Free Space propagation model, with and without correction for the transmit antenna patterns. Two observations can readily be made: 1) The median signal strength predicted by the free-space propagation model utilized in the figures is an extremely poor predictor of the actual median signal level observed; 2) There are significant (orders of magnitude) variations in the received signal levels observed at any given radius from the cell tower, and this is observed even for distances 100 meters and less from the base station site.

For these reasons, it is not possible or meaningful to use GPS device adjacent band measurement results to identify a fixed-radius "GPS interference zone" around a cell site, where the interference radius would be defined as the distance from the cell tower outside which a GPS receiver's functionality will not be impacted. It is possible, however, to *statistically* quantify the likelihood that a GPS receiver's functionality will be impaired in the service area of a base station or multisite deployment, if the areal distribution of received LTE signal strengths is known. This is the approach taken in the RAA GPS and Adjacent Band Compatibility Study. In the remainder of this section, we therefore assess the distribution of received signal strengths that a GPS receiver would experience in the LTE deployment environments measured as part of the 2011 TWG tests.

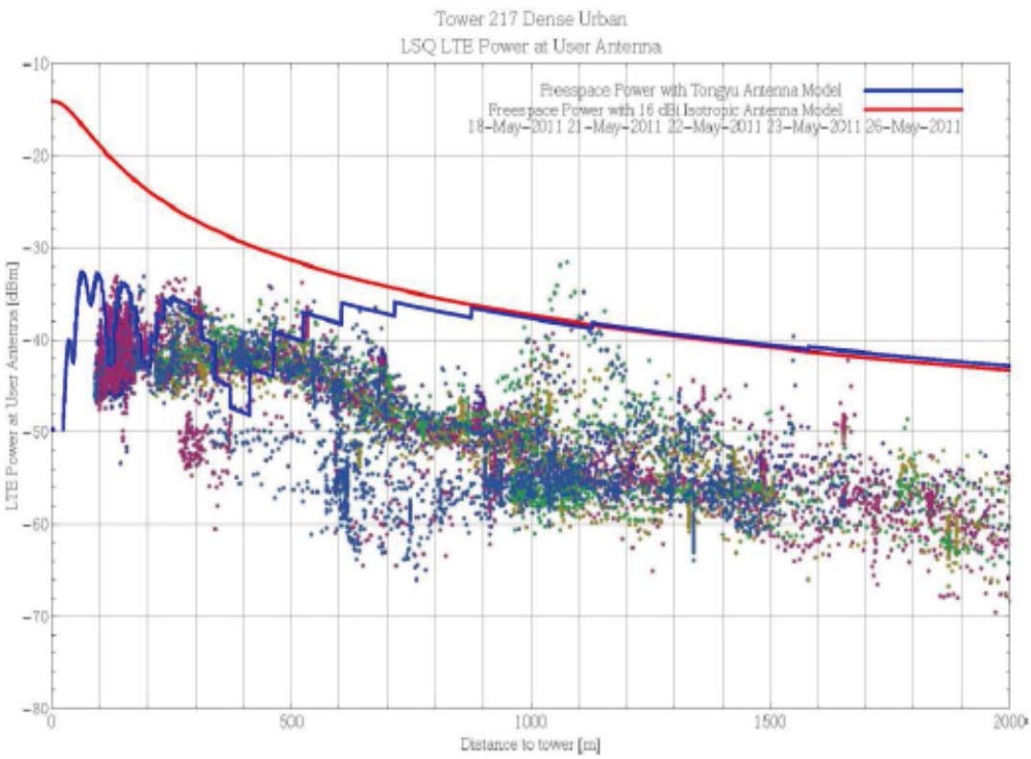

Figure 2. TWG Las Vegas Measured Signal Levels, Tower 217, Dense Urban

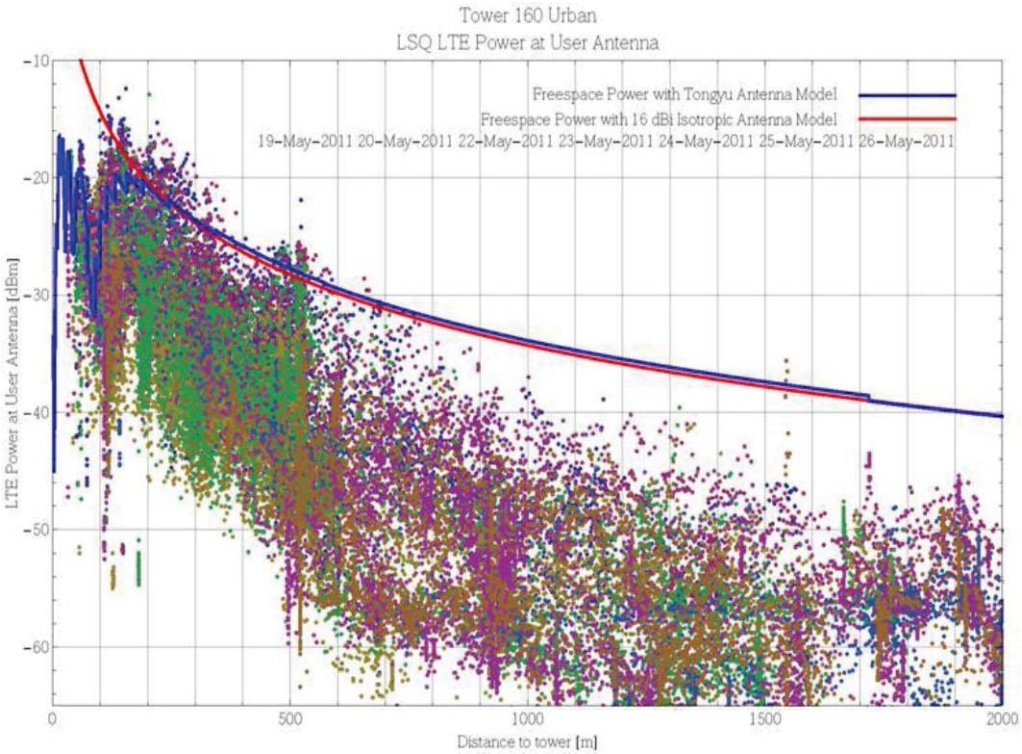

Figure 3. TWG Las Vegas Measured Signal Levels, Tower 160, Urban

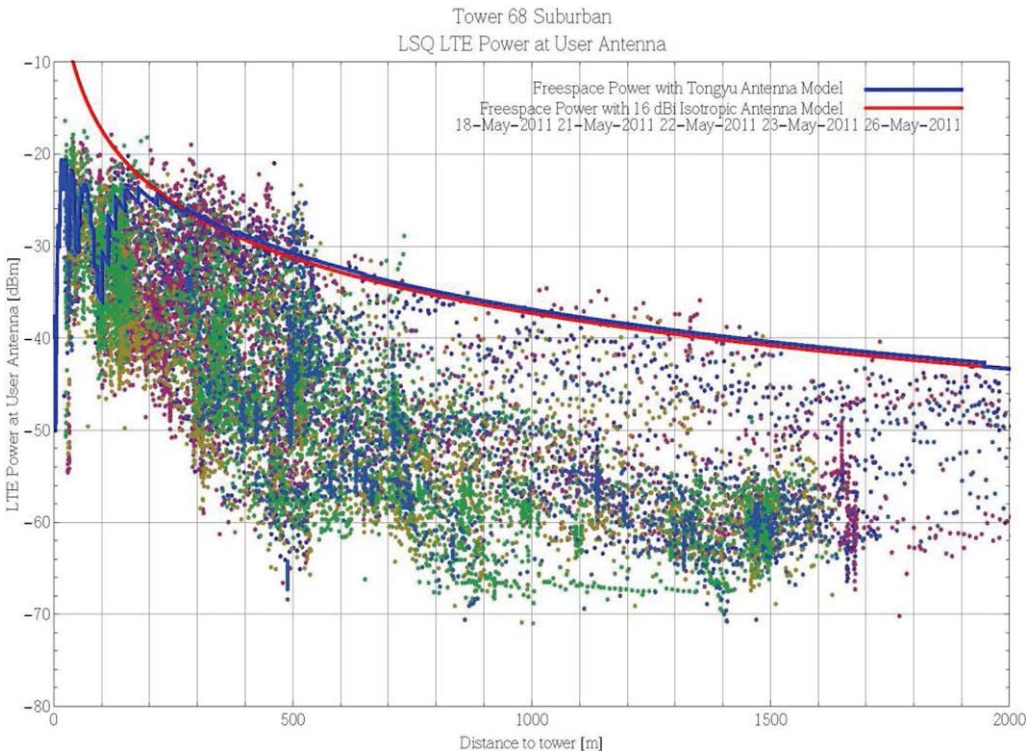

Figure 4. TWG Las Vegas Measured Signal Levels, Tower 68, Suburban

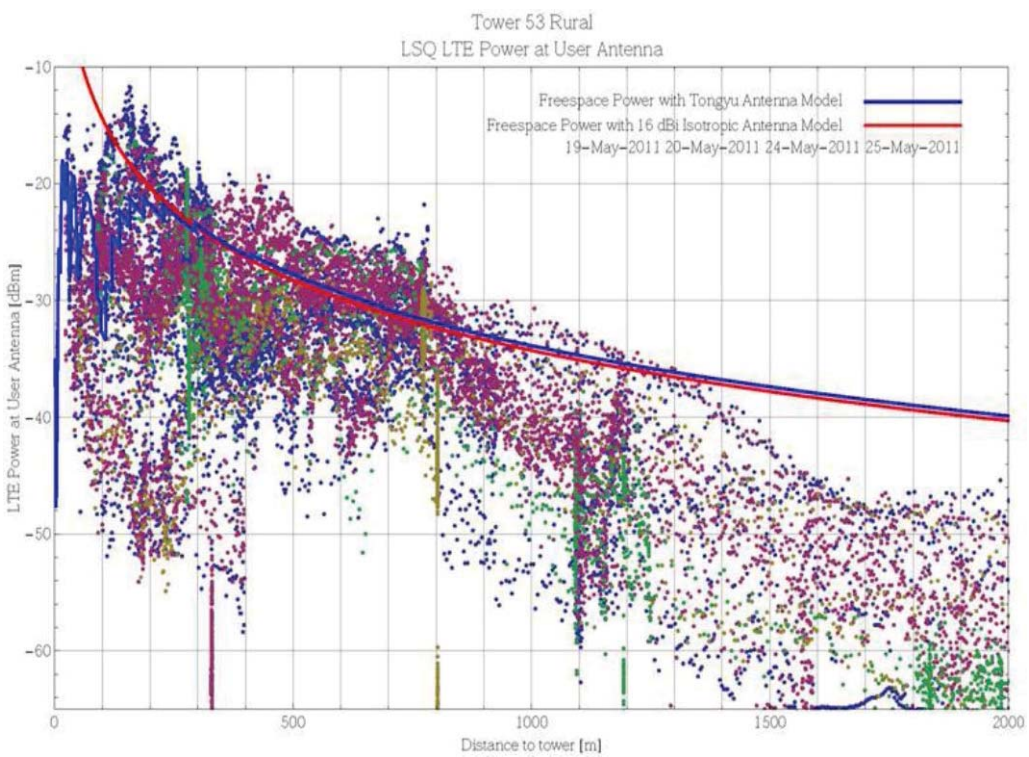

Figure 5. TWG Las Vegas Measured Signal Levels, Tower 53, Rural

7.3.1.2 Analysis of TWG Measurements

The figure below shows the cumulative distribution of the LTE power levels based on the analysis of the TWG measurement data for the four deployment scenarios described above. It can be seen that the Dense Urban case had generally the lowest signal levels (due to the large amount of shadowing that occurs in such environments) and that the Rural case had the highest (due to the lack of shadowing obstructions).

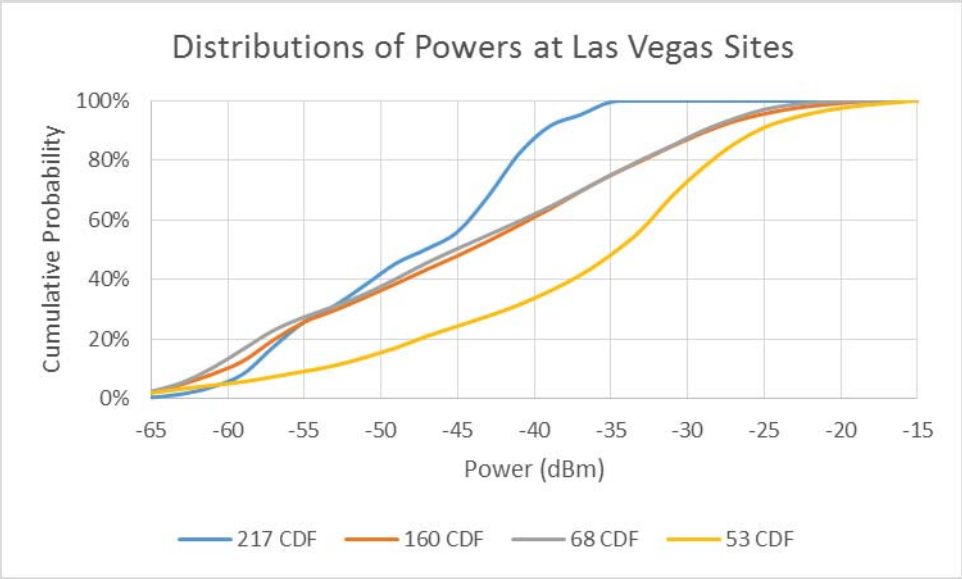

Figure 6. Distribution of TWG Las Vegas Measured Signal Levels

The table below summarizes the key statistics for the four Las Vegas measurement cases. Using 99% as the criteria for no impact to GPS over an LTE service area, the analysis reveals that a GPS receiver will experience LTE signals levels less than -20 dBm more than 99% of time in all environments, except for the Rural case, where the value is nearly 99%, at 98.54%.[6] The value -20 dBm for LTE downlink was therefore chosen as the "threshold of LTE impact" for the GPS device measurement graphs.

Examination of Table 1 shows that the choice of -20 dBm is conservative (protective of GPS receivers) considering all the environments, since all environments exhibited essentially 99% or greater probabilities that the -20 dBm signal level will not be exceeded.

Table 1: LTE Signal Strength Distributions - 2011 TWG Field Tests

[6] It should be noted that the Rural case had an antenna height of only 18.3 meters (60 feet), and that in more typical circumstances a significantly higher antenna would be used (so as to maximize coverage across a large rural area). Therefore, we would expect the associated probability level for -20 dBm to exceed 99% for a typical rural scenario.

	Single Site (TWG Field Test)
TWG Environment	Probability LTE signal level does not exceed -20 dBm
Dense Urban	100.00%
Urban	99.46%
Suburban	99.80%
Rural	98.54%

Range Distribution in TWG Measurements for the Rural Case

Analysis of the distribution of ranges (distances) from the base station for the 2011 TWG measurement locations reveals that the measurement dataset exhibited a bias towards measurements reported closer to the base station, compared to a uniform distribution of locations within the 2 km radius service area of the cell tower. The distribution of ranges for the measurements is plotted in Figure 7 below based on the range distributions published in Appendix H.1.2 of the TWG Report. By way of contrast, the expected range distribution corresponding to a uniform area distribution of measurement locations within the 2 km service area of the tower location is also shown. This demonstrates that the measurement data for the Las Vegas scenarios were biased to closer-in distances, and signal strength distributions from the original dataset would not be representative of the distributions that would be experienced by users at random locations within the area of the cell tower. Instead, a randomly located user would generally experience lower expected LTE signal levels.

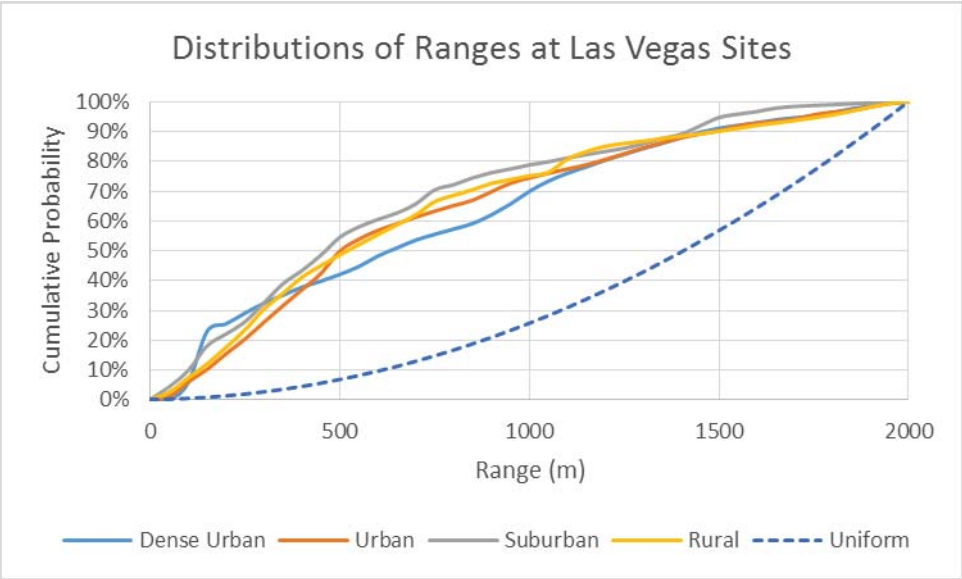

Figure 7. Distribution of Ranges of TWG Las Vegas Power Level Measurements

7.3.2 Multi-Site LTE Network Model

As described in Section 7.3.1 above, due to the order of magnitude variations in received signal strength at any given radius from a cell site, it is not possible to identify a fixed GPS "interference radius" around a cell site, outside which radius a GPS receiver's functionality will not be impacted. It is possible, however, to *statistically* quantify the probability that a GPS receiver's functionality will be impaired in the service area of a base station or multisite deployment, if the areal distribution of received LTE signal strengths is known. In this section, we assess the distribution of received signal strengths that a GPS receiver would experience in four hypothetical Ligado multi-site LTE deployments, using a Monte Carlo based multi-site simulation model, with underlying path loss models derived from the 2011 TWG Las Vegas measurements.

The key outputs from the simulation study are Cumulative Distribution Functions (CDFs) of the expected LTE signal levels over the entire geographic area of a Ligado network deployment, which quantify the probability that a GPS unit randomly located within the deployment areas sees interference above a specified power level.

7.3.2.1 Multi-Site Model Description

Simulation models were constructed to study power levels on the ground in the area of an LTE deployment representative of a Ligado network. Two deployment scenarios in the Washington, DC metro area were analyzed. The first consisted of a deployment of 135 sites with varying tower heights and sectorized antenna orientations. This deployment scenario is based on that described in the 2011 TWG report. The second scenario has 392 sites with fixed 30 meter antenna heights and identical 1 - 120 - 240 degree sector orientations, a deployment scenario defined as part of a CSMAC WG-5 study.[7] Maps of the site locations for each deployment scenario are shown below.

7

[7] Commerce Spectrum Management Advisory Committee (CSMAC) Working Group 5 (WG-5) 1755-1850 MHz Airborne Operations *(Air Combat Training System, Small Unmanned Aircraft Systems, Precision-Guided Munitions, Aeronautical Mobile Telemetry)* - Final Report, March 4 2014, https://www.ntia.doc.gov/files/ntia/publications/wg5_final_report_posted_03042014.pdf

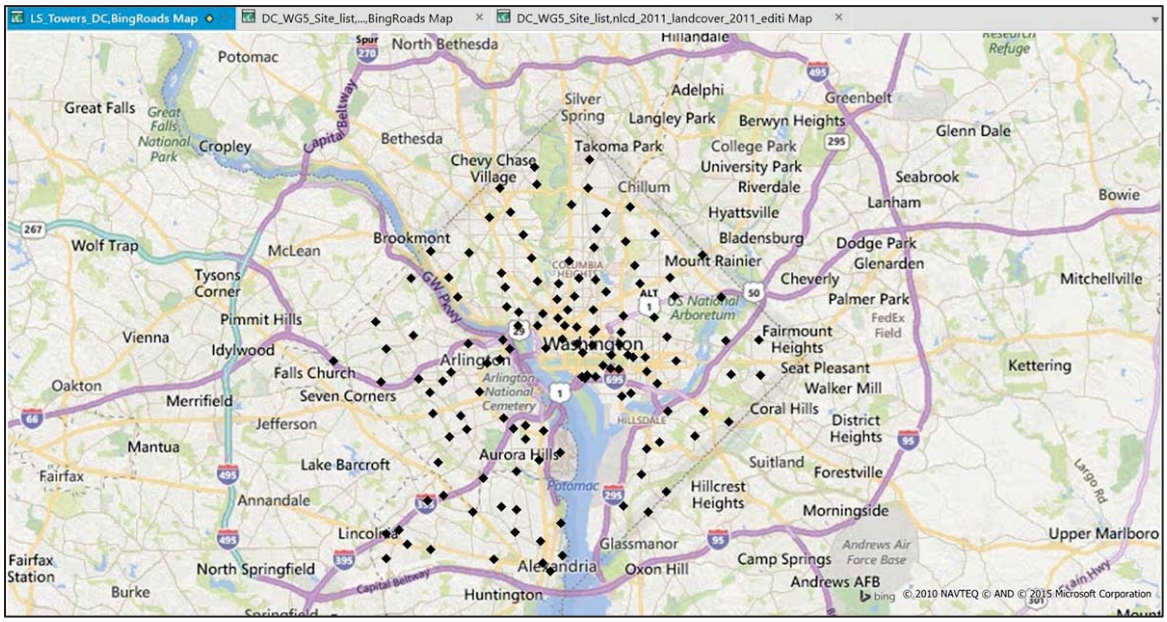

Figure 8. Map of Base Site Locations for Washington DC 135-site Deployment Scenario 1

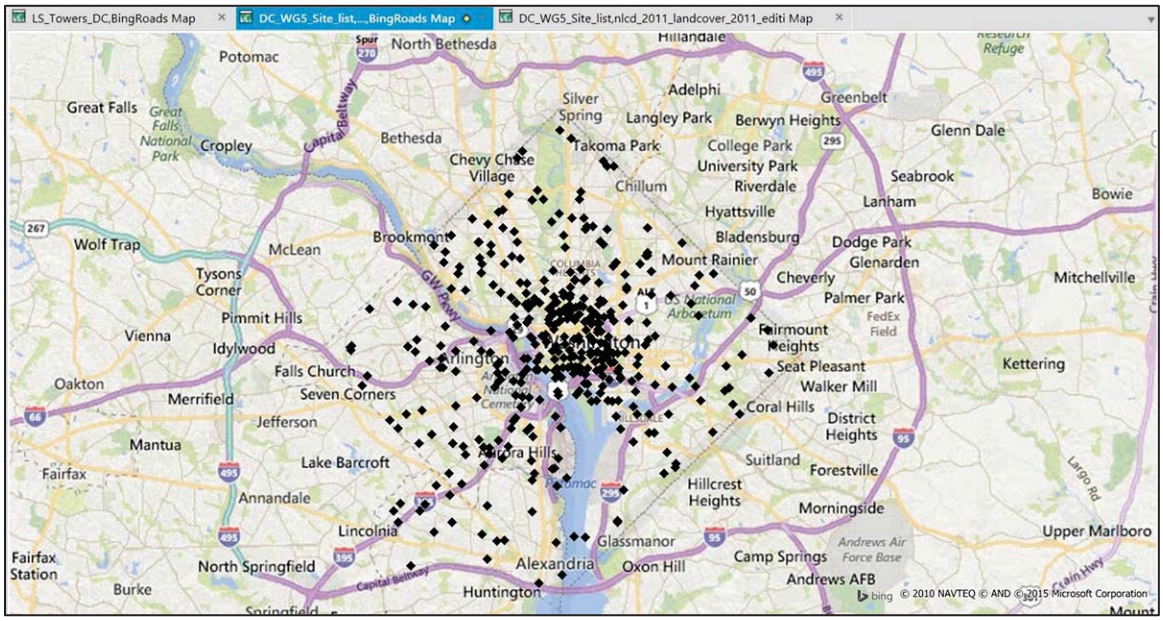

Figure 9. Map of Base Site Locations for Washington DC 392-Site Deployment Scenario 2

Additionally, urban and suburban regions within the Washington, DC metro area were identified based on the degree of developed land cover, per the National Land

Cover Database (NCLD)[8]. The map below shows the regions identified as urban (primarily "High Intensity" development) and suburban (primarily "Medium" or "Low Intensity" – although there are scattered areas of High Intensity in the Suburban regions, making the modeling slightly conservative).

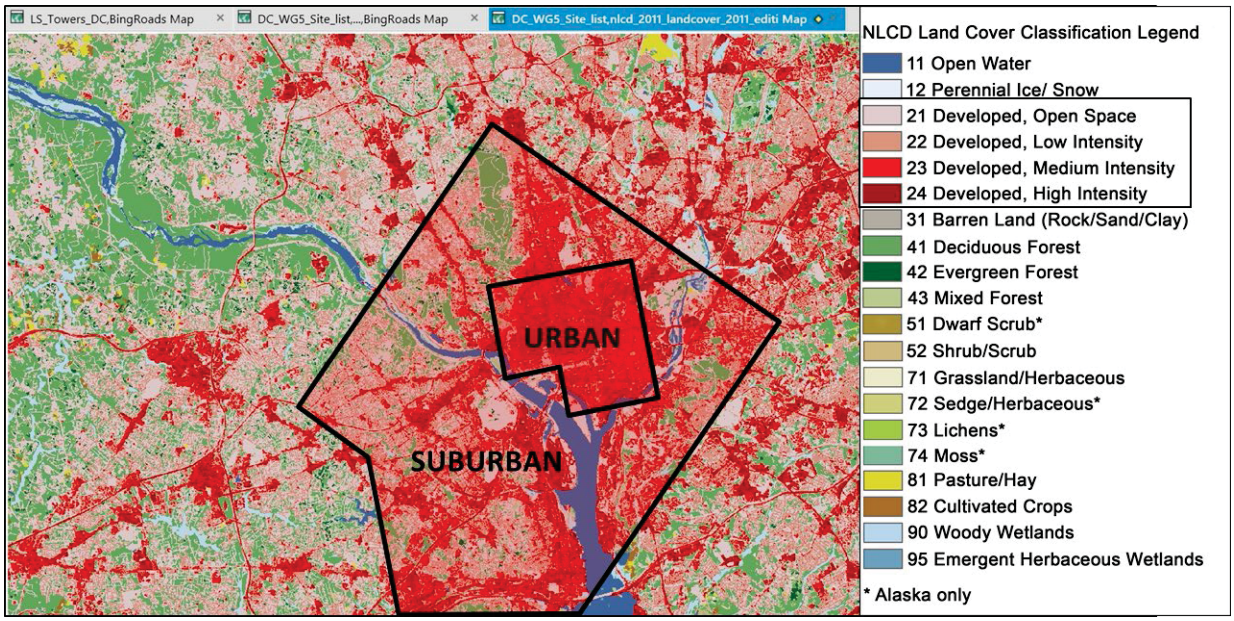

Figure 10. Land Cover Map of Washington DC Area, with Urban and Suburban Regions Identified

The diagram below illustrates the basic construction of the simulation models, with the following common features:

- LTE base station towers with vertical and horizontal (sectored) antenna patterns, which are based on manufacturer specifications;
- Base heights H(b) and transmit powers P(tx), which are defined according to the site lists for each scenario;
- Assumed average height H(r) and separation b, of buildings based on the propagation environment (Urban or Suburban);
- Fixed GPS receiver heights of 1.5 m;
- GPS antenna gains varied to reflect random orientation and polarizations;
- Elevation based on Shuttle Radar Topography Mission (SRTM)[9] terrain files of the Washington DC area (elevations are relative to the receiver).

[8] http://www.mrlc.gov/nlcd11_leg.php
[9] http://www2.jpl.nasa.gov/srtm/

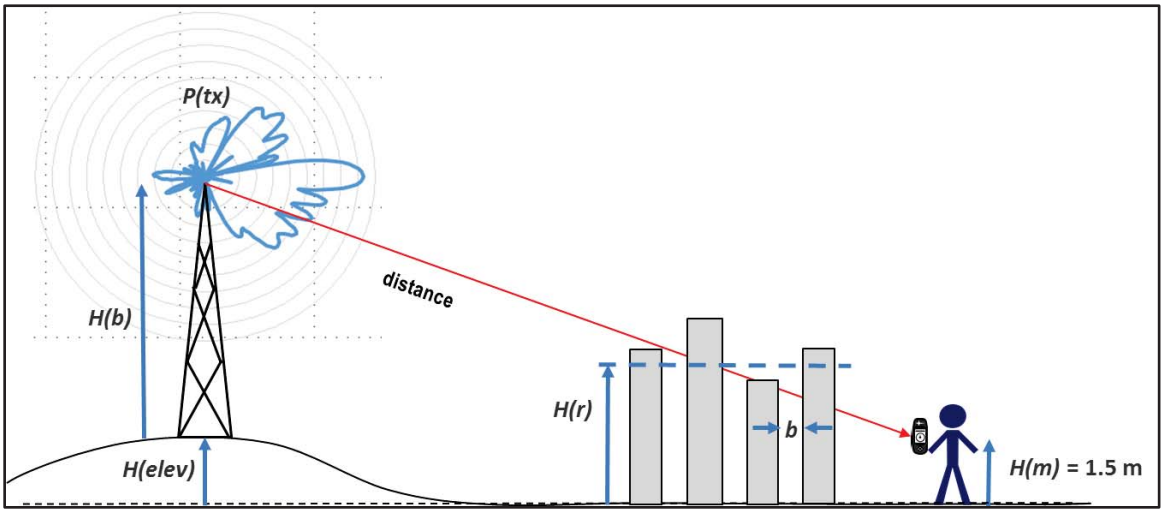

Figure 11. Diagram of Key Components of Multi-Site Simulation Model

The sources of variation in the simulation model are listed below:

- Median path loss (based on random receiver locations relative to transmitter sites);
- Transmitter antenna gain (based on random receiver locations relative to transmitter antenna patterns);
- Shadowing loss (Monte-Carlo based log-normal variation with a specified sigma);
- GPS antenna gain (based on assumed random orientations);
- GPS antenna polarization loss (based on assumed random orientations).

Propagation models for the Urban and Suburban scenarios were developed based on testing different published models against the "ground truth" data from the TWG Las Vegas Final Report, and the model parameters were adjusted to achieve the closest fit to the measured data. The final propagation model chosen was based on a combination of two models from the European Union's (EU) COST Action 231 report[10]:

- COST 231 Walfisch-Ikegami Line of Sight Model (WI-LOS);
- COST 231 Walfisch-Ikegami Non-LOS (WI-NLOS) (modified per ITU-R Rec 1411-2).

Specifically, a "blended" model was used, in which the LOS (line of site) portion was used at distances close to the transmitter site, and the NLOS portion at farther distances, with intermediate distances representing a transition region in which the two model predictions were blended in a linear fashion. Such a blended model showed the best fit against the TWG Las Vegas data for both high and low ends of the power level

[10] http://www.lx.it.pt/cost231/final_report.htm

distributions. The diagram below illustrates how the blending of the propagation models was constructed.

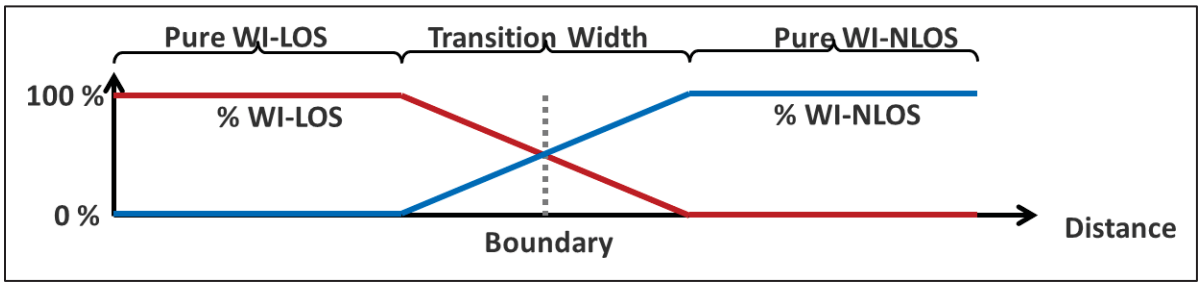

Figure 12. Blending of LOS and NLOS Propagation Models

The model parameters of average building height and building separation / street width were adjusted to get the best fits versus the urban and suburban datasets. Additionally, a log-normal variation was added to the mean path loss to account for variations in shadowing. The table below lists the parameter values for each scenario.

Table 2: Multi-Site Simulation Model Parameters

Parameter	Scenario 1 Urban Area (DC)	Scenario 1 Suburban Area (DC)	Scenario 2 Urban Area (DC alt)	Scenario 2 Suburban Area (DC alt)
Transmitter antenna height	Per Ligado Site List	Per Ligado Site List	30 m	30 m
Transmitter Location	135 Sites Wash DC	135 Sites Wash DC	392 Sites Wash DC	392 Sites Wash DC
Sector Directions (deg)	Per Ligado Site List	Per Ligado Site List	0, 120, 240	0, 120, 240
Transmit Pwr (dBW)	32	32	32	32
Receiver location	DC Urban area	DC Suburban area	DC Urban area	DC Suburban area
Xmtr and rcvr elevation	SRTM Data	SRTM Data	SRTM Data	SRTM Data
Avg. building height (m)	12	9	12	9
Avg. building separation / street width (m)	30	30	30	30
Transition boundary (m)	600	400	600	400
Transition width (m)	600	600	600	600
Receiver antenna gain	-3 dBi to +3 dBi with uniform distribution	-3 dBi to +3 dBi with uniform distribution	-3 dBi to +3 dBi with uniform distribution	-3 dBi to +3 dBi with uniform distribution
Polarization mismatch	-3 dB to -1 dB uniform distribution	-3 dB to -1 dB uniform distribution	-3 dB to -1 dB with uniform distribution	-3 dB to -1 dB with uniform distribution
Number Monte-Carlo iterations	50,000	50,000	50,000	50,000

The steps comprising the Multi-Site Simulation Model are illustrated in the diagram below.

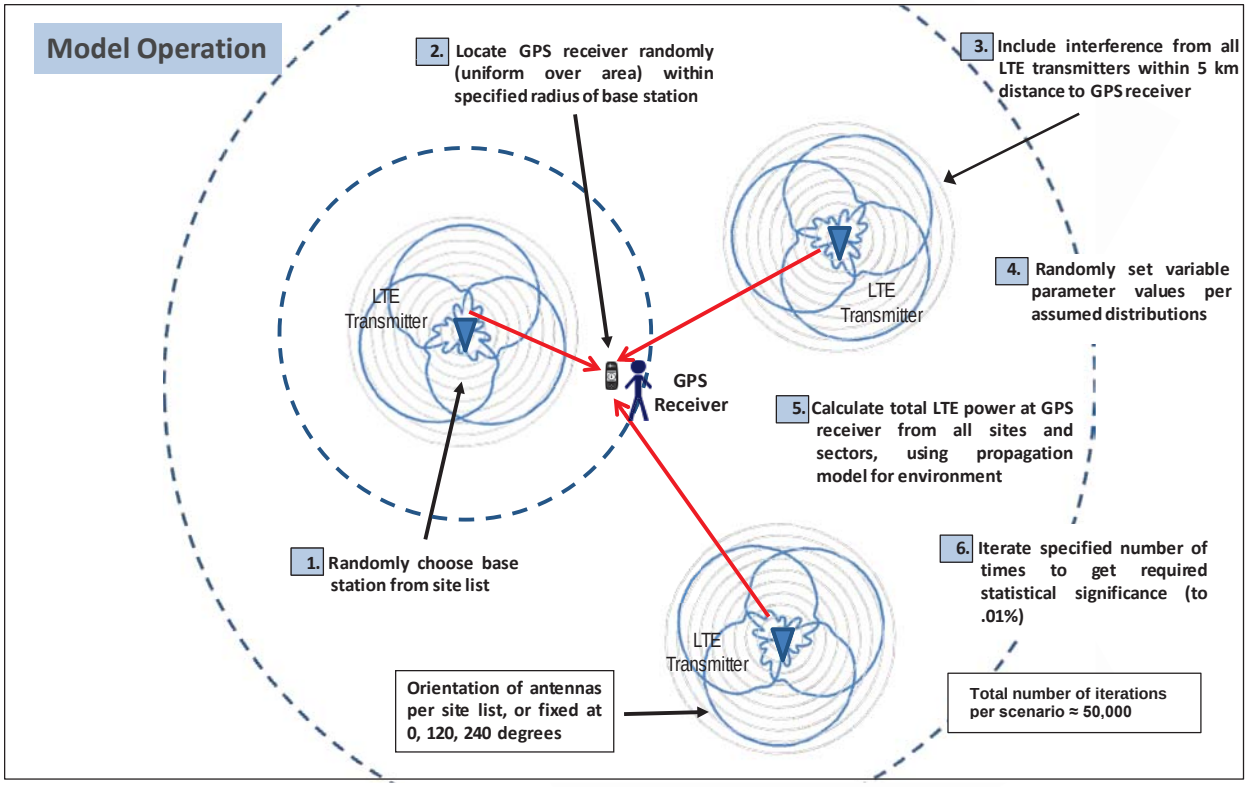

Figure 13. Diagram of Multi-Site Simulation Model Operation

7.3.2.2 Multi-Site Simulation Model Results

Figures 14 through 17 below show the resulting heat maps of interference power for the two simulation scenarios, for the Urban and Suburban areas.

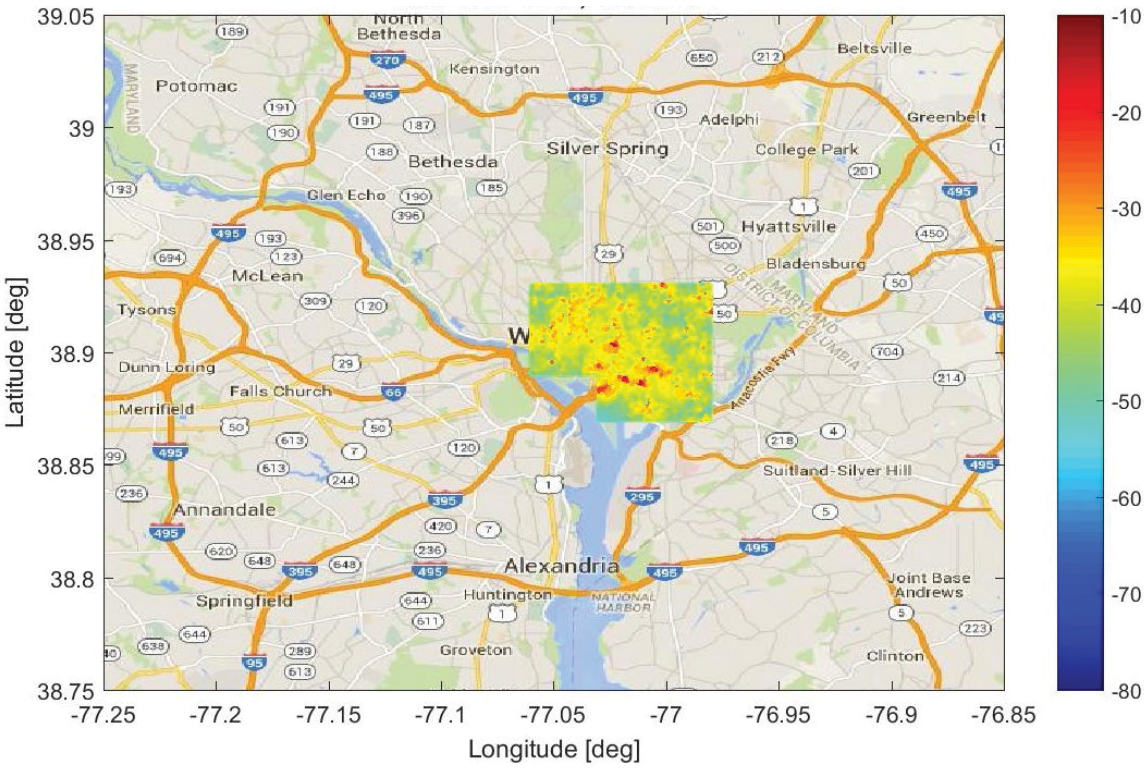

Figure 14. Interference power (dBm) from simulation scenario 1, Urban area

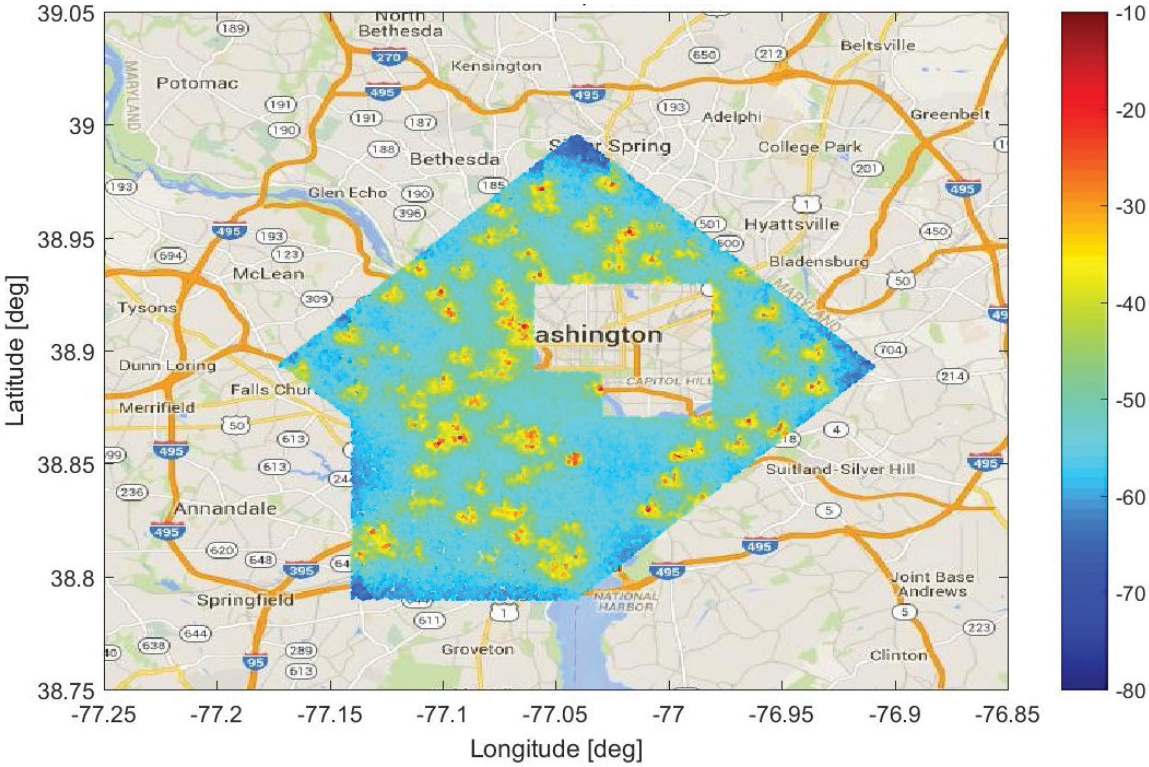

Figure 15. Interference power (dBm) from simulation scenario 1, Suburban area

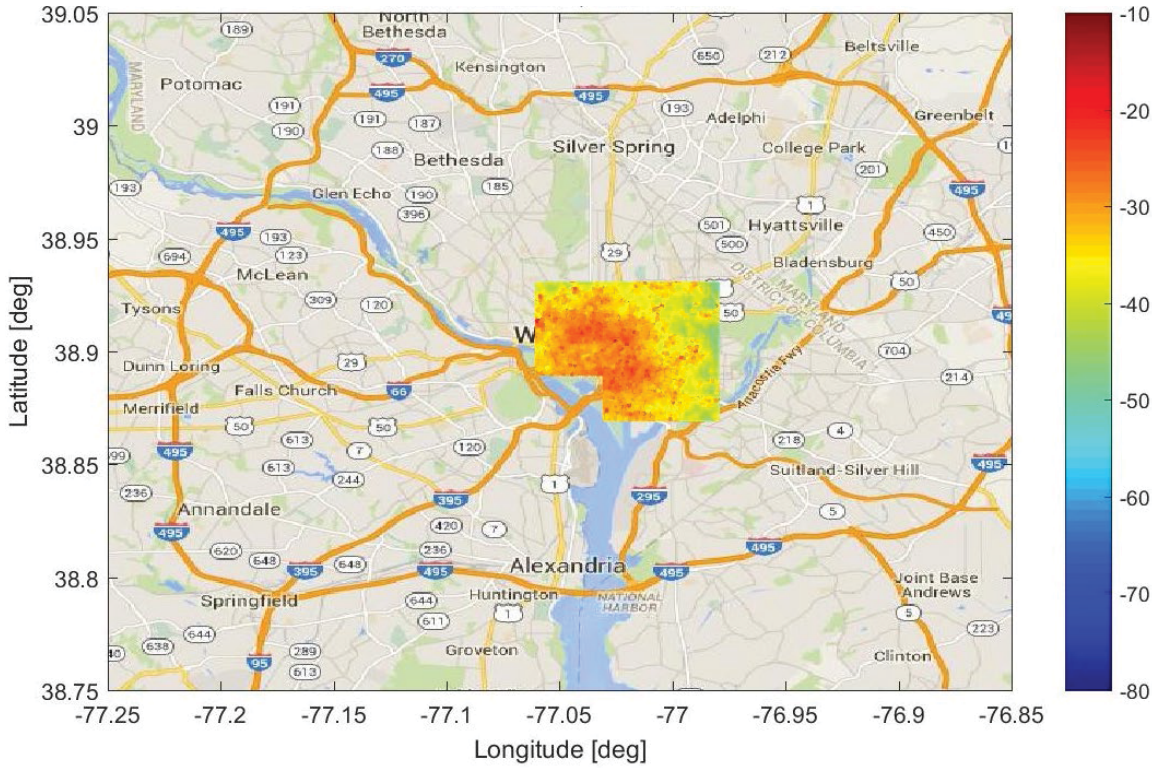

Figure 16. Interference power (dBm) from simulation scenario 2, Urban area

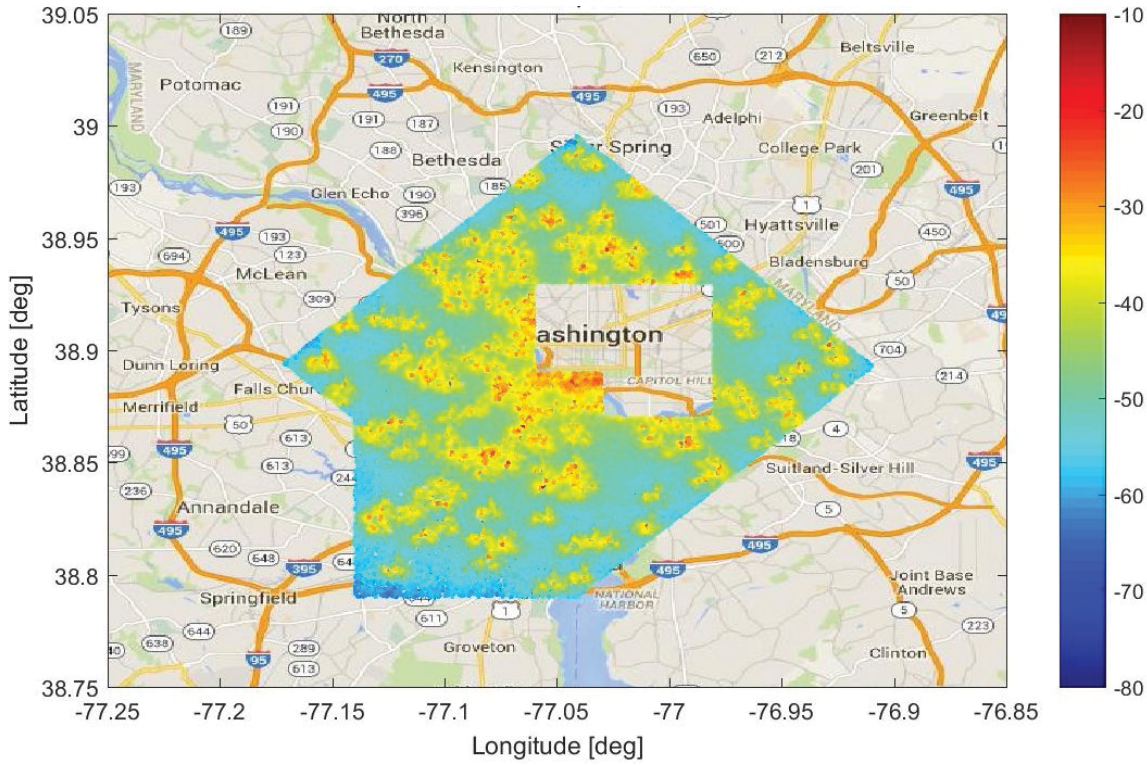

Figure 17. Interference power (dBm) from simulation scenario 2, Suburban area

The resulting distributions for LTE signal strengths from the Multi-Site simulations for the four deployment scenarios are shown in Figure 18 below, and the power levels corresponding to select percentiles are shown in the subsequent table.

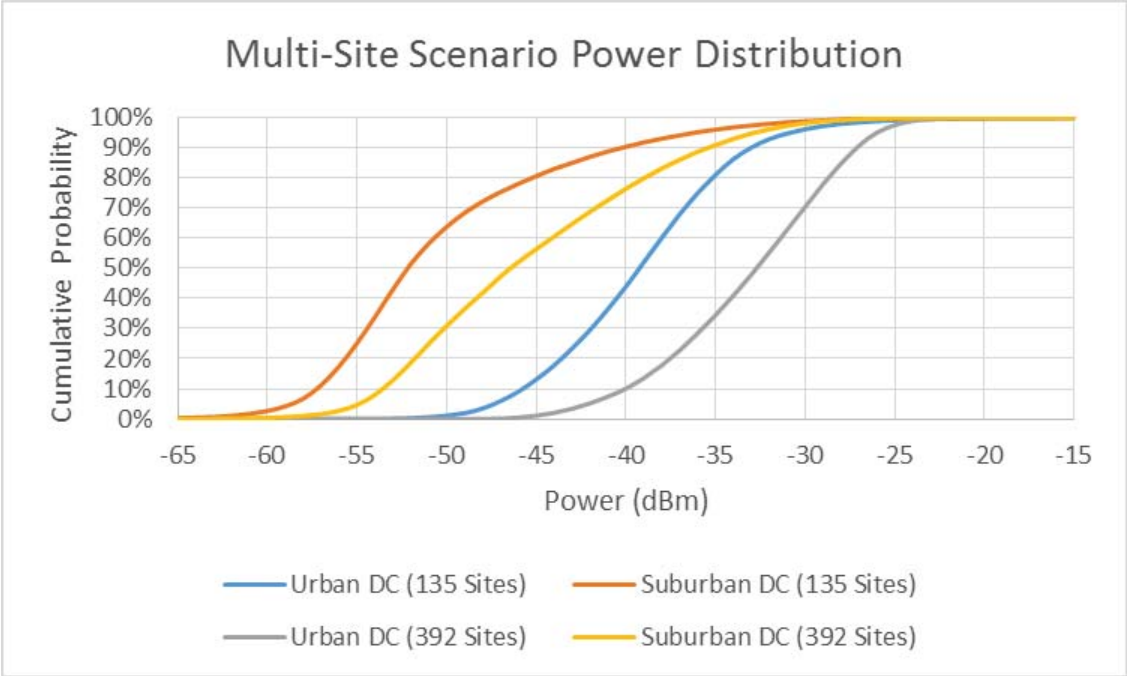

Figure 18. Power Level Distributions for Multi-site Simulation Model Analyses

Table 3: LTE Signal Strength Distributions—Multi-Site Deployment Model

	Multi-Site Model	
	LTE Signal Level, dBm	
Deployment Scenario	90%tile	99%tile
1-Urban Wash DC (135 Sites)	-33.0	-25.5
1-Suburban Wash DC (135 Sites)	-40.2	-29.4
2-Urban Wash DC (392 Sites)	-27.1	-23.9
2-Surburban Wash DC (392 Sites)	-35.4	-28.6

Using the same 99% as the criteria for no impact to GPS as was used in Section 7.3.1.2 for the TWG measurements, the table reveals that a GPS receiver will experience signals levels less than about -24 dBm over more than 99% of locations across all four environments. This is lower (less potential impact to a GPS receiver) than the -20 dBm threshold level derived from analysis of the 2011 TWG measurements.

The conclusion from the Multi-Site model analysis is that if -20 dBm is the level where impact to a GPS receiver occurs, there will be no functional impact to GPS receivers in greater than 99% of the entire service area.

7.3.3 LTE Drive Test Measurements: Washington, DC

This section describes a drive test conducted in the Washington, DC metropolitan area to assess the distributions of received signal strengths for seven commercial LTE deployments. The drive tests were used to assess the distributions of LTE power levels that GPS receivers could experience in actual, practical LTE deployments, and to compare to the results of the TWG measurement analysis in Section 7.3.1 and the multi-site Washington DC deployment model results in Section 7.3.2.

7.3.3.1 Drive Test Description

A company with experience in cellular network testing drove specific routes in the Washington DC area.[11] LTE power measurements were recorded using a PCTEL SeaHawk MX Measurement System with a maximum RF input power range of -10 dBm. The antenna used was a wide band (698-2700 MHz) omnidirectional PCTEL BMLPVMB/LTE. The purpose of the test was to assess the likelihood of encountering LTE at certain power levels in real world LTE deployments. LTE networks in the 700 and 1900 MHz bands were measured. The 700 MHz band was consistently received at higher powers than 1900 MHz band, likely due to the lower propagation loss for the lower frequency.

The following table shows the frequency bands and the (anonymized) service providers measured during the drives. Four of the measured frequencies were licensed to Provider A. Channels 900 and 8340 are BOTH at the same frequency. This frequency was scanned twice and generated additional measurements. As Figure 19 illustrates, Provider A, Provider B, and Provider C all have one 700 MHz channel in Washington, DC. As previously noted, the 700 MHz channels consistently had the highest received power measurements.

Provider	A	A	B	C	A	A	D
EARFCN	CH900	CH1150	CH5035	CH5230	CH5780	CH8340	CH8665
DL Freq. (MHz)	1960 MHZ	1985 MHz	731.5 MHz	751 MHz	739 MHz	1960 MHz	1992.5 MHz

Figure 19. Carrier and Frequency Bands Measured

Six drive test regions were selected. Drive test location data was later overlaid with National Land Cover Database information from the Multi-Resolution Land

[11] PCTEL, Inc.

Characteristics Consortium (MRLC) so that subsequent analysis by land use type could be performed.[12]

Table 4: Urban GIS National Land Cover Definitions

Urban GIS and TWG (Technical Working Group) Terminology		
National Land Cover Classification		RAA And Technical Working Group
Class	Description	
11	Open Water	
12	Perennial Ice / Snow	
21	Developed, Open Space	Rural
22	Developed, Low Intensity	Suburban
23	Developed, Medium Intensity	Suburban
24	Developed, High Intensity	Urban
31	Barren Land (Rock / Sand / Clay)	NOT ENCOUNTERED
41	Deciduous Forest	Rural Shadowed
42	Evergreen Forest	Rural Shadowed
43	Mixed Forest	Rural Shadowed
51	Dwarf Scrub	NOT ENCOUNTERED
52	Shrub / Scrub	Undeveloped Rural Open
71	Grassland / Herbaceous	Undeveloped Rural Open
72	Sedge / Herbaceous	NOT ENCOUNTERED
73	Lichens	NOT ENCOUNTERED
74	Moss	NOT ENCOUNTERED
81	Pasture / Hay	Undeveloped Rural Open
82	Cultivated Crops	Undeveloped Rural Open
90	Woody Wetlands	Undeveloped Rural Open
95	Emergent Herbaceous Wetlands	Undeveloped Rural Open

Views of the drive regions are shown in the following figures.

[12] Detailed information can be found at www.mrlc.gov.

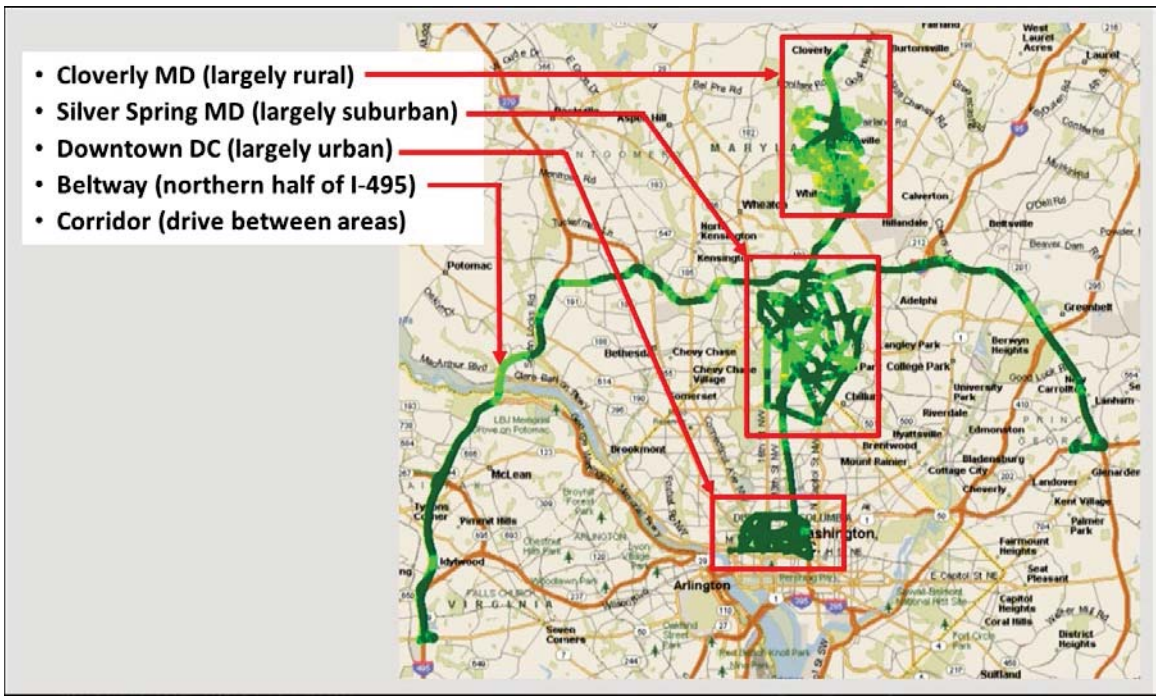

Figure 20. Overview of Washington DC Drive Test Areas

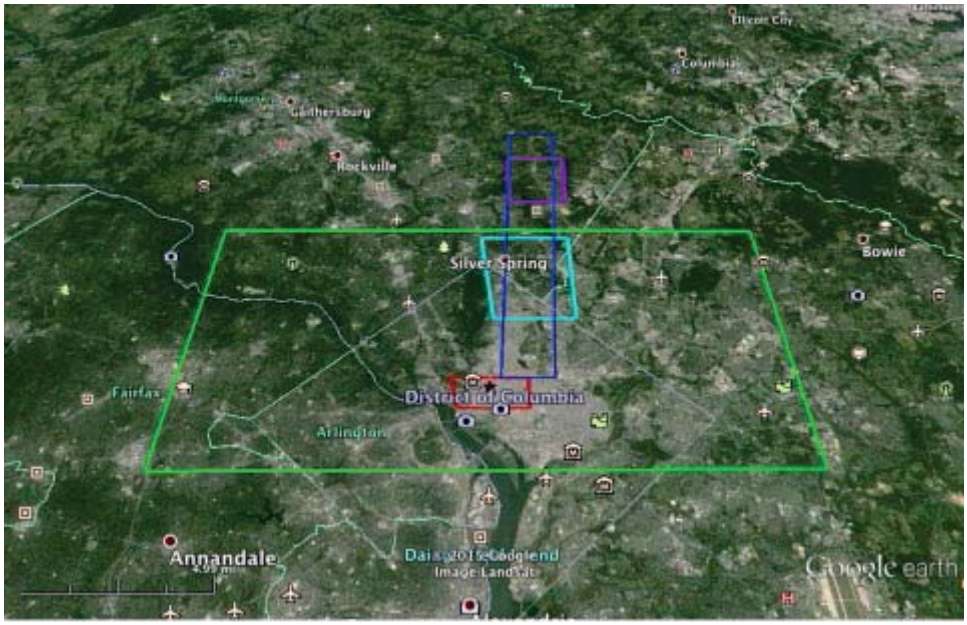

Figure 21. Satellite View of Washington DC Drive Test Areas (box colors explained below)

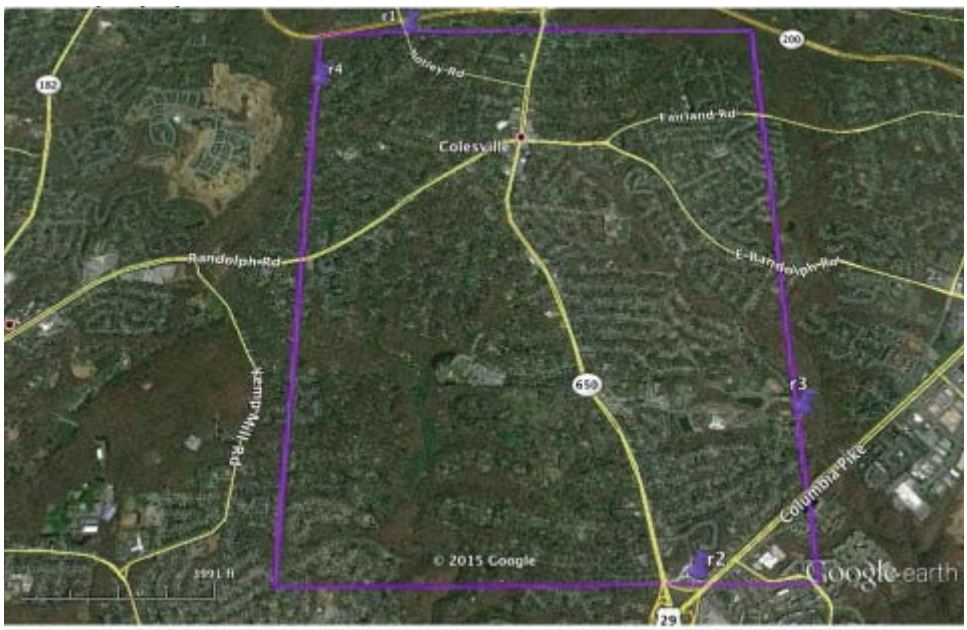

Figure 22. Cloverly Drive Test Area (Purple Boundary)

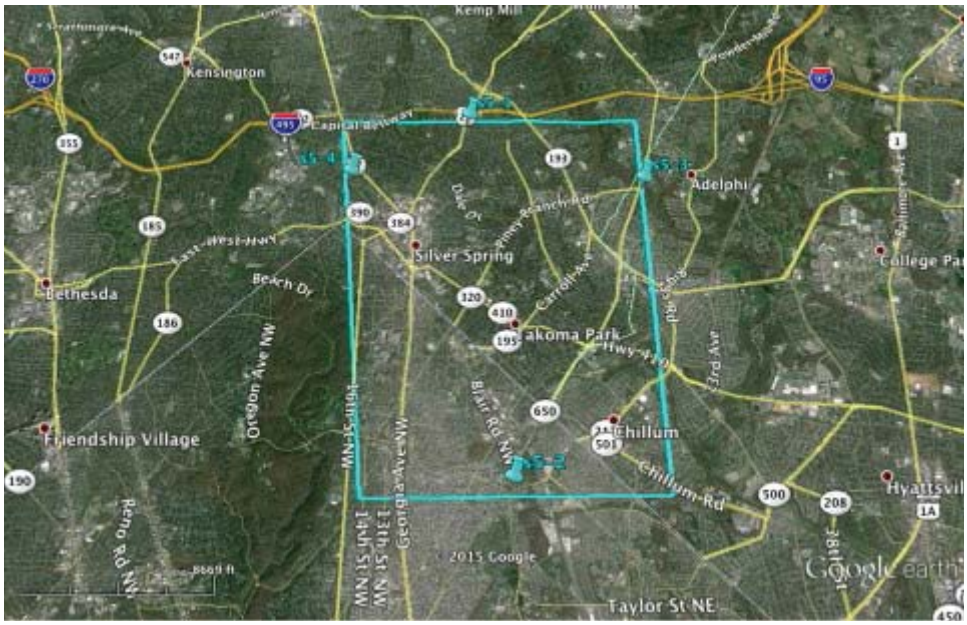

Figure 23. Silver Spring Drive Test Area (Turquoise Boundary)

Figure 24. Downtown DC Drive Test Area (Red Boundary)

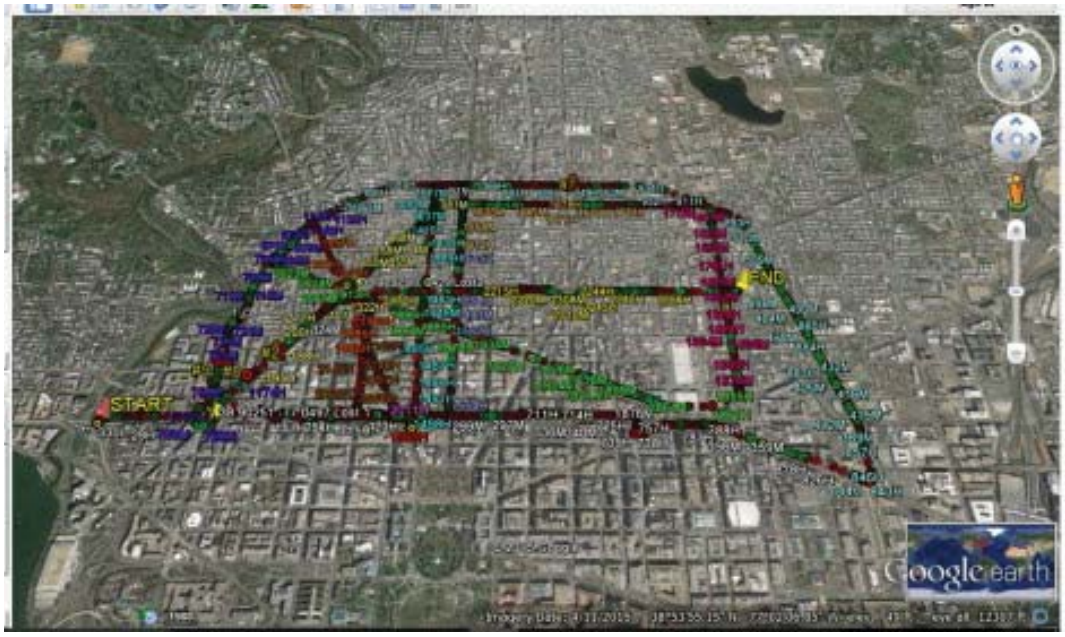

Figure 25. Drive Route: Downtown Washington, DC (colors indicate signal levels)

Figure 26. Beltway Drive Area (Green Boundary)

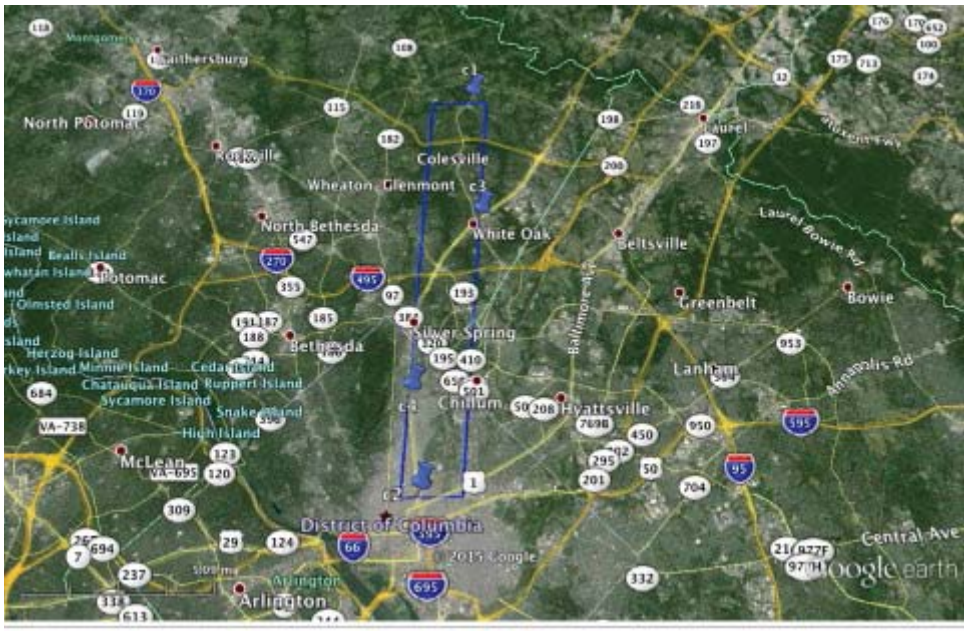

Figure 27. Corridor Drive Test Area (Blue Boundary)

7.3.3.2 Drive Test Data Analysis

The data files from the five drive test areas were separated into smaller groups with respect to the Land Type classification for subsequent analysis. As expected, the largely rural Cloverly area had the most land types and the Downtown area had the least. In total 13 areas were analyzed and then combined into the four land use types as follows:

- Developed, High Intensity = Urban
- Developed, Medium Intensity + Developed, Low Intensity = Suburban
- Developed, Open Space + Cultivated Crops + Pasture/Hay + Grassland/Herbaceous + Shrub/Scrub + Woody Wetlands + Emergent Herbaceous Wetlands = Rural Open
- Deciduous Forest + Evergreen Forest + Mixed Forest = Rural Shadowed

The following shows the percentages of each type of land type across all of the measured frequency bands and service providers.

Cloverly Drive Area:

1. 44.99% Suburban
2. 39.61% Rural Open
3. 9.54% Rural Shadowed
4. 5.32% Urban

Corridor Drive Area:

1. 68.27% Suburban
2. 28.10% Urban
3. 3.63% Rural Open
4. 0.00% Rural Shadowed

Beltway Drive Area:

1. 77.49% Suburban
2. 12.70% Urban
3. 9.45% Rural Open
4. 0.31% Rural Shadowed

Downtown Drive Area:

1. 65.24% Urban
2. 34.66% Suburban
3. 0.04% Rural Open
4. 0% Rural Shadowed

Silver Spring 1 Drive Area:

1. 26.72% Urban
2. 61.73% Suburban
3. 10.49% Rural Open
4. 0.89% Rural Shadowed

Silver Spring 2 Drive Area:

1. 27.09% Urban
2. 56.60% Suburban
3. 12.13% Rural Open
4. 3.99% Rural Shadowed

The measured power (at the cellular carrier frequency) was adjusted to nominal antennas used and the path loss was adjusted to the Ligado lower downlink frequency. The average GPS antenna gain used in the TWG report was -5 dB (an average value for a handheld device, to account for random device orientation). However, to be conservative, an antenna gain of -2 dBi, a value representative of a high-precision GPS device for a typical angle of arrival of the LTE signal, was assumed instead. Mathematically this is calculated by the following equation:

Adjusted Power = Road Received Power (dBm) + 20*log10(LTE Frequency (MHz)/1540) – 2 dB

7.3.3.3 Drive Test Results

The following is a summary of the drive tests conditions and description of the adjustment to the received signal levels in order to assess the signal level that a GPS receiver would experience at its antenna input if subjected to adjacent band interference.

Drive Test Conditions

- Data gathered continuously as the test vehicle drove the indicated routes
  - No knowledge of:
    - Tower locations, heights, density, radiated power, polarization
- Measurements Recorded
  - RSSI (Received Signal Strength Indication); Cell ID; CINR; GPS Sat. count
- Receiving Antenna Type
  - 0 dBi Monopole on Vehicle Roof
- Post Drive Measurement Environment Classification
  - Analyzed by NLCD land use type by Urban GIS Corp.
  - Classification Categories: Urban, Suburban, Rural Open, Rural Shadowed
- Post Drive Analysis Signal Level Adjustment for Equivalent High-Precision GPS Receiver
  - Carrier Frequency Correction: $20*\log10 (f_{LTE} / f_{\text{Ligado Downlink}})$
  - - 2 dBi average GPS antenna gain

The table below summarizes the results of the drive tests by LTE channel number and drive test area. These are the unprocessed signal level statistics, without corrections for frequency or antenna gain.

Table 5: Measured LTE Signal Levels (dBm), not adjusted for GPS Antenna Gain and Frequency

DOWNTOWN DC Drive Area				CORRIDOR Drive Area		
Channel	Median	99%		Channel	Median	99%
5035	-68.4	-42.4		5035	-64.5	-38.0
5780	-48.9	-28.2		5780	-62.0	-33.1
5230	-47.8	-26.9		5230	-60.7	-33.2
900	-51.8	-31.4		900	-81.9	-37.5
8340	-52.3	-31.2		8340	-81.9	-37.6
1150	-71.8	-48.1		1150	-93.1	-58.5
8665	-68.3	-40.9		8665	-71.5	-38.8
SILVER SPRING Drive Area (1)				SILVER SPRING Drive Area (2)		
Channel	Median	99%		Channel	Median	99%
5035	-61.1	-33.0		5035	-65.1	-37.4
5780	-61.0	-36.5		5780	-63.2	-32.0
5230	-61.0	-35.4		5230	-63.9	-33.0
900	-73.0	-41.6		900	-77.0	-40.6
8340	-73.2	-41.9		8340	-76.9	-40.8
1150	-97.2	-69.0		1150	-97.2	-65.6
8665	-69.7	-39.8		8665	-71.9	-41.3
BELTWAY Drive Area				CLOVERLY Drive Area		
Channel	Median	99%		Channel	Median	99%
5035	-67.6	-40.8		5035	-69.7	-43.4
5780	-59.7	-34.9		5780	-70.3	-37.4
5230	-60.8	-34.2		5230	-70.3	-33.9
900	-71.7	-45.7		900	-86.0	-64.9
8340	-73.0	-45.3		8340	-86.2	-64.9
1150	-98.3	-67.5		1150	-107.1	-96.3
8665	-68.0	-42.2		8665	-82.6	-46.0

The table below summarizes the same results of the drive tests by LTE channel number and drive test area, in this case with the corrections for frequency and antenna gain. Across all the drive test areas, more than 99% of the measurements were below -30 dBm level. The highlighted cell illustrates the highest LTE level recorded at the 99% level.

Table 6: Measured LTE Signal Levels (dBm), Adjusted for GPS Antenna Gain and Frequency

DOWNTOWN DC Drive Area			CORRIDOR Drive Area		
Channel	Median	99%	Channel	Median	99%
5035	-76.9	-50.9	5035	-72.9	-46.5
5780	-57.3	-36.5	5780	-70.3	-41.5
5230	-56.1	-35.1	5230	-68.9	-41.4
900	-51.7	-31.3	900	-81.8	-37.4
8340	-52.2	-31.1	8340	-81.8	-37.5
1150	-71.6	-47.9	1150	-92.9	-58.3
8665	-68.1	-40.6	8665	-71.3	-38.6
SILVER SPRING Drive Area (1)			SILVER SPRING Drive Area (2)		
Channel	Median	99%	Channel	Median	99%
5035	-69.5	-41.5	5035	-73.6	-45.9
5780	-69.4	-44.8	5780	-71.6	-40.3
5230	-69.2	-43.7	5230	-72.1	-41.2
900	-72.9	-41.5	900	-76.9	-40.5
8340	-73.1	-41.8	8340	-76.8	-40.7
1150	-97.0	-68.8	1150	-97.0	-65.4
8665	-69.4	-39.5	8665	-71.7	-41.1
BELTWAY Drive Area			CLOVERLY Drive Area		
Channel	Median	99%	Channel	Median	99%
5035	-76.1	-49.3	5035	-78.1	-51.8
5780	-68.0	-43.2	5780	-78.6	-45.8
5230	-69.1	-42.4	5230	-78.5	-42.2
900	-71.6	-45.6	900	-85.9	-64.8
8340	-72.9	-45.2	8340	-86.1	-64.8
1150	-98.1	-67.3	1150	-106.9	-96.1
8665	-67.7	-42.0	8665	-82.3	-45.8

7.3.3.4 Drive Test Conclusions

Since at least 99% of the drive test measurements were less than -30 dBm (per Table 6 data), the choice of -20 dBm as the signal level not exceeding 99% of the time, based on the 2011 TWG single site measurements, is extremely protective of GPS receivers. Stated another way, the measurements of the commercial LTE deployments in Greater Washington, D.C. indicate that signal strengths greater than -30 dBm will be encountered in a very small fraction (less than 1%) of an LTE deployment area.

7.4 Uplink Characterization

The following graph (Figure 28) illustrates the distribution of LTE handheld device signal power.[13] The graph shows that LTE handheld devices with a maximum allowed EIRP of 23 dBm operate with an EIRP less than 20 dBm at least 99% of the time. Using the more conservative value of 23 dBm as the starting point, the calculation in Section 3.4.1 establishes that a signal level of -19 dBm would be experienced less than 99% of the time by a GPS receiver at a distance of 1 meter from the LTE device.

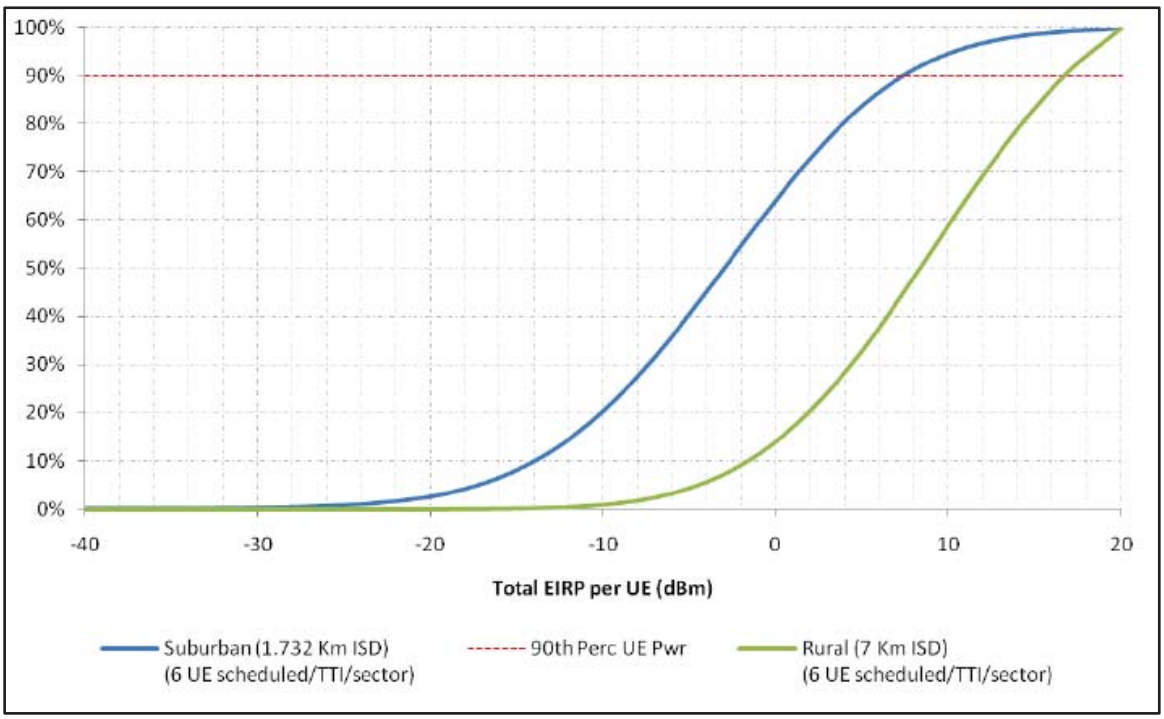

Figure 28. Distribution of LTE User Device EIRP

[13] Commerce Spectrum Management Advisory Committee, Final Report, Working Group 1 – 1695-1710 MHz Meteorological-Satellite (January 22, 2013), *available at* http://www.ntia.doc.gov/files/ntia/publications/wg-1_report_v2.pdf.

Before the
Federal Communications Commission
Washington, D.C. 20554

	)	
In the Matter of	)	IB Docket No. 11-109
Comment Sought on Ligado's	)	
Modification Applications	)	
	)	
	)	

DECLARATION OF MARK A. STURZA

1. My name is Mark A. Sturza. I am the President of 3C Systems Company; in this capacity I consult with startups and established corporations on GPS-related issues. I have over forty years of experience in the design, development, analysis, and application of GPS systems.

2. Prior to founding 3C Systems, I worked at several major electronics companies developing GPS technology. At Teledyne Systems Company (1975 – 1979), I supported development of the Tactical GPS Guidance receiver, the GPS Phase IIA program, development of a GPS satellite simulator, and development of the Missile Accuracy Evaluator GPS receiver. At Magnavox (1979 – 1981), I designed the set moding for their GPS Phase II User Equipment receivers. As Director, GPS Development at Litton Aero Products (1981 – 1987), I led the development of the first GPS receivers specifically designed for the commercial aviation market. At Litton Guidance and Control Systems (1987 – 1989), I provided my expertise to all of the company's integrated GPS/inertial navigation system developments.

3. Since founding 3C Systems in 1989 (twenty-seven years ago), I have been involved in a wide range of GPS product developments, including development of SiRF

Technology's SiRFstar GPS chipsets, development of NAVSYS's TIDGET GPS receiver, development of one of the first software GPS receivers, and redesign of Allen Osborne Associates' Rogue GPS receiver RF section.

4. I have been awarded thirty patents in GPS and related fields, nine of which specifically cover GPS technology. These patents include innovations for acquiring extremely weak GPS signals (such as those received indoors) and operating GPS chipsets in micro power mode to improve battery life. I have presented over thirty technical papers, twenty-one of which focus on GPS technology. Two of these papers were published in *Navigation*, the journal of the Institute of Navigation. I have lectured at GPS short courses on thirteen occasions.

5. I am a Senior Member of the Institute of Electrical and Electronic Engineers, a Senior Member of the American Institute of Aeronautics and Astronautics, and a member of the Institute of Navigation, the Pacific Telecommunications Council, and the Society of Satellite Professionals International. I hold a General Radiophone Operator License from the FCC.

6. I earned a BS degree from Caltech, an MSEE degree from USC, and an MBA degree from Pepperdine University.

7. I have been retained by Ligado Networks' counsel to monitor and review the GPS and Adjacent Band Co-Existence Study performed by Roberson and Associates ("RAA"). To do so, I took the actions described in the following paragraphs.

8. I met with the RAA team, including Dennis Roberson, President and CEO, Dr. Kenneth Zdunek, Vice President and CTO, William Alberth, Senior Consultant, and Dr. John Grosspietsch, Principal Engineer III. I reviewed the RAA test plan, monitored the test campaign at the testing lab AT4 Wireless, and reviewed the test results.

9. I reviewed RAA's calibration plan, as described in Appendix B of RAA's final report, and reviewed the raw calibration data reports prepared by AT4 Wireless.

10. I visited AT4 Wireless' facility in Herndon, VA, where I inspected the anechoic chamber and test equipment used for the RAA study. I met with Bryan Mikes, COO, Sai Sushma Mallela, Business Development and Program Manager, and Patricia Medina, Testing Engineer. I reviewed AT4's ISO/IEC 17025:2005 accreditation certificate issued by the American Association for Laboratory Accreditation ("A2LA"). I noted that the certificate is valid to October 31, 2016 and grants accreditation to AT4 to perform the following tests: LTE: RF/RRM and Protocol, NFC Devices and Protocol Tests, Continua Health Alliance: Continua Design Guidelines, Near Field Communications (NFC), OTA tests for LTE, CDMA, CDMA 1xRTT, CDMA 1xEVDO, GSM, GPRS, EGPRS, UMTS (W-CDMA), Wi-Fi, Field Trials (GSM, UMTS, and LTE), and Rezence Alliance for Wireless Charging (Conformance and IOP).

11. Based on this research and my forty years of experience in this field, I find that the RAA study was well designed and well executed. Furthermore, RAA's decision to examine KPIs is consistent with good science and consumers' expectations. Policy makers should credit this study. This declaration is true and accurate to the best of my knowledge.

Signed: ____/s/_____

Mark A. Sturza

Date: June 10, 2016