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1 Executive Summary

This is a second and final report on a study undertaken by LightSquared on the overload vulnerability of GPS receivers used in cellular communications, when such receivers are in proximity to base stations transmitting in the L-band (3GPP Band 24). A previous document [1] described the results of outdoor field testing of three cellphones with built-in GPS receivers; the report also included a description of work done on characterizing the performance of fixed, timing-unit GPS receivers and methods of improving their performance for collocated deployment with LightSquared's Band 24 base station antennas.

In this report, laboratory results are provided of three additional cellphone GPS receivers. The key performance indicators (KPI's) were changed from those of the field test to Position Error and SNR (as reported by the GPS processor). The results are interesting in that the Position Error was found to have a very sharp threshold, which often occurred at relatively high values of SNR degradation (in some cases around 10 dB) relative to the case of zero OOB power. Also included in this report is a description of a field trial to gather data about GPS received signal levels from different satellites in suburban and urban morphologies.

Although results have been provided to date of a limited number of devices (6), LightSquared proposes to close the study at this stage as a more comprehensive study, covering a wider variety of GPS receivers than those involved in cellular applications, has now been initiated under the auspices of the FCC [2]. This study will be conducted by a cross-industry group led by LightSquared and USGPSIC, the reports of the study having complete public visibility.

2 Lab Testing of Mobile GPS Receivers

2.1 Introduction

This section describes the test results obtained by a certified laboratory, AT4 Wireless, under contract to LightSquared, for evaluating the blocking performance of GPS receivers embedded in cellular phones, when strong L-band LTE signals are present. Such adjacent-band signals may be present owing to physical proximity of the cellular phone to either a LightSquared base station or User Equipment (UE).

Section 3 describes the results of a field trial to gather GPS received signal strength data in suburban and urban morphologies, in order to check the validity of the GPS received signal levels used in the laboratory tests.

2.2 Test Results

Testing was performed by AT4 Wireless on three smartphones with GPS. The test set up is illustrated in Figure 1. The three smartphones are noted as Device 1, Device 2, and Device 3 in this Section.

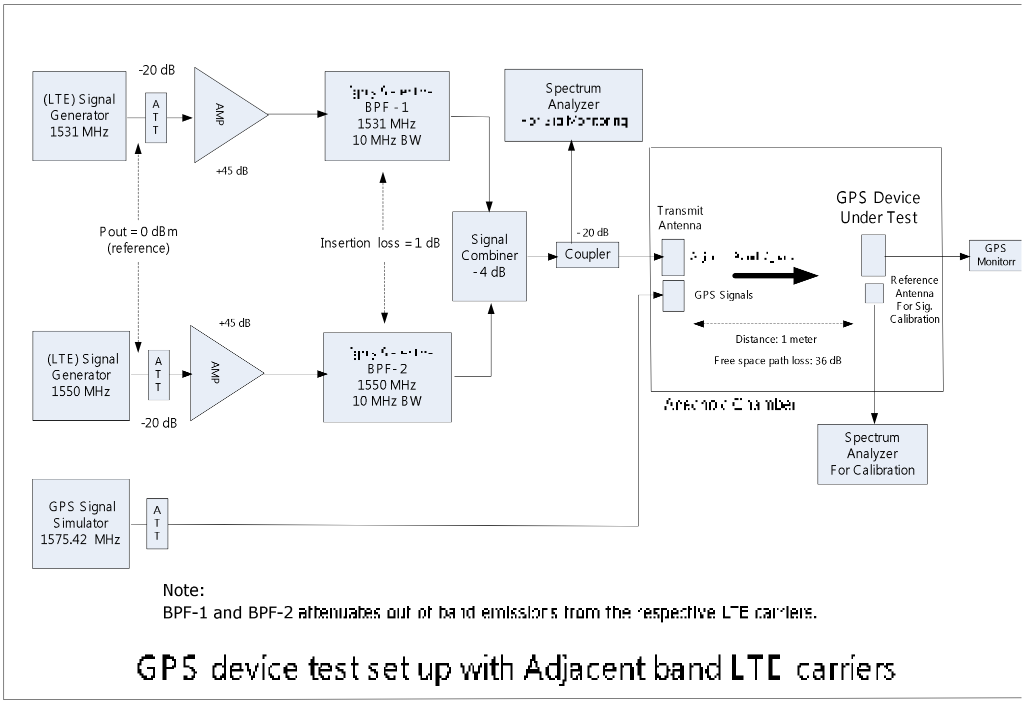

Figure 1: AT4 Wireless Lab Test Set Up

The testing approach was changed from that used in the field test described in [1] to make it more operationally relevant. The devices used in the laboratory tests were different from those used in the field tests in [1]. The Key Performance Indicator (KPI) was based on a user perceptible parameter, the position error. The received SNR reported by the GPS processor was also monitored. Eight (8) satellites were emulated for desired signal levels of -125 dBm and -130 dBm. In a given test, all emulated satellites had the same desired signal level. It is noteworthy, that these devices were tested in standalone GPS mode with no A-GPS assistance. In the real world, the mobile device may benefit from increased sensitivity offered by the mobile assistance data.

The results for GPS signal levels at -125 dBm per Space Vehicle (SV) are shown in Table 1, Table 2 and Table 3 for 3 devices under test. The results for GPS signal levels at -130 dBm per SV are shown in Table 4, Table 5 and Table 6. The average values were taken over 75 samples.

Table 1: Device 1 Measurements at -125 dBm GPS Rx Level

GPS/Sat dBm	LTE dBm	Avg Error (2D) in meters	Avg SNR	Sat 11	Sat 14	Sat 17	Sat 20	Sat 23	Sat 24	Sat 31	Sat 32
-125	OFF	**8.60**	35.07	35.06	35.05	35.15	35.04	35.05	35.15	35.05	35.03
-125	**-50**	**9.68**	**34.60**	**34.41**	**34.63**	**34.76**	**34.51**	**34.67**	**34.77**	**34.71**	**34.34**
-125	**-40**	**7.60**	**34.40**	**34.47**	**34.43**	**34.42**	**34.51**	**34.49**	**34.03**	**34.51**	**34.32**
-125	**-30**	**9.64**	**34.76**	**34.75**	**34.73**	**34.84**	**34.75**	**34.77**	**34.74**	**34.78**	**34.68**
-125	**-25**	**9.60**	**33.63**	**33.79**	**34.06**	**34.09**	**33.56**	**33.09**	**33.70**	**33.51**	**33.26**
-125	**-20**	**9.59**	**32.21**	**32.30**	**32.17**	**32.17**	**32.28**	**32.30**	**31.92**	**32.37**	**32.17**
-125	**-15**	**9.57**	**31.68**	**31.78**	**32.45**	**31.96**	**31.51**	**31.52**	**31.42**	**31.49**	**31.28**
-125	**-10**	**6.97**	**28.30**	**25.76**	**31.35**	**28.25**	**29.52**	**26.1**	**29**	**25.2**	**31.17**

Table 2: Device 2 Measurements at -125 dBm GPS Rx Level

GPS/Sat dBm	LTE dBm	Avg Error (2D) in Meters	Avg SNR	Sat 11	Sat 14	Sat 17	Sat 20	Sat 23	Sat 24	Sat 31	Sat 32
-125	OFF	**8.06**	36.11	36.11	36.11	36.14	36.11	36.08	36.11	36.14	36.08
-125	**-50**	**8.23**	**36.05**	**36.04**	**36.04**	**36.06**	**36.06**	**36.02**	**36.04**	**36.04**	**36.06**
-125	**-40**	**7.62**	**35.33**	**35.34**	**35.36**	**35.36**	**35.34**	**35.32**	**35.27**	**35.39**	**35.29**
-125	**-30**	**7.63**	**33.05**	**33.04**	**33.11**	**33.26**	**32.96**	**32.94**	**33.06**	**33.06**	**32.94**
-125	**-25**	**6.51**	**32.38**	**32.19**	**32.51**	**32.39**	**32.38**	**32.48**	**32.18**	**32.47**	**32.45**
-125	**-20**	**8.53**	**27.84**	**27.81**	**27.94**	**27.77**	**27.90**	**27.75**	**27.79**	**27.92**	**27.87**
-125	**-15**	**48.29**	**27.09**	**27.83**	**26.75**	**26.70**	**27.19**	**26.55**	**27.72**	**26.80**	**27.16**
-125	**-10**	**47679.09**	**22.44**	**25.79**	**23.81**	**19.29**	**20.00**	**20.41**	**26.27**	**19.76**	**24.18**

Table 3: Device 3 Measurements at -125 dBm GPS Rx Level

GPS/Sat dBm	LTE dBm	Avg Error (2D) in Meters	Avg SNR	Sat 11	Sat 14	Sat 17	Sat 20	Sat 23	Sat 24	Sat 31	Sat 32
-125	OFF	**3.43**	34.21	34.21	34.20	34.23	34.18	34.20	34.23	34.24	34.20
-125	**-50**	**4.39**	**34.73**	**34.74**	**34.74**	**34.75**	**34.71**	**34.72**	**34.76**	**34.71**	**34.73**
-125	**-40**	**7.95**	**34.77**	**34.77**	**34.78**	**34.80**	**34.72**	**34.74**	**34.83**	**34.74**	**34.75**
-125	**-30**	**5.65**	**34.69**	**34.67**	**34.70**	**34.70**	**34.67**	**34.69**	**34.73**	**34.66**	**34.68**
-125	**-25**	**6.71**	**34.62**	**34.63**	**34.62**	**34.63**	**34.60**	**34.61**	**34.66**	**34.59**	**34.61**
-125	**-20**	**5.81**	**34.45**	**34.45**	**34.46**	**34.48**	**34.45**	**34.42**	**34.49**	**34.40**	**34.44**
-125	**-15**	**6.82**	**33.44**	**33.44**	**33.42**	**33.46**	**33.46**	**33.41**	**33.49**	**33.41**	**33.42**
-125	**-10**	**6.07**	**31.44**	**31.55**	**31.53**	**31.58**	**31.57**	**31.51**	**31.02**	**31.56**	**31.21**

Table 4: Device 1 Measurements at -130 dBm GPS Rx Level

GPS/Sat dBm	LTE dBm	Avg Error (2D) in meters	Avg SNR	Sat 11	Sat 14	Sat 17	Sat 20	Sat 23	Sat 24	Sat 31	Sat 32
-130	OFF	15.37	29.69	30.03	30.09	29.39	29.19	28.35	30.03	30.31	30.09

-130	**-50**	**11.61**	**30.09**	**30.25**	**30.11**	**29.88**	**30.02**	**30.15**	**30.29**	**30.35**	**29.68**
-130	**-40**	**6.14**	**30.57**	**30.66**	**30.47**	**30.70**	**30.75**	**30.61**	**30.62**	**30.69**	**30.10**
-130	**-30**	**7.82**	**30.18**	**30.17**	**30.17**	**30.19**	**N/A**	**30.17**	**30.20**	**30.17**	**30.17**
-130	**-25**	**3.46**	**28.05**	**29.80**	**27.22**	**26.45**	**29.65**	**29.83**	**29.40**	**22.06**	**29.97**
-130	**-20**	**12.30**	**23.14**	**29.00**	**N/A**	**N/A**	**20.08**	**18.24**	**19.36**	**29.00**	**N/A**
-130	**-15**	**5.86**	**25.18**	**26.83**	**26.85**	**26.45**	**N/A**	**19.50**	**26.63**	**23.14**	**26.83**
-130	**-10**	**12.43**	**23.81**	**24.88**	**25.00**	**18.00**	**25.00**	**23.79**	**26.00**	**N/A**	**24.00**

Table 5: Device 2Measurements at -130 dBm GPS Rx Level

GPS/Sat	**LTE**	**Avg**	**Avg**	**Sat**	**Sat**	**Sat**	**Sat**	**Sat**	**Sat**	**Sat**	**Sat**
dBm	**dBm**	**Error (2D) in meters**	**SNR**	**11**	**14**	**17**	**20**	**23**	**24**	**31**	**32**
-130	OFF	12.51	30.91	30.91	30.89	30.95	30.89	30.87	31.12	30.81	30.83
-130	**-50**	**9.39**	**30.57**	**30.60**	**30.54**	**30.61**	**30.48**	**30.54**	**30.67**	**30.59**	**30.53**
-130	**-40**	**7.52**	**29.19**	**29.16**	**29.19**	**29.18**	**29.21**	**29.18**	**29.18**	**29.23**	**29.21**
-130	**-30**	**8.09**	**28.11**	**28.15**	**28.14**	**28.27**	**28.12**	**28.05**	**28.14**	**28.29**	**27.73**
-130	**-25**	**7.83**	**26.60**	**27.01**	**25.06**	**26.11**	**26.88**	**26.67**	**27.07**	**27.01**	**26.97**
-130	**-20**	**28864.32**	**25.46**	**27.66**	**24.49**	**23.46**	**25.57**	**23.17**	**27.92**	**23.54**	**27.85**
-130	**-15**	**56018.61**	**25.38**	**26.60**	**21.78**	**27.30**	**24.52**	**20.46**	**27.47**	**26.61**	**28.32**
-130	**-10**	**57516.56**	**22.56**	**27.14**	**17.57**	**20.26**	**20.97**	**19.00**	**27.58**	**21.04**	**26.93**

Table 6: Device 3 Measurements at -130 dBm GPS Rx Level

GPS/Sat	**LTE**	**Avg**	**Avg**	**Sat**	**Sat**	**Sat**	**Sat**	**Sat**	**Sat**	**Sat**	**Sat**
dBm	**dBm**	**Error (2D) in meters**	**SNR**	**11**	**14**	**17**	**20**	**23**	**24**	**31**	**32**
-130	OFF	6.77	30.56	30.56	30.58	30.58	30.55	30.53	30.61	30.53	30.56

-130	**-50**	**5.37**	**30.17**	**30.20**	**30.21**	**30.18**	**30.13**	**30.17**	**30.21**	**30.13**	**30.14**
-130	**-40**	**20.23**	**30.62**	**30.61**		**30.64**	**30.62**	**30.63**	**30.64**		**30.59**
-130	**-30**	**6.91**	**29.74**	**29.75**	**29.76**	**29.75**	**29.72**	**29.73**	**29.77**	**29.70**	**29.76**
-130	**-25**	**7.61**	**29.93**	**29.95**	**29.92**	**29.96**	**29.91**	**29.91**	**29.95**	**29.92**	**29.92**
-130	**-20**	**6.80**	**29.71**	**29.73**	**29.72**	**29.73**	**29.71**	**29.76**	**29.75**	**29.63**	**29.67**
-130	**-15**	**6.80**	**28.53**	**28.62**	**28.60**	**28.58**	**28.46**	**28.49**	**28.47**	**28.52**	**28.53**
-130	**-10**	**56063.06**	**27.31**	**26.94**	**27.08**	**27.37**	**27.59**	**26.77**	**27.61**	**27.06**	**28.06**

It is understood that lower desired GPS signal levels may be observed in indoor environments. Moreover, some GPS receivers may be able to operate at levels as low as -150 dBm with data assistance (as a part of AGPS operation). However, if the received signal levels of all satellites lie below -130 dBm, it is likely that this indicates an indoor scenario, in which case the L-band signal levels would also be attenuated by the building penetration loss. As it was impractical to test a very large number of use cases, LightSquared's testing conformed to desired signal levels, which are believed to represent an outdoor environment in suburban or urban morphologies. The following section describes the results of a field trial to gather GPS received signal strength data in suburban and urban morphologies, in order to verify the GPS received signal levels used in this Section.

2.3 Conclusion

It may be observed from Tables 1 – 6 that, typically, the position error does not increase linearly with the OOB power level. As the OOB power level is increased, the SNR decreases more gradually than the position error increases. For example, in Table 2, as the OOB power is increased from zero to -30 dBm, the average SNR reduces by approximately 3 dB (from 36.11 to 33.05 dB), while the position error actually diminishes from 8.05 to 7.63 m. This suggests that, at this level of OOB power, the position error variation is being caused by the randomness of noise and interference waveforms and that no direct, causal relationship to the level of OOB power has been established. In contrast, a relationship with the reported SNR is clearly evident.

These results show that, from an operational, or user perceptible standpoint, traditional metrics such as the 3 dB desensitization point may be too pessimistic. In the same table, it can be seen that the position error increases rapidly beyond the OOB power level of -20 dBm, which happens to correspond to the 10 dB SNR degradation point.

3 Field Trial to Gather GPS Signal Strength Data

The objective of the trial was to determine actual GPS signal levels in various environments. The measurements included a static and a mobile component. In each case, GPS signals were collected over a 12 hour period to allow a full rotation of the GPS satellite constellation. Static measurements were made in the following environments:

- Open Sky – *no blockage from trees or local reflections from structures*
- Foliage Blockage – an *area where at least 50% of open sky GPS signals are blocked by trees*

- Urban Roof Top – *typical Urban rooftop*

Mobile measurements collections were made in the following environments:

- Urban "canyons"

- Typical suburban streets

The data was collected with a widely used commercial GPS receiver, which allowed the C/N of signals received from individual satellites to be monitored. The antenna was mounted on the roof of a vehicle as shown in Figure 2.

Figure 2: Antenna Mounting on Vehicle for GPS Received Power Measurement

The C/N was mapped to receive signal power by calibrating the antenna at an accredited laboratory. The characterization was performed by injecting a GPS signal at a known level into the device and reading the output C/N values. The calibration curve is shown in Figure 3.

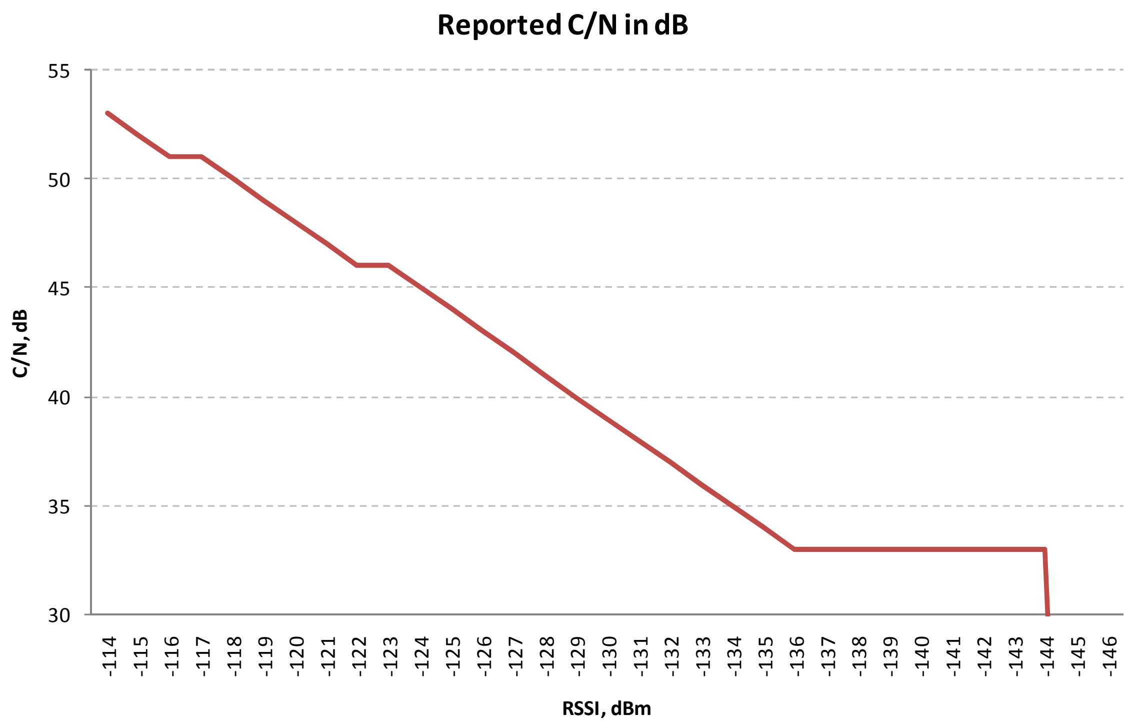

Figure 3: Antenna Calibration for GPS Received Power Measurement

The results for static measurements are shown in Table 7 below.

Table 7: Static Measurement Results

Environment Type	Average C/N in dB (4 strongest Satellites)	Average RSSI in dBm
Open Sky	45	-124
Foliage Blocked	41	-128
Rooftop	45	-124

The results for mobile measurements in urban clutter are shown in Figure 4, together with the routes traversed. It was observed that in urban clutter, the GPS signal varies between -124 to -128 dBm (41-45 dB C/N) with few instances of -130 dBm and -121 dBm.

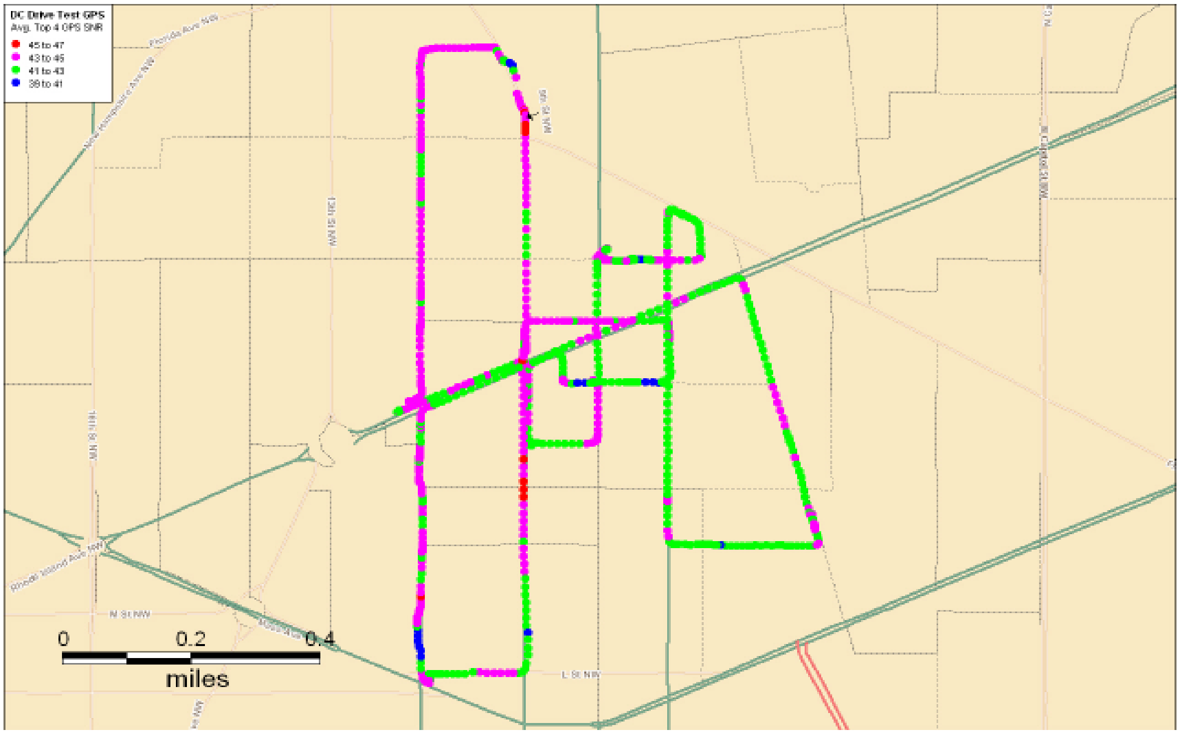

Figure 4: Route and results for mobile measurements in Downtown Washington DC (urban morphology)

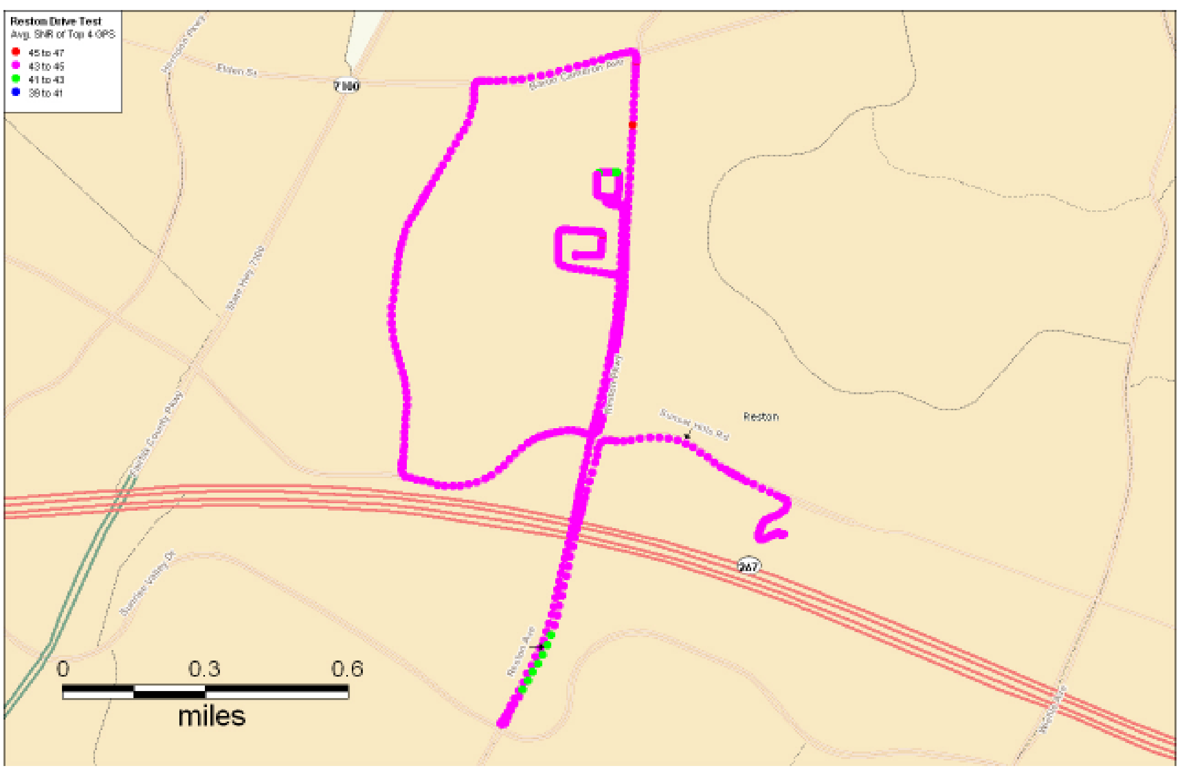

Figure 5: Route and results for mobile measurements in Reston, VA (suburban morphology)

The results for mobile measurements in suburban clutter are shown in Figure 5, together with the routes traversed. It was observed that in suburban clutter, the GPS signals generally remain steady between -126 dBm & -124 dBm (corresponding to 43 to 45 dB C/N).

It may be concluded from the above that, for the 4 strongest satellites (the minimum number required for a fix), desired signal levels of -125 dBm and -130 dBm are representative values for suburban and urban morphologies.

4 References

[1] R4-110470, "Preliminary results on Overload Characteristics of GPS Receivers in Proximity to LightSquared's L-band Terrestrial Base Stations (BTS) and User Equipment (UE)", RAN4 #57AH, LightSquared, Austin, TX, Jan. 2010

[2] FCC Report DA-11-133, January 26, 2011, http://www.fcc.gov/Daily_Releases/Daily_Business/2011/db0126/DA-11-133A1.pdf