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February 24, 2016

Ms. Marlene H. Dortch
Secretary
Federal Communications Commission
445 12th Street, S.W.
Washington, D.C. 20554

Re: Written *ex parte* presentation in RM-11681; IB Docket No. 12-340; IB Docket No. 11-109; IBFS File Nos. SES-MOD-20151231-00981, SAT-MOD-20151231-00090, and SAT-MOD-20151231-00091

Dear Ms. Dortch:

As we have shared previously with the Commission, the undersigned as counsel to Ligado Networks (née LightSquared) hired Roberson and Associates ("RAA") to conduct tests on whether deployment of LTE in adjacent channels affects the ability of GPS devices to provide consumers with accurate location and timing results.[1] These tests have been ongoing, and after the company reached co-existence agreements with Deere,[2] Garmin,[3] and Trimble[4] in December

[1] *See* Letter from Gerard J. Waldron to Marlene H. Dortch, IB Docket No. 12-340; IBFS File Nos. SAT-MOD-20101118-00239; SAT-MOD-20120928-00160; SAT-MOD-20120928-00161; SES-MOD-20121001-00872 (filed Aug. 25, 2015); Letter from Gerard J. Waldron to Marlene H. Dortch, IB Docket No. 12-340; IBFS File Nos. SAT-MOD-20101118-00239; SAT-MOD-20120928-00160; SAT-MOD-20120928-00161; SES-MOD-20121001-00872 (filed July 15, 2015); Gerard J. Waldron to Marlene H. Dortch, IB Docket No. 12-340; IBFS File Nos. SAT-MOD-20101118-00239; SAT-MOD-20120928-00160; SAT-MOD-20120928-00161; SES-MOD-20121001-00872 (filed June 24, 2015).

[2] *See* Letter from Gerard J. Waldron to Marlene H. Dortch, IB Docket No. 12-340; IB Docket No. 11-109; IBFS File Nos. SAT-MOD-20120928-00160; SAT-MOD-20120928-00161; SES-MOD-20121001-00872; SES-RWL-20110908-01047; SES-MOD-20141030-00835 (filed Dec. 8, 2015).

[3] *See* Letter from Gerard J. Waldron to Marlene H. Dortch, IB Docket No. 12-340; IB Docket No. 11-109; IBFS File Nos. SAT-MOD-20120928-00160; SAT-MOD-20120928-00161; SES-MOD-20121001-00872; SES-RWL-20110908-01047; SES-MOD-20141030-00835 (filed Dec. 17, 2015).

2015, the testing also addresses how GPS devices perform in terms of locational accuracy given the reduced operating parameters agreed to by the company in the context of those agreements, and as embodied in the license modification applications filed on December 31, 2015.[5]

On January 11, 2016, Ligado representatives met with Commission staff and representatives from the Department of Transportation ("DOT"), Department of Defense, and the National Telecommunications and Information Administration to discuss the settlement agreements referenced above, the license modification applications, and the need for prompt Commission issuance of a public notice on these and related issues.[6] During that meeting, a question was raised by one of the Executive Branch representatives whether the operational limitations contained in the agreement reached by Garmin and Ligado were in fact protective of Garmin's consumers. The undersigned responded that while the RAA testing and analysis of all the subject GPS devices was not completely finished, the results for Garmin devices were sufficiently complete that (a) they showed that the tested Garmin devices performed at the same accuracy level in the presence of LTE operating at the stipulated power levels as without; and (b) RAA was in a position to present those results in a briefing to the Executive Branch officials at RAA's testing facility.

The attached presentation, with an accompanying explanation by the RAA team, was provided to representatives of the Department of Transportation, Department of Defense, and NTIA in a meeting at AT4 Technologies, the lab in Herndon, VA that conducted the tests, on February 5, 2016. As shown in the attached presentation, the testing results demonstrate

- The Garmin and non-Garmin general navigation devices tested showed no degradation in performance at the operating levels contained in the settlement agreements and reflected in the license modification applications;[7]
- Smartphones tested showed no degradation, and in fact have become more resilient over time;[8] and

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[4] *See* Letter from Gerard J. Waldron to Marlene H. Dortch, RM-11681; IB Docket No. 12-340; IB Docket No. 11-109; IBFS File Nos. SES-MOD-20151231-00981, SAT-MOD-20151231-00090, and SAT-MOD-20151231-00091(filed Feb. 3, 2016).
[5] Letter from Gerard J. Waldron to Marlene H. Dortch, IB Docket No. 12-340; IB Docket No. 11-109; IBFS File Nos. SAT-MOD-20120928-00160; SAT-MOD-20120928-00161; SES-MOD-20121001-00872 (filed Dec. 31, 2015).
[6] Letter from Gerard J. Waldron to Marlene H. Dortch, IB Docket No. 12-340; IB Docket No. 11-109; IBFS File Nos. SAT-MOD-20120928-00160; SAT-MOD-20120928-00161; SES-MOD-20121001-00872; SES-MOD-20151231-00981; SAT-MOD-20151231-00090; SAT-MOD-20151231-00091 (filed Jan. 13, 2016).
[7] Roberson and Associates, LLC, *GPS and Adjacent Band Co-Existence Study*, 4, 16–27 (Feb. 5, 2016).
[8] *Id.* at 28–30.

- More fundamentally, the metric the DoT has proposed to use in its testing of adjacent bands—a 1 dB rise in the carrier to noise ratio (the "1 dB proposal")—is fatally flawed because it does not accurately predict impact of adjacent band signals on GPS device positioning performance. Indeed, the testing demonstrated that average carrier to noise ratio value reported by the receiver (averaged over all GPS satellites) showed small, random variations that *can exceed 1dB in the absence of adjacent band signals*.[9]

The purpose of the attached presentation was to address the question raised by an Executive Branch representative whether the limits agreed to by Garmin do, in fact, protect users of Garmin equipment. The presentation also shows that the relationship between 1 dB and GPS devices not delivering promised results to consumers is what statisticians call "stochastic"—which is to say, there is no correlation between 1 dB and GPS performance and instead the results are marked by randomness. Clearly, as the RAA testing demonstrates, this stochastic relationship means that a 1 dB metric cannot be a guide for a worthwhile study.

Preliminary results from other testing are consistent with these results for Garmin devices, and the RAA testing and analysis is entering the final phase. We are also using this opportunity to provide an updated version of RAA's GPS Sensitivity Measurement Plan, the test plan that was used in connection with the testing results discussed herein. We expect to share the complete results and analysis from the testing as necessary and appropriate.

[9] *Id.* at 5, 31–32.

Please direct any questions to the undersigned.

Sincerely,

/s/Gerard J. Waldron
Gerard J. Waldron
Michael Beder
Counsel to Ligado Networks LLC

cc:

Phil Verveer
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Louis Peraertz
Joanna Thomas
Travis Litman
Jessica Almond
Erin McGrath
Brendan Carr
Mindel De La Torre
Paul Murray
Karl Kensinger
Bob Nelson
Jon Wilkins
Charles Mathias
Julius Knapp
Ron Repasi
Jon Chambers
Jennifer Tatel

Attachment

LightSquared

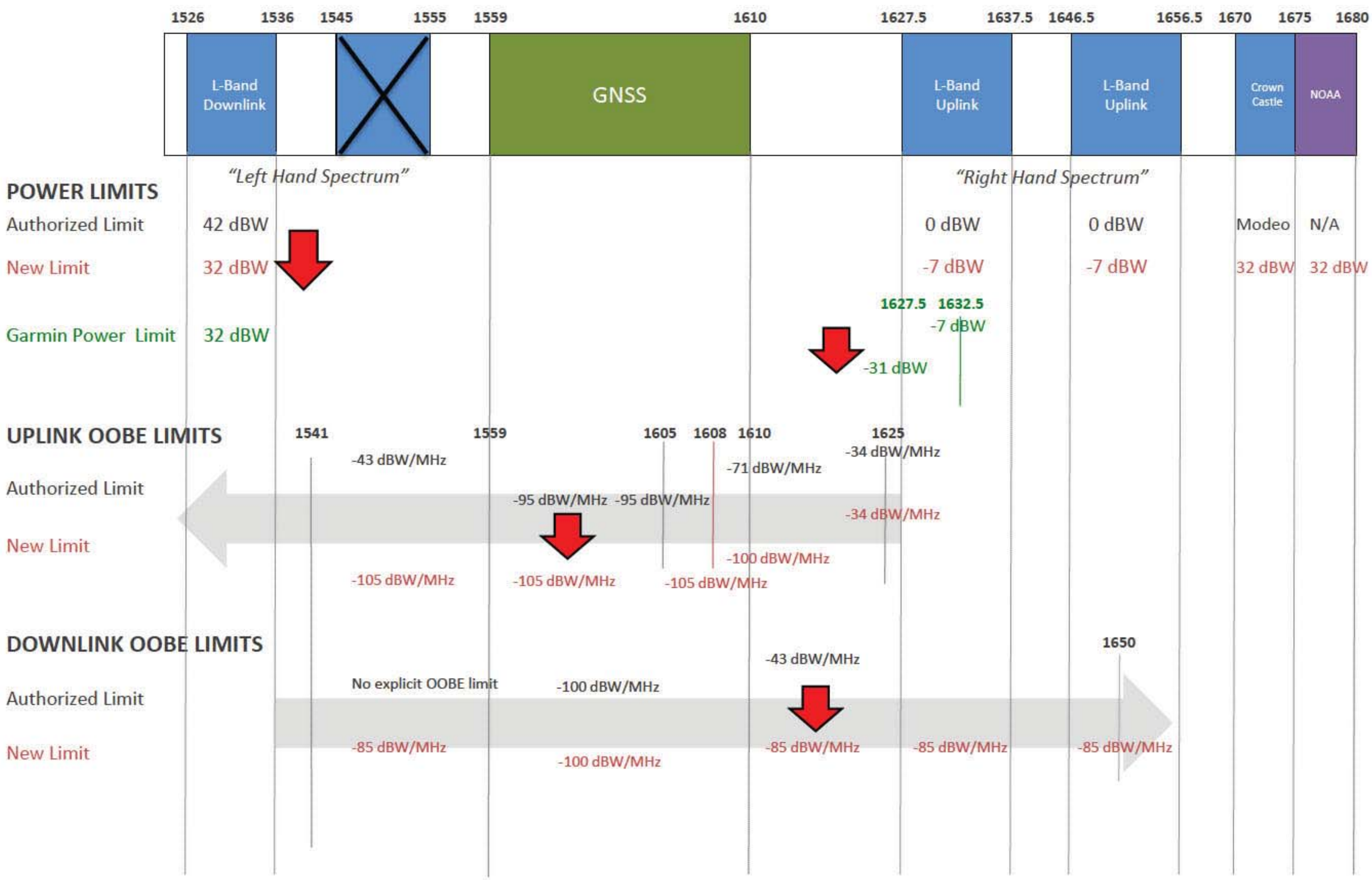
GPS and Adjacent Band Co-Existence Study: Illustration of Method and Selected Results

February 5, 2016

Topics

GPS-New LightSquared Plan Requires Substantial Modifications of License Conditions

Roberson and Associates, LLC
Technology and Management Consultants



Note: The Coexistence Plans also include narrowband limits not depicted here.

Conclusions: Garmin Devices Not Affected By Plan

Under the GPS-New LightSquared Plan, all seven (7) Garmin GLN devices perform in accordance with the marketing promise

- LightSquared adjacent band signals do not impact position accuracy

Test Performance under the GPS-New LightSquared Plan

Device	Test	1526 - 1536 MHz Downlink	1627.5 – 1637.5 MHz Uplink	1646.5 – 1656.5 MHz Uplink	1670 – 1680 MHz Downlink
GPSMAP 76 CSx	Motion	No Impact	No Impact	No Impact	No Impact
eTrex H	Motion	No Impact	No Impact	No Impact	No Impact
Nuvi 55LM	Motion	No Impact	No Impact	No Impact	No Impact
Nuvi 2597LMT	Motion	No Impact	No Impact	No Impact	No Impact
Nuvi 2495LMT	Motion	No Impact	No Impact	No Impact	No Impact
GPSMAP 78 SC	Motion	No Impact	No Impact	No Impact	No Impact
Montana 650t	Motion	No Impact	No Impact	No Impact	No Impact

Conclusions: Plan’s Impact Can be Tested; 1 dB C/N_0 not predictive

- RAA successfully tested GPS user performance metrics for four 10MHz bands
  - 1526-1536 MHz, 1627.5-1637.5 MHz, 1646.5-1656.5 MHz, and 1670-1680 MHz
- GPS-New LightSquared Plan’s signal levels do not affect GPS user performance metrics for selected Garmin, Motorola, and Samsung devices
- The Plan provides sufficient limits to adjacent band signals to assure GPS receiver performance
- 1 dB C/N_0 degradation does not predict impact of adjacent band signals on GPS device positioning performance

Measurement and Assessment Approach

1. Establish performance baseline for each device

- Measure position error without LTE
- GPS signal for 2 hours

2. Measure performance with LTE

- Apply increasing LTE signal up to and beyond levels in the Plan
- Test all four 10 MHz bands
- Test devices in simulated motion

3. Compare device performance with and without LTE to determine the difference

4. Report device performance under the GPS-New LightSquared Plan

Definitions and Terminology (1 of 3)

Transmitted or received power can be measured in dBW or dBm

- dBW (decibel referenced to 1 Watt)
  - ✓ 0 dBW = 1 Watt
  - ✓ 32 dBW = 1585 Watts
  - ✓ 42 dBW = 15848 Watts
  - ✓ -7 dBW = 0.2 Watts
- dBm (decibel referenced to 1 milliWatt)
  - ✓ 0 dBm = 1 mW
  - ✓ 23 dBm = 0.2 Watt
  - ✓ -19 dBm = 1.3 X 10^{-5} Watts

Definitions and Terminology (2 of 3)

Carrier to Noise

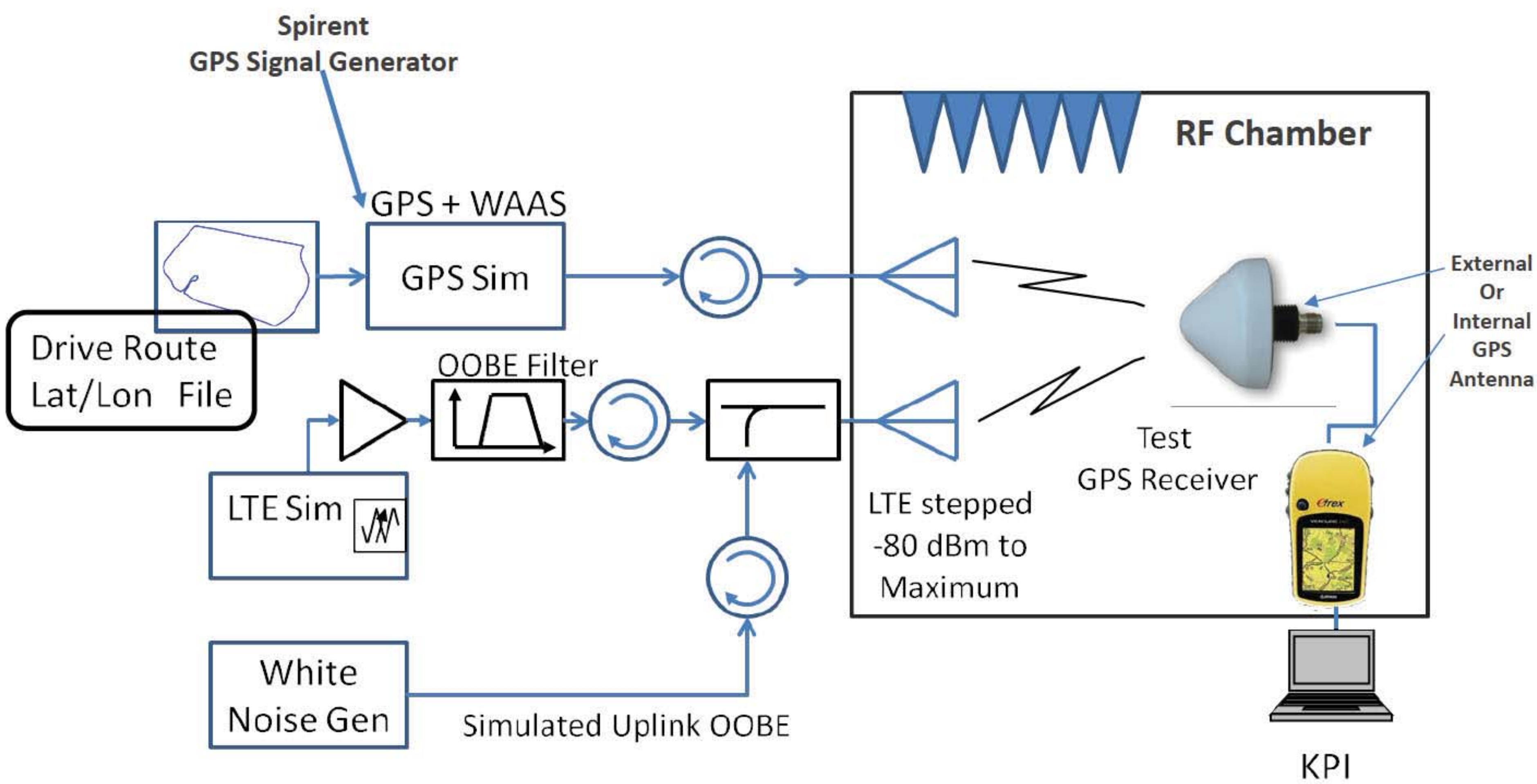
- C/N_0 (Carrier to Noise Power Spectral Density Ratio)
- Measured in dB-Hz
- This is a measure of signal quality as *perceived by the receiver* (<u>it is a metric produced by the receiver, not measured by external lab instruments</u>)

Definitions and Terminology (3 of 3)

Position Error

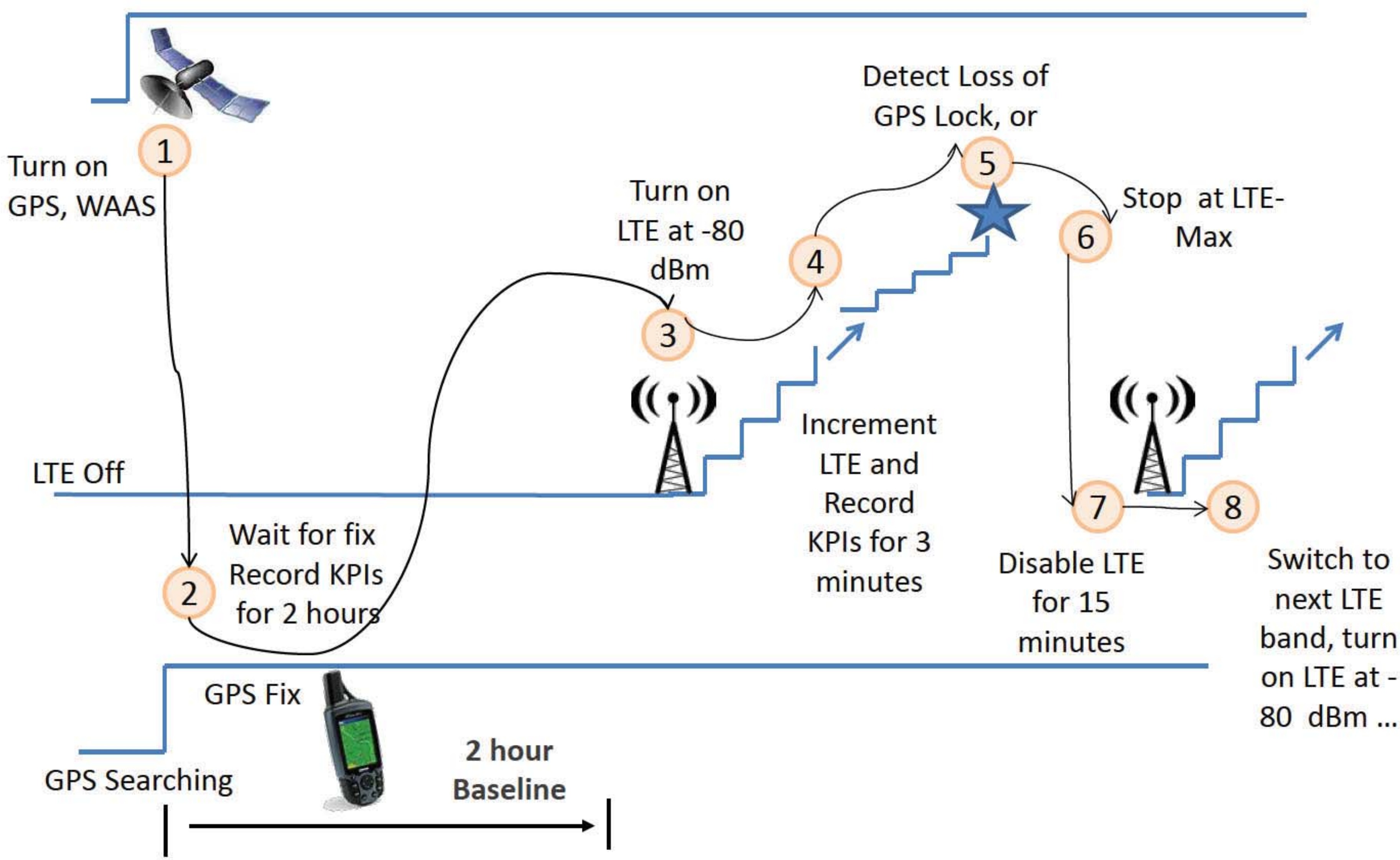
- 2D position error is the difference between the device’s true position and the position measured by the device, in any horizontal direction, in meters
- 2D position error is always a positive number
- 3D position error is the difference between the device’s true position and the position measured by the device, in any direction in three dimensions, in meters
- 3D position error is always positive

Motion Testing and Test Set Up



- **LTE simulated with all 50 Resource Blocks populated for uplink and downlink**

Basic KPI (Position Error) Measurement Sequence: General Location and Navigation and High Precision Devices



Motion Testing Procedure

Create a "Golden" file of Lat-Lon versus Time pairs by driving a test route

↓

Load Lat-Lon/Time file onto GPS simulator

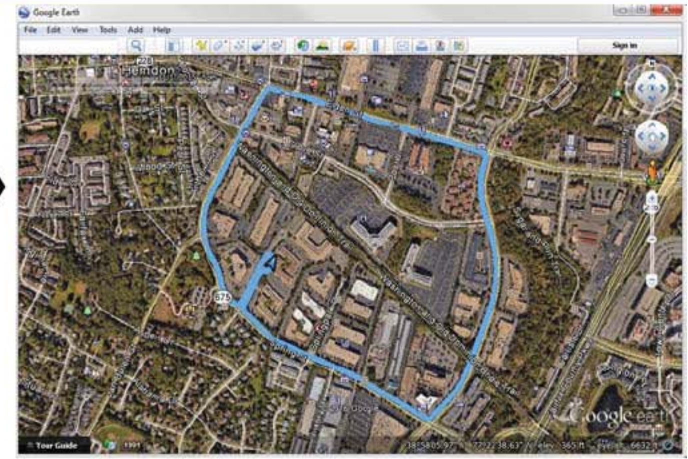
↓

Enter date and time of simulation start

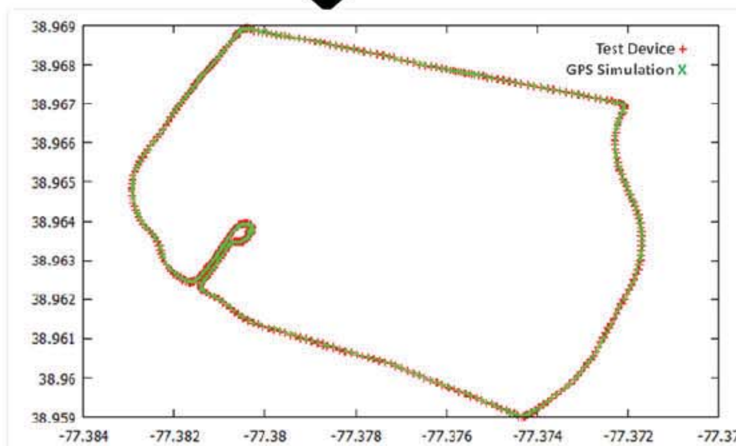
↓

Simulator calculates orbits and generates ideal GPS satellite signals to the device as if it were moving over the test route at the simulated speed

Google earth view of drive route used



Simulated drive route provided to GPS generator

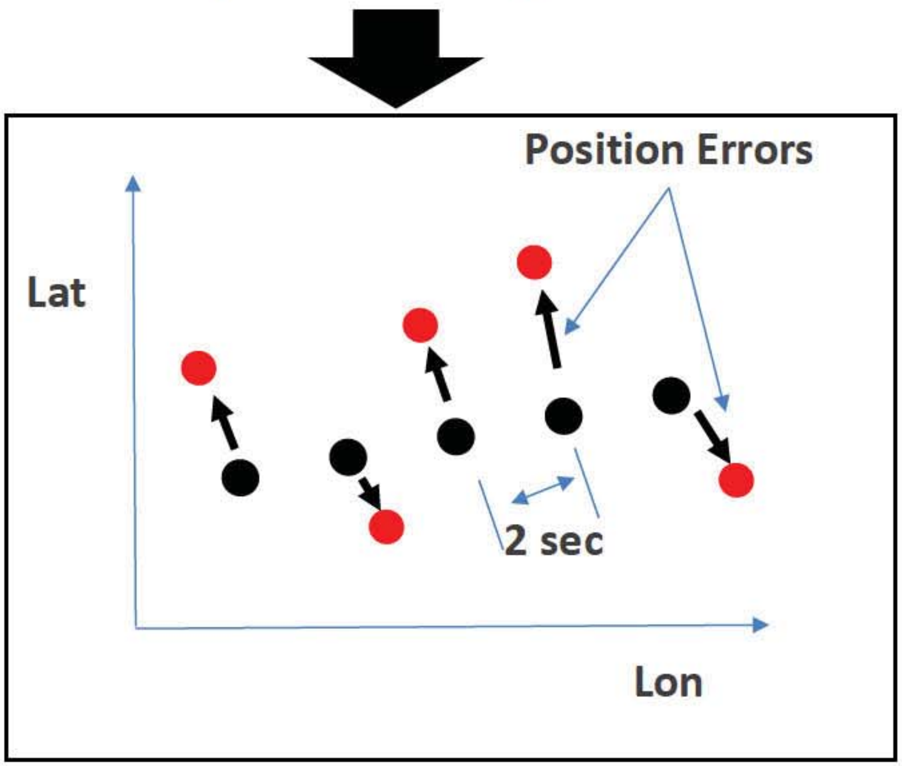


Device testing with Motion is feasible and has been performed on multiple devices

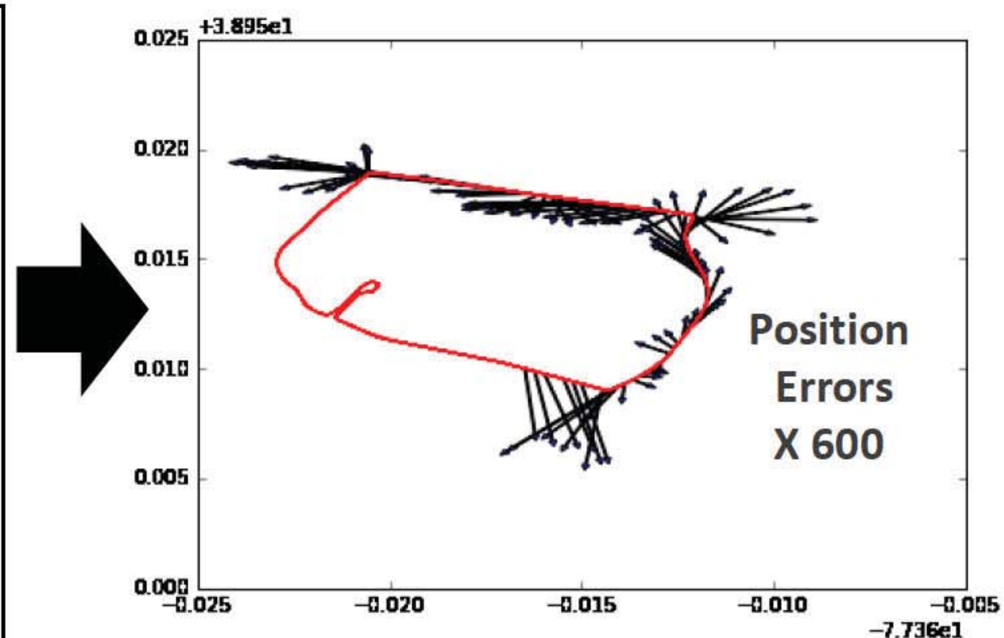
Calculating 2D Position Error of GPS Devices

Garmin eTrex Generates a Location Estimate (Position Measurement) Every Two-Seconds

(Garmin eTrex)



- True Positions from GPS Generator
- Position Measurements from Device

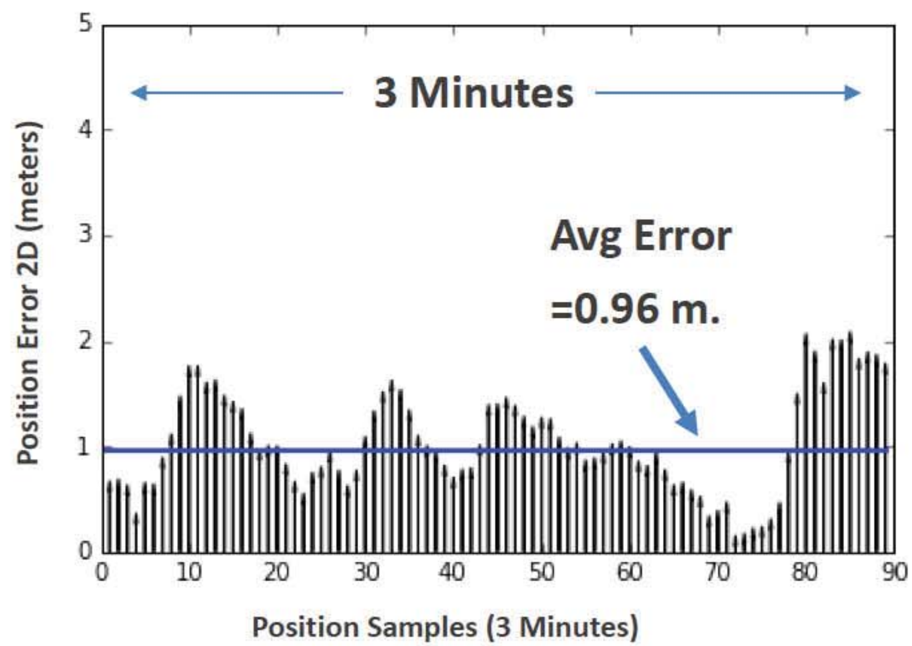


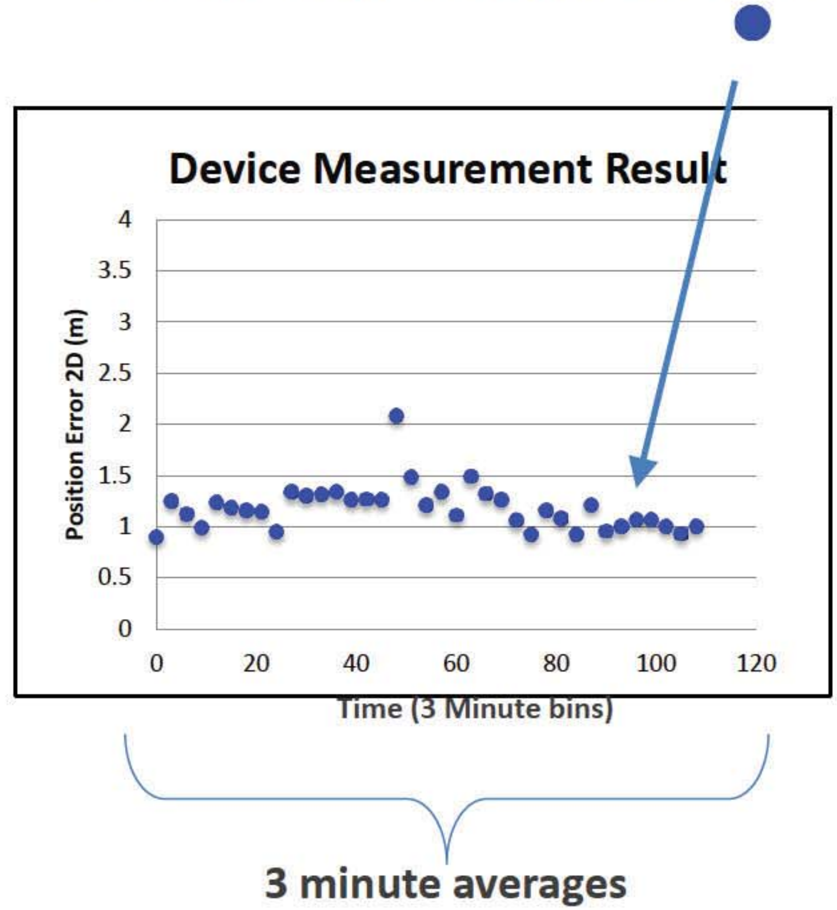
Position Errors are Calculated Over the Simulated Drive Route

Plotting Average Position Error: Device Measurement Results

90 Position Errors Are Calculated from 90 Device Measurements

The Average Position Errors are Calculated And Plotted as Blue Dots





Plan Power Limits on Transmitter (Modified License) Translate to Received Power

- GPS-New LightSquared Plan
  - Uplink Power at Handset Transmitter
    - -7 dBW (which equals 23 dBm) handset output EIRP*
      - Reduced power in 1627.5 – 1632.5 MHz until 2021
    - Projected value at GPS receiver
      - Based on -7 dBW transmit EIRP, free space pathloss, 1 m separation and 5 dB antenna coupling loss: -**19 dBm**
  - Downlink Power at LTE Base Station Transmitter
    - 32 dBW (which equals 62 dBm) base station output EIRP*
    - Projected value at GPS receiver based on observed power on the ground during TWG Las Vegas trials: **-20 dBm**

*** Effective Isotropic Radiated Power**

Appendix*

Specifications

Physical

Case: Fully-gasketed, high-impact plastic alloy, waterproof to IPX7 standards (waterproof to 1 meter for 30 minutes)

Size: 4.4"H x 2"W x 1.2"D (11.2 x 5.1 x 3.0 cm)

Weight: Approx. 5.3 ounces (150g) w/batteries

Temperature Range: 5° to 158°F (-15° to 70°C)[1]

Performance

Receiver: WAAS enabled, high-sensitivity

Acquisition time: Approx. 3 seconds (hot start)
Approx. 32 seconds (warm start)
Approx. 39 seconds (cold start)

Update Rate: 1/second, continuous

GPS Accuracy: <10 meters (33 ft) RMS[2]

DGPS (WAAS) Accuracy: 3 meters (10ft) 95% typical with DGPS corrections[3]

Velocity Accuracy: .1 knot RMS steady state

Dynamics: Performs to specifications to 6 g's

Interfaces: NMEA 0183 (versions 2.00-3.0), RTCM 104 (for DGPS corrections) and RS-232 for computer interface

Antenna: Built-In

Power

Input: Two 1.5-volt AA batteries, External power adapter

Battery Life: Up to 17 hours of typical use

Specifications subject to change without notice.

1 The temperature rating for the eTrex may exceed the usable range of some batteries. External power can only be applied using the Garmin Auto Power Adapter or computer Interface Cable with Auto Power Adapter; this cable contains a voltage regulator).

2 Subject to accuracy degradation to 100m 2DRMS under the U.S.DOD Selective Availability program.

3 Optional Differential Beacon Receiver Input (by others).

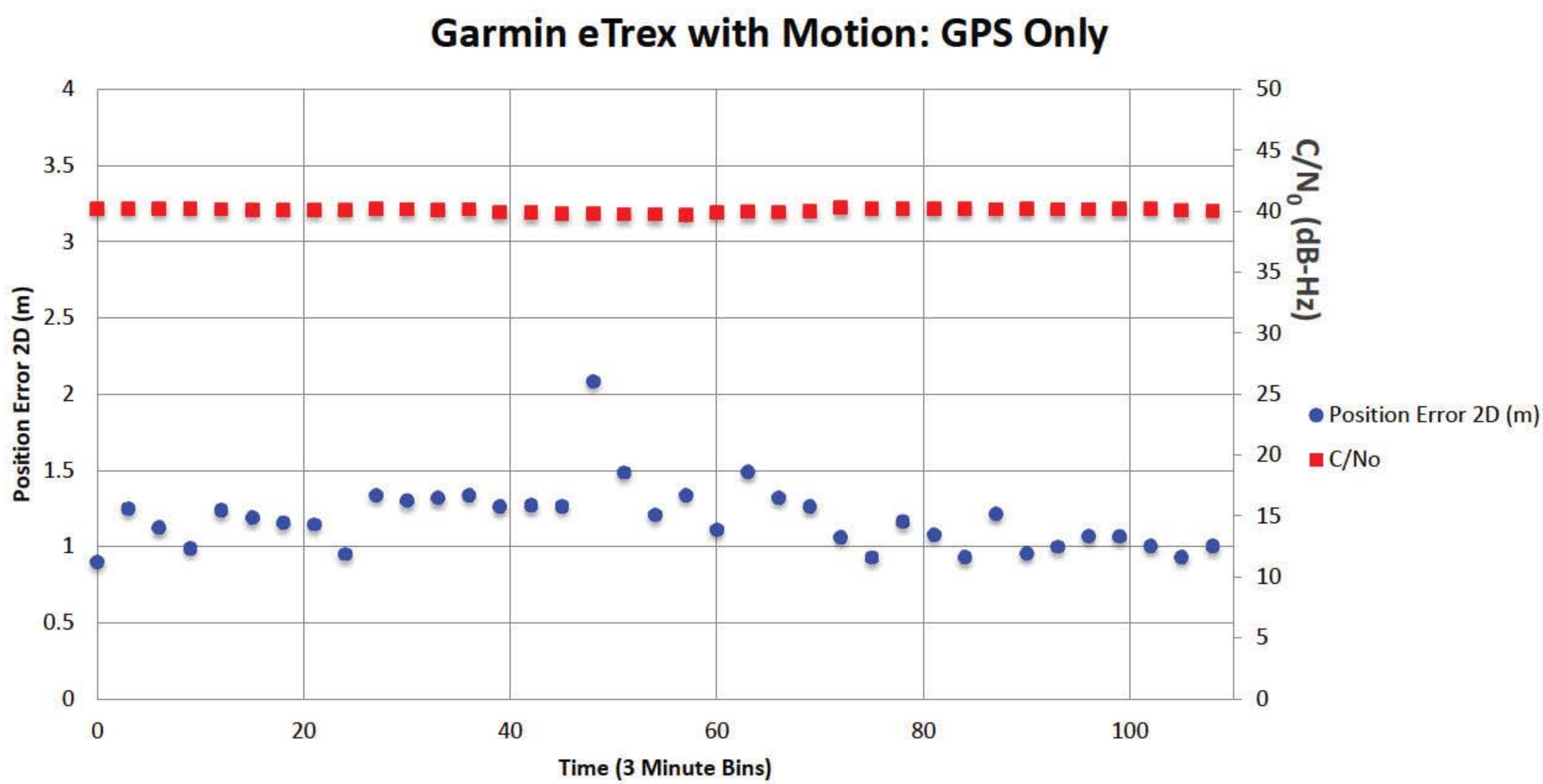
Garmin eTrex

Results: Plan does not affect device performance on any of the four 10 MHz bands

*static.garmin.com/pumac/eTrexH_OwnersManual.pdf

Garmin eTrex with Open Sky GPS with Motion GPS Only (Baseline)

Device: Garmin Etrex   Device Category: GLN
GPS Condition: Open Sky GPS with Motion
Antenna: Internal   WAAS locked during test
KPI: 2D Position Error, meters (3 Minute Averaging Window)

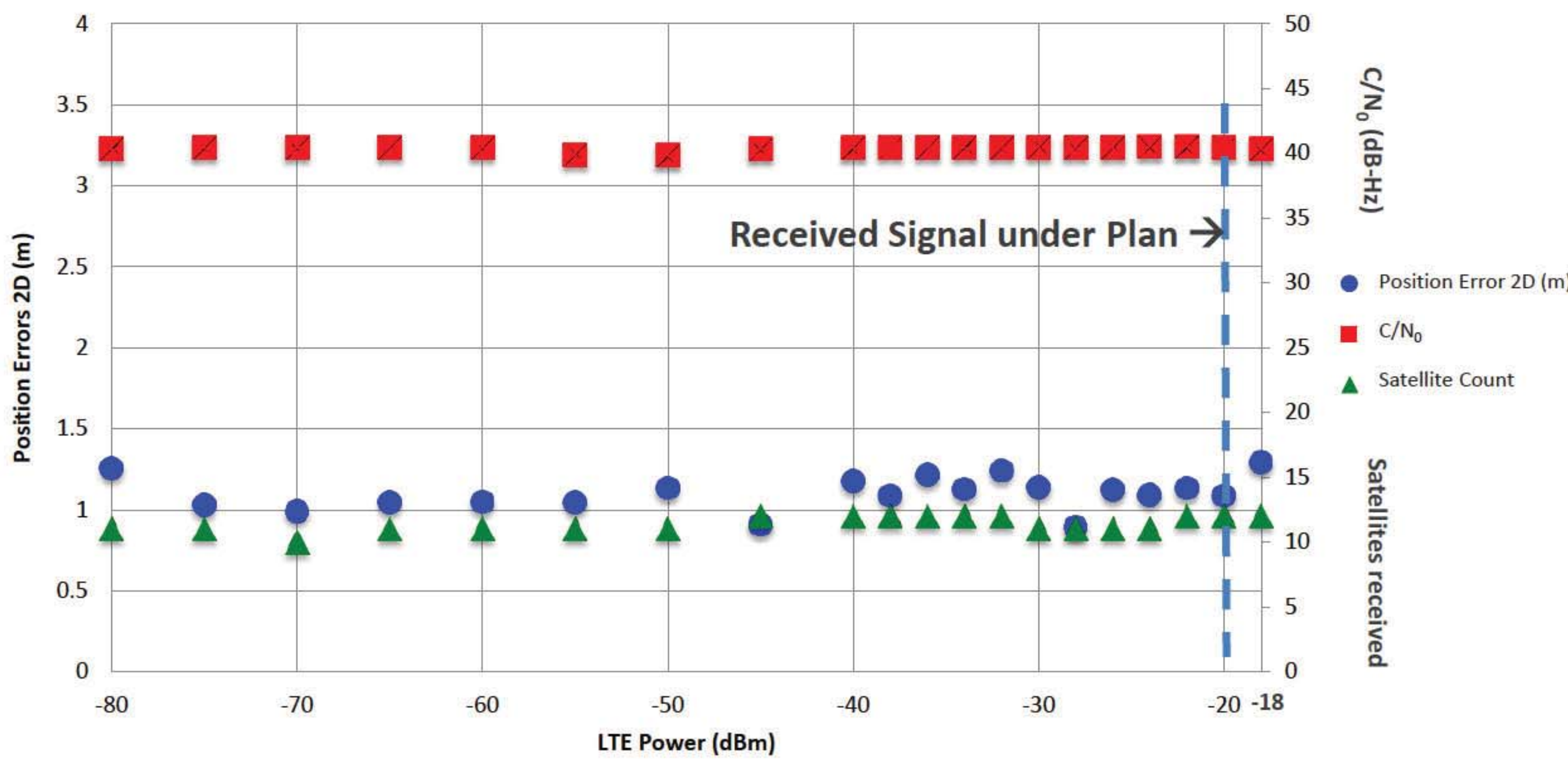


Garmin eTrex: 1526-1536 MHz LTE – Downlink

Device: Garmin Etrex   Device Category: GLN
GPS Condition: Open Sky GPS with Motion
Antenna: Internal   WAAS locked during test
KPI: 2D Position Error, meters (3 Minute Averaging Window)

Conclusion: Plan signal does not change performance

Garmin eTrex: Average 2D Position Error vs.. LTE Power

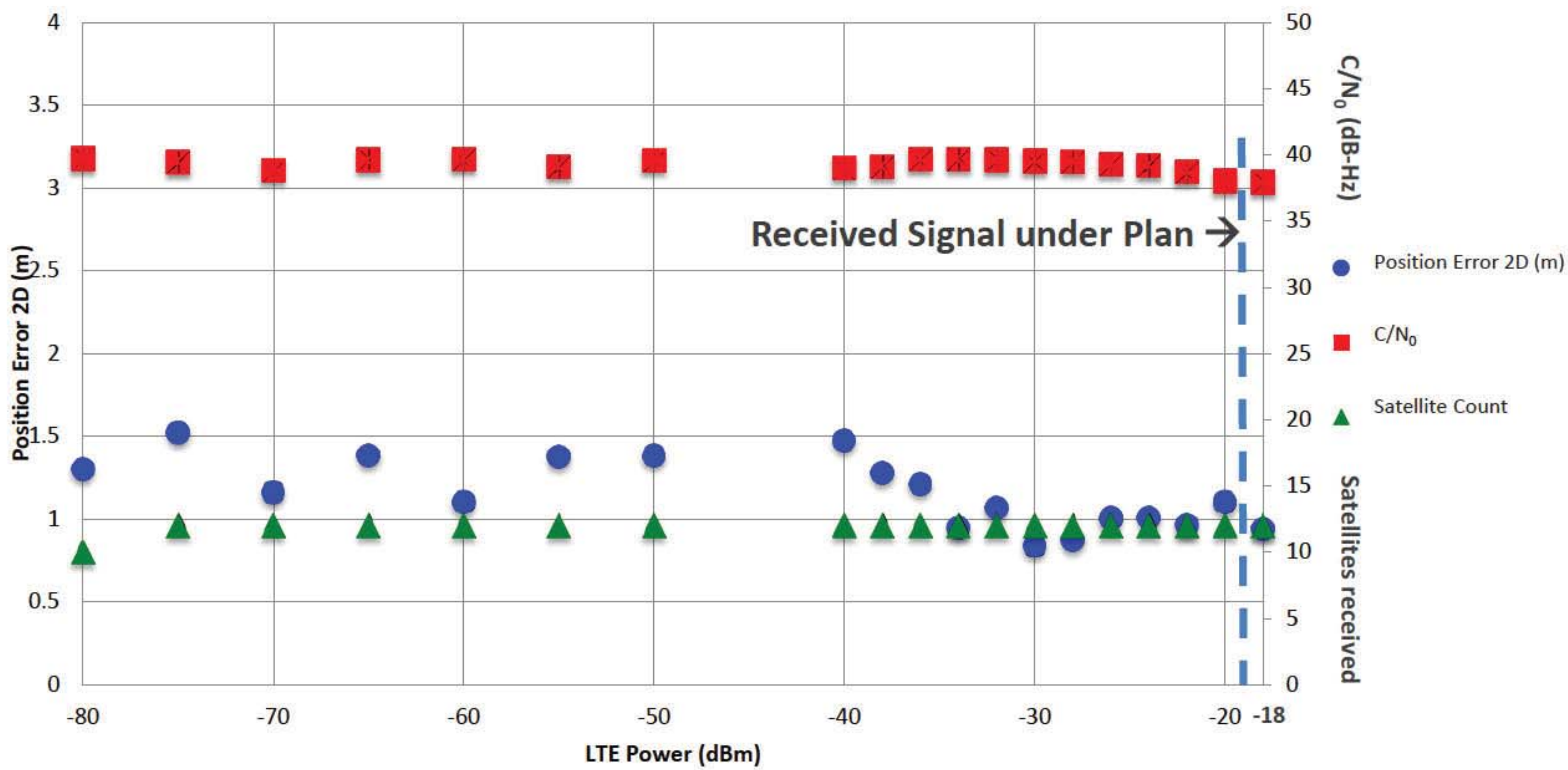


Garmin eTrex: 1627.5-1637.5 MHz LTE – Uplink

Device: Garmin Etrex   Device Category: GLN
GPS Condition: Open Sky GPS with Motion
Antenna: Internal   WAAS locked during test
KPI: 2D Position Error, meters (3 Minute Averaging Window)

Conclusion: Plan signal does not change performance

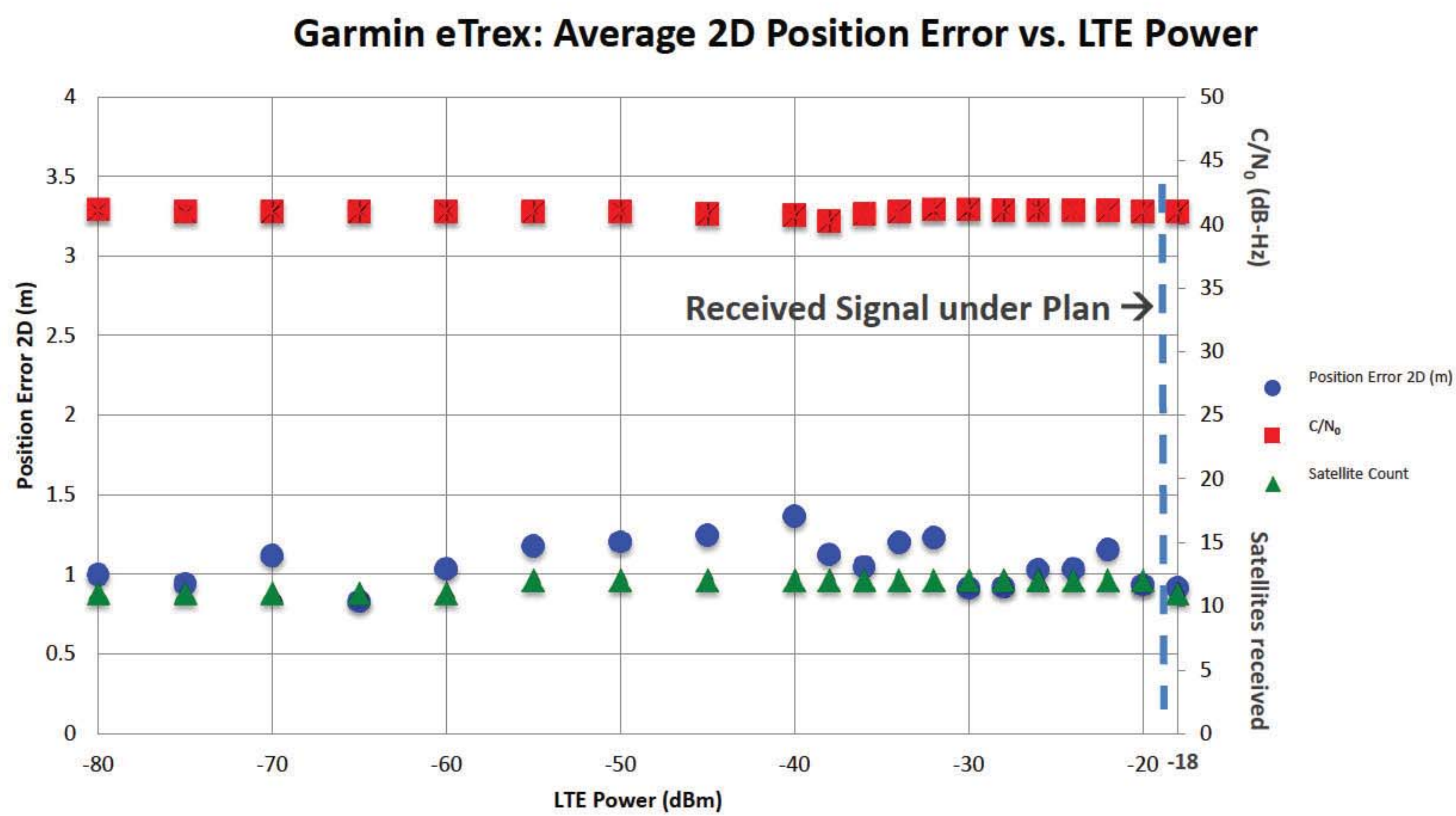
Garmin eTrex: Average 2D Position Error vs. LTE Power



Garmin eTrex: 1646.5-1656.5 MHz LTE – Uplink

Device: Garmin Etrex   Device Category: GLN
GPS Condition: Open Sky GPS with Motion
Antenna: Internal   WAAS locked during test
KPI: 2D Position Error, meters (3 Minute Averaging Window)

Conclusion: Plan signal does not change performance

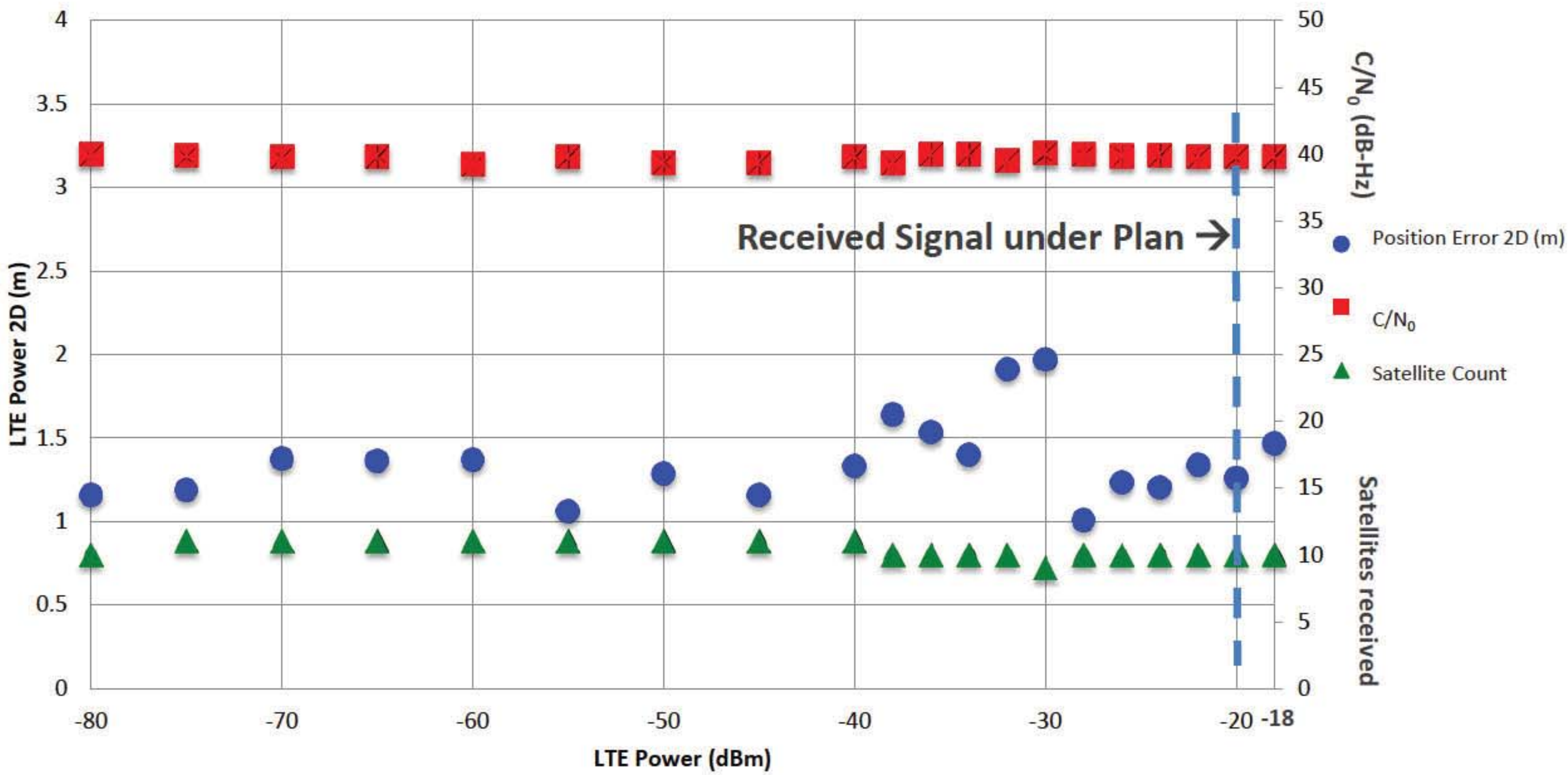


Garmin eTrex: 1670-1680 MHz LTE – Downlink

Device: Garmin Etrex **Device Category: GLN**
GPS Condition: Open Sky GPS with Motion
Antenna: Internal WAAS locked during test
KPI: 2D Position Error, meters (3 Minute Averaging Window)

Conclusion: Plan signal does not change performance

Garmin eTrex: Average 2D Position Error vs. LTE Power



1.4 GP-2106 Technical Specification

Impedance : 50Ω

No	Function	Specification
GPS receiver		
1	Chipset	SiRFstarIV GSD4e-9311-TR Signature ROM
2	Frequency	L1 1575.42MHz
3	Code	C.A. Code.
4	Channels	48 track verification channels
5	Chipset Sensitivity	High sensitivity navigation engine (PVT) tracks as low as -163dBm
6	Chipset Cold start	35 sec (open sky)
7	Chipset Warm start	35 sec (open sky)
8	Hot start	1 sec (open sky)
9	Reacquisition	0.1sec typical
10	Position accuracy	2.5meters(50% 24hr static, -130dBm)
11	Maximum altitude	18288 m
12	Maximum velocity	514 m/s
13	Update rate	1Hz

Motorola MW810

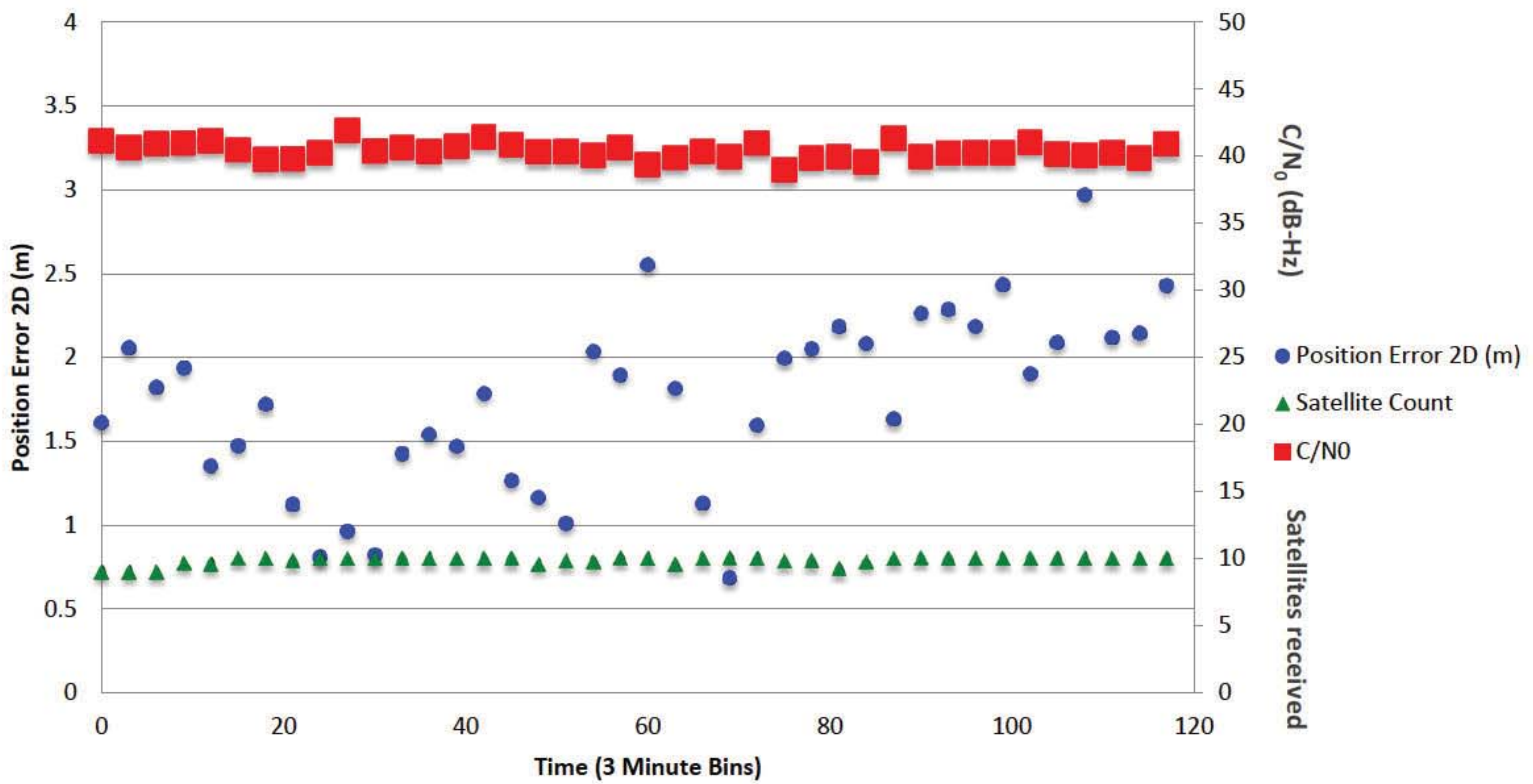
Results: Plan does not affect device performance on any of the four 10 MHz bands

*From Page 5 of the specification for the GP-2106 SIRFSTAR IV Module. An exemplary module using the chipset included in the MW810. Position accuracy of the MW810 was not available from the device specification.

MW810 with Motion Open Sky GPS Only (Baseline)

Device: MW810 Device Category: GLN
GPS Condition: Open Sky GPS with Motion
Antenna: Motorola
KPI: 2D Position Error, meters (3 Minute Averaging Window)

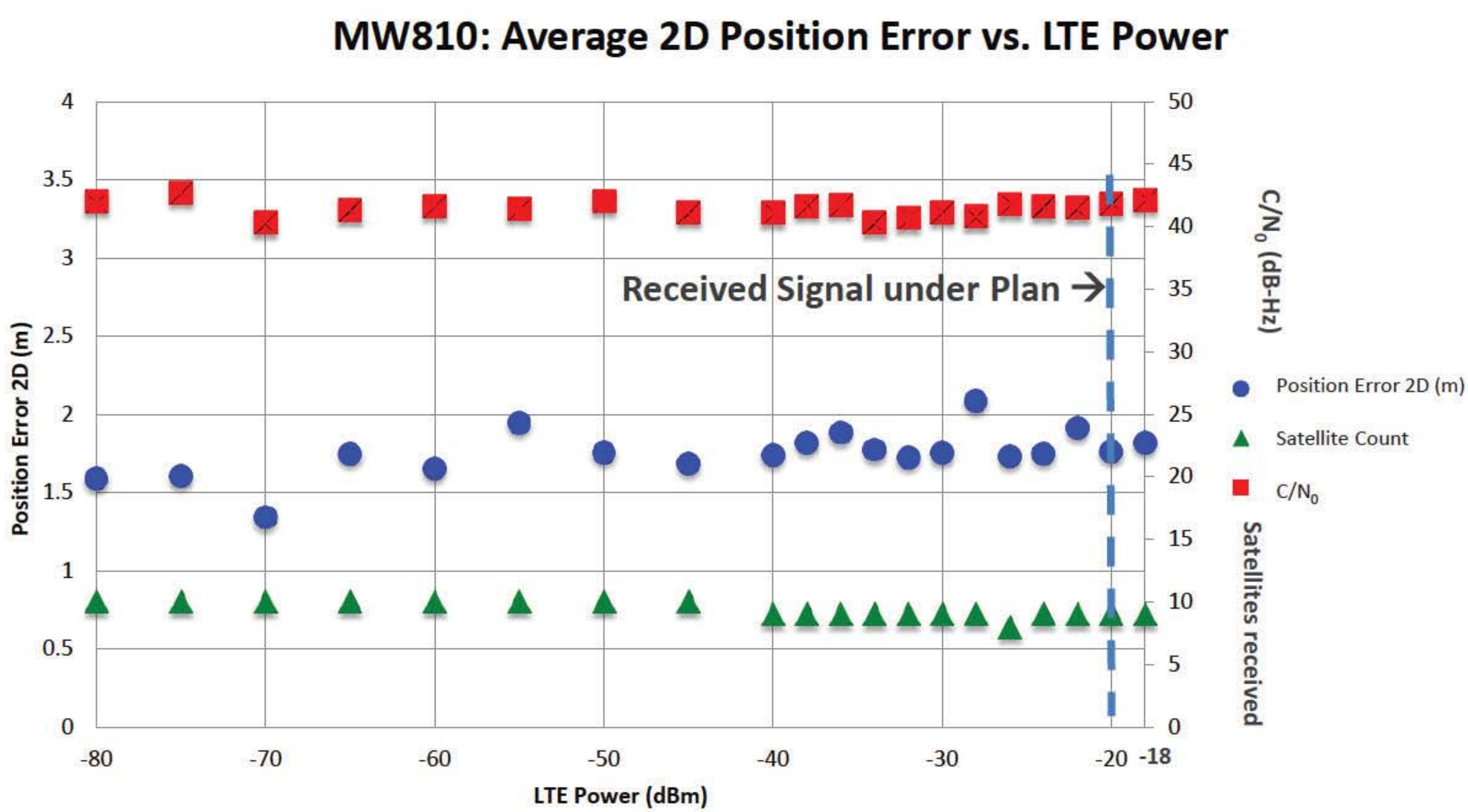
MW810 with Motion: GPS Only



MW810: 1526-1536 MHz LTE – Downlink

Device: MW810 Device Category: GLN
GPS Condition: Open Sky GPS with Motion
Antenna: Motorola
KPI: 2D Position Error, meters (3 Minute Averaging Window)

Conclusion: Plan signal does not change performance

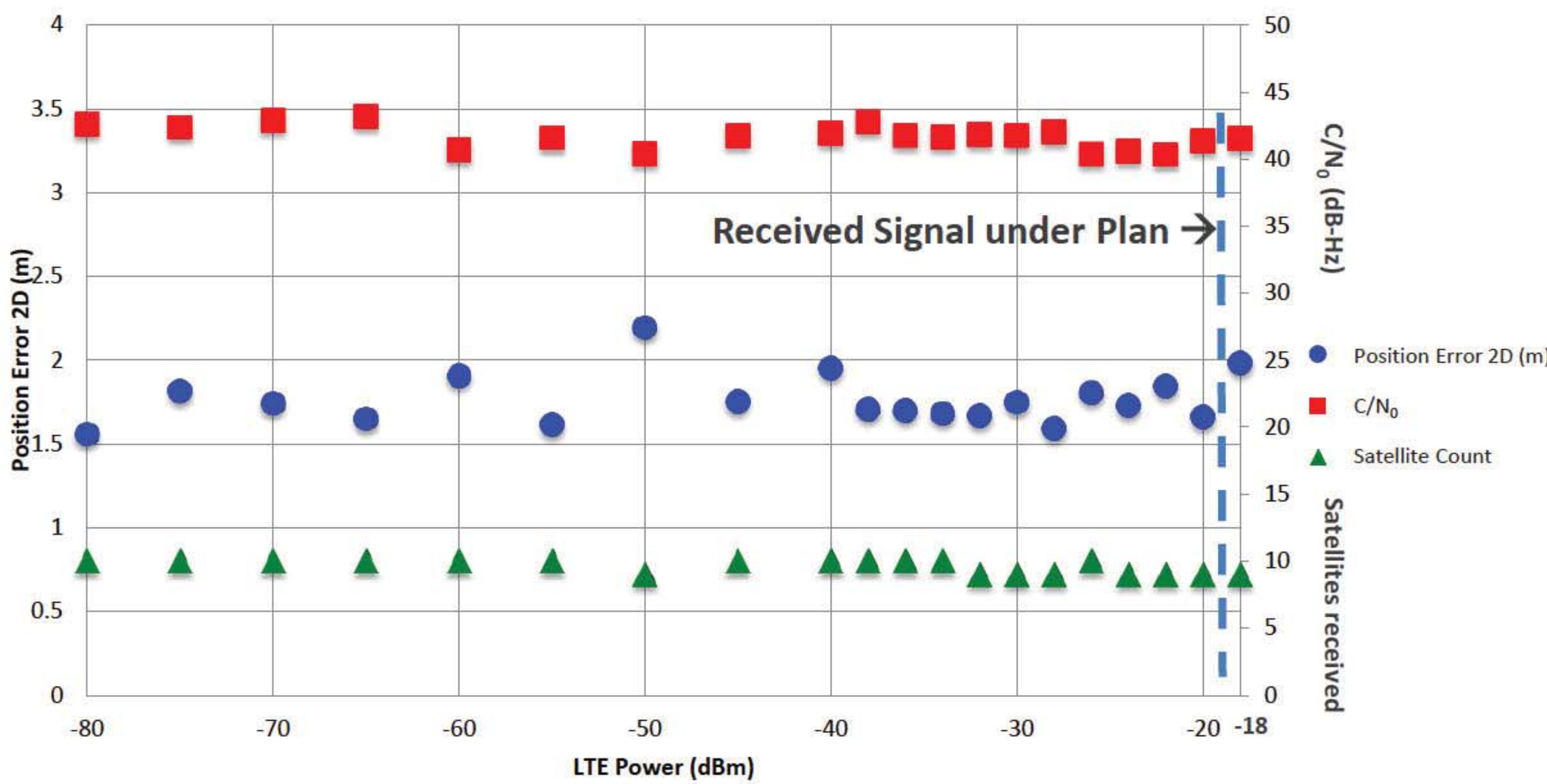


MW810: 1627.5-1637.5 MHz LTE – Uplink

Device: MW810 Device Category: GLN
GPS Condition: Open Sky GPS with Motion
Antenna: Motorola
KPI: 2D Position Error, meters (3 Minute Averaging Window)

Conclusion: Plan signal does not change performance

MW810: Average 2D Position Error vs. LTE Power

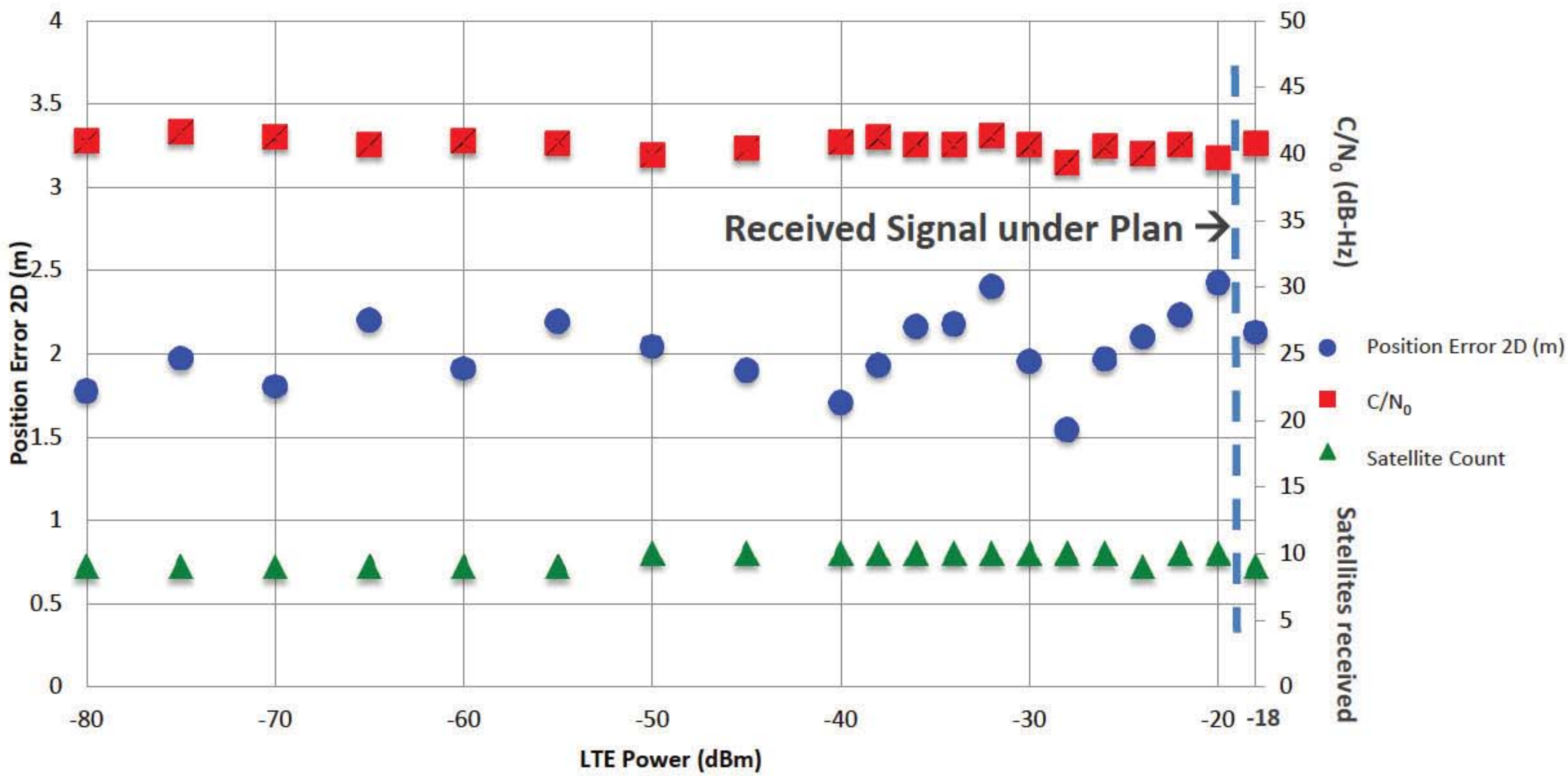


MW810: 1646.5-1656.5 MHz LTE – Uplink

Device: MW810 Device Category: GLN
GPS Condition: Open Sky GPS with Motion
Antenna: Motorola
KPI: 2D Position Error, meters (3 Minute Averaging Window)

Conclusion: Plan signal does not change performance

MW810: Average 2D Position Error vs. LTE Power



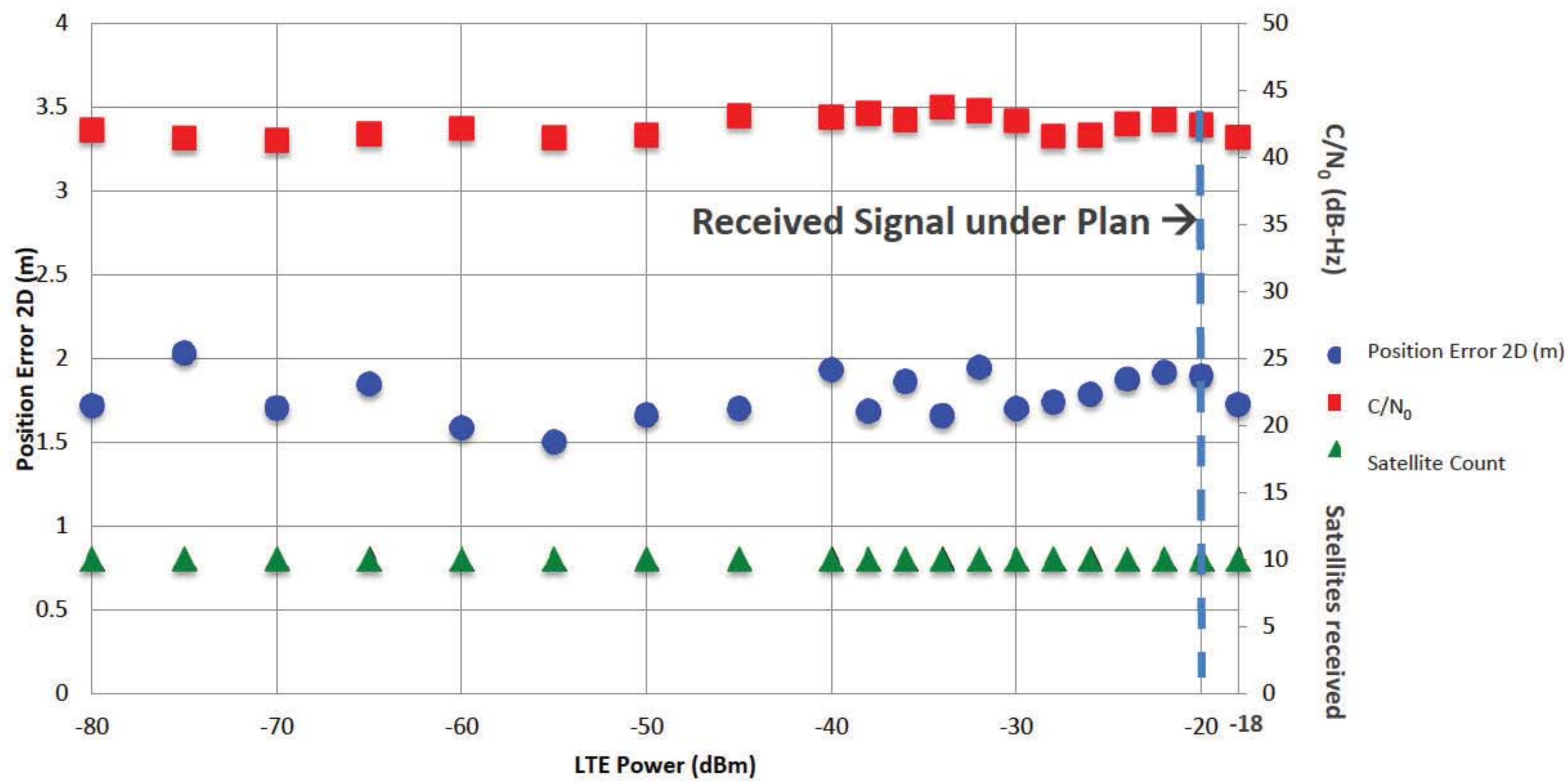
MW810: 1670-1680 MHz LTE – Downlink

Roberson and Associates, LLC
Technology and Management Consultants

Device: MW810 **Device Category: GLN**
GPS Condition: Open Sky GPS with Motion
Antenna: Motorola
KPI: 2D Position Error, meters (3 Minute Averaging Window)

Conclusion: Plan signal does not change performance

MW810: Average 2D Position Error vs. LTE Power



Description of AGPS Testing for Cellphones

- AGPS (Assisted GPS) is a method of sending information to a mobile device from the network to improve GPS performance. Tests for AGPS are defined in 3GPP (Third Generation Partnership Project)
- Samsung S5 and S6 were tested for AGPS 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 -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 -20 dBm LTE received level

Test Results Samsung Galaxy S5, S6

(all tests Passed with -20dBm of LTE, all four bands)

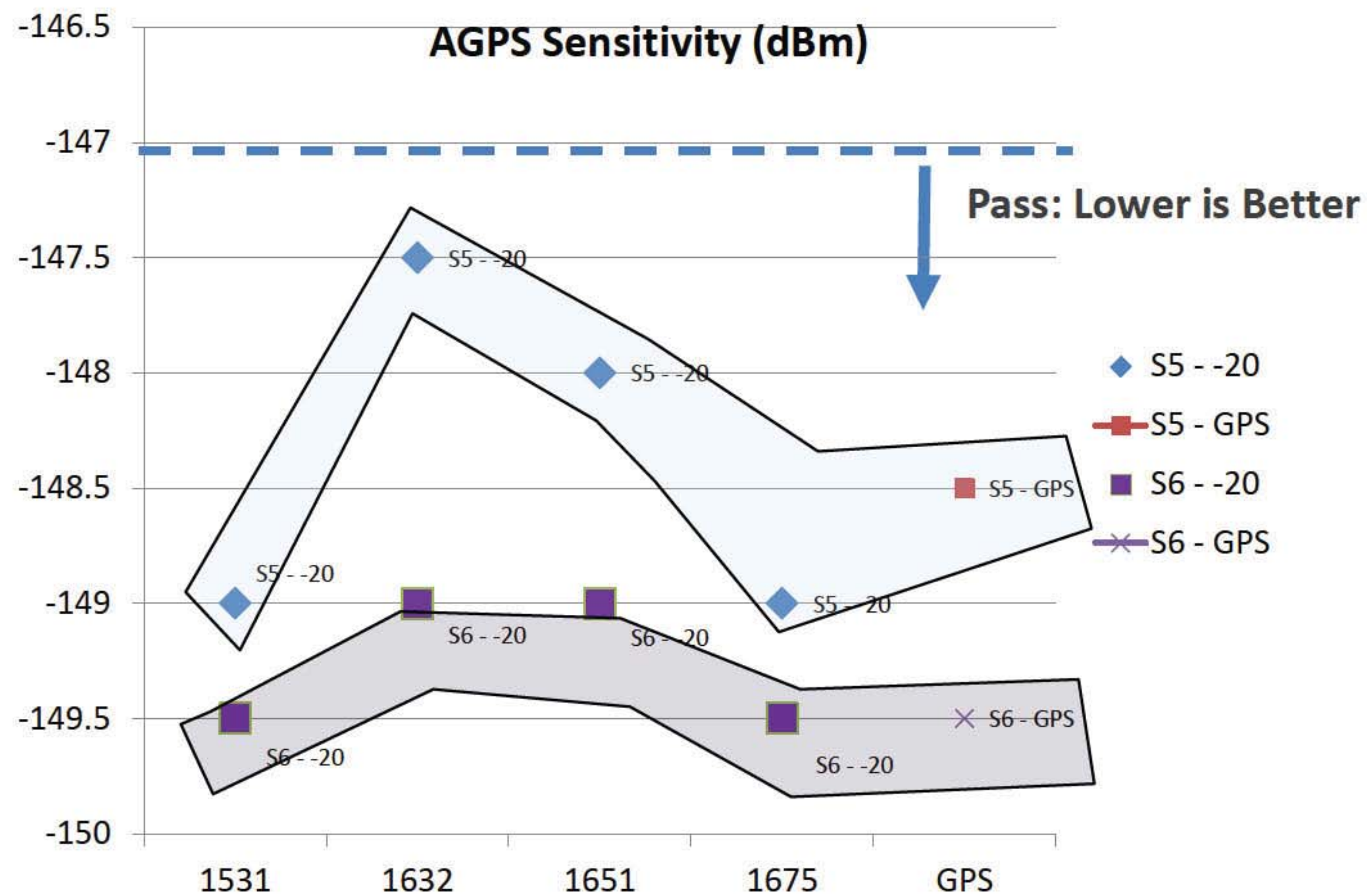
LTE Center Frequency (MHz)

S5	GPS Only	1531	1632	1651	1675
Accuracy: #Fails/144 (-20 dBm)	0	0	0	0	0
Dynamic Range #Fails/77 (-20 dBm)	0	1	0	3	3
95% Sensitivity (-20 dBm)	-148.5	-149	-147.5	-148	-149

S6	GPS Only	1531	1632	1651	1675
Accuracy: #Fails/144 (-20 dBm)	0	0	0	2	0
Dynamic Range #Fails/77 (-20 dBm)	0	0	0	0	0
95% Sensitivity (-20 dBm)	-149.5	-149.5	-149	-149	-149.5

(Sensitivity Pass Threshold is -147dBm)

Samsung AGPS Sensitivity Performance



Conclusions: At -20 dBm, S5 and S6 devices pass;

S6 has greater margin; receivers improving

C/N_0 Does Not Accurately Predict Position Error

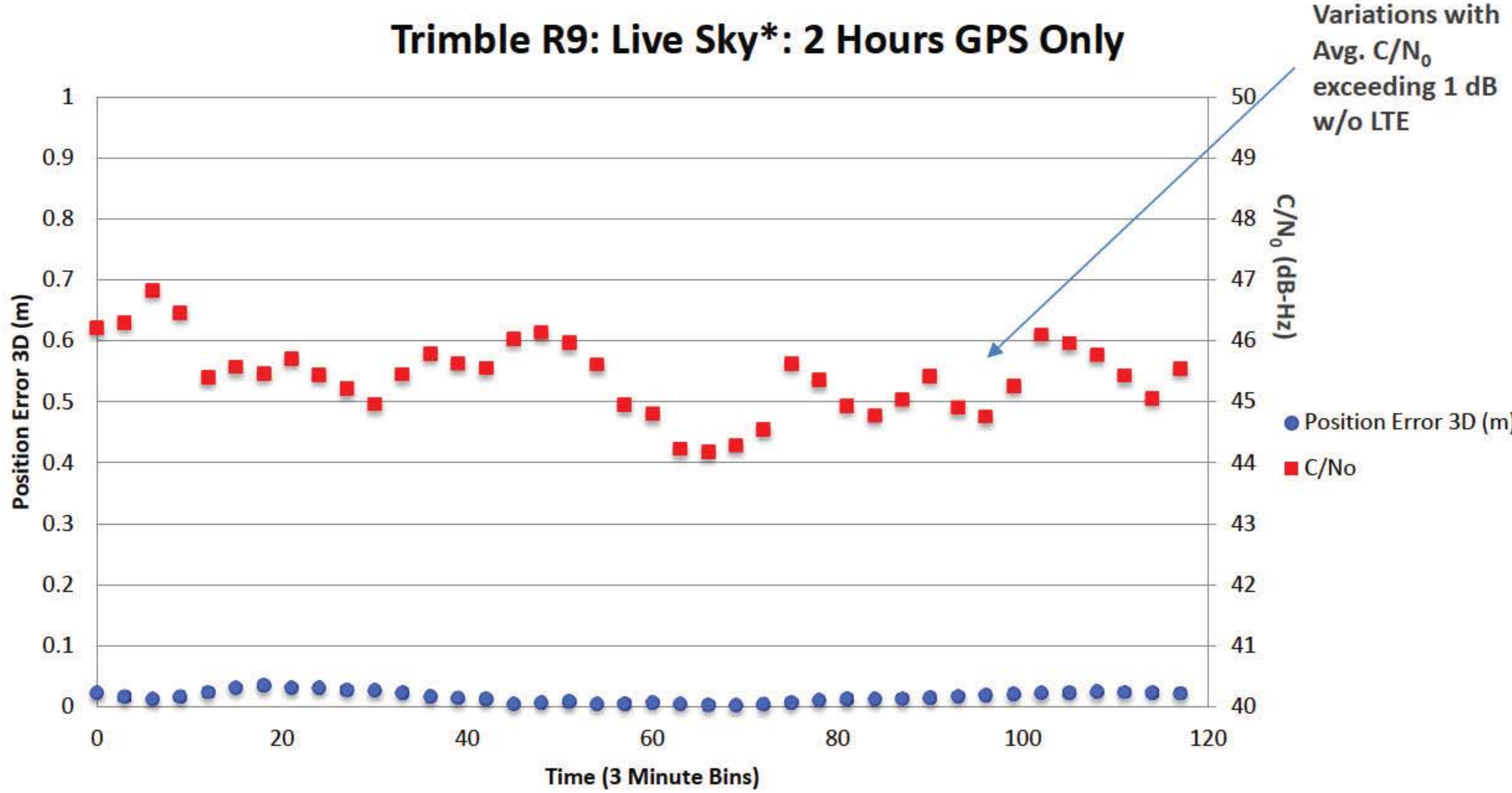
- Average C/N_0 value reported by the receiver (averaged over all GPS satellites) showed small, random variations in absence of adjacent band signals

- Normal variations can exceed 1 dB

- 1 dB degradation in C/N_0 does not accurately predict GPS position performance

1 dB C/N_0 Does Not Accurately Predict Position Error

Device: TRIMBLE R9 **Device Category: HP**
GPS Condition: LIVE SKY with RTK
Antenna:
KPI: 3D Position Error, meters (3 Minute Averaging Window)



* For Live Sky, real GPS signals are captured with an antenna and piped into the anechoic chamber

Conclusions: Plan's Impact Can be Tested; 1 dB C/N_0 not predictive

- RAA successfully tested GPS user performance metrics for four 10 MHz bands
  - 1526-1536 MHz, 1627.5-1637.5 MHz, 1646.5-1656.5 MHz, and 1670-1680 MHz
- GPS-New LightSquared Plan's signal levels do not affect GPS user performance metrics for selected Garmin, Motorola, and Samsung devices
- The Plan provides sufficient limits to adjacent band signals to assure GPS receiver performance
- 1 dB C/N_0 degradation does not predict impact of adjacent band signals on GPS device positioning performance

Roberson and Associates, LLC

Technology and Management Consultants

GPS SENSITIVITY MEASUREMENT PLAN

FEBRUARY 16, 2016

V1.6

1 MEASUREMENT PLAN EXECUTIVE SUMMARY

1.1 Purpose

The purpose of the GPS receiver measurement project is to collect supporting data to establish the impact on Key Performance Indicators (KPIs) that a GPS device user may experience when L-band LTE downlink and uplink signals are present. Signal to noise ratios in the form of reported C/N_0 values and other GPS receiver data will also be collected. Emphasis is on real world expected LTE signal levels.

1.2 Deliverables

For each device in each category the main deliverables are detailed records of the KPI statistics observed as a function of LTE signal levels at the input to the GPS device. A determination is made of the received power levels in adjacent bands versus observed changes in KPI statistics without any pass/fail determination.

2 KPI MEASUREMENT PLAN

2.1 Key Performance Indicators (KPIs) for Cellular GPS Devices

Cellular GPS devices will be tested using radiated signals as per the TWG devised test plans for Accuracy [TWG Report, Sections 3.2.9.2.2 and 3.2.9.2.3] and Sensitivity [TWG Report, Section 3.2.9.2.1]. In addition, 3GPP Dynamic Range tests will be performed. These 3GPP tests are found in 3GPP Specification TS 37.571-1 for UTRAN and E-UTRAN based systems. The Sensitivity test is described in section 7.1, the Accuracy test is described in section 7.2, and the Dynamic Range test is described in section 7.3 of 3GPP TS 37.571-1.

The three figures below are taken from TS 37-571-1 summarize the performance requirements and test conditions for the three KPIs described above.

Table 7.1.1.2: Requirements Sensitivity Coarse time assistance

Success rate	2-D position error	Max response time
95 %	100 m	20 s

Table 7.1.1.3: Parameters Sensitivity Coarse time assistance - Sub-Test 1

Parameters	Unit	Value
Number of generated satellites	-	8
HDOP Range	-	1.1 to 1.6
Propagation conditions	-	AWGN
GPS Coarse time assistance error range	seconds	±2
GPS L1 C/A Signal for one satellites	dBm	-142
GPS L1 C/A Signal for remaining satellites	dBm	-147

Figure 1 3GPP Sensitivity KPI and test conditions from TS 37.571-1

Table 7.2.2: Requirements Nominal Accuracy - Sub-Test 1

Success rate	2-D position error	Max response time
95 %	30 m	20 s

Table 7.2.4: Parameters Nominal Accuracy - Sub-Test 1

Parameters	Unit	Value
Number of generated satellites	-	8
HDOP Range	-	1.1 to 1.6
Propagation conditions	-	AWGN
GPS Coarse Time assistance error range	seconds	±2
GPS L1 C/A Signal for all satellites	dBm	-130

Figure 2 3GPP Accuracy KPI and test setup from TS 37.571-1

Table 7.3.2: Requirements Dynamic Range

Success rate	2-D position error	Max response time
95 %	100 m	20 s

Table 7.3.3: Parameters Dynamic Range - Sub-Test 1

Parameters	Unit	Value
Number of generated satellites	-	6
HDOP Range	-	1.4 to 2.1
GPS Coarse Time assistance error range	seconds	±2
Propagation conditions	-	AWGN
GPS L1 C/A Signal for 1st satellite	dBm	-129
GPS L1 C/A Signal for 2nd satellite	dBm	-135
GPS L1 C/A Signal for 3rd satellite	dBm	-141
GPS L1 C/A Signal for 4th satellite	dBm	-147
GPS L1 C/A Signal for 5th satellite	dBm	-147
GPS L1 C/A Signal for 6th satellite	dBm	-147

Figure 3 3GPP Dynamic Range from TS 37.571-1

2.2 Key Performance Indicators (KPIs) for General Navigation and High Precision

The table below provides a preliminary list of the KPIs of the different GPS device classes. Dilution of Precision (DOP) is a function of the position of satellites and not a KPI dependent on LTE signals level. Since C/N_0 is reported in NMEA messages by some devices, along with other data it will be collected if available.

C/N_0 and the number of satellites are reported for each satellite in NMEA messages and will also be collected and included in the statistical analysis. However, not all devices report C/N_0 as mentioned above.

Table 1 KPIs for GPS device category

	High Precision	Cellular	General Nav
KPI	• 3D Position Error • Loss of RTK and/or WAAS lock	• 3GPP KPIs • 2D Position Error	• 2D Position Error. • WAAS lock
System Data	• Satellites in view • C/N_0	• Satellites in view • C/N_0	• Satellites in view • C/N_0

2.3 GPS Device List

The list of 28 GPS devices to be tested is provided below.

General location and navigation
Garmin Nuvi 2597LMT
Garmin Nuvi 55LM
Garmin GPSMAP 76 CSx (Tested in 2011)
Garmin eTrex H (Tested in 2011)
Garmin Nuvi 2495LMT
Trimble TM3000
Motorola APX 7000
Motorola MW810
Garmin GPSMAP 78 SC
Garmin Montana 650t
Furuno GP32
Wabtec Navigation Sensor Module
Cellular
Samsung Galaxy S5
Samsung Galaxy S6
iPad (w/cellular data)
Samsung Galaxy Tab 4G LTE
High precision
Deere Starfire 3000
NovAtel Smart6 or Smart6-L
Topcon SGR-1
Topcon System 310
Trimble AgGPS 542
NAVCOM SF-3050
Trimble Geo 7x
Trimble SPS855 GNSS Receiver
Trimble SPS985
Trimble Net R9
Trimble R8s Rover
Topcon HiPer V

2.4 Antennas

Listed below are some antennas that are resilient to adjacent channel signals.

Vendor	Class	Model
PCTel	Mobile	3915D-HR
PCTel	Mobile	8171D-HR
PCTel	Timing	GPS-TMG-HR-26N
JAVAD (LSQ Provided)	High Precision	N/A

2.5 Radiated Measurements

Radiated tests are preferred since they closely model real world conditions. Conducted tests are not feasible for devices with internal antennas. Compared to a conducted test, the LTE signal levels will have to be amplified significantly to compensate for the propagation losses in an RF anechoic chamber. The GPS and WAAS signals will also have to be produced at levels high enough to compensate for the chamber losses. Simulated WAAS signals will be added to the applied signals when the GPS receiver is capable of receiving and processing WAAS signals. Time to First Fix ("TTFF") testing will include WAAS (Wide Area Augmentation Signals) as was tested by the TWG during 2011.

Several different radiated GPS signal conditions will be used: 1) Static GPS device with simulated Open Sky GPS received signal conditions; Simulated GPS device motion with simulated Open Sky GPS received signal conditions, and 3) Live Sky GPS signals collected with a static roof top antenna, amplified and radiated inside the anechoic chamber. The different radiated methods are documented in Section 2.6.3. LTE signals were presented according to the ramped power levels described below.

The diagram in Figure 4 below shows the basic schematic of the radiated tests. A computer shown on the left, or a test engineer, controls the signal frequencies and levels while the computer on the right records the desired KPI information.

Not shown in Figure 4 is the means for ensuring the correct LTE signal level at the GPS receiver, which is based on measuring the received LTE power with a calibrated antenna of known gain placed in the position of the Device under test and oriented toward the LTE emitter. The LTE signals need to be amplified significantly to be able to apply up to -10 dBm LTE power at the GPS device under test. Both the free space path loss in the chamber and the high peak to average ratio of the LTE waveform need to be considered in the choice of amplifier.

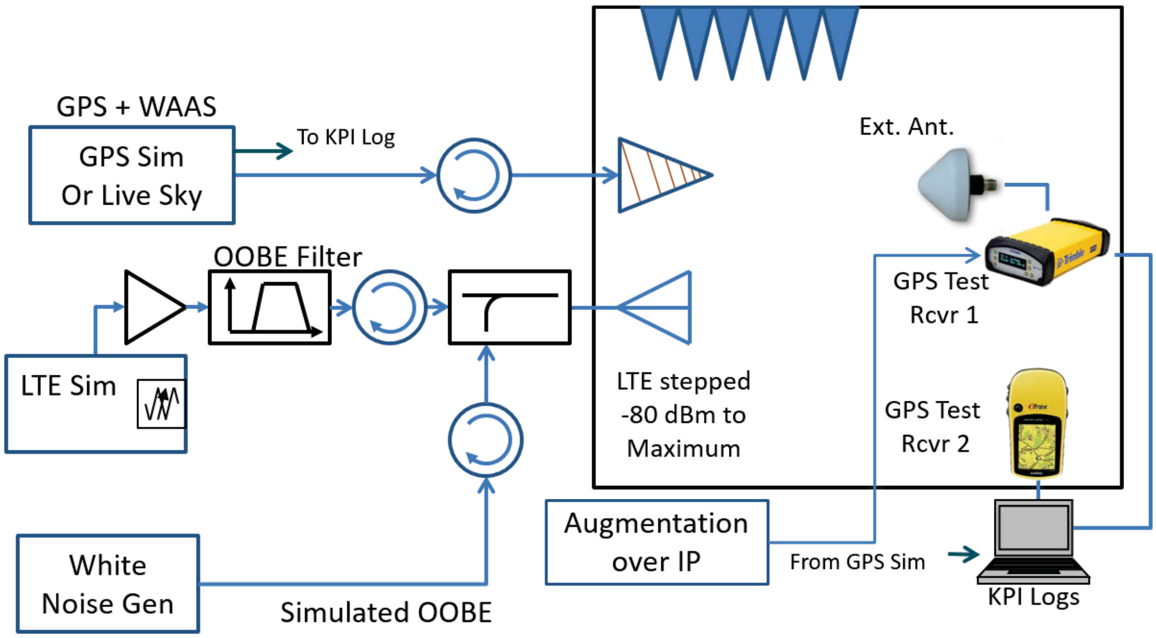


Figure 4 Simplified radiated GPS KPI measurement schematic. MSS augmented High Precision receivers will use live sky GPS+Augmentation signals.

Knowledge of GPS receiver antenna gain patterns (azimuth, elevation, and polarization) will be required if it is necessary to project the received power levels back to emitter antennas in use case analyses. To avoid taking radiated measurements at multiple incidence angles on the antenna, devices will be tested at one angle measured in the laboratory, and, in the use case analyses, adjusted for the angles of arrival called for by specific use cases. The 3D antenna pattern data from the equipment manufacturers will be required for this purpose, absent which, realistic assumptions will be made. Note that the laboratory set up will <u>not</u> try to emulate the actual angles of arrival of the LTE and GPS signals – they will be set up with convenient angles of arrival that produce strong responses from the GPS antenna.

Note also that the GPS signals from different satellites will be combined and radiated as one composite signal towards the GPS receiver, most likely with an angle of arrival corresponding to the antenna's boresight. The LTE signal will likewise be radiated with an angle of arrival within +/- 45^0 of boresight. In the use case analyses, the received powers of LTE signals will be adjusted by the difference in an antenna gain between the angle of arrival used in the laboratory and that called for by a specific use case.

2.5.1.1 Motion Testing

General Navigation devices will be tested with motion. This means that the GPS simulator will use an NMEA file recorded during a short drive around a loop. During GPS sensitivity testing the latitudes and longitudes from the NMEA file along with the start date and time of the simulation are used to calculated satellite positions and therefore the received GPS signals.

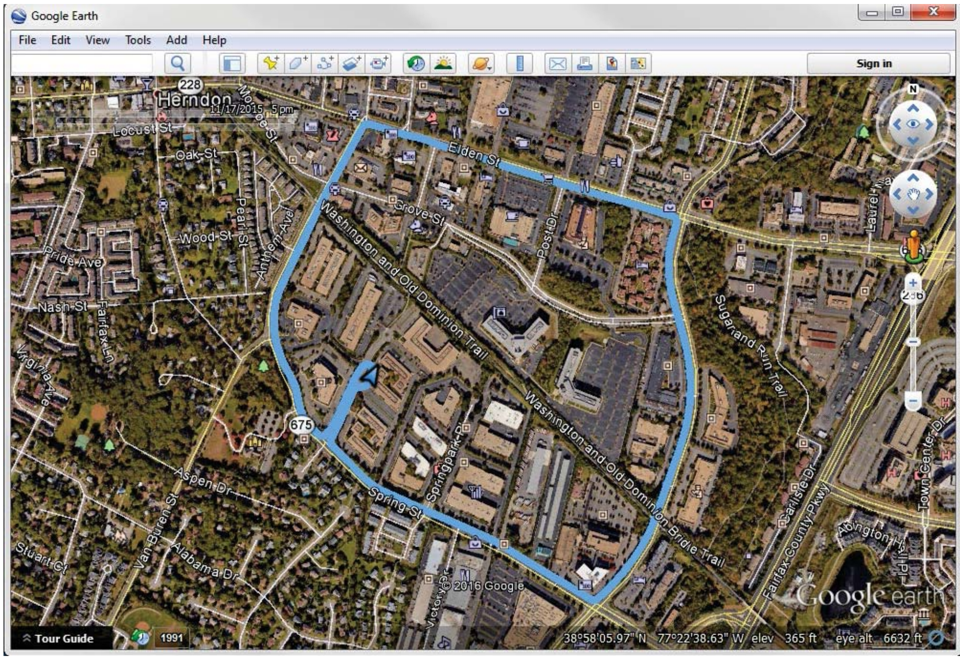


Figure 5 Google Earth view of motion testing drive route. The route was driven in the clockwise direction.

2.5.1.2 Static Testing

Static testing is the condition where the GPS simulator generates GPS signals corresponding to those that a GPS receiver at a fixed location would receive. The GPS device is not moving.

2.5.1.3 Live Sky

Live sky testing will be used for High Precision devices that are augmented with real time correction signals. The reason is that the current ionospheric conditions must be present in the received GPS signals for the correction signals to be accurate. A high quality GPS antenna will be installed on the roof of the building where the RF anechoic chamber is located. The GPS signal will be amplified and connect to the GPS source antenna in the chamber to produce the "Live Sky" signal.

2.6 Dependencies and Assumptions

The post measurement analysis of the data involves comparison of the measured received estimated positions (for navigation receivers) and time with the true values. The basic process is to compare true position and time with received values measured by the device. 2D and 3D mean position errors, both calculated over 3 minute observation periods, as well as C/N_0 values reported by the GPS receiver and averaged over all satellites, will be recorded as functions of LTE downlink and uplink signal levels at the receiver. Additional analysis outside the scope of this document will be performed to assess the impact to the user of KPI degradation in real life scenarios.

Analyzing test results with motion testing will be based on matching GPS timestamps of the recorded simulator output and the device being tested and comparing the 2D or 3D positions at each timestamp.

2.6.1 LTE Signals and Bands

Only the full 10 MHz bandwidth version of LTE signals will be used in the measurements. Downlink LTE signals will be assumed to be supporting many devices and have all LTE resource blocks assigned.

Uplink LTE signals will be representative of high data rate, with all resources blocks assigned and the device transmitting at the maximum EIRP of 23 dBm. The high data rate case is the extreme worst case since this represents transmitting on the most resource blocks over time. Lower data rates will be experienced in the field as well as lower radiated power, since many of the resource blocks are not being used, and a base station will rarely if ever assign 100% of the resources to a single device.

The bands for the LTE signals to be used in the KPI measurements are shown below: Only 10 MHz bandwidth LTE signals will be used.

LTE Direction	LTE Band	LTE Throughput (Simulated)
Downlink	1526-1536 MHz	Max. Throughput
Downlink	1670-1680	Max. Throughput
Uplink	1627.5-1637.5	Max. Throughput
Uplink	1646.5-1656.5	Max. Throughput

2.6.2 LTE Uplink Signal Generation OOBE Noise Floor

The uplink LTE signals will simulate the entire output power spectrum that is the maximum that can be transmitted from an LTE device. The OOBE EIRP Emission limit for the handheld LTE devices is -105 dBW/MHz from 1559 MHz to 1608 MHz. The tests will emulate the LTE devices emitting OOBE at representative levels..

The LTE uplink has a maximum power of +23 dBm over a 10 MHz bandwidth. The noise floor should not exceed -105 dBW/MHz referenced to the inband level. These are EIRP values.

The schematic shows a wideband white noise generator output combined with the LTE uplink signal to produce a test signal with the power spectral density shown above. The power spectral density (PSD) of the added white noise represents Ligado's current commitment of uplink OOBE, projected from a Ligado device to a GPS receiver at a standoff distance of 1 m and assuming a net antenna coupling loss of 5 dB,

Table 2 shows the conversion from -105dBW/MHz at the transmitter to OOBE power received at the device under test.

Table 2 Basis of OOBE PSD applied to the GPS device under test

-105 dBW/MHz	OOBE limit of Ligado LTE Devices	
-165 dBW/Hz	- 60dB	Convert MHz to Hz
-135 dBm/Hz	+30dB	Convert dBW to dBm
-171.4 dBm/Hz	-36.4 dB	Path loss 1m separation
-176.5 dBm/Hz	-5 dB	Antenna Coupling
-176.5 dBm/Hz	Power at the GPS Device Under Test	

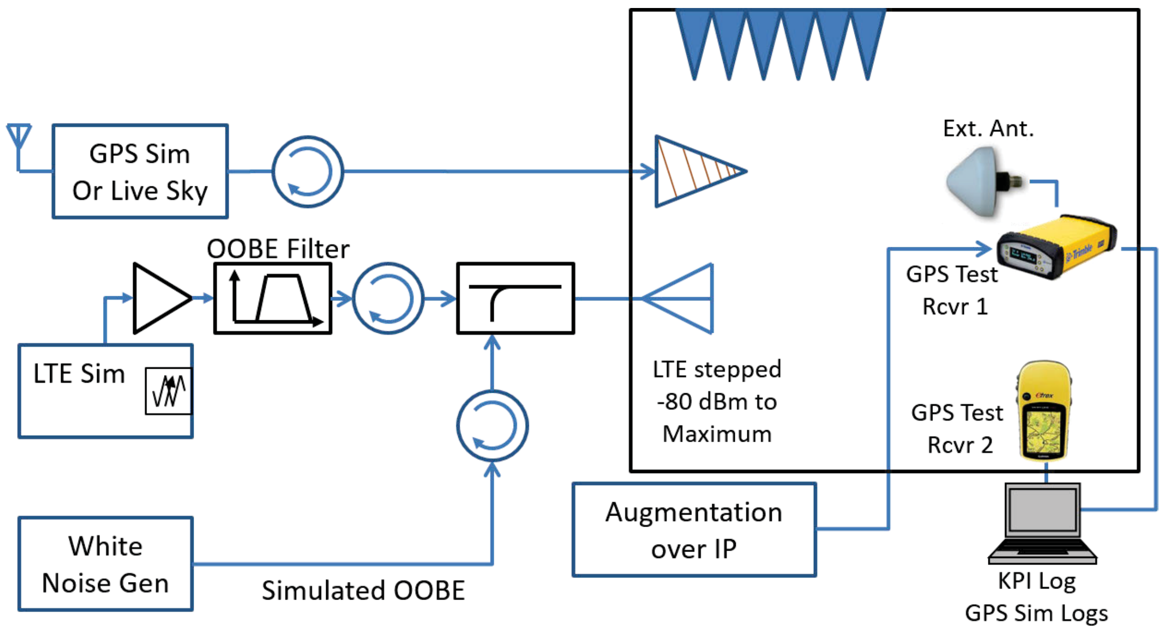


Figure 6 Schematic for producing LTE uplink OOBE noise -176.5 dBm/Hz at the GPS receiver

2.6.3 GPS Condition

The GPS signal condition is shown below and will be simulated during static and motion testing depending on the device type.

Condition	Number	GPS Level	WAAS Levels
Open Sky	8+ satellites	-130 dBm	-128.5 dBm

The combinations of GPS signal condition and device dynamics used in testing are summarized in the table below.

GPS Signal Condition	GPS Device Condition
Open Sky	Static Simulator
Open Sky	Motion Simulator
Live Sky	Live Sky (antenna mounted on roof of testing lab)

2.6.4 GPS Impairments

No GPS impairments are added to the simulations.

2.7 Equipment List

The list below includes the equipment that is needed for measuring the sensitivity of GPS KPIs to LTE signal levels

1. Spirent or other GPS Test Set capable of introducing WAAS signals, and capable of playing back recorded NMEA motion files
2. MSS Augmentation signal sources
3. RTK Augmentation message generation and RF, WiFi, or Ethernet RTK signal source
4. LTE Signal Generator
5. RF Amplifiers
6. RF Attenuators
7. RF Signal Combiners, isolators, couplers
8. LTE TX OOBE Filters
9. LTE TX and GPS TX Antennas
10. GPS RX Antennas
11. GPS RX Filters

2.8 Calibration and Pretest

Prior to collecting detailed KPI data the devices need to be characterized for their basic performance levels to ensure the devices are operating properly. It is also vital to understand the intrinsic random variations in KPIs that the GPS system produces under "no-interference" conditions. This involves applying a GPS constellation signal at a fixed, known level to each device and recording the reported C/N_0 for each device. No adjacent band signal will be present during these measurements.

Prior to data collection it is important to verify that the thermal noise floor has not been increased and that no spurious intermodulation signal produced by interactions between the GPS and LTE signal generators.

3 KPI MEASUREMENT PROCEDURE

3.1 Measurement Sequence

The basic sequence to measure the changes in KPIs as a function of LTE signal level is shown below. The approach is to apply LTE signal and increase the level in small steps and capturing statistically valid KPI data sets at each step. A baseline set of KPI data without the LTE signal will also be collected during the GPS-only phase. The duration of the GPS-only phase is 2 hours. The reason is to capture both the short-term random position variations as well as the long-term position variations caused by changes in the satellite constellation which modify the composition of satellites used to calculate position.

The GPS simulator will, in addition to standard L1 band C/A GPS signals, provide WAAS augmentation signals when the test receiver is WAAS capable. In the case of non-MSS-augmented High Precision receivers, the augmentation signal will be provided by an IP network connection; in the case of MSS augmented High Precision receivers, the augmentation and GPS signals will be received by a wideband antenna, amplified and re-radiated in the RF chamber if feasible. Receivers using augmentation signals may be able to remove a large part of these errors but non-augmented receives (including High Precision receivers operated in Autonomous mode) will experience a baseline rms error, as they do in real life operation, that will be present in the absence of LTE signals. The KPI statistics will show the impact of the LTE signals on the baseline error.

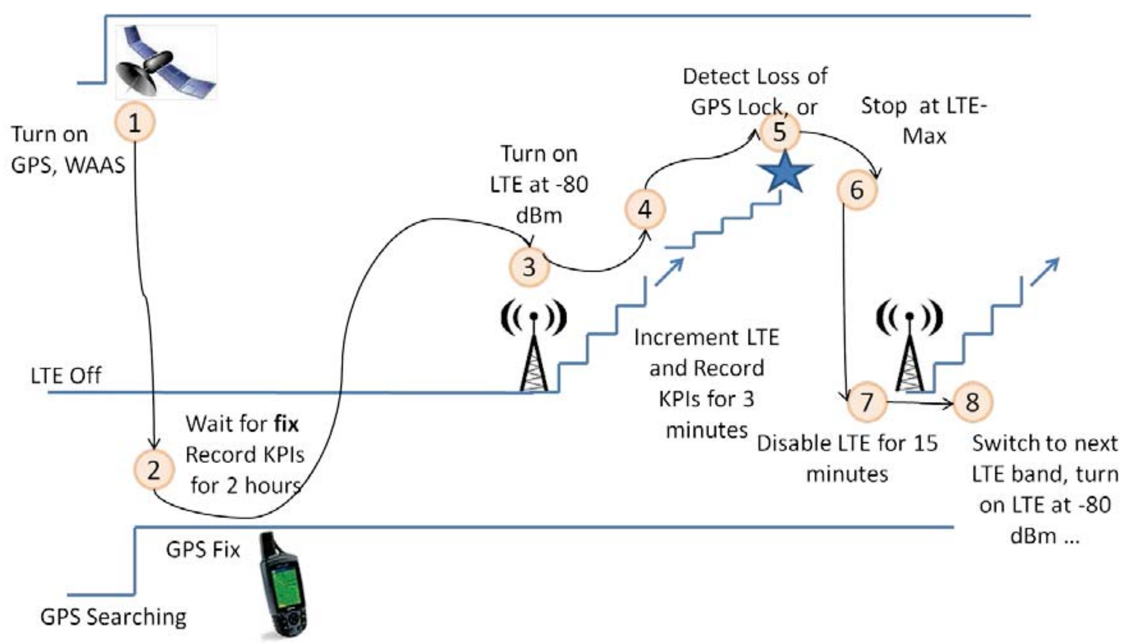


Figure 7 Generic GPS KPI measurement sequence

The pseudo-code description for the MEASURE_KPI_SET() sequence is given below. The parameter TRECORD must be long enough to capture a large enough set of KPI measurements so that statistically valid KPI averages and standard deviations can be calculated. TRECORD may be as long as one minute or more for devices reporting KPI values at a low rate.

```
Power GPS device
  Apply GPS signal
  Wait for the GPS receiver to enter the fix-found state
  Record baseline GPS NMEA signal parameters, and KPI values for
        2 Hours.
  Apply LTE signal, and OOBE signal if in an uplink band, at a
signal level of -80 dBm.
  Loop from -80 dBm until LTE level reaches -10 dBm.
    record GPS NMEA signal parameters and KPI values for 3
        minutes.
    increase LTE level by (coarse 5 dB steps up to -40 dBm and
then fine 2 dB steps)
  Remove LTE Signal
```

3.2 High Precision Measurements

3.2.1 Situation: High Precision Location

High Precision GPS receivers may have wider RF front end bandwidths than other GPS devices.

This may be motivated by a need to receive an MSS augmentation signal in the adjacent 1525-1559 MHz MSS band and to share the RF front end circuitry between the MSS augmentation signal receiver and the GPS receiver. Others use augmentation signals in the UHF and other bands and do not need to have such wide passbands.

3.2.2 Goals

First, characterize the performance of the High Precision receivers and antennas in the target list. Second, for receivers where the antenna and receiver are not integrated into one unit, determine if the use of known high immunity antennas can improve adjacent band compatibility. Test and compare the performance of high precision receivers which use antennas which limit the receive bandwidth to the GNSS band.

3.2.3 Plan

Measure representative high precision GPS receivers, capture and store KPI data as a function of LTE signal strength.

Repeat the measurement with a high interference immunity antenna.

3.2.4 Analysis:

Compare true position with received values. Plot RMS 3D location errors, satellite count, and C/N_0 vs. LTE signal levels for each test frequency, with and without high immunity antennas present. Record the availability of augmentation signal vs. signal level.

3.2.5 Assumptions

MSS augmentation signals and RTK augmentation signals can be generated and supplied to the GPS device under test.

Access is available to 3D location error data.

3.2.6 Measurement Test Sequence

Pseudo-code for static measurement of high performance GPS receivers is given below for static testing

```
For each GPS condition (Open Static, Live Sky)
  For each downlink frequency band (1531, 1675)

    MEASURE_KPI_SET()
For each uplink frequency band (1631, 1651)
    MEASURE_KPI_SET()
```

```
Enable Augmentation Signals
Setup test for Live Sky GPS condition
  For each downlink frequency band (1531, 1675)
    MEASURE_KPI_SET()
  For each uplink frequency band (1631, 1651)
    MEASURE_KPI_SET()
```

3.2.7 Potential Issues: Augmentation Signals

Certain augmentation signals will likely require cooperation from the manufacturers. GPS signal constellation generators may be able to produce some augmentations signals. Providing an augmentation signal may require a second base unit in addition to the unit being tested.

3.2.8 MSS Augmentation Signal

If a proprietary source of MSS augmentation signal is not able to be obtained and installed, then an alternative is to use available commercial MSS augmentation signals. The schematic in Figure 8 below shows how an external antenna can be used to gather GPS and MSS augmentation signals and apply them to a GPS receiver under test in an anechoic chamber. Without a location reference from a GPS signal generator the "true" location will have to be estimated from a long term average under LTE signal "Off" conditions.

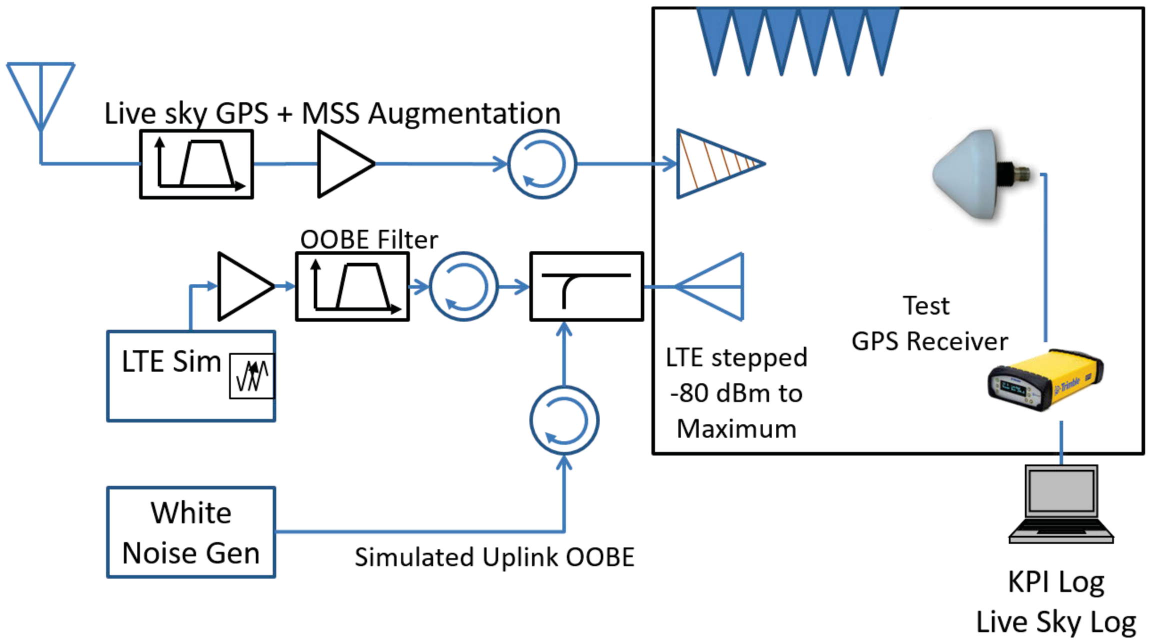


Figure 8 External GPS plus MSS augmentation signal capture

3.2.9 RTK Augmentation Signal

Commercial and public RTK correction data is available from many sources. There are statewide networks and commercial networks that make RTK correction data available over cellular internet connections. The schematic below shows a system for gathering commercial cellular RTK correction data from a cellular or other wireless data network for application to the GPS receiver under test.

An alternative would be to use commercial internet (IP network) based RTK services as shown in Figure 9 below.

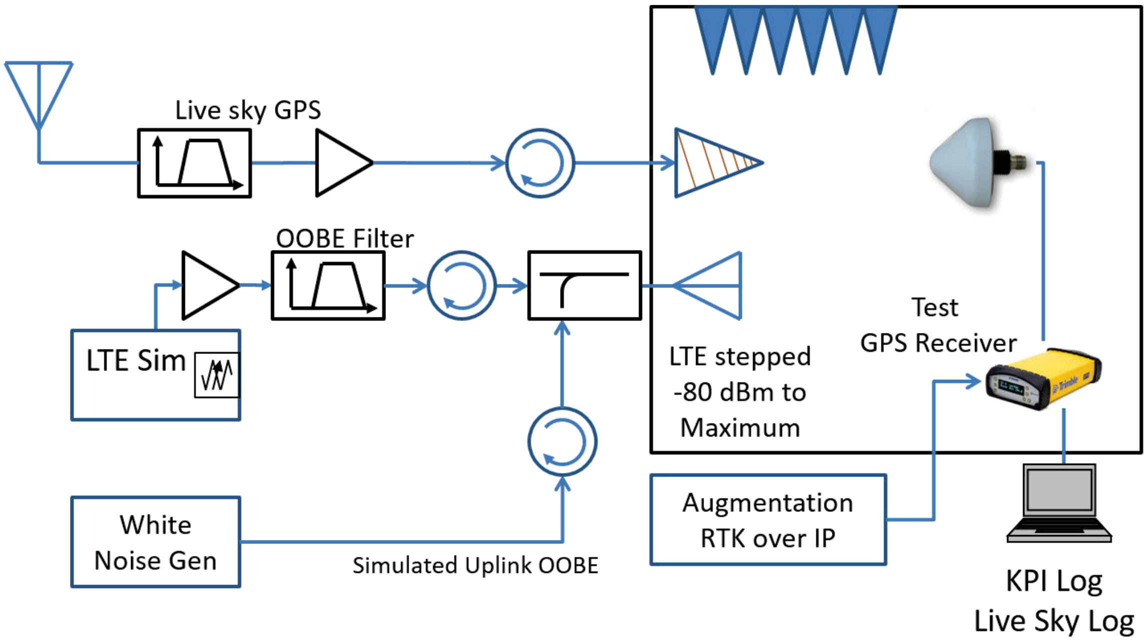


Figure 9 Insertion of commercial RTK into test chamber

3.3 Cellular Device Measurements

3.3.1 Cellular Device Situation

Cellular devices and smart phones have rapid replacement cycles. Smart-phones are very commonly used for mapping, location, and navigation relying on embedded GPS receivers as well as network provided location information. Bestselling devices in the latter half of 2015, the time of these measurements, were not available or marketed in 2011. GLONASS capability is now included in high volume GPS chipsets and this capability may have resulted in different RF front end filter characteristics for the embedded GNSS receiver in Cellular devices.

3.3.2 Desired Goals

Characterize the performance of the latest, high sales volume cellular devices to update the performance baseline.

3.3.3 Plan

First, measure only the high sales volume devices and capture and store location KPI data as function of LTE signal strength.

Second, use 3GPP sensitivity, Accuracy, and Dynamic Range testing in a radiated environment to capture 3GPP KPIs,

Analysis: Use TWG defined, 3GPP-adapted test plans, which are based on measuring statistics of 2D position error.

The Figure 10 below shows the use of a cellular base station simulator to capture 3GPP AGPS KPIs.

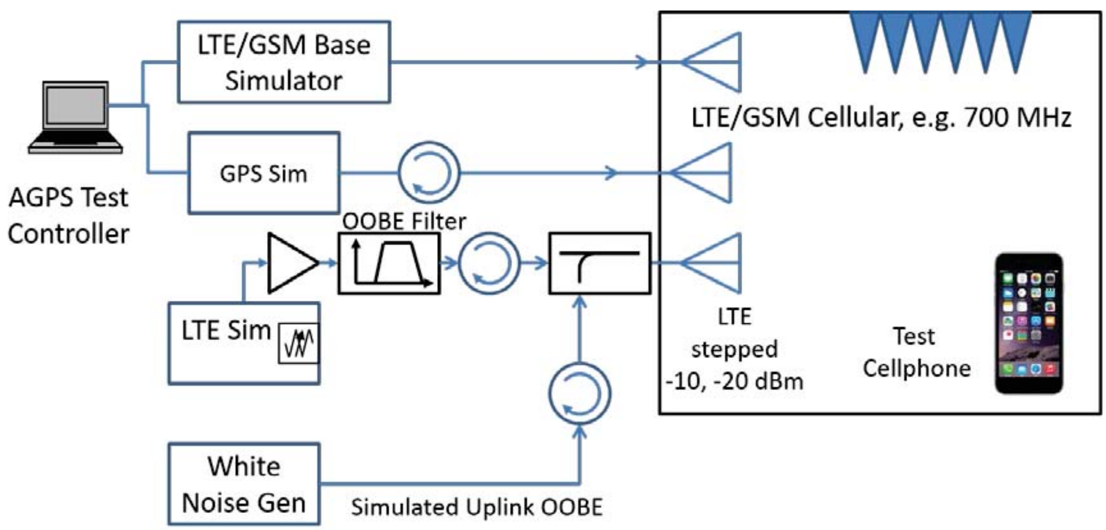


Figure 10 Cell phone KPI measurement with 3GPP base station simulator

3.3.4 Assumptions

Reception of signals from other GNSS constellations will not be tested.

Access to KPIs or NMEA sequences is available and exportable to an external logging system.

3.3.5 AGPS KPI Measurement Sequence

The three AGPS tests listed in Section 2.1 are implemented as functions in an AGPS test controller. This controller controls the output of the GPS simulator while querying the cellular device for information about its current state and position.

3.3.6 Position Error KPI Measurement Sequence

A pseudo-code description of the cellular device measurement sequence is listed below for position error KPI measurements.

```
For each GPS condition (Motion Open)
  For each downlink frequency band (1531, 1675)
    MEASURE_KPI_SET()
  For each uplink frequency band (1632, 1651)
    MEASURE_KPI_SET()
Calculate KPI averages and standard deviations for each LTE level
```

3.4 General Navigation Device Measurements

3.4.1 General Navigation Situation

The present tests will limit the maximum received LTE power to -10 dBm. Desired Goals

Characterize the KPI performance of the latest, high sales volume general navigation GPS devices.

3.4.2 Plan

Measure high sales volume devices and capture and store detailed KPI data as function of LTE signal strength.

3.4.3 Assumptions

Access to KPIs or NMEA sequences is available and exportable to an external logging system.

3.4.4 Measurement Sequence

A pseudo-code description of the cellular device measurement sequence is listed below.

```
For each GPS condition (Motion Open)
  For each downlink frequency band (1531, 1675)
    MEASURE_KPI_SET()
  For each uplink frequency band (1631, 1651)
    MEASURE_KPI_SET()
Calculate KPI averages and standard deviations for each LTE level
```

4 Time To first Fix (TTFF) and GPS Re-acquisition Testing

Time to First Fix is an important KPI for users who transition in and out of GPS coverage and simultaneously in and out of LTE coverage. For example, a public safety user exiting a building could be exposed to a strong LTE signal at the same time the GPS receiver in his two-way radio is re-acquiring GPS signals. The presence of strong adjacent band signals may increase the TTFF. TTFF is tested under warm-start conditions which refer to how much information the GPS receiver already possesses about the satellites and the GPS system time.

The goal of re-acquisition testing is to determine and quantify differences in GPS re-acquisition time as a function of the presence of LTE adjacent band signals and the absence of these signals. The LTE signal levels will be selected to fall in a range above and below the level where significant position errors were observed. The reason for this is to conserve test time in part because TTFF may take several minutes in cold-start mode.

Re-acquisition refers to the situation where lock is lost and the GPS receiver tracking loops need to re-lock onto the GPs signal. If the outage is brief then re-acquiring satellite lock is also rapid.

To test re-acquisition the LTE signal needs to be applied at the level where loss of lock was observed.

4.1.1 Assumptions

- Access to a lock indicator is available to be able to determine when the GPS receiver has achieved lock.

4.1.2 TTFF Plan

Apply GPS signal only for 15 minutes to allow the device to load an updated almanac and lock to current (simulated) GPS time. Apply the LTE signal. Remove the GPS signal for at least a minute and then re-enable the GPS signal. Record the time until LOCK is indicated. Repeat the cycle of removing and re-enabling the GPS signal at least 5 times.

Calculate average TTFF vs. LTE power for a small set of LTE powers. The figure below illustrates the re-acquisition measurement sequence.

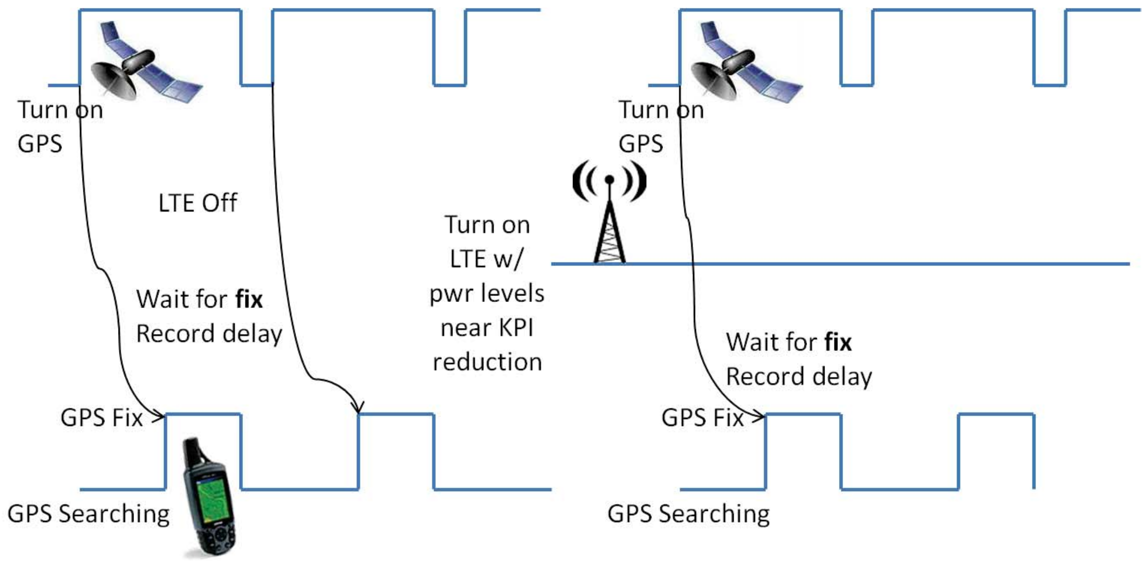


Figure 11 TTFF measurement sequence

Like position error, re-acquisition time will also be subject to random variations from one measurement to another. For each choice of LTE power level, including no LTE signal, a set of at least 5 re-acquisition delay values will be collected. These will be subjected to statistical analysis to determine KPI impact of the LTE signal.

Re-acquisition data may be available from the ramped LTE power tests used to capture position KPI data if the devices loose LOCK at the higher LTE power levels. The LTE power levels where LOCK is lost and the power level where LOCK is regained will be available.

Re-acquisition testing will be performed on public safety devices. The device will be locked onto GPS. GPS signal will be eliminated for a period of time (5 minutes is proposed), device time to relock onto GPS will be measured with and without the presence of a strong LTE signal.

5 ANALYSIS

At each LTE power level many KPI data samples will be collected. The mean value of each KPI, over a 3 minute observation period, will be calculated for each power level sample set and logged in one of the KPI Test Data Tables.

Raw NMEA and other data from GPS devices will be stored in the format it is received in. It is likely that the formats will be different for each device.

Relative changes in the mean KPI error will be the measure of interference used in later work.

Position error KPIs will use different reference locations (true positions) depending on the device type. The reference location types are shown below. Certain devices will require a search procedure to find the best fit since timestamps provided in synthetic NMEA data reflect device clock time and not GPS system time. This analysis calls for extending the measurement interval.

GPS Condition	Location Reference
Static	Static Simulator Reference
Motion	GPS Simulator Output Log
Live Sky	R9 Average
AGPS	GPS Simulator Internal

5.1 Statistical Analysis

In order to translate the KPI vs. LTE signal level statistics collected in the measurements to a probability of GPS functionality impairment, analysis beyond device measurements is needed to determine the likelihood, frequency, and expected duration that a user will experience LTE levels that cause an increase in KPI standard deviation. Data is available from previous adjacent band compatibility testing, as well as from existing LTE networks that can be used to develop a statistical model for LTE signal levels experienced by GPS receivers under different LTE deployment plans. Comparison of these statistics and scenarios with the KPI sensitivities to LTE signal strength will produce an assessment of how often and how much the presence of the LTE network will impact user functionality.

6 CHANGE HISTORY

Version	Date	Description
V0.6	June 25, 2015	Preliminary Draft
V0.8	July 22, 2015	Added detail regarding 3GPP specific tests for cell phones Updated Device List Updated KPI Table Updated GPS Impairments table Added detail for pretest scenario: added un-impaired GPS pretest
V1.0	July 27,2015	Version 1.0
V1.1	August 24, 2015	Updates to warm start TTFF section in response to NPSTC. Updates to certified aviation section
V1.2	Sept. 28, 2015	Add WAAS testing added note to test at higher LTE power in response to NPSTC. Added re-acquisition test in response to NPSTC. Updated testing diagrams. Updated OOBE description

V1.5	February 5, 2016	Updated to reflect final test procedures Updated device list. Certain devices could not be made to export KPI data. Aviation devices were removed. Single ramp-up LTE signal level and GPS only intervals detailed.. Added detail regarding re-acquisition testing.