

Non-Certified Aviation Device

Condition: Open Sky

Test Performance under the Ligado GPS Proposal

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.

Description of A-GPS Testing for Cellphones

- 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.

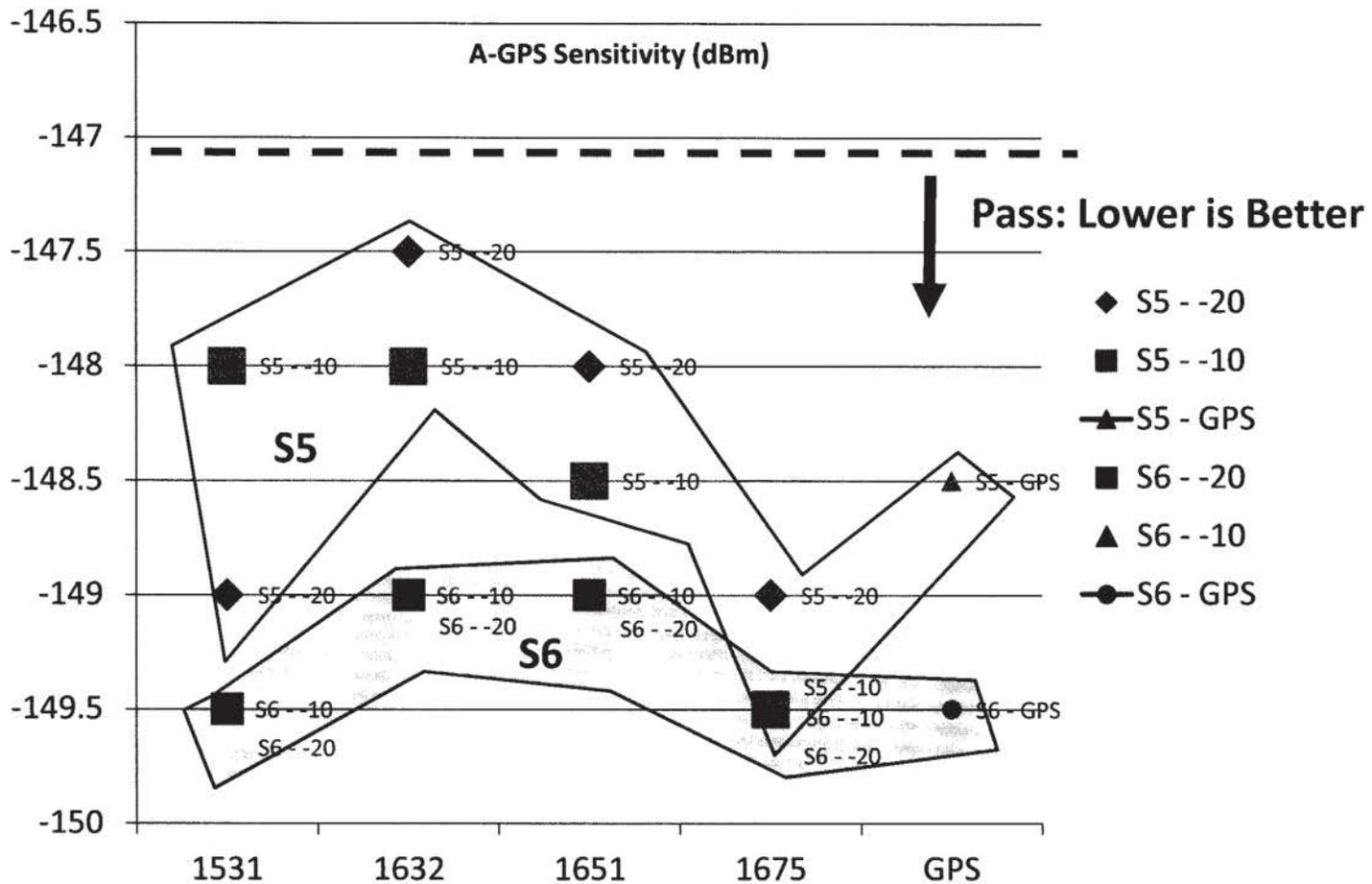
Test Results Samsung Galaxy S5 and S6

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

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.

Samsung A-GPS Sensitivity Performance



Both Samsung S5 and S6 devices passed at -10 dBm and -20 dBm LTE received level

Device Performance Improving Over Time: S6 is better than S5

Consumer GPS Device Conclusions Under Ligado's Deployment

- 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
- Study demonstrates feasibility of using Key Performance Indicators (KPIs) for GPS Devices
 - 2D Position Errors were captured
 - Testing included static and simulated motion of the device
- 16 Devices Successfully Tested*
 - Two Smartphones and One Tablet
 - Twelve General Location and Navigation (GLN) devices
 - One Non-Certified Aviation Device
 - * *We were unable to obtain usable data for the iPad.*
- Comparing device performance with and without LTE to determine the difference, the RAA analysis demonstrates that GPS user performance shows:
 - No impact for Smartphone and Tablet devices
 - No impact for GLN devices in Open Sky conditions
 - No impact in 15 out of 16 use cases for GLN devices under Impaired GPS Signal test conditions
 - No impact for Non-Certified Aviation device
- 1 dB C/N_0 degradation does not predict impact of adjacent band signals on Consumer GPS device positioning performance

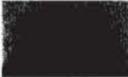
High Precision GPS Device Conclusions Under Ligado's Deployment

- 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
- Study demonstrates feasibility of using Key Performance Indicators (KPIs) for GPS Devices
 - 3D Position Errors were captured
- 11 High Precision (HP) Devices Successfully Tested
 - *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.*
- Comparing device performance with and without LTE to determine the difference, the RAA analysis demonstrates that GPS user performance shows:
 - No impact on four HP devices from two different Device OEMs
 - One Device OEM that experienced no user impacts on three of its HP devices, did show impacts on some 10 MHz bands for three other HP devices. When each of these impacted HP devices, however, were re-tested using filtered antennae, all three HP devices showed no impact to user performance from LTE
 - One HP device manufactured by a separate Device OEM also showed impacts on some 10 MHz bands
 - This device is intended for maritime or agriculture use
 - Three HP devices manufactured by another Device OEM show performance impacts on just the lower downlink 1526-1536 MHz band, for which Ligado has agreed to operate at power levels consistent with FAA requirements
- 1 dB C/N₀ degradation does not predict impact of adjacent band signals on High Precision GPS device positioning performance

Appendix A: GLN Devices with NMEA Data

GLN Devices with NMEA Data

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GLN Devices with NMEA Data

Condition: Open Sky with Motion

Test Performance under the Ligado GPS Proposal

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.

GLN Devices with NMEA Data

Condition: Impaired GPS Signal with Motion

Test Performance under the Ligado GPS Proposal

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.

GLN Devices with NMEA Data

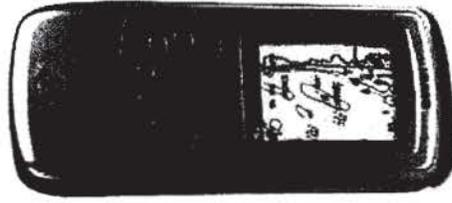
Condition: Impaired GPS Signal with Various Antennae

Test Performance under the Ligado GPS Proposal

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.

Garmin GPSMAP 76CSx





Garmin GPSMAP 76CSx

Condition: Open Sky with Motion

1526-1536 MHz Downlink

1627.5-1637.5 MHz Uplink

1646.5-1656.5 MHz Uplink

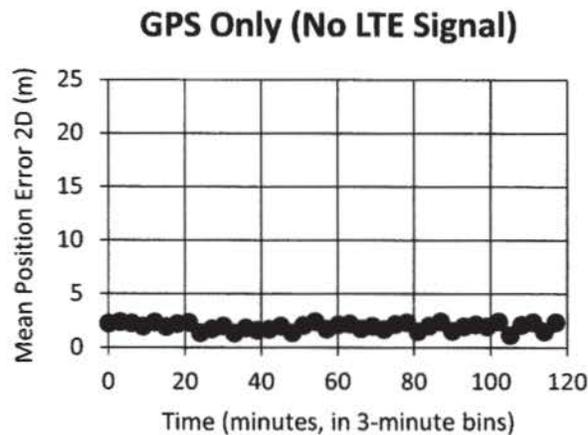
1670-1680 MHz Downlink

No Impact

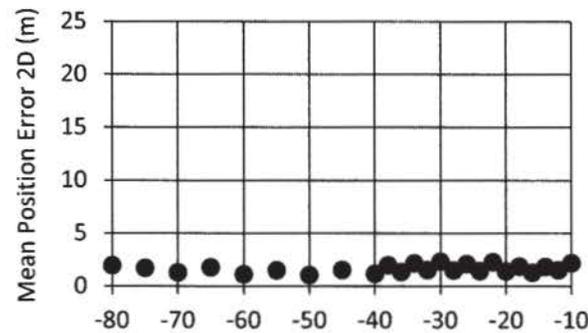
No Impact

No Impact

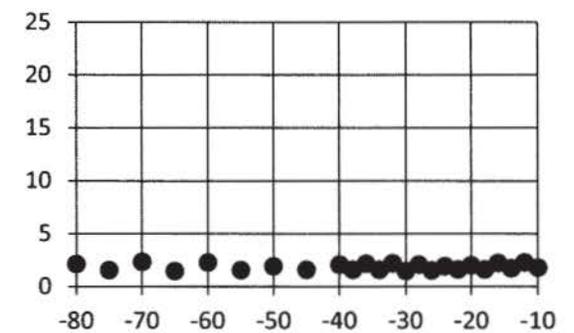
No Impact



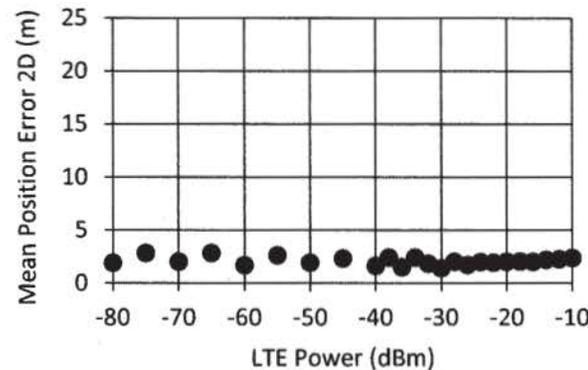
1526-1536 MHz LTE



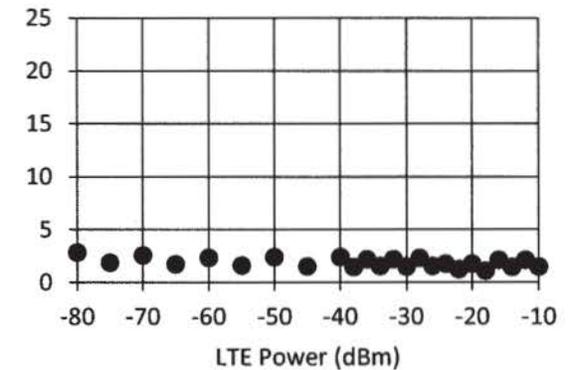
1627.5-1637.5 MHz LTE



1646.5-1656.5 MHz LTE



1670-1680 MHz LTE



Garmin GPSMAP 76CSx

Open Sky with Motion | GPS Only (No LTE Signal)

Device Category: GLN

Key Performance Indicator:

Mean Position Error 2D (m)
(3-minute averaging window)

Device: Garmin GPSMAP 76CSx

Antenna: Internal

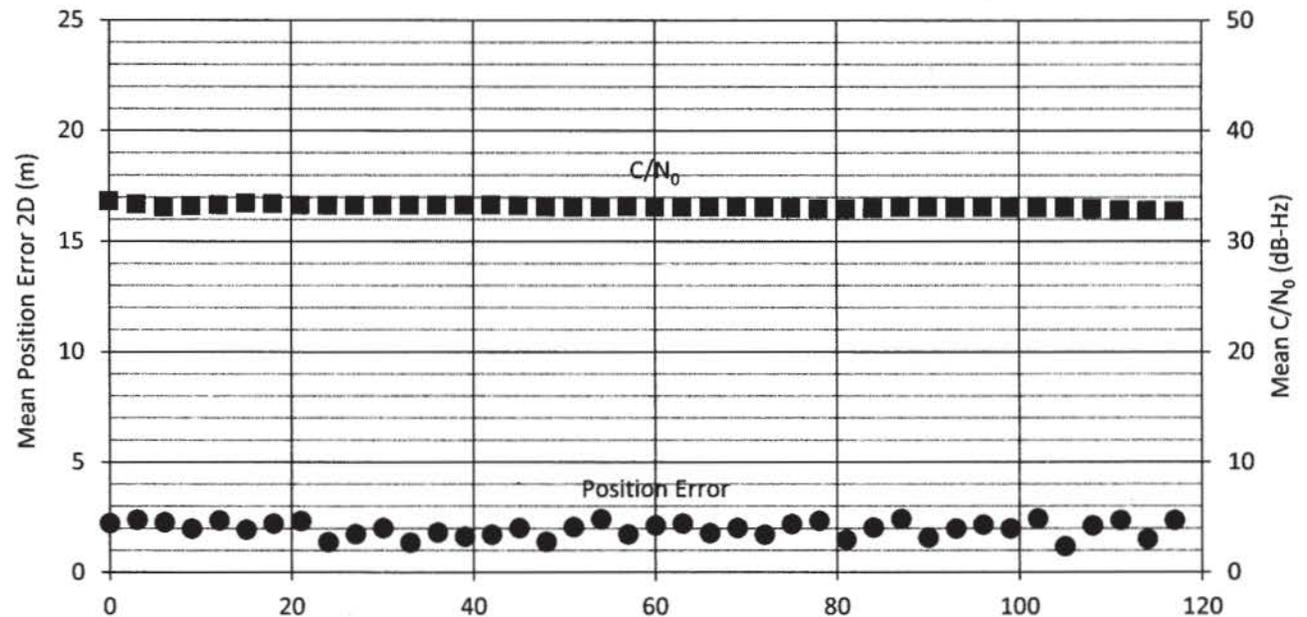
GPS Condition:

Open Sky with Motion

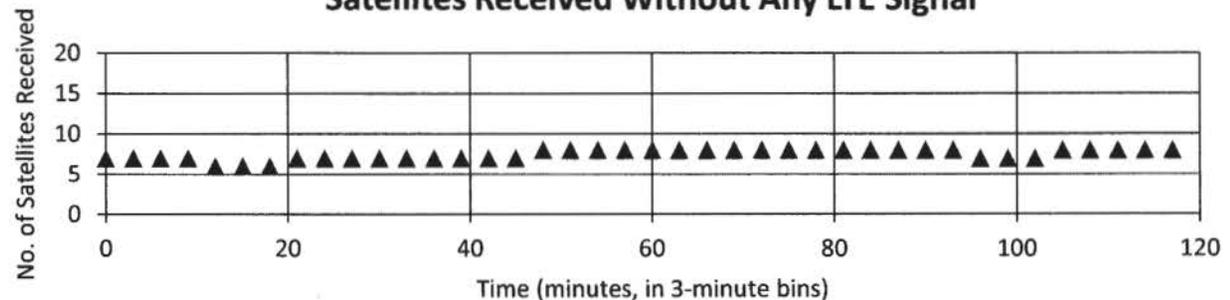
LTE Condition:

GPS Only (No LTE Signal)

Position Error and C/N₀ Without Any LTE Signal



Satellites Received Without Any LTE Signal



- Mean Position Error 2D (m)
- Mean C/No (dB-Hz)
- ▲ No. of Satellites Received

Garmin GPSMAP 76CSx

Open Sky with Motion | 1526-1536 MHz LTE (Downlink)

Device Category: GLN

Key Performance Indicator:

Mean Position Error 2D (m)
(3-minute averaging window)

Device: Garmin GPSMAP 76CSx

Antenna: Internal

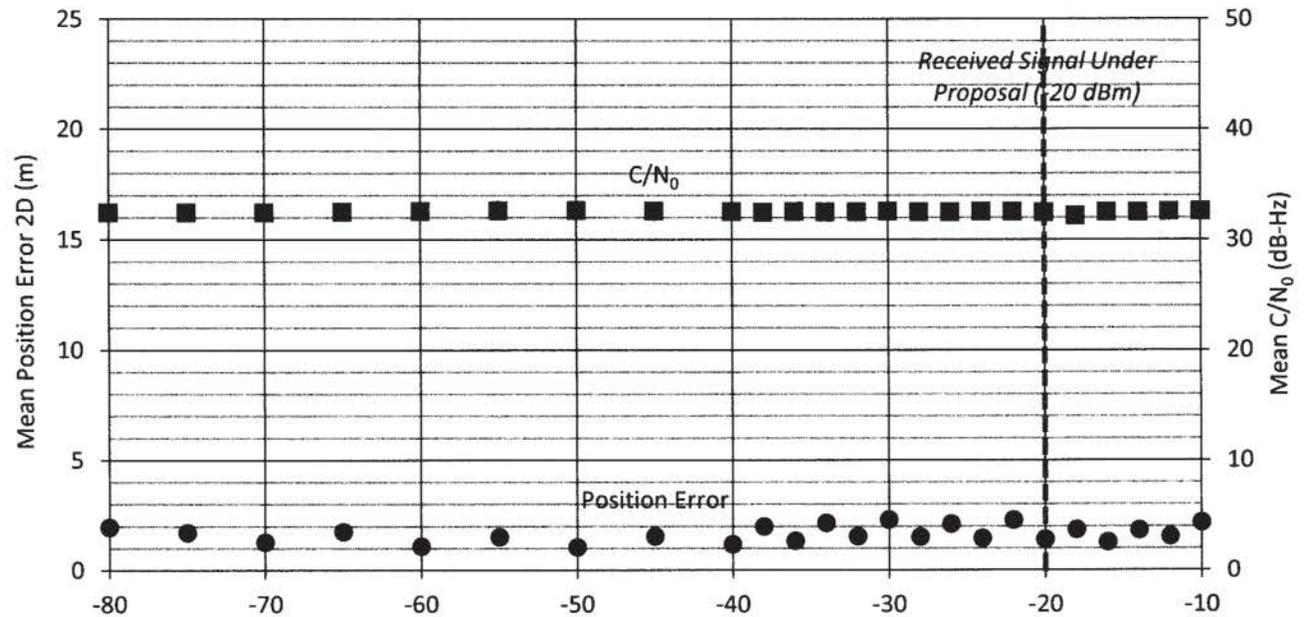
GPS Condition:

Open Sky with Motion

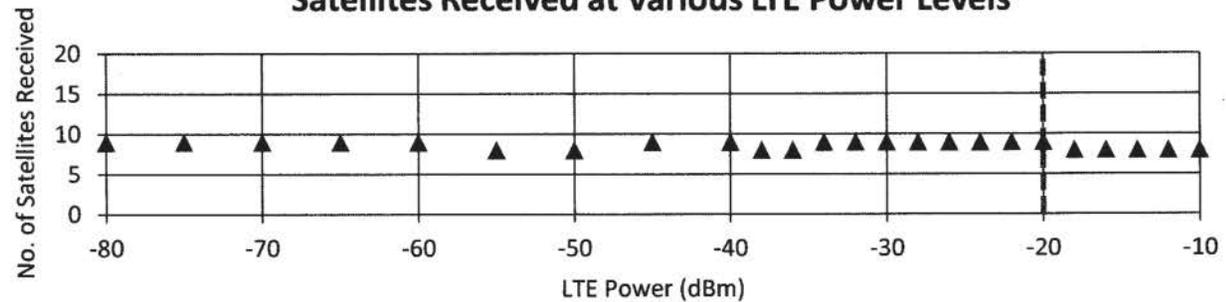
LTE Condition:

1526-1536 MHz LTE (Downlink)

Position Error and C/N₀ at Various LTE Power Levels



Satellites Received at Various LTE Power Levels



- Mean Position Error 2D (m)
- Mean C/No (dB-Hz)
- ▲ No. of Satellites Received

Garmin GPSMAP 76CSx

Open Sky with Motion | 1627.5-1637.5 MHz LTE (Uplink)

Device Category: GLN

Key Performance Indicator:

Mean Position Error 2D (m)
(3-minute averaging window)

Device: Garmin GPSMAP 76CSx

Antenna: Internal

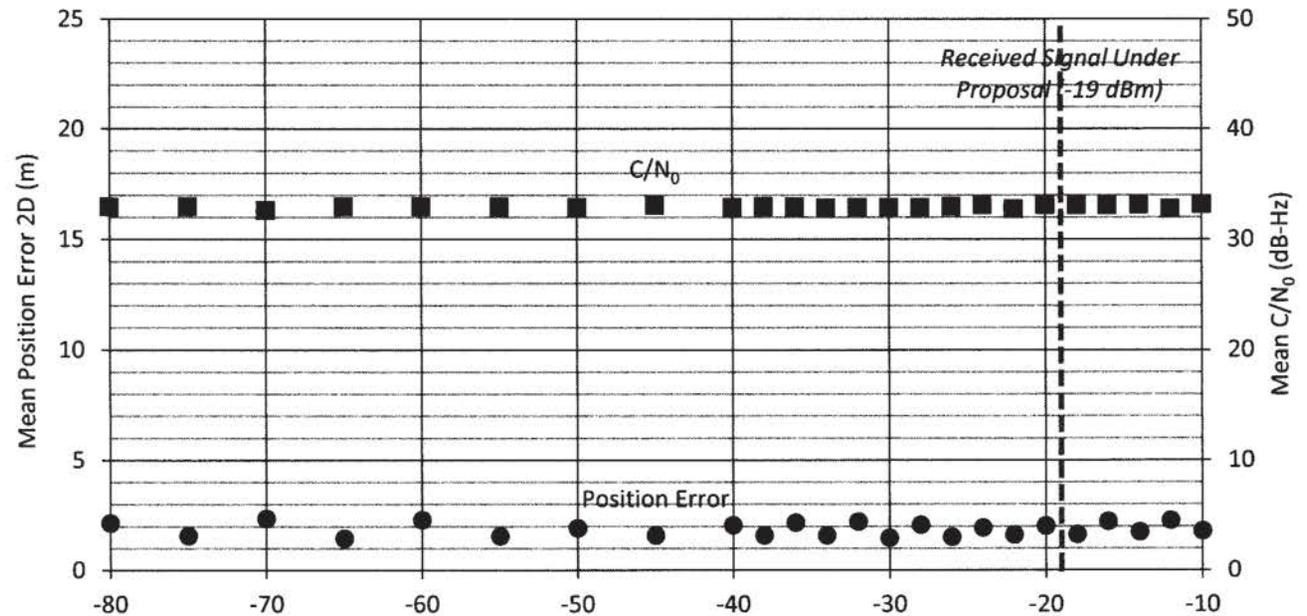
GPS Condition:

Open Sky with Motion

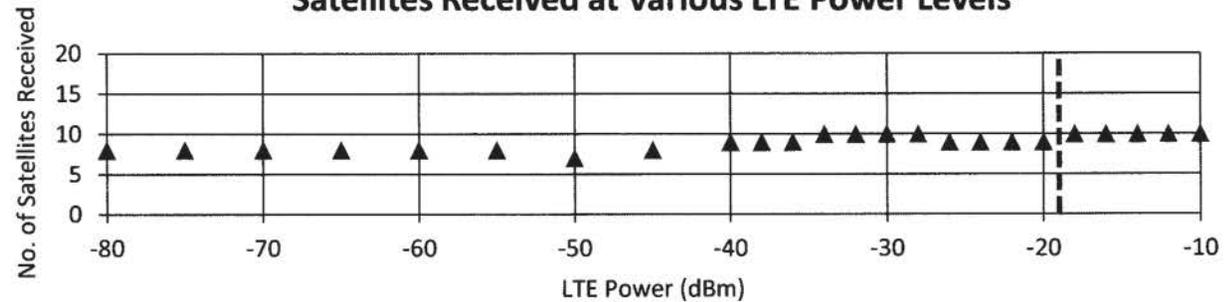
LTE Condition:

1627.5-1637.5 MHz LTE (Uplink)

Position Error and C/N₀ at Various LTE Power Levels



Satellites Received at Various LTE Power Levels



- Mean Position Error 2D (m)
- Mean C/No (dB-Hz)
- ▲ No. of Satellites Received

Garmin GPSMAP 76CSx

Open Sky with Motion | 1646.5-1656.5 MHz LTE (Uplink)

Device Category: GLN

Key Performance Indicator:

Mean Position Error 2D (m)
(3-minute averaging window)

Device: Garmin GPSMAP 76CSx

Antenna: Internal

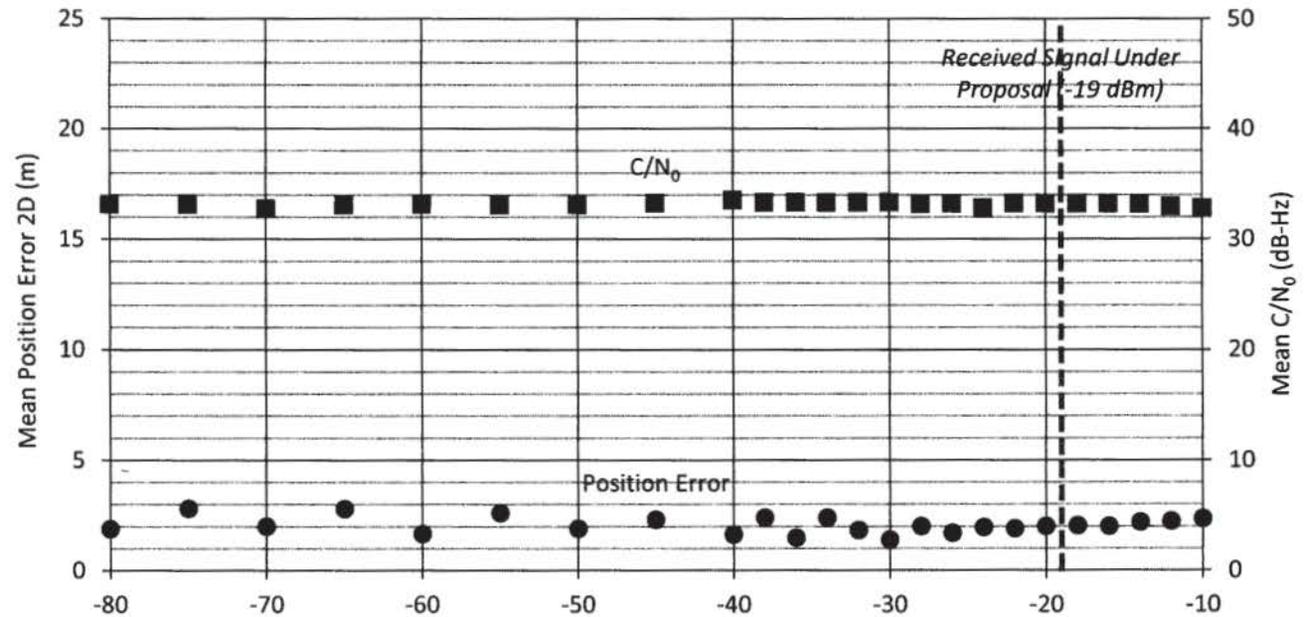
GPS Condition:

Open Sky with Motion

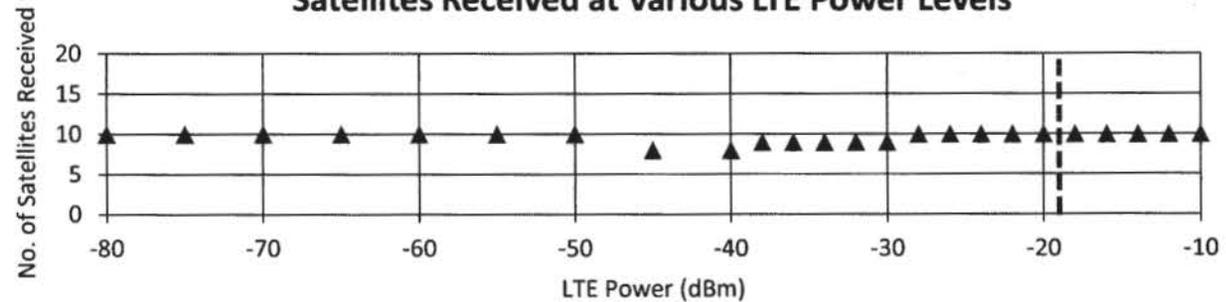
LTE Condition:

1646.5-1656.5 MHz LTE (Uplink)

Position Error and C/N₀ at Various LTE Power Levels



Satellites Received at Various LTE Power Levels



- Mean Position Error 2D (m)
- Mean C/No (dB-Hz)
- ▲ No. of Satellites Received

Garmin GPSMAP 76CSx

Open Sky with Motion | 1670-1680 MHz LTE (Downlink)

Device Category: GLN

Key Performance Indicator:

Mean Position Error 2D (m)
(3-minute averaging window)

Device: Garmin GPSMAP 76CSx

Antenna: Internal

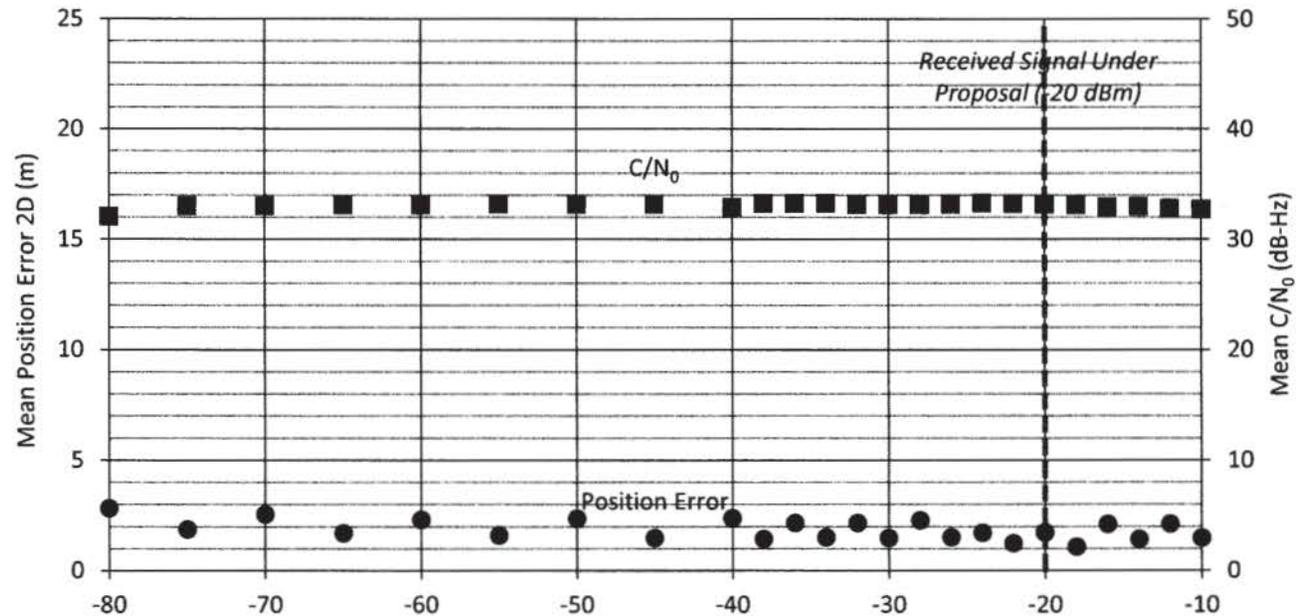
GPS Condition:

Open Sky with Motion

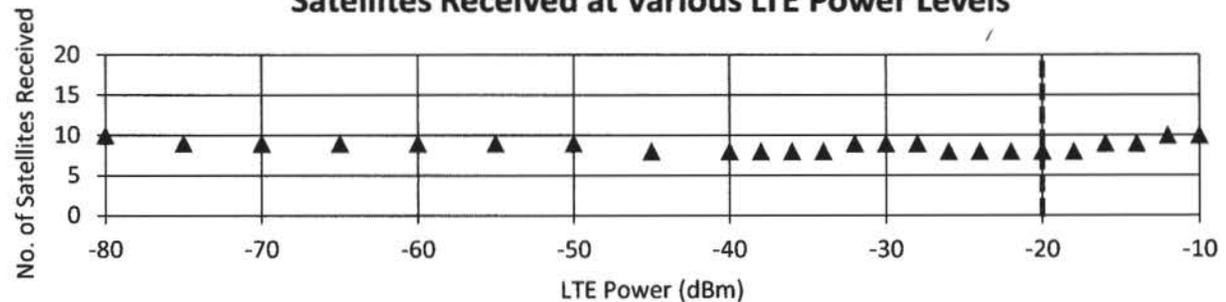
LTE Condition:

1670-1680 MHz LTE (Downlink)

Position Error and C/N₀ at Various LTE Power Levels

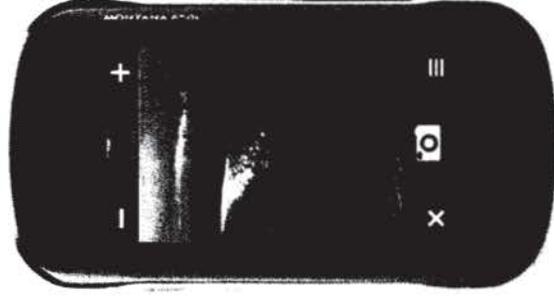


Satellites Received at Various LTE Power Levels



- Mean Position Error 2D (m)
- Mean C/No (dB-Hz)
- ▲ No. of Satellites Received

Garmin Montana 650t





Garmin Montana 650t

Condition: Open Sky with Motion

1526-1536 MHz Downlink

1627.5-1637.5 MHz Uplink

1646.5-1656.5 MHz Uplink

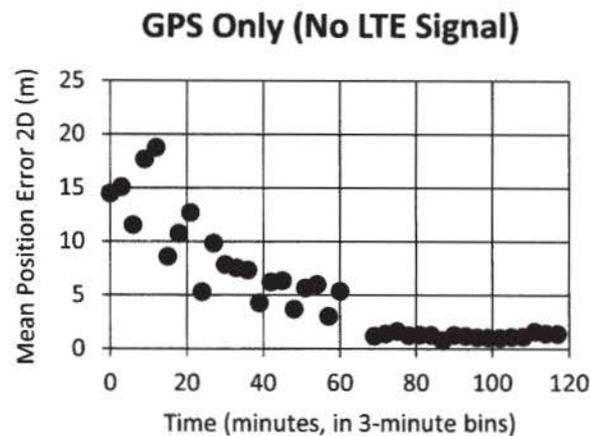
1670-1680 MHz Downlink

No Impact

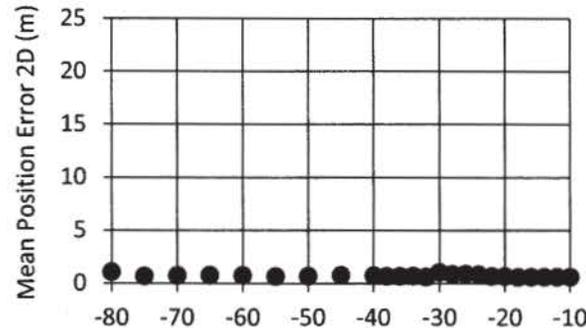
No Impact

No Impact

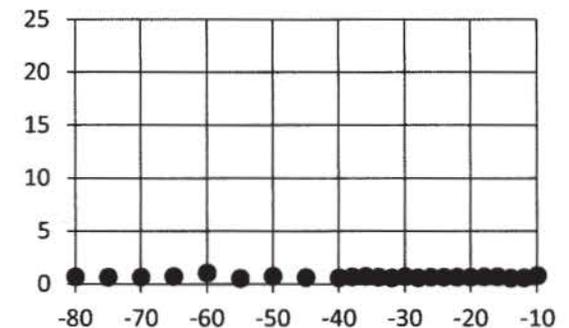
No Impact



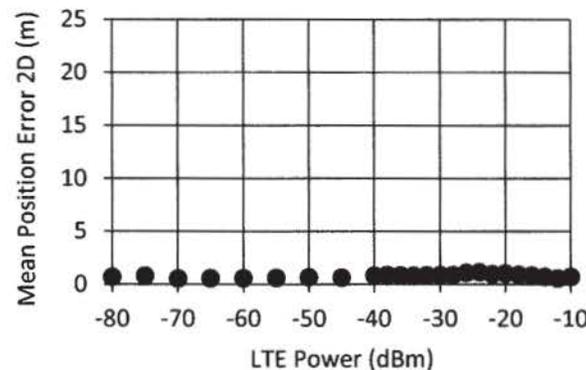
1526-1536 MHz LTE



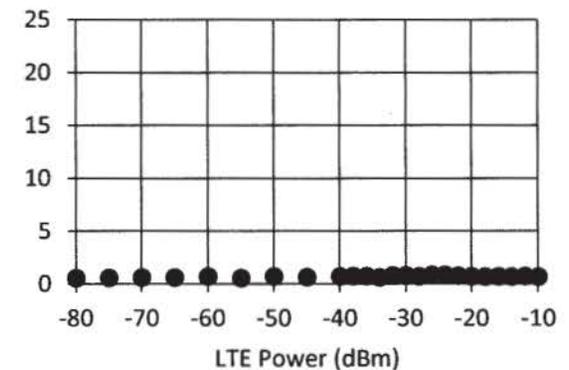
1627.5-1637.5 MHz LTE



1646.5-1656.5 MHz LTE



1670-1680 MHz LTE



Garmin Montana 650t

Open Sky with Motion | GPS Only (No LTE Signal)

Device Category: GLN

Key Performance Indicator:

Mean Position Error 2D (m)
(3-minute averaging window)

Device: Garmin Montana 650t

Antenna: Internal

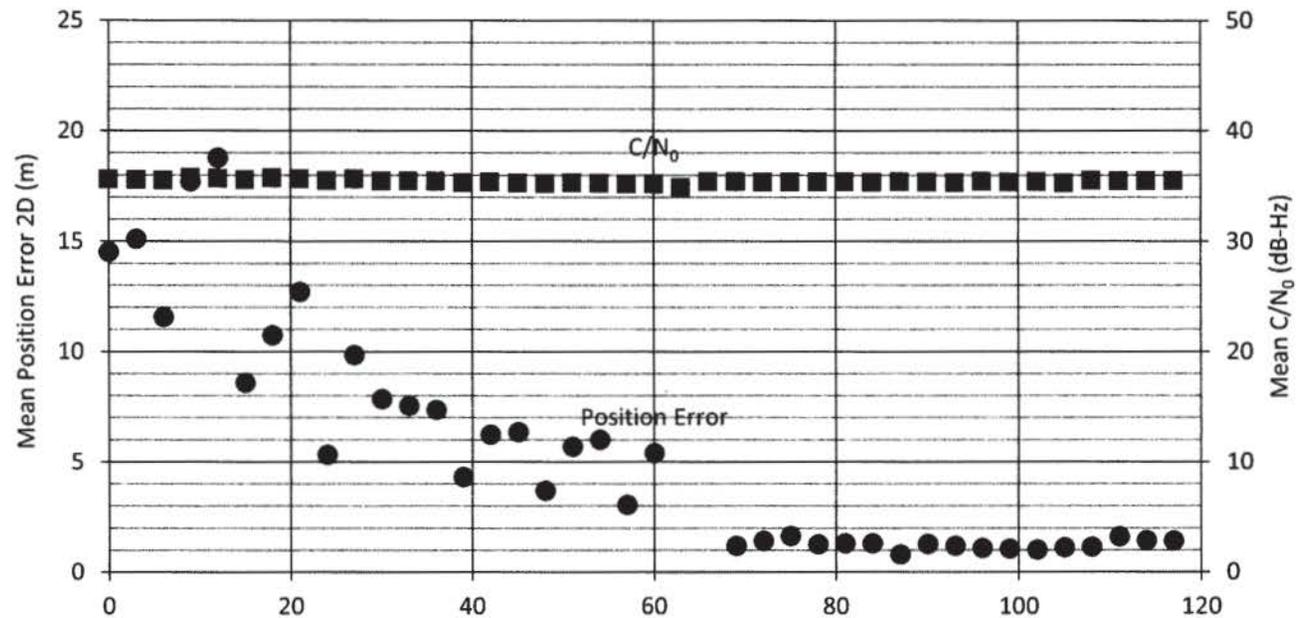
GPS Condition:

Open Sky with Motion

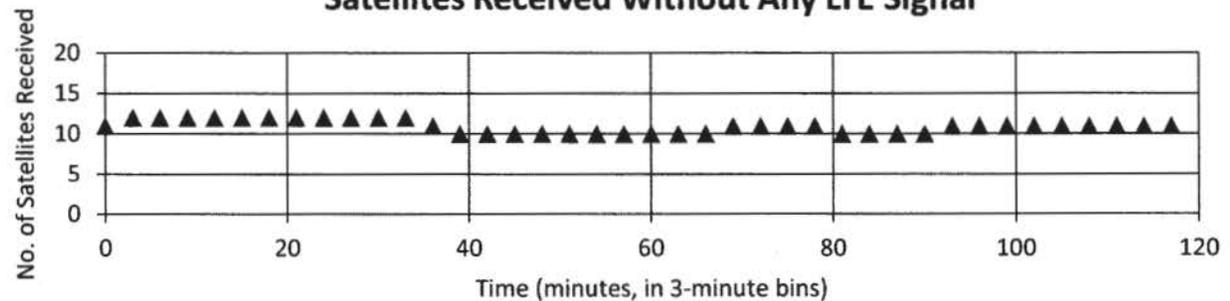
LTE Condition:

GPS Only (No LTE Signal)

Position Error and C/N₀ Without Any LTE Signal



Satellites Received Without Any LTE Signal



- Mean Position Error 2D (m)
- Mean C/No (dB-Hz)
- ▲ No. of Satellites Received

Garmin Montana 650t

Open Sky with Motion | 1526-1536 MHz LTE (Downlink)

Device Category: GLN

Key Performance Indicator:

Mean Position Error 2D (m)
(3-minute averaging window)

Device: Garmin Montana 650t

Antenna: Internal

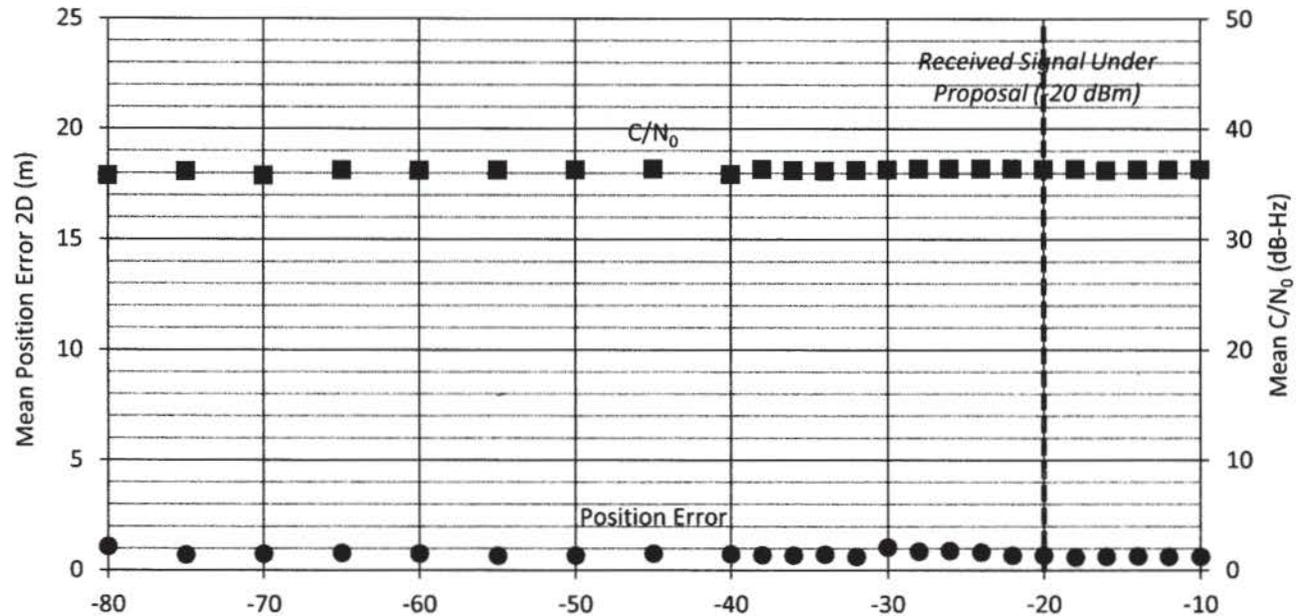
GPS Condition:

Open Sky with Motion

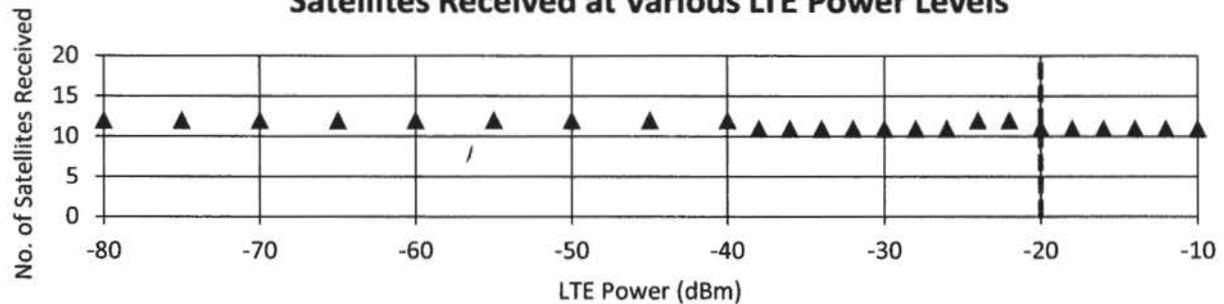
LTE Condition:

1526-1536 MHz LTE (Downlink)

Position Error and C/N₀ at Various LTE Power Levels



Satellites Received at Various LTE Power Levels



- Mean Position Error 2D (m)
- Mean C/No (dB-Hz)
- ▲ No. of Satellites Received

Garmin Montana 650t

Open Sky with Motion | 1627.5-1637.5 MHz LTE (Uplink)

Device Category: GLN

Key Performance Indicator:

Mean Position Error 2D (m)
(3-minute averaging window)

Device: Garmin Montana 650t

Antenna: Internal

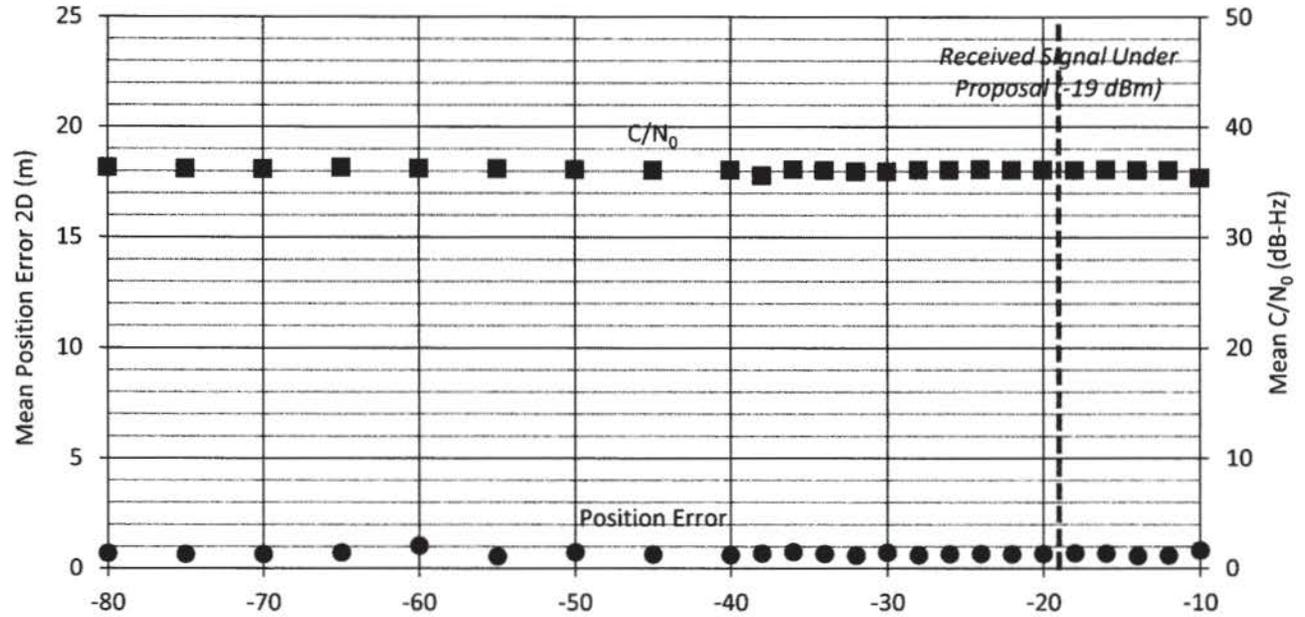
GPS Condition:

Open Sky with Motion

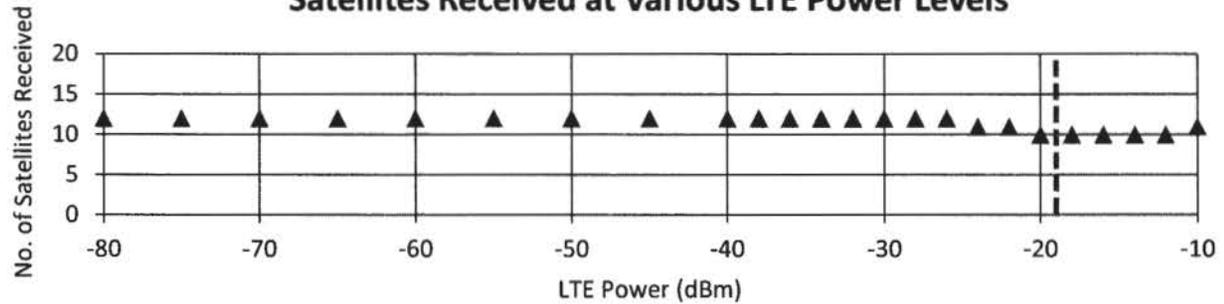
LTE Condition:

1627.5-1637.5 MHz LTE (Uplink)

Position Error and C/N₀ at Various LTE Power Levels



Satellites Received at Various LTE Power Levels



- Mean Position Error 2D (m)
- Mean C/No (dB-Hz)
- ▲ No. of Satellites Received

Garmin Montana 650t

Open Sky with Motion | 1646.5-1656.5 MHz LTE (Uplink)

Device Category: GLN

Key Performance Indicator:

Mean Position Error 2D (m)
(3-minute averaging window)

Device: Garmin Montana 650t

Antenna: Internal

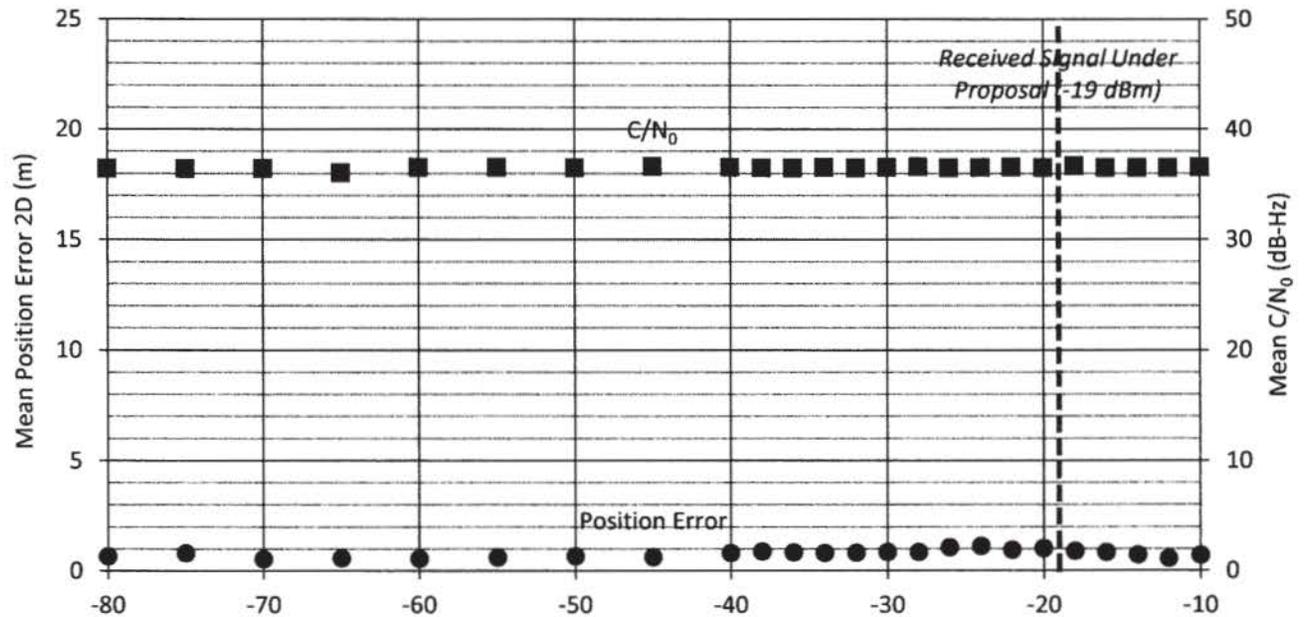
GPS Condition:

Open Sky with Motion

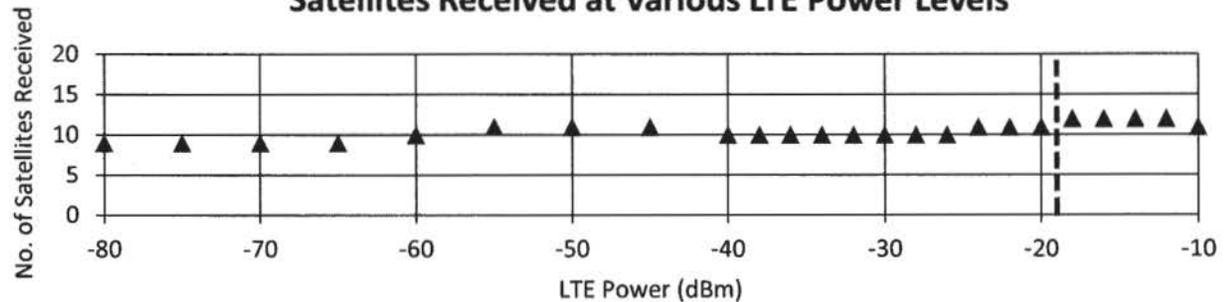
LTE Condition:

1646.5-1656.5 MHz LTE (Uplink)

Position Error and C/N₀ at Various LTE Power Levels



Satellites Received at Various LTE Power Levels



- Mean Position Error 2D (m)
- Mean C/No (dB-Hz)
- ▲ No. of Satellites Received