NTIA TM-20-536

ASSESSMENT OF COMPATIBILITY BETWEEN GLOBAL POSITIONING SYSTEM RECEIVERS AND ADJACENT BAND BASE STATION AND USER EQUIPMENT TRANSMITTERS

Technical Memorandum

U.S. DEPARTMENT OF COMMERCE • National Telecommunications and Information Administration

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ASSESSMENT OF COMPATIBILITY BETWEEN GLOBAL POSITIONING SYSTEM RECEIVERS AND ADJACENT BAND BASE STATION AND USER EQUIPMENT TRANSMITTERS

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December 2020

ACKNOWLEDGEMENTS

The National Telecommunications and Information Administration (NTIA) and the authors would like to thank the members of the Interdepartment Radio Advisory Committee's Technical Focus Group (TFG) for their support in completing this assessment of the compatibility between Global Positioning System (GPS) receivers and adjacent band base station and user equipment transmitters. GPS is perhaps best known for its utility as a navigation aid in automobiles and for its use in mobile Internet applications as a location based service offered by commercial providers. However, GPS is relied upon worldwide in aeronautical, maritime, and ground-based navigation; surveying; construction; precision agriculture; timing synchronization (e.g., telecommunications, digital television, power distribution, banking, financial transactions, and the Internet); emergency medical response (e.g., E911) and disaster management; and search and rescue operations.

While this technical memorandum presents NTIA's technical analyses, the inputs provided by representatives on the TFG from the United States Air Force GPS Directorate, Department of Energy, Department of Transportation, Federal Aviation Administration, National Aeronautics and Space Administration, Department of Defense Office of Chief Information Officer, and Federal Communications Commission were essential to completing this assessment.

The authors would like to thank William Doolan and Jeffery Deveraux, formerly with NTIA's Office of Spectrum Management Spectrum Engineering and Analysis Division (SEAD) for their contributions to the initial analyses and early drafts of this technical memorandum along with Suzette Williams, also from SEAD, for providing technical editing support in preparing this document.

The authors also acknowledge and appreciate the technical support provided by Paul McKenna from NTIA's Institute for Telecommunication Sciences.

EXECUTIVE SUMMARY

On December 31, 2015, Ligado Networks submitted applications to the Federal Communications Commission (FCC) to modify licenses for the ancillary terrestrial component (ATC) of its L-band mobile satellite service (MSS) in order to enable the provision of commercial wireless services. The proposed terrestrial operations would use three radio frequency spectrum band segments: base stations in the 1526-1536 MHz portion of the MSS downlink band and user equipment in the 1627.5-1637.5 MHz and 1646.5-1656.5 MHz portions of the MSS uplink band. Ligado has agreed to limit unwanted emissions (spurious emissions and out-of-band emissions) in the 1559-1610 MHz Radionavigation-Satellite Service (RNSS) allocation and to reduce the ATC base station power in the 1526-1536 MHz band.[1]

On April 22, 2016, the FCC released a public notice seeking comment on, among other things, the extent to which Ligado's modified applications would address Global Positioning System (GPS) interference concerns. Soon thereafter, the Chair of the Interdepartment Radio Advisory Committee (IRAC) established a Technical Focus Group (TFG) to address technical issues raised in the FCC's public notice. Engineers from NTIA's Office of Spectrum Management, in collaboration with subject matter experts from the United States Air Force GPS Directorate, Department of Energy, Department of Transportation, Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), the Department of Defense Office of Chief Information Officer, and the FCC, participated in the TFG.

This technical memorandum provides the results of the TFG's compatibility assessment between terrestrial GPS L1 coarse/acquisition (C/A) code receivers operating in the 1559-1610 MHz RNSS band and terrestrial operations in the 1526-1536 MHz, 1627.5-1637.5 MHz, and 1646.5-1656.5 MHz bands. The TFG assessed compatibility between different categories of GPS L1 C/A code receivers and the proposed terrestrial deployment by examining the degradation in carrier-to-noise density ratio (C/N_0), loss-of-lock, position error, and increase in acquisition/reacquisition time for GPS receivers.[2]

This technical memorandum summarizes the results of the TFG's GPS receiver analyses and terrestrial deployment simulations. The GPS receiver analyses consisted of data synthesis of the measurements from the different test programs for tracking and acquisition/reacquisition modes, effects of the antenna on measured interference power levels, and position error distribution measurements. The GPS receiver categories measured included: high precision, general location/navigation, timing, cellular, and general aviation. Based upon the measurement data from multiple test programs:

[1] On May 31, 2018, Ligado amended the pending license modification applications to reduce the ATC base station power in the 1526-1536 MHz band to not exceed 9.8 dB relative to a Watt and proposed other operating conditions.

[2] No information was made available that describes the specific terrestrial deployment. Therefore, the information used to model the base station deployment was obtained from submissions to the FCC and from other publicly available documents and information from International Telecommunication Union Radiocommunication Sector recommendations and reports.

- It is difficult to isolate the specific interference mechanism for each GPS receiver in the different measurement programs without sufficient technical information from the GPS receiver manufacturers.
- A wide range of interfering signal power levels can cause degradation in C/N_0 within the high precision and general location/navigation receiver categories.[3]
- In general, degradations in C/N_0 can be correlated with increases in acquisition/reacquisition time and position error distribution.
- Such degradations are more likely to occur when the GPS receiver filter bandwidth extends outside of the RNSS allocation and are less likely to be caused by the base station and user equipment within the RNSS Radionavigation-Satellite Service allocation under proposed out-of-band emission limits.
- External antenna filter selectivity can be a contributing factor to the interference power level that causes degradations in C/N_0.

The terrestrial deployment analysis simulations incorporated the measurement data synthesis into single and aggregate base station and user equipment interference analysis, using statistical (e.g., Monte Carlo) techniques. The analysis examined the relationship between the received interfering signal power at the GPS receiver that causes degradation in C/N_0, the base station or user equipment equivalent isotropically radiated power (EIRP) and the separation distance between a GPS receiver and a base station or user equipment. Based upon the results of the analyses, there do not appear to be any practical combinations of EIRP levels and separation distances that can be employed for compatible operation between Ligado's proposed terrestrial operations and *all* of the GPS receivers measured.

The FAA and NASA performed separate analyses that calculated the maximum base station EIRP for compatible operation with certified aviation receivers and the TriG spaceborne receiver. Additionally, the FAA's analysis concluded that user equipment (handsets), operating under the frequency, power and out-of-band emission characteristics in Ligado's modified applications, should not cause harmful interference to certified GPS avionics. However, the analysis for certified avionics was based on the concept of a 250-foot radius assessment zone inside which GPS performance may be compromised or unavailable.

[3] High precision receivers can receive correction signals from MSS systems in the 1525-1559 MHz band to improve accuracy. Each measurement campaign used different representations of the GPS signal constellation (e.g., number of space vehicles in view and received signal power levels) and the interfering test signals. These differences can be a contributing factor in the variability seen in the measured interfering signal power levels.

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ACRONYMS AND ABBREVIATIONS

3GPP	3rd Generation Partnership Project
ABC	Adjacent Band Compatibility
AF	Activity Factor
AFSS	Autonomous Flight Safety System
AFTU	Automated Flight Termination Unit
ATC	Ancillary Terrestrial Component
AZ	Azimuth
BS	Base Station
BAW	Bulk Acoustic Wave
C/A	Coarse/Acquisition
C/N_0	Carrier-to-Noise Density (dB-Hz)
CEL	Cellular Receiver Category
CFR	Code of Federal Regulations
CORS	Continuously Operating Reference Station
CR	Cell Radius
CW	Continuous Wave
CYGNSS	Cyclone Global Navigation Satellite System
dB	Decibel
dB-Hz	Decibel-Hertz
dBi	Decibel relative to an isotropic antenna
dBic	dBi gain for circularly polarized receive antenna
dBm	dB relative to a milliwatt (1 dBm = -30 dBW)
dBW	dB relative to a Watt (1 dBW = 30 dBm)
dBW/Hz	dBW as measured in a 1 Hertz bandwidth
dBW/kHz	dBW as measured in a 1 kHz bandwidth
dBW/MHz	dBW as measured in a 1 MHz bandwidth
DGPS	Differential GPS
DL	Downlink Band (1526-1536 MHz)
DOC	Department of Commerce
DOJ	Department of Justice
DOP	Dilution of Precision
DOT	Department of Transportation
DUT	Device Under Test
EIRP	Equivalent Isotropically Radiated Power
EL	Elevation
EPD	Electron Density Profile
ES	Earth Station
ETSO	European Technical Standards Order
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
FRA	Federal Railroad Administration

FSPL	Free Space Propagation Loss
$FSPL_{200m}$	Free Space Propagation Loss at 200 meters
GAGE	Geodesy Advancing Geoscience and EarthScope
GAV	General Aviation Receiver Category
GBAS	Ground Based Augmentation System
GEO	Geostationary-Earth-Orbit
GGN	Global GNSS Network
GHz	Gigahertz – $1x10^9$ Hz
GLN	General Location/Navigation Receiver Category
GLONASS	GLObalnaya NAvigatsionnaya Sputnikovaya Sistema
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPSDO	GPS-disciplined oscillator, a timing receiver
Hz	Hertz (cycle per second)
HITL	Human-in-the-Loop
HP	High Precision Receiver Category
H-pol	Horizontal Polarization
HTAWS	Helicopter Terrain Awareness Warning System
ICAO	International Civil Aeronautics Organization
ICD	Interface Control Document
IF	Intermediate Frequency
IFR	Instrument Flight Rules
IGOR	Integrated GPS Occultation Receiver
IGS	International GNSS Service
IMT	International Mobile Telecommunication
IRAC	Interdepartment Radio Advisory Committee
IS	Interface Specification
ISD	Inter-site Distance
ISS	International Space Station
ITM	Irregular Terrain Model Propagation Loss
ITM_{200m}	Irregular Terrain Model Propagation Loss at 200 meters
$ITM_{AreaMode}$	Irregular Terrain Model Propagation Loss in Area Prediction Mode
ITS	Institute for Telecommunication Sciences
ITU	International Telecommunication Union
ITU-R	ITU – Radiocommunication Sector
JPL	Jet Propulsion Laboratory
kHz	Kilohertz - 1000 Hertz - 10^3 Hertz
km	Kilometer
L1	GPS L1 channel at 1575.42 MHz
L1C	GPS L1 Civil Code
L2	GPS L2 channel at 1227.60 MHz
L5	GPS L5 channel at 1176.45 MHz
LEO	Low Earth Orbiting
LNA	Low noise amplifier
LOL	Loss of Lock

LTE	Long Term Evolution
M&S	Modeling and Simulation
MHz	Megahertz - 10^6 Hertz
MOPS	Minimum Operational Performance Standards
MSS	Mobile-Satellite Service
NASA	National Aeronautics and Space Administration
NASCTN	National Advanced Spectrum and Communications Test Network
NMEA	National Marine Electronics Association
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NPEF	National Space-Based Positioning, Navigation, and Timing (PNT) Systems Engineering Forum
NTIA	National Telecommunications and Information Administration
OFDM	Orthogonal Frequency Division Multiplex
OOBE	Out-of-band emissions
OSM	Office of Spectrum Management
P Code	Precision Code
PBO	Plate Boundary Observatory
PNT	Position Navigation and Timing
PNTEXCOM	National Executive Committee for Space Based PNT
POD	Precise Orbit Determination
PRN	Pseudo random noise
PSD	Power spectral density
PTC	Positive Train Control
QZSS	Quasi Zenith Satellite System
R&A	Roberson and Associates
RF	Radio Frequency
RFI	Radio Frequency Interference
RHCP	Right Hand Circular Polarization
RMS	Root Mean Square (the square root of the arithmetic mean of the squares of a set of numbers)
RNSS	Radionavigation-Satellite Service
RO	Radio Occultation
RPE	Radiation Pattern Envelope
RTK	Real Time Kinematics
SARPs	Standards and Recommended Practices
S/m	seimans per meter
SAW	Surface Acoustic Wave
SBAS	Satellite Based Augmentation System
SC-FDMA	Single Carrier Frequency Division Multiple Access
SEAD	Spectrum Engineering and Analysis Division
SGP	Space Geodesy Project
SNR	Signal-to-noise ratio
SPB	Space-Based Receiver Category

SV	Satellite Vehicle
SWO	Space Weather Observation
TAWS	Terrain Awareness Warning System
TEC	Total Electron Count
TFF	Time to First Fix
TFG	Technical Focus Group (IRAC)
TFR	Time to First Reacquisition
TIM	Timing Receiver Category
Tri-G	A GNSS Precise Orbit and Radio Occultation Space Receiver
TSO	Technical Standards Order
TWG	Technical Working Group (FCC)
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
UE	User Equipment
UL1	Uplink Band 1 (1627.5-1637.5 MHz)
UL2	Uplink Band 2 (1646.5-1656.5 MHz)
UNAVCO	University NAVSTAR Consortium
V-pol	Vertical polarization
WAAS	Wide Area Augmentation System
WSMR	White Sands Missile Range
P(Y) Code	Encrypted P Code

SECTION 1
INTRODUCTION

1.1 BACKGROUND

On December 31, 2015, New LightSquared (now Ligado Networks) submitted applications to the Federal Communications Commission (FCC) to modify licenses for the ancillary terrestrial component (ATC) of its L-band mobile-satellite service (MSS) networks. Ligado's applications proposed that additional operational restrictions, in the form of license conditions, be placed on its ATC authorization to address Global Positioning System (GPS) interference concerns. These conditions included abandoning the 1545-1555 MHz band for base stations; reducing the equivalent isotropically radiated power (EIRP)[1] for user equipment from 0 dB relative to a Watt (dBW) to -7 dBW in the 1627.5-1637.5 and 1646.5-1656.5 MHz bands; reducing the base station EIRP in the 1526-1536 MHz band from 42 dBW to 32 dBW; and proposing out-of-band emission (OOBE) limits for base stations and user equipment.[2] Ligado also proposed a license condition to address interference concerns related to certified aviation use of GPS. On April 22, 2016 the FCC released a public notice seeking comment on Ligado's modified applications.[3]

On May 31, 2018, Ligado amended the pending license modification applications requesting that the FCC: 1) require that Ligado's ATC base stations operating in the 1526-1536 MHz band not exceed an EIRP of 9.8 dBW with a ± 45 degree cross-polarized base station antenna; 2) prohibit any Ligado ATC base station antenna in the 1526-1536 MHz band from operating at a location less than 250 feet laterally or less than 30 feet below an obstacle clearance surface established by the Federal Aviation Administration (FAA); and 3) for ATC base station operations in the 1526-1536 MHz band, require Ligado to comply with the reporting, notification, and monitoring obligations set forth in Exhibit 1 of its amendment.[4]

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[1] The EIRP levels are expressed in terms of decibel watt or dBW, a unit for the measurement of the strength of a signal expressed in decibels relative to one watt. In this technical memorandum, the EIRP levels will be expressed in terms of decibel milliwatt or dBm. A given dBW value expressed in dBm is always 30 more because 1 watt is 1,000 milliwatts, and a ratio of 1,000 (in power) is 30 decibels (dB).

[2] *See* Letter from Gerard J. Waldron, Counsel to New LightSquared LLC, to Marlene H. Dortch, Secretary, FCC, IB Docket Nos. 12-340 and 11-109; IBFS File Nos. SAT-MOD-20120928-00160, SAT-MOD-20120928-0061, and SE-MOD-20121001-00872 (filed Dec. 31, 2015) at 10. The EIRP reduction in the 1627.5-1637.5 MHz band is provided that the EIRP level in 1627.5-1632.5 MHz segment be allowed to increase from -31 dBW to -7 dBW for a period of 5 years and then revert to -7 dBW.

[3] *See Comment Sought of Ligado's Modification Applications*, IB Docket No. 11-109; IB Docket No. 12-340, Public Notice, DA 16-442 (Apr. 22, 2016) (*FCC PN*), *available at* https://ecfsapi.fcc.gov/file/60001690548.pdf.

[4] Letter from Gerard J. Waldron, Counsel to Ligado Networks LLC, to Marlene H. Dortch, Secretary, FCC, Amendment to License Modification Applications, IB Docket No. 11-109 (May 31, 2018), *available at* https://go.usa.gov/xQFf4.

The National Telecommunications and Information Administration (NTIA) Interdepartment Radio Advisory Committee (IRAC)[5] Chair established a Technical Focus Group (TFG) and directed it to address the following technical issues raised in the FCC's Public Notice:

> *To the extent . . . there remains potential for harmful interference from the proposed terrestrial operations (under the agreed-upon technical parameters) in the 1526-1536 MHz, 1627.5-1637.5 MHz, and 1646.5-1656.5 MHz bands, [what is] the basis for these concerns and what actions would be necessary to mitigate such potential (e.g., frequency offset, power limits, OOBE limits).*
>
> *[The FCC] request[s] specific relevant technical information about affected GPS receivers (e.g., receiver category, receiver bandwidth) and their performance or functioning (e.g., break lock, loss of tracking, specific effects on location and timing accuracy) that support [any] assertion that additional measures would be necessary to resolve remaining concerns of potential harmful interference should Ligado operate a terrestrial mobile network in accordance with the specified set of technical parameters proposed.*[6]

Since no established threshold exists for assessing harmful interference[7] to the Radionavigation-Satellite Service (RNSS), the TFG examined several parameters and the relationship of those parameters in assessing compatibility between GPS receivers operating in the RNSS and adjacent band base stations and user equipment.[8] The parameters examined by the TFG included: degradation in carrier-to-noise density ratio (C/N_0), loss-of-lock, position error, and increase in acquisition/reacquisition time.

1.2 OBJECTIVE

The objective of this assessment was to evaluate compatibility between different categories of GPS L1 C/A code receivers and a proposal to operate terrestrial base stations in the

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[5] The IRAC, consisting or representatives of 19 federal agencies, serves in an advisory capacity to the Assistant Secretary of Commerce for Communications and Information. The IRAC, in existence since 1922, assists the Assistant Secretary in the discharge of his or her responsibilities pertaining to use of the electromagnetic spectrum.

[6] *FCC PN* at 8.

[7] The FCC's rules define "harmful interference" as "[i]nterference which endangers the functioning of a radionavigation service or other safety of life services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with Radio Regulations." 47 CFR § 2.1(c). In 2003, in the Report and Order authorizing ATC operations in the MSS allocation (47 CFR § 25.255), the FCC stated that "If harmful interference is caused to other services by ancillary MSS ATC operations, either from base stations or mobile terminals, the MSS ATC operator must resolve any such interference." It should be noted that there is a GPS receiver interference mask (DO-229F) and a harmonized international mask, in ICAO SARPs, specifying the interference power level for co-channel and adjacent channel frequencies.

[8] There is a 23 megahertz frequency separation between the upper edge of the base station signal at 1536 MHz and the lower edge of the RNSS allocation at 1559 MHz; and a 17.5 megahertz frequency separation between the lower edge of the user equipment signal at 1627.5 MHz and the upper edge of the RNSS allocation at 1610 MHz.

1526-1536 MHz band and user equipment in the 1627.5-1637.5 MHz and 1646.5-1656.5 MHz bands.[9]

1.3 APPROACH

A team of engineers in NTIA's Office of Spectrum Management (OSM) Spectrum Engineering and Analysis Division (SEAD), in collaboration with subject matter experts and others from interested IRAC agencies, held regular TFG meetings to evaluate the available GPS receiver interference measurement data and to perform analysis assessing the compatibility of base station and user equipment emissions, operating with the proposed technical parameters in Ligado's modified applications, with different categories of GPS L1 Course/Acquisition (C/A) code receivers. IRAC agency participants in the TFG included: the U. S. Air Force GPS Directorate, Department of Energy (DOE), Department of Transportation (DOT), Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), the Department of Defense (DOD)/Chief Information Officer (CIO), and the FCC.

This technical memorandum covers the measurements from the different test programs for tracking and acquisition/reacquisition modes, effects of the antenna on measured interference power levels, and position error distribution measurements. The measurements are incorporated into the following:

- Single-emitter base station analysis,
- Single-emitter user equipment analysis,
- Single-emitter loss-of-lock interference analysis,
- Single emitter non-certified aviation analysis,
- Aggregate[10] base station analysis,
- Aggregate user equipment analysis, and
- Aggregate loss-of-lock interference analysis.

Additional analyses on certified aviation receivers (FAA) and a spaceborne receiver (NASA) are also summarized.

This technical memorandum is organized as follows: Section 2 discusses the measurements performed on the different categories of GPS L1 C/A code receivers in the tracking and acquisition modes of operation. The measurement parameters for each GPS receiver category examined included: degradation in C/N_0, loss-of-lock, position error, and increase in acquisition/reacquisition time. Section 3 presents the analysis results considering single and multiple base station and user equipment interactions. Section 4 provides an overall summary of the report. Additional information on the evaluation of the measurement data and the analysis performed by NTIA as well as the independent studies performed by the FAA for certified aviation GPS receivers and NASA for space-based GPS receivers are included in the following detailed technical appendices:

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[9] This technical memorandum does not address interference to receivers processing other RNSS signals (e.g., Galileo).

[10] The aggregate interference analysis was computed using statistical (e.g., Monte Carlo) analysis techniques.

Appendix A:	GPS Receiver Tracking Mode Interference Power Levels
Appendix B:	GPS Receiver Acquisition/Re-acquisition Mode Interference Power Levels
Appendix C:	Effects of Antenna Filter Selectivity on Measured Interference Power Levels
Appendix D:	Position Error Distribution as a Measurand for Assessing Interference Effects
Appendix E:	Single-Entry Base Station Analysis
Appendix F:	Aggregate Base Station Analysis
Appendix G:	Fixed GPS Infrastructure - Exclusion Zone Analysis
Appendix H:	User Equipment Analysis
Appendix I:	GPS Receiver Loss-of-Lock Interference Analysis
Appendix J:	Certified Aviation GPS Receiver Use Case Analysis
Appendix K:	Non-Certified Aviation GPS Receiver Analysis
Appendix L:	Pseudorange and Position RMS Error Versus C/N_0 for Simple L1 C/A Receiver Architecture
Appendix M:	Spaceborne and Science-Applications Analysis

SECTION 2
MEASUREMENT OVERVIEW

2.1 TRACKING MODE INTERFERENCE POWER LEVELS

The measured interference power levels for high precision (HP), general location/navigation (GLN), timing (TIM), cellular (CEL), general aviation (GAV), and space-based (SPB) L1 C/A Code GPS receivers in the tracking mode are presented in Appendix A. The measurements are from test programs performed by the DOT Adjacent Band Compatibility (DOT ABC), DOD, Roberson and Associates (R&A), and National Advanced Spectrum and Communications Test Network (NASCTN). GPS receiver interference measurements from the 2011 FCC Technical Working Group (TWG) and the 2012 National Positioning, Navigation, and Timing (PNT) Systems Engineering Forum (NPEF) testing are also included. The measured interfering signal power levels presented in Appendix A are based on degradations to carrier-to-noise density ratio (C/N_0) as reported by the C/N_0 estimator of a GPS receiver for each space vehicle (SV). Figure 1 to 3 summarize the measured interference power levels for 1 dB, 3 dB, and 5 dB degradations in C/N_0.[11] Additional measurements were performed by the TWG for GPS receivers in the CEL category using the 3GPP Assisted GPS performance standard.[12]

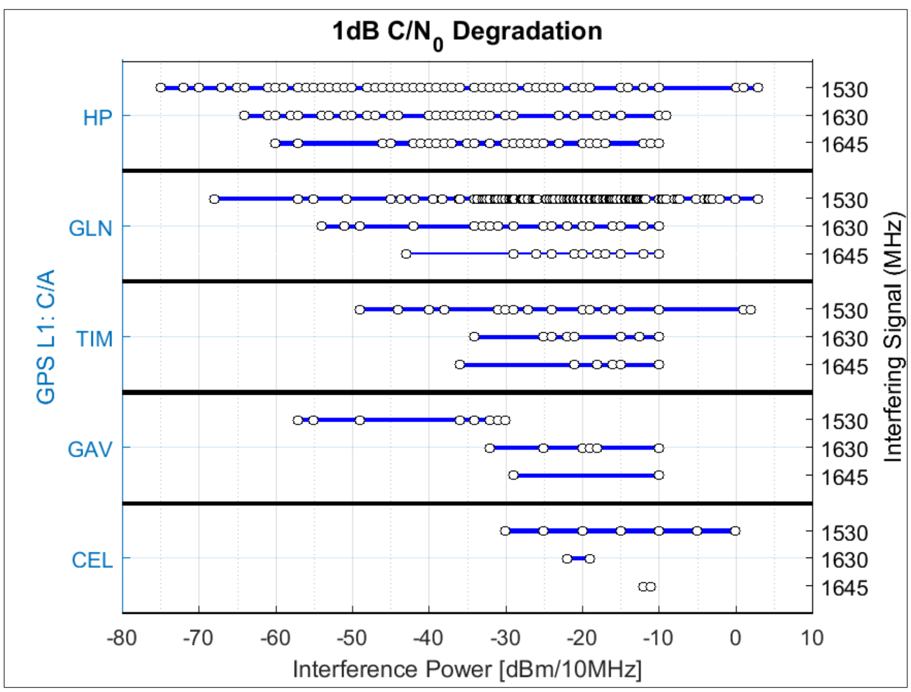

Figure 1. Distribution of Interfering Signal Power Levels Causing 1 dB C/N_0 Degradation

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[11] A 1 dB degradation in C/N_0 has been used as an interference protection criterion for the GPS service.

[12] 3GPP Specification TS 37.571-1, *Universal Terrestrial Radio Access (UTRA) and Evolved UTRA (E-UTRA) and Evolved Packet Core (EPC); User Equipment (UE) conformance specification for UE positioning; Part 1: Conformance Test Specification*, Rel. 9 (2015).

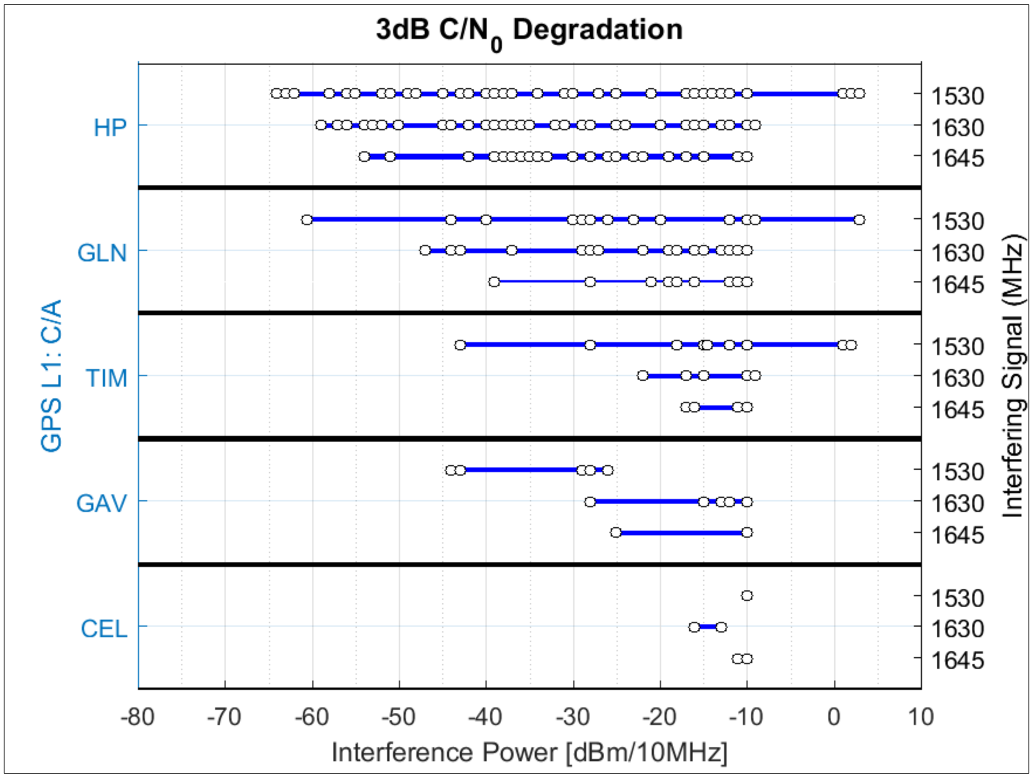

Figure 2. Distribution of Interfering Signal Power Levels Causing 3 dB C/N₀ Degradation

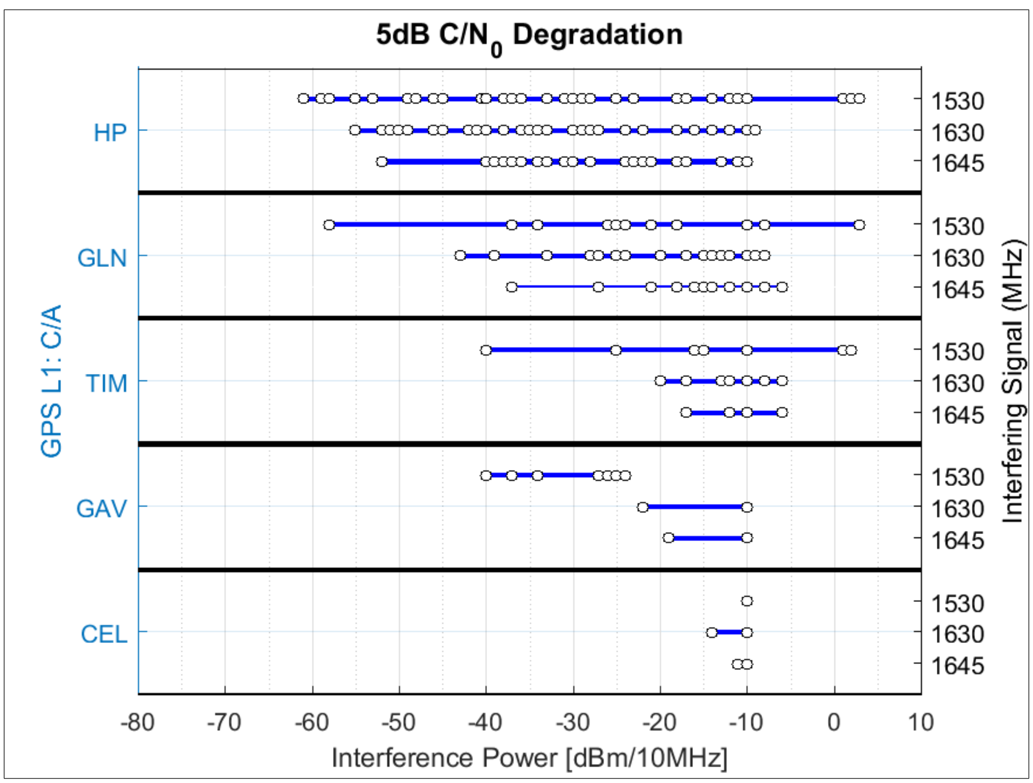

Figure 3. Distribution of Interfering Signal Power Levels Causing 5 dB C/N₀ Degradation

The measurement data were evaluated to ensure the stability and consistency of the GPS receivers under interference-free (i.e., baseline) conditions. Measurement data for GPS receivers where the C/N_0 was not stable under interference-free conditions were eliminated from further consideration. As discussed in Appendix A, a method was developed to select the interference power levels corresponding to 1 dB, 3 dB, and 5 dB C/N_0 degradations to eliminate the variations that can occur in the reported C/N_0. The measured interference power levels for each C/N_0 degradation were placed into bins, where the percentage of impacted receivers from all of the measurement programs can be determined.[13] The percentage of receivers referred to in this document only represents the percentage of receivers tested in the different measurement programs, does not represent the percentage of receivers actually deployed currently or in the future, and does not necessarily constitute a representative selection of all receivers for any Global Navigation Satellite System (GNSS) application or the service in general.

Most GPS receivers tested were equipped with circuitry that provides an estimate of the receiver C/N_0 for each satellite being tracked; this data is regularly updated and can be logged externally to facilitate analysis. The degradation of C/N_0 reported by the receiver subject to interference compared to the baseline value of C/N_0 when interference is not present can be used as an indicator of the onset of interference. As discussed in Appendix L, C/N_0 degradation can affect the code tracking loop error for medium accuracy applications and the carrier tracking loop for high accuracy applications. Under low C/N_0 conditions, the same amount of degradation can result in larger carrier tracking errors than for a situation where clear line-of-sight and high elevation SV conditions exist.

Appendix A details a wide range of interference power levels that can cause degradation to C/N_0 within a GPS receiver category. The range of interference power levels that cause a 1dB C/N_0 degradation are: 78 dB for HP receivers, 71 dB for GLN receivers, 51 dB for TIM receivers, and 25 dB for CEL receivers. As discussed in Appendix A, each measurement campaign used different representations of the GPS signal constellation (e.g., number of SVs in view and received signal power levels from each SV) and the interfering test signals. The differences in the test configurations can be a contributing factor in the variability seen in the measured interfering signal power levels.

There are multiple ways that interference can degrade the C/N_0 reported by a GPS receiver. However, it is difficult to isolate the specific cause for each GPS receiver in the different measurement programs without sufficient technical information, such as receiver design, radio frequency filter selectivity, and low noise amplifier (LNA) specifications.[14]

[13] No claim is being made on the relationship between the number of receivers tested and the percentage of receivers actually deployed in any given application or user program.

[14] DOT requested information on the receiver radiofrequency filter selectivity, the gain, noise figure, 1 dB gain compression point and third-order intercept point of the LNA from the GPS receiver manufacturers in their ABC test plan, *Test Plan to Develop Interference Tolerance Masks for GNSS Receivers in the L1 Radiofrequency Band (1559-1610 MHz)* (Mar. 2016), at 2, *available at* https://rosap.ntl.bts.gov/view/dot/37033. The GPS receiver manufacturers did not provide the requested information and were not under obligation to provide the data based on the DOT ABC test plan.

An interfering signal can cause a LNA in the GPS receiver to operate in the non-linear gain region. It should be noted that most GPS receivers have several cascaded LNAs with filtering in between. In the presence of in-band interference, it is typically the last gain stage that saturates first as the interference power increases. In the presence of near-band or out-of-band interference, the gain stage that saturates first depends on the progression along the front-end of cumulative LNA gain versus cumulative filter attenuation at the interference frequency. When the interference signal level at the input to an LNA is near the 1 dB compression point, non-linear effects can result in spreading of the energy of the signal and noise as well as an increase in the LNA noise figure, resulting in a lower C/N_0.[15]

Reciprocal mixing can occur in a receiver when, during the reception of a wanted signal, a strong out-of-band interfering signal mixes with out-of-band skirt noise from the synthesizer, producing mixing products which fall into the receiver intermediate frequency (IF) band, causing the receiver output signal-to-noise ratio to be degraded.

Interference can occur from aliasing due to sampling within the receiver's analog-to-digital converter.[16] A GPS receiver typically has increased sensitivity to interference concentrated on frequencies that will be folded, through the aliasing process, on top of the power spectrum of the desired signal.[17]

Interference can also occur from unwanted emissions, when an interfering signal operating at frequencies near the frequency range of the GPS receiver adds to the receiver noise, resulting in a lower C/N_0. Ligado has agreed to limit unwanted emissions (spurious emissions and out-of-band-emissions (OOBE)) in the 1559-1610 MHz RNSS frequency band.[18]

Based on a review of the available data, differences between the measured interference power levels that cause 1 dB and 5 dB degradations in C/N_0 for a given receiver are within 9 dB. Based on a review of the data, the degradations in C/N_0 do not appear to be caused by the OOBE into the 1559-1610 MHz RNSS allocation from the adjacent band base station and user equipment signals.

The measured interference power levels in Appendix A were used to assess the compatibility of GPS receivers with signals from base stations operating in the 1526-1536 MHz band and user equipment (UE) operating in the 1627.5-1637.5 MHz and 1646.5-1656.5 MHz bands.

One category of GPS receivers, certified avionics, operates in accordance with internationally-adopted standards that include an interference tolerance mask. Given the performance required by these standards, the FAA determined that additional testing was not

[15] The gain and 1 dB gain compression point of the LNA can also impact the effects of saturation.

[16] Aliasing is an effect that causes different signals to become indistinguishable (or aliases of one another) when sampled.

[17] J. B. Tsui, *Fundamentals of Global Positioning System Receivers A Software Approach*, John Wiley and Sons, New York, 2000 at 117-118.

[18] *FCC PN* at 10.

necessary. Instead, analyses were utilized to determine limits on base station transmitter EIRP necessary to protect certified avionic equipment. Appendix J provides further details on those analyses.

2.2 ACQUISITION AND REACQUISITION MODE INTERFERENCE POWER LEVELS

In Appendix B, the GPS receiver acquisition and reacquisition mode interference measurements performed by the DOT ABC, R&A, and NASCTN test programs are evaluated. The methodologies used by each test program differed. For example, the DOT ABC measurements were performed with the GPS receiver operating in the Warm or Hot Start acquisition mode. The R&A test program measured the 90th percentile of the reacquisition time.[19] NASCTN performed two types of measurements: Time-to-First-Fix for HP receivers and Time-to-First-Reacquisition for GLN receivers. Different GPS signal power levels were used by each test program. However, even with the differences in the approaches used by each test program the following general observations can be made:

- For GPS receivers where there is no impact to the signal acquisition mode there is also no degradation in the tracking mode C/N_0; and
- a range of interfering signal power levels generally corresponding to a 1 dB to 5 dB degradation in C/N_0 in tracking mode can be correlated with the impact to signal acquisition and reacquisition time.

2.3 EFFECTS OF ANTENNA FILTER SELECTIVITY ON MEASURED INTERFERENCE POWER LEVELS

Appendix C discusses filtering techniques used in antennas to control interfering signals. The interfering signal level necessary to cause a given C/N_0 degradation can vary by up to 70 dB depending on the spatial and/or band limiting filtering provided by the external antenna employed. Antenna variability, specifically filtering and the 1 dB gain compression point for the LNA, complicates the selection of an allowable C/N_0 degradation for the different categories of GPS receivers. Appendix C does not address the impact on overall GPS receiver performance (*e.g.*, position accuracy) of employing antennas with greater filter selectivity. Nor does Appendix C address the impact of these antennas on MSS-augmented GPS receivers whose performance depends on reception of the MSS signals. Finally, Appendix C also does not consider the cost of such a modification, or viability in terms of size (e.g., for aircraft platforms) or accessibility (e.g., for space platforms or already fielded receivers). Moreover, antenna filtering can cause deleterious effects on receiver performance, such as group delay and other distortions that have not been examined in this evaluation but which should be examined before any decisions are made based on antenna filtering techniques. Appendix C does not address the question as to whether a given operational capability could be accommodated at all, if new constraints (e.g., filtering and reduced gain) are imposed on these antennas.

[19] Data provided by R&A was used to compute the 99th percentile of reacquisition time.

2.4 POSITION ERROR DISTRIBUTION AS A MEASURAND FOR ASSESSING INTERFERENCE EFFECTS

Appendix D documents the analysis to assess the impact of interference on the GPS receiver position error. The analysis suggests there is a correlation between the standard deviation of the position error data distribution and the degradation of the C/N_0 (the estimated signal power from a GPS satellite). The analysis also suggests that the mean value of the position error data distribution is not a good indicator of the GPS receiver performance.

A common pattern was identified when analyzing the C/N_0 and position error data in the NASCTN measurement. In plotting the collection of the C/N_0 and position error as a function of the interfering signal power, it was observed that the data distribution in the plot expands as the interfering signal power increases. It was also observed that the mean value of the data distribution remains stable as the distribution expands. From these observations, the following conclusions can be reached:

- The mean value of position error does not reflect the real performance because averaging neutralizes the large and small values of position error; and
- The position error distribution, being the probability function of the position error, can be used as a performance measure and to evaluate the interference effect to GPS receivers.

Appendix D documents the result of the C/N_0 and position error data analysis. Since the position is derived from the pseudorange, the position is highly correlated to the pseudorange, and thus the position error is highly correlated to the pseudorange error. The analysis in Appendix D suggests that in general there is a correlation between the standard deviation of the position error and degradations in C/N_0. The C/N_0 degradations and mean position error percentage increase and the deviation of position error percentage increase are shown in Figure 4.

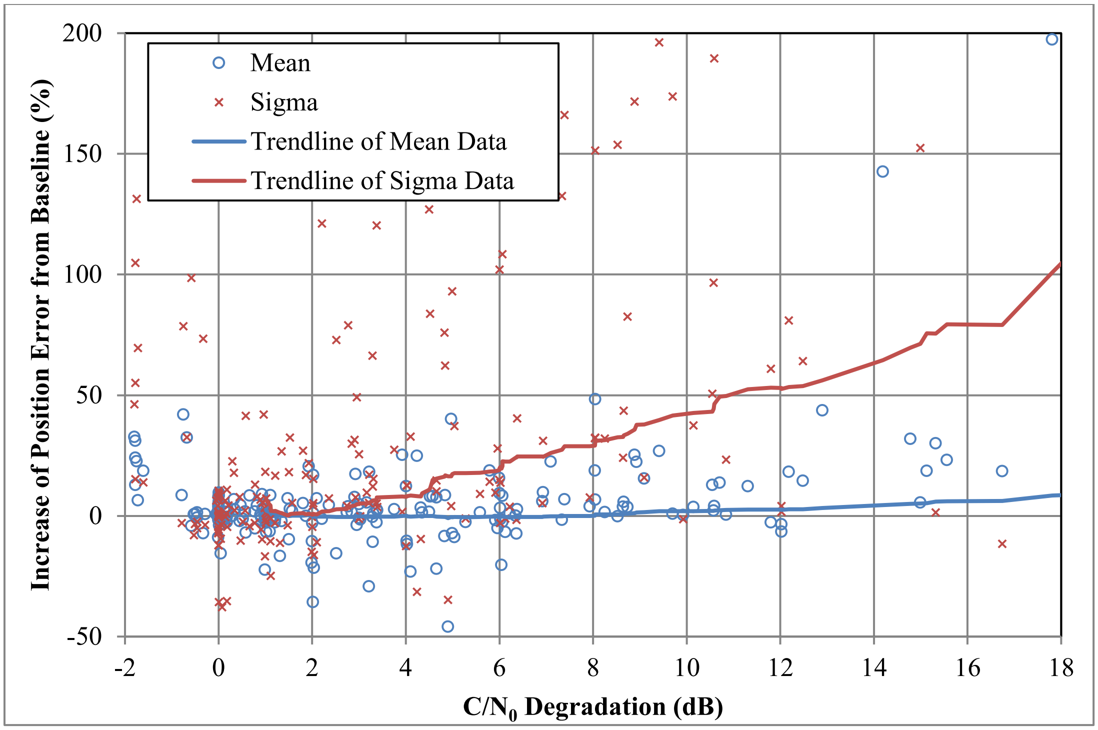

Figure 4. Mean and Sigma of GPS Receiver Position Error Distribution as a Function of C/N_0 Degradation

SECTION 3
ANALYSIS OVERVIEW

3.1 ANALYSIS APPROACH

An analysis was performed to calculate the received power at the input of a GPS receiver from base stations operating in the 1526-1536 MHz band and user equipment operating in the 1627.5-1637.5 MHz and 1646.5-1656.5 MHz bands.[20] The calculated received power at the GPS receiver was compared to the measured interference power levels for each category of GPS receiver to assess the potential for interference. The analysis considered single-entry and aggregate base station and user equipment interference.[21]

The following general equation was used to calculate the received power at the input of a GPS receiver:[22]

$$P_R = EIRP - L_{GPS} - L_{BS/UE} - L_P$$

where:

P_R is the received power at the front end of a GPS antenna (dBm/10 MHz);
EIRP is the equivalent isotropically radiated power of the base station/user equipment (dBm/10 MHz);
L_{GPS} is the normalized, off-boresight GPS antenna loss (dB);[23]
$L_{BS/UE}$ is the off-axis antenna loss of the base station/user equipment (dB);[24] and
L_P is the propagation loss from a base station/user equipment transmit antenna to the GPS receive antenna (dB).

For the macro base station analysis, a dual orthogonal linear polarization transmission was assumed, where each orthogonal polarization is rotated 45 degrees. It is assumed that the signals transmitted in each diagonal polarization are mutually uncorrelated and have equal transmit EIRP. The aggregate power was calculated for the horizontal and vertical polarization

[20] The analysis took into account of all of the gains and losses from the transmitter, through the medium to the receiver. It accounts for the attenuation of the transmitted signal due to propagation, as well as the antenna gains, cables, and other miscellaneous losses. Randomly varying parameters in the analysis can be modeled statistically using Monte Carlo techniques.

[21] The EIRP levels in Ligado's proposal are expressed in terms of decibel watt or dBW, a unit for the measurement of the strength of a signal expressed in decibels relative to one watt. In this technical memorandum, the EIRP levels are expressed in terms of decibel milliwatt or dBm. A given dBW value expressed in dBm is always 30 more because 1 watt is 1,000 milliwatts, and a ratio of 1,000 (in power) is 30 dB. The EIRP levels of 9.8 dBW and 39.8 dBm are equivalent. In this technical memorandum, the EIRP of 39.8 dBm is rounded off to 40 dBm.

[22] The link budget analysis approach used in this technical memorandum is described in Joint Spectrum Center, JSC-CR-10-004, *Communications Receiver Performance Degradation Handbook* (Aug. 11, 2010), Section 2, *available at* https://www.ntia.doc.gov/files/ntia/publications/jsc-cr-10-004final.pdf.

[23] GPS off-boresight antenna loss is used because the test data was taken at the GPS antenna boresight.

[24] The off-boresight base station antenna loss is used because the base station transmit EIRP is specified in terms of the maximum antenna gain.

separately, converted to watts and summed, and converted back to dBm to represent the total received power.

$$P_{R_{Horizontal}} = (EIRP - 3dB) - L_{GPS_{Horizontal}} - L_{BS/UE} - L_{P_{Horizontal}} \quad \text{(dBm/10 MHz)}$$

$$P_{R_{Vertical}} = (EIRP - 3dB) - L_{GPS_{Vertical}} - L_{BS/UE} - L_{P_{Vertical}} \quad \text{(dBm/10 MHz)}$$

$$P_{R_{Watts}} = \frac{10^{\left(\frac{P_{R_{Vertical}}}{10}\right)}}{1000} + \frac{10^{\left(\frac{P_{R_{Horizontal}}}{10}\right)}}{1000} \quad \text{(Watts)}$$

$$P_{R_{dBm}} = 10\, log_{10}\left(1000 * P_{R_{Watts}}\right) \quad \text{(dBm/10 MHz)}$$

Measured data for vertical and horizontal polarization at specific frequencies was used to compute the normalized, off-boresight loss of a GPS antenna for each receiver category. The normalized gain was calculated for each category of GPS antenna. Each normalized antenna gain was then converted from decibel(s) relative to an isotropic antenna (dBi) to linear units, and averaged, from -180° to 0° and 0° to 180°, to make the GPS antenna gains symmetrical from -180° to 180°. The GPS antenna gains were then converted back to dBi.

As no information was available for the base station antenna pattern, the off-axis loss was computed using the International Telecommunication Union Radiocommunication Sector (ITU-R) antenna models.[25] An omnidirectional antenna pattern with 0 dBi gain was employed for the off-axis loss of the user equipment in the analysis.

The propagation model used in the analysis is a combination of the free space loss model[26] and the Irregular Terrain Model (ITM) in the area prediction mode.[27] Free space loss is used for separation distances of less than 100 meters. A blend of the free space loss model and the ITM area prediction mode is used for separation distances between 100 to 200 meters. For separation distances greater than 200 meters, ITM in the area prediction mode is used. The distance constraints associated with the propagation loss model used in the analysis are shown below:

[25] Report ITU-R M.2292-0, *Characteristics of terrestrial IMT-Advanced systems for frequency sharing/interference analyses* (Dec. 2013), *available at* https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2292-2014-PDF-E.pdf.

[26] Free space propagation loss is the loss in signal strength of a signal that would result from a line-of-sight path through free space (usually air), with no obstacles nearby to cause reflection, scattering, or diffraction. Terrain specific propagation loss and building blockage loss were not considered in the base station and user equipment analysis. Clutter loss was considered in the aggregate base station analysis.

[27] National Telecommunications and Information Administration, *NTIA Report 82-100, A Guide to the Use of the ITS Irregular Terrain Model in the Area Prediction Mode* (Apr. 1982), *available at* https://www.ntia.doc.gov/files/ntia/publications/ntia_82-100_20121129145031_555510.pdf.

$$ITM_{Blend} = \begin{cases} FSPL & d \leq 100 \, meters \\ FSPL + \frac{\Delta L_P}{100}(d - 100) & 100 \, d \leq 200 \, meters \\ ITM_{AreaMode} & d > 200 \, meters \end{cases}$$

where:

$$\Delta L_P = ITM_{200m} - FSPL_{200m}$$

ITM area prediction mode is "based on the two-ray reflection theory and extrapolated diffraction theory. For distances greater than d_x, the point where diffraction and scatter losses are equal, the reference attenuation is calculated by means of a forward scatter formulation."[28] Reflections of an interference signal can constructively add to increase the received interference power.

The ITM in the area prediction mode is not a site-specific model, providing a statistical propagation loss. ITM in the point-to-point mode, a site-specific model, was used in the exclusion zone analysis, where the locations of GPS receivers were available. The calculated median exclusion zone distance, using a site-specific model, was equivalent to the calculated exclusion zone distance using ITM in the area prediction mode, providing validation for ITM in the area prediction mode. See Appendix G for more details for specific separation distances based upon GPS receiver location.

In the documentation for ITM in the area prediction mode, a lower limit of 1 kilometer (km) is specified. This lower limit is probably best described as an engineering compromise, in the sense that certain approximations (e.g., small angle approximations) used by the model will ultimately be violated for very short (much less than 200 meters) separation distances. A median value of ITM area prediction mode propagation loss was used in the single-entry and aggregate interference analysis. Using the median propagation loss (50% time/situation/location variability) when either the transmitter or receiver are mobile (i.e., no fixed location) or in an aggregate analysis is a reasonable approach for assessing potential interference.

The technical details of the base station analysis are provided in Appendix E and Appendix F. The technical details for the user equipment analysis are provided in Appendix H.

3.2 BASE STATION INTERFERENCE ANALYSIS

3.2.1 Single Base Station Analysis

Ligado's initial proposal was to operate base stations in the 1526-1536 MHz band with an EIRP limit of 62 dBm/10 MHz. The proposed out-of-band emission (OOBE) limits were expressed as an EIRP of: -85 dBW/MHz from 1541 to 1559 MHz; -100 dBW/MHz from 1559 to 1610 MHz; and -85 dBW/MHz from 1610 to 1650 MHz. For macro cell base stations the proposed EIRP limit of 62 dBm/10 MHz was used in the TFG's preliminary analysis. Based on the protection of certified aviation GPS receivers described in Appendix J, an EIRP limit of 40 dBm/10 MHz was used by the FAA in the analysis for small cell base stations.

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[28] *NTIA Report 82-100*, at 15-16.

No specific information was made available to describe the deployment of base stations in the 1526-1536 MHz band. Therefore, the information used to model the base station deployment in the single-entry interference analysis (i.e., interference from one base station) was obtained from submissions to the FCC and from other publicly available documents and information within ITU-R recommendations and reports.[29]

3.2.1.1 Single Macro Cell Base Station Analysis

The analysis of a single macro cell base station is contained in Appendix E. The use case considered in the analysis is a single macro cell base station interaction with GPS receivers from the HP, GLN, TIM, and CEL categories. In the analysis, the maximum received power level from a macro cell base station at a ground-based GPS receiver as a function of separation distance is calculated for all combinations of antenna height and down-tilt angle. Base station antenna heights of 5 to 45 meters and down-tilt angles of 2 to 6 degrees are varied in the analysis. Off-axis antenna gain for the base station and GPS receiver are also included in the calculation of the received power. The maximum computed received power levels are compared to the measured interference power levels in Appendix A for 1 dB, 3 dB, and 5 dB degradations in C/N_0 within a given GPS receiver category. The analysis results are presented in terms of the number and percentage of GPS receivers degraded within a category and the separation distance necessary to reduce the received power from the base station to below the measured interference power level.

An inter-site distance (ISD) of 693 meters was used in the analysis for an urban macro cell base station network deployment.[30] For a 693-meter ISD, the distance from a base station to the edge of the cell is approximately 462 meters.[31] If the separation distance exceeds 462 meters, the GPS receiver will be impacted by a base station in one of the neighboring cells. The separation distances needed to preclude degradations in C/N_0 of 1 dB, 3 dB, and 5 dB for HP, GLN, and TIM GPS receivers exceed 462 meters. For GPS CEL receivers, there are limited geographic areas around base stations where a 1 dB, 3 dB, and 5 dB degradation in C/N_0 will not occur.

The analysis results are summarized in Figure 5, showing the percentage of receivers with a 1 dB C/N_0 degradation as a function of separation distance for each GPS receiver category. The percentages are based on the GPS receivers tested in the different measurement programs and may not be representative of all receivers actually deployed. For the measured HP receivers, a separation distance of greater than approximately 15 kilometers from a macro cell base station would be necessary to preclude a 1 dB degradation in C/N_0. The measured GLN receivers require a separation distance exceeding approximately 10 kilometers to preclude a 1 dB degradation in C/N_0. For the measured TIM receivers, a separation distance of 1,662 meters is

[29] Roberson and Associates, *Final Report: GPS and Adjacent Band Co-Existence Study* (June 10, 2016), *available at* https://ecfsapi.fcc.gov/file/60002112686.pdf; Report ITU-R M.2292-0, *Characteristics of terrestrial IMT-Advanced systems for frequency sharing/interference analyses* (Dec. 2013), *available at* https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2292-2014-PDF-E.pdf.

[30] RTCA Paper No. 333-16/SC159-1055, *Summary of Ligado Proposal Review by RTCA SC-159, WG6 as approved by RTCA SC-159* at 14 (Dec. 13, 2016), *available at* https://www.rtca.org/wp-content/uploads/2020/08/sc-159_wg6_response_ligado_with_tasking.pdf (*RTCA Paper*). ISD is the distance between adjacent base stations.

[31] For an ISD of 693 meters the edge of a single base station cell is the ISD/(3/2) or approximately 462 meters.

necessary to preclude a 1 dB degradation in C/N_0. The measured CEL receivers require a separation distance of 757 meters to preclude a 1 dB degradation in C/N_0.

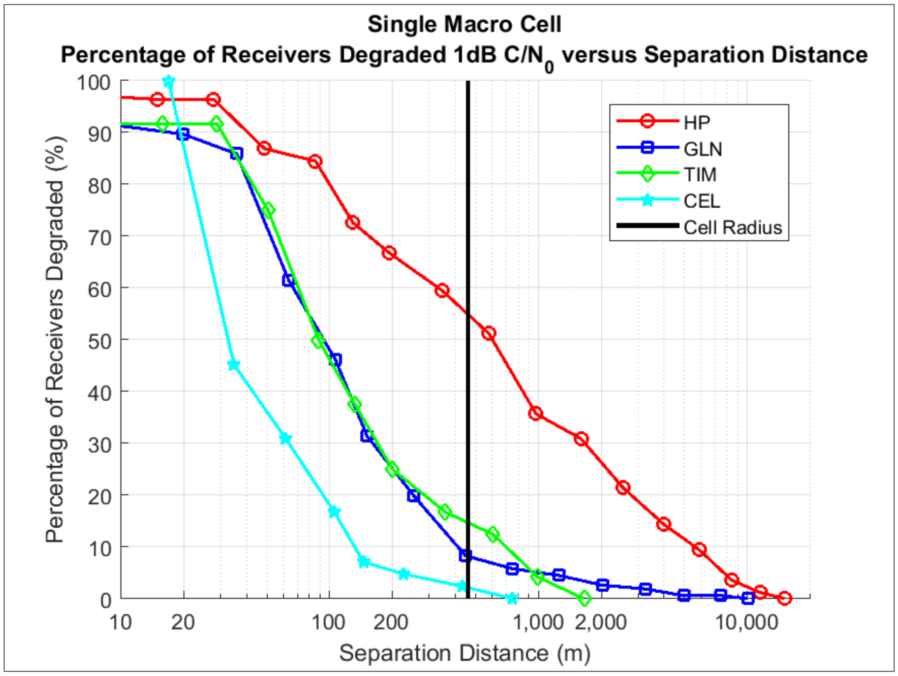

Figure 5. GPS Receiver C/N_0 Degradation from a Single Macro Cell Base Station

As shown in Figures 5 and 6, the separation distances necessary to protect the GPS receivers measured are much larger than the base station cell radius. There does not appear to be a practical separation distance that would protect *all* of the GPS receivers measured.

3.2.1.2 Single Small Cell Base Station Analysis

The analysis of a small cell base station is contained in Appendix E. The use case considered in the analysis is a single small cell base station and a GPS receiver in the HP, GLN, TIM, and CEL categories. In the analysis, the received power level from a small cell base station at a ground-based GPS receiver as a function of separation distance for all combinations of antenna height and down-tilt angle is computed. Base station antenna heights of 5 to 30 meters and down-tilt angles of 2 to 6 degrees are varied in the analysis. Off-axis antenna gain for the base station and GPS receiver are included in the calculation of the received power. The computed maximum received power levels are compared to the measured interference power levels in Appendix A for 1 dB, 3 dB, and 5 dB degradations in C/N_0 within a given GPS receiver category. The analysis results are presented in terms of the number and percentage of GPS receivers degraded and the separation distance necessary to reduce the received power from the base station to below the measured interference power level.

An ISD of 433 meters was used in the analysis for a small cell base station network deployment.[32] For a 433-meter ISD, the distance from a base station to the edge of the cell is approximately 250 meters.[33] If the separation distance exceeds 250 meters, the GPS receiver will be impacted by a base station in one of the neighboring cells. For a deployment of small cell base stations with an ISD of 433 meters, the separation distances needed to preclude degradations in C/N_0 of 1 dB, 3 dB, and 5 dB for HP and GLN receivers exceed 250 meters. For TIM and CEL receivers, there are limited geographic areas around a base station where a 1 dB, 3 dB, and 5 dB degradation in C/N_0 will not occur.

The analysis results are summarized in Figure 6, showing the percentage of receivers with a 1 dB C/N_0 degradation as a function of separation distance for each GPS receiver category. The percentages are based on the GPS receivers tested in the different measurement programs and may not be representative of all receivers actually deployed. For the measured HP receivers, a separation distance of greater than approximately 2,697 meters from a micro cell base station would be necessary to preclude a 1 dB degradation in C/N_0. The measured GLN receivers require a separation distance exceeding approximately 1,348 meters to preclude a 1 dB degradation in C/N_0. For the measured TIM receivers, a separation distance of 168 meters is necessary to preclude a 1 dB degradation in C/N_0. The measured CEL receivers require a separation distance of 88 meters to preclude a 1 dB degradation in C/N_0.

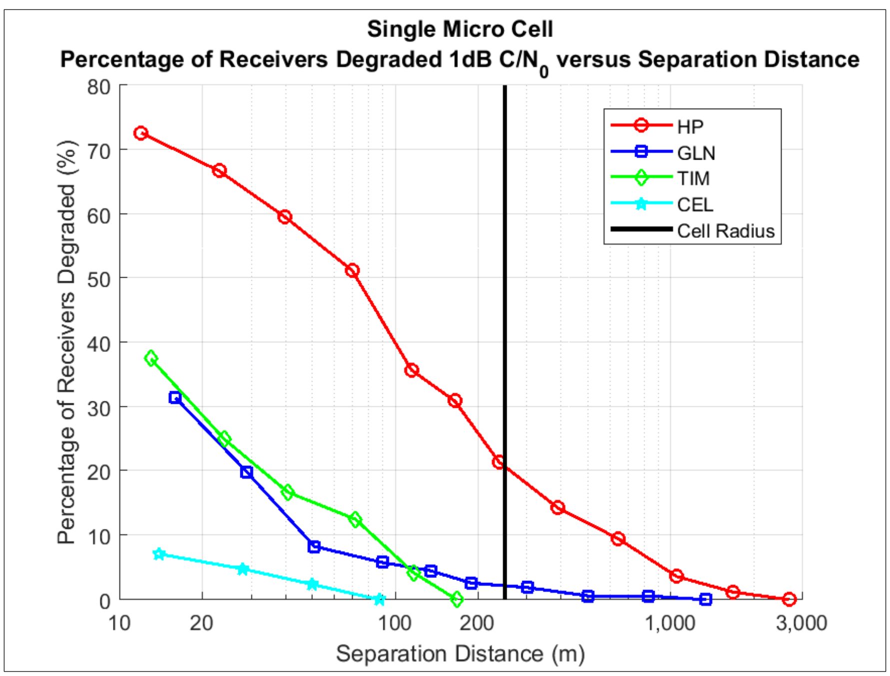

Figure 6. GPS Receiver C/N_0 Degradation from a Single Small Cell Base Station

32 *RTCA Paper* at 9.

33 For an ISD of 433 meters, the edge of a single base station cell is $\frac{ISD*\left(\frac{\sqrt{3}}{2}\right)}{\left(3/2\right)}$ or approximately 250 meters.

3.2.2 Aggregate Base Station Analysis

3.2.2.1 Interference Scenarios

Appendix F considers the aggregate power from base stations operating in the 1526-1536 MHz band and statistically quantifies the probability and percentage of GPS receivers, from all the measurement campaigns, that will experience a given C/N_0 degradation. There is no specific Ligado deployment information, (e.g., EIRP, base station height, down tilt angle, number of base stations ((macro or small cell), and ISD) for base stations in the 1526-1536 MHz band. However, four base station deployment types[34] were considered in the analysis based upon the deployment parameters in the R&A aggregate report.[35] ITU-R M.2292 also guided additional terrestrial mobile telecommunication simulation parameters.

Three base station/GPS receiver geometries were simulated:

1) For a GPS receiver operating within a cell, Figure 7, GPS receiver locations were randomly distributed within the yellow highlighted, center cell/sector.
2) For a GPS receiver operating outside of a cell (offset), Figure 8, the GPS receivers are located along the red line. The separation distance is found along the red line.
3) For a GPS receiver operating outside of a cell (exclusion zone), Figure 9, the GPS receiver is located at the center and the separation distance is represented by the red line, which is a multiple of the ISD. This geometry was used to calculate the GPS receiver exclusion zone distance.

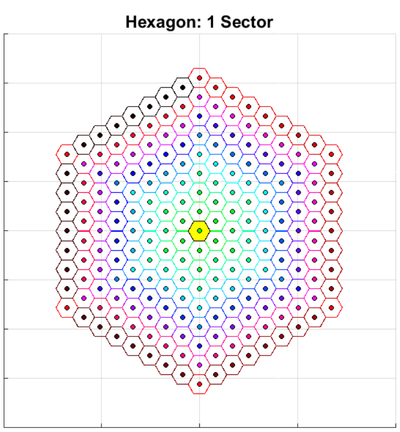

Figure 7. GPS Receiver Operating Within a Cell

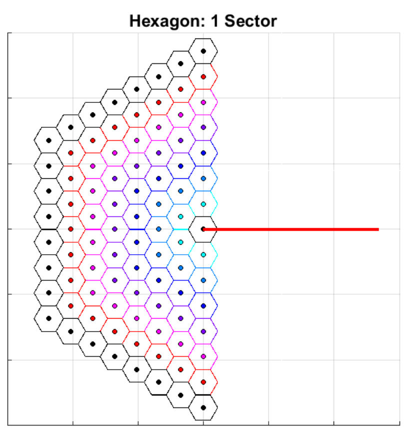

Figure 8. GPS Receiver Operating Outside of a Cell (Offset)

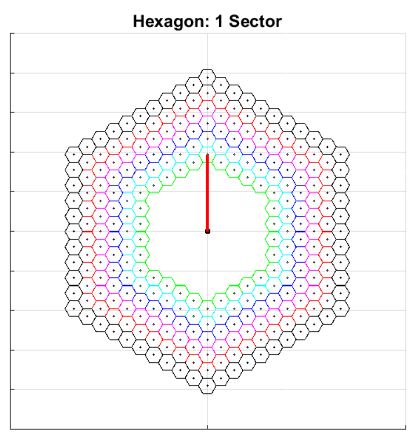

Figure 9. GPS Receiver Operating Outside of a Cell (Exclusion Zone)

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[34] The base station deployments described in ITU-R M.2292 are: macro urban, macro suburban, macro rural, and micro urban. The parameters that vary for each base station deployment include: number of antenna sectors, antenna height, down-tilt angle, and ISD.

[35] Roberson and Associates, *Final Report: GPS and Adjacent Band Co-Existence Study* (June 10, 2016), *available at* https://ecfsapi.fcc.gov/file/60002112686.pdf.

3.2.2.2 GPS Receiver Located Within a Cell

Table 1 provides the percentage of GPS receivers that will experience 1 dB C/N_0 degradation within a cell for the four base station deployments. For each table, the 99th percentile of the power received at the GPS receiver is calculated. The 99th percentile locations are within 100 meters of a base station, which means that the propagation model to compute the 99th percentile is free space path loss. Additionally, the results show that the 99th percentile is approximately the same for the single base station case scenario, aggregate with no clutter, and aggregate with clutter.

Table 1. Percentage of GPS Receivers Degraded When Operating Within a Cell

Base Station Deployment	Base Station EIRP (dBm/10 MHz)	GPS Receiver Received Power (dBm/10 MHz) 99th Percentile	Percentage of GPS Receivers with 1 dB C/N_0 Degradation		
			HP	GLN	TIM
Macro Urban [693m ISD]	62	-22	80%	40%	42%
	40	-44	40%	5%	8%
Macro Suburban [750m ISD]	62	-26	70%	26%	38%
	40	-48	31%	3%	4%
Macro Rural [4.5km ISD]	62	-30	65%	16%	21%
	40	-52	24%	2%	0%
Micro Urban [433m ISD]	40	-32	64%	13%	17%
Interfering signal in the 1525-1535 MHz/1526-1536 MHz bands.					

Based on the Micro Urban base station scenario analyzed in Appendix F, in order to protect all GPS receivers measured, the EIRP would have to be reduced from a value of 39.8 dBm/10 MHz (9.8 dBW or 10 Watts) to -1 dBm/10 MHz (0.0008 Watts). It does not appear there is a practical base station EIRP that would protect *all* of the GPS receivers measured.

3.2.2.3 Probability of C/N_0 Degradation When Operating in a Cell

Table 2 provides the probability of 1 dB C/N_0 degradation within a cell for each type of GPS receiver from all the measurement campaigns. For example, there are 84 measurements points for 1 dB C/N_0 degradation for HP GPS receivers. Every HP receiver was checked for 1 dB C/N_0 degradation at each randomized location, totaling 4.2 million (50,000 x 84) calculations to find the probability of degradation for a single table entry for each scenario. It should be noted that the 3 dB and 5 dB probability values is higher than some 1 dB probability values for the GLN GPS. This discrepancy is due to the number of measurement data points for the different GPS receiver categories.

Table 2. Probability of GPS Receiver Degradation When Operating Within a Cell

Base Station Deployment	Base Station EIRP (dBm/10 MHz)	Probability of GPS Receivers with 1 dB C/N_0 Degradation		
		HP	GLN	TIM
Macro Urban [693m ISD]	62	59.4%	49.0%	43.0%
	40	18.6%	13.6%	8.7%
Macro Suburban [750m ISD]	62	61.5%	50.3%	47.3%
	40	20.2%	14.2%	11.5%
Macro Rural [4.5km ISD]	62	34.4%	27.6%	22.2%
	40	4.6%	1.0%	0.5%
Micro Urban [433m ISD]	40	28.0%	21.4%	17.0%
Interfering signal in the 1525-1535 MHz/1526-1536 MHz bands.				

3.2.2.4 Base Station Deployment Offset from GPS Receiver

Two base stations deployment scenarios (Macro Urban with an EIRP of 62 dBm/10 MHz and Micro Urban with an EIRP of 40 dBm/10 MHz) were considered in the aggregate analysis. In Appendix F, the base station EIRP is varied and the received power is calculated as a function of separation distance for the different GPS receiver categories. The percentage of GPS receivers that will experience a 1 dB C/N_0 degradation is also provided.

Figure 10 and Figure 11 provide the minimum separation distance from the closest base station to preclude a 1 dB C/N_0 degradation for the different categories of GPS receivers. This analysis emulates the use case of a GPS receiver operating outside of an area where there is a base station deployment (e.g., GPS receivers used for farming).

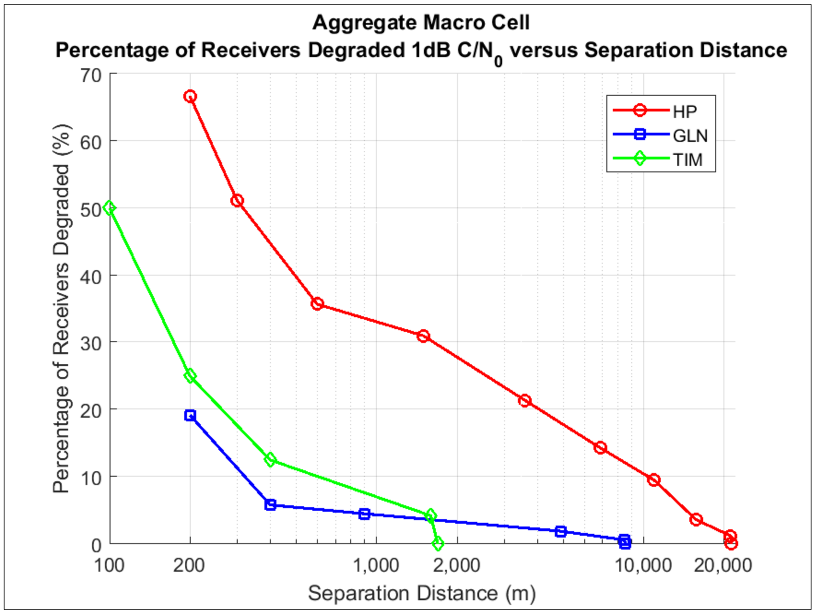

Figure 10. Separation Distance for Macro Cell Base Station Deployment Offset from GPS Receiver to Preclude a 1 dB C/N_0 Degradation

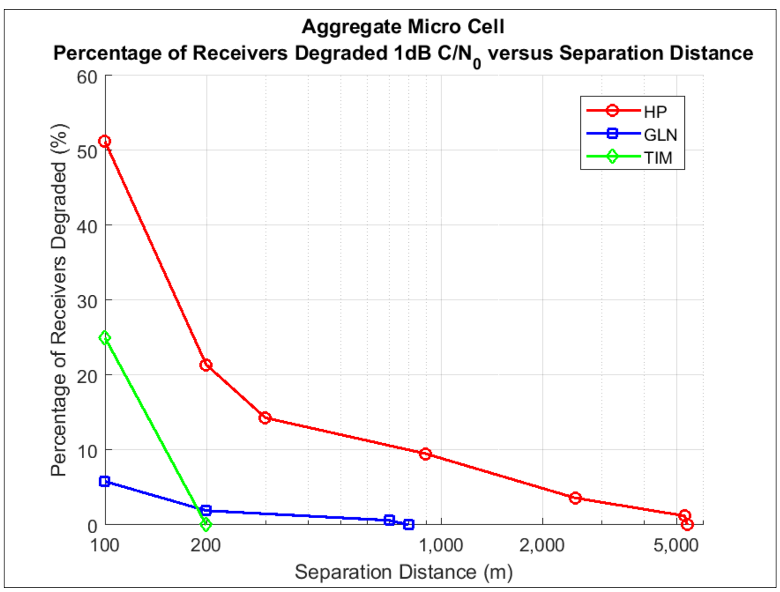

Figure 11. Separation Distance for Micro Cell Base Station Deployment Offset from GPS Receiver to Preclude a 1 dB C/N_0 Degradation

3.2.2.5 Exclusion Zone for Base Station Deployment

For a GPS receiver operating outside of a cell (exclusion zone in Figure 9), the GPS receiver is located at the center and the separation distance is represented by the red line, which is a multiple of the ISD. This geometry was used to calculate the GPS receiver exclusion zone distance. Figure 12 and Figure 13 provide the 1 dB C/N_0 degradation exclusion zone separation distance for HP receivers, from all the measurement campaigns, for a base station EIRP of 62 dBm/10 MHz and 40 dBm/10 MHz.

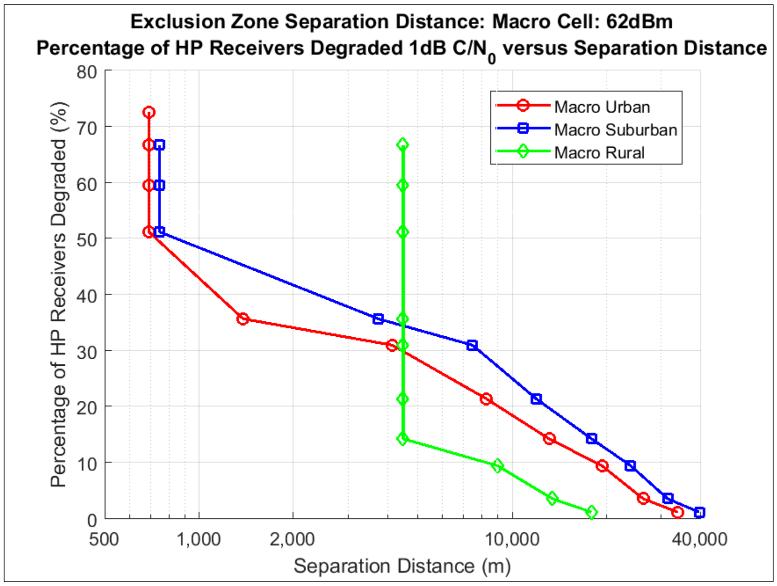

Figure 12. Exclusion Zone for Macro Cell Base Station Deployment to Preclude a 1 dB C/N_0 Degradation

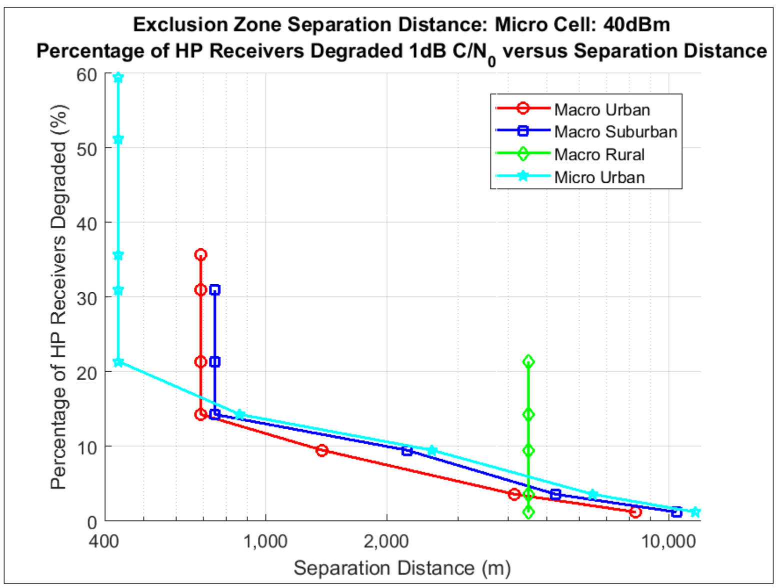

Figure 13. Exclusion Zone for Micro Cell Base Station Deployment to Preclude a 1 dB C/N_0 Degradation

As discussed in Appendix G, this analysis methodology was applied to analyze the concept of exclusion zones around fixed GPS receiver infrastructure, providing the percentage of population, outside of the exclusion zone, that is available to be provided coverage in the 1526-1536 MHz band. The following fixed GPS applications are included in the analysis:

- National Oceanic and Atmospheric Administration (NOAA) - Continuously Operating Reference Stations (CORS)[36]
- United States Coast Guard - Differential Global Positioning System (DGPS)[37]
- Federal Railroad Administration (FRA) - Positive Train Control (PTC)
    - Amtrak[38]
- National Science Foundation (NSF) [awarded] - UNAVCO Geodesy Advancing Geosciences and EarthScope (GAGE) Facility[39]
    - Plate Boundary Observatory (PBO)
    - NASA Global GNSS Network (GGN)
        - International GNSS Service (IGS) stations
        - NASA's Space Geodesy Project (SGP)
    - NSF-funded community GPS networks for Earth, atmospheric, and polar science applications
- FAA - Wide Area Augmentation System (WAAS).[40]

Based upon the separation distances from Figure 12 and Figure 13, exclusion zones were drawn around each GPS receiver location, and the percentage of population outside of those circles was calculated. The 2010 Census data was used to determine the population percentage.[41] Table 3 provides the analysis to determine the percentage of population available by state for a Macro base station deployment with an EIRP of 40 dBm/10 MHz. Figure 14 shows an example of the GPS exclusion zones.

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[36] A list of the locations is *available at* https://www.ngs.noaa.gov/CORS_Map/.

[37] A list of the locations is *available at* https://www.navcen.uscg.gov/?pageName=dgpsSiteInfo&All.

[38] A list of the locations *is available at* http://fragis.fra.dot.gov/GISFRASafety/ or http://osav-usdot.opendata.arcgis.com/datasets/4e32613ba4c9450880118b2fd639e8cb_0.

[39] A list of the locations is *available at* https://www.unavco.org/.

[40] NSTB/WAAS T&E Team, *Wide-Area Augmentation System Performance Analysis Report #26*, Atlantic City International Airport, New Jersey: FAA/William J. Hughes Technical Center, pp. 93–95 (Oct. 2008), *available at* http://www.nstb.tc.faa.gov/reports/waaspan26.pdf.

[41] The population centers, and their corresponding coordinates and population counts were downloaded from the Centers of Population by Census Tract *available at* https://www.census.gov/geographies/reference-files/2010/geo/2010-centers-population.html.

Table 3. Percentage of Population Outside of Exclusion Zones

STATE	CORS	NDGPS	PTC (Amtrak)	GAGE	WAAS	Combined Applications
TOTAL	79%	100%	62%	89%	99%	50%
Alabama	83%	100%	80%	92%	100%	69%
Arizona	70%	100%	83%	98%	100%	62%
Arkansas	83%	100%	80%	90%	100%	67%
California	79%	99%	45%	46%	99%	22%
Colorado	86%	100%	75%	95%	98%	65%
Connecticut	80%	100%	44%	99%	100%	40%
Delaware	71%	100%	50%	77%	100%	36%
District of Columbia	20%	100%	6%	21%	100%	6%
Florida	90%	99%	64%	99%	98%	59%
Georgia	96%	100%	78%	99%	100%	74%
Idaho	70%	100%	95%	92%	100%	64%
Illinois	62%	100%	42%	94%	98%	30%
Indiana	83%	100%	67%	100%	100%	59%
Iowa	89%	100%	92%	100%	100%	83%
Kansas	78%	100%	73%	87%	93%	51%
Kentucky	86%	100%	95%	91%	100%	83%
Louisiana	62%	97%	65%	87%	100%	48%
Maine	95%	100%	83%	100%	100%	77%
Maryland	85%	100%	47%	94%	100%	42%
Massachusetts	88%	100%	46%	99%	100%	40%
Michigan	68%	98%	60%	93%	100%	43%
Minnesota	87%	100%	66%	98%	99%	59%
Mississippi	96%	100%	71%	100%	100%	70%
Missouri	77%	100%	66%	99%	100%	50%
Montana	67%	100%	94%	76%	89%	61%
Nebraska	57%	100%	53%	86%	100%	43%
Nevada	51%	100%	87%	81%	100%	44%
New Hampshire	85%	100%	82%	91%	92%	69%
New Jersey	75%	99%	61%	95%	100%	53%
New Mexico	79%	100%	64%	84%	91%	53%
New York	72%	100%	53%	97%	99%	39%
North Carolina	82%	100%	68%	98%	100%	60%
North Dakota	67%	100%	62%	88%	100%	46%
Ohio	79%	100%	69%	96%	100%	56%
Oklahoma	87%	100%	86%	94%	100%	77%
Oregon	78%	100%	52%	85%	100%	38%
Pennsylvania	82%	100%	59%	93%	100%	53%
Rhode Island	91%	100%	32%	95%	100%	27%
South Carolina	89%	100%	66%	94%	100%	62%
South Dakota	85%	100%	100%	100%	100%	85%
Tennessee	87%	100%	93%	96%	97%	81%
Texas	73%	100%	68%	94%	99%	53%
Utah	86%	100%	51%	86%	92%	41%
Vermont	72%	100%	57%	82%	100%	50%
Virginia	74%	100%	58%	94%	99%	48%
Washington	80%	96%	40%	81%	98%	36%
West Virginia	90%	100%	75%	95%	100%	68%
Wisconsin	95%	99%	72%	99%	100%	69%
Wyoming	74%	100%	100%	85%	100%	74%

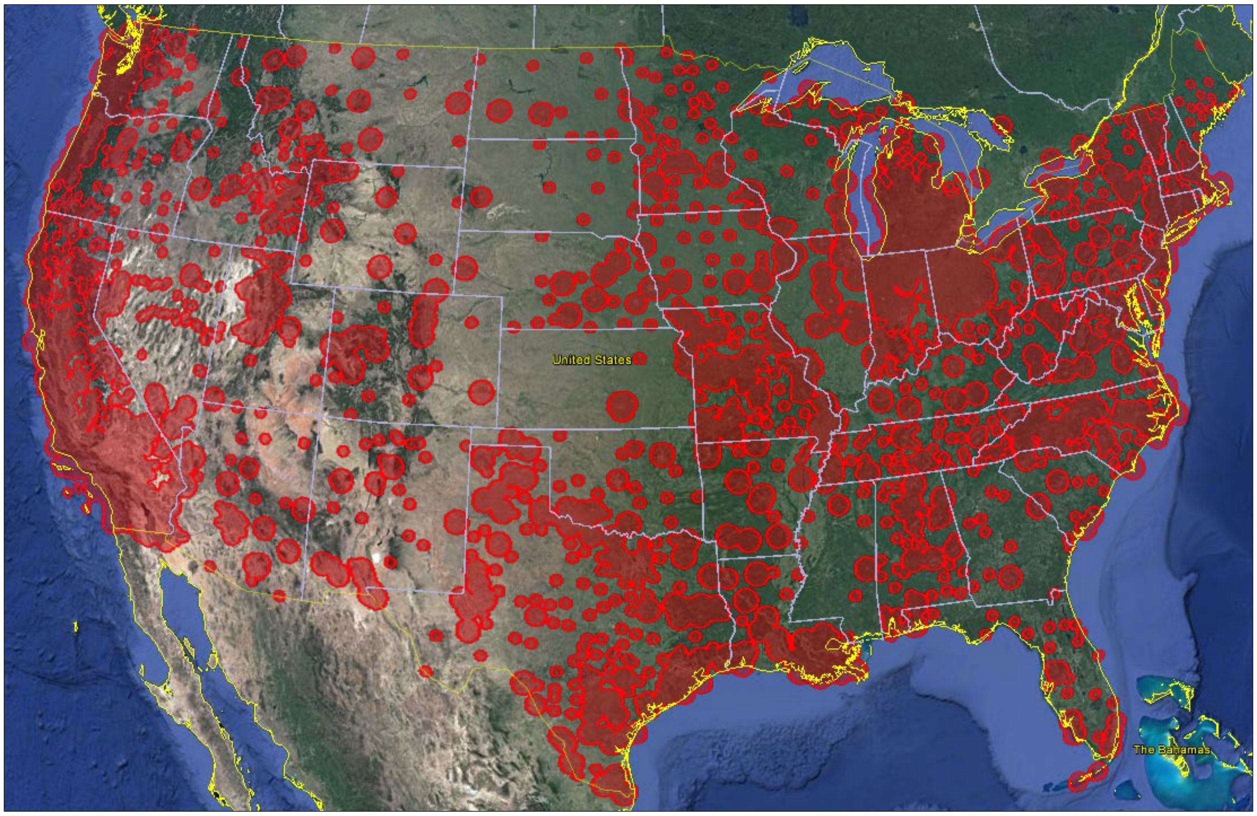

Figure 14. Example of Exclusion Zones for Macro Base Station Deployment

3.3 USER EQUIPMENT ANALYSIS

The current proposal is to operate UE in the 1627.5-1637.5 MHz and 1646.5-1656.5 MHz bands. The maximum EIRP limit for UE of 23 dBm/10 MHz is considered in the analysis. The OOBE limits for UE are expressed as an EIRP of: -34 dBW/MHz at 1625 MHz; -100 dBW/MHz at 1610 MHz ramping up between values at 1625 MHz and 1610 MHz; -105 dBW/MHz at 1608 MHz ramping up between values at 1610 MHz and 1608 MHz; and -105 dBW/MHz from 1541 to 1608 MHz.

Appendix H considers the single transmitter case and the aggregate power from user equipment (UE) operating in the Uplink 1 band (1627.5-1637.5 MHz) and Uplink 2 band (1646.5-1656.5 MHz) and statistically quantifies the percentage of GPS receivers that will experience a 1 dB, 3 dB, and 5 dB C/N_0 degradation with a corresponding minimum separation distance. The results of the UE analysis summarized in Table 4 show the 1 dB C/N_0 separation distances for all GPS receivers measured in a category for a UE EIRP level of 23 dBm/10 MHz.

Table 4. Separation Distance between GPS Receiver and UE Transmitter to Preclude 1 dB C/N_0 Degradation

GPS Receiver Category	Separation Distance for Precluding 1 dB C/N_0 Degradation (meters)	
	UE in Uplink 1	UE in Uplink 2
HP	96	62
GLN	45	7
TIM	5	5

When assessing potential interference between two mobile systems, a minimum separation distance of 2 meters has been used by NTIA.[42] Table 5 provides the percentages of GPS receivers in the different categories degraded by a 1dB C/N_0 for a 2-meter separation distance with the UE operating at the proposed EIRP limit of 23 dBm/10 MHz in the 1627.5-1637.5 MHz and 1646.5-1656.5 MHz bands.

Table 5. Percentage of GPS Receivers Degraded by Single UE Transmitter

GPS Receiver Category	Separation Distance (meters)	Percentage of Receivers with 1 dB C/N_0 Degradation	
		UE in Uplink 1	UE in Uplink 2
HP	2	71.7%	38.9%
GLN	2	26.5%	14.7%
TIM	2	18.2%	27.3%

Given the large distance separations shown in Table 4, and the impact on GPS receivers operating at a separation distance of 2 meters shown in Table 5, there are no practical separation distances between a UE operating at an EIRP of -7 dBW/10 MHz and HP, GLN, and TIM receivers to preclude a 1 dB degradation in C/N_0.

Table 6 provides the percentage of GPS receivers, from all the measurement campaigns, that will experience a 1 dB C/N_0 degradation from the corresponding 99th percentile of the aggregate power for Uplink 1 and Uplink 2 when the UE has an EIRP of 23 dBm/10 MHz (no power control) and power control employed.[43] For TIM GPS receivers, the 9% in Uplink 2 (23 dBm and no power control) represents a single GPS receiver. For TIM GPS receivers in Uplink 1 (23 dBm and no power control), the 99th percentile of aggregate power received is within 0.5 dB to cause interference to a single TIM GPS receiver (or 9%). For GLN GPS, the 3% in Uplink 1 (23 dBm and no power control) represents a single GPS receiver.

[42] *See* Letter from Fredrick Wentland, Acting Associate Administrator, Office of Spectrum Management, National Telecommunications and Information Administration, to Edmond Thomas, Chief, Office of Engineering and Technology, Federal Communications Commission, IB Docket No. 01-185, at Attachment 1 (Jan. 24, 2003), *available at* https://www.ntia.doc.gov/files/ntia/publications/mssatcltr_012403.pdf.

[43] In this analysis, only the fundamental signal of the user equipment is reduced by the power control algorithm. Power control does not reduce the out-of-band emissions. The range of user equipment transmit power is -40 dBm to 23 dBm.

Table 6. Percentage of GPS Receivers Degraded by Aggregate Interference from UE Transmitters When Operating Within a Cell

UE Frequency Band and Power Level	GPS Receiver Received Power (dBm/10 MHz) 99th Percentile	Percentage of Receivers with 1 dB C/N_0 Degradation		
		HP	GLN	TIM
Uplink1 [23dBm]	-34.5	58%	12%	0%
Uplink1 [Power Control]	-73.3	0%	0%	0%
Uplink 2 [23dBm]	-33.6	35%	3%	9%
Uplink 2 [Power Control]	-72.4	0%	0%	0%

As discussed in Appendix J, UEs operating under the assumed frequency, EIRP, and OOBE characteristics should not cause interference to certified GPS avionics.

3.4 GPS RECEIVER LOSS-OF-LOCK ANALYSIS

Appendix I describes an analysis of GPS receiver loss-of-lock (LOL) based on single and aggregate base station interference. The analysis is used to determine the separation distances necessary to reduce the base station power level at the GPS receiver to below the interference power level based on LOL.[44] For the purpose of this analysis, LOL occurs when the interfering signal causes the GPS receiver to stop reporting C/N_0 values for all satellites. The analysis considered macro cell and small cell base stations. The analysis results summarize the number and percentage of HP, GLN, and TIM categories of GPS receivers and the interfering signal power level causing an LOL condition to occur.

For the single macro cell base station analysis, an LOL condition occurs for 49 HP receivers; 32 GLN receivers; and 12 TIM receivers. A separation distance of 5,518 meters is necessary to ensure that an LOL condition does not occur for any HP receivers. The separation distances range from less than 5 to 5,518 meters depending on the percentage of HP receivers where an LOL condition occurs. A separation distance of 1,885 meters is necessary to ensure that an LOL condition does not occur for any GLN receivers. The separation distances range from less than 5 to 1,885 meters depending on the percentage of GLN receivers where an LOL condition occurs. A separation distance of 235 meters is necessary to ensure that an LOL

[44] Loss of lock means the GNSS receiver no longer tracks the signal accurately. Status navigation messages cannot be further decoded, leading to less visible satellites for positioning, thus degrading positioning accuracy. *See* "Study of GNSS Loss of Lock Characteristics under Ionosphere Scintillation with GNSS Data at Weipa (Australia) During Solar Maximum Phase," *available at*

https://www.ncbi.nlm.nih.gov/pubmed/28946676.

condition does not occur for any TIM receivers. The separation distances range from less than 5 to 235 meters depending on the percentage of TIM receivers where an LOL condition occurs.

For the single small cell base station analysis, an LOL condition occurs for 25 HP receivers; 1 GLN receiver; and 1 TIM receiver. A separation distance of 562 meters is necessary to ensure that an LOL condition does not occur for any HP receivers. The separation distances range from less than 5 to 562 meters depending on the percentage of HP receivers where an LOL condition occurs. A separation distance of 169 meters is necessary to ensure that an LOL condition does not occur for any GLN receivers. The separation distances range from less than 5 to 169 meters depending on the percentage of GLN receivers where an LOL condition occurs. A separation distance of 23 meters is necessary to ensure that an LOL condition does not occur for any TIM receivers. The separation distances range from less than 5 to 23 meters depending on the percentage of TIM receivers where an LOL condition occurs.

The simulation scenarios described in Appendix I were used to assess potential GPS receiver LOL based on aggregate base station interference. Table 7 provides the percentage of GPS receivers for each category that will experience LOL within a cell for the different simulation scenarios. The 99th percentile of the power received at the GPS receiver located within a cell is also provided. From the received power calculations, the percentage of GPS receivers from all of the measurement programs is provided that will experience an LOL.

Table 7. Percentage of GPS Receiver Loss of Lock When Operating Within a Cell (Aggregate)

Base Station Deployment	Base Station EIRP (dBm/10 MHz)	GPS Receiver Received Power (dBm/10 MHz) 99th Percentile	Percentage of GPS Receivers Loss of Lock		
			HP	GLN	TIM
Macro Urban [693m ISD]	62	-22	51%	3%	8%
	40	-44	14%	3%	0%
Macro Suburban [750m ISD]	62	-26	45%	3%	8%
	40	-48	6%	0%	0%
Macro Rural [4.5km ISD]	62	-30	43%	3%	0%
	40	-52	2%	0%	0%
Micro Urban [433m ISD]	40	-32	41%	3%	0%
Interfering signal in the 1525-1535 MHz/1526-1536 MHz bands					

3.5 CERTIFIED AVIATION GPS RECEIVER ANALYSIS

As shown in Appendix J, protection of certified avionics, operating under the assumption of the described 250-foot (76.2-meter) radius standoff cylinder, requires that the base station EIRP not exceed 9.8 dBW (39.8 dBm) cross-polarized at 1531 MHz. It is very important to note that this result assumes (equal power split) dual polarization and highlights that a requirement for cross-polarization emissions from the base stations must be captured in any license application or issuance. A vertical polarization (only) based limit would be approximately 7.9 dBW

(37.9 dBm). The analysis described in Appendix J did account for aggregate interference effects.

Finally, in addition to single and aggregate base station interference, impacts on dynamic applications such as certified aviation due to transition through repeated geographic areas without GPS service must be considered. For example, an aircraft could not only be impacted by the loss of navigation inside a given standoff cylinder, but if there are multiple cylinders (e.g., 433 meters apart) there is a potential continuity impact as well as a reacquisition issue caused by flight through multiple standoff cylinders.

3.6 NON-CERTIFIED AVIATION GPS RECEIVER SINGLE BASE STATION ANALYSIS

Appendix K documents the results of a single macro cell base station and small cell base station analysis for GPS receivers in the HP and GAV categories. The analysis examines two non-certified aviation use cases: an unmanned aerial vehicle (UAV) using a high precision GPS receiver and a general aviation receiver. The analysis considers a small cell base station where the maximum EIRP level of 40 dBm/10 MHz at a fixed height of 30 meters and a macro cell base station where the maximum EIRP is 62 dBm/10 MHz at a fixed height of 45 meters. In the small cell analysis, the received power is computed for UAV heights of from 1 to 60 meters. In the macro cell analysis, the received power is computed for UAV heights of from 16 to 75 meters. These values are all calculated in 1-meter steps and then plotted to show the received power as a function of height and separation distance. Using the measured interference power levels corresponding to C/N_0 degradations of 1 dB, 3 dB, and 5 dB, the percent of the GPS receivers in the HP and GAV categories degraded is determined for the corresponding separation distance.

Figure 15 and Figure 16 summarizes the results for the banked UAV non-certified aviation GPS receiver use case interference analysis. The banking of the UAV considered in this analysis increases the received power by approximately 4 dB.

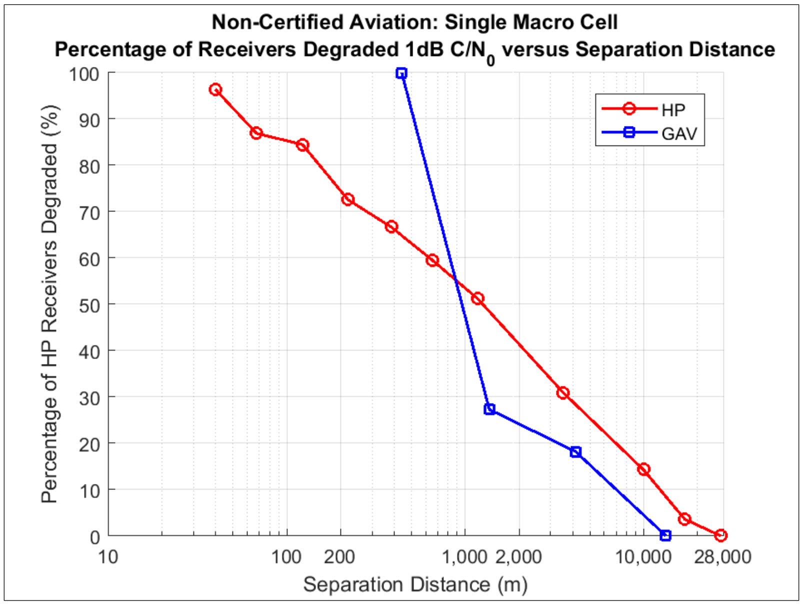

Figure 15. Percentage of Non-Certified Aviation GPS Receivers Experiencing 1 dB C/N_0 Degradation When Approaching Macro Cell Base Station

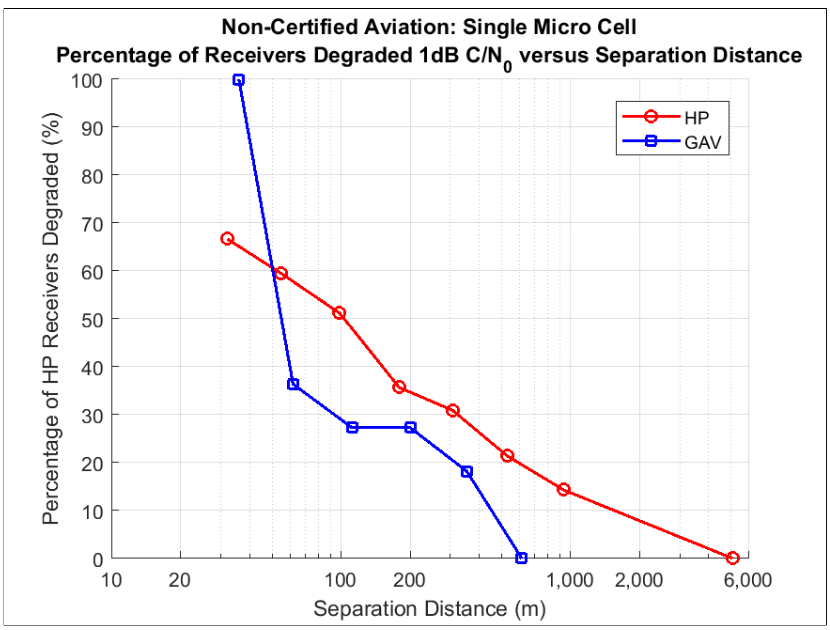

Figure 16. Percentage of Non-Certified Aviation GPS Receiver Experiencing 1 dB C/N_0 Degradation When Approaching Micro Cell Base Station

The approach in Appendix J for certified aviation GPS receivers is based upon a 250 foot (76.2 meter) radius cylinder around a base station. A similar approach would have to be developed for non-certified aviation GPS receivers.

3.7 SPACEBORNE GNSS RECEIVER ANALYSIS

In Appendix M, NASA assessed the impact of a proposed LTE base station network operating on adjacent radio frequency band (1526-1536 MHz) to space-based receivers, specifically radio occultation (RO), where space-based GNSS receivers are used to perform measurements of the troposphere, stratosphere, and up through the layers of the atmosphere until reaching the ionosphere.

RO measurements of the atmosphere, coupled with traditional methodologies for Earth observation, have significantly improved accuracy and predictability of weather forecasts. RO measurements of the ionosphere have also improved our ability to monitor space weather (the distribution of charged particles in the uppermost part of the atmosphere), which is essential to ensure the successful operation of satellites. This is not to say that the other GNSS-based science applications are not affected by a proposed LTE base station network, but RO science is an application that is particularly susceptible. Appendix M describes the analysis and evaluation of a proposed LTE base station network operating on adjacent radio frequency bands to space-based receivers.

Interference is a problem when GNSS signals are being used for science applications. During RO measurements, the GNSS signal is attenuated by tens of decibels at low ray heights. Because of the low signal-to-noise ratio (SNR), tracking loops cannot be closed and the captured data is running open loop. Additional noise from interference lowers the signal-to-noise ratio of the signal over specific areas, providing incorrect weather predictions over the affected areas.

NASA's assessment focuses on the RO receiver, called the TriG (formerly also known as TriGNSS), which was developed by the NASA/Jet Propulsion Laboratory (JPL). The TriG is the newest RO receiver of the BlackJack class of GNSS receivers and can perform substantially more (up to three times more) measurements than previous versions. The increase in performance is partially due to the TriG's ability to receive signals from all GNSS constellations, including the GPS, GLONASS, Galileo, BeiDou, regional space-based navigation constellations such as QZSS and NaVic, and Space Based Augmentation System, such as the FAA's WAAS, and the European Geostationary Navigation Overlay Service (EGNOS).

NASA participated in the DOT ABC testing of GPS/GNSS receivers. The 1 dB C/N_0 degradation interference threshold for the TriG receiver was -73 dBm/10 MHz in the 1526-1536 MHz band. It should be noted that interference started to occur at -90 dBm/10 MHz. For comparison, the TriG receiver has a similar sensitivity as the most sensitive HP receivers. The TriG receiver measurement result was an input to the analysis.

For the spaceborne receiver analysis, the aggregate interference power at the output of the GPS receiver antenna was calculated in 10 second time steps for a 10-day orbit of the satellite. The simulations yielded that a maximum EIRP of 41 dBm/10 MHz per sector, per channel could be tolerated by the TriG receiver.

SECTION 4
SUMMARY

NTIA and agency subject matter experts analyzed interference measurement data for over 300 GPS L1 C/A code receivers to assess compatibility with Ligado's proposed base station and user equipment operations.

The measured data for the different GPS L1 C/A code receiver categories showed:

- There are large variances in interference power levels expected to cause a 1 dB C/N_0 degradation for most GPS receiver categories (78 dB for HP receivers, 71 dB for GLN receivers, 51 dB for TIM receivers, and 25 dB for CEL receivers);
- A 1 dB C/N_0 degradation to GPS L1 C/A code operations is more likely to occur when the GPS receiver filter bandwidth extends outside of the RNSS allocation;
- A 1 dB C/N_0 degradation is less likely to occur when out-of-band emission levels are within the RNSS allocation;
- The external antenna filter selectivity can be a contributing factor to the interference power level that causes degradations in C/N_0;
- HP receivers can process RNSS signals in the 1559-1610 MHz band and MSS signals in the 1525-1559 MHz band to improve accuracy;
- For HP and GLN receivers, the analysis results using a 1 dB and 5 dB C/N_0 degradation criterion had similar results;
- Signal acquisition/reacquisition time is generally impacted at interference power levels corresponding to a 1 dB to 5 dB C/N_0 degradation; and
- The mean value of position error does not reflect the real interference performance impact to GPS receivers because averaging neutralizes the large and small values of position error.[45]

Distance separations from a single base station in the 1526-1536 MHz band to avoid potential degradation in C/N_0 for all receivers are approximately 10 km for an EIRP of 62 dBm/10 MHz (32 dBW), and between 1 to 2 km for an EIRP of 39.8 dBm/10 MHz (9.8 dBW). For single user equipment operating at an EIRP of 23 dBm/10 MHz (-7 dBW), separation distances to avoid potential C/N_0 degradation for all categories of receivers is: 96 meters for user equipment in the 1627.5-1637.5 MHz band and 62 meters for user equipment in the 1646.5-1656.5 MHz band.

For an aggregate micro-urban base station deployment with an EIRP of 39.8 dBm/10 MHz (9.8 dBW), 64 percent of measured HP receivers and 13 percent of measured GLN receivers within a cell will experience a 1 dB C/N_0 degradation. A loss of lock condition occurred in 41 percent of the HP receivers measured. For an aggregate deployment with user equipment operating in the 1627.5-1637.5 MHz band, 58 percent of the HP receivers within a cell can experience a 1 dB C/N_0 degradation. The percentage decreases to 35 percent for user equipment operating in the 1646.5-1656.5 MHz band.

[45] The position error distribution, being the probability function of the position error, can be used as a performance measure and to evaluate the interference effect to GPS receivers and does correlate to degradations in C/N_0.

Based upon the results of the analyses, there do not appear to be any practical combinations of EIRP levels and separation distances that can be employed for compatible operation between Ligado's proposed terrestrial operations and *all* of the GPS receivers measured. The analysis results (e.g., required separation distances and EIRP) do not significantly change when a 1 dB, 3 dB, or 5 dB C/N_0 degradation criterion is applied for HP and GLN receivers.

The FAA analysis for certified aviation GPS receivers determined that under the deployment conditions outlined in Appendix J, the base station EIRP cannot exceed 39.8 dBm, taking into account the effects of aggregate interference. The FAA analysis determined that user equipment operating under the frequency, EIRP, and out-of-band emission characteristics proposed by Ligado should not cause interference to certified GPS avionics. The approach in Appendix J for certified aviation GPS receivers is based upon the assumption that those receivers do not need to enter a 250 foot (76.2 meter) radius cylinder around a base station, however the operational impacts of that assumption have not been assessed. A similar approach for non-certified aviation GPS receivers where smaller separation distances from base stations are expected (e.g., UAVs) needs to be developed.

Taking into account aggregate base station interference, the NASA analysis for spaceborne GPS receivers determined that a maximum EIRP of 41 dBm/10 MHz per sector could be tolerated by the TriG spaceborne receiver.

APPENDIX A
GPS RECEIVER TRACKING MODE INTERFERENCE POWER LEVELS

A.1 INTRODUCTION

This appendix provides a summary of analysis conducted by the Technical Focus Group (TFG) of the Global Positioning System (GPS) receiver interference power levels for high precision (HP), general location/navigation (GLN), timing (TIM), cellular (CEL), general aviation (GAV), and space-based (SPB) L1 Course/Acquisition (C/A) Code GPS receivers in the tracking mode. The measurements are from the Department of Transportation Adjacent Band Compatibility
(DOT ABC)[1], Department of Defense (DOD), Roberson and Associates (R&A)[2], and National Advanced Spectrum and Communications Test Network (NASCTN)[3] test programs. GPS receiver interference measurements from the 2011 Federal Communications Commission Technical Working Group (TWG)[4] and the 2012 National Positioning, Navigation, and Timing (PNT) Systems Engineering Forum (NPEF)[5] testing will also be included.

A.2 C/N_0 DEGRADATION INTERFERENCE MEASURAND

The measured interfering signal power levels presented in this appendix are based on degradations in carrier-to-noise density ratio (C/N_0) as reported by the GPS receiver for each space vehicle (SV). Interference power levels in this appendix are presented for 1 dB, 3 dB, and 5 dB degradations in C/N_0.

Technical information on GPS receiver front-end designs such as the radio frequency filter selectivity, low noise amplifier (LNA) gain, and 1 dB gain compression point of the LNA is not generally available outside the receiver manufacturers, themselves. Without this information, it is difficult to isolate the specific cause(s) of interference that degrades C/N_0 for the GPS receivers in the different measurement programs.

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[1] United States Department of Transportation, *Global Positioning System (GPS) Adjacent Band Compatibility Assessment*, Final Report (Apr. 2018), *available at* https://www.transportation.gov/sites/dot.gov/files/docs/subdoc/186/dot-gps-adjacent-band-final-reportapril2018.pdf (*DOT ABC Final Report*).

[2] *See* Letter from Gerard J. Waldron, Counsel to Ligado, to Marlene H. Dortch, Secretary, FCC, IB Docket No. 11-109 (filed May 11, 2016), Roberson and Associates, *Results of GPS and Adjacent Band Co-Existence Study*, *available at* https://ecfsapi.fcc.gov/file/60001841466.pdf (*R&A Report*).

[3] National Institute of Standards and Technology, NIST Technical Note 1952, *LTE Impacts on GPS*, Final Report (Feb. 15, 2017), *available at* https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1952.pdf (*NIST Technical Note 1952*).

[4] Federal Communications Commission GPS Technical Working Group Final Report (June 30, 2011), *available at* https://ecfsapi.fcc.gov/file/7021690471.pdf. Full data set is *available at* ftp://twg:freeforall@ftp.novatel.ca.

[5] National Space-Based Positioning, Navigation, and Timing Systems Engineering Forum (NPEF), *Follow-On Assessment of LightSquared Ancillary Terrestrial Component Effects on GPS Receivers* (Jan. 6, 2012) *available at* https://www.ntia.doc.gov/files/ntia/publications/npef_lsq_follow-on_test_report_final_public_release.pdf. The NPEF measurements considered interfering signals in the 1526-1536 MHz, 1627.5-1637.5 MHz, and 1646.7-1656.7 MHz bands. Only the measurements for the interfering signal in the 1526-1536 MHz band are included in this document.

A.3 EVALUATION OF MEASUREMENT DATA

The data for the DOT ABC, DOD, R&A, and NASCTN measurement programs was evaluated to ensure its stability and consistency. Measured data was not used for GPS receivers that could not maintain track on a sufficient number of satellites and with C/N_0 levels that are degraded under interference-free conditions. The following criteria were applied to all of the measurements to evaluate whether the receivers were performing properly before the interfering signal is introduced:

- Position-Velocity-Time Solution Availability: Under baseline conditions (no interference) the number of tracked satellites as a function of time should not vary.
- Carrier-to-Noise Ratio Sustainability: Under baseline conditions (no interference) the C/N_0 as a function of time should not vary.

A.4 SELECTION OF C/N_0 DEGRADATION INTERFERING SIGNAL POWER LEVELS

A method was developed to process the measurement data to determine the C/N_0 degradations caused by the interfering signal. The first step was to determine the minimum C/N_0 value for each SV in the baseline data (if it exists). This serves as the initial point, for each SV, to determine the 1 dB, 3 dB, and 5 dB decreases in C/N_0.[6] The mean C/N_0 was then calculated for each SV at each interfering signal power level. Next, all of the mean C/N_0 values (for each SV) that are 1 dB, 3 dB, and 5 dB below the minimum C/N_0 and assigned a Boolean value of '1' or '0' were identified , producing a string of '1s' and '0s'. The last set of continuous '1s' were identified for each string eliminating the possibility that if the C/N_0 decreases and then increases, a 'false' 1 dB, 3 dB, or 5 dB point will not be selected. A check was then made for special cases when the C/N_0 decreases, and then increases again, possibly higher than the C/N_0 baseline or as a local maximum, as the interfering signal power increases. In those cases, the local maximum(s) were identified, and in some cases, it can re-establish the 1 dB, 3 dB and 5 dB point. These cases were flagged for further review. An example plot demonstrating how the 1 dB, 3 dB, and 5 dB C/N_0 degradations were selected is shown in Figure A.1. Using this method of selecting interfering signal power levels corresponding to degradations of C/N_0 eliminates the variations that can occur without interference present
(e.g., noise estimator algorithms).

[6] A 1 dB degradation in C/N_0 has been used domestically and internationally as an interference protection criteria for the GPS service. An interference protection criterion is a relative or absolute interfering signal level defined at the receiver input, under specified conditions, such that the allowable performance degradation is not exceeded. National Telecommunications and Information Administration, NTIA Report 05-432*, Interference Protection Criteria: Phase 1 - Compilation from Existing Sources* (Oct. 2005), *available at* https://www.ntia.doc.gov/files/ntia/publications/ipc_phase_1_report.pdf.

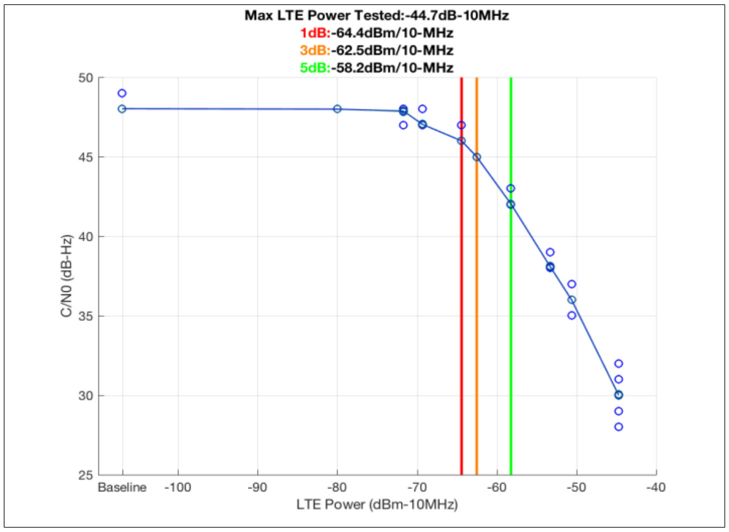

Figure A.1.

A.5 OVERVIEW OF INTERFERING AND GPS SIGNAL SCENARIOS

A.5.1 DOT ABC and DOD Measurements

The DOT ABC and DOD measurements are for interfering signals in three frequency bands: 1525-1535 MHz, 1625-1635 MHz, and 1640-1650 MHz.[7] The interfering signal in the 1525-1535 MHz band is a fully loaded Orthogonal Frequency Division Multiplex (OFDM) signal. The interfering signal in the 1625-1635 MHz and 1640-1650 MHz bands is a Sub-Carrier OFDM signal.

The DOT ABC testing was not intended to specifically emulate Ligado's base station emission proposal in the 1526-1536 MHz band. The closest center frequency to Ligado's proposal is 1530 MHz. At that frequency, the cavity filter used was specified to provide 65 dB of rejection at/above 1550 MHz with the actual response shown in Figure 3-8b in the DOT ABC Final Report.[8] For the maximum power level used during the testing at 1535 MHz (-10 dB relative to a milliwatt (dBm)/MHz), the generated emissions are shown in Figure A-22 in the DOT ABC Final Report.[9] The emissions at 1530 MHz are approximately the same, except shifted to the left by
5 MHz. The DOT ABC test signal emissions achieve the equivalent of -85 dBW/MHz for most of 1541-1559 MHz frequency range. The exception is the lowest approximate 1.3 MHz from 1541-1542.3 MHz at the maximum received power of -10 dBm/10 MHz for the signal at

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[7] DOT performed measurements from 1475 to 1675 MHz in 10 megahertz band segments.

[8] *DOT ABC Final Report* at 34.

[9] *Id.* at 38 of Appendix A.

1530 MHz. The relative strength of the DOT ABC test signal emissions in the 1541-1559 MHz frequency range were lower for other power settings.[10]

The DOT ABC and DOD measurements simulated GNSS signals representing GPS L1 C/A-code, GPS L1 P-code, GPS L1C, GPS L1 M-code, GPS L2 P-code, SBAS L1, GLONASS L1 C, GLONASS L1 P, BeiDou B1I, and Galileo E1 B/C. For each simulated signal the minimum received power levels referenced to a 0 dBi circularly polarized receive antenna (dBic) antenna where: GPS C/A-code: -158.5 dBW for 8 SVs, -168.5 dBW for 1 SV, -178.5 dBW for 1 SV; GPS L1 P(Y)-code: -161.5 dBW for 8 SVs, -171.5 dBW for 1 SV, -181.5 dBW for 1 SV; GPS L1C: -157 dBW for 8 SVs, -167 dBW for 1 SV, -177 dBW for 1 SV; GPS L1 M-code: -158 dBW for 8 SVs, -168 dBW for 1 SV, -178 dBW for 1 SV GPS; L2 P(Y)-code: -164.5 dBW for 8 SVs, -174.5 dBW for 1 SV, -184.5 dBW for 1 SV; GPS L2 M-code: -161 dBW for 8 SVs, -171 dBW for 1 SV, -181 dBW for 1 SV; SBAS L1: -158.5 dBW for 2 SVs; GLONASS L1 C: -161 dBW for 10 SVs, -171 dBW for 1 SV, -181 dBW for 1 SV; GLONASS L1 P: -161 dBW for 10 SVs, -171 dBW for 1 SV, -181 dBW for 1 SV; BeiDou B1I: -163 dBW for 10 SVs, -173 dBW for 1 SV, -183 dBW for 1 SV; Galileo E1 B/C: -157dBW for 10 SVs, -167 dBW for 1 SV, -177 dBW for 1 SV.[11]

The DOT ABC and DOT testing used a filter for the base station signal to achieve the emission levels in the Ligado proposal of -85 dBW/MHz in the 1541-1559 MHz frequency range and -100 dBW/MHz in the 1559-1610 MHz frequency range.

A.5.2 R&A Measurements

The R&A measurements are for interfering signals in three frequency bands: 1526-1536 MHz, 1627.5-1637.5 MHz, and 1646.5-1656.5 MHz. The interfering signals are Long Term Evolution (LTE) signals with a bandwidth of 10 MHz and all resource blocks assigned.

The R&A testing used a filter for the base station signal to achieve the emission levels in the Ligado proposal of -85 dBW/MHz in the 1541-1559 MHz frequency range and -100 dBW/MHz in the 1559-1610 MHz frequency range.

For the GPS L1 C/A code receivers, the R&A measurements simulated the following GPS signal conditions:

- Open Sky: The simulator created a moving constellation of GPS signals representative of a static location. The simulator was configured to provide a nominal received GPS signal level of -130 dBm for all GPS SV in view (minimum of 8).

[10] Figure A-22 in the DOT ABC Final Report shows the emission for the entire test signal generation chain including the high power amplifier and the cavity filter at the maximum tested power level for which spectral regrowth was maximal.

[11] *DOT ABC Final Report* at 31.

- Open Sky with Motion: The simulator created a moving constellation of GPS signals representative of a moving vehicle, which were presented to the GPS receiver along with LTE signals. To simulate motion, a file of position (latitude/longitude) was recorded in National Marine Electronics Association (NMEA) format while driving in a test loop that was loaded into the GPS simulator along with date and start time of simulation. The simulator calculated the relevant GPS satellite orbits and generated GPS satellite signals to the device under test as if the GPS receiver were moving over the test route at the simulated speed. The simulator was configured to provide a nominal received GPS signal level of -130 dBm for all GPS SVs in view (minimum of 8).
- Impaired GPS Signal with Motion: The simulator created a moving constellation of GPS signals representative of a moving vehicle. To simulate motion, a file of positon (latitude/longitude) was recorded in NMEA format while driving in a test loop that was loaded into the simulator along with date and start time of simulation. The simulator calculated the relevant GPS SV orbits and generated GPS SV signals to the GPS receiver as if the device were moving over the test route at the simulated speed. The simulator was configured to provide a nominal received GPS signal level of -142 dBm for all GPS SVs in view (minimum of 8).

R&A also performed Live Sky measurements with a rooftop antenna that captured outdoor GPS signals which were conveyed into the test chamber and presented along with the interfering signals. The test setup for the Live Sky measurements included a Zephyr Geodetic 2 antenna (50 dB specification minimum active gain, up to 5 dBi passive element gain), followed by 60 feet of LMR400 cable (3 dB loss), then conical right hand circularly polarized antenna (+3 dBi), then 2.6-meter path loss to devices under test (-44.7 dB). All of these gain/loss values, except for the passive element gain, are from the R&A filing.[12] The passive element gain was measured at MITRE. Using the gain/loss values above, the GPS signal levels seen at the GPS receiver location out of a 0 dBic antenna would be up to 10.3 dB stronger than seen outside with the same reference (0 dBic) antenna. GPS re-radiators re-radiate not only the GPS signals but also noise. Assuming that the Zephyr front-end has the same noise floor as the GPS receiver, if there is a net active gain of 5.3 dB for the re-radiating system, the noise floor of the GPS receiver would be set by the re-radiated noise in the chamber and not by the noise floor of the GPS receiver. After further analysis, the R&A Live Sky measurements were not used in establishing the GPS receiver interference power levels.

A.5.3 NASCTN Measurements

The NASCTN measurements are for an interfering signal in the 1526-1536 MHz, 1627.5-1637.5 MHz, and 1646.5-1656.5 MHz bands, and a combination of interfering signals in the 1526-1536 MHz and 1627.5-1637.5 MHz bands.[13] The interfering signal in the 1526-1536 MHz band is a 10 MHz LTE OFDM signal with all resource blocks active. The interfering

[12] *See* Letter from Gerard J. Waldron, Counsel to Ligado, to Marlene H. Dortch, Secretary, FCC, IB Docket No. 11-109, (filed June 10, 2016) at 33-34, *available at* https://ecfsapi.fcc.gov/file/60002112685.pdf.

[13] The interfering signal in the 1526-1536 MHz band was held constant at a power level of -50 dBm and the power level of the interfering signal in the 1627.5-1637.5 MHz band was varied. The interference power levels for the combination signals were not used in this analysis.

signals in the 1627.5-1637.5 and 1646.5-1656.5 MHz bands are 10 MHz LTE Single Carrier Frequency Division Multiple Access (SC-FDMA) signals, with 70 percent of the resource blocks active.[14]

The NASCTN test program used a filter for the base station signal to achieve the emission levels in the Ligado proposal of -85 dBW/MHz in the 1541-1559 MHz frequency range and -100 dBW/MHz in the 1559-1610 MHz frequency range.

For the GPS L1 C/A code receivers, the NASCTN measurements simulated the following GPS signal conditions:

- Nominal Scenario: The simulator created a constellation of 11 GPS SVs in view with a received signal level of -128.5 dBm ± 2.7 dB. Two geostationary Wide Area Augmentation System (WAAS) satellites with a received signal level of -128.5 dBm ± 2.7 dB were also simulated. Additional L1C Pilot, Pseudo Y, and M-code signals were also simulated.
- Limited Exposure Scenario: The simulator created a constellation of 11 GPS SVs with the received signal levels distributed across four values: -128.5 dBm ± 2.7 dB, -133.5 dBm ± 2.7 dB, -138.5 dBm ± 2.7 dB, and -143.5 dBm ± 2.7 dB. Two geostationary WAAS satellites with a received signal level of -128.5 dBm ± 2.7 dB were also simulated. Additional L1C Pilot, Pseudo Y, and M-code signals were also simulated.
- Timing Scenario: The simulator created a constellation of 16 GPS SVs in view with a nominal received signal level of -128.5 dBm ± 2.7 dB. Two geostationary WAAS satellites with a received signal level of -128.5 dBm ± 2.7 dB were also simulated.

A.6 INTERFERING SIGNALS IN 1525-1535 MHZ AND 1526-1536 MHZ BANDS

A.6.1 1 dB C/N_0 Degradation

The number of HP GPS receivers and their associated interference power levels are summarized in Table A.1.[15]

[14] The details of the interfering signal generation are provided in Appendix C of the NASCTN report.

[15] HP GPS receivers can receive correction signals from mobile satellite service systems in the 1525-1559 MHz band (e.g., StarFire and OmniSTAR) to improve performance.

Table A.1. Summary of HP GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of Receivers 1 dB C/N_0 Degradation				
	DOT ABC	**DOD**	**R&A**	**NASCTN**	**TWG**
-79 to -75					1
-74 to -70	1				1
-69 to -65			1	3	1
-64 to -60	1	1		1	1
-59 to -55	3				3
-54 to -50	1		2	2	3
-49 to -45		1			3
-44 to -40	7				6
-39 to -35	1	1	1		4
-34 to -30	2	1			3
-29 to -25	2				3
-24 to -20	6				4
-19 to -15	1				1
-14 to -10	4		4		
-9 to -5					
-4 to 0				1	
1 to 5				2	
Total Number of Receivers	29	4	8	9	34

The percentage of HP GPS receivers impacted is shown in Table A.2.

Table A.2. Percentage of HP GPS Receivers Impacted
1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -75	1	1.2 %
≤ -70	3	3.6 %
≤ -65	8	9.5 %
≤ -60	12	14.3 %
≤ -55	18	21.4 %
≤ -50	26	30.9 %
≤ -45	30	35.7 %
≤ -40	43	51.2 %
≤ -35	50	59.5 %
≤ -30	56	66.7 %
≤ -25	61	72.6 %
≤ -20	71	84.5 %
≤ -15	73	86.9 %
≤ -10	81	96.4 %
≤ -5	81	96.4 %
≤ 0	82	97.6 %
≤ 5	84	100 %

The number of GLN GPS receivers and their associated interference power levels are summarized in Table A.3.

Table A.3. Summary of GLN GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of Receivers 1 dB C/N_0 Degradation					
	DOT ABC	DOD	R&A	NASCTN	NPEF	TWG
-69 to -65		1				
-64 to -60						
-59 to -55	2					
-54 to -50					1	
-49 to -45		1			2	
-44 to -40					2	
-39 to -35	1				3	
-34 to -30	7				8	3
-29 to -25	2				16	
-24 to -20					19	4
-19 to -15	1	1	1		20	
-14 to -10	4	1	7		23	4
-9 to -5				1		5
-4 to 0				1		4
1 to 5				2		9
Total Number of Receivers	17	4	8	4	94	29

The percentage of GLN GPS receivers impacted is shown in Table A.4.

Table A.4. Percentage of GLN GPS Receivers Impacted
1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -65	1	0.6 %
≤ -60	1	0.6 %
≤ -55	3	1.9 %
≤ -50	4	2.6 %
≤ -45	7	4.5 %
≤ -40	9	5.8 %
≤ -35	13	8.3 %
≤ -30	31	19.9 %
≤ -25	49	31.4 %
≤ -20	72	46.2 %
≤ -15	96	61.5 %
≤ -10	134	85.9 %
≤ -5	140	89.7 %
≤ 0	145	92.9 %
≤ 5	156	100 %

The number of TIM GPS receivers and their associated interference power levels are summarized in Table A.5.

Table A.5. Summary of TIM GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of Receivers 1 dB C/N_0 Degradation		
	DOT ABC	NASCTN	TWG
-49 to -45	1		
-44 to -40			2
-39 to -35			1
-34 to -30	1		1
-29 to -25			3
-24 to -20	1	1	1
-19 to -15	2		4
-14 to -10	4		
-9 to -5			
-4 to 0			
1 to 5		2	
Total Number of Receivers	9	3	12

The percentage of TIM GPS receivers impacted is shown in Table A.6.

Table A.6. Percentage of TIM GPS Receivers Impacted
1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -45	1	4.2%
≤ -40	3	12.5%
≤ -35	4	16.7%
≤ -30	6	25%
≤ -25	9	37.5%
≤ -20	12	50%
≤ -15	18	75%
≤ -10	22	91.7%
≤ -5	22	91.7%
≤ 0	22	91.7%
≤ 5	24	100%

The number of CEL GPS receivers tested by the DOT ABC and their associated interference power levels are summarized in Table A.7.

Table A.7. Summary of CEL GPS Receiver Interference Power Levels in DOT ABC Test

Range of Interference Power Levels (dBm/10 MHz)	Number of Receivers DOT ABC
-14 to -10	2
Total Number of Receivers	2

The percentage of CEL GPS receivers impacted in the DOT ABC test is shown in Table A.8.

Table A.8. Percentage of CEL GPS Receivers Impacted in DOT ABC Test
1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -10	2	100%

The number of CEL GPS receivers tested by the TWG and their associated interference power levels are summarized in Table A.9.

Table A.9. Summary of CEL GPS Receiver Interference Power Levels in TWG Test

Range of Interference Power Levels (dBm/10 MHz)	Number of Receivers TWG
-34 to -30	1
-29 to -25	1
-24 to -20	1
-19 to -15	4
-14 to -10	4
-9 to -5	6
-4 to 0	23
Total Number of Receivers	40

The percentage of CEL GPS receivers impacted in the TWG test is shown in Table A.10.

Table A.10. Percentage of CEL GPS Receivers Impacted in TWG Test

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -30	1	2.5%
≤ -25	2	5%
≤ -20	3	7.5%
≤ -15	7	17.5%
≤ -10	11	27.5%
≤ -5	17	42.5%
≤ 0	40	100%

The number of GAV GPS receivers and their associated interference power levels are summarized in Table A.1.

Table A.11. Summary of GAV GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 1 dB C/N_0 Degradation
	DOT ABC
-59 to -55	2
-54 to -50	
-49 to -45	1
-44 to -40	
-39 to -35	1
-34 to -30	7
Total Number of Receivers	11

The percentage of GAV GPS receivers impacted is shown in Table A.12.

Table A.12. Percentage of GAV GPS Receivers Impacted
1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
$\leq$ -55	2	18.2%
$\leq$ -50	2	18.2%
$\leq$ -45	3	27.3%
$\leq$ -40	3	27.3%
$\leq$ -35	4	36.4%
$\leq$ -30	11	100%

A.6.2 3 dB C/N_0 Degradation

The number of HP GPS receivers and their associated interference power levels are summarized in Table A.13.

Table A.13. Summary of HP GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers 3 dB C/N_0 Degradation			
	DOT ABC	DOD	R&A	NASCTN
-64 to -60	1		1	3
-59 to -55	3	1		
-54 to -50	1			1
-49 to -45	1		2	2
-44 to -40	2	1		
-39 to -35	5			
-34 to -30	2	2	1	
-29 to -25	2			
-24 to -20	2			
-19 to -15	4			
-14 to -10	6		4	
-9 to -5				
-4 to 0				
1 to 5				3
Total Number of Receivers	29	4	8	9

The percentage of HP GPS receivers impacted is shown in Table A.14.

Table A.14. Percentage of HP GPS Receivers Impacted 3 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -60	5	10%
≤ -55	9	18%
≤ -50	11	22%
≤ -45	16	32%
≤ -40	19	38%
≤ -35	24	48%
≤ -30	29	58%
≤ -25	31	62%
≤ -20	33	66%
≤ -15	37	74%
≤ -10	47	94%
≤ -5	47	94%
≤ 0	47	94%
≤ 5	50	100%

The number of GLN GPS receivers and their associated interference power levels are summarized in Table A.15.

Table A.15. Summary of GLN GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers 3 dB C/N0 Degradation			
	DOT ABC	DOD	R&A	NASCTN
-64 to -60		1		
-59 to -55				
-54 to -50				
-49 to -45				
-44 to -40	2	1		
-39 to -35				
-34 to -30	1			
-29 to -25	7			
-24 to -20	2			
-19 to -15				
-14 to -10	5	2	8	
-9 to -5				1
-4 to 0				
1 to 5				3
Total Number of Receivers	17	4	8	4

The percentage of GLN GPS receivers impacted is shown in Table A.16.

Table A.16. Percentage of GLN GPS Receivers Impacted
3 dB C/N0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -60	1	3%
≤ -55	1	3%
≤ -50	1	3%
≤ -45	1	3%
≤ -40	4	12.1%
≤ -35	4	12.1%
≤ -30	5	15.2%
≤ -25	12	36.4%
≤ -20	14	42.4%
≤ -15	14	42.4%
≤ -10	29	87.9%
≤ -5	30	90.9%
≤ 0	30	90.9 %
≤ 5	33	100%

The number of TIM GPS receivers and their associated interference power levels are summarized in Table A.17.

Table A.17. Summary of TIM GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers 3 dB C/N_0 Degradation	
	DOT ABC	NASCTN
-44 to -40	1	
-39 to -35		
-34 to -30		
-29 to -25	1	
-24 to -20		
-19 to -15	2	1
-14 to -10	5	
-9 to -5		
-4 to 0		
1 to 5		2
Total Number of Receivers	9	3

The percentage of TIM GPS receivers impacted is shown in Table A.18.

Table A.18. Percentage of TIM GPS Receivers Impacted
3 dB C/N_0 Degradation

Interference Power Level (dBm/MHz)	Number of Receivers	Percentage of Receivers
≤ -40	1	8.3%
≤ -35	1	8.3%
≤ -30	1	8.3%
≤ -25	2	16.7%
≤ -20	2	16.7%
≤ -15	5	41.7%
≤ -10	10	83.3%
≤ -5	10	83.3%
≤ 0	10	83.3%
≤ 5	12	100%

The number of CEL GPS receivers and their associated interference power levels are summarized in Table A.19.

Table A.19. Summary of CEL GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 3 dB C/N_0 Degradation
	DOT ABC
≤ -10	2
Total Number of Receivers	2

The percentage of CEL GPS receivers impacted is shown in Table A.20.

Table A.20. Percentage of CEL GPS Receivers Impacted 3 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -10	2	100%

The number of GAV GPS receivers and their associated interference power levels are summarized in Table A.21.

Table A.21. Summary of GAV GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 3 dB C/N_0 Degradation
	DOT ABC
-44 to -40	3
-39 to -35	
-34 to -30	
-29 to -25	8
Total Number of Receivers	11

The percentage of GAV GPS receivers impacted is shown in Table A.22.

Table A.22. Percentage of GAV GPS Receivers Impacted 3 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -40	3	27.3%
≤ -35	3	27.3%
≤ -30	3	27.3%
≤ -25	11	100%

A.6.3 5 dB C/N_0 Degradation

The number of HP GPS receivers and their associated interference power levels are summarized in Table A.23.

Table A.23. Summary of HP GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers 5 dB C/N_0 Degradation			
	DOT ABC	DOD	R&A	NASCTN
-64 to -60				2
-59 to -55	2		1	1
-54 to -50	2	1		
-49 to -45	1			3
-44 to -40	2	1	2	
-39 to -35	5			
-34 to -30	2		1	
-29 to -25	2	2		
-24 to -20	1			
-19 to -15	2			
-14 to -10	10		4	
-9 to -5				
-4 to 0				
1 to 5				3
Total Number of Receivers	29	4	8	9

The percentage of HP GPS receivers impacted is shown in Table A.24.

Table A.24. Percentage of HP GPS Receivers Impacted 5 dB C/N_0 Degradation

Interference Power Levels (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -60	2	4%
≤ -55	6	12%
≤ -50	9	18%
≤ -45	13	26%
≤ -40	18	36%
≤ -35	23	46%
≤ -30	26	52%
≤ -25	30	60%
≤ -20	31	62%
≤ -15	33	66%
≤ -10	47	94%
≤ -5	47	94%
≤ 0	47	94%
≤ 5	50	100%

The number of GLN GPS receivers and their associated interference power levels are summarized in Table A.25.

Table A.25. Summary of GLN GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers 5 dB C/N_0 Degradation			
	DOT ABC	DOD	R&A	NASCTN
-59 to -55		1		
-54 to -50				
-49 to -45				
-44 to -40				
-39 to -35	1	1		
-34 to -30	1			
-29 to -25	4			
-24 to -20	5			
-19 to -15	1			
-14 to -10	5	2	8	
-9 to -5				1
-4 to 0				
1 to 5				3
Total Number of Receivers	17	4	8	4

The percentage of GLN GPS receivers impacted is shown in Table A.26.

Table A.26. Percentage of GLN GPS Receivers Impacted 5 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -55	1	3%
≤ -50	1	3%
≤ -45	1	3%
≤ -40	1	3%
≤ -35	3	9.1%
≤ -30	4	12.1%
≤ -25	8	24.2%
≤ -20	13	39.4%
≤ -15	14	42.4%
≤ -10	29	87.9%
≤ -5	30	90.9%
≤ 0	30	90.9%
≤ 5	33	100%

The number of TIM GPS receivers and their associated interference power levels are summarized in Table A.27.

Table A.27. Summary of TIM GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 5 dB C/N_0 Degradation	
	DOT ABC	NASCTN
-44 to -40	1	
-39 to -35		
-34 to -30		
-29 to -25	1	
-24 to -20		
-19 to -15	1	1
-14 to -10	6	
-9 to -5		
-4 to 0		
1 to 5		2
Total Number of Receivers	9	3

The percentage of TIM GPS receivers impacted is shown in Table A.28.

Table A.28. Percentage of TIM GPS Receivers Impacted
5 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -40	1	8.3%
≤ -35	1	8.3%
≤ -30	1	8.3%
≤ -25	2	16.7%
≤ -20	2	16.7%
≤ -15	4	33.3
≤ -10	10	83.3%
≤ -5	10	83.3%
≤ 0	10	83.3%
≤ 5	12	100%

The number of CEL GPS receivers and their associated interference power levels are summarized in Table A.29.

Table A.29. Summary of CEL GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 5 dB C/N_0 Degradation
	DOT ABC
≤ -10	2
Total Number of Receivers	2

The percentage of CEL GPS receivers impacted is shown in Table A.30.

Table A.30. Percentage of CEL GPS Receivers Impacted
5 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -10	2	100%

The number of GAV GPS receivers and their associated interference power levels are summarized in Table A.31.

Table A.31. Summary of GAV GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 5 dB C/N_0 Degradation
	DOT ABC
-44 to -40	1
-39 to -35	1
-34 to -30	1
-29 to -25	6
-24 to -20	2
Total Number of Receivers	11

The percentage of GAV GPS receivers impacted is shown in Table A.32.

Table A.32. Percentage of GAV GPS Receivers Impacted
5 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -40	1	9.1%
≤ -35	2	18.2%
≤ -30	3	27.3%
≤ -25	9	81.8%
≤ -20	11	100%

A.7 INTERFERING SIGNALS IN 1625-1635 MHZ AND 1627.5-1637.5 MHZ BANDS

A.7.1 1 dB C/N_0 Degradation

The number of HP GPS receivers and their associated interference power levels are summarized in Table A.33.

Table A.33. Summary of HP GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of Receivers 1 dB C/N_0 Degradation			
	DOT ABC	DOD	R&A	NASCTN
-64 to -60	2	1		
-59 to -55	4			
-54 to -50	3			4
-49 to -45	1		1	1
-44 to -40	1	1	1	1
-39 to -35	9	1		
-34 to -30	5	1		2
-29 to -25	1			
-24 to -20	3			1
-19 to -15	3		1	
-14 to -10	1	1	5	
Total Number of Receivers	33	4	8	9

The percentage of HP GPS receivers impacted is shown in Table A.34.

Table A.34 Percentage of HP GPS Receivers Impacted
1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -60	3	5.6%
≤ -55	7	12.9%
≤ -50	14	25.9%
≤ -45	17	31.5%
≤ -40	21	38.9%
≤ -35	31	57.4%
≤ -30	38	70.3%
≤ -25	39	72.2%
≤ -20	43	79.6%
≤ -15	47	87%
≤ -10	54	100%

The number of GLN GPS receivers and their associated interference power levels are summarized in Table A.35.

Table A.35 Summary of GLN GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of Receivers 1 dB C/N_0 Degradation			
	DOT ABC	**DOD**	**R&A**	**NASCTN**
-54 to -50	1	1		
-49 to -45	1			
-44 to -40	1			
-39 to -35				
-34 to -30	3		1	
-29 to -25	4			1
-24 to -20	6	1	1	1
-19 to -15	1	1		2
-14 to -10	1	1	6	
Total Number of Receivers	18	4	8	4

The percentage of GLN GPS receivers impacted is shown in Table A.36.

Table A.36. Percentage of GLN GPS Receivers Impacted 1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -50	2	5.9%
≤ -45	3	8.8%
≤ -40	4	11.8%
≤ -35	4	11.8%
≤ -30	8	23.5%
≤ -25	13	38.2%
≤ -20	22	64.7%
≤ -15	26	76.5%
≤ -10	34	100%

The number of TIM GPS receivers and their associated interference power levels are summarized in Table A.37.

Table A.37. Summary of TIM GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of Receivers 1 dB C/N_0 Degradation	
	DOT ABC	NASCTN
-34 to -30	1	
-29 to -25	1	
-24 to -20	2	1
-19 to -15		2
-14 to -10	4	
-9 to -5		
-4 to 0		
1 to 5		
Total Number of Receivers	8	3

The percentage of TIM GPS receivers impacted is shown in Table A.38.

Table A.38. Percentage of TIM GPS Receivers Impacted
1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -30	1	9.1%
≤ -25	2	18.2%
≤ -20	5	45.5%
≤ -15	7	63.6%
≤ -10	11	100%

The number of CEL GPS receivers and their associated interference power levels are summarized in Table A.39.

Table A.39. Summary of CEL GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of Receivers 1 dB C/N_0 Degradation
	DOT ABC
-24 to -20	1
-19 to -15	1
Total Number of Receivers	2

The percentage of CEL GPS receivers impacted is shown in Table A.40.

Table A.40. Percentage of CEL GPS Receivers Impacted
1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -20	1	50%
≤ -15	2	100%

The number of GAV GPS receivers and their associated interference power levels are summarized in Table A.41.

Table A.41. Summary of GAV GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 1 dB C/N_0 Degradation
	DOT ABC
-34 to -30	1
-29 to -25	2
-24 to -20	4
-19 to -15	3
-14 to -10	1
Total Number of Receivers	11

The percentage of GAV GPS receivers impacted is shown in Table A.42.

Table A.42. Percentage of GAV GPS Receivers Impacted
1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -30	1	9.1%
≤ -25	3	27.3%
≤ -20	7	63.6%
≤ -15	10	90.9%
≤ -10	11	100%

A.7.2 3 dB C/N_0 Degradation

The number of HP GPS receivers and their associated interference power levels are summarized in Table A.43.

Table A.43. Summary of HP GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers 3 dB C/N_0 Degradation			
	DOT ABC	**DOD**	**R&A**	**NASCTN**
-59 to -55	2	1		
-54 to -50	5			1
-49 to -45				4
-44 to -40	2		1	
-39 to -35	5	1	1	1
-34 to -30	7	1		
-29 to -25	3			2
-24 to -20	2			
-19 to -15	2		1	1
-14 to -10	4	1	5	
Total Number of Receivers	32	4	8	9

The percentage of HP GPS receivers impacted is shown in Table A.44.

Table A.44. Percentage of HP GPS Receivers Impacted
3 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -55	3	9.4%
≤ -50	9	17%
≤ -45	13	24.5%
≤ -40	16	30.2%
≤ -35	24	45.3%
≤ -30	32	60.4%
≤ -25	37	69.8%
≤ -20	39	73.6%
≤ -15	43	81.1%
≤ -10	53	100%

The number of GLN GPS receivers and their associated interference power levels are summarized in Table A.45.

Table A.45. Summary of GLN GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers 3 dB C/N_0 Degradation			
	DOT ABC	**DOD**	**R&A**	**NASCTN**
-49 to -45	1			
-44 to -40	1	1		
-39 to -35	1			
-34 to -30				
-29 to -25	2		1	1
-24 to -20	2			
-19 to -15	3	1	1	1
-14 to -10	8	2	6	2
Total Number of Receivers	18	4	8	4

The percentage of GLN GPS receivers impacted is shown in Table A.46.

Table A.46. Percentage of GLN GPS Receivers Impacted
3 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -45	1	2.9%
≤ -40	3	8.8%
≤ -35	4	11.8%
≤ -30	4	11.8%
≤ -25	8	23.5%
≤ -20	10	29.4%
≤ -15	16	47.1%
≤ -10	34	100%

The number of TIM GPS receivers and their associated interference power levels are summarized in Table A.47.

Table A.47. Summary of TIM GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers 3 dB C/N_0 Degradation	
	DOT ABC	**NASCTN**
-24 to -20	2	
-19 to -15	1	1
-14 to -10	5	1
-9 to -5		1
Total Number of Receivers	8	3

The percentage of TIM GPS receivers impacted is shown in Table A.48.

Table A.48. Percentage of TIM GPS Receivers Impacted
3 dB C/N_0 Degradation

Interference Power Level (dBm/MHz)	Number of Receivers	Percentage of Receivers
≤ -20	2	18.2%
≤ -15	4	36.4%
≤ -10	10	90.9%
≤ -5	11	100%

The number of CEL GPS receivers and their associated interference power levels are summarized in Table A.49.

Table A.49. Summary of CEL GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 3 dB C/N_0 Degradation
	DOT ABC
-19 to -15	1
-14 to -10	1
Total Number of Receivers	2

The percentage of CEL GPS receivers impacted is shown in Table A.50.

Table A.50. Percentage of CEL GPS Receivers Impacted
3 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -15	1	50%
≤ -10	2	100%

The number of GAV GPS receivers and their associated interference power levels are summarized in Table A.51.

Table A.51. Summary of GAV GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 3 dB C/N_0 Degradation
	DOT ABC
-29 to -25	1
-24 to -20	0
-19 to -15	2
-14 to -10	8
Total Number of Receivers	11

The percentage of GAV GPS receivers impacted is shown in Table A.52.

Table A.52. Percentage of GAV GPS Receivers Impacted
3 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -25	1	9.1%
≤ -20	1	9.1%
≤ -15	3	27.3%
≤ -10	11	100%

A.7.3 5 dB C/N_0 Degradation

The number of HP GPS receivers and their associated interference power levels are summarized in Table A.53.

Table A.53. Summary of HP GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers 5 dB C/N_0 Degradation			
	DOT ABC	DOD	R&A	NASCTN
-59 to -55		1		
-54 to -50	3			
-49 to -45	3			2
-44 to -40	2		1	2
-39 to -35	4	1	1	2
-34 to -30	3			
-29 to -25	8	1		
-24 to -20	2			2
-19 to -15	1		1	
-14 to -10	6	1	5	1
Total Number of Receivers	32	4	8	9

The percentage of HP GPS receivers impacted is shown in Table A.54.

Table A.54. Percentage of HP GPS Receivers Impacted

5 dB C/N_0 Degradation

Interference Power Levels (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -55	1	1.9 %
≤ -50	4	7.5 %
≤ -45	9	17 %
≤ -40	14	26.4 %
≤ -35	22	41.5 %
≤ -30	25	47.2 %
≤ -25	34	64.2 %
≤ -20	38	71.7 %
≤ -15	40	75.5 %
≤ -10	53	100 %

The number of GLN GPS receivers and their associated interference power levels are summarized in Table A.55.

Table A.55. Summary of GLN GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers 5 dB C/N_0 Degradation			
	DOT ABC	DOD	R&A	NASCTN
-44 to -40		1		
-39 to -35	2			
-34 to -30	1			
-29 to -25	2			1
-24 to -20	1		1	
-19 to -15	1	1		1
-14 to -10	11	2	7	
-9 to -5				2
Total Number of Receivers	18	4	8	4

The percentage of GLN GPS receivers impacted is shown in Table A.56.

Table A.56. Percentage of GLN GPS Receivers Impacted
5 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -40	1	2.9 %
≤ -35	3	8.8 %
≤ -30	4	11.8 %
≤ -25	7	20.6 %
≤ -20	9	26.5 %
≤ -15	12	35.3 %
≤ -10	32	94.1 %
≤ -5	34	100 %

The number of TIM GPS receivers and their associated interference power levels are summarized in Table A.57.

Table A.57. Summary of TIM GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 5 dB C/N_0 Degradation	
	DOT ABC	**NASCTN**
-24 to -20	1	
-19 to -15		1
-14 to -10	7	
-9 to -5		2
Total Number of Receivers	8	3

The percentage of TIM GPS receivers impacted is shown in Table A.58.

Table A.58. Percentage of TIM GPS Receivers Impacted
5 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -20	1	9.1 %
≤ -15	2	18.2 %
≤ -10	9	81.8 %
≤ -5	11	100 %

The number of CEL GPS receivers and their associated interference power levels are summarized in Table A.59.

Table A.59. Summary of CEL GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 5 dB C/N_0 Degradation
	DOT ABC
-14 to -10	2
Total Number of Receivers	2

The percentage of CEL GPS receivers impacted is shown in Table A.60.

Table A.60. Percentage of CEL GPS Receivers Impacted
5 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -10	2	100 %

The number of GAV GPS receivers and their associated interference power levels are summarized in Table A.61.

Table A.61. Summary of GAV GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 5 dB C/N_0 Degradation
	DOT ABC
-24 to -20	1
-19 to -15	
-14 to -10	10
Total Number of Receivers	11

The percentage of GAV GPS receivers impacted is shown in Table A.62.

Table A.62. Percentage of GAV GPS Receivers Impacted
5 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -20	1	9.1%
≤ -15	1	9.1%
≤ -10	11	100%

A.8 INTERFERING SIGNALS IN 1640-1650 MHZ AND 1646.5-1656.5 MHZ BANDS

A.8.1 1 dB C/N_0 Degradation

The number of HP GPS receivers and their associated interference power levels are summarized in Table A.63.

Table A.63. Summary of HP GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of Receivers 1 dB C/N_0 Degradation			
	DOT ABC	DOD	R&A	NASCTN
-59 to -55	2			
-54 to -50				
-49 to -45	1	1		1
-44 to -40	5			1
-39 to -35	3			4
-34 to -30	1	1		1
-29 to -25	3		1	1
-24 to -20	5			1
-19 to -15	1	1		
-14 to -10	12	1	7	
Total Number of Receivers	33	4	8	9

The percentage of HP GPS receivers impacted is shown in Table A.64.

Table A.64. Percentage of HP GPS Receivers Impacted
1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -55	2	3.7%
≤ -50	2	3.7%
≤ -45	5	9.3%
≤ -40	11	20.4%
≤ -35	18	33.3%
≤ -30	21	38.9%
≤ -25	26	48.1%
≤ -20	32	59.3%
≤ -15	34	62.9%
≤ -10	54	100%

The number of GLN GPS receivers and their associated interference power levels are summarized in Table A.65.

Table A.65. Summary of GLN GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of Receivers 1 dB C/N_0 Degradation			
	DOT ABC	DOD	R&A	NASCTN
-44 to -40	1			
-39 to -35				
-34 to -30				
-29 to -25	2	1		1
-24 to -20		1		
-19 to -15	2	1	1	3
-14 to -10	13	1	7	
Total Number of Receivers	18	4	8	4

The percentage of GLN GPS receivers impacted is shown in Table A.66.

Table A.66. Percentage of GLN GPS Receivers Impacted
1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -40	1	2.9%
≤ -35	1	2.9%
≤ -30	1	2.9%
≤ -25	5	14.7%
≤ -20	6	17.6%
≤ -15	13	38.2%
≤ -10	34	100%

The number of TIM GPS receivers and their associated interference power levels are summarized in Table A.67.

Table A.67. Summary of TIM GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of Receivers 1 dB C/N_0 Degradation	
	DOT ABC	NASCTN
-34 to -30	1	
-29 to -25		
-24 to -20		1
-19 to -15	2	2
-14 to -10	5	
-9 to -5		
-4 to 0		
1 to 5		
Total Number of Receivers	8	3

The percentage of TIM GPS receivers impacted is shown in Table A.68.

Table A.68. Percentage of TIM GPS Receivers Impacted
1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -30	1	9.1%
≤ -25	1	9.1%
≤ -20	2	18.2%
≤ -15	6	54.5%
≤ -10	11	100%

The number of CEL GPS receivers and their associated interference power levels are summarized in Table A.69.

Table A.69. Summary of CEL GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of Receivers 1 dB C/N_0 Degradation
	DOT ABC
-14 to -10	5
Total Number of Receivers	5

The percentage of CEL GPS receivers impacted is shown in Table A.70.

Table A.70. Percentage of CEL GPS Receivers Impacted
1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -10	5	100%

The number of GAV GPS receivers and their associated interference power levels are summarized in Table A.71.

Table A.71. Summary of GAV GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 1 dB C/N_0 Degradation
	DOT ABC
-29 to -25	1
-24 to -20	
-19 to -15	
-14 to -10	10
Total Number of Receivers	11

The percentage of GAV GPS receivers impacted is shown in Table A.72.

Table A.72. Percentage of GAV GPS Receivers Impacted
1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -25	1	9.1%
≤ -20	1	9.1%
≤ -15	1	9.1%
≤ -10	11	100%

3 dB C/N_0 Degradation

The number of HP GPS receivers and their associated interference power levels are summarized in Table A.73.

Table A.73. Summary of HP GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers 3 dB C/N0 Degradation			
	DOT ABC	**DOD**	**R&A**	**NASCTN**
-54 to -50	2			
-49 to -45				
-44 to -40	1			
-39 to -35	6	1		4
-34 to -30	2			2
-29 to -25	2	1	1	2
-24 to -20	1			
-19 to -15	5			1
-14 to -10	14	2	7	
Total Number of Receivers	33	4	8	9

The percentage of HP GPS receivers impacted is shown in Table A.74.

Table A.74. Percentage of HP GPS Receivers Impacted
3 dB C/N0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -50	2	3.7%
≤ -45	2	3.7%
≤ -40	3	5.6%
≤ -35	14	25.9%
≤ -30	18	33.3%
≤ -25	24	44.4%
≤ -20	25	46.3%
≤ -15	31	57.4%
≤ -10	54	100%

The number of GLN GPS receivers and their associated interference power levels are summarized in Table A.75.

Table A.75. Summary of GLN GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers 3 dB C/N0 Degradation			
	DOT ABC	DOD	R&A	NASCTN
-39 to -35	1			
-34 to -30				
-29 to -25				1
-24 to -20	1	1		
-19 to -15	1	1	1	
-14 to -10	15	2	7	3
Total Number of Receivers	18	4	8	4

The percentage of GLN GPS receivers impacted is shown in Table A.76.

Table A.76. Percentage of GLN GPS Receivers Impacted 3 dB C/N0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -35	1	2.9%
≤ -30	1	2.9%
≤ -25	2	5.9%
≤ -20	4	11.8%
≤ -15	7	20.6%
≤ -10	34	100%

The number of TIM GPS receivers and their associated interference power levels are summarized in Table A.77.

Table A.77. Summary of TIM GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers 3 dB C/N0 Degradation	
	DOT ABC	NASCTN
-19 to -15	1	1
-14 to -10	7	2
Total Number of Receivers	8	3

The percentage of TIM GPS receivers impacted is shown in Table A.78.

Table A.78. Percentage of TIM GPS Receivers Impacted 3 dB C/N0 Degradation

Interference Power Level (dBm/MHz)	Number of Receivers	Percentage of Receivers
≤ -15	2	18.2%
≤ -10	11	100%

The number of CEL GPS receivers and their associated interference power levels are summarized in Table A.79.

Table A.79. Summary of CEL GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 3 dB C/N_0 Degradation
	DOT ABC
-14 to -10	5
Total Number of Receivers	5

The percentage of CEL GPS receivers impacted is shown in Table A.80.

Table A.80. Percentage of CEL GPS Receivers Impacted
3 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -10	5	100%

The number of GAV GPS receivers and their associated interference power levels are summarized in Table A.81.

Table A.81. Summary of GAV GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 3 dB C/N_0 Degradation
	DOT ABC
-29 to -25	1
-24 to -20	
-19 to -15	
-14 to -10	10
Total Number of Receivers	11

The percentage of GAV GPS receivers impacted is shown in Table A.82.

Table A.82. Percentage of GAV GPS Receivers Impacted
3 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -25	1	9.1%
≤ -20	1	9.1%
≤ -15	1	9.1%
≤ -10	11	100%

A.8.2 5 dB C/N_0 Degradation

The number of HP GPS receivers and their associated interference power levels are summarized in Table A.83.

Table A.83. Summary of HP GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers 5 dB C/N_0 Degradation			
	DOT ABC	**DOD**	**R&A**	**NASCTN**
-54 to -50	1			
-49 to -45				
-44 to -40	1			
-39 to -35	3	1		2
-34 to -30	6			3
-29 to -25				1
-24 to -20	3	1		2
-19 to -15	1		1	
-14 to -10	18	2	7	1
Total Number of Receivers	33	4	8	9

The percentage of HP GPS receivers impacted is shown in Table A.84.

Table A.84. Percentage of HP GPS Receivers Impacted
5 dB C/N_0 Degradation

Interference Power Levels (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -50	1	1.9%
≤ -45	1	1.9%
≤ -40	2	3.7%
≤ -35	8	14.8%
≤ -30	17	31.5%
≤ -25	18	33.3%
≤ -20	24	44.4%
≤ -15	26	48.1%
≤ -10	54	100%

The number of GLN GPS receivers and their associated interference power levels are summarized in Table A.85.

Table A.85. Summary of GLN GPS Receiver Interference Power Levels

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers 5 dB C/N_0 Degradation			
	DOT ABC	**DOD**	**R&A**	**NASCTN**
-39 to -35	1			
-34 to -30				
-29 to -25				1
-24 to -20	1			
-19 to -15		2		
-14 to -10	16	2	8	
-9 to -5				3
Total Number of Receivers	18	4	8	4

The percentage of GLN GPS receivers impacted is shown in Table A.86.

Table A.86. Percentage of GLN GPS Receivers Impacted
5 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -35	1	2.9%
≤ -30	1	2.9%
≤ -25	2	5.9%
≤ -20	3	8.8%
≤ -15	5	14.7%
≤ -10	31	91.2%
≤ -5	34	100%

The number of TIM GPS receivers and their associated interference power levels are summarized in Table A.87.

Table A.87. Summary of TIM GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 5 dB C/N_0 Degradation	
	DOT ABC	**NASCTN**
-19 to -15		1
-14 to -10	8	
-9 to -5		2
Total Number of Receivers	8	3

The percentage of TIM GPS receivers impacted is shown in Table A.88.

Table A.88. Percentage of TIM GPS Receivers Impacted
5 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -15	1	9.1%
≤ -10	9	81.8%
≤ -5	11	100%

The number of CEL GPS receivers and their associated interference power levels are summarized in Table A.89.

Table A.89. Summary of CEL GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 5 dB C/N_0 Degradation
	DOT ABC
-14 to -10	5
Total Number of Receivers	5

The percentage of CEL GPS receivers impacted is shown in Table A.90.

Table A.90. Percentage of CEL GPS Receivers Impacted
5 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -10	5	100%

The number of GAV GPS receivers and their associated interference power levels are summarized in Table A.91.

Table A.91. Summary of GAV GPS Receiver Interference Power Levels

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers 5 dB C/N_0 Degradation
	DOT ABC
-19 to -15	1
-14 to -10	10
Total Number of Receivers	11

The percentage of GAV GPS receivers impacted is shown in Table A.92.

Table A.92. Percentage of GAV GPS Receivers Impacted
5 dB C/N0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤ -15	1	9.1%
≤ -10	11	100%

A.9 COMPARISON OF GPS RECEIVER IMPACT

A.9.1 Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands

The DOT ABC and DOD test programs performed measurements with interfering signals in the1525-1535 MHz band. The R&A, NASCTN, NPEF, and TWG test programs performed measurements with interfering signals in the 1526-1536 MHz band. Tables A.93 through A.98 compare the results from the different measurement programs for GPS receivers in the HP, GLN, TIM, CEL, and GAV categories.

Table A.93. Comparison of HP GPS Receiver Impact

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands						
Interference Power Level (dBm/10 MHz)	Number of Receivers			Percentage of Receivers		
	Degradation in C/N0					
	1 dB	3 dB	5 dB	1 dB	3 dB	5 dB
≤ -75	1			1.2%		
≤ -70	3			3.6%		
≤ -65	8			9.5%		
≤ -60	12	5	2	14.3%	10%	4%
≤ -55	18	9	6	21.4%	18%	12%
≤ -50	26	11	9	30.9%	22%	18%
≤ -45	30	16	13	35.7%	32%	26%
≤ -40	43	19	18	51.2%	38%	36%
≤ -35	50	24	23	59.5%	48%	46%
≤ -30	56	29	26	66.7%	58%	52%
≤ -25	61	31	30	72.6%	62%	60%
≤ -20	71	33	31	84.5%	66%	62%
≤ -15	73	37	33	86.9%	74%	66%
≤ -10	81	47	47	96.4%	94%	94%
≤ -5	81	47	47	96.4%	94%	94%
≤ 0	82	47	47	97.6%	94%	94%
≤ 5	84	50	50	100%	100%	100%

Table A.94. Comparison of GLN GPS Receiver Impact Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands

Interference Power Level (dBm/10 MHz)	Number of Receivers			Percentage of Receivers		
	Degradation in C/N_0					
	1 dB	3 dB	5 dB	1 dB	3 dB	5 dB
≤ -65	1			0.6%		
≤ -60	1	1		0.6%	3%	
≤ -55	3	1	1	1.9%	3%	3%
≤ -50	4	1	1	2.6%	3%	3%
≤ -45	7	1	1	4.5%	3%	3%
≤ -40	9	4	1	5.8%	12.1%	3%
≤ -35	13	4	3	8.3%	12.1%	9.1%
≤ -30	31	5	4	19.9%	15.2%	12.1%
≤ -25	49	12	8	31.4%	36.4%	24.2%
≤ -20	72	14	13	46.2%	42.4%	39.4%
≤ -15	96	14	14	61.5%	42.4%	42.4%
≤ -10	134	29	29	85.9%	87.9%	87.9%
≤ -5	140	30	30	89.7%	90.9%	90.9%
≤ 0	145	30	30	92.9%	90.9%	90.9%
≤ 5	156	33	33	100%	100%	100%

Table A.95. Comparison of TIM GPS Receiver Impact Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands

Interference Power Level (dBm/10 MHz)	Number of Receivers			Percentage of Receivers		
	Degradation in C/N_0					
	1 dB	3 dB	5 dB	1 dB	3 dB	5 dB
≤ -45	1			4.2%		
≤ -40	3	1	1	12.5%	8.3%	8.3%
≤ -35	4	1	1	16.7%	8.3%	8.3%
≤ -30	6	1	1	25%	8.3%	8.3%
≤ -25	9	2	2	37.5%	16.7%	16.7%
≤ -20	12	2	2	50%	16.7%	16.7%
≤ -15	18	5	4	75%	41.7%	33.3%
≤ -10	22	10	10	91.7%	83.3%	83.3%
≤ -5	22	10	10	91.7%	83.3%	83.3%
≤ 0	22	10	10	91.7%	83.3%	83.3%
≤ 5	24	12	12	100%	100%	100%

Table A.96. Comparison of CEL GPS Receiver Impact Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands

Interference Power Level (dBm/10 MHz)	Number of Receivers			Percentage of Receivers		
	Degradation in C/N_0					
	1 dB	3 dB	5 dB	1 dB	3 dB	5 dB
≤ -10	2	2	2	100%	100%	100%

The CEL receiver measurements performed by the TWG based on the 3GPP AGPS performance standard are presented in Table A.97.

Table A.97. Summary of CEL GPS Receiver Impact

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands		
Interference Power Level (dBm/10 MHz)	**Number of Receivers**	**Percentage of Receivers**
≤ -30	1	2.5%
≤ -25	2	5%
≤ -20	3	7.5%
≤ -15	7	17.5%
≤ -10	11	27.5%
≤ -5	17	42.5%
≤ 0	40	100%

Table A.98. Comparison of GAV GPS Receiver Impact

Interfering Signal in the 1525-1535 MHz Band						
Interference Power Level (dBm/10 MHz)	**Number of Receivers**			**Percentage of Receivers**		
	Degradation in C/N_0					
	1 dB	**3 dB**	**5 dB**	**1 dB**	**3 dB**	**5 dB**
≤ -55	2			18.2%		
≤ -50	2			18.2%		
≤ -45	3			27.3%		
≤ -40	3	3	1	27.3%	27.3%	9.1%
≤ -35	4	3	2	36.4%	27.3%	18.2%
≤ -30	11	3	3	100%	27.3%	27.3%
≤ -25		11	9		100%	81.8%
≤ -20			11			100%

A.9.2 Interfering Signal in the 1625-1635 MHz/1627.5-1637.5 MHz Bands

The DOT ABC and DOD test programs performed measurements with interfering signals in the1625-1635 MHz band. The R&A and NASCTN test programs performed measurements with interfering signals in the 1627.5-1637.5 MHz band. Tables A.99 through A.103 compare the results from the different measurement programs for GPS receivers in the HP, GLN, TIM, CEL, and GAV categories.

Table A.99. Comparison of HP GPS Receiver Impact

Interfering Signal in the 1625-1635 MHz/1627.5-1637.5 MHz Bands						
Interference Power Level (dBm/10 MHz)	Number of Receivers			Percentage of Receivers		
	Degradation in C/N0					
	1 dB	3 dB	5 dB	1 dB	3 dB	5 dB
≤ -60	3			5.6%		
≤ -55	7	3	1	12.9%	9.4%	1.9%
≤ -50	14	9	4	25.9%	17%	7.5%
≤ -45	17	13	9	31.5%	24.5%	17%
≤ -40	21	16	14	38.9%	30.2 %	26.4%
≤ -35	31	24	22	57.4%	45.3%	41.5%
≤ -30	38	32	25	70.3%	60.4%	47.2%
≤ -25	39	37	34	72.2%	69.8%	64.2%
≤ -20	43	39	38	79.6%	73.6%	71.7%
≤ -15	47	43	40	87%	81.1%	75.5%
≤ -10	54	53	53	100%	100%	100%

Table A.100. Comparison of GLN GPS Receiver Impact

Interfering Signal in the 1625-1635 MHz/1627.5-1637.5 MHz Bands						
Interference Power Level (dBm/10 MHz)	Number of Receivers			Percentage of Receivers		
	Degradation in C/N0					
	1 dB	3 dB	5 dB	1 dB	3 dB	5 dB
≤ -50	2			5.9%		
≤ -45	3	1		8.8%	2.9%	
≤ -40	4	3	1	11.8%	8.8%	2.9%
≤ -35	4	4	3	11.8%	11.8%	8.8%
≤ -30	8	4	4	23.5%	11.8%	11.8%
≤ -25	13	8	7	38.2%	23.5%	20.6%
≤ -20	22	10	9	64.7%	29.4%	26.5%
≤ -15	26	16	12	76.5%	47.1%	35.3%
≤ -10	34	34	32	100%	100%	94.1%
≤ -5			34			100%

Table A.101. Comparison of TIM GPS Receivers Impacted

Interfering Signal in the 1625-1635 MHz/1627.5-1637.5 MHz Bands						
Interference Power Level (dBm/10 MHz)	Number of Receivers			Percentage of Receivers		
	Degradation in C/N0					
	1 dB	3 dB	5 dB	1 dB	3 dB	5 dB
≤ -30	1			9.1%		
≤ -25	2			18.2%		
≤ -20	5	2	1	45.5%	18.2%	9.1%
≤ -15	7	4	2	63.6%	36.4%	18.2%
≤ -10	11	10	9	100%	90.9%	81.8%
≤ -5		11	11		100%	100%

Table A.102. Comparison of CEL GPS Receiver Impact

Interfering Signal in the 1625-1635 MHz/1627.5-1637.5 MHz Bands						
Interference Power Level (dBm/10 MHz)	Number of Receivers			Percentage of Receivers		
	Degradation in C/N_0					
	1 dB	3 dB	5 dB	1 dB	3 dB	5 dB
≤ -20	1			50%		
≤ -15	2	1		100%	50%	
≤ -10		2	2		100%	100%

Table A.103. Comparison of GAV GPS Receiver Impact

Interfering Signal in the 1625-1635 MHz Band						
Interference Power Level (dBm/10 MHz)	Number of Receivers			Percentage of Receivers		
	Degradation in C/N_0					
	1 dB	3 dB	5 dB	1 dB	3 dB	5 dB
≤ -30	1			9.1%		
≤ -25	3	1		27.3%		
≤ -20	7	1	1	63.6%	9.1%	9.1%
≤ -15	10	3	1	90.9%	27.3%	9.1%
≤ -10	11	11	11	100%	100%	100%

A.9.3 Interfering Signal in the 1640-1650 MHz/1646.5-1646.5 MHz Bands

The DOT ABC and DOD test programs performed measurements with interfering signals in the1640-1650 MHz band. The R&A and NASCTN test programs performed measurements with interfering signals in the 1646.5-1656.5 MHz band. Tables A.104 through A.108 compare the results from the different measurement programs for GPS receivers in the HP, GLN, TIM, CEL, and GAV categories.

Table A.104. Comparison of HP GPS Receiver Impact

Interfering Signal in the 1640-1650 MHz/1646.5-1656.5 MHz Bands						
Interference Power Level (dBm/10 MHz)	Number of Receivers			Percentage of Receivers		
	Degradation in C/N_0					
	1 dB	3 dB	5 dB	1 dB	3 dB	5 dB
≤ -55	2			3.7%		
≤ -50	2	2	1	3.7%	3.7%	1.9%
≤ -45	5	2	1	9.3%	3.7%	1.9%
≤ -40	11	3	2	20.4%	5.6%	3.7%
≤ -35	18	14	8	33.3%	25.9%	14.8%
≤ -30	21	18	17	38.9%	33.3%	31.5%
≤ -25	26	24	18	48.1%	44.4%	33.3%
≤ -20	32	25	24	59.3%	46.3%	44.4%
≤ -15	34	31	26	62.9%	57.4%	48.1%
≤ -10	54	54	54	100%	100%	100%

Table A.105. Comparison of GLN GPS Receiver Impact

Interfering Signal in the 1640-1650 MHz/1646.5-1656.5 MHz Bands						
Interference Power Level (dBm/10 MHz)	Number of Receivers			Percentage of Receivers		
	Degradation in C/N0					
	1 dB	3 dB	5 dB	1 dB	3 dB	5 dB
≤ -40	1			2.9%		
≤ -35	1	1	1	2.9%	2.9%	2.9%
≤ -30	1	1	1	2.9%	2.9%	2.9%
≤ -25	5	2	2	14.7%	5.9%	5.9%
≤ -20	6	4	3	17.6%	11.8%	8.8%
≤ -15	13	7	5	38.2%	20.6%	14.7%
≤ -10	34	34	31	100%	100%	91.2%
≤ -5			34			100%

Table A.106. Comparison of TIM GPS Receiver Impact

Interfering Signal in the 1640-1650 MHz/1646.5-1656.5 MHz Bands						
Interference Power Level (dBm/10 MHz)	Number of Receivers			Percentage of Receivers		
	Degradation in C/N0					
	1 dB	3 dB	5 dB	1 dB	3 dB	5 dB
≤ -30	1			9.1%		
≤ -25	1			9.1%		
≤ -20	2			18.2 %		
≤ -15	6	2	1	54.5%	18.2%	9.1%
≤ -10	11	11	9	100%	100%	81.8%
≤ -5			11			100%

Table A.107. Comparison of CEL GPS Receiver Impact

Interfering Signal in the 1640-1650 MHz/1646.5-1656.5 MHz Bands						
Interference Power Level (dBm/10 MHz)	Number of Receivers			Percentage of Receivers		
	Degradation in C/N0					
	1 dB	3 dB	5 dB	1 dB	3 dB	5 dB
≤ -10	5	5	5	100%	100%	100%

Table A.108. Comparison of GAV GPS Receiver Impact

Interfering Signal in the 1640-1650 MHz Band						
Interference Power Level (dBm/10 MHz)	Number of Receivers			Percentage of Receivers		
	Degradation in C/N0					
	1 dB	3 dB	5 dB	1 dB	3 dB	5 dB
≤ -25	1	1		9.1%	9.1%	
≤ -20	1	1		9.1%	9.1%	
≤ -15	1	1	1	9.1%	9.1%	9.1%
≤ -10	11	11	11	100%	100%	100%

A.10 SPACE-BASED RECEIVERS

Interference power levels that cause a 1, 3, and 5 dB degradation in C/N_0 for the two SPB GPS receivers measured in the DOT ABC program are summarized in Table A.109.

Table A.109. Summary of SPB Receiver Interference Power Levels

C/N_0 Degradation	Interfering Signal Power Level (dBm/10 MHz)	
	SPB-1	SPB-2
Interfering Signal in 1525-1535 MHz Band		
1 dB	-55	-72
3 dB	-47	-67
5 dB	-37	-65
Interfering Signal in 1625-1635 MHz Band		
1 dB	-73	-75
3 dB	-59	-72.5
5 dB	-53	-72.5
Interfering Signal in 1640-1650 MHz Band		
1 dB	-10	-72
3 dB	-10	-68
5 dB	-10	-65

APPENDIX B
GPS RECEIVER ACQUISITION AND REACQUISITION MODE INTERFERENCE POWER LEVELS

B.1 INTRODUCTION

This appendix summarizes the Technical Focus Group analysis of acquisition/reacquisition interference measurements from the different test programs.

Acquisition (also reacquisition) time is the time required by a Global Positioning Receiver (GPS) receiver to determine the carrier frequency of the GPS signal and the time delay of the GPS signal as it is sent from a GPS satellite accurately enough to correctly demodulate and decode the GPS signal. The exact carrier frequency of a GPS signal received on Earth is continually changing due to the Doppler effects. This effect is due to the changing velocity of a GPS satellite relative to a receiver on Earth. The distance from a GPS satellite to a GPS receiver also changes continually due to the relative motion between a GPS satellite and a receiver. Thus the time delay of the GPS signal also continually changes.

To know the carrier frequency and time delay accurately enough, that is to "acquire" the GPS signal, the receiver processes the GPS signal through its correlators using thousands of combinations of time delays and frequencies for each satellite acquired. When the signal level after the correlators exceeds a receiver-specific threshold, the receiver decides the GPS signal is present for a particular frequency and time delay and then decodes the signal. Wideband interference to a GPS receiver will raise the effective noise level in a GPS receiver. If the threshold is fixed, the interference will cause more incorrect decisions, or false alerts, that the GPS signal is present when it is only noise and interference that is present. If the receiver is designed with an adaptive threshold based on the effective noise level, the threshold can increase, reducing the increase in the false alert rate, and decreasing the probability that the receiver correctly detects that the GPS signal is present (given that it actually is present). If the threshold is fixed, the acquisition (and reacquisition) time can increase due to time spent identifying and recovering from false alerts. If the threshold is increased, the acquisition (and reacquisition) time can increase due to time spent waiting for the GPS signal plus noise to be processed at a particular frequency and time delay to exceed the threshold (when the GPS signal actually does have that frequency and time delay).

Acquisition and reacquisition interfering signal power measurements were performed by the Department of Transportation Adjacent Band Compatibility (DOT ABC), Roberson and Associates (R&A), and the National Advanced Spectrum and Communications Test Network (NASCTN) programs. The GPS receivers being tested cover the categories of high precision (HP), general location/navigation (GLN), timing (TIM), and cellular (CEL).

B.2 DOT ABC MEASUREMENTS

The DOT ABC signal acquisition tests were performed via a direct connection to the GPS receiver (i.e., conducted). The signal acquisition tests were executed at adjacent-band frequencies using Long Term Evolution (LTE) interfering signals in the 1520-1530 MHz, 1615-1625 MHz, and 1640-1650 MHz bands. The test sequences removed the GPS signals for 30 seconds and then allowed at least 90 seconds after they were reintroduced for the receiver to reacquire and track. These tests are therefore more indicative of Warm or Hot Start versus the potentially more challenging acquisition condition of Cold Start. This sequence of removing and reintroducing signals was repeated in sets of five iterations starting with a set where interference was turned Off. After this quiescent period, the interference was turned On and after each successive completion of 5 iterations its power was incremented by 2 decibels (dB). The interference power ranged from -60 to -10 dB relative to a milliwatt (dBm)/10 MHz for the 1525 and 1645 MHz frequency bands and -80 to -30 dBm/10 MHz for the 1625-1635 MHz band.

The GPS receiver acquisition time was computed for L1 Course/Acquisition (C/A) signals at the GPS Interface Specification (IS) minimum power level (-128.5 dBm for L1 C/A) and also for one satellite that was set 10 dB lower to represent low elevation or challenged environments.[1] For the IS minimum signals, the acquisition time was defined as the receiver acquiring and tracking four or more satellites. Since more than four satellites are generally in view at the specified minimum levels this is considered a modest criterion for establishing acquisition. For the low elevation satellite, the acquisition time was simply when this satellite was first acquired and tracked. At each interference power level, acquisition time from the five iterations was averaged to provide a single value. At each power step an acquisition time was computed only if the receiver met the acquisition criterion for all five iterations.

The DOT ABC GPS receiver acquisition measurement results are summarized in Tables B.1 through B.3 showing the interfering signal power levels where signal acquisition no longer satisfies the criteria for the IS minimum and low elevation signals. The interfering signal power levels that cause degradations of 1 dB, 3 dB, and 5 dB in Carrier-to-Noise Density (C/N_{0}) are also included.

[1] Global Positioning System Directorate System Engineering and Integration, Interface Specification, IS-GPS-200H, *Navstar GPS Space Segment/Navigation User Interfaces* at 17 (Sept. 24, 2013), *available at* http://www.gps.gov/technical/icwg/IS-GPS-200H.pdf.

Table B.1. DOT ABC Acquisition Time Measurement Summary
Interfering Signal in 1525-1535 MHz Band

GPS Receiver Category	Interfering Signal Power Level (dBm/10 MHz)				
	Low Elevation Satellite Signal	IS Satellite Signal	C/N_0 Degradation		
			1 dB	3 dB	5 dB
HP	No signal tracking	-52	-68	-62	-58
HP	-12	-10	-14	-10	-10
HP	-28	-22	-30	-26	-24
HP	-18	-14	-18	-14	-14
HP	-32	-30	-44	-38	-34
HP	-16	No loss of signal acquisition	-12	-12	-12
TIM	-12	No loss of signal acquisition	-22	-18	-16
HP	No signal tracking	-50	-60	-54	-50
CEL	No loss of signal acquisition	No loss of signal acquisition	No degradation in C/N_0	No degradation in C/N_0	No degradation in C/N_0
GLN	-26	-22	-42	-26	-22
HP	-28	-20	-28	-24	-24
HP	-30	-18	-36	-26	-22

Table B.2. DOT ABC Acquisition Time Measurement Summary
Interfering Signal in 1625-1635 MHz Band

GPS Receiver Category	Interfering Signal Power Level (dBm/10 MHz)				
	Low Elevation Satellite Signal	IS Satellite Signal	C/N_0 Degradation		
			1 dB	3 dB	5 dB
HP	-64	-46	-62	-58	-54
HP	No loss of signal acquisition	No loss of signal acquisition	No degradation in C/N_0	No degradation in C/N_0	No degradation in C/N_0
HP	No signal tracking	-74	-88	-82	-78
HP	No loss of signal acquisition	No loss of signal acquisition	No degradation in C/N_0	No degradation in C/N_0	No degradation in C/N_0
HP	-58	-56	-64	-60	-58
HP	No loss of signal acquisition	No loss of signal acquisition	No degradation in C/N_0	No degradation in C/N_0	No degradation in C/N_0
TIM	-54	-48	-60	-58	-58
HP	No signal tracking	-46	-54	-46	-42
CEL	No signal tracking	No loss of signal acquisition	-50	-48	-46
GLN	-46	-42	-68	-60	-56
HP	No loss of signal acquisition	No loss of signal acquisition	No degradation in C/N_0	No degradation in C/N_0	No degradation in C/N_0
HP	No loss of signal acquisition	No loss of signal acquisition	No degradation in C/N_0	No degradation in C/N_0	No degradation in C/N_0

Table B.3. DOT ABC Acquisition Time Measurement Summary Interfering Signal in 1640-1650 MHz Band

GPS Receiver Category	Interfering Signal Power Level (dBm/10 MHz)				
	Low Elevation Satellite Signal	IS Satellite Signal	C/N_0 Degradation		
			1 dB	3 dB	5 dB
HP	No signal tracking	-46	-56	-52	-50
HP	No loss of signal acquisition	No loss of signal acquisition	No degradation in C/N_0	No degradation in C/N_0	No degradation in C/N_0
HP	-30	-24	-30	-26	-26
HP	No loss of signal acquisition	No loss of signal acquisition	No degradation in C/N_0	No degradation in C/N_0	No degradation in C/N_0
HP	-24	-24	-32	-28	-26
HP	No loss of signal acquisition	No loss of signal acquisition	No degradation in C/N_0	No degradation in C/N_0	No degradation in C/N_0
TIM	No loss of signal acquisition	No loss of signal acquisition	-12	-12	-12
HP	No Signal Tracking	-48	-52	-48	-46
CEL	No loss of signal acquisition	No loss of signal acquisition	No degradation in C/N_0	No degradation in C/N_0	No degradation in C/N_0
GLN	-16	-14	-36	-32	-28
HP	-26	-22	-24	-22	-20
HP	-24	-16	-24	-22	-20

As shown in Tables B.1 through B.3, for GPS receivers where there is no impact to the signal acquisition mode there is also no degradation in the C/N_0 for the tracking mode. Based on a review of the DOT ABC measurements for the low elevation signal and the IS minimum signal, a range of interfering signal power levels generally corresponding to a 1 dB to 5 dB degradation in C/N_0 can be correlated with signal acquisition impacts.

B.3 R&A MEASUREMENTS

R&A performed reacquisition testing in an anechoic chamber using their Open Sky GPS signal constellation where there are eight satellites simulated each with a nominal signal power level of -130 dBm.[2]

[2] Letter from Gerard J. Waldron, Counsel to Ligado Networks LLC, to Marlene H. Dortch, Secretary, FCC, IB Docket Nos. 12-340 and 11-109, Roberson and Associates, *Summary of GPS Reacquisition Testing* (Dec. 22, 2016), *available at*

Eighteen receiver/antenna combinations were tested with an interfering signal in the 1526-1536 MHz band and an interfering signal in the 1627.5-1637.5 MHz band.[3] The GPS receivers were first tested without an interfering signal present in the chamber. Initially, the GPS receivers were allowed to acquire and run for 20 minutes. Then the GPS signal feed was disconnected for approximately 60 seconds to allow the receiver to lose lock, waiting at least 60 seconds but no more than 70 seconds. The signal was reapplied to the GPS receivers and the time to reacquire was recorded and the receivers allowed to operate for another 60 seconds before the GPS signal was again disconnected. The test was repeated 50 times and the reacquisition times were recorded and the average time of the 50 iterations was computed. The data is summarized in Table B.4 for an interfering signal in the 1526-1536 MHz band and Table B.6 for an interfering signal in the 1627.5-1637.5 MHz band.

The summary in Table B.4 reports the 90th and 99th percentile for interfering signal off (baseline), and interfering signal power levels of -37, -20, and -10 dBm/10 MHz for 14 receiver/antenna combinations for each of the 50 iterations with interfering signals in the 1526-1536 and 1627.5-1637.5 MHz bands.

https://ecfsapi.fcc.gov/file/122228424456/Ligado%20Ex%20Parte%20Letter%20re%20Reacquisition%20Testing%20(12.22.16).pdf.

[3] Four receiver/antenna pairings used the Live Sky signal conditions because the GPS receiver did not reliably lock onto the GPS signals from the simulator. The NavCom SF-3050 (both antennas), the Trimble R8s, and Trimble R9 were not included in this analysis.

Table B.4. R&A Reacquisition Time Measurement Summary
Interfering Signal in 1526-1536 MHz Band

GPS Receiver	Category	Antenna	Reacquisition Time (Seconds)							
			Baseline GPS Only		-37 dBm/10 MHz		-20 dBm/10 MHz		-10 dBm/10 MHz	
			90%	99%	90%	99%	90%	99%	90%	99%
*Furuno GP32	GLN	Furuno GPA-017	3	4	3	3.5	4	4	3	4
Garmin eTrex H	GLN	Internal	8.2 6.1***	10 7***	8.5	8.5	10	12	12	13
Garmin GPSMAP 76CSx	GLN	Internal	4	4	5	5.5	4	4	4	4.5
Garmin GPSMAP 78SC	GLN	Internal	6	6.5	5	6	6	7	5	6.5
Garmin Montana 650t	GLN	Internal	5	6	6	9.6	5.1	6.5	5	6
**Motorola APX 7000	GLN	Internal	5.1	7	5	5	5	5.5	7	7
Motorola MW810	GLN	Motorola 8508851K66	2	3	3	3	2.1	3	2	2
*Trimble TM3000	GLN	Gilsson	2	3	2	3	3	3	2	2
*Topcon HiPer V	HP	Internal	13	15.5	13	14.5	No data	No data	Did not obtain lock within 2 minutes	
Topcon System 310	HP	PG S3	16	17	17	17	No data	No data	No data	No data
Trimble AgGPS 542	HP	Filtered Antenna	3	11.7	4	4	3	4	4	4
Trimble Geo 7x	HP	Internal	4.1	5.5	4	4	4	5.5	65	74
Trimble SPS855	HP	Filtered Antenna	< 4	< 4.5	4	4	3	3	4	5
Trimble SPS985	HP	Internal	3	4	3	4	4	4	3.1	4

* No C/N_0 data reported. The only measurands reported were position error and number of satellites.
** No C/N_0 data reported. The only measurand reported was position error.
*** Data was collected 5/31/16-6/1/16 and 8/5/16-8/6/16.

Considering the data in Table B.4 and associated C/N_0 measurements, they are similar to the DOT ABC acquisition measurements, in that for most cases, when there is no degradation to the tracking mode C/N_0 there is no impact on signal acquisition. Figure B.1 shows the impact on C/N_0 as reported by a GPS receiver in the presence of the interfering signal varied from -80 to -10 dBm/10 MHz. This is consistent with the measured data in Table B.4 for the Garmin Montana 650t that shows no increase in reacquisition time.

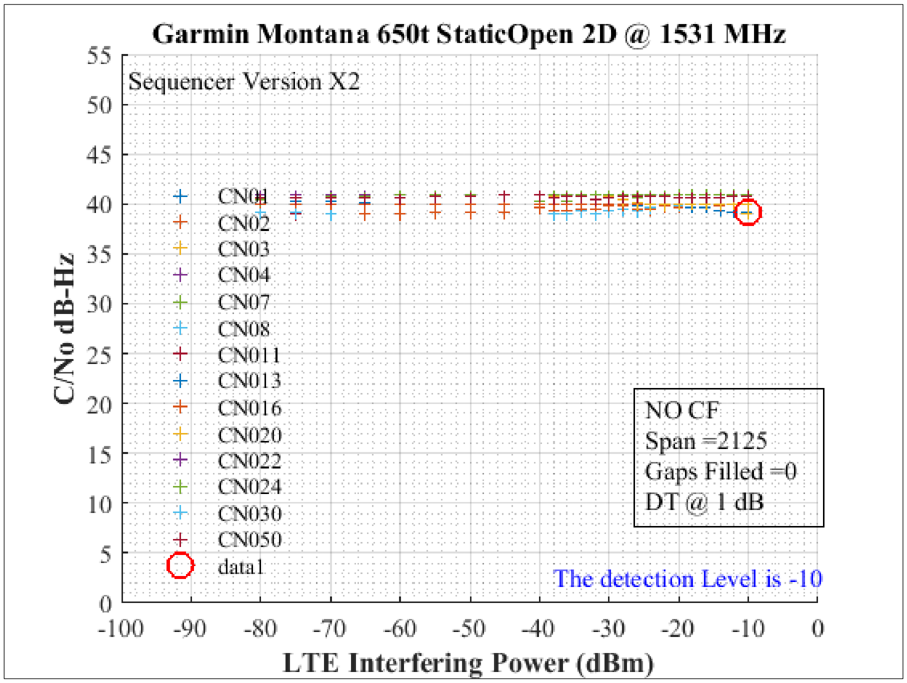

Figure B.1. Garmin Montana 650t C/N$_0$ as a Function Interfering Signal Power

Results for the Garmin GPSMAP 76CSx, Garmin GPSMAP 78SC, Trimble SPS855 Javad, and Trimble SPS985 are similar to the Garmin Montana 650t in that they also show virtually no increase in reacquisition time and similarly, no drop in C/N$_0$ with increasing interference signal power.

The measurements for the Garmin eTrex H in Figure B.2, however shows a slight degradation of C/N$_0$ near -10 dBm/10 MHz, however the reacquisition time increases from 8.2 to 12 seconds and 6.1 to 13 seconds for interference power levels between -20 and -10 dBm/10 MHz. There are two baseline values because this receiver was measured on two different days.

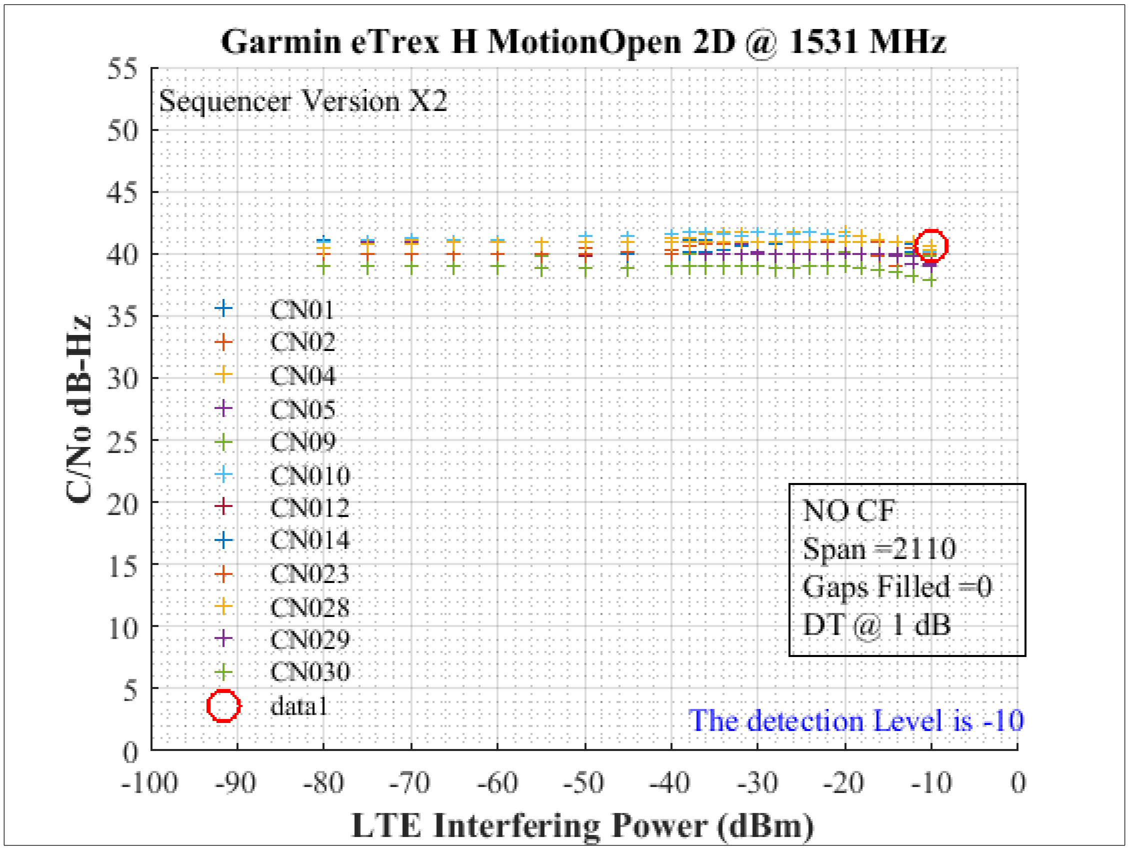

Figure B.2. Garmin eTrex H C/N_0 as a Function of Interfering Signal Power

The measurements of the Trimble Geo 7x in Figure B.3 show no drop in C/N_0, until the interfering signal power is increased from -20 to -10 dBm/10 MHz over which the C/N_0 drops from 40 to 35 dB-Hz and the reacquisition time increases from 4 to 65 seconds.

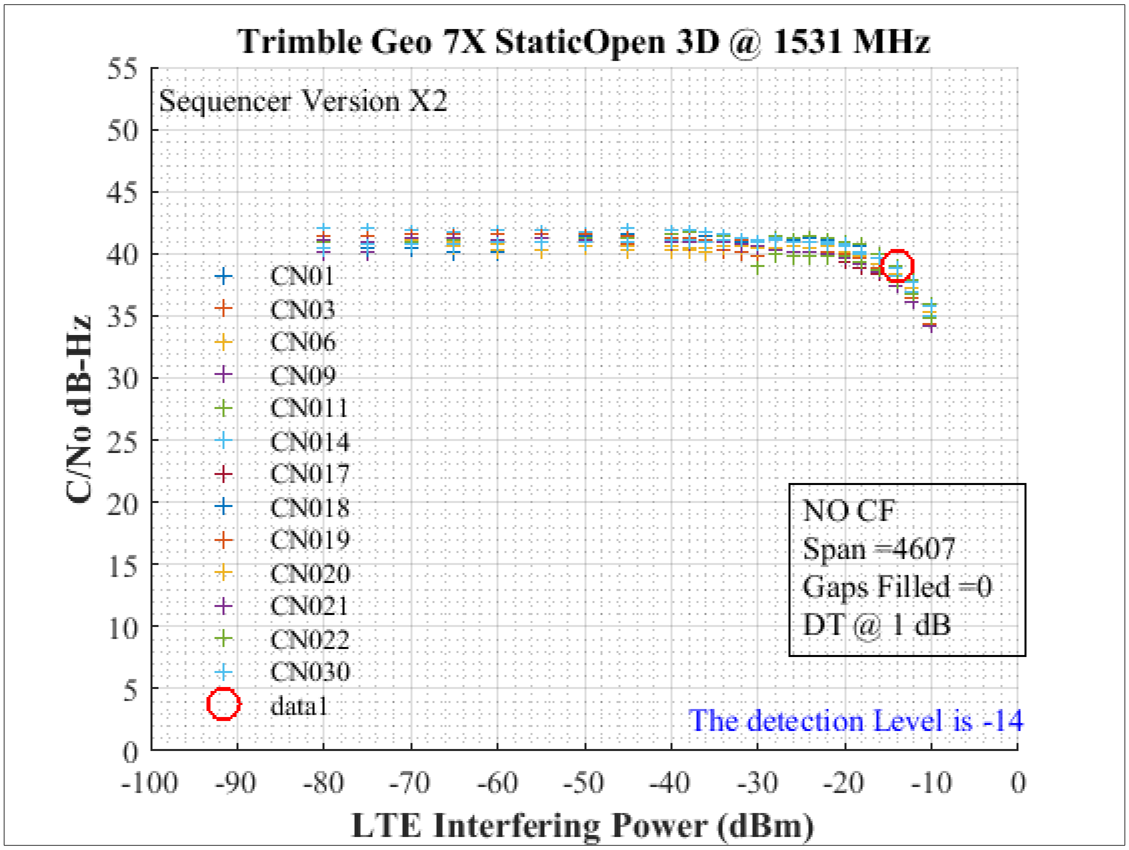

Figure B.3. Trimble Geo7X C/N$_0$ as a Function of Interfering Signal Power

In one case, the reacquisition measurement data appears to be inconsistent with measured data showing C/N$_0$ as a function of interfering signal power. The reacquisition data indicates that in better than 90 percent of the 50 iterations of the Topcon System 310, the receiver is reacquiring the GPS signals with the interfering signal power at -10 dBm/10 MHz, with only a 1-second increase over the baseline reacquisition time. However, Figure B.4 indicates that the receiver has lost lock and is no longer reporting data at an interfering signal power level greater than -32 dBm/10 MHz. This interfering signal power coincides with at least a 5 dB decrease in the C/N$_0$ as reported by the receiver.

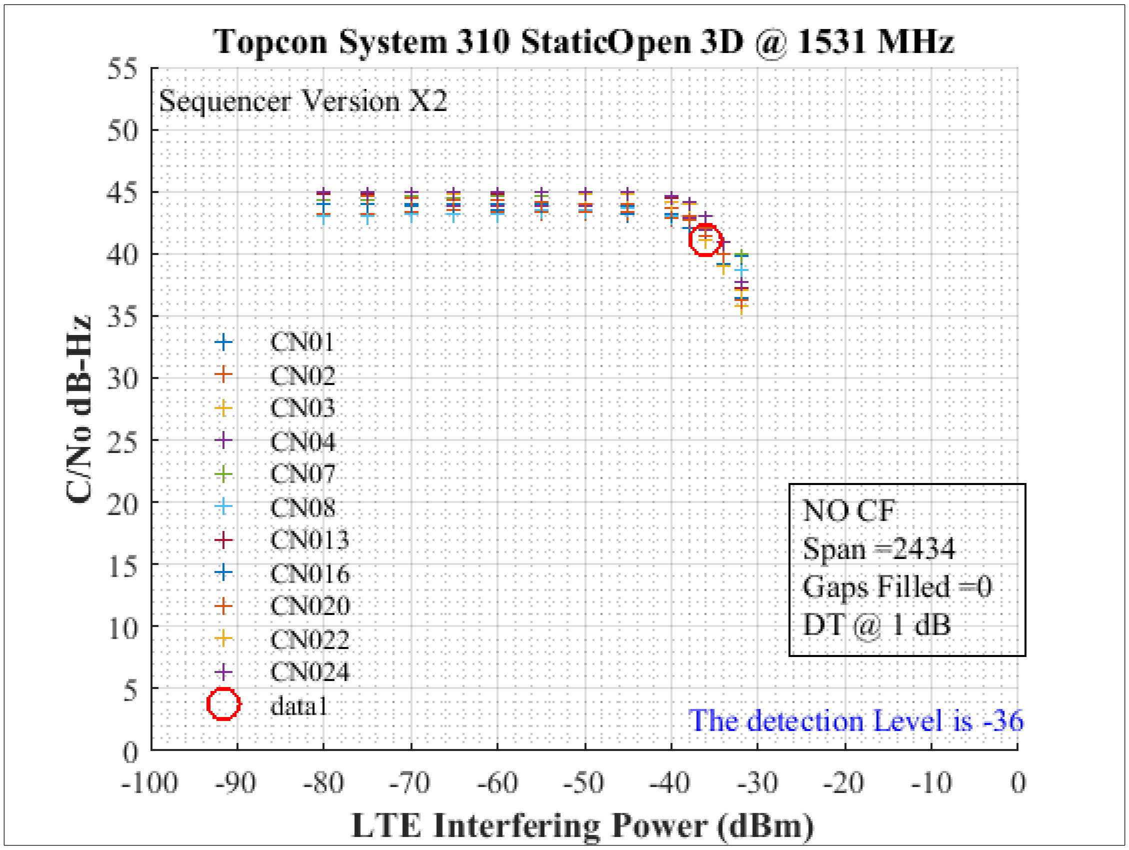

Figure B.4. Topcon 310 C/N_0 as a Function of Interfering Signal Power

The data presented for Furuno GP32, Motorola MW810, Trimble TM3000, and Topcon HiPer V only included position error and the number of satellites as a function of interfering signal power. In the case of the Motorola APX 7000, only position error was reported. Since C/N_0 values were not reported for these receivers no comparison can made between reacquisition time and C/N_0 degradation.

Table B.5 is a comparison of C/N_0 data with the reacquisition times shown in Table B.4. In 7 of the 14 cases shown in the Table B.5, C/N_0 remains virtually unchanged with increasing interfering signal power level. In these cases, the reacquisition time is virtually constant, indicating no impact from the interference signal power on either C/N_0 or reacquisition time. In four cases, no comparison can be made since the receivers measured reported only position error and the number of satellites locked.

Of the two cases, the Garmin eTerx H shows measurements of increasing acquisition time and decreasing C/N_0 commensurate with increasing interfering signal power level. In the case of the Topcon 310, the data appears inconsistent as the two devices indicate loss of lock at -30 dBm/10 MHz while reacquisition times are reported for an interfering signal power level of -10 dBm/10 MHz.

Table B.5. Comparison of R&A C/N_0 Degradation Interference Power Levels with 99th Percentile Reacquisition Time - Interfering Signal in 1526-1536 MHz Band

GPS Receiver	C/N_0	Reacquisition Time Compared to Baseline
*Furuno GP32	C/N_0 is not reported	No change
Garmin eTrex H	No degradation in C/N_0	50 to 100 % increase between -20 dBm/10 MHz and -10 dBm/10 MHz
Garmin GPSMAP 76CSx	No degradation in C/N_0	Varies 1 to 1.5 seconds
Garmin GPSMAP 78sc	No degradation in C/N_0	Varies by 0.5 seconds
Garmin Montana 650t	No degradation in C/N_0	Increases up to 4 seconds
*Motorola APX 7000	C/N_0 is not reported	Varies by 2 seconds
Motorola MW810	No degradation in C/N_0	Decreases by 1 second
*Trimble TM3000	C/N_0 is not reported	Decreases by 1 second
*Topcon HiPer V	C/N_0 is not reported	No reacquisition between -20 and -10 dBm/10 MHz
Topcon System 310	No C/N_0 values are reported above -32 dBm/10 MHz	No reacquisition between -20 and -10 dBm/10 MHz
Trimble AgGPS 542	No degradation in C/N_0	Baseline 12 seconds 4 seconds at -20 and -10 dBm/10 MHz
Trimble Geo 7x	C/N_0 decreases by 5 dB between -20 dBm/10 MHz and -10 dBm/10 MHz interfering signal power level	Increases by 69 seconds between -20 dBm/10 MHz and -10 dBm/10 MHz
Trimble SPS855	No degradation in C/N_0	Increases by 0.5 seconds
Trimble SPS985	No degradation in C/N_0	No change

* No C/N_0 data reported. The only measurands reported were position error and/or number of satellites.

Table B.6 below reports the 90th and 99th percentile for interfering signal off, and interfering signal power levels of -20 and -10 dBm/10 MHz for 14 receiver/antenna combinations for each of the 50 iterations with an interfering signal in the 1627.5-1637.5 MHz band.

Table B.6. R&A Reacquisition Time Measurement Summary
Interfering Signal in 1627.5-1637.5 MHz Band

GPS Receiver	Category	Antenna	Reacquisition Time (Seconds)					
			Baseline GPS Only		-20 dBm/10 MHz		-10 dBm/10 MHz	
			90 %	99 %	90 %	99 %	90 %	99 %
*Furuno GP32	GLN	Furuno GPA-017	3	4	4	4	4	4
Garmin eTrex H	GLN	Internal	8.2/6.1	10/ 7	7	8	15	22.5
Garmin GPSMAP 76CSx	GLN	Internal	4	4	4	5	4	4.5***
Garmin GPSMAP 78sc	GLN	Internal	6	6.5	7	7.5	5	6
Garmin GPSMAP 650t	GLN	Internal	5	6	6	7	5.1	6.51
**Motorola APX 7000	GLN	Internal	5.1	7	5	6	6	6.5
Motorola MW810	GLN	Motorola 8508851K66	2	3	3	3	3	3
*Trimble TM3000	GLN	Gilsson	2	3	3	3	3	3
*Topcon HiPer V	HP	Internal	13	15.5	12	13.5	Did not obtain lock within 2 minutes	
Topcon System 310	HP	PG S3	16	17	16.1	18	17	17
Trimble AgGPS 542	HP	Filtered Antenna	3	11.7	4	4	4	4
Trimble Geo 7x	HP	Internal	4.1	5.5	4	5	4***	4.5***
Trimble SPS855	HP	Filtered Antenna	< 4	< 4.5	4	4	4	4
Trimble SPS985	HP	Internal	3	4	4	4.5	4****	4****

* No C/N_0 data reported. Only measurands reported were position error and number of satellites.
** No C/N_0 data. Only measurand reported was position error.
*** For C/N_0 data -15 dBm/10 MHz is the highest interfering power level measured.
**** For C/N_0 data -18 dBm/10 MHz is the highest power interfering power level measured.

Table B.7 is a comparison of C/N_0 measurement data with the reacquisition times shown in Table B.6. In 8 of the 14 cases shown in the Table B.7, there is no degradation in C/N_0 with increasing interfering signal power level. In these cases, the reacquisition time is virtually constant indicating no impact from the interfering signal power on either C/N_0 or reacquisition time. No comparison can be made in four cases since the receivers measured reported only position error and the number of satellites tracked. In one case the C/N_0 drops to 15 dB-Hz at -20 dBm/10 MHz and the reacquisition time doubles. In another case a reacquisition time is reported at -10 dBm/10 MHz and the C/N_0 plot indicates lock was lost at -15 dBm/10 MHz.

Table B.7. Comparison of R&A C/N_0 Degradation Interference Power Level with 99th Percentile Reacquisition Time - Interfering Signal 1627.5-1637.5 MHz Band

GPS Receiver	C/N_0	Reacquisition Time Compared to Baseline
*Furuno GP32	C/N_0 is not reported	No change compared to baseline
Garmin eTrex H	No degradation in C/N_0 below -20 dBm C/N_0 - then drops 15 dB-Hz between interfering power level of -20 dBm/10 MHz	100% increase between -20 dBm/10 MHz and -10 dBm/10 MHz
Garmin GPSMAP 76CSx	No degradation in C/N_0	0.5 to 1 second increase
Garmin GPSMAP 78sc	No degradation in C/N_0	1 second increase at -20 dBm/10 MHz 0.5 second decrease at -10 dBm/10 MHz
Garmin GPSMAP 650t	No degradation in C/N_0	1 second increase
*Motorola APX 7000	C/N_0 is not reported	0.5 second decrease
Motorola MW810	No degradation in C/N_0	No change compared to baseline
*Trimble TM3000	C/N_0 is not reported	No change compared to baseline
*Topcon HiPer V	C/N_0 is not reported	No reacquisition at -10 dBm/10 MHz
Topcon System 310	No degradation in C/N_0	1-second increase at -20 dBm/10 MHz
Trimble AgGPS 542	No degradation in C/N_0	Decreases from 12 seconds at baseline to 4 seconds from -20 dBm/10 MHz to -10 dBm/10 MHz
Trimble Geo 7x	C/N_0 no longer reported for interfering signal power level above -15 dBm/10 MHz	Decreases by 1 second
Trimble SPS855	No degradation in C/N_0	Decreases by 0.5 seconds
Trimble SPS985	No degradation in C/N_0	No change compared to baseline
* No C/N_0 data reported. The only measurands reported were position error and/or number of satellites.		

As shown in Tables B.1 through B.7, for GPS receivers where there is no impact to the signal acquisition mode there is also no degradation in the C/N_0 for the tracking mode.

B.4 NASCTN MEASUREMENTS

NASCTN performed two types of acquisition measurements, Time to First Fix (TTFF), or cold start, and Time to First Reacquisition (TTFR), or warm start.[4] The receiver categories tested were HP, Real Time Kinematics (RTK), Development Board Devices (DEV), and GLN

[4]Time to First Fix (TTFF) is a measure of the time required for a GPS receiver to acquire satellite signals and navigation data, and calculate a position solution (referred to as a fix).

devices. The signal acquisition tests were executed at two frequencies using 10 MHz LTE interfering signals in the 1526-1536 and 1627.5-1637.5 MHz bands. The simulated GPS constellation used is referred to a "Nominal Scenario".[5] The simulator created a constellation of 11 GPS satellites with a signal level of -128.5 dBm and two geostationary Wide Area Augmentation System (WAAS) satellites with a signal level of -128.5 dBm. The RTK receivers are not considered in this analysis because the measurement procedures and definition of acquisition time is different than the HP receivers

For the TTFF measurements, the GPS receivers were set to a cold start mode where the receiver does not have prior location or time information and allowed to run for 2 minutes. The time to acquire was recorded, the GPS signal was removed and this process was repeated 100 times. The interfering signal power was increased and the process repeated. For the TTFR tests, the GPS was allowed to acquire the satellites and run for 2 minutes. The GPS signal was then removed for 3 minutes. This simulates losing the GPS signal as if in a long tunnel. The signal was replaced and reacquisition time recorded. This process was repeated 100 times. The LTE interfering signal power level was then increased and the process repeated at several different power levels. For HP receivers the first fix was declared when the first valid position solution was reported.[6]

The TTFF and TTFR acquisition measurement results are summarized in Tables B.8 through B.11 showing results for the different interfering signal power levels tested. The interfering signal power levels that caused degradations of 1, 3, and 5 dB in C/N_0 are included.

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[5] *NIST Technical Note 1952* at 20.

[6] *Id.* at 82.

Table B.8. Summary of NASCTN TTFF Measurements
Interfering Signal in 1627.5-1637.5 MHz Band

DUT TYPE	Baseline Mean TTFF (seconds)	Interfering Power Level (dBm) (± Measurement Uncertainty)	Increase in Mean TTFF Compared to Baseline (seconds)	Interfering Power Level (dBm/10 MHz) C/N_0 Degradation 1 dB	3 dB	5 dB
DUT 7 HP	40.64	-46.3 ± 2.7	-0.36	-43.8	-38.8	-36.3
		-41.3 ± 2.7	8.11			
		-35.8 ± 2.7	78.36			
		-33.8 ± 2.7	Did not acquire			
DUT 8 HP	44.62	-51.3 ± 2.7	5.23	-53.7	-50.2	-46.3
		-50.2 ± 2.7	7.39			
		-46.3 ± 2.7	44.53			
DUT 9 Ant C HP	33.35	-50.0 ± 2.7	2.77	-48.1	-44.8	-39.9
		-45.9 ± 2.7	35.82			
		-42.9 ± 2.7	Did not acquire			
DUT 9 Ant D HP	33.48	-33.8 ± 2.7	6.68	-32.4	-28.5	-23.6
		-27.5 ± 2.7	Did not acquire			
DUT 10 HP	41.39	-47.2 ± 2.7	1.2	-54	-45.4	-40.3

Table B.9. Summary of NASCTN TTFF Measurements
Interfering Signal in 1526-1536 MHz Band

DUT TYPE	Baseline Mean TTFF (seconds)	Interfering Power Level (dBm/10 MHz) (± Measurement Uncertainty)	Increase in Mean TTFF Compared to Baseline (seconds)	Interfering Power Level (dBm/10 MHz) C/N_0 Degradation		
				1 dB	3 dB	5 dB
DUT 7 HP	40.64	-61.2 ± 2.7	20.23	-67.3	-51.6	-45.8
		-54.5 ± 2.7	17.26			
		-45.8 ± 2.7	35.0			
		-40.5 ± 2.7	56.9			
DUT 8 HP	45.32	-63.4 ± 2.7	16.23	-67.1	-64.2	-61
		-62.3 ± 2.7	35.67			
DUT 9 Ant C HP	33.35	-52.3 ± 2.7	8.77	-52.2	-48.6	-44.6
DUT 9 Ant D HP	33.44	-1.5 ± 3.1	1.89	0.1	2.2	2.2
		0.4 ± 3.1	21.84			
DUT 10 HP	41.39	-62.5 ± 2.7	1.64	-64.4	-62.5	-58.2

For an interfering signal in the 1627.5-1637.5 MHz band, there are four receivers where the TTFF measurements were performed at multiple interfering signal power levels: DUT 7, DUT 8, DUT 9 with Antenna C, and DUT 9 with Antenna D. For DUT 7 there was a significant increase in the mean TTFF from 8.11 to 78.36 seconds. The corresponding interference power level ranges from -33.1 to -38.5 dBm/10 MHz taking into account measurement uncertainty, which generally corresponds to an interfering signal power that causes a 3 dB degradation in C/N_0. A significant increase in the mean TTFF for DUT 8 of 7.39 seconds to 44.53 seconds occurs at an interfering signal in the range of -43.6 to -49 dBm/10 MHz taking into account measurement uncertainty, which generally corresponds to an interfering signal power that causes a 3 dB to 5 dB degradation in C/N_0. A significant increase in the mean TTFF for DUT 9 with Antenna C of 2.77 seconds to 35.82 seconds occurs for an interfering signal power level in the range of -43.2 to -48.6 dBm/10 MHz taking into account measurement uncertainty, which generally corresponds to an interfering signal that causes a C/N_0 degradation in the range of 1 dB to 5 dB. DUT 9 with Antenna D could not acquire at an interfering power level in the range of -24.8 to -30.2 dBm/10 MHz taking into account measurement uncertainty. This corresponds generally to an interfering signal that causes a C/N_0 degradation in the range of 1 dB to 5 dB.

For an interfering signal in the 1526-1536 MHz band, there are three receivers where the TTFF measurements were performed at multiple interfering signal power levels: DUT 7, DUT 8, and DUT 9 with Antenna D. For DUT 7 there was a significant increase in the mean TTFF from 17.26 to 35 seconds. The corresponding interference power level ranges from -43.1 to -48.5 dBm/10 MHz taking into account measurement uncertainty, which generally corresponds to an interfering signal power that causes a C/N_0 degradation in the range of 3 dB to 5 dB. A significant increase in the mean TTFF for DUT 8 of 16.23 to 35.67 seconds occurs at an interfering signal level in the range of -59.6 to -65 dBm/10 MHz taking into account measurement uncertainty, which generally corresponds to an interfering signal that causes a 3 dB to 5 dB degradation C/N_0. An increase in the mean TTFF for DUT 9 with Antenna D of 1.89 to 21.84 seconds occurs for an interfering signal power level in the range of 3.5 to -2.7 dBm/10 MHz taking into account measurement uncertainty, which generally corresponds to an interfering signal level that causes a C/N_0 degradation in the range of 3 dB to 5 dB.

Table B.10 and Table B.11, summarize the TTFR measurements for interfering signals in the 1526-1536 and 1627.5-1637.5 MHz bands.

Table B.10. Summary of NASCTN TTFR Measurements Interfering Signal in 1526-1536 MHz Band

DUT Type	Baseline Mean TTFR (seconds)	Interfering Power Level (dBm/10 MHz) (± Measurement Uncertainty)	Increase in Mean TTFR Compared to Baseline (seconds)	Interfering Power Level (dBm/10 MHz) C/N_0 Degradation 1 dB	3 dB	5 dB
DUT 1 GLN	5.3	2.4 ± 3.1	-1.2	3	3	3
DUT 2 GLN	3.4	0.8 ± 3.1	1.4	-3	3	3
DUT 3 GLN	3.4	2.8 ± 3.1	0.5	-3	3	3

Table B.11. Summary of NASCTN TTFR Measurements Interfering Signal in 1627.5-1637.5 MHz Band

DUT Type	Baseline Mean TTFR (seconds)	Interfering Power Level (dBm/10 MHz) (± Measurement Uncertainty)	Increase in Mean TTFR Compared to Baseline (seconds)	Interfering Power Level (dBm/10 MHz) C/N_0 Degradation 1 dB	3 dB	5 dB
DUT 1 GLN	5.3	-12.7 ± 2.7	2.3	-16	-11	-9
DUT 2 GLN	3.4	-12.9 ± 2.7	2.0	-15	-11	-8
DUT 3 GLN	3.4	-15.3 ± 2.7	8.8	-20	-15	-15

All of the TTFR measurements for GLN receivers were performed at a single interfering signal power level. There were no significant increases in the mean TTFR as compared to the baseline mean TTFR. In general, there is minimal impact on the C/N_0 for the GLN receivers measured. This is consistent with measurements performed in the other test programs.

B.5 SUMMARY

Time to first fix, time-to first reacquisition, acquisition, and reacquisition are time consuming tests as evidenced by the data sets produced and presented in these three measurement programs. Given the limited number of receivers, and disparity of the data sets, any conclusions are general and may not be based on a statistically significant data set for comparison. Based on an evaluation of the acquisition and reacquisition measurements performed in the DOT ABC, R&A, and NASCTN test programs, the following general observations were made:

- For GPS receivers where there is no impact to the signal acquisition mode there is also no degradation in the tracking mode C/N_0; and
- A range of interfering signal power levels generally corresponding to a 1 dB to 5 dB degradation in C/N_0 can be correlated with signal acquisition/reacquisition time impacts.

APPENDIX C
ANTENNA FILTER SELECTIVITY IMPACT ON MEASURED INTERFERENCE POWER LEVELS

C.1 INTRODUCTION

This appendix summarizes the results of the Technical Focus Group (TFG)'s analysis of the correlation between the GPS receivers' antenna spectral characteristics and the receivers' performance amid interference from signals in the adjacent frequency bands.

Antennas are usually designed with a specific frequency, and their performance characteristics, such as gain and radiation pattern, are generally associated with that specific frequency. These characteristics change, generally deteriorate, as the operating frequency deviates from the specified frequency. The frequency range within which the performance characteristics maintain a certain level with respect to the specified performance characteristics, (e.g., 90 percent), is referred to as the antenna bandwidth. The antenna becomes a poor transmitter or receiver when a radio signal's frequency band is offset spectrally from the antenna bandwidth.

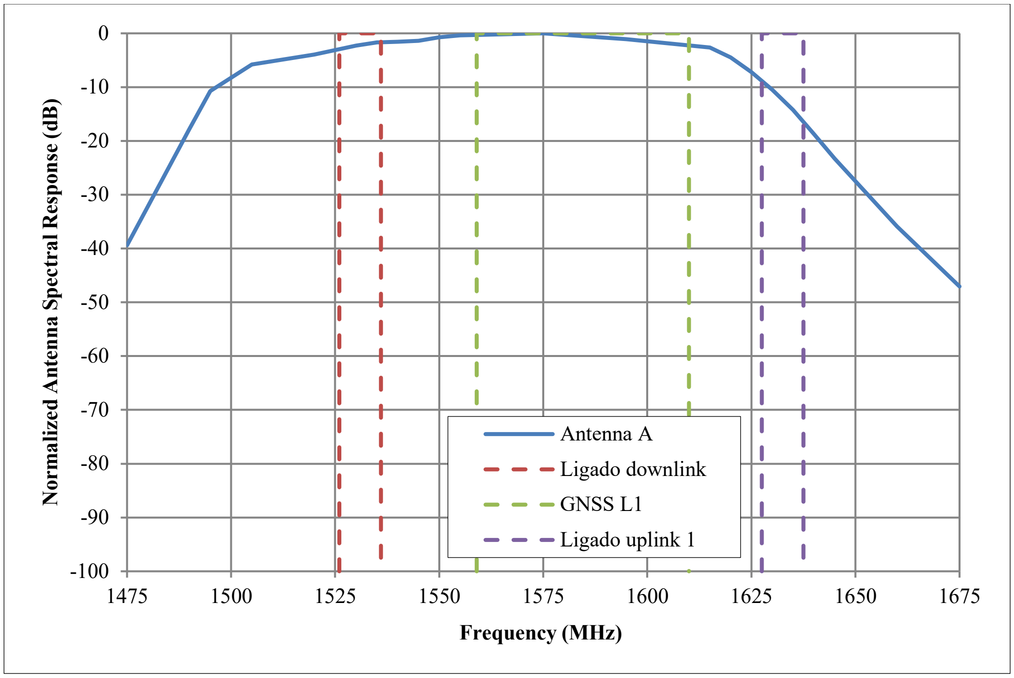
Different types and shapes of antennas, for example, wire or aperture antenna have different spectral characteristics. For instance in general, wire antennas are narrow bandwidth antennas and aperture antennas are wide bandwidth antennas. Therefore, when necessary, antennas can be designed with special physical shapes to achieve the desired frequency bandwidths.

The analysis first shows the antenna spectral characteristics overlaid with the Ligado downlink band in 1526-1536 MHz, the GNSS L1 band in 1559-1610 MHz, and the Ligado uplink 1 band in 1627.5-1637.5 MHz. Such a plot can be used to illustrate the receiver's sensitivity to interference from base stations and user equipment operating in the adjacent bands. The analysis then lists, the receivers using these antennas, and the measured interfering signal power level causing a 1 dB degradation in carrier-to-noise-density ratio (C/N_0). Finally, the interfering signal power data are compared with the spectral characteristics to evaluate the correlation.

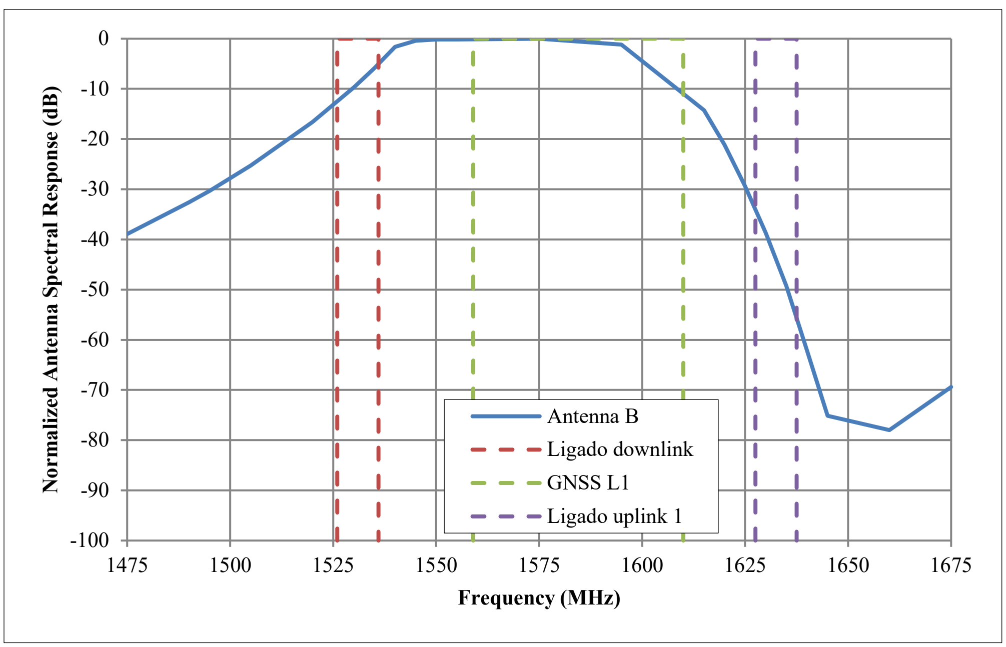
The measurement data from Department of Transportation (DOT), Roberson and Associates (R&A), and National Advanced Spectrum and Communications Test Network (NASCTN) are used in this analysis.

C.2 DOT MEASUREMENTS

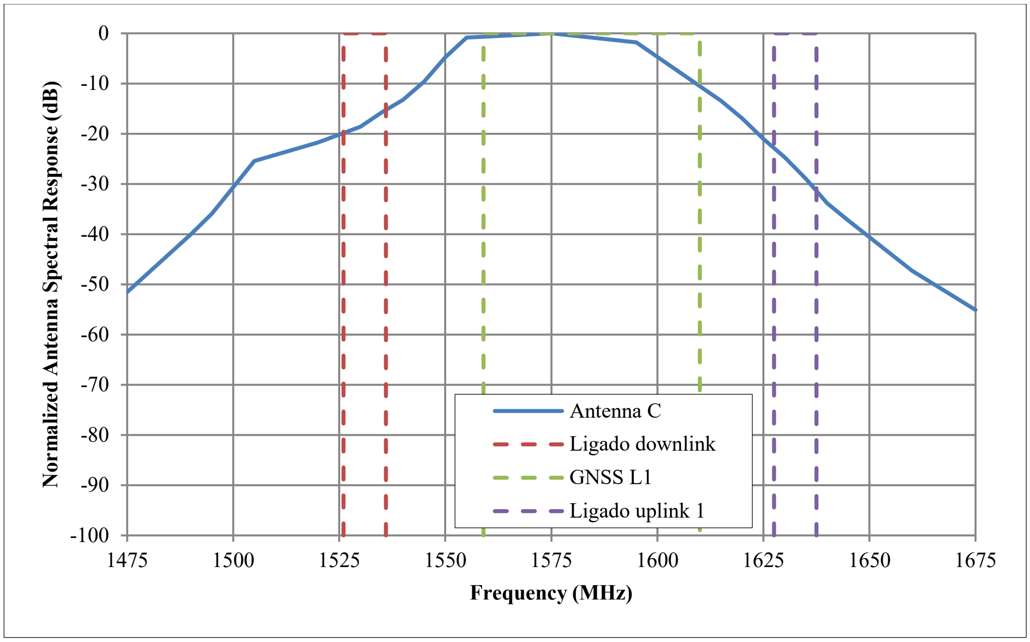
DOT provided the National Telecommunications and Information Administration (NTIA) several antenna spectral characteristics, and five antennas are used in this analysis. The spectral characteristics of these antennas are shown in Figure C.1. The plots are sequenced from the most to the least overlap between the antenna spectral characteristics and the 1526-1536 MHz downlink band.



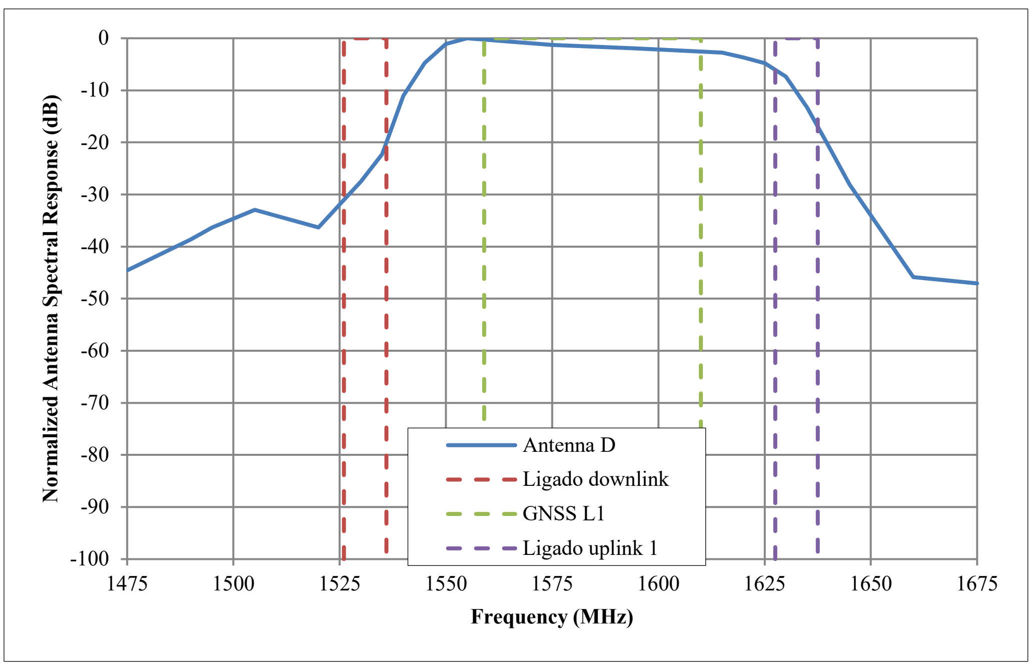
(a) Antenna A Used With DUT 37



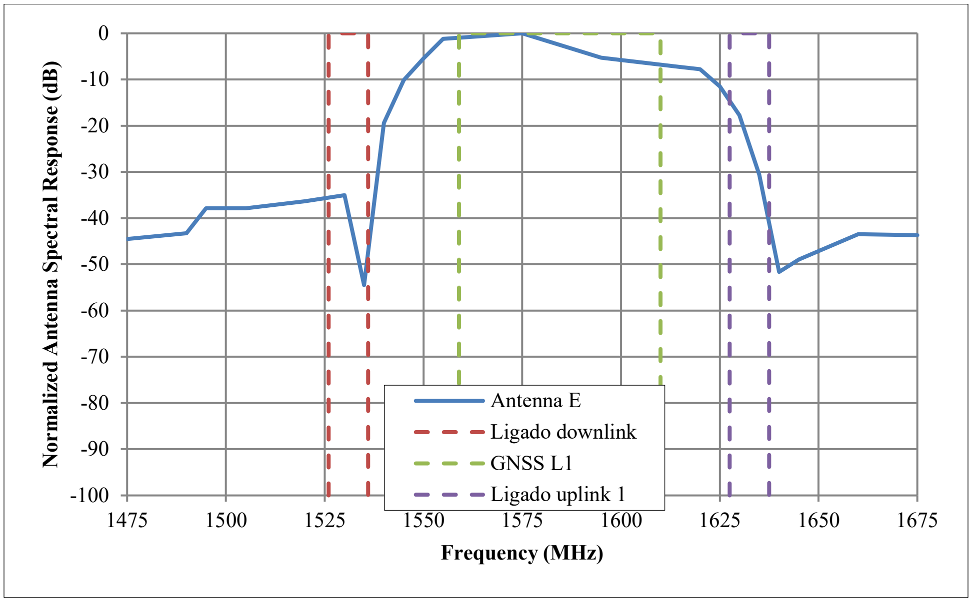
(b) Antenna B Used With DUTs 24, 25, 28, 29, 30, 31, 32, 33, 34, 35, 36



(c) Antenna C Used With DUT 20



(d) Antenna D Used With DUT 16



(e) Antenna E Used by DUT 47

Figure C.1. DOT Measurement Antenna Spectral Characteristics

The interfering signal power levels that cause a 1 Decibel (dB) reduction in C/N_0 for the receivers using these antennas are listed in Table C.1; the listing is sequenced the same as that in Figure C.1. Examining the data in the column for the interfering signal in the 1526-1536 MHz band, except for Device Under Test (DUT) 28 and 31, there is strong correlation between the interfering signal power and the degree of overlap between the antenna's spectral characteristics and the downlink band.

Table C.1. DOT Measurement Interfering Signal Power Level Causing a 1 dB Reduction in C/N_0

DUT	Receiver Category	Antenna Identifier	Measured Interfering Signal Power Level Causing 1 dB Reduction in C/N_0 (dBm/10 MHz)	
			Interfering Signal in the 1526-1536 MHz Band	Interfering Signal in the 1627.5-1637.5 MHz Band
37	High Precision Receiver Category (HP)	A	-41	-35
24	General Aviation Receiver Category (GAV)	B	-32	-18
25	GAV	B	-32	-18
28	GAV, General Location/Navigation Receiver Category (GLN)	B	-55	-20
29	GAV, GLN	B	-31	-20
30	GAV, GLN	B	-30	-19
31	GAV, GLN	B	-57	-20
32	GAV, GLN, TIM	B	-31	-25
33	GAV, GLN	B	-34	-25
34	GAV, GLN	B	-34	-20
35	GLN	B	-30	-25
36	GLN	B	-32	-20
20	HP	C	-24	-18
16	HP	D	-24	-34
47	GLN	E	-10	-31

C.3 R&A MEASUREMENTS

The R&A report provided antenna types for some of its receivers, but it did not provide antenna spectral characteristics for any of its receivers. NTIA conducted a search of publicly available information on those antennas, and found spectral characteristics for one antenna. This antenna is Javad GrAnt with J-shield filter, model G3-JS or G3T-JS, and its spectral characteristic is shown in Figure C.2.[1] It should be noted that the R&A data file only provided the general model name "Javad HP" without more specification, therefore the spectral characteristics in Figure C.2 may not be representative of what was used in the interference measurements.

[1] The antenna spectral characteristic for the Javad HP antenna considered in this analysis is available at http://download.javad.com/sheets/GrAnt_Datasheet.pdf.

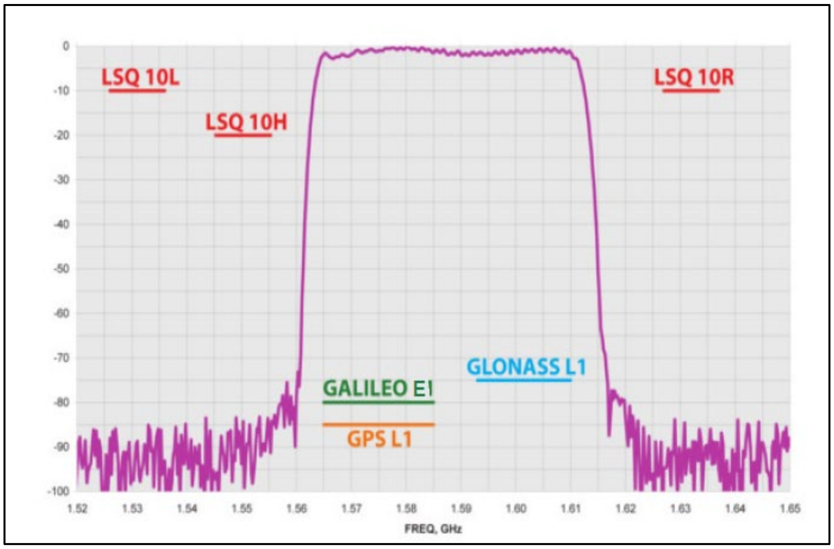


Figure C.2. R&A Measurement Antenna Spectral Characteristic

The interfering signal power levels that cause a 1 dB reduction in C/N_0 for the receivers using this antenna are shown in Table C.2. It is evident from the antenna's spectral characteristics that the receivers have strong performance, approximately 80 dB of rejection, in the presence of interference from signals in the downlink and uplink bands.

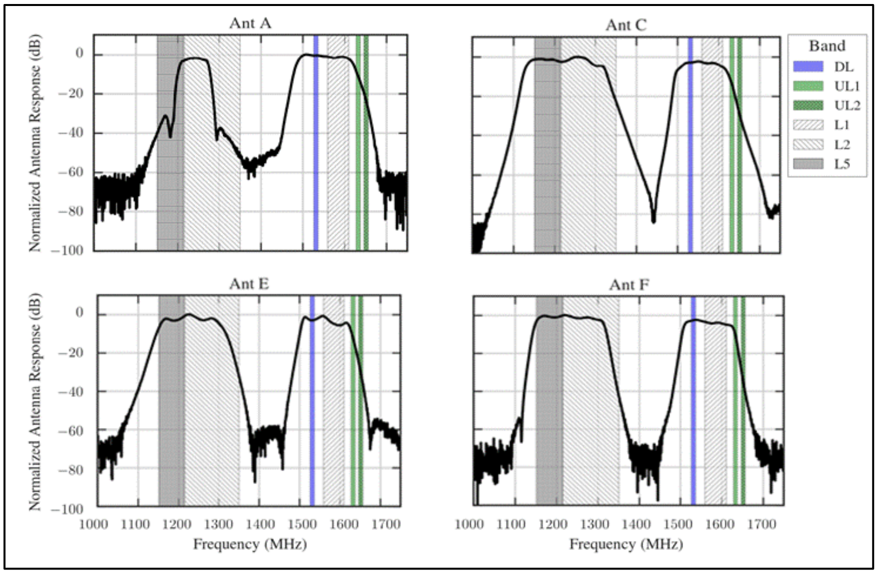
Table C.2. R&A Measurement Interfering Signal Power Level Causing a 1 dB Reduction in C/N_0

Receiver	Receiver Category	Antenna Identifier	Measured Interfering Signal Power Level Causing 1 dB Reduction in C/N_0 (dBm/10 MHz)	
			Interfering Signal in the 1526-1536 MHz Band	Interfering Signal in the 1627.5-1637.5 MHz Band
Trimble AgGPS 542	HP	Javad	-10	-10
Trimble SPS855	HP	Javad	-10	-10

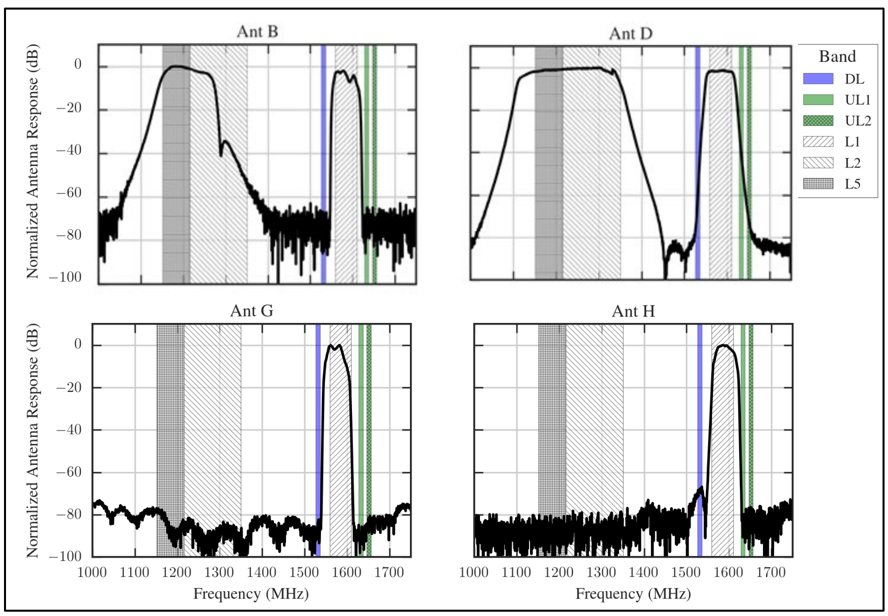
C.4 NASCTN MEASUREMENTS

NASCTN provided spectral characteristics for eight antennas shown in Figure C.3.[2] The plots in Figure C.3(a) show that antennas A, C, E, and F have wider spectral characteristics. The plots in Figure C.3(b) show that antennas B, D, G, and H have narrower spectral characteristics. In the NASCTN measurements several DUTs were tested with antennas that have wider and narrower spectral characteristics to evaluate how the antenna spectral characteristics may affect the receiver performance in the presence of interference.

[2] *NIST Technical Note 1952*, Figure 6.2 on p. 122 and Figure 6.3 on p. 123.



(a) Antennas A, C, E, F - Wider Spectral Masks Around GPS L1 Band



(b) Antennas B, D, G, H - Narrower Spectral Masks Around GPS L1 Band

Figure C.3. NASCTN Measurement Antenna Spectral Characteristics

The interfering signal power levels that cause a 1 dB reduction in C/N_0 for the receivers using these antennas are listed in Table C.3. The listing is sequenced the same as that shown in Figure C.3. Comparing the plots Figure C.3 with the values in Table C.3, it is clear that receivers with antennas of wider spectral characteristics provide less attenuation, and thus are more sensitive, to the interfering signals.

Table C.3. NASCTN Measurement Interfering Signal Power Level Causing a 1 dB Reduction in C/N_0

DUT	Receiver Category	Antenna Identifier	Measured Interfering Signal Power Level Causing 1 dB Reduction in C/N_0 (dBm/10 MHz)[a]	
			Interfering Signal in the 1526-1536 MHz Band	Interfering Signal in the 1627.5-1637.5 MHz Band
8	HP	A	-67	-54
11	RTK Rover	A	-67	-53
9	HP	C	-49	-48
12	RTK Rover	C	-52	-50
7	HP	E	-67	-44
10	HP	F	-64	-54
11	RTK Rover	B	3	-21
9	HP	D	2	-32
12	RTK Rover	D	1	-30
15	GPSDO	H	1	-15
Note A: The measured interference power levels have a standard deviation of ± 1 dB.[3]				

By examining several DUTs being tested with two types of antennas, for example for DUT 9 with antennas C and D and the interfering signal in the 1526-1536 MHz band, the interfering signal received by antenna C is through the antenna's spectral main band, while the signal received by antenna D is through the lower edge of the skirt of its spectral main band. The difference is approximately 50 dB, thus explaining the difference in the interfering signal levels that cause a 1 dB degradation in C/N_0. Similarly for DUT 11 with antennas A and B and the interfering signal in the 1526-1536 MHz band, the spectral response of antenna A overlaps with the interfering signal while the spectral response of antenna B does not. The difference is approximately 70 dB, thus explaining the difference in the interfering signal levels that cause a 1 dB degradation in C/N_0.

C.5 SUMMARY

Based on the available data, the antenna spectral characteristics can have a significant effect on the receiver's performance in the presence of adjacent band interfering signals.

It should be noted that the data presented in this appendix does not address the impacts on GPS receiver performance (e.g., position accuracy) when an antenna with a filter of greater selectivity is employed.[4] This analysis does not address the impact of these antennas on mobile-satellite service (MSS) augmented GPS receivers whose performance depends on the reception of MSS signals. Furthermore, this analysis does not consider the cost of such a modification, or

[3] *NIST Technical Note 1952*, Section 3.6.2.1.

[4] The impacts include: more insertion loss, more distortion of signal phase versus frequency, more variations of pseudorange and phase versus temperature (vital for timing receivers), higher system noise, and less capability for advanced techniques such as onboard multipath reduction.

viability in terms of size (e.g., for aircraft platforms) or accessibility (e.g.., for space platforms or already fielded receivers).

The variability of the antenna filtering, the low noise amplifier gain, and the 1 dB gain compression point for active antennas are additional factors that complicate the selection of an allowable C/N_0 degradation to protect for the different categories of GPS receivers.

The analysis finds that the receivers' response to interference from signals in the adjacent bands is closely correlated to its antenna spectral characteristics.

APPENDIX D
POSITION ERROR DISTRIBUTION AS A MEASURAND FOR ASSESSING INTERFERENCE EFFECTS

D.1 INTRODUCTION

This appendix summarizes the results of the Technical Focus Group (TFG)'s analysis of a suitable performance measure to represent the position error distribution for assessing the interference effect. The statistical analysis suggests that the mean of the distribution is not a good indicator for the distribution because it does not reflect the change of the distribution when carrier-to-noise density ratio (C/N_0) degrades. The statistical analysis also suggests there is a correlation between the standard deviation (sigma) of the distribution and the degradation of C/N_0 (the estimated signal power received by a Global Positioning System (GPS) receiver).

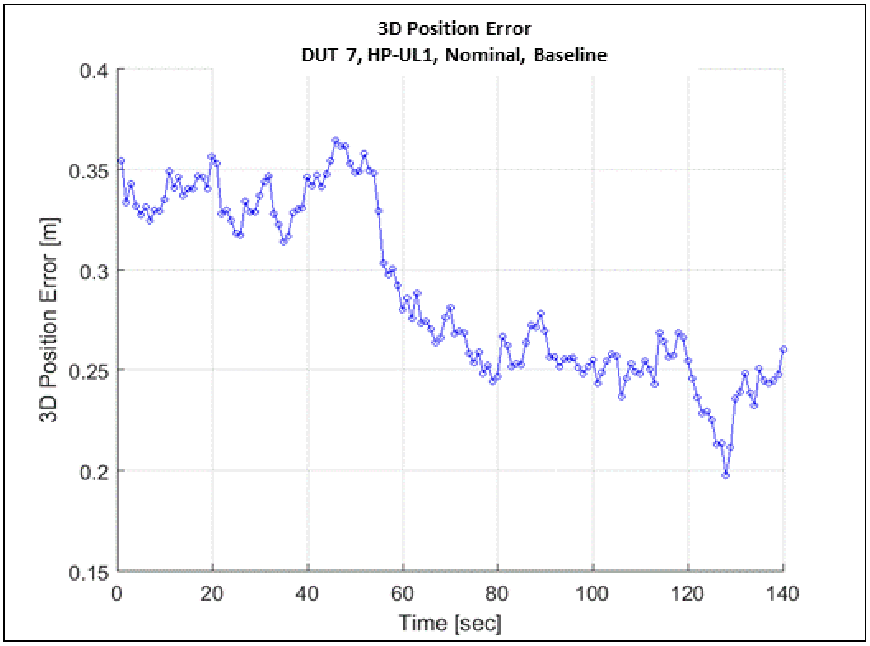
The National Advanced Spectrum and Communications Test Network (NASCTN) performed position error measurements with the GPS receivers of the general location/navigation (GLN), high precision (HP), and real time kinematic (RTK) categories. Measurements were performed with the Long Term Evolution (LTE) interfering signals in the 1526-1536 (DL), 1627.5-1637.5 (UL1), and 1646.5-1656.5 MHz (UL2) bands. Roberson and Associates (R&A) also performed position error measurements with the GPS receivers of the GLN, HP, and general aviation (GAV) categories. Measurements were performed with the LTE interfering signals in the DL, UL1, and UL2 bands.

The C/N_0 and position error data in the NASCTN and R&A reports was analyzed. In plotting the collection of the C/N_0 and position error data as a function of the interfering signal power, it was observed that the data distribution in the plot expands as the interfering signal power increases. It was also observed that the mean value of the data distribution remains stable as the distribution expands. Based on the data analyzed in this appendix, the data distribution represents the probability function of the position error, and should be used to assess potential interference effects on GPS receiver performance.

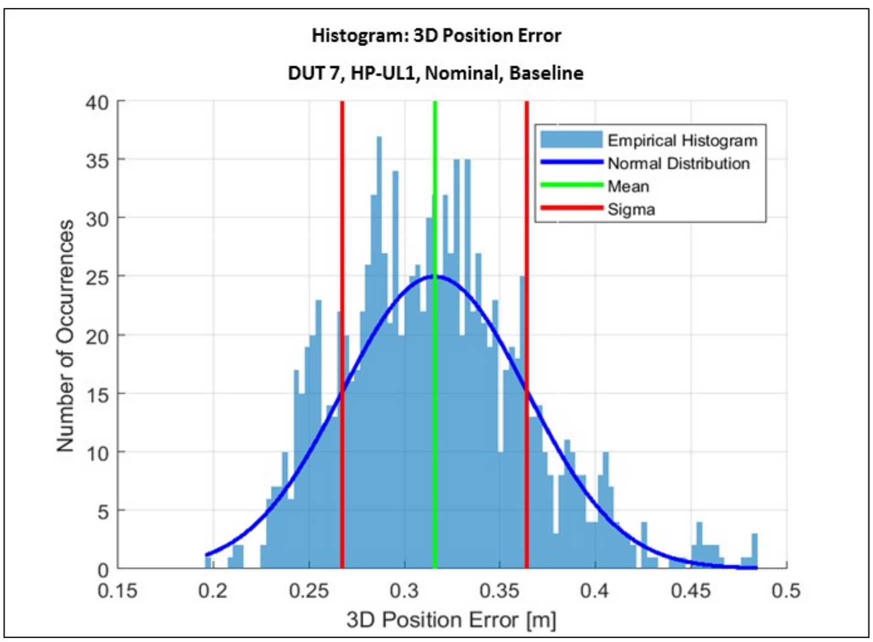
D.2 EXAMINATION OF C/N_0 AND POSITION ERROR

A GPS receiver measures pseudorange and/or phase. Pseudorange is the time difference between the receiver clock at the time of reception and the satellite clock at the time of transmission multiplied by the speed of light. This time difference is the sum of the offset between the satellite clock and the receiver clock and the transit time. To determine the receiver's location, it requires four pseudoranges to solve for three position coordinates and the clock bias at a single epoch of data, with the clock bias data used to calibrate the receiver clock.

In the NASCTN measurement report, the position error is the difference between the position truth data from the simulator and the position data reported from the GPS receiver. To explore the probabilistic nature of the position error, a portion (140 seconds out of 1200 seconds measurement time period) of the NASCTN Device Under Test (DUT) 7 baseline (no LTE signal) 3-D position error data is presented in Figure D.1(a), and the histogram of this measurement data is shown in Figure D.1(b). In Figure D.1(b), the light blue lines are the histogram showing the data distribution, the dark blue curve is the curve fit of a theoretical normal distribution, the green line is the mean of the normal distribution, and the red lines are the standard deviations (sigma) of the normal distribution.



(a) Partial Measured Data

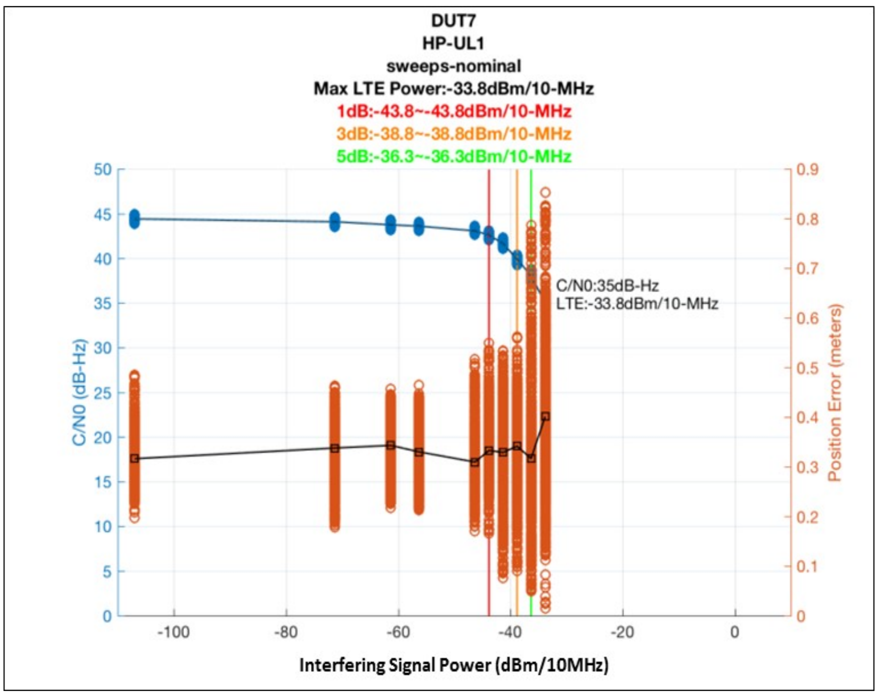


(b) Histogram

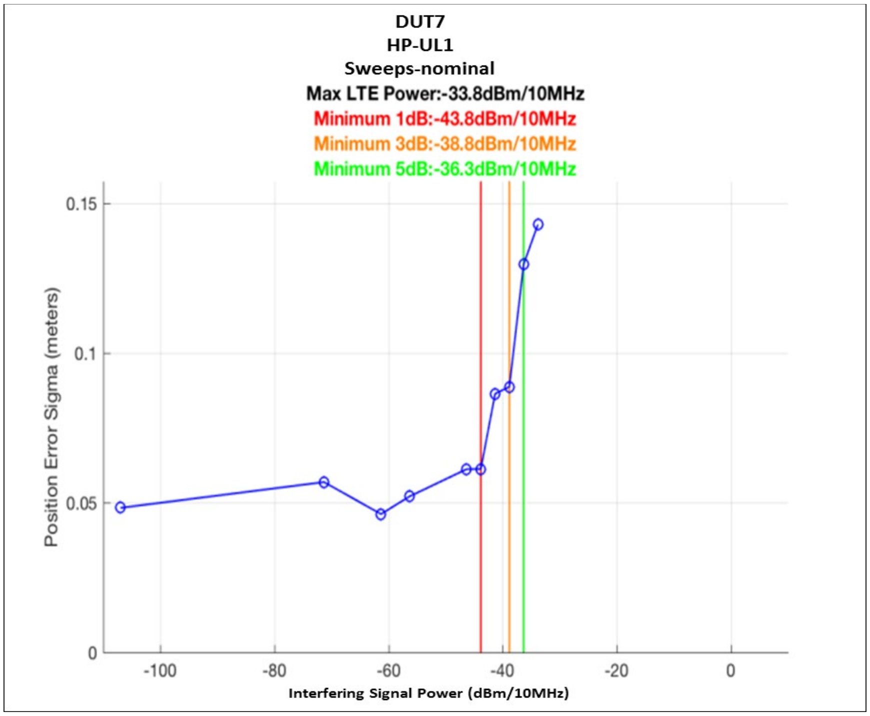
Figure D.1. 3-D Position Error of NASCTN DUT 7 Baseline Measurement

The histogram in Figure D.1(b) can be viewed as the probability distribution of the 3-D position error. In this example, the mean value is approximately 0.32 meters, the sigma line indicates that it is highly probable that the error may reach 0.37 meters, and the tail of the distribution is approximately 0.46 meters which is about one-and-half times the mean value. Since the realistic position error may be any value within the distribution, using the mean data may grossly misrepresent the real position.

To investigate how the mean and sigma of the position error distribution vary as a function of the interfering signal power level, the C/N_0 and 3-D position error distribution of DUT 7 when the interfering LTE signal is in the UL1 band is shown in Figure D.2(a), and the corresponding sigma of the 3-D position error distribution is shown in Figure D.2(b). The baseline measurement data when there is no interfering signal is placed at LTE power level of -107 dBm/10 MHz for comparison. It can be seen that the 3-D position error distribution starts to increase when the interfering signal power is larger than -40 dBm/10 MHz, while the center of the distribution remains relatively constant throughout the measurement.



(a) C/N_0 and 3-D Position Error Distribution



(b) Sigma of 3-D Position Error Distribution

Figure D.2. C/N$_0$ and 3-D Position Error Distribution of NASCTN DUT 7 Interfering Signal in UL1 Band

The parametric values in Figure D.2 are presented in Table D.1 together with the percentage of increase from the baseline. The shaded cells in the tables indicate when the mean and sigma begin to diverge significantly.

Table D.1. 3-D Position Error Distribution of NASCTN DUT 7 Interfering Signal in UL1 Band

Interfering Signal Power (dBm/10 MHz)	C/N$_0$		3-D Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
none	44.4	Baseline	0.316	Baseline	0.048	Baseline
-71.3	44.1	0.3	0.338	6.8%	0.057	17.8%
-61.3	43.7	0.7	0.343	8.5%	0.046	-4.3%
-56.3	43.6	0.8	0.330	4.4%	0.052	7.9%
-46.3	43.1	1.3	0.309	-2.1%	0.061	26.8%
-43.8	42.6	1.8	0.333	5.3%	0.061	27.0%
-41.3	41.6	2.8	0.329	4.0%	0.086	79.0%
-38.8	39.9	4.5	0.341	8.0%	0.089	83.8%
-36.3	38.1	6.3	0.316	0.1%	0.130	168.6%
-33.8	35.0	9.4	0.401	26.8%	0.143	196.1%

With the information in Figure D.2 and Table D.1, the C/N$_0$ and mean and sigma of the 3-D position error are compared to explore their correlation. From Table D.1, the increases of mean and sigma as a function of C/N$_0$ degradation is plotted in Figure D.3. In Figure D.3, it can be seen that the change of mean is insensitive to C/N_0 degradation, but the increase of sigma follows the trend of C/N_0 degradation. Compared to the mean, the sigma appears to be a better representation of how the position error distribution function responds to C/N_0 degradation, and thus represents a suitable performance index for assessing potential interference effects.

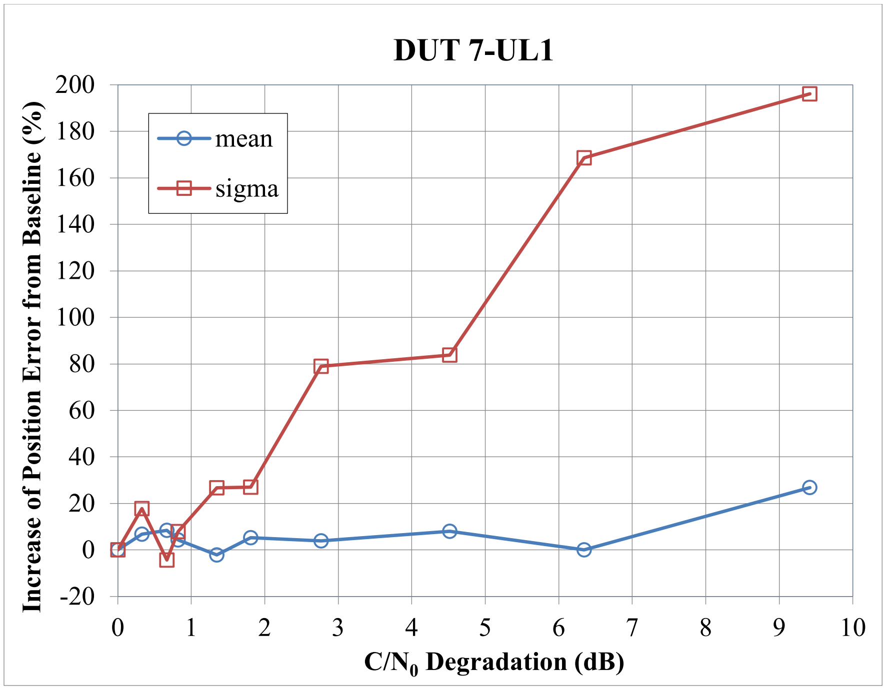


Figure D.3. Increase of Mean and Sigma of 3-D Position Error as a Function of C/N_0 Degradation for NASCTN DUT 7 Interfering Signal in UL1 Band

D.3 SUMMARY AND ANALYSIS OF C/N_0 AND POSITION ERROR DISTRIBUTION

The complete set of plots and the parametric values of the analysis of C/N_0 and position error distribution for the NASCTN and R&A measurements are presented in Addendum A and Addendum B of this appendix.

The analysis in Addendum A of the NASCTN measurement data does not include the RTK receiver category. The position data being reported from a RTK receiver has been corrected with the reference base station position data that reduces its position error on the order of 0.1 meter to 0.1 millimeter. The correction breaks the correlation between the pseudorange and the position. As a result, the correlation between the position error and the C/N_0 dissolves, thus making it irrelevant to this evaluation. From Addendum A, the interfering signal power and its corresponding C/N_0 and C/N_0 degradation when the mean and sigma show significant degradation are compared in Table D.2, and the C/N_0 degradations where the position error sigma significantly deviates from the mean are shown in Table D.3.

Table D.2. NASCTN Measurement Threshold Interfering Signal Power, C/N_0, and C/N_0 Degradation Where Mean and Sigma Show Significant Degradation

(a) GLN Receiver Category

Interfering Signal Frequency Band	DUT	Threshold for Mean			Threshold for Sigma		
		LTE Power (dBm/10 MHz)	C/N_0 Mean (dB-Hz)	C/N_0 Degra-dation (dB)	LTE Power (dBm/10 MHz)	C/N_0 Mean (dB-Hz)	C/N_0 Degra-dation (dB)
DL	DUT 2	> 3.0	< 39.0	> 4.0	1.2	40.1	2.9
	DUT 4	> -8	< 35.8	> 4.6	-9.3	37.9	2.5
UL1	DUT 1	-6.3	33.0	8.0	-11.3	36.3	4.7
	DUT 2	> -6.6	< 35.0	> 8.1	-6.6	35.0	8.1
	DUT 3	-15.4	37.0	4.2	> -15.4	< 37.0	> 4.2
	DUT 4	-20.1	23.7	18.3	-22.5	30.2	11.8
UL2	DUT 1	> -6.3	< 32.0	> 8.9	-7.7	34.0	6.9
	DUT 2	> -6.4	< 34.0	> 6.0	-9.6	37.0	3.0
	DUT 3	-7	33.9	7.1	-9.5	36.9	4.1

DL DUT1 and DUT3 cases were not analyzed because of insignificant C/N_0 degradation.
">" & "<": indicates mean or sigma does not degrade at the maximum LTE power.

(b) HP Receiver Category

Interfering Signal Frequency Band	DUT	Threshold for Mean			Threshold for Sigma		
		LTE Power (dBm/10 MHz)	C/N_0 Mean (dB-Hz)	C/N_0 Degra-dation (dB)	LTE Power (dBm/10 MHz)	C/N_0 Mean (dB-Hz)	C/N_0 Degra-dation (dB)
DL	DUT 7	-41.4	36.9	8.9	-58.3	42.5	3.3
	DUT 8	-54.2	32.0	15.1	-64.2	42.6	4.5
	DUT 9 Antenna C	> -41.8	< 33.8	> 10.6	-44.6	36.1	8.3
	DUT 9 Antenna D	> 2.2	< 31.7	> 10.8	2.2	31.7	10.8
	DUT 10	-64.4	46.0	2.0	-64.4	46.0	2.0
UL1	DUT 7	-33.8	35.0	9.4	-41.3	41.6	2.8
	DUT 8	-38.8	33.1	14.8	-46.3	41.8	6.1
	DUT 9 Antenna C	-37.1	32.0	12.5	-39.9	35.8	8.6
	DUT 9 Antenna D	-20.6	31.7	12.2	-20.6	31.7	12.2
	DUT 10	-45.4	44.8	3.2	-45.4	44.8	3.2
UL2	DUT 7	> -29.5	< 37.1	> 8.7	-32.8	41.0	4.8
	DUT 8	> -27.7	< 31.9	> 15.0	-35.7	44.1	2.8
	DUT 9 Antenna C	> -33.5	< 34.3	> 10.1	-33.5	34.3	10.1
	DUT 9 Antenna D	-18.3	33.4	10.5	-20.0	35.3	8.7
	DUT 10	-38.3	42.2	5.8	-38.3	42.2	5.8

">" & "<": indicates mean or sigma does not degrade at the maximum LTE power.

Table D.3. NASCTN Measurement C/N_0 Degradation Values Where Position Error Distribution Sigma Deviates from Mean

(a) GLN Receiver Category

DUT Identifier	Interfering Signal Frequency Band	C/N_0 Degradation (dB)
DUT 2	DL	2.9
DUT 4	DL	2.5
DUT 1	UL 1	4.7
DUT 2	UL 1	8.1
DUT 3	UL 1	No significant deviation
DUT 4	UL 1	11.8
DUT 1	UL 2	6.9
DUT 2	UL 2	3.0
DUT 3	UL 2	4.1
DL DUT1 and DUT3 cases were not analyzed because of insignificant C/N_0 degradation.		

(b) HP Receiver Category

DUT Identifier	Interfering Signal Frequency Band	C/N_0 Degradation (dB)
DUT 7	DL	3.3
DUT 8	DL	4.5
DUT 9 Antenna C	DL	8.3
DUT 9 Antenna D	DL	10.8
DUT 10	DL	No significant deviation
DUT 7	UL 1	2.8
DUT 8	UL 1	6.1
DUT 9 Antenna C	UL 1	8.6
DUT 9 Antenna D	UL 1	12.2
DUT 10	UL 1	No significant deviation
DUT 7	UL 2	4.8
DUT 8	UL 2	2.8
DUT 9 Antenna C	UL 2	10.1
DUT 9 Antenna D	UL 2	8.7
DUT 10	UL 2	No significant deviation

The measurement cases being analyzed in Addendum B of the R&A measurement data are only a small portion of the overall cases. Only 12 out of 76 cases show both C/N_0 and position error distribution degradations. Since the analysis is to examine the position error distribution degradation and its correlation with the C/N_0 degradation, only the cases with both C/N_0 and position error distribution degradations are examined. Also, the analysis does not include the live sky scenario. In the live sky scenario, the position is derived from pseudorange of various C/N_0 levels. In this situation, it is difficult to correlate the position error with the C/N_0 level. From Addendum B, the interfering signal power and its corresponding C/N_0 and C/N_0 degradation when the mean and sigma show significant degradation are compared in Table D.4 for the GLN and HP receivers, and the C/N_0 degradations where the position error distribution sigma significantly deviates from the mean are shown in Table D.5 for the GLN and HP receivers. All receivers in the GAV category have virtually no change in C/N_0 for all LTE power levels and thus no C/N_0 degradation; therefore, they are not presented.

Table D.4. R&A Measurement Threshold Interfering Signal Power, C/N_0, and C/N_0 Degradation Where Mean and Sigma Show Significant Degradation

(a) GLN Receiver Category

Interfering Signal Frequency Band	**DUT**	**Threshold for Mean**			**Threshold for Sigma**		
		LTE Power (dBm/10 MHz)	**C/N_0 Mean (dB-Hz)**	**C/N_0 Degradation (dB)**	**LTE Power (dBm/10 MHz)**	**C/N_0 Mean (dB-Hz)**	**C/N_0 Degradation (dB)**
UL 1	Garmin eTrex H under open sky with motion	-14	32.0	8.0	-14	32.0	8.0
	Garmin eTrex H under impaired GPS signal with motion	-28	25.6	3.0	-28	25.6	3.0
UL 2	Garmin eTrex H under impaired GPS signal with motion	-18	26.4	2.5	-22	26.8	2.0

(b) HP Receiver Category

Interfering Signal Frequency Band	DUT	Threshold for Mean			Threshold for Sigma		
		LTE Power (dBm/10 MHz)	C/N_0 Mean (dB-Hz)	C/N_0 Degradation (dB)	LTE Power (dBm/10 MHz)	C/N_0 Mean (dB-Hz)	C/N_0 Degradation (dB)
DL	Novatel Smart6-L	-50	29.8	14.4	-60	40.0	4.1
	Topcon System 310	-32	37.5	6.7	-36	42.1	2.1
	Trimble AgGPS 542 with Zephyr Antenna	-32	27.2	18.3	-36	31.9	13.7
	Trimble Geo 7X	> -10	< 35.1	> 5.9	-12	37.0	3.9
	Trimble SPS855 with GA530 Antenna	-34	25.8	19.8	-45	41.2	4.3
UL 1	Novatel Smart6-L	-30	34.9	9.0	-38	39.6	4.3
	Trimble AgGPS 542 with Zephyr Antenna	-36	28.3	16.2	-38	32.0	12.5
	Trimble SPS985	-10	28.3	16.9	-18	42.5	2.8

Table D.5. R&A Measurement C/N_0 Degradation Values Where Position Error Distribution Sigma Deviates Significantly from Mean

(a) GLN Receiver Category

DUT	Interfering Signal Frequency Band	C/N_0 Degradation (dB)
Garmin eTrex H under open sky with motion	UL 1	No significant deviation
Garmin eTrex H under impaired GPS signal with motion	UL 1	No significant deviation
Garmin eTrex H under impaired GPS signal with motion	UL 2	No significant deviation

(b) HP Receiver Category

DUT	Interfering Signal Frequency Band	C/N_0 Degradation (dB)
Novatel Smart6-L	DL	1.4
Topcon System 310	DL	2.1
Trimble AgGPS 542 with Zephyr Antenna	DL	13.7
Trimble Geo 7X	DL	3.9
Trimble SPS855 with GA530 Antenna	DL	4.3
Novatel Smart6-L	UL 1	4.3
Trimble AgGPS 542 with Zephyr Antenna	UL 1	12.5
Trimble SPS985	UL 1	2.8

As shown in Tables 2 through 5, with the exception of the GPS receivers employing external antennas with filtering capability (antennas B and D in the NASCTN measurements, Zephyr antenna in the R&A measurement, see Appendix C) the interference power corresponding to the sigma of the position error distribution is lower than the interference power corresponding to the mean of the position error distribution. In general, the interfering signal power where the sigma of the position error distribution begins to diverge from the mean corresponds to C/N_0 degradations in the range of 3 dB to 5 dB.

From these plots and data, the following general patterns can be observed:

- The increase in sigma preceeds the increase in mean, and
- The change in mean is stable as the C/N_0 degradation increases, while the change in sigma increases when the C/N_0 degradation increases.

The second observation confirms the comment from the example case that the mean is not a suitable performance index to assess the interference effect because it does not reflect the change of the position error distribution. On the other hand, the sigma can reflect the change of the position error distribution as the C/N_0 degrades, thus is a more suitable performance index to assess potential interference effects.

The analysis and conclusions in this appendix is based on measurements of a limited number of GPS receivers.

ADDENDUM A NASCTN MEASUREMENT DATA

D.A.1 Introduction

This addendum presents the analysis of C/N_0 and position error distribution of the NASCTN measurements.

NASCTN performed measurements of GPS receivers in the general location/navigation (GLN), high precision (HP), and real time kinematic (RTK) categories. Measurements were performed without interfering Long Term Evolution (LTE) signal and with LTE interfering signal in the 1526-1536 MHz, 1627.5-1637.5 MHz, and 1646.5-1656.5 MHz bands.

NASCTN conducted measurements with two Global Positioning Systems (GPS) signal scenarios:

- **Nominal Scenario:** The simulator created a constellation of 11 GPS satellites in view with a received signal level of -128.5 dBm ± 2.7 dB. Two geostationary Wide Area Augmentation System (WAAS) satellites with a received signal level of -128.5 dBm ± 2.7 dB were also simulated. Signal codes being simulated include L1 C/A, L1C Pilot, Pseudo Y, and M-code.
- **Limited Exposure Scenario:** The simulator created a constellation of 8 GPS satellites with the received signal levels distributed across four values: -128.5 dBm ± 2.7 dB, -133.5 dBm ± 2.7 dB, -138.5 dBm ± 2.7 dB, and -143.5 dBm ± 2.7 dB. Two geostationary WAAS satellites with a received signal level of -128.5 dBm ± 2.7 dB were also simulated. Signal codes being simulated include L1 C/A, L1C Pilot, Pseudo Y, and M-code.

For a given LTE interfering signal and power level, the condition is maintained for 20 minutes, and 1 measurement is taken in every 1 second, resulting in 1200 data points for each measurement condition.

The analysis in this addendum only considered the data of the nominal GPS signal scenario. In the nominal scenario, the GPS signal levels are the same for all the satellites, thus making it feasible to relate GPS performance to the C/N_0 level. In the limited exposure GPS signal scenario, the position is derived from four sets of pseudorange of four C/N_0 levels. In this situation, it is difficult to attribute the position error to the pseudorange, making it difficult to correlate the position error with the C/N_0 level.

Also, the analysis in this addendum does not include the RTK receiver category. The position data being reported from a RTK receiver has been corrected with the reference base station position that reduces its position error from the order of 0.1 meter to 0.1 millimeter. The correction breaks the correlation between the pseudorange and the position error. As a result, the correlation between the position error and the C/N_0 diminishes, thus making it irrelevant to this evaluation.

The analysis for the GLN and HP receivers are presented in Sections D.A.2 and D.A.3, respectively. They are presented in graphs and tables containing the following information:

- C/N_0 distribution and its mean, and the position error distribution and its mean as a function of interfering signal power;
- Sigma of the position error distribution as a function of interfering signal power; and
- Increases (relative to the baseline) in mean and sigma of the position error distribution as a function of the C/N_0 degradation.

In the graphs, the baseline measurement data when the interfering signal is absent is placed at an LTE power level of -107 dBm/10 MHz for comparison purposes. Figures (a) and (b) also have 3 vertical lines corresponding to the interfering signal power levels that cause C/N_0 degradations of 1 dB, 3 dB, and 5 dB. Every figure is followed by a table listing the parametric values in figures (a), (b), and (c), i.e., the interfering signal power level, the mean and degradation of C/N_0, the mean and sigma of the position error distribution, and the increase in mean and sigma relative to the baseline. In several cases when the baseline data appear to be faulty, the data with the lowest interfering signal power is used as the new baseline; this is indicated in the tables and reflected in figure (c). The shaded cells in the tables indicate when the mean and sigma begin to increase significantly. In numerous cases it is a judgement call when the increase occurs, and the fluctuating situation further complicates the selection.

In several cases the C/N_0 degrades only by a small amount. Since the main task is to analyze the correlation between the C/N_0 degradation and the coresponding change in the position error distribution, these cases are not analyzed. For these cases, only a plot showing the C/N_0 distribution and the position error distribution is presented.

D.A.2 GLN Receiver Category

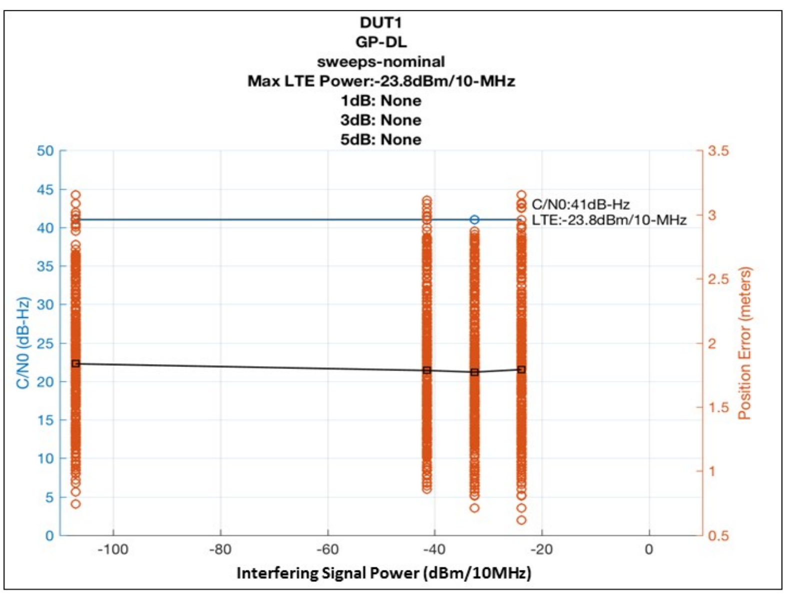
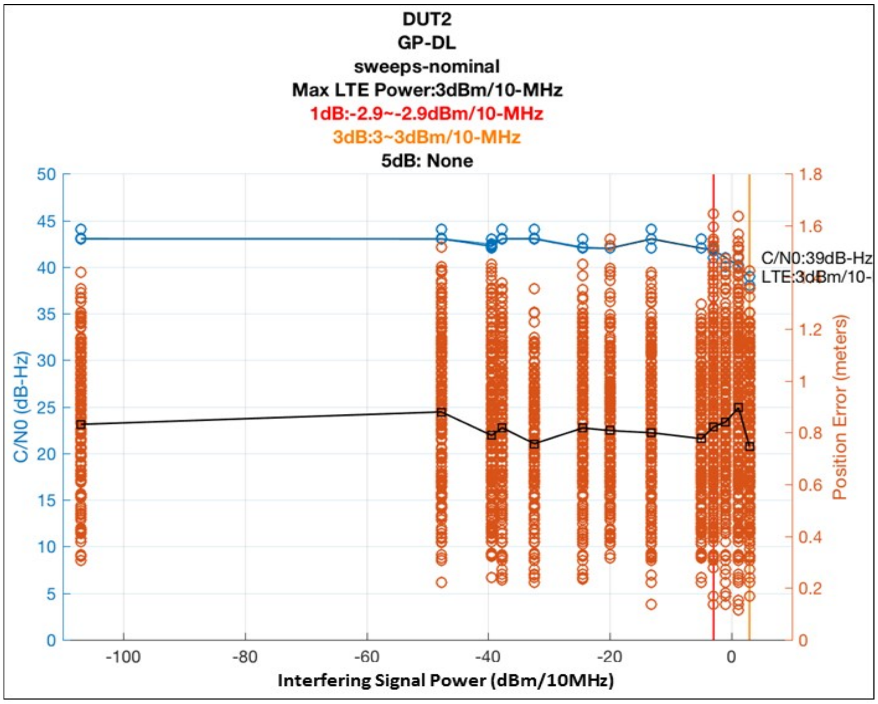
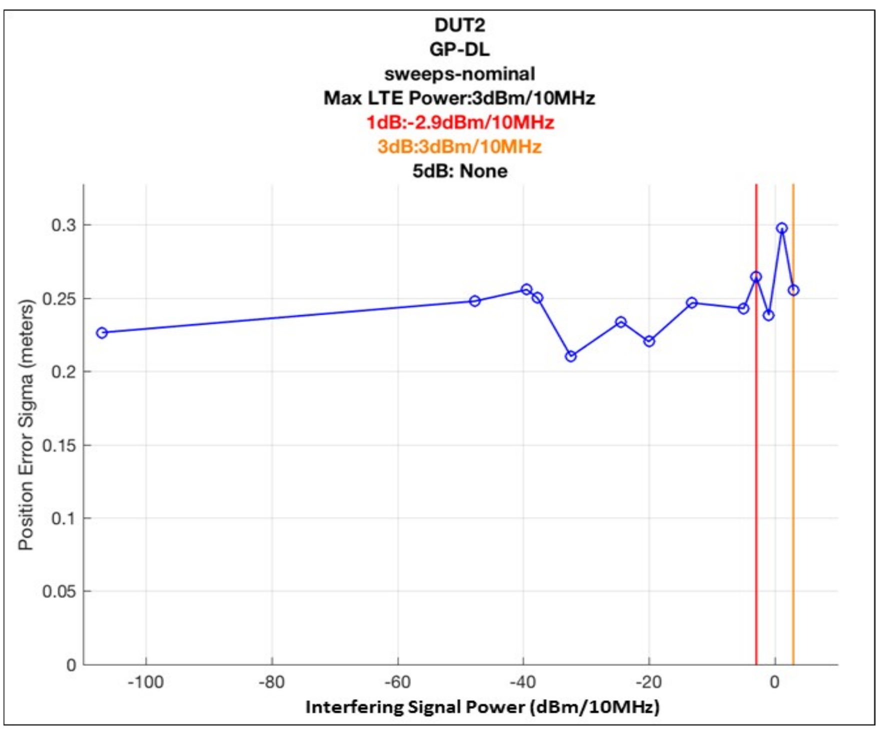


Figure D.A.2.1. C/N_0 and Position Error Distribution for GLN DUT 1 Interfering Signal in DL Band

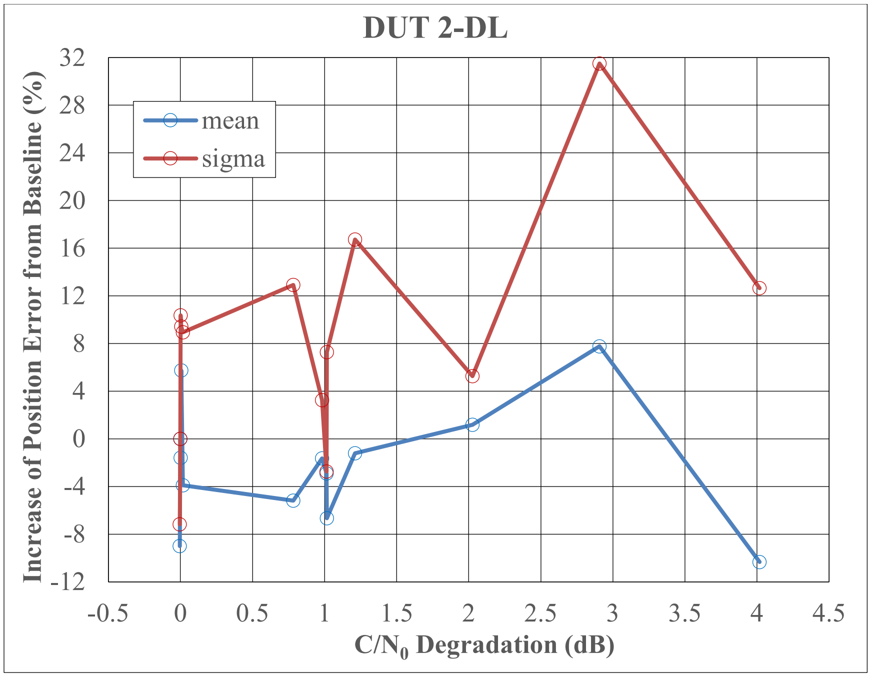
This data was not analyzed because Carrier-to-Noise Density (C/N_0) degrades by less than 1 Decibel (dB).



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution



(c) Increase of Mean and Sigma of Position Error Distribution
Figure D.A.2.2. Position Error Distribution for GLN DUT 2 Interfering Signal in DL Band

Table D.A.2.2. Position Error Distribution for GLN DUT 2 Interfering Signal in DL Band

Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-107	43.0	Baseline	0.832	Baseline	0.226	Baseline
-47.7	43.0	0.01	0.880	5.8%	0.248	9.4%
-39.4	42.2	0.78	0.789	-5.2%	0.256	12.9%
-37.7	43.0	0.00	0.819	-1.6%	0.250	10.4%
-32.4	43.0	0.00	0.757	-9.0%	0.210	-7.2%
-24.4	42.0	0.98	0.818	-1.7%	0.234	3.3%
-20.0	42.0	1.01	0.808	-2.9%	0.220	-2.7%
-13.1	43.0	0.02	0.799	-3.9%	0.247	8.9%
-4.9	42.0	1.02	0.776	-6.7%	0.243	7.3%
-2.9	41.8	1.21	0.822	-1.2%	0.264	16.7%
-0.9	41.0	2.03	0.842	1.2%	0.238	5.3%
1.2	40.1	2.91	0.896	7.8%	0.298	31.5%
3.0	39.0	4.02	0.746	-10.3%	0.255	12.6%

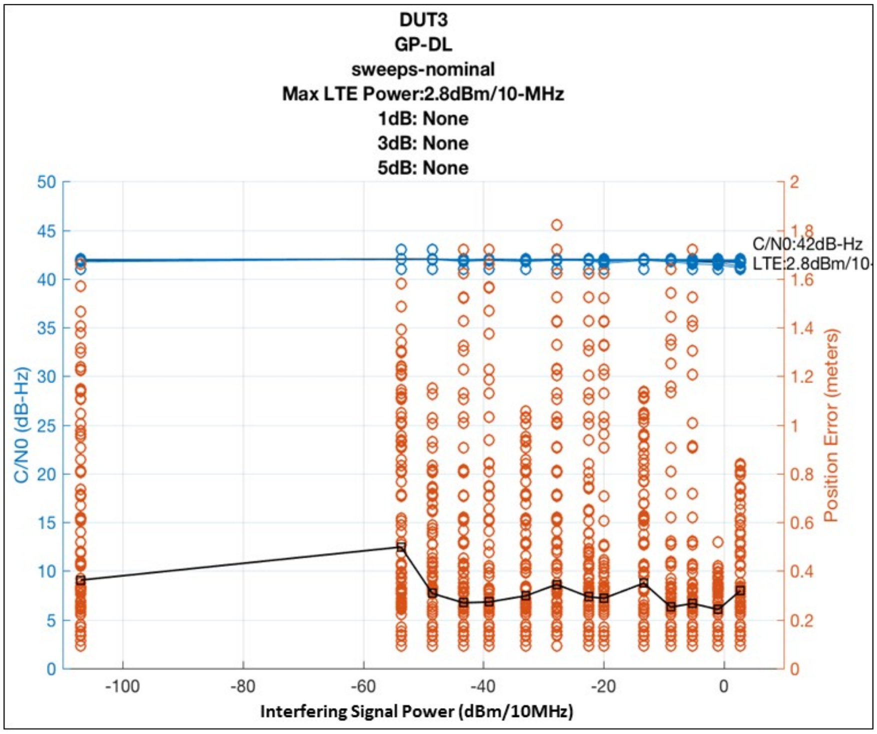
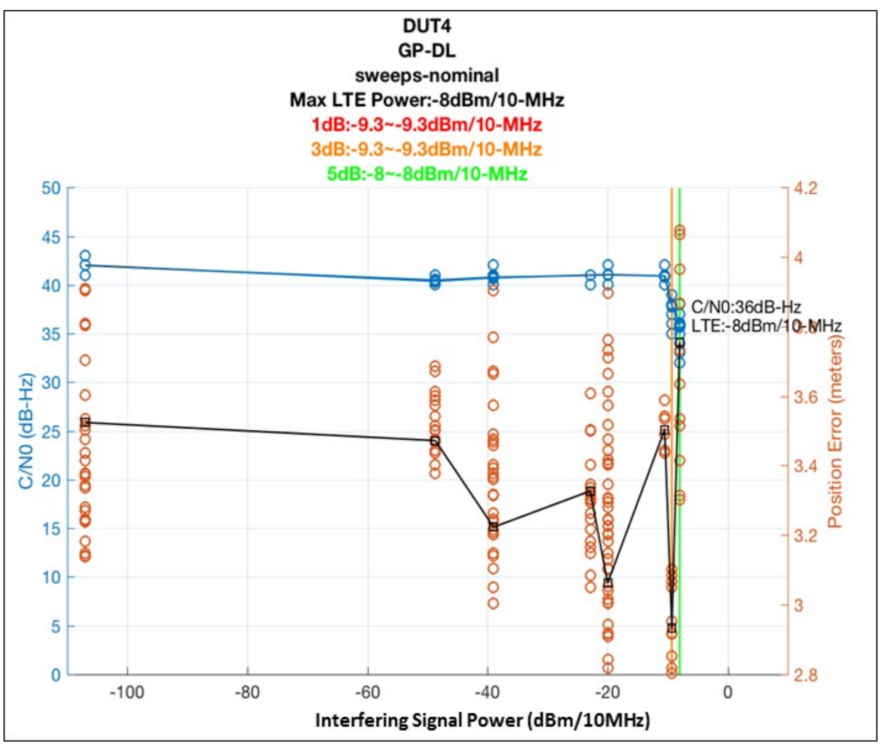
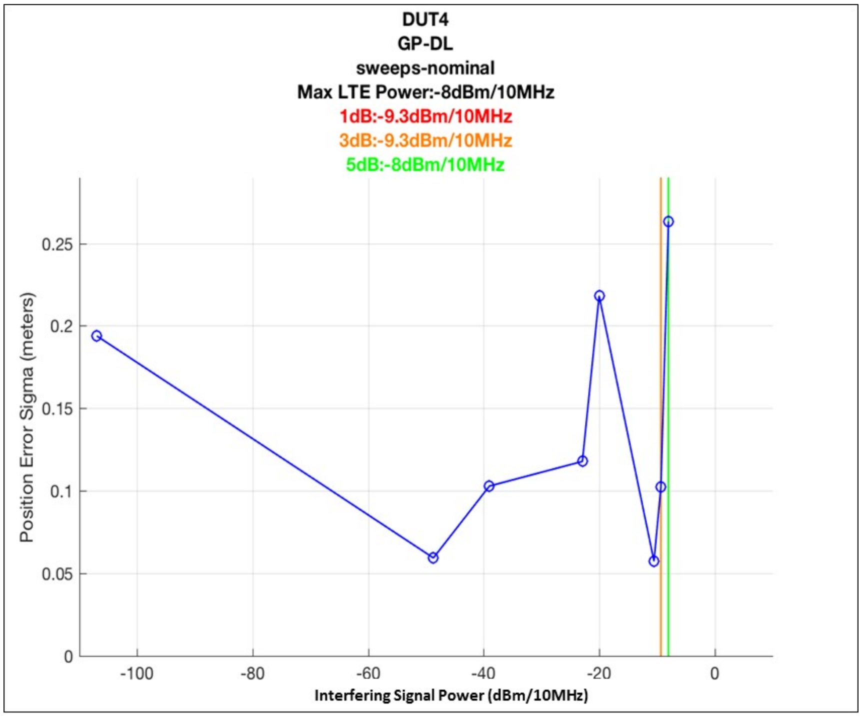


Figure D.A.2.3. C/N_0 and Position Error Distribution for GLN DUT 3 Interfering Signal in DL Band

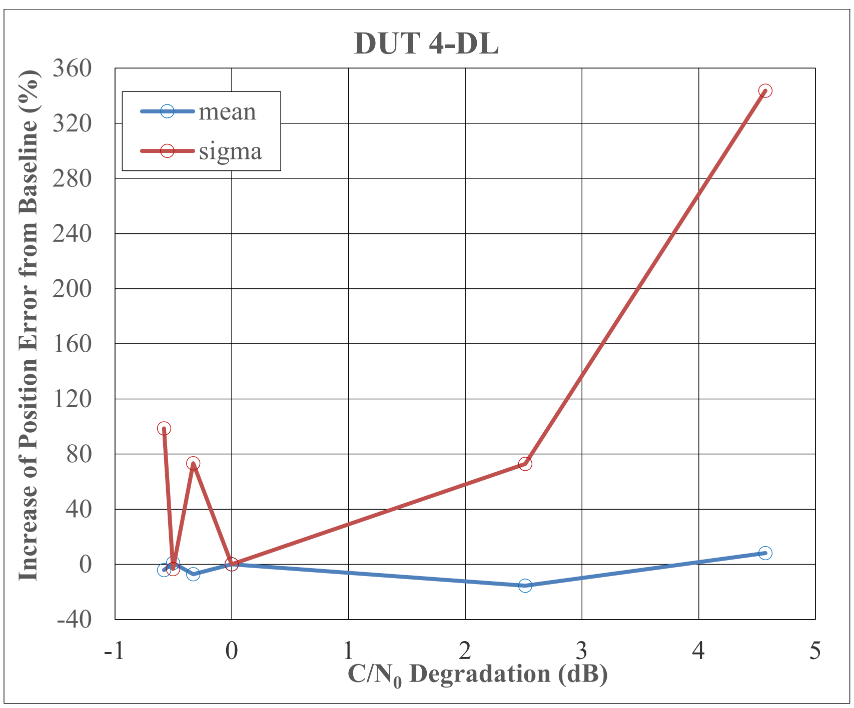
This data was not analyzed because C/N_0 degrades by less than 1 dB.



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution



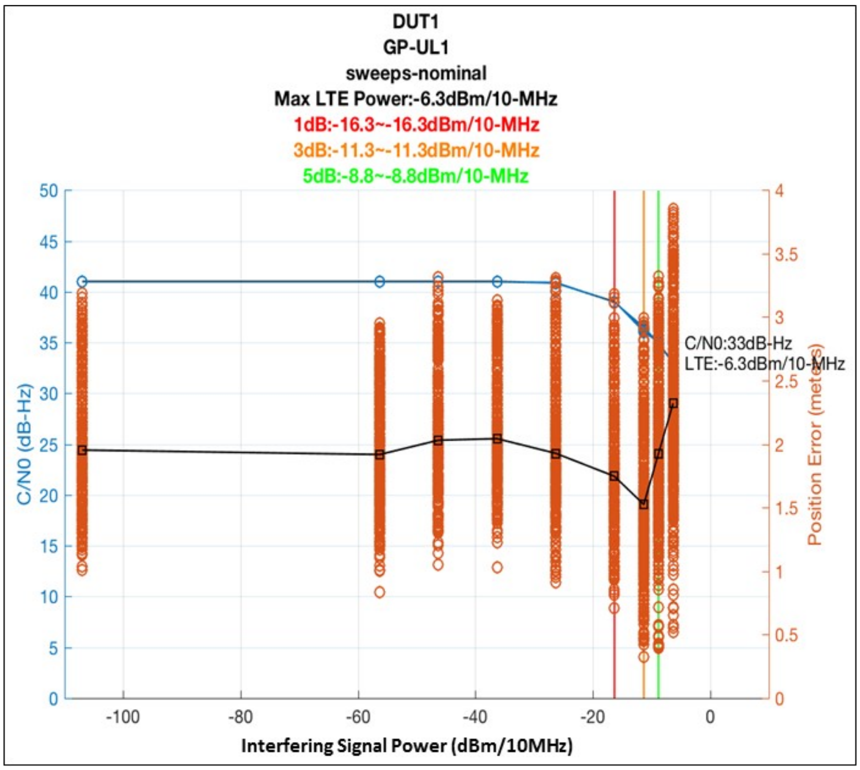
(c) Increase of Mean and Sigma of Position Error Distribution

Figure D.A.2.4. Position Error Distribution for GLN DUT 4 Interfering Signal in DL Band

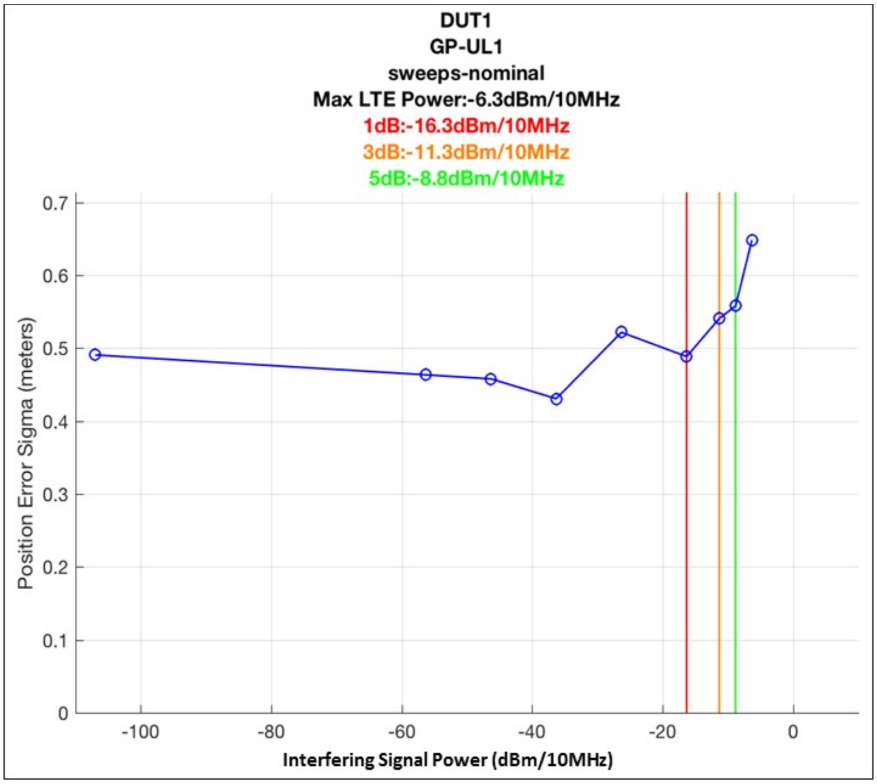
Table D.A.2.4. Position Error Distribution for GLN DUT 4 Interfering Signal in DL Band

Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-107	42.0	-	3.52	-	0.19	-
-48.7	40.4	Baseline	3.47	Baseline	0.06	Baseline
-39	40.7	-0.33	3.22	-7.2%	0.10	73.4%
-22.9	41.0	-0.58	3.33	-4.2%	0.12	98.5%
-20	41.0	-0.64*	3.06	-11.8%*	0.22	267.6%*
-10.5	40.9	-0.50	3.50	0.9%	0.06	-3.4%
-9.3	37.9	2.52	2.93	-15.5%	0.10	72.8%
-8	35.8	4.57	3.75	8.1%	0.26	343.7%

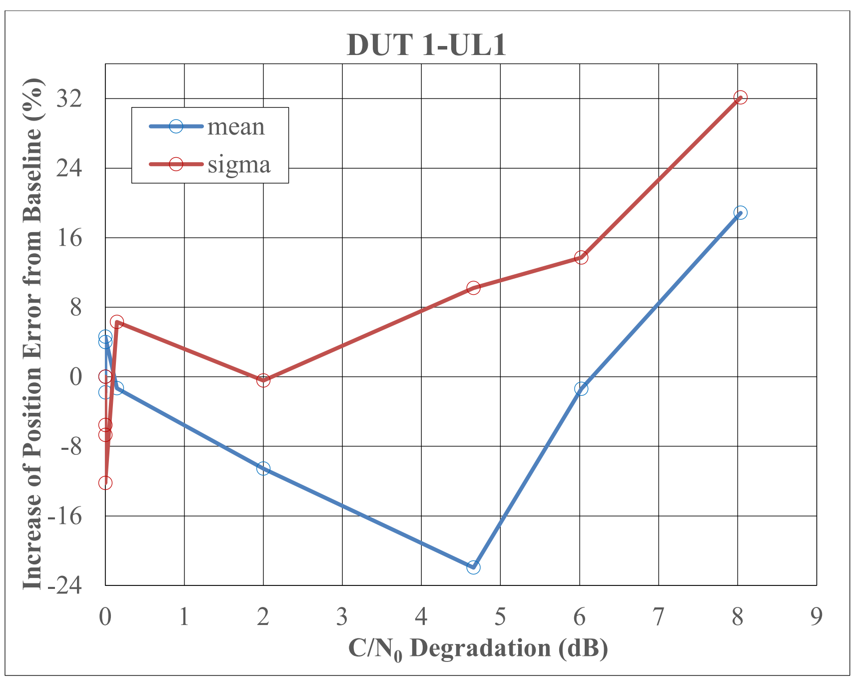
-: Not used as baseline because its sigma value appears to be unreliable.
*: Data point not included in figure (c) because the data appears to be unreliable.



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution

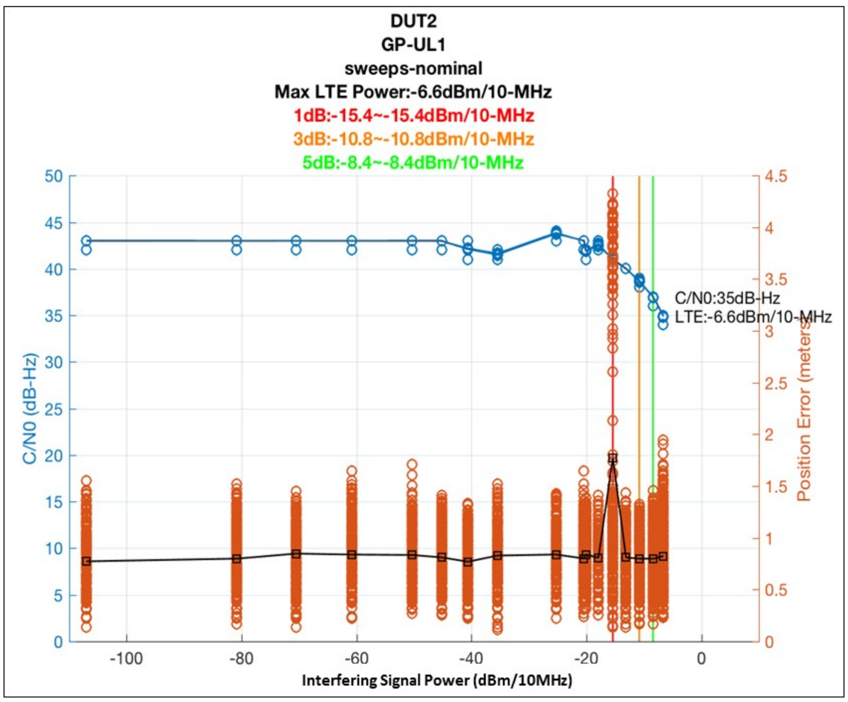


(c) Increase of Mean and Sigma of Position Error Distribution

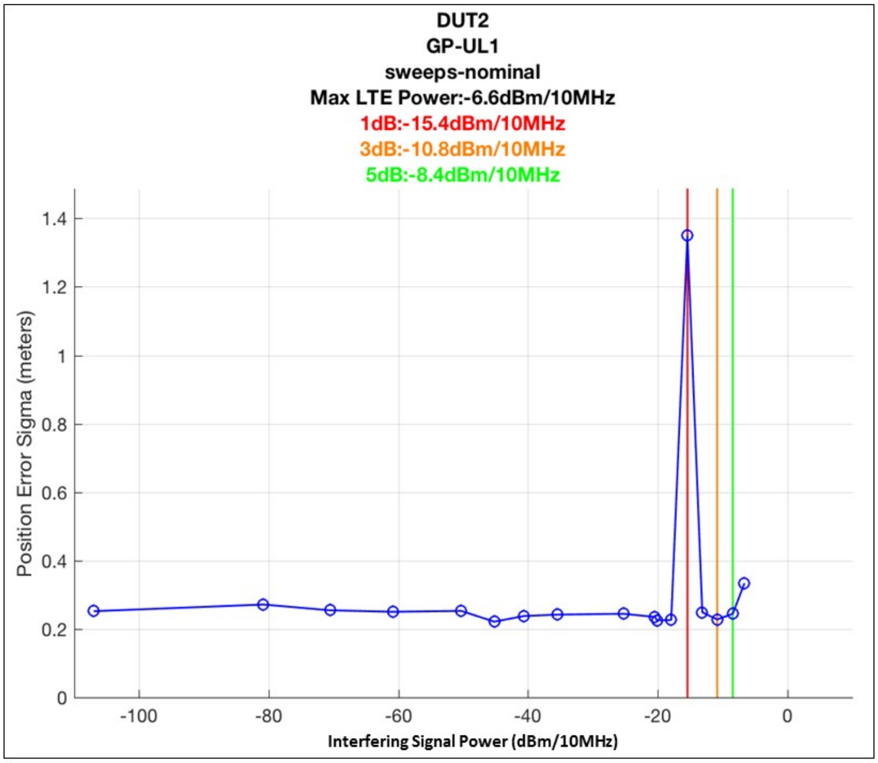
Figure D.A.2.5. Position Error Distribution for GLN DUT 1 Interfering Signal in UL1 Band

Table D.A.2.5. Position Error Distribution for GLN DUT 1
Interfering Signal in UL1 Band

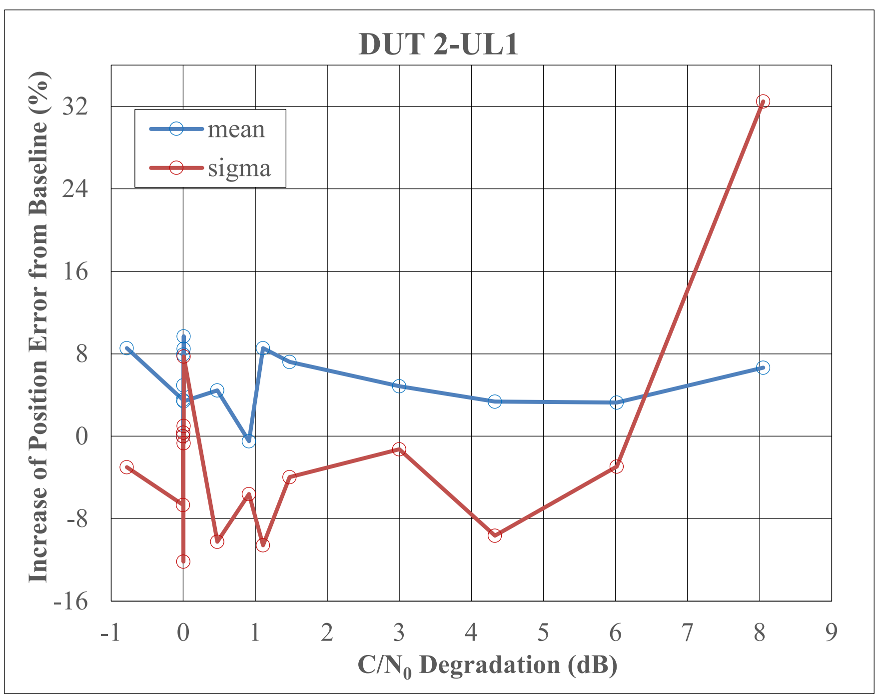
Interfering Signal Power (dBm/10 MHz)	C/N₀		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-107	41.0	Baseline	1.95	Baseline	0.49	Baseline
-56.3	41.0	0.0	1.92	-1.8%	0.46	-5.6%
-46.3	41.0	0.0	2.03	4.0%	0.46	-6.7%
-36.3	41.0	0.0	2.04	4.6%	0.43	-12.2%
-26.3	40.9	0.1	1.93	-1.3%	0.52	6.3%
-16.3	39.0	2.0	1.75	-10.6%	0.49	-0.4%
-11.3	36.3	4.7	1.52	-22.0%	0.54	10.2%
-8.8	35.0	6.0	1.93	-1.4%	0.56	13.7%
-6.3	33.0	8.0	2.32	18.8%	0.65	32.1%



(a) C/N₀ and Position Error Distribution



(b) Sigma of Position Error Distribution



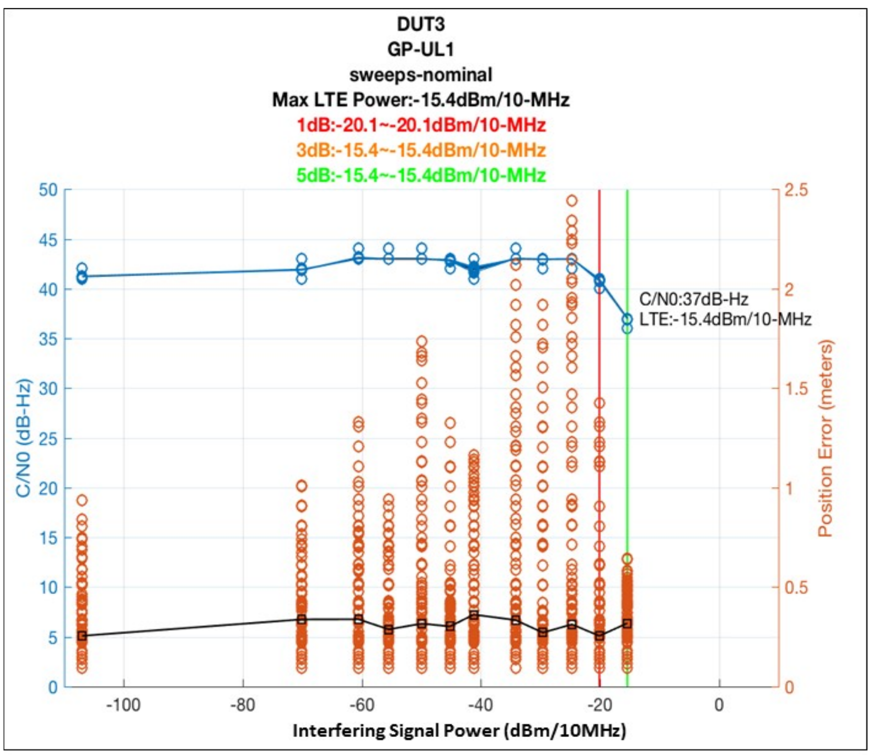
(c) Increase of Mean and Sigma of Position Error Distribution

Figure D.A.2.6. Position Error Distribution for GLN DUT 2 Interfering Signal in UL1 Band

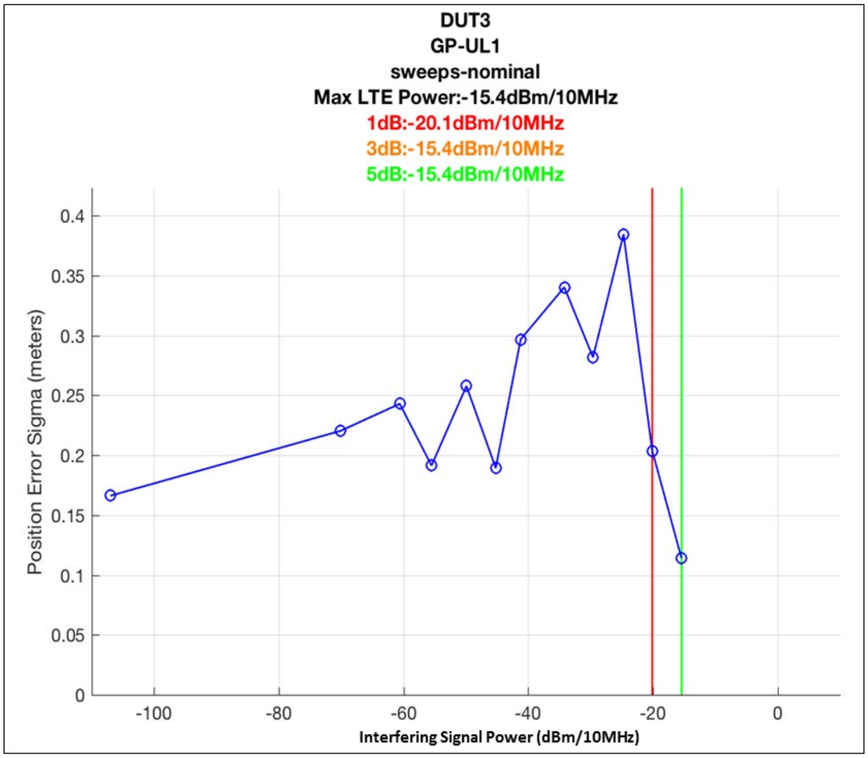
Table D.A.2.6. Position Error Distribution for GLN DUT 2 Interfering Signal in UL1 Band

Interfering Signal Power (dBm/10 MHz)	C/N0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-107	43.0	Baseline	0.772	Baseline	0.252	Baseline
-80.8	43.0	0.01	0.798	3.4%	0.271	7.7%
-70.5	43.0	0.01	0.847	9.7%	0.254	1.0%
-60.8	43.0	0.01	0.838	8.5%	0.250	-0.7%
-50.3	43.0	0.00	0.834	7.9%	0.253	0.4%
-45.2	43.0	0.00	0.811	4.9%	0.221	-12.2%
-40.6	42.1	0.91	0.769	-0.5%	0.238	-5.6%
-35.5	41.5	1.48	0.828	7.2%	0.242	-4.0%
-25.3	43.8	-0.78	0.838	8.5%	0.244	-3.0%
-20.4	43.0	0.00	0.800	3.5%	0.235	-6.7%
-20.1	41.9	1.11	0.838	8.6%	0.225	-10.6%
-17.9	42.5	0.47	0.807	4.5%	0.226	-10.2%
-15.4	41.0	2.00 *	1.774	129.6% *	1.351	436.8% *
-13.1	40.0	3.00	0.810	4.8%	0.248	-1.3%
-10.8	38.7	4.32	0.798	3.4%	0.227	-9.7%
-8.4	37.0	6.02	0.798	3.3%	0.244	-2.9%
-6.6	35.0	8.05	0.824	6.7%	0.333	32.5%

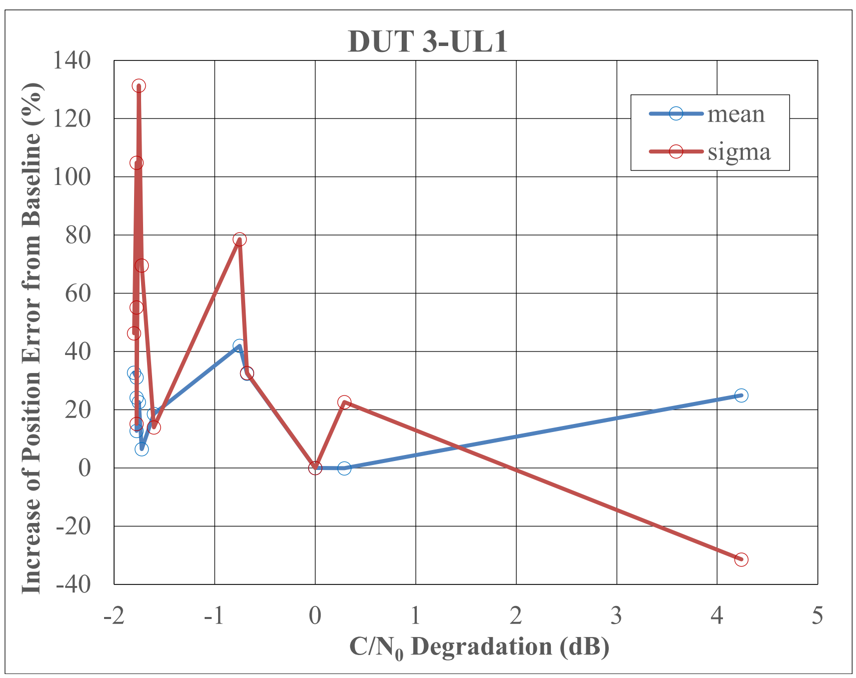
*: Data point not included in figure (c) because the data appears to be unreliable.



(a) C/N0 and Position Error Distribution



(b) Sigma of Position Error Distribution

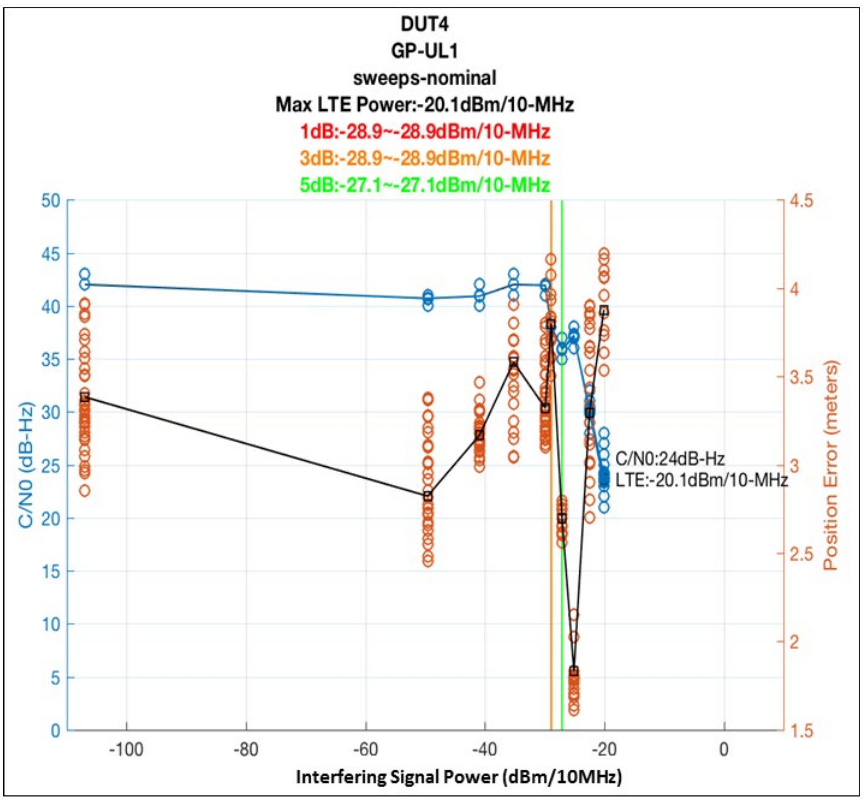


(c) Increase of Mean and Sigma of Position Error Distribution

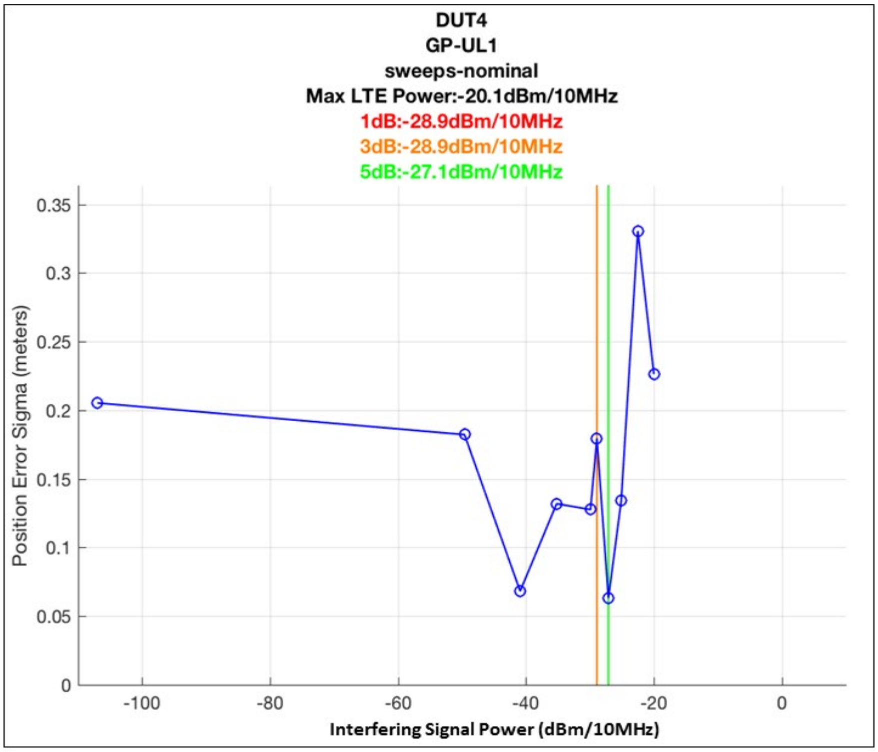
Figure D.A.2.7. Position Error Distribution for GLN DUT 3 Interfering Signal in UL1 Band

Table D.A.2.7. Position Error Distribution for GLN DUT 3
Interfering Signal in UL1 Band

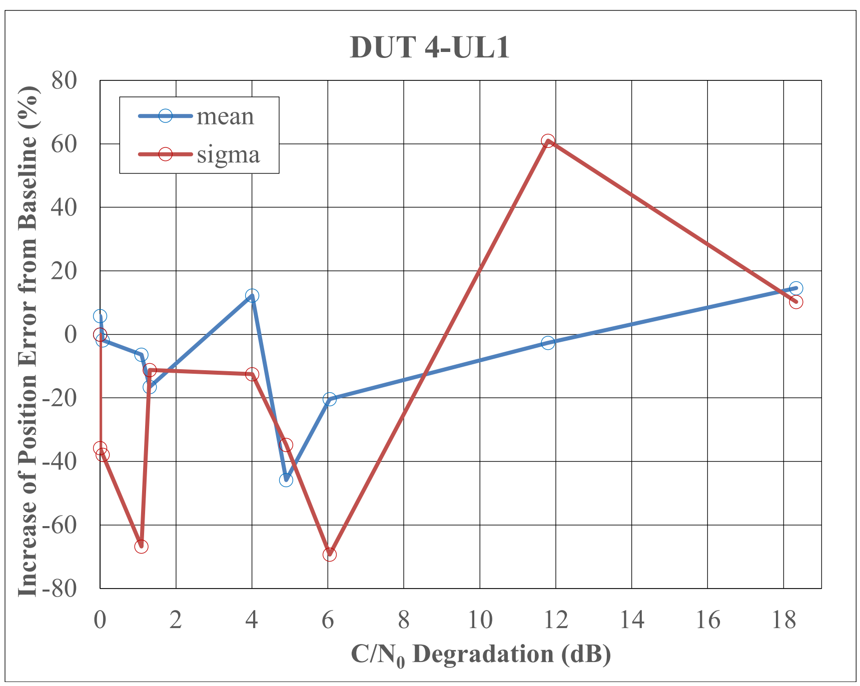
Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-107	41.2	Baseline	0.255	Baseline	0.166	Baseline
-70.1	41.9	-0.7	0.337	32.4%	0.220	32.6%
-60.6	43.0	-1.8	0.338	32.7%	0.243	46.2%
-55.5	43.0	-1.8	0.287	12.8%	0.191	15.1%
-49.9	43.0	-1.8	0.316	24.1%	0.258	55.1%
-45.2	42.8	-1.6	0.302	18.6%	0.189	13.9%
-41.2	42.0	-0.8	0.362	41.9%	0.297	78.6%
-34.2	43.0	-1.8	0.334	31.1%	0.340	104.8%
-29.6	42.9	-1.7	0.271	6.4%	0.282	69.6%
-24.7	43.0	-1.8	0.312	22.6%	0.385	131.4%
-20.1	40.9	0.3	0.254	-0.1%	0.204	22.6%
-15.4	37.0	4.2	0.318	24.9%	0.114	-31.4%



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution

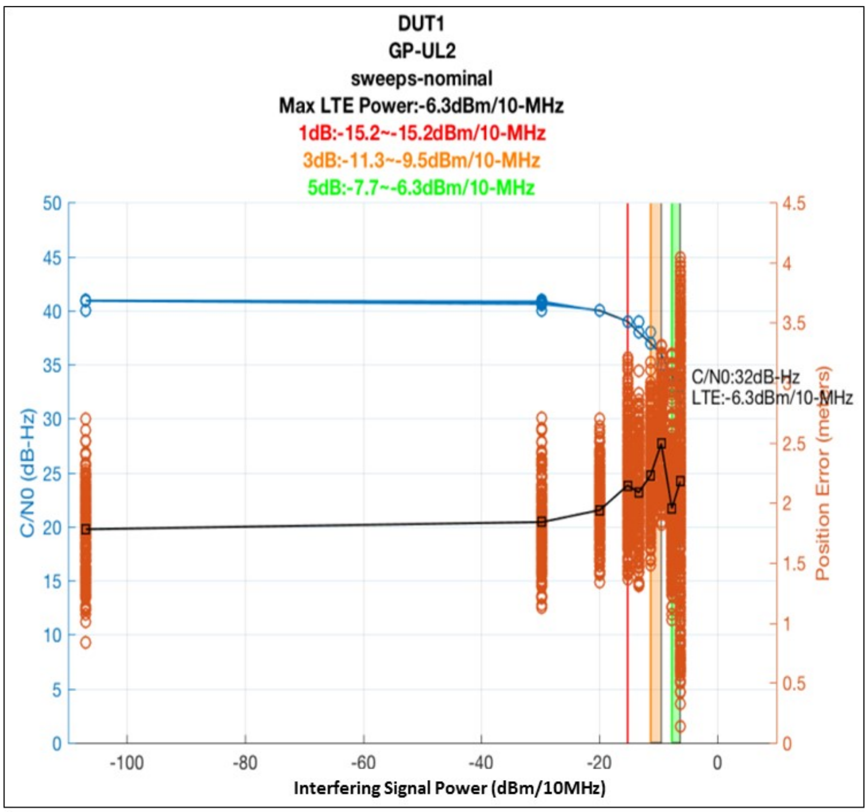


(c) Increase of Mean and Sigma of Position Error Distribution

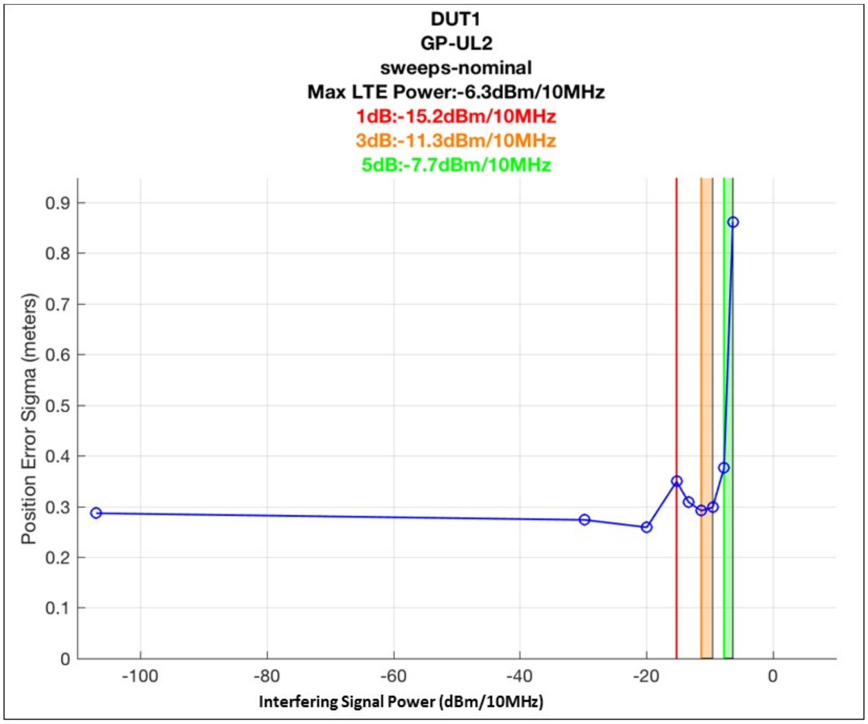
Figure D.A.2.8. Position Error Distribution for GLN DUT 4 Interfering Signal in UL1 Band

Table D.A.2.8. Position Error Distribution for GLN DUT 4
Interfering Signal in UL1 Band

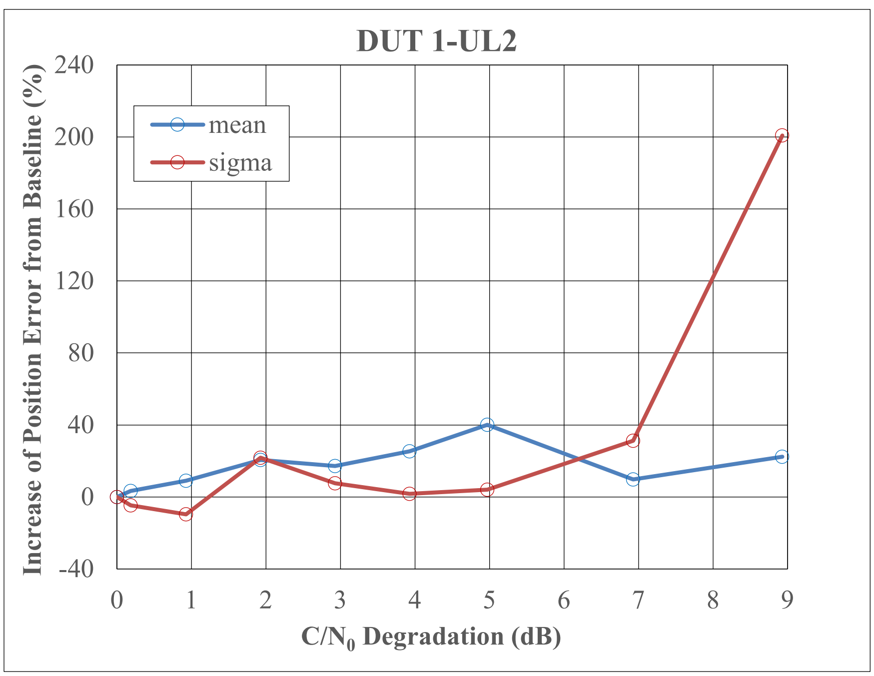
Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-107	42.0	Baseline	3.38	Baseline	0.21	Baseline
-49.6	40.7	1.31	2.82	-16.6%	0.18	-11.2%
-40.9	40.9	1.09	3.17	-6.4%	0.07	-66.8%
-35.2	42.0	0.01	3.58	5.8%	0.13	-35.8%
-29.9	41.9	0.07	3.32	-1.8%	0.13	-37.8%
-28.9	38.0	4.01	3.80	12.2%	0.18	-12.5%
-27.1	36.0	6.05	2.70	-20.3%	0.06	-69.3%
-25.1	37.1	4.90	1.83	-45.9%	0.13	-34.8%
-22.5	30.2	11.80	3.29	-2.7%	0.33	61.0%
-20.1	23.7	18.33	3.88	14.6%	0.23	10.2%



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution

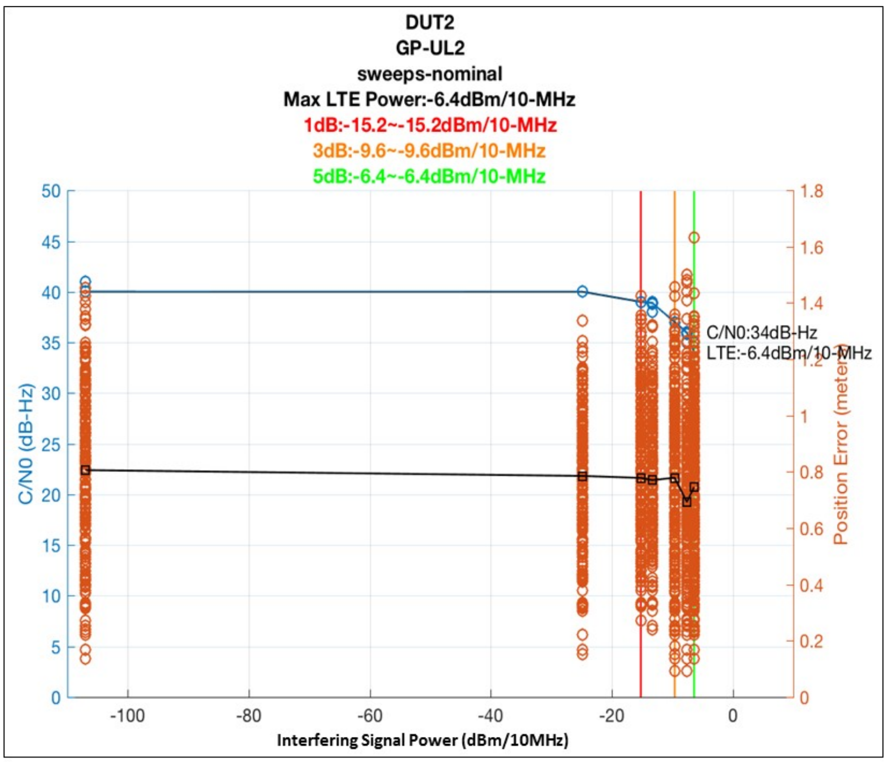


(c) Increase of Mean and Sigma of Position Error Distribution

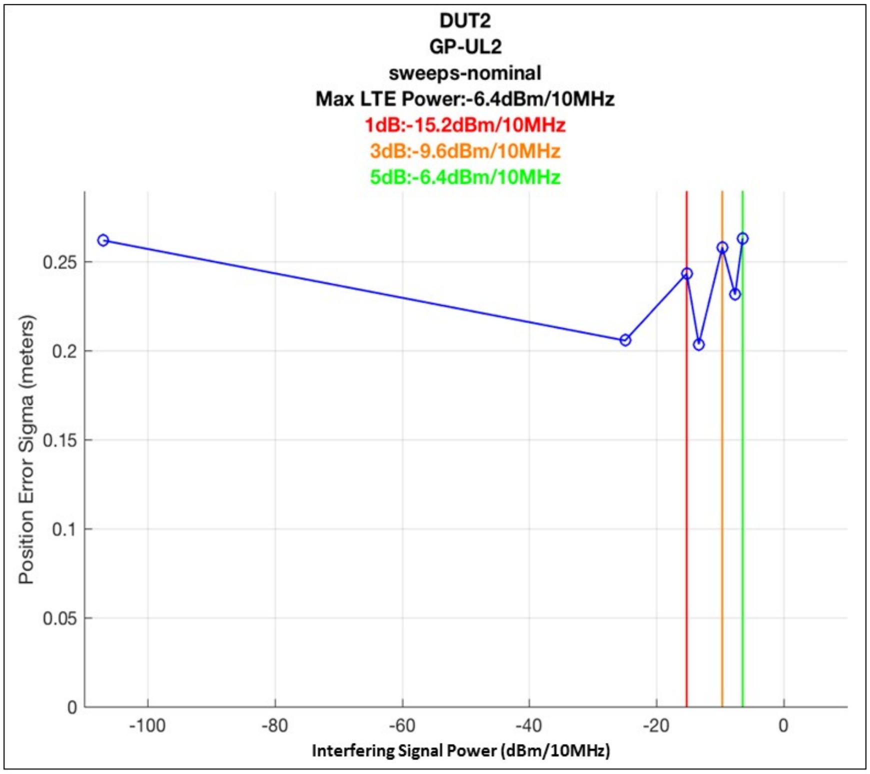
Figure D.A.2.9. Position Error Distribution for GLN DUT 1 Interfering Signal in UL2 Band

Table D.A.2.9. Position Error Distribution for GLN DUT 1
Interfering Signal in UL2 Band

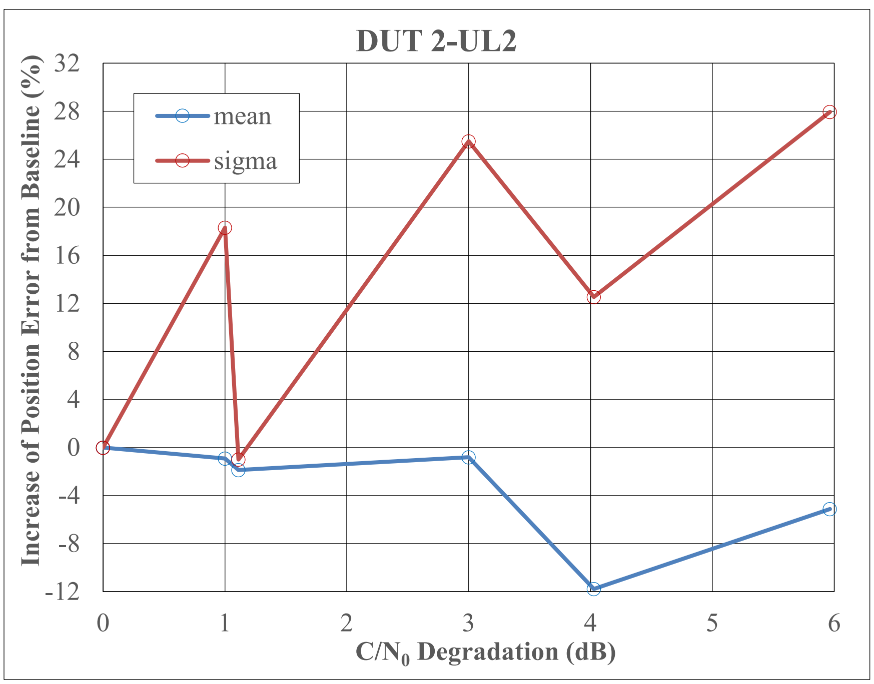
Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-107	40.9	Baseline	1.78	Baseline	0.29	Baseline
-29.7	40.7	0.2	1.84	3.3%	0.27	-4.6%
-19.9	40.0	0.9	1.94	9.0%	0.26	-9.7%
-15.2	39.0	1.9	2.14	20.5%	0.35	21.9%
-13.3	38.0	2.9	2.09	17.3%	0.31	7.7%
-11.3	37.0	3.9	2.23	25.3%	0.29	1.7%
-9.5	36.0	5.0	2.49	40.1%	0.30	4.0%
-7.7	34.0	6.9	1.95	9.7%	0.38	31.2%
-6.3	32.0	8.9	2.18	22.3%	0.86	200.8%



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution

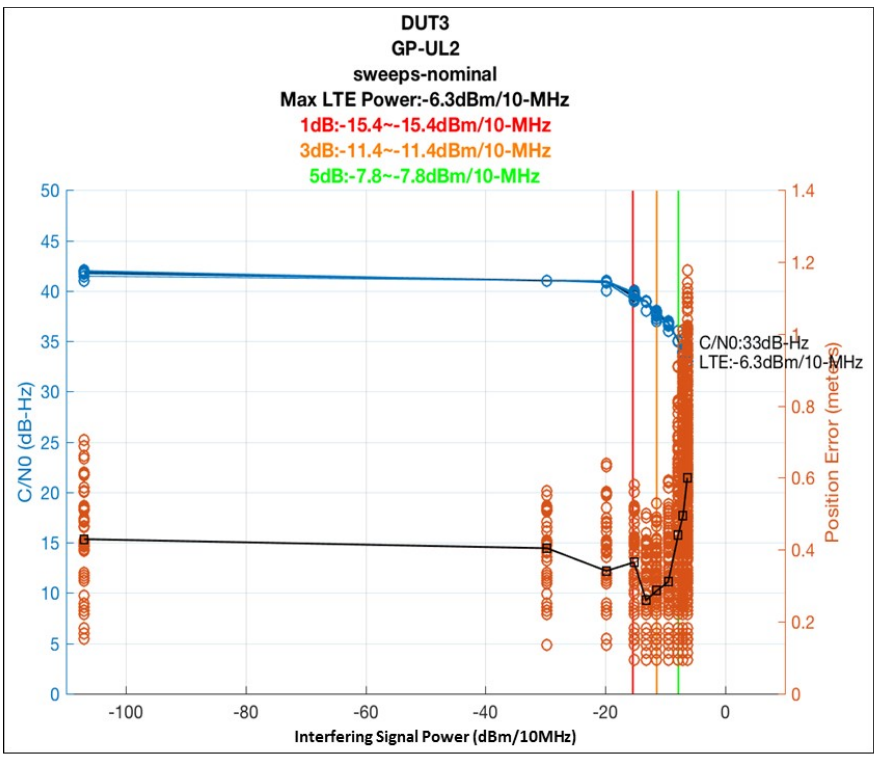


(c) Increase of Mean and Sigma of Position Error Distribution

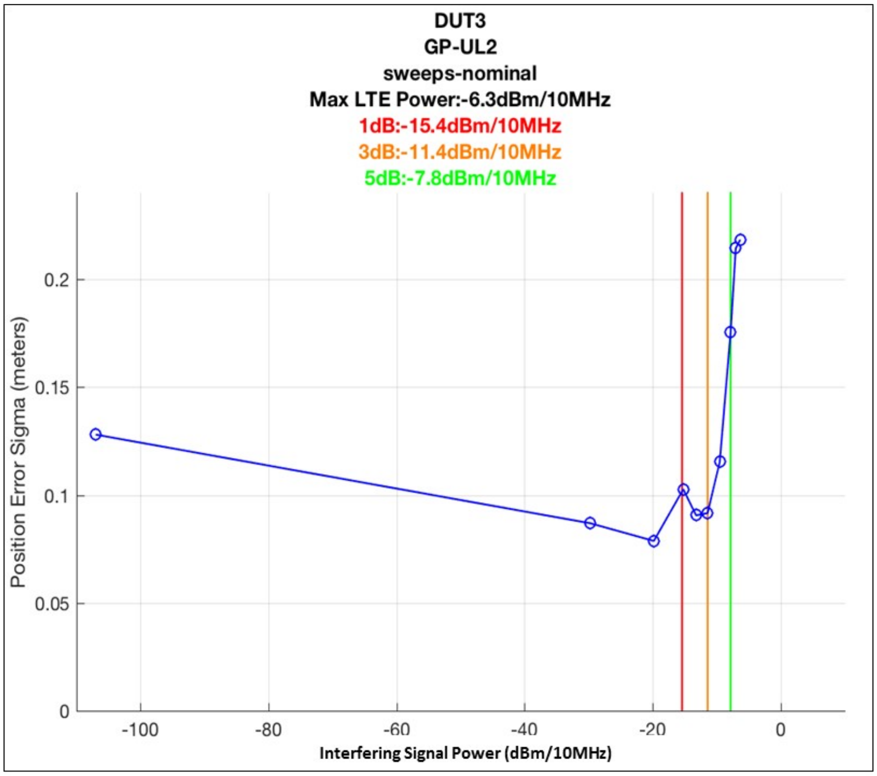
Figure D.A.2.10. Position Error Distribution for GLN DUT 2 Interfering Signal in UL2 Band

Table D.A.2.10. Position Error Distribution for GLN DUT 2
Interfering Signal in UL2 Band

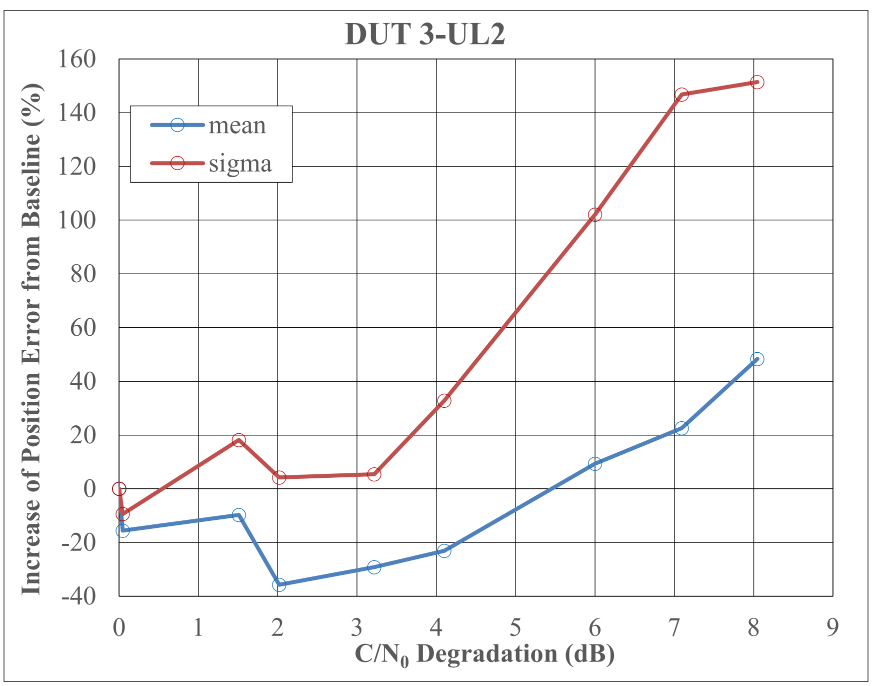
Interfering Signal Power (dBm/10 MHz)	C/N_0 Mean (dB-Hz)	C/N_0 Degradation (dB)	Position Error Mean (meter)	Position Error Increase of Mean	Position Error Sigma (meter)	Position Error Increase of Sigma
-107	40.0	-	0.806	-	0.262	-
-24.9	40.0	Baseline	0.785	Baseline	0.206	Baseline
-15.2	39.0	1.0	0.778	-0.9%	0.243	18.3%
-13.3	38.9	1.1	0.771	-1.9%	0.204	-1.0%
-9.6	37.0	3.0	0.779	-0.8%	0.258	25.5%
-7.6	36.0	4.0	0.693	-11.8%	0.232	12.5%
-6.4	34.0	6.0	0.745	-5.1%	0.263	27.9%
-: Not used as baseline because its sigma value appears to be unreliable.						



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution



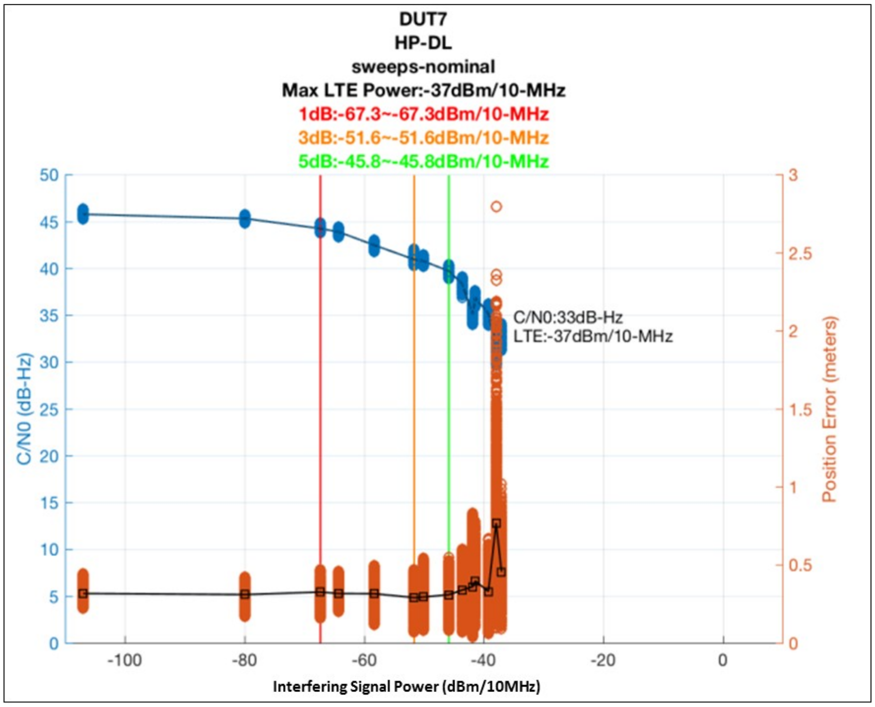
(c) Increase of Mean and Sigma of Position Error Distribution

Figure D.A.2.11. Position Error Distribution for GLN DUT 3 Interfering Signal in UL2 Band

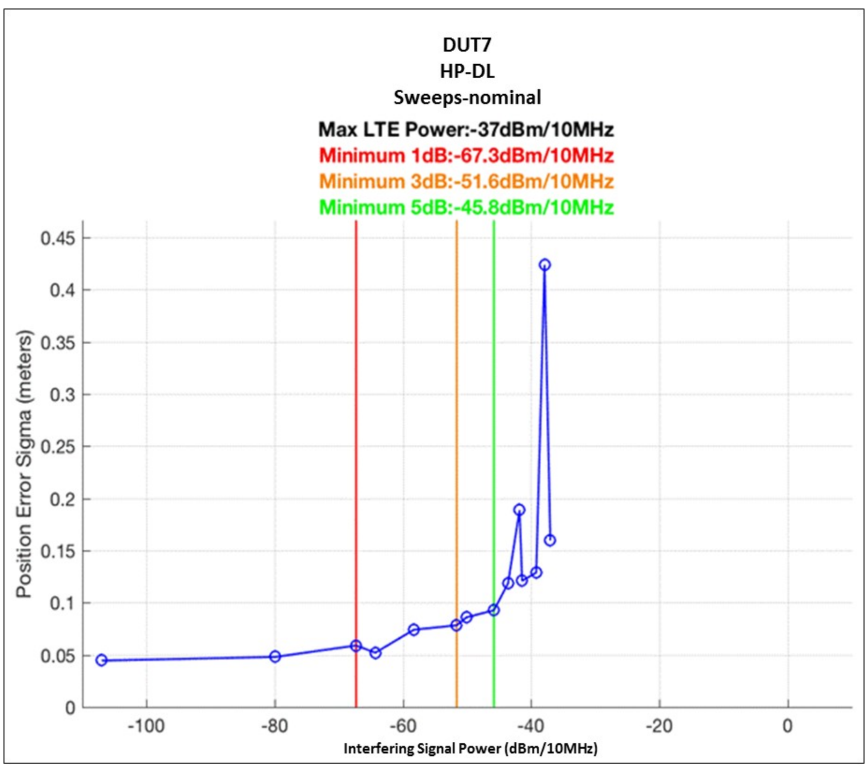
Table D.A.2.11. Position Error Distribution for GLN DUT 3
Interfering Signal in UL2 Band

Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-107	41.9	-	0.429	-	0.128	-
-29.7	41.0	Baseline	0.404	Baseline	0.087	Baseline
-19.8	41.0	0.0	0.341	-15.6%	0.079	-9.4%
-15.2	39.5	1.5	0.365	-9.7%	0.103	18.2%
-13.2	39.0	2.0	0.260	-35.7%	0.091	4.3%
-11.4	37.8	3.2	0.286	-29.2%	0.092	5.4%
-9.5	36.9	4.1	0.311	-23.1%	0.115	32.8%
-7.8	35.0	6.0	0.442	9.3%	0.176	102.0%
-7	33.9	7.1	0.495	22.5%	0.214	146.8%
-6.3	33.0	8.0	0.600	48.3%	0.218	151.4%
-: Not used as baseline because its sigma value appears to be unreliable.						

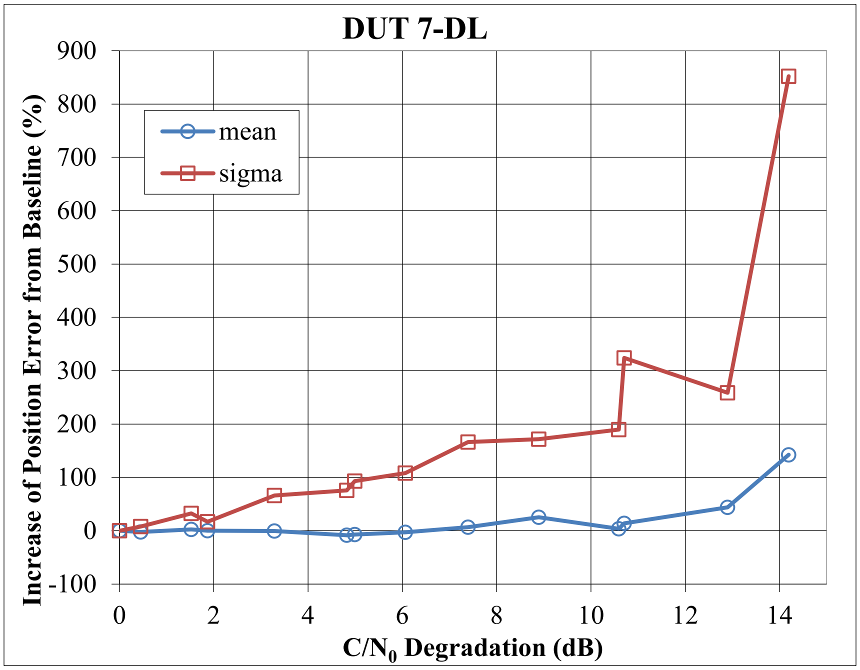
D.A.3 HP Receiver Category



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution

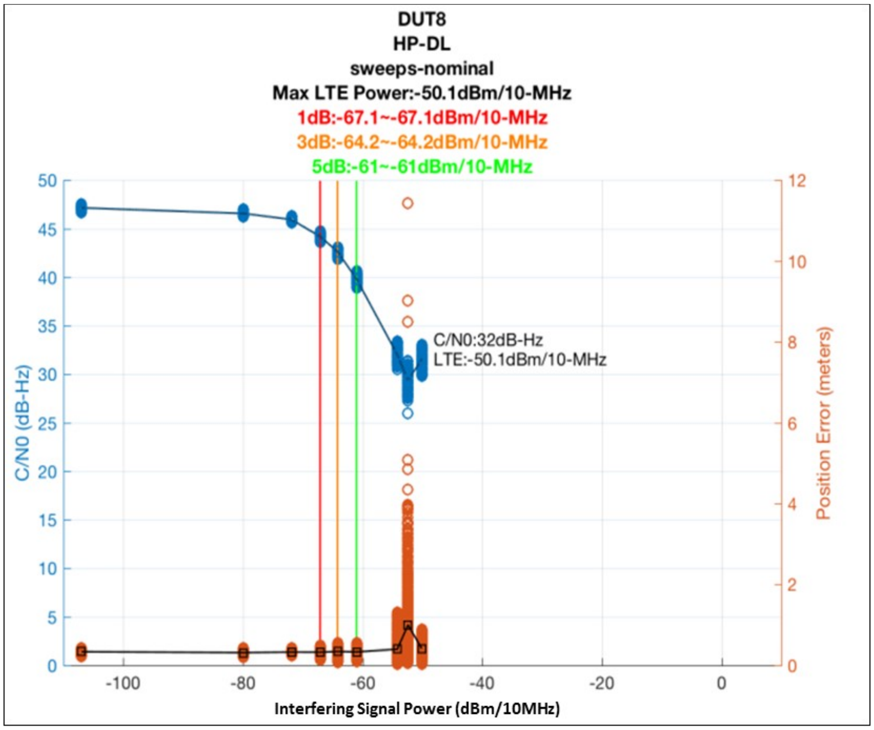


(c) Increase of Mean and Sigma of Position Error Distribution

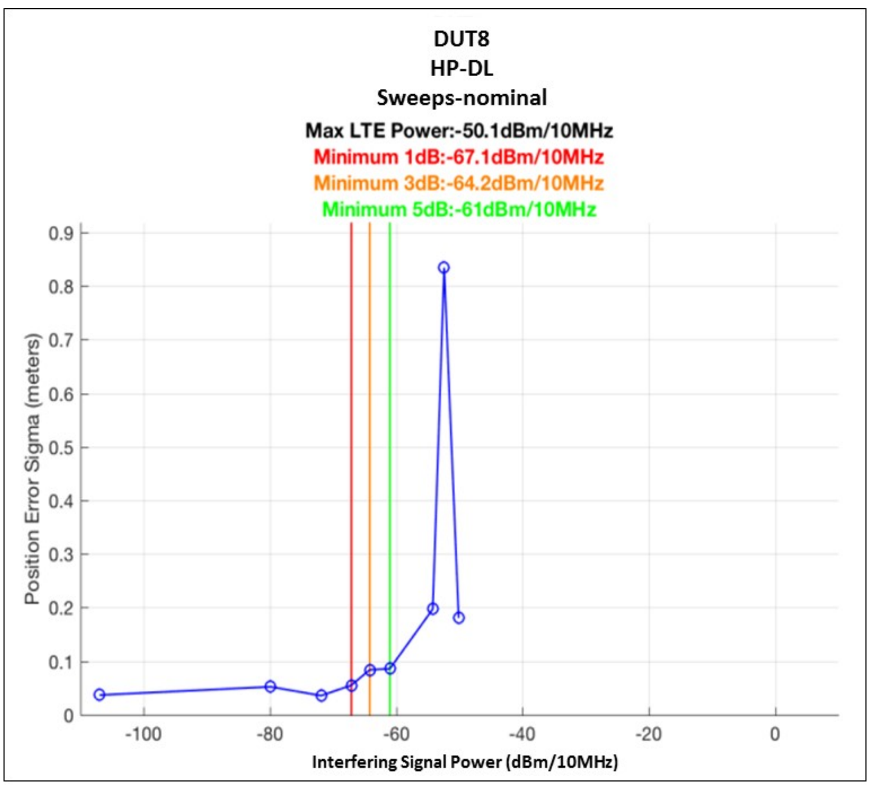
Figure D.A.3.1. 3-D Position Error Distribution for HP DUT 7 Interfering Signal in DL Band

Table D.A.3.1. 3-D Position Error Distribution for HP DUT 7 Interfering Signal in DL Band

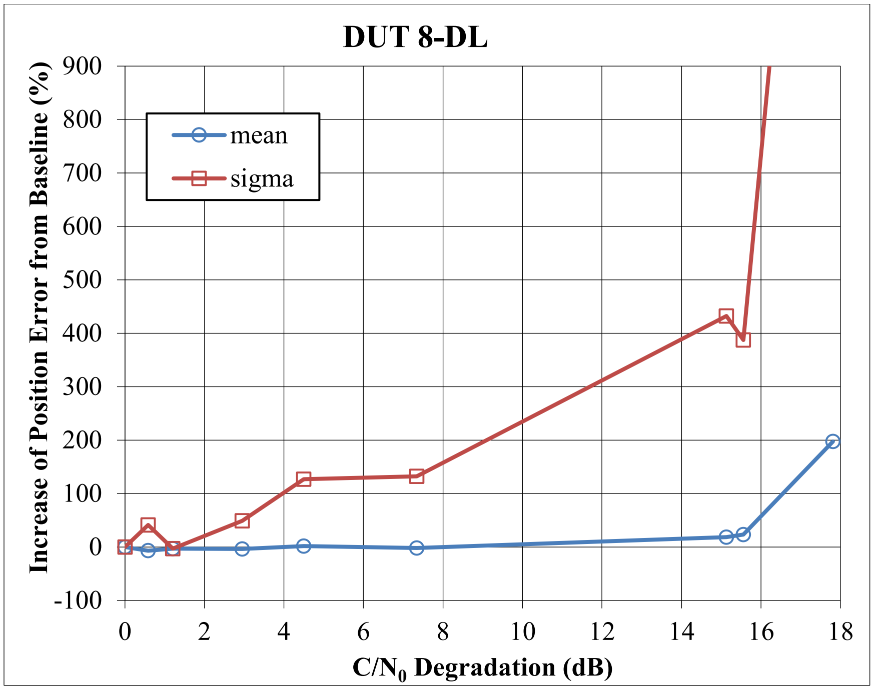
Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
None	45.8	Baseline	0.317	Baseline	0.045	Baseline
-79.9	45.3	0.5	0.310	-2.2%	0.048	7.8%
-67.3	44.2	1.5	0.325	2.8%	0.059	32.4%
-64.3	43.9	1.9	0.316	0.0%	0.052	16.9%
-58.3	42.5	3.3	0.315	-0.5%	0.074	66.4%
-51.6	40.9	4.8	0.290	-8.4%	0.078	76.0%
-50.1	40.8	5.0	0.294	-7.2%	0.086	93.1%
-45.8	39.7	6.1	0.308	-2.5%	0.093	108.4%
-43.6	38.4	7.4	0.338	6.8%	0.118	166.1%
-41.8	35.0	10.7	0.360	13.7%	0.189	324.0%
-41.4	36.9	8.9	0.397	25.3%	0.121	171.7%
-39.2	35.2	10.6	0.329	4.1%	0.129	189.5%
-37.9	31.6	14.2	0.768	142.6%	0.424	852.1%
-37.0	32.9	12.9	0.455	43.7%	0.160	258.6%



(a) C/N$_0$ and Position Error Distribution



(b) Sigma of Position Error Distribution

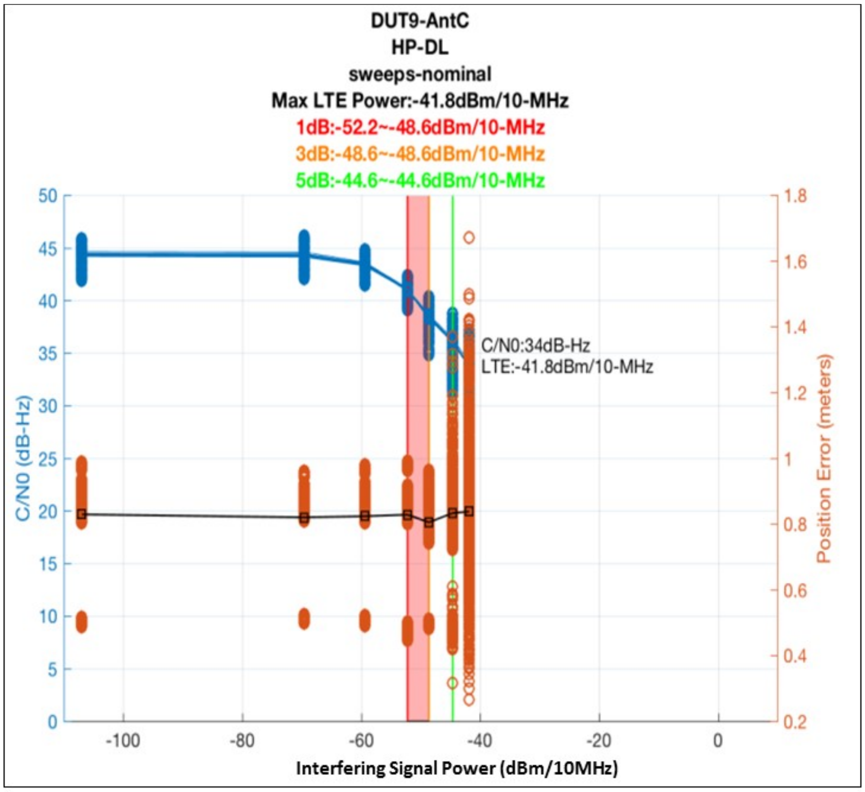


(c) Increase of Mean and Sigma of Position Error Distribution

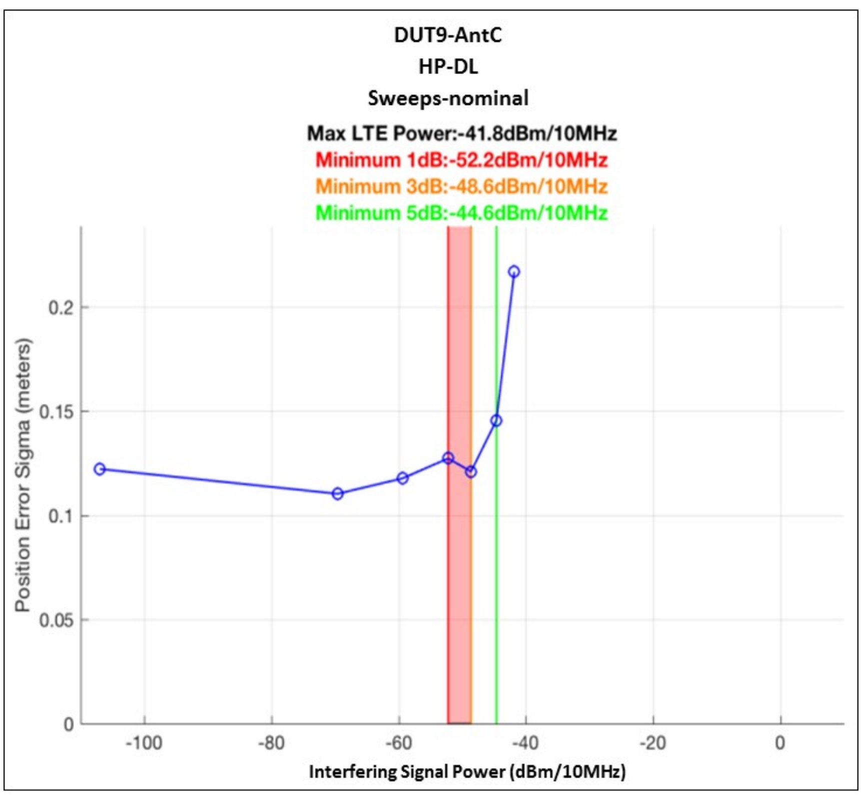
Figure D.A.3.2. 3-D Position Error Distribution for HP DUT 8 Interfering Signal in DL Band

Table D.A.3.2. 3-D Position Error Distribution for HP DUT 8 Interfering Signal in DL Band

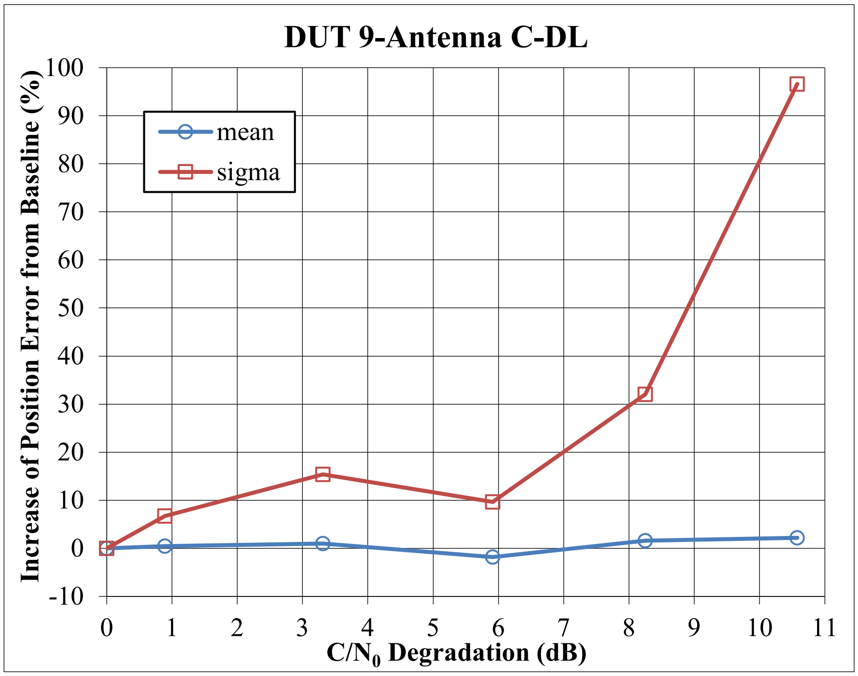
Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
None	47.1	Baseline	0.335	Baseline	0.037	Baseline
-79.9	46.6	0.6	0.312	-6.9%	0.053	41.5%
-71.9	45.9	1.2	0.326	-2.8%	0.036	-3.0%
-67.1	44.2	3.0	0.323	-3.7%	0.055	49.2%
-64.2	42.6	4.5	0.341	1.7%	0.084	127.0%
-61.0	39.8	7.3	0.330	-1.6%	0.086	132.5%
-54.2	32.0	15.1	0.398	18.7%	0.198	432.2%
-52.4	29.3	17.8	0.996	197.4%	0.835	2148%
-50.1	31.6	15.6	0.413	23.1%	0.181	387.4%



(a) C/N$_0$ and Position Error Distribution



(b) Sigma of Position Error Distribution

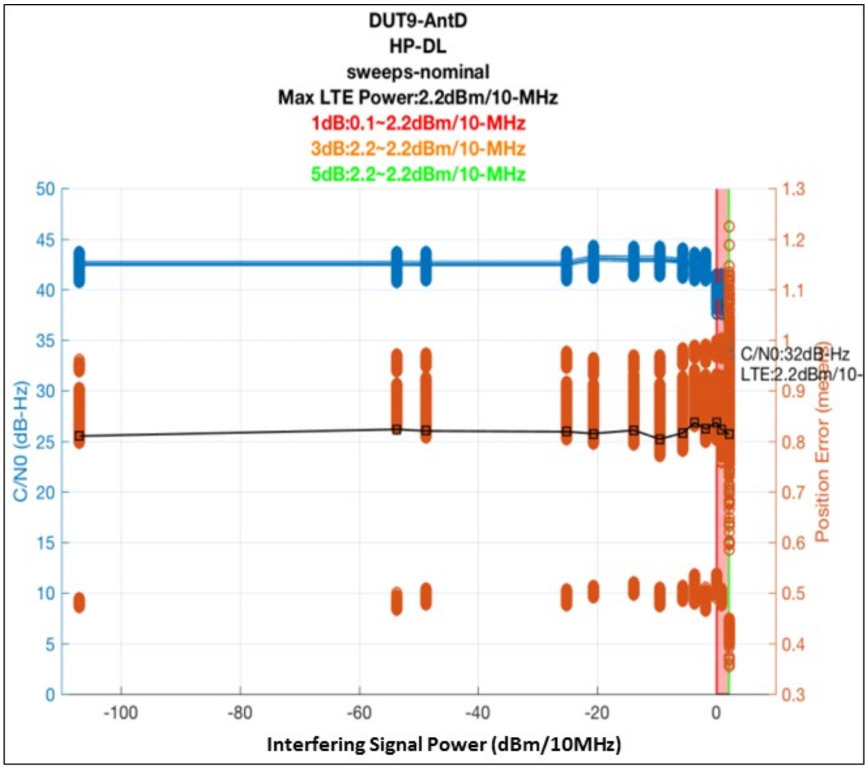


(c) Increase of Mean and Sigma of Position Error Distribution

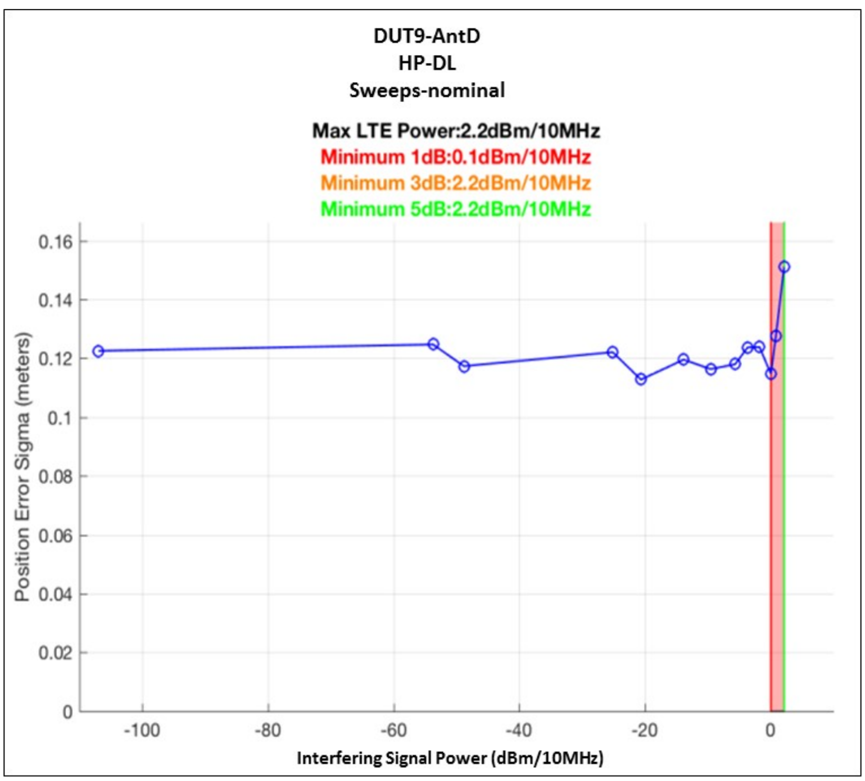
Figure D.A.3.3. 3-D Position Error Distribution for HP DUT 9 with Antenna C Interfering Signal in DL Band

Table D.A.3.3. 3-D Position Error Distribution for HP DUT 9 with Antenna C Interfering Signal in DL Band

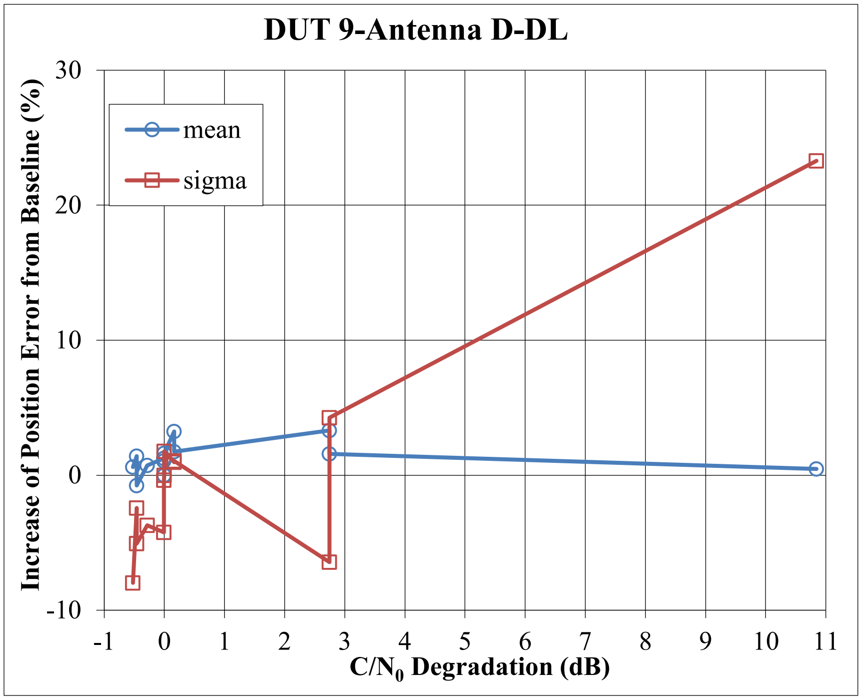
Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
None	44.4	-	0.829	-	0.122	-
-69.6	44.3	Baseline	0.820	Baseline	0.110	Baseline
-59.4	43.4	0.9	0.823	0.4%	0.118	6.7%
-52.2	41.0	3.3	0.828	1.0%	0.127	15.4%
-48.6	38.4	5.9	0.805	-1.8%	0.121	9.7%
-44.6	36.1	8.3	0.833	1.6%	0.145	32.0%
-41.8	33.8	10.6	0.838	2.2%	0.217	96.6%
-: Not used as baseline because its sigma value appears to be unreliable.						



(a) C/N$_0$ and Position Error Distribution



(b) Sigma of Position Error Distribution

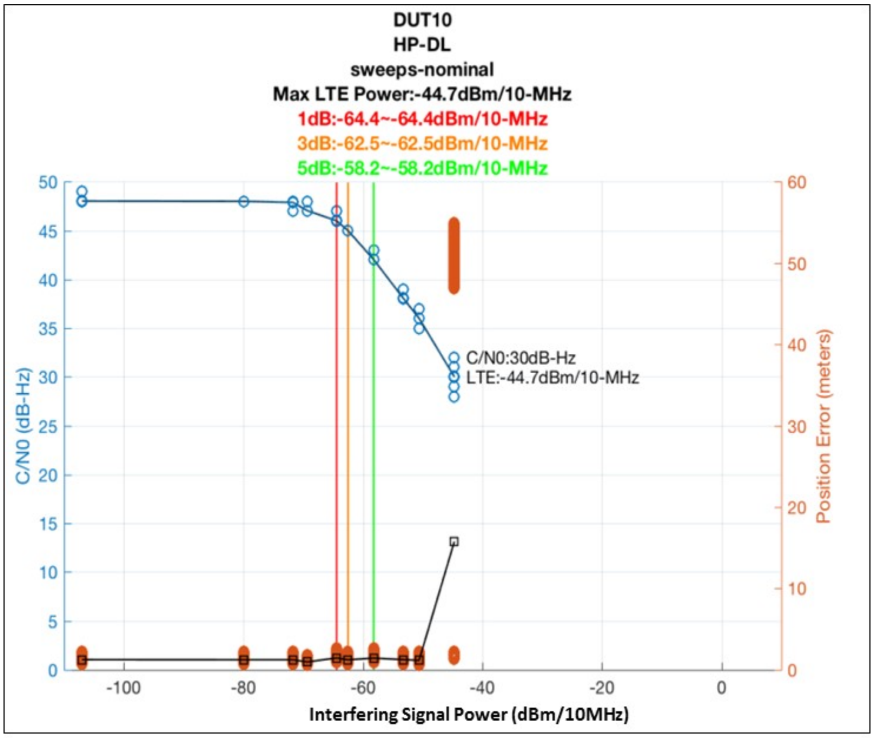


(c) Increase of Mean and Sigma of Position Error Distribution

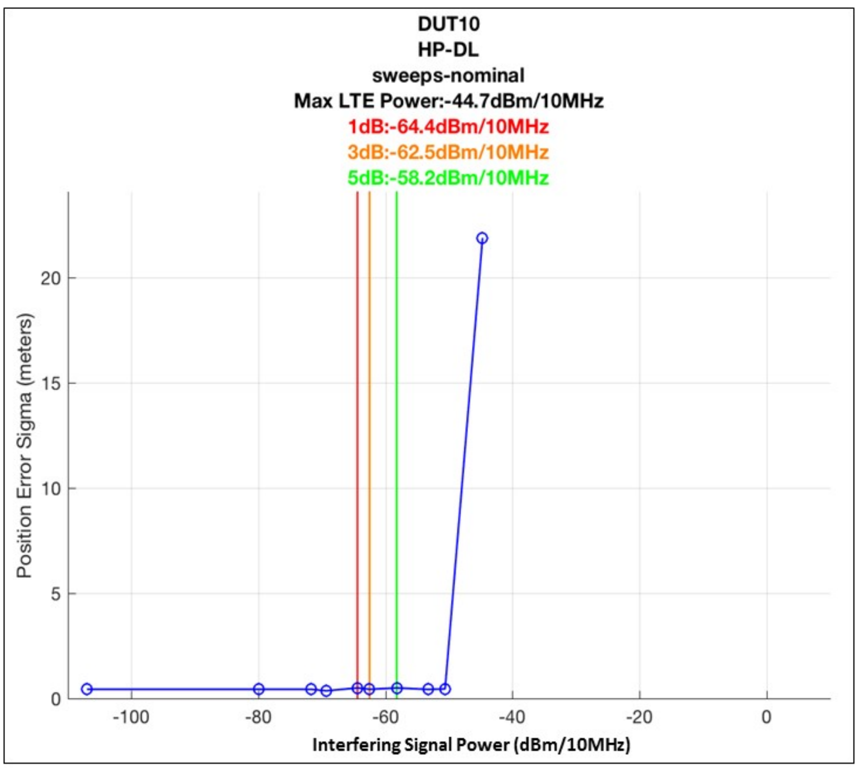
Figure D.A.3.4. 3-D Position Error Distribution for HP DUT 9 with Antenna D Interfering Signal in DL Band

Table D.A.3.4. 3-D Position Error Distribution for HP DUT 9 with Antenna D Interfering Signal in DL Band

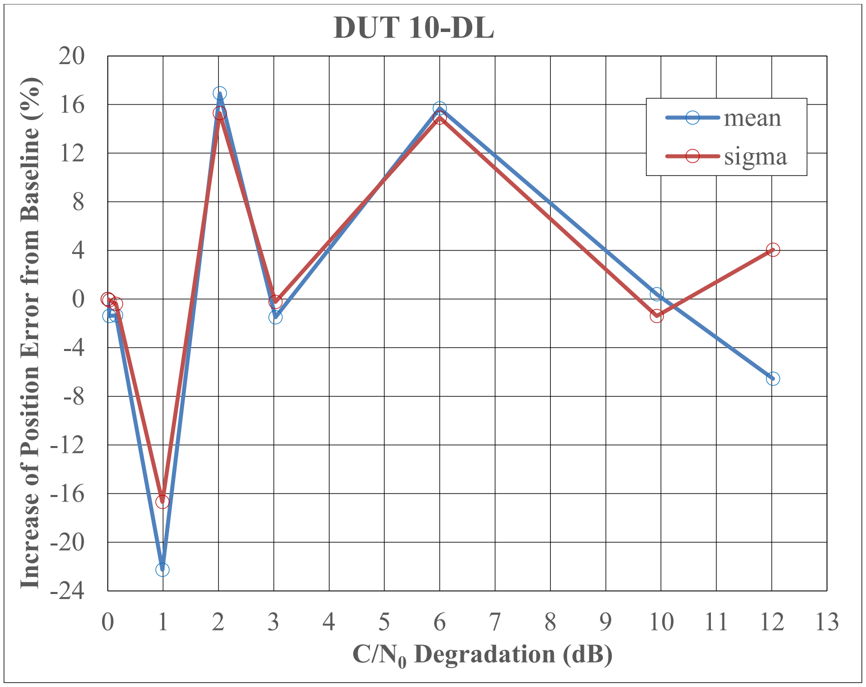
Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
None	42.5	Baseline	0.810	Baseline	0.123	Baseline
-53.7	42.5	0.00	0.823	1.6%	0.125	1.8%
-48.8	42.5	-0.01	0.820	1.2%	0.117	-4.2%
-25.1	42.5	-0.01	0.819	1.1%	0.122	-0.4%
-20.6	43.1	-0.52	0.815	0.6%	0.113	-8.0%
-13.8	43.0	-0.46	0.822	1.4%	0.120	-2.4%
-9.5	43.0	-0.46	0.804	-0.8%	0.116	-5.1%
-5.6	42.8	-0.29	0.816	0.7%	0.118	-3.7%
-3.6	42.4	0.16	0.836	3.2%	0.124	1.0%
-1.7	42.4	0.16	0.824	1.7%	0.124	1.0%
0.1	39.8	2.74	0.837	3.3%	0.115	-6.4%
0.9	39.8	2.74	0.823	1.6%	0.128	4.3%
2.2	31.7	10.85	0.814	0.5%	0.151	23.3%



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution

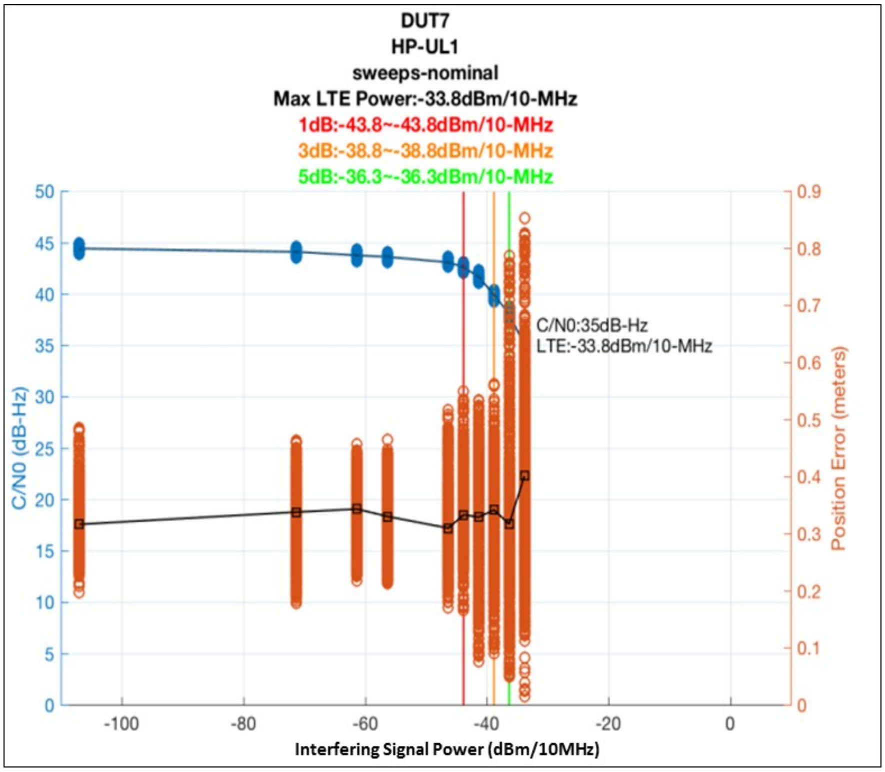


(c) Increase of Mean and Sigma of Position Error Distribution

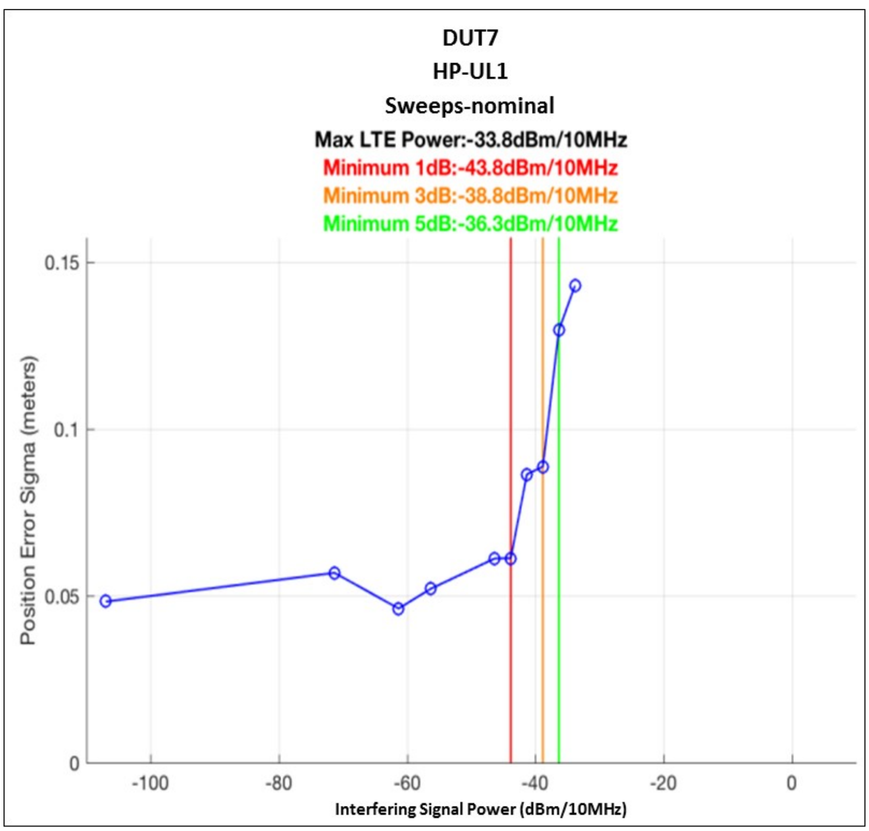
Figure D.A.3.5. 3-D Position Error Distribution for HP DUT 10 Interfering Signal in DL Band

Table D.A.3.5. 3-D Position Error Distribution for HP DUT 10 Interfering Signal in DL Band

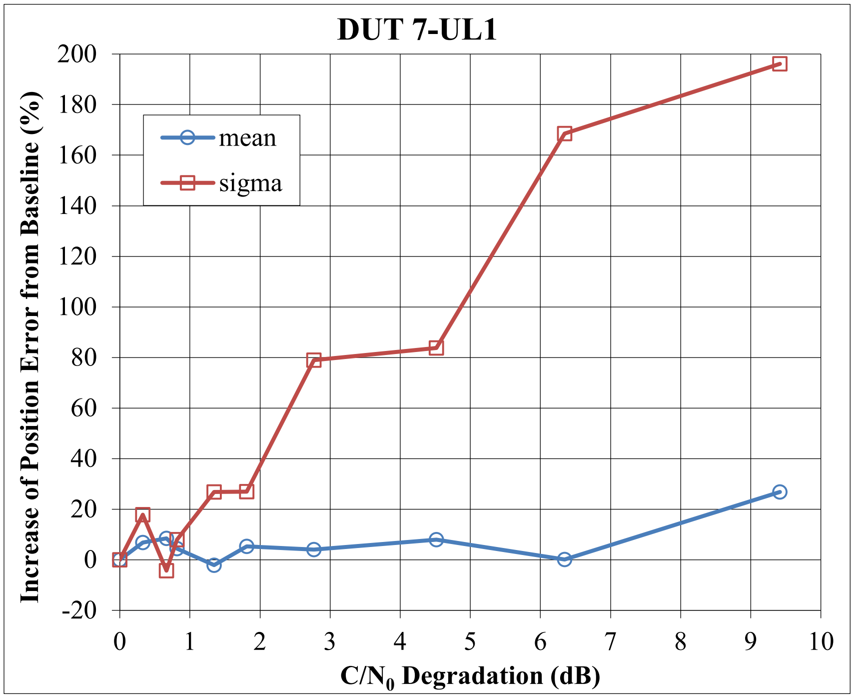
Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-107	48.0	Baseline	1.24	Baseline	0.43	Baseline
-80	48.0	0.03	1.22	-1.4%	0.43	-0.1%
-71.7	47.9	0.15	1.22	-1.3%	0.43	-0.4%
-69.3	47.0	0.99	0.96	-22.3%	0.36	-16.7%
-64.4	46.0	2.03	1.45	16.9%	0.49	15.3%
-62.5	45.0	3.03	1.22	-1.5%	0.43	-0.2%
-58.2	42.0	6.00	1.43	15.7%	0.49	14.9%
-53.3	38.1	9.92	1.24	0.4%	0.42	-1.4%
-50.6	36.0	12.02	1.16	-6.5%	0.45	4.1%
-44.7	30.0	18.01*	15.76	1175%*	21.86	5006%*
*: Data point not included in figure (c) because the data appears to be unreliable.						



(a) C/N$_0$ and Position Error Distribution



(b) Sigma of Position Error Distribution

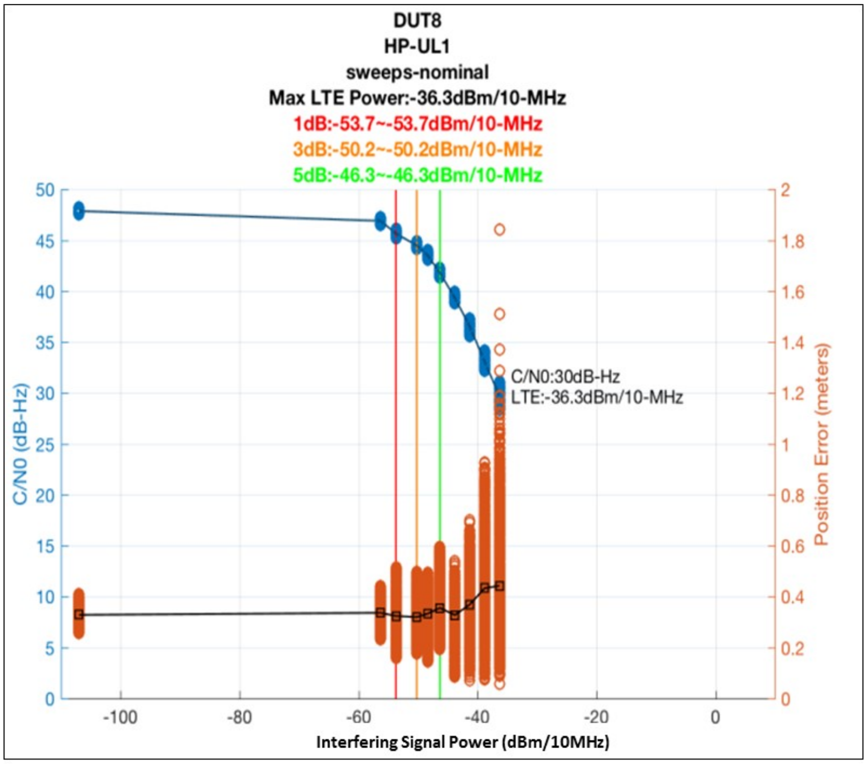


(c) Increase of Mean and Sigma of Position Error Distribution

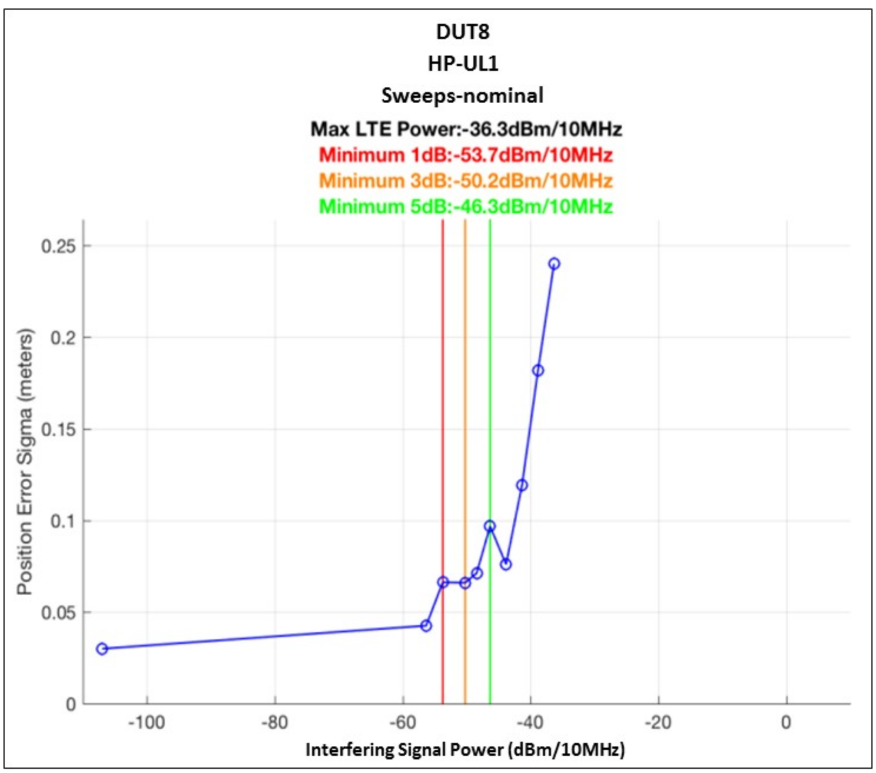
Figure D.A.3.6. 3-D Position Error Distribution for HP DUT 7 Interfering Signal in UL1 Band

Table D.A.3.6. 3-D Position Error Distribution for HP DUT 7 Interfering Signal in UL1 Band

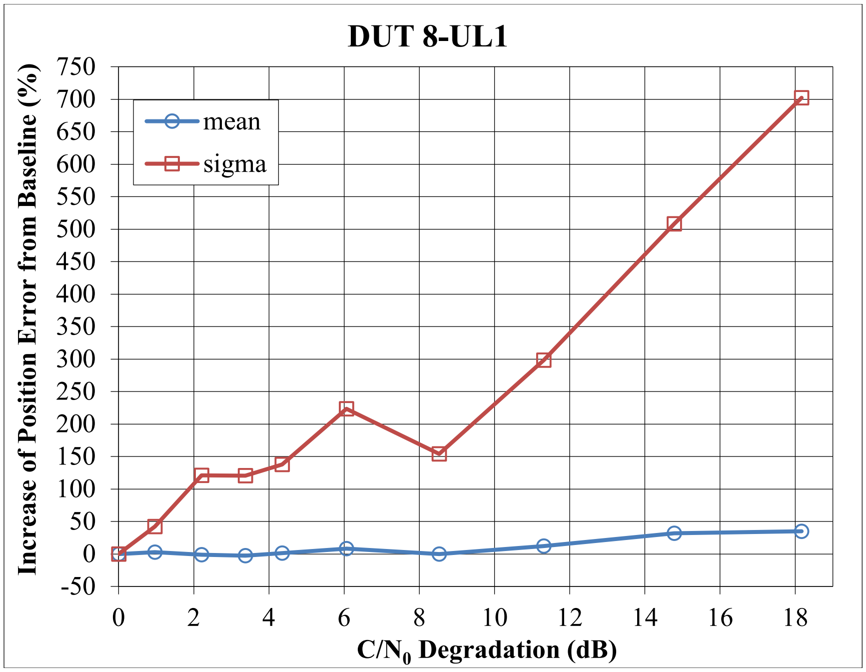
Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
None	44.4	Baseline	0.316	Baseline	0.048	Baseline
-71.3	44.1	0.3	0.338	6.8%	0.057	17.8%
-61.3	43.7	0.7	0.343	8.5%	0.046	-4.3%
-56.3	43.6	0.8	0.330	4.4%	0.052	7.9%
-46.3	43.1	1.3	0.309	-2.1%	0.061	26.8%
-43.8	42.6	1.8	0.333	5.3%	0.061	27.0%
-41.3	41.6	2.8	0.329	4.0%	0.086	79.0%
-38.8	39.9	4.5	0.341	8.0%	0.089	83.8%
-36.3	38.1	6.3	0.316	0.1%	0.130	168.6%
-33.8	35.0	9.4	0.401	26.8%	0.143	196.1%



(a) C/N$_0$ and Position Error Distribution



(b) Sigma of Position Error Distribution

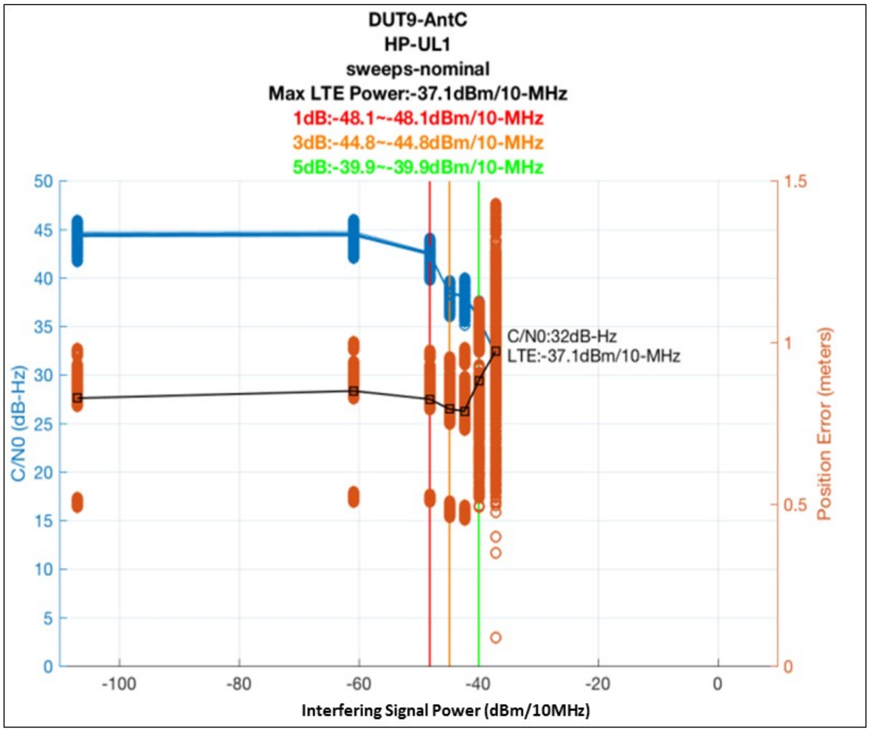


(c) Increase of Mean and Sigma of Position Error Distribution

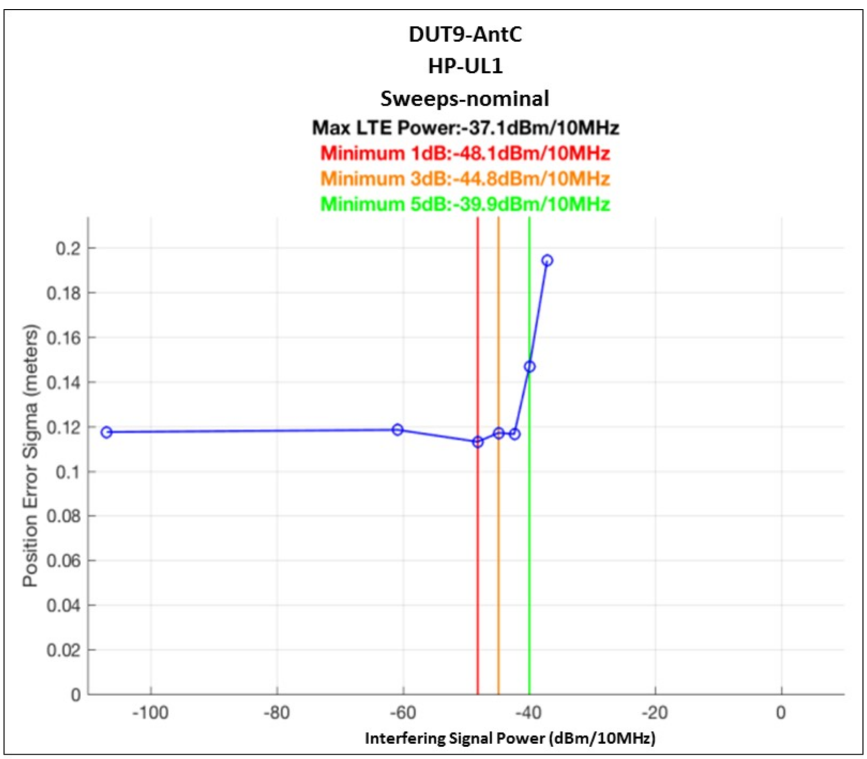
Figure D.A.3.7. 3-D Position Error Distribution for HP DUT 8 Interfering Signal in UL1 Band

Table D.A.3.7. 3-D Position Error Distribution for HP DUT 8 Interfering Signal in UL1 Band

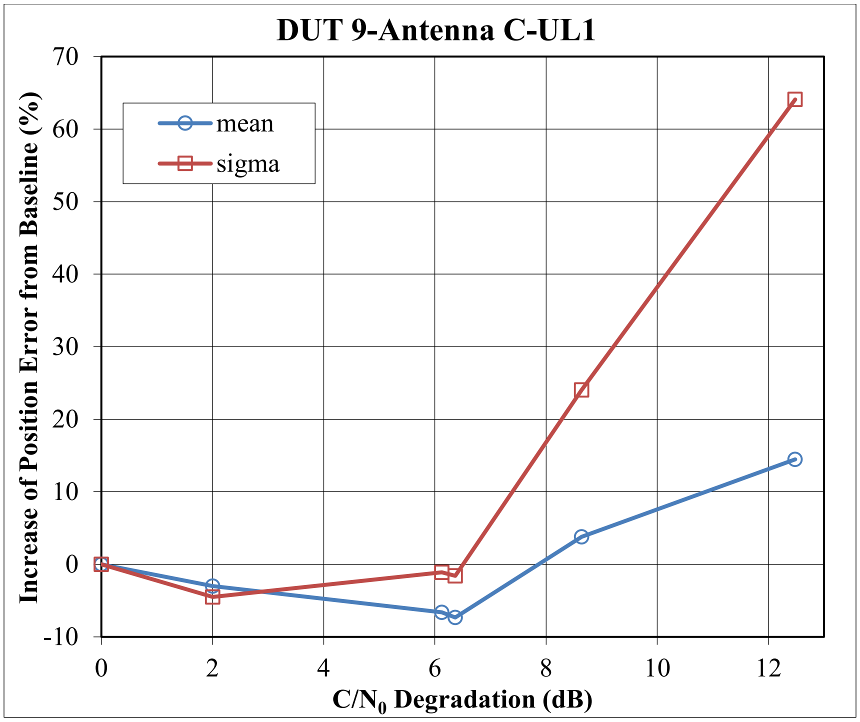
Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
none	47.9	Baseline	0.328	Baseline	0.030	Baseline
-56.3	46.9	1.0	0.336	2.5%	0.043	42.0%
-53.7	45.7	2.2	0.324	-1.3%	0.066	121.2%
-50.2	44.5	3.4	0.319	-2.7%	0.066	120.3%
-48.4	43.5	4.3	0.333	1.4%	0.071	137.8%
-46.3	41.8	6.1	0.355	8.3%	0.097	223.4%
-43.8	39.3	8.5	0.327	-0.2%	0.076	153.8%
-41.3	36.6	11.3	0.368	12.3%	0.119	298.5%
-38.8	33.1	14.8	0.433	31.9%	0.182	508.0%
-36.3	29.7	18.2	0.443	34.9%	0.240	702.2%



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution



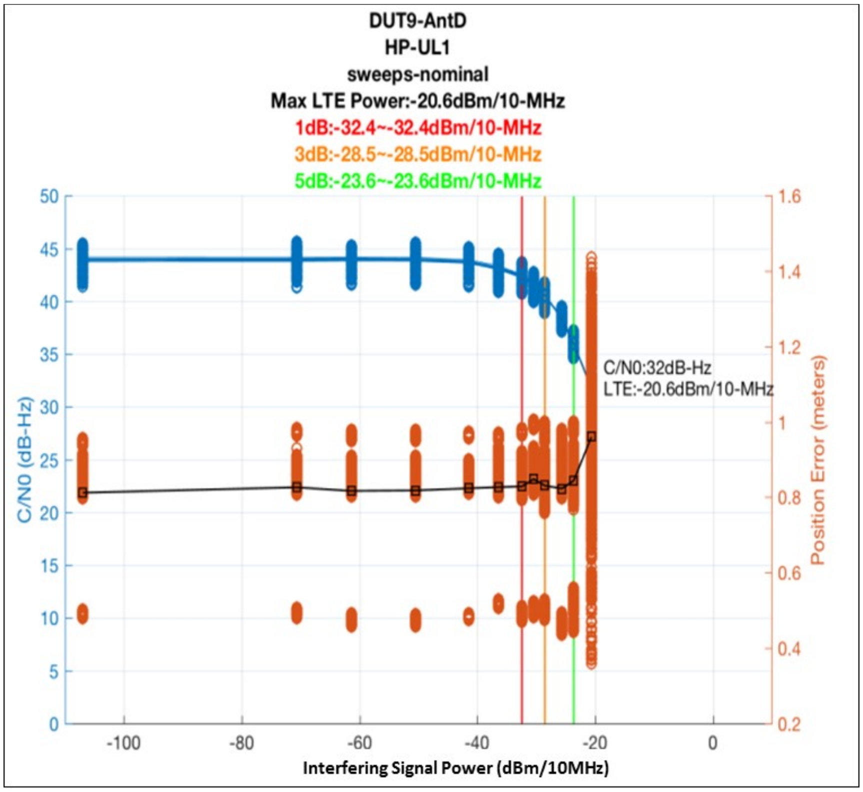
(c) Increase of Mean and Sigma of Position Error Distribution

Figure D.A.3.8. 3-D Position Error Distribution for HP DUT 9 with Antenna C Interfering Signal in UL1 Band

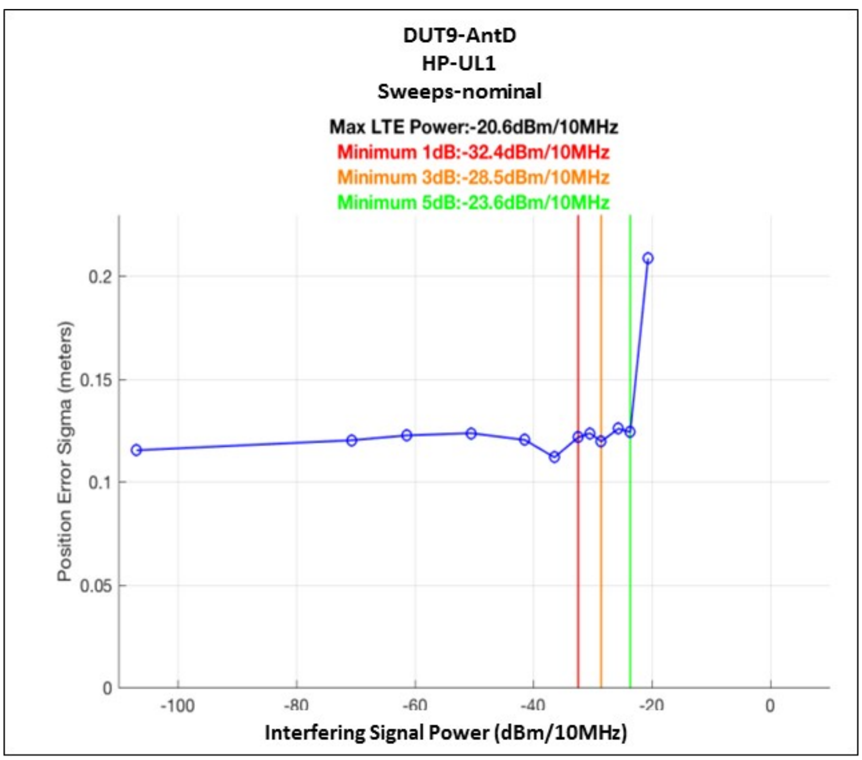
Table D.A.3.8. 3-D Position Error Distribution for HP DUT 9 with Antenna C Interfering Signal in UL1 Band

Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
None	44.4	-	0.828	-	0.117	-
-60.8	44.5	Baseline	0.850	Baseline	0.118	Baseline
-48.1	42.5	2.0	0.825	-3.0%	0.113	-4.5%
-44.8	38.4	6.1	0.794	-6.6%	0.117	-1.1%
-42.3	38.1	6.4	0.788	-7.3%	0.117	-1.6%
-39.9	35.8	8.6	0.882	3.8%	0.147	24.0%
-37.1	32.0	12.5	0.973	14.5%	0.194	64.1%

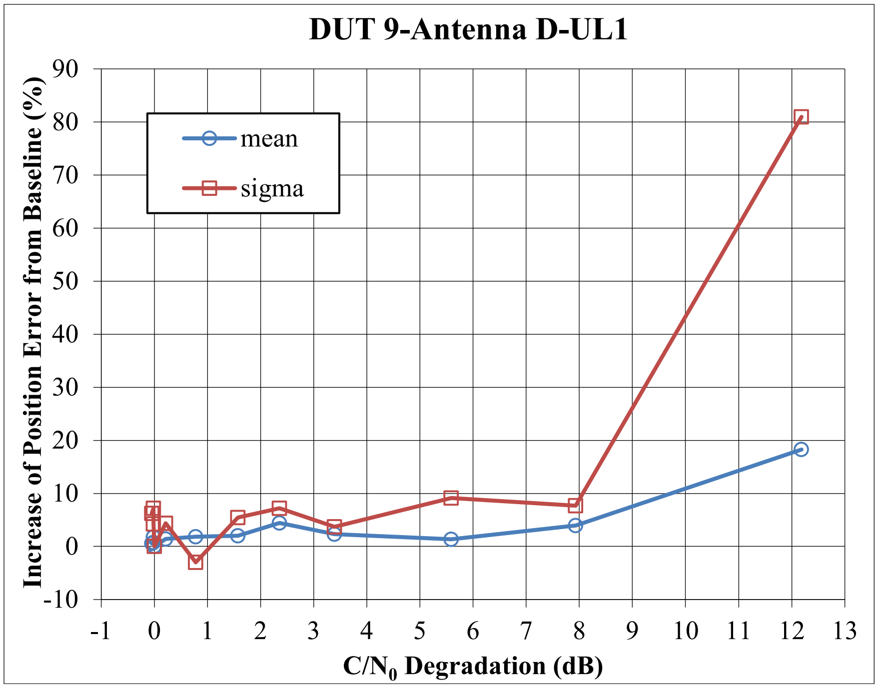
-: Not used as baseline because C/N_0 is less when there is no interfering signal.



(a) C/N$_0$ and Position Error Distribution



(b) Sigma of Position Error Distribution

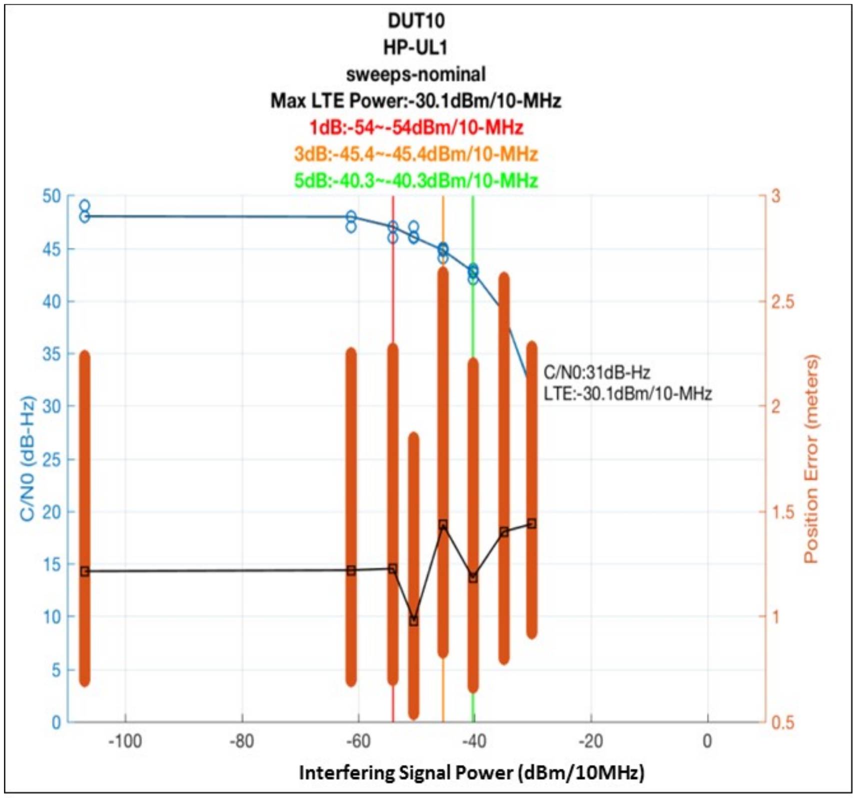


(c) Increase of Mean and Sigma of Position Error Distribution

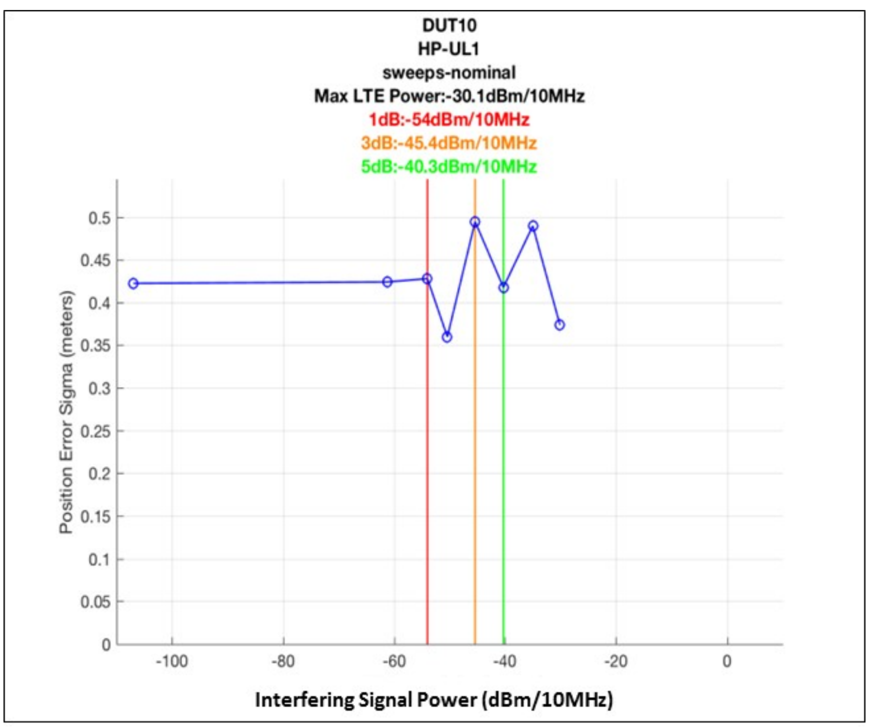
Figure D.A.3.9. 3-D Position Error Distribution for HP DUT 9 with Antenna D Interfering Signal in UL1 Band

Table D.A.3.9. 3-D Position Error Distribution for HP DUT 9 with Antenna D Interfering Signal in UL1 Band

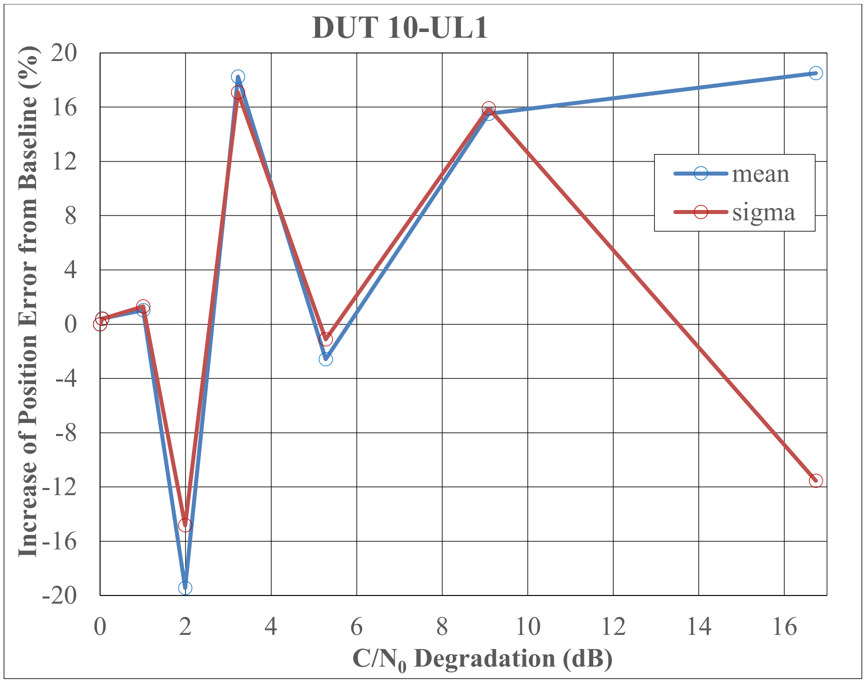
Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
None	43.9	Baseline	0.812	Baseline	0.115	Baseline
-70.7	43.9	0.0	0.826	1.8%	0.120	4.2%
-61.4	44.0	0.0	0.817	0.6%	0.123	6.3%
-50.5	43.9	0.0	0.818	0.8%	0.124	7.2%
-41.4	43.7	0.2	0.824	1.4%	0.120	4.4%
-36.4	43.2	0.8	0.827	1.8%	0.112	-3.0%
-32.4	42.4	1.6	0.829	2.0%	0.122	5.5%
-30.4	41.6	2.4	0.848	4.4%	0.124	7.2%
-28.5	40.5	3.4	0.831	2.3%	0.120	3.7%
-25.6	38.3	5.6	0.823	1.4%	0.126	9.1%
-23.6	36.0	7.9	0.844	4.0%	0.124	7.7%
-20.6	31.7	12.2	0.960	18.3%	0.209	80.9%



(a) C/N$_0$ and Position Error Distribution



(b) Sigma of Position Error Distribution

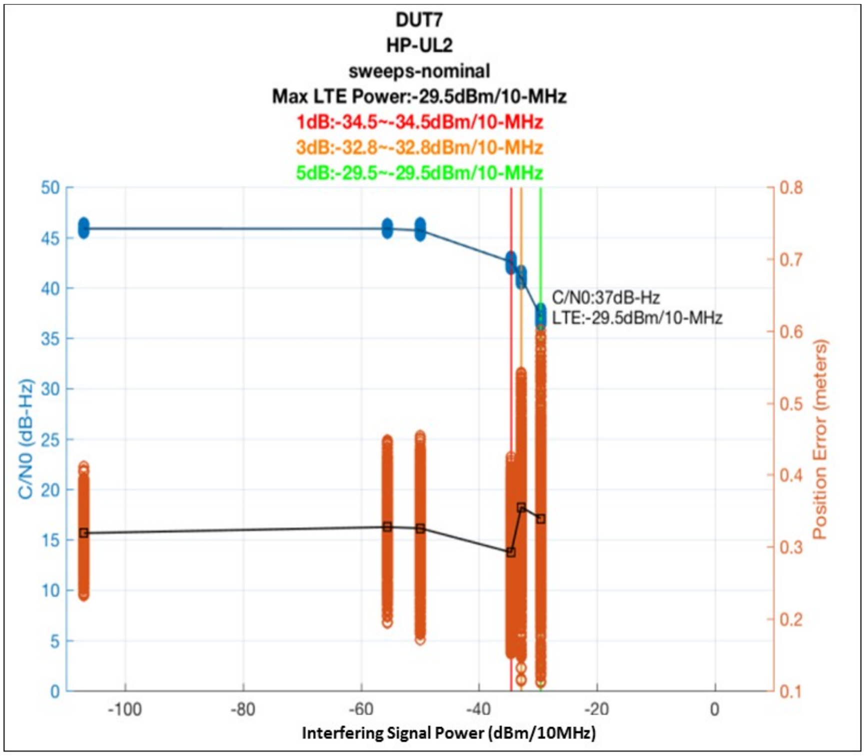


(c) Increase of Mean and Sigma of Position Error Distribution

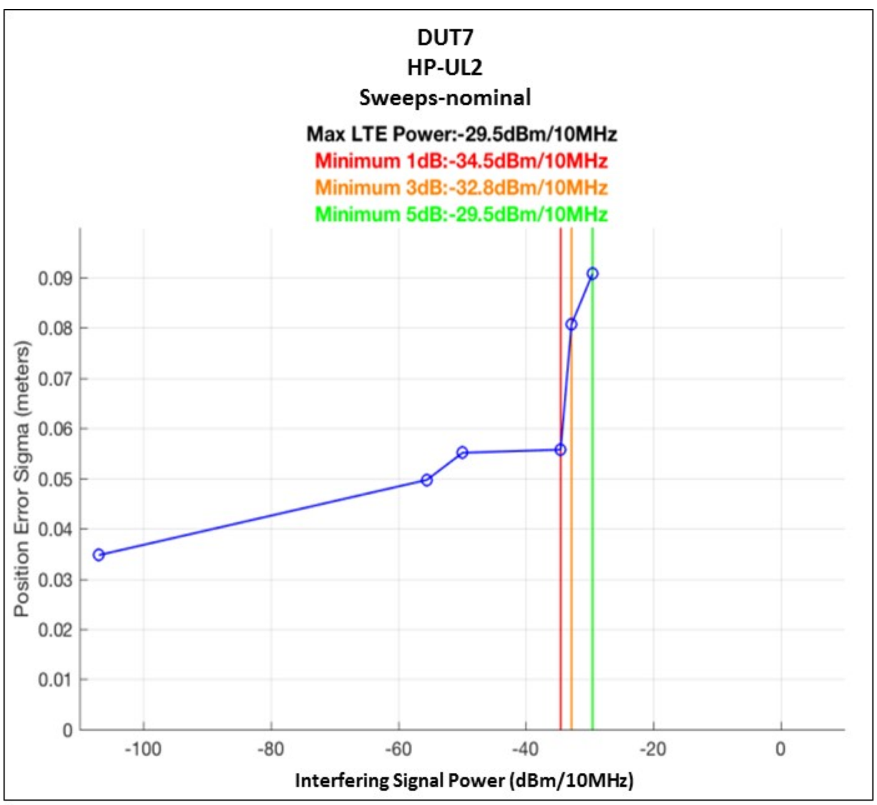
Figure D.A.3.10. 3-D Position Error Distribution for HP DUT 10 Interfering Signal in UL1 Band

Table D.A.3.10. 3-D Position Error Distribution for HP DUT 10 Interfering Signal in UL1 Band

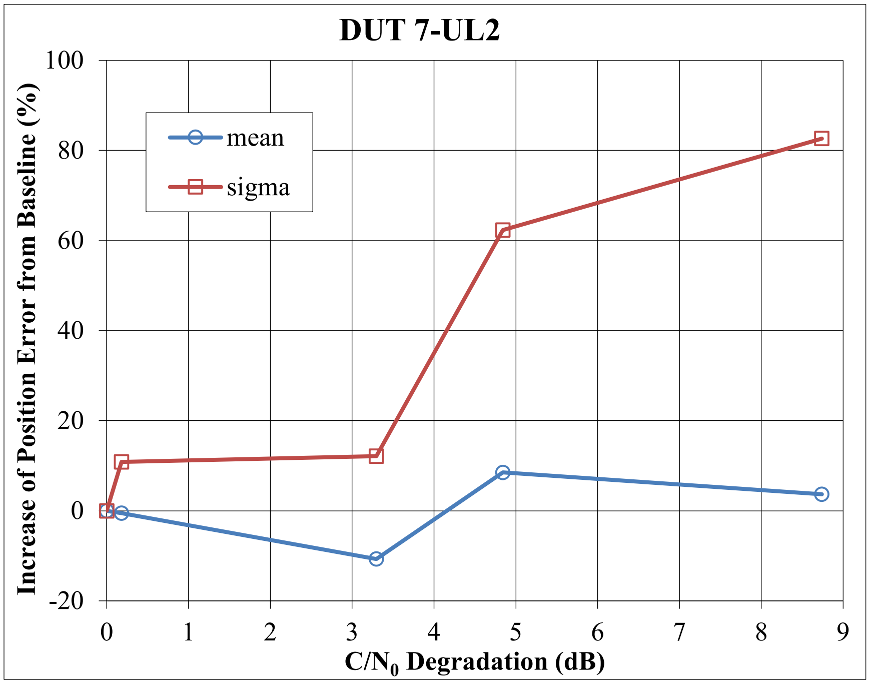
Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-107	48.0	0.00	1.21	0.0%	0.42	0.0%
-61.2	48.0	0.05	1.22	0.4%	0.42	0.4%
-54	47.0	1.01	1.23	1.0%	0.43	1.3%
-50.4	46.0	1.99	0.98	-19.4%	0.36	-14.8%
-45.4	44.8	3.22	1.44	18.2%	0.49	17.1%
-40.3	42.7	5.28	1.18	-2.6%	0.42	-1.1%
-35	38.9	9.09	1.40	15.5%	0.49	15.9%
-30.1	31.3	16.74	1.44	18.5%	0.37	-11.5%



(a) C/N$_0$ and Position Error Distribution



(b) Sigma of Position Error Distribution



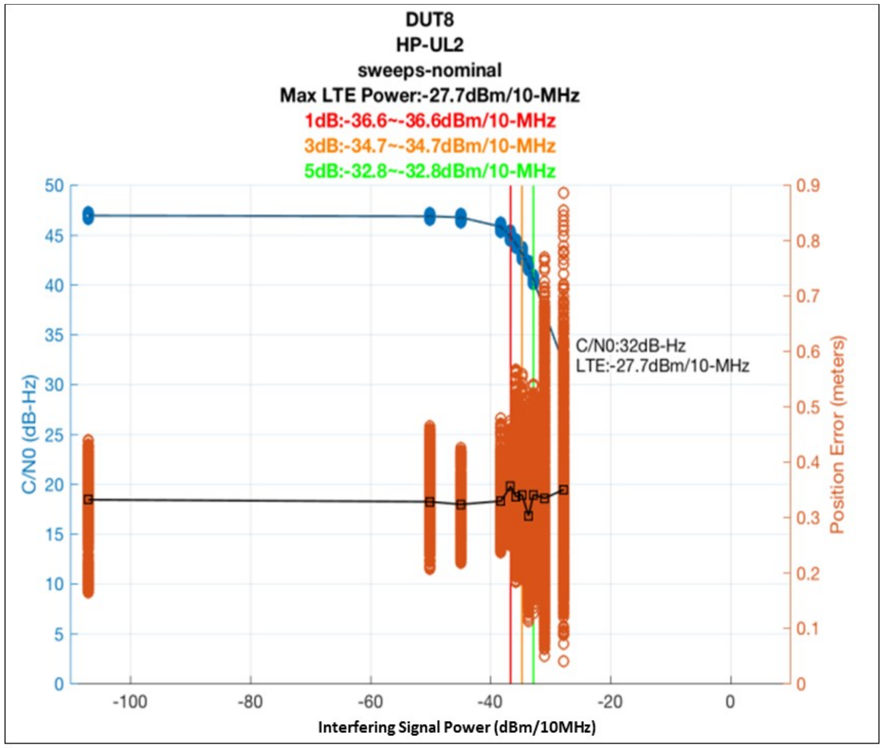
(c) Increase of Mean and Sigma of Position Error Distribution

Figure D.A.3.11. 3-D Position Error Distribution for HP DUT 7 Interfering Signal in UL2 Band

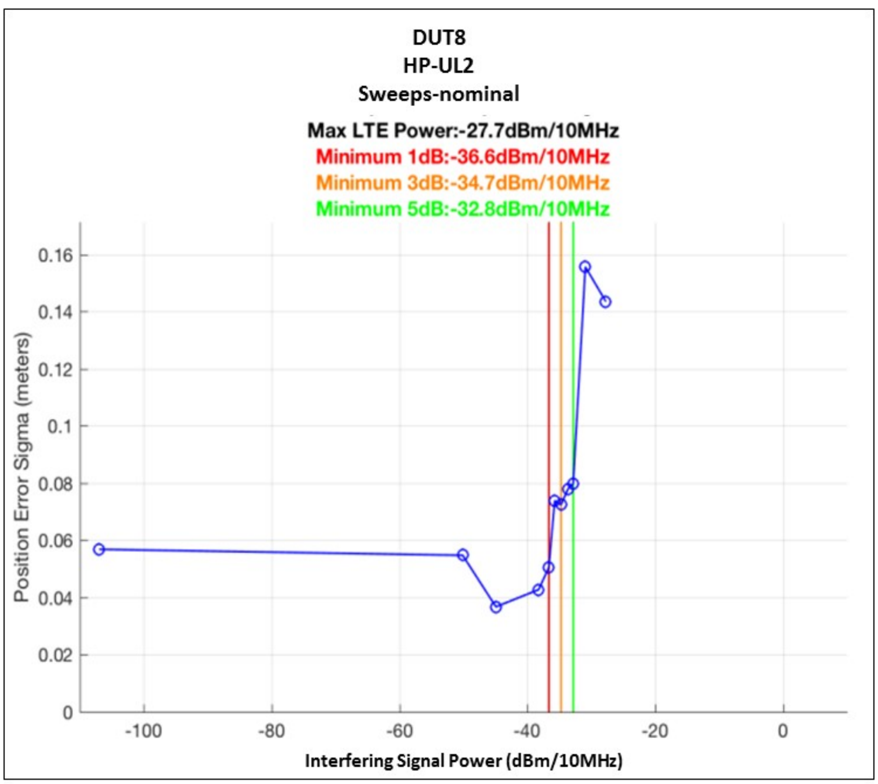
Table D.A.3.11. 3-D Position Error Distribution for HP DUT 7 Interfering Signal in UL2 Band

Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
None	45.9	-	0.319	-	0.035	-
-55.5	45.9	Baseline	0.327	Baseline	0.050	Baseline
-49.9	45.7	0.2	0.326	-0.5%	0.055	10.9%
-34.5	42.6	3.3	0.292	-10.7%	0.056	12.1%
-32.8	41.0	4.8	0.355	8.5%	0.081	62.3%
-29.5	37.1	8.7	0.339	3.7%	0.091	82.6%

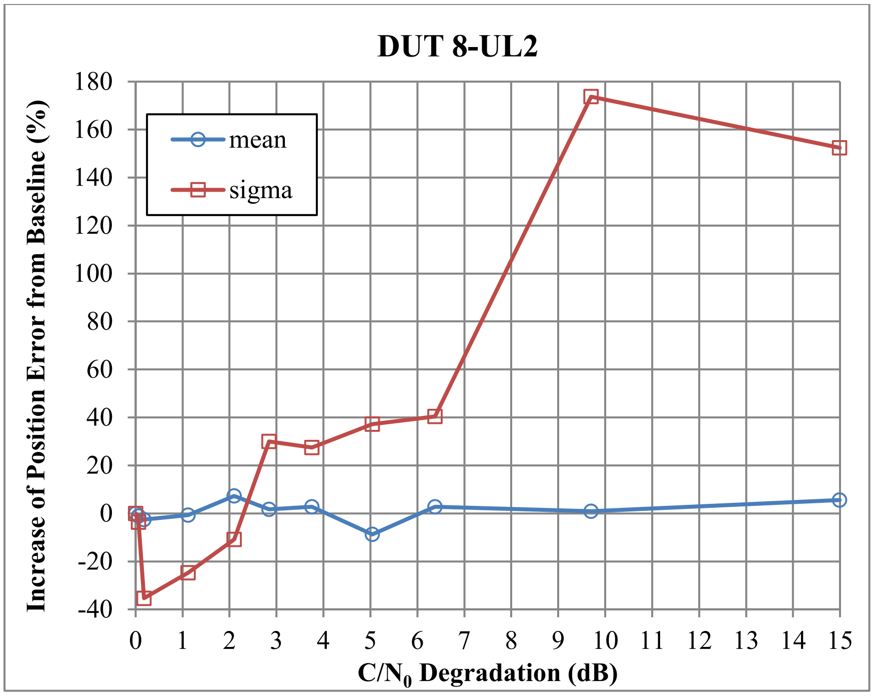
-: Not used as baseline because its sigma value appears to be unreliable.



(a) C/N$_0$ and Position Error Distribution



(b) Sigma of Position Error Distribution

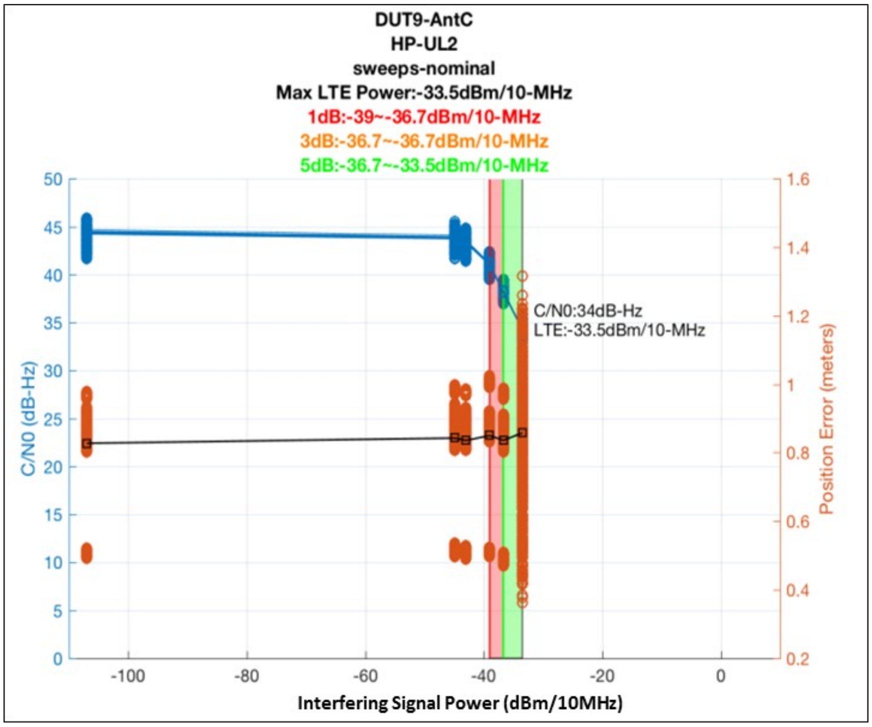


(c) Increase of Mean and Sigma of Position Error Distribution

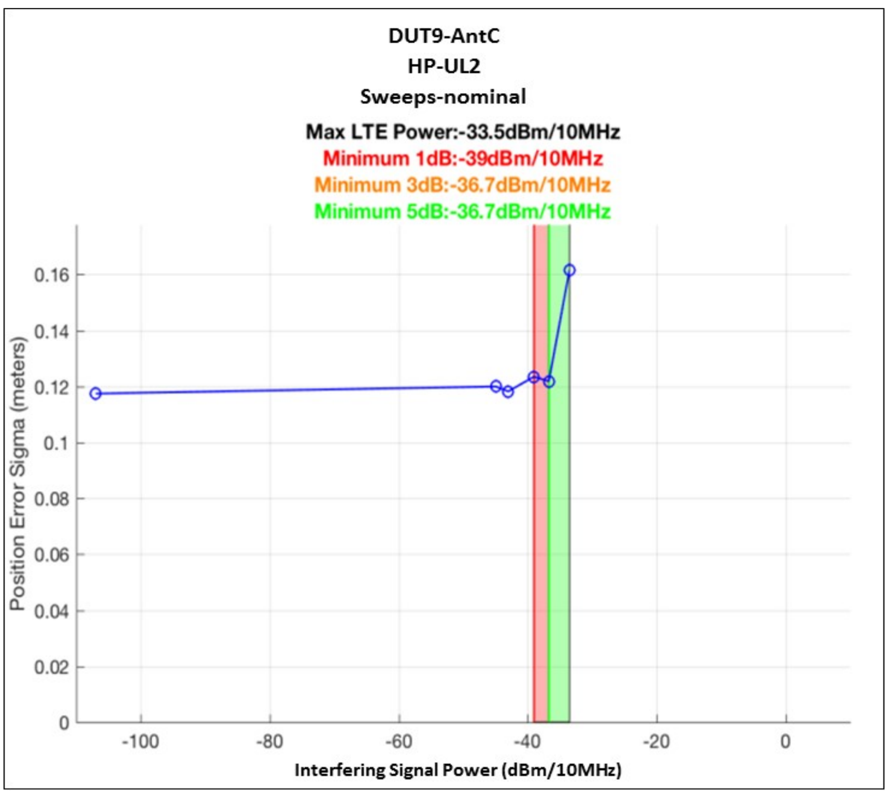
Figure D.A.3.12. 3-D Position Error Distribution for HP DUT 8 Interfering Signal in UL2 Band

Table D.A.3.12. 3-D Position Error Distribution for HP DUT 8 Interfering Signal in UL2 Band

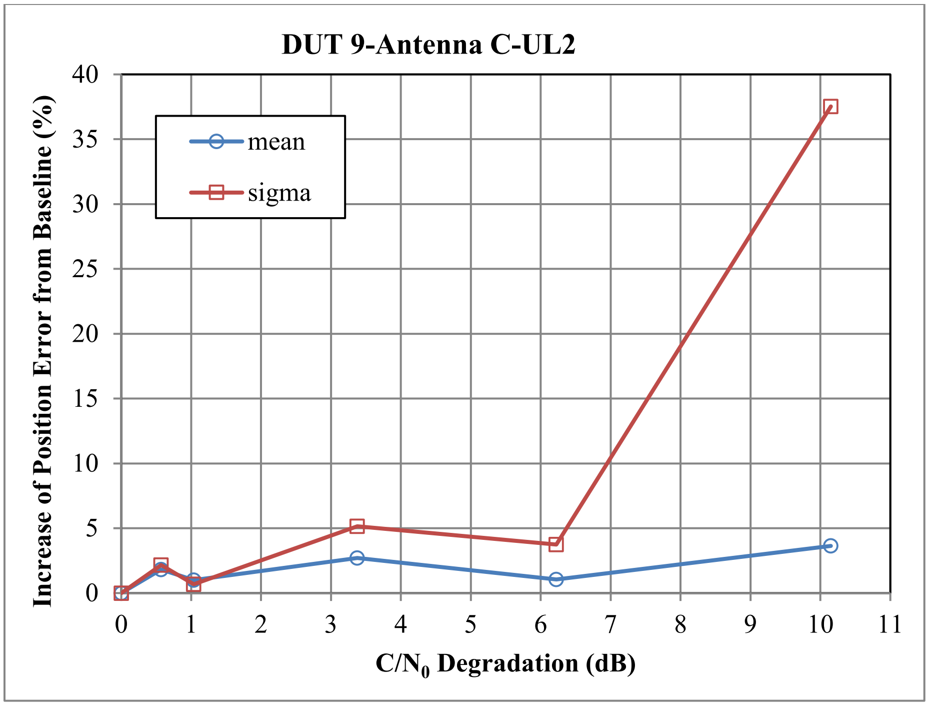
Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
None	46.9	Baseline	0.332	Baseline	0.057	Baseline
-50.1	46.9	0.1	0.328	-1.1%	0.055	-3.7%
-44.9	46.7	0.2	0.323	-2.5%	0.037	-35.4%
-38.2	45.8	1.1	0.329	-0.8%	0.043	-24.8%
-36.6	44.8	2.1	0.356	7.3%	0.051	-10.9%
-35.7	44.1	2.8	0.337	1.7%	0.074	29.9%
-34.7	43.2	3.8	0.341	2.8%	0.072	27.5%
-33.6	41.9	5.0	0.302	-8.8%	0.078	37.3%
-32.8	40.5	6.4	0.341	2.7%	0.080	40.4%
-30.9	37.2	9.7	0.334	0.8%	0.156	173.7%
-27.7	31.9	15.0	0.350	5.6%	0.144	152.4%



(a) C/N$_0$ and Position Error Distribution



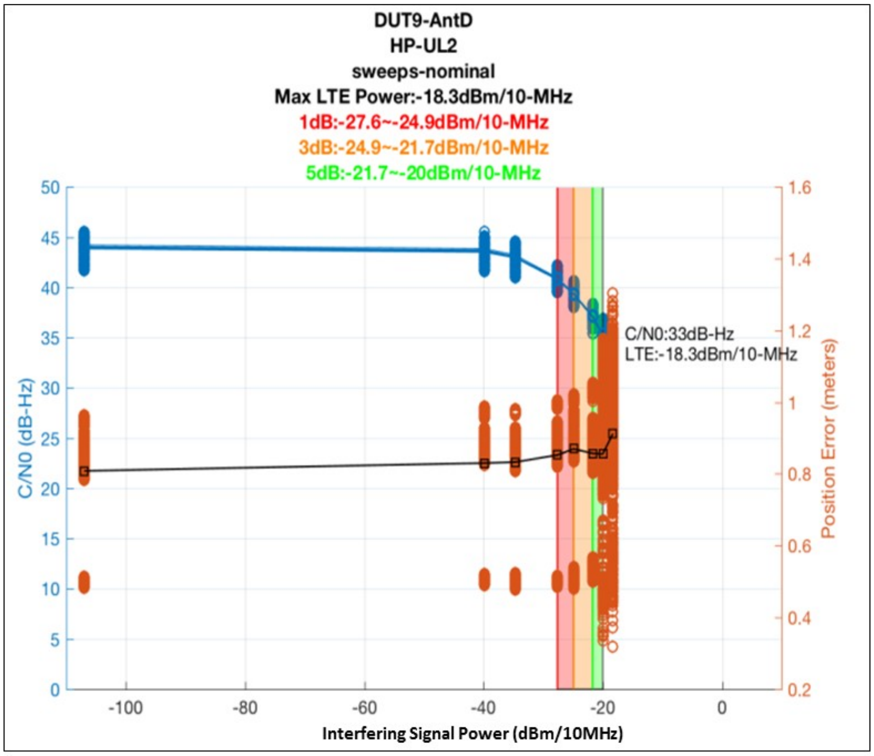
(b) Sigma of Position Error Distribution



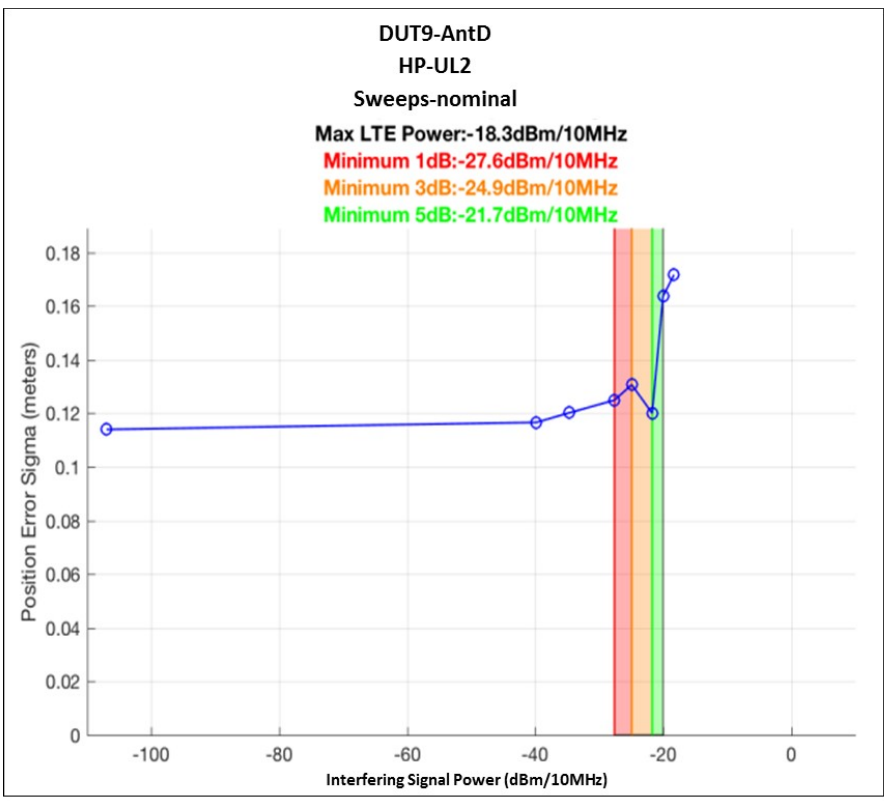
(c) Increase of Mean and Sigma of Position Error Distribution
Figure D.A.3.13. 3-D Position Error Distribution for HP DUT 9 with Antenna C Interfering Signal in UL2 Band

Table D.A.3.13. 3-D Position Error Distribution for HP DUT 9 with Antenna C Interfering Signal in UL2 Band

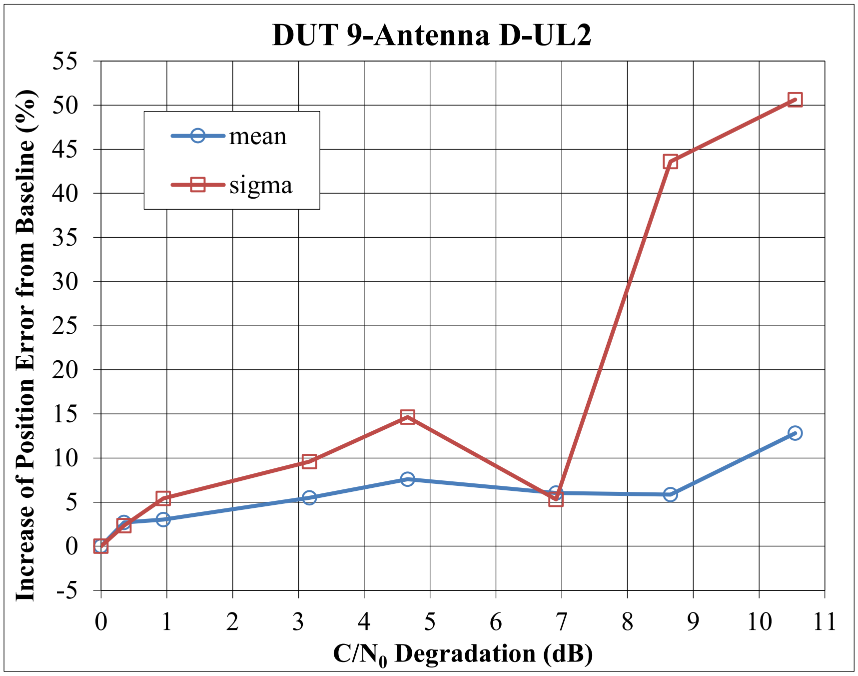
Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
none	44.4	Baseline	0.828	Baseline	0.117	Baseline
-44.9	43.9	0.6	0.843	1.8%	0.120	2.2%
-43	43.4	1.0	0.836	1.0%	0.118	0.7%
-39	41.1	3.4	0.850	2.7%	0.124	5.2%
-36.7	38.2	6.2	0.836	1.0%	0.122	3.7%
-33.5	34.3	10.1	0.858	3.6%	0.162	37.5%



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution

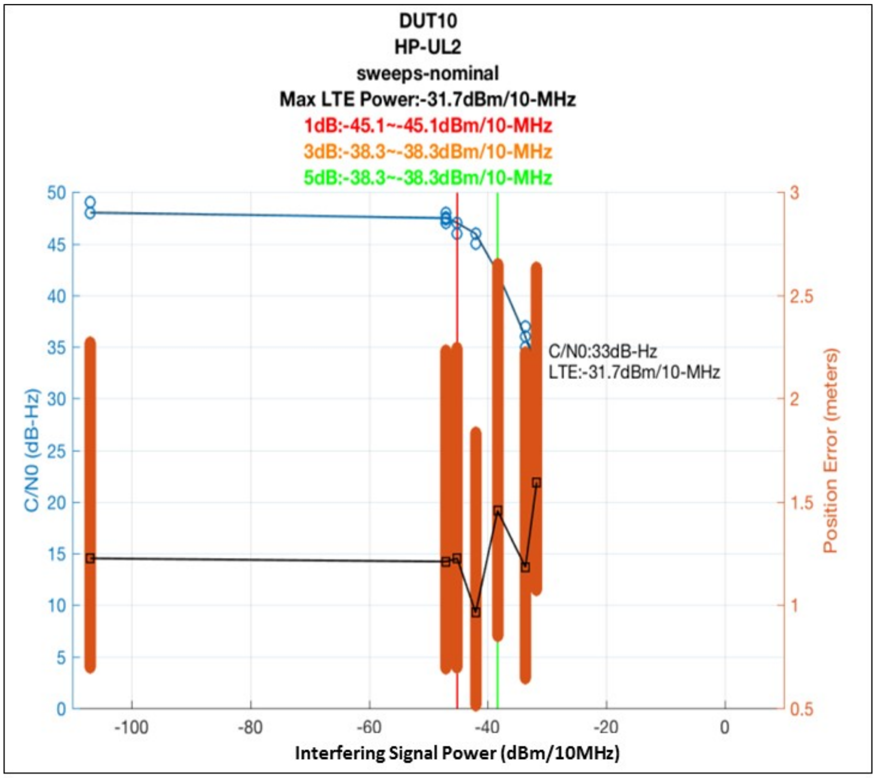


(c) Increase of Mean and Sigma of Position Error Distribution

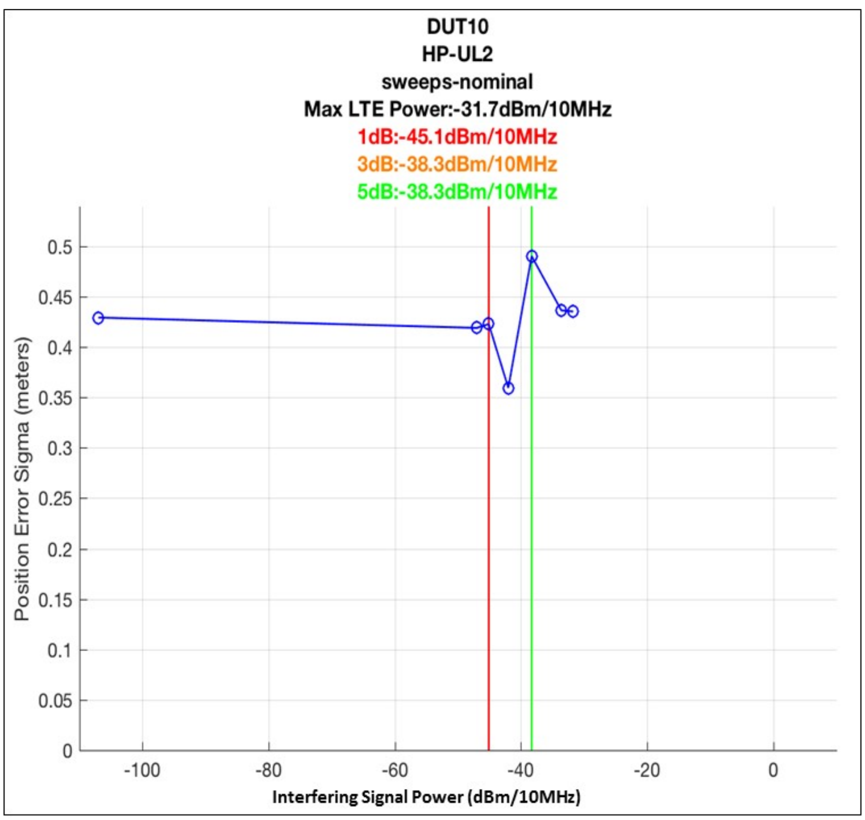
Figure D.A.3.14. 3-D Position Error Distribution for HP DUT 9 with Antenna D Interfering Signal in UL2 Band

Table D.A.3.14. 3-D Position Error Distribution for HP DUT 9 with Antenna D Interfering Signal in UL2 Band

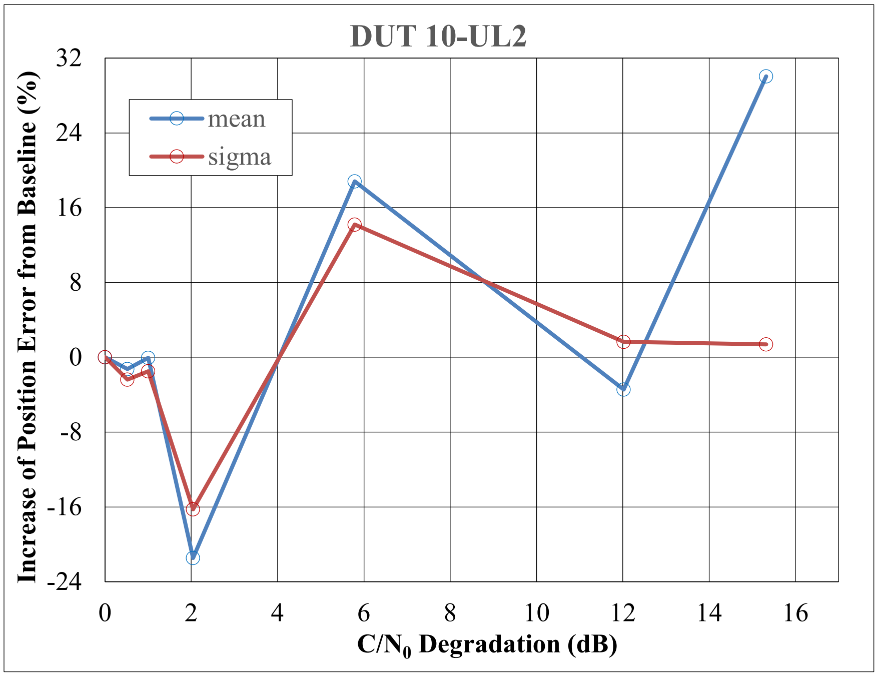
Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
none	44.0	Baseline	0.808	Baseline	0.114	Baseline
-39.8	43.6	0.3	0.830	2.7%	0.117	2.3%
-34.7	43.0	0.9	0.833	3.0%	0.120	5.4%
-27.6	40.8	3.2	0.853	5.5%	0.125	9.6%
-24.9	39.3	4.7	0.870	7.6%	0.131	14.6%
-21.7	37.1	6.9	0.857	6.1%	0.120	5.3%
-20.0	35.3	8.7	0.856	5.8%	0.164	43.6%
-18.3	33.4	10.5	0.912	12.8%	0.172	50.6%



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution



(c) Increase of Mean and Sigma of Position Error Distribution

Figure D.A.3.15. 3-D Position Error Distribution for HP DUT 10 Interfering Signal in UL2 Band

Table D.A.3.15. 3-D Position Error Distribution for HP DUT 10 Interfering Signal in UL2 Band

Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-107	48.0	Baseline	1.23	Baseline	0.43	Baseline
-47	47.5	0.52	1.21	-1.3%	0.42	-2.4%
-45.1	47.0	1.01	1.23	0.0%	0.42	-1.5%
-42	46.0	2.04	0.96	-21.5%	0.36	-16.3%
-38.3	42.2	5.79	1.46	18.8%	0.49	14.2%
-33.6	36.0	12.02	1.18	-3.5%	0.44	1.7%
-31.7	32.7	15.32	1.59	30.0%	0.44	1.4%

D.A.4 Summary

From the above plots and data, the interfering signal power and its corresponding C/N_0 and C/N_0 degradation when the mean and sigma show significant degradation are compared in Table D.A.4.1.

Table D.A.4.1. Threshold Interfering Signal Power, C/N_0, and C/N_0 Degradation Where Mean and Sigma Show Significant Degradation

(a) GLN Receiver Category

Interfering Signal Frequency Band	DUT	Threshold for Mean			Threshold for Sigma		
		LTE Power (dBm/10 MHz)	C/N_0 Mean (dB-Hz)	C/N_0 Degradation (dB)	LTE Power (dBm/10 MHz)	C/N_0 Mean (dB-Hz)	C/N_0 Degradation (dB)
1526-1536 MHz band (DL)	DUT 2	> 3.0	< 39.0	> 4.0	1.2	40.1	2.9
	DUT 4	> -8	< 35.8	> 4.6	-9.3	37.9	2.5
1627.5-1637.5 MHz Uplink band (UL1)	DUT 1	-6.3	33.0	8.0	-11.3	36.3	4.7
	DUT 2	> -6.6	< 35.0	> 8.1	-6.6	35.0	8.1
	DUT 3	-15.4	37.0	4.2	> -15.4	< 37.0	> 4.2
	DUT 4	-20.1	23.7	18.3	-22.5	30.2	11.8
1646.5-1656.5 MHz Uplink band (UL2)	DUT 1	> -6.3	< 32.0	> 8.9	-7.7	34.0	6.9
	DUT 2	> -6.4	< 34.0	> 6.0	-9.6	37.0	3.0
	DUT 3	-7	33.9	7.1	-9.5	36.9	4.1

DL DUT1 and DUT3 cases were not analyzed because of insignificant C/N_0 degradation.
“>” & “<” signs indicate mean or sigma does not degrade at the maximum LTE power.

(b) HP Receiver Category

Interfering Signal Frequency Band	DUT	Threshold for Mean			Threshold for Sigma		
		LTE Power (dBm/10 MHz)	C/N_0 Mean (dB-Hz)	C/N_0 Degradation (dB)	LTE Power (dBm/10 MHz)	C/N_0 Mean (dB-Hz)	C/N_0 Degradation (dB)
DL	DUT 7	-41.4	36.9	8.9	-58.3	42.5	3.3
	DUT 8	-54.2	32.0	15.1	-64.2	42.6	4.5
	DUT 9 Antenna C	> -41.8	< 33.8	> 10.6	-44.6	36.1	8.3
	DUT 9 Antenna D	> 2.2	< 31.7	> 10.8	2.2	31.7	10.8
	DUT 10	-64.4	46.0	2.0	-64.4	46.0	2.0
UL1	DUT 7	-33.8	35.0	9.4	-41.3	41.6	2.8
	DUT 8	-38.8	33.1	14.8	-46.3	41.8	6.1
	DUT 9 Antenna C	-37.1	32.0	12.5	-39.9	35.8	8.6
	DUT 9 Antenna D	-20.6	31.7	12.2	-20.6	31.7	12.2
	DUT 10	-45.4	44.8	3.2	-45.4	44.8	3.2
UL2	DUT 7	> -29.5	< 37.1	> 8.7	-32.8	41.0	4.8
	DUT 8	> -27.7	< 31.9	> 15.0	-35.7	44.1	2.8
	DUT 9 Antenna C	> -33.5	< 34.3	> 10.1	-33.5	34.3	10.1
	DUT 9 Antenna D	-18.3	33.4	10.5	-20.0	35.3	8.7
	DUT 10	-38.3	42.2	5.8	-38.3	42.2	5.8
">" & "<" signs indicate mean or sigma does not degrade at the maximum LTE power.							

Also, the C/N_0 degradations where the position error sigma significantly deviates from the mean are shown in Table D.A.4.2.

Table D.A.4.2. C/N_0 Degradation Values Where Position Error Distribution Sigma Deviates Significantly from Mean

(a) GLN Receiver Category

DUT Identifier	Interfering Signal Frequency Band	C/N_0 Degradation (dB)
DUT 2	DL	2.9
DUT 4	DL	2.5
DUT 1	UL1	4.7
DUT 2	UL1	8.1
DUT 3	UL1	No significant deviation
DUT 4	UL1	11.8
DUT 1	UL2	6.9
DUT 2	UL2	3.0
DUT 3	UL2	4.1
DL DUT1 and DUT3 cases were not analyzed because of insignificant C/N_0 degradation.		

(b) HP Receiver Category

DUT Identifier	Frequency Band	C/N_0 Degradation (dB)
DUT 7	DL	3.3
DUT 8	DL	4.5
DUT 9 Antenna C	DL	8.3
DUT 9 Antenna D	DL	10.8
DUT 10	DL	No significant deviation
DUT 7	UL1	2.8
DUT 8	UL1	6.1
DUT 9 Antenna C	UL1	8.6
DUT 9 Antenna D	UL1	12.2
DUT 10	UL1	No significant deviation
DUT 7	UL2	4.8
DUT 8	UL2	2.8
DUT 9 Antenna C	UL2	10.1
DUT 9 Antenna D	UL2	8.7
DUT 10	UL2	No significant deviation

ADDENDUM B R&A MEASUREMENT DATA

D.B.1 Introduction

Addendum B presents the analysis of Carrier-to-Noise Density (C/N_0) and position error distribution of the Roberson and Associates (R&A) measurement data.

R&A performed measurements of Global Position System (GPS) receivers in the General Location/Navigation Receiver Category (GLN), High Precision Receiver Category (HP), Cellular Receiver Category (CEL), Timing Receiver Category (TIM), and General Aviation Receiver Category (GAV) categories. Measurements were performed without interfering signal and with Long Term Evaluation (LTE) interfering signal in the 1526-1536 MHz band (DL), 1627.5-1637.5 (UL1), and 1646.5-1656.5 MHz (UL2) bands.

In this addendum the results of the following three measurement scenarios are analyzed:[1]

- Open sky with motion. The simulator created a moving constellation of GPS signals representative of a moving GPS receiver. This scenario was used for GLN and CEL receivers.
- Open sky and static. The simulator created a moving constellation of GPS signals representative of a static location. This scenario was predominantly used for HP receivers.
- Impaired GPS signals with motion. The simulator created a moving constellation of GPS signals at reduced GPS power levels representative of a moving GPS receiver. The GPS signal levels were 12 Decibel (dB) lower than those in the open sky scenario. This scenario was used for GLN receivers.

For a given interfering signal frequency allocation and power level, the condition is maintained for 3 minutes, and 1 measurement is taken every 2 seconds, resulting in 90 data points for each measurement condition.

The DUTs whose measurement data have C/N_0 and position error are shown in Table D.B.1 together with the operating scenarios and the ranges of C/N_0 variation during the measurement. Overall, there are only 12 cases where the C/N_0 variation exceeds 3 dB. Furthermore, only these 12 cases show expansion in the position error distribution. These cases are in shaded cells in Table D.B.1.

[1] R&A also conducted a fourth measurement scenario referred to as “live sky” which used a rooftop antenna to receive both the GPS signals and the augmentation signals and presented the signals to receivers in the anechoic chamber. This scenario was used for some HP receivers. These results are not analyzed here because it is difficult to develop the correlation between C/N_0 and the position error performance.

Table D.B.1. DUTs and the Range of Mean C/N$_0$ in R&A Measurement

DUT	Scenario	Range of Mean C/N$_0$ Throughout Measurement		
		Interfering Signal Frequency Band		
		DL	UL1	UL2
Garmin eTrex H	Open Sky With Motion	1 dB	20 dB	0.5 dB
Garmin eTrex H	Impaired GPS Signal With Motion	1.7 dB	14 dB	11 dB
Garmin GPSMAP 76 CSx	Open Sky With Motion	0.2 dB	0.4 dB	0.8 dB
Garmin GPSMAP 78 SC	Open Sky With Motion	0.5 dB	1.1 dB	0.5 dB
Garmin GPSMAP 78 SC	Impaired GPS Signal With Motion	0.5 dB	0.4 dB	0.6 dB
Garmin Montana 650t	Open Sky With Motion	0.3 dB	1 dB	0.3 dB
Garmin Montana 650t	Impaired GPS Signal With Motion	0.7 dB	0.4 dB	0.7 dB
Garmin Montana 650t	Open Sky and Static	0.4 dB	0.5 dB	0.5 dB
Motorola MW810	Open Sky With Motion	2.7 dB	2.2 dB	1.7 dB
Motorola MW810	Impaired GPS Signal With Motion	3.5 dB	1.5 dB	1.6 dB

(a) GLN Receiver Category

DUT	Scenario	Range of Mean C/N$_0$ Throughout Measurement		
		Interfering Signal Frequency Band		
		DL	UL1	UL2
Novatel Smart6	Open Sky and Static	15 dB	15 dB	1.0 dB
Topcon System 310	Open Sky and Static	8 dB	1.1 dB	0.4 dB
Trimble AgGPS 542, Javad (Filtered) Antenna	Open Sky and Static	0.7 dB	0.7 dB	0.7 dB
Trimble AgGPS 542, Zephyr Antenna	Open Sky and Static	21 dB	22 dB	19 dB
Trimble Geo 7X	Open Sky and Static	6 dB	2.2 dB	0.7 dB
Trimble SPS855, Javad (Filtered) Antenna	Open Sky and Static	0.6 dB	0.7 dB	0.7 dB
Trimble SPS855 with GA 530 Antenna	Open Sky and Static	21 dB	1.4 dB	0.6 dB
Trimble SPS985	Open Sky and Static	0.6 dB	18 dB	0.5 dB

(b) HP Receiver Category

DUT	Scenario	Range of Mean C/N0 Throughout Measurement		
		Interfering Signal Frequency Band		
		DL	UL1	UL2
Garmin GPSMAP 696	Open Sky and Static	1.3 dB	0.7 dB	0.9 dB

(c) GAV Receiver Category

For the other cases whose C/N0 and position error distribution have little degradation, a sample of the C/N0 and position error distribution variations is shown in Figure D.B.1. In Figure D.B.1, the "+" signs are the marks of the C/N0 data points, the solid blue line is the mean of the position error distribution, the broken blue line is the maximum of the position error distribution, and the broken brown line is the minimum of the position error distribution.

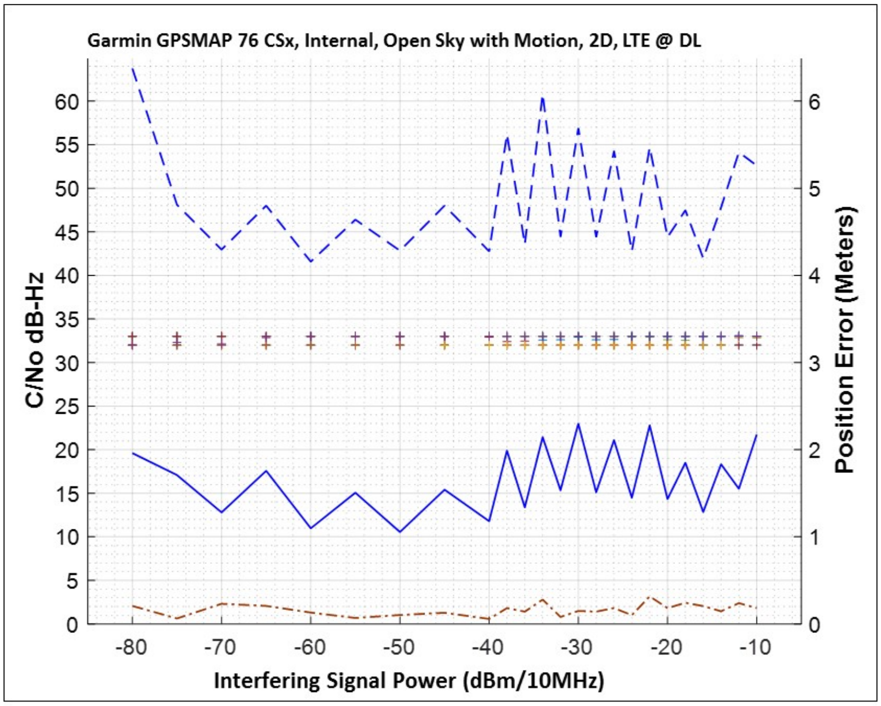


Figure D.B.1. Sample of Stable C/N0 and Position Error Throughtout Measurement

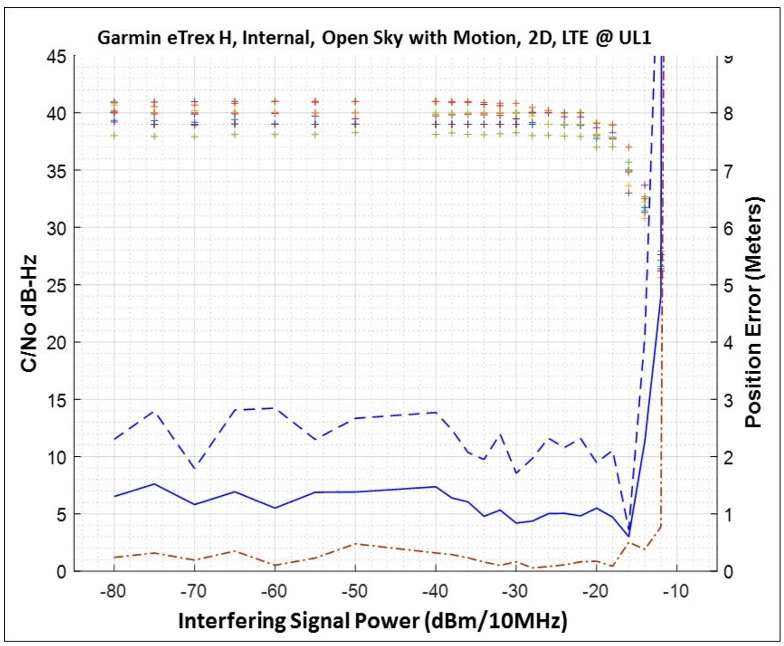
Since this addendum analyzes the position error distribution degradation and its correlation with the C/N0 degradation, only the cases with position error distribution degradations are analyzed. Also, the analysis does not include the live sky scenario. In the live sky scenario, the position is derived from pseudorange of various C/N0 levels. In this situation, it is difficult to correlate the position error with the C/N0 level. The analysis are presented in Sections D.B.1 and D.B.2 for the GLN and HP receivers, respectively. In this analysis, the sigma of the position error distribution is used as the index to evaluate the data distribution. The graphs and tables contain the following information:

- C/N0 distribution and its mean, and the position error distribution and its mean as a function of interfering signal power;

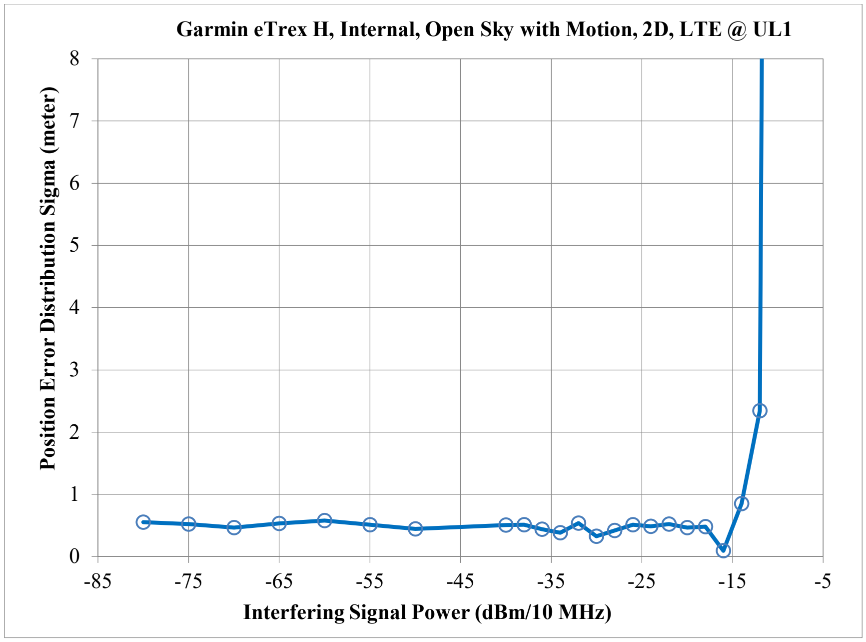
- Sigma of the position error distribution (the difference between the maximum and the minimum position error data) as a function of interfering signal power; and
- Increases (relative to the baseline) in the mean and sigma of the position error distributions as a function of the C/N_0 degradation. Here the baseline is the measurement data when the interfering signal power is at the minumum level -80 dBm/10 MHz.

Every figure is followed by a table listing the parametric values in figures (a), (b), and (c), i.e., the interfering signal power level, the mean and degradation of C/N_0, the mean and sigma of the position error distribution, and the increase in mean and sigma relative to the baseline. In several cases when the baseline data appear to be unrealiable, a more reasonable measurement data is used as the new baseline; this is indicated in the tables and reflected in figure (c). The shaded cells in the tables indicate when the mean and sigma begin to increase noticeably. In numerous cases it is a judgement call when the increase occurs, and the fluctuation of the data further complicates this selection.

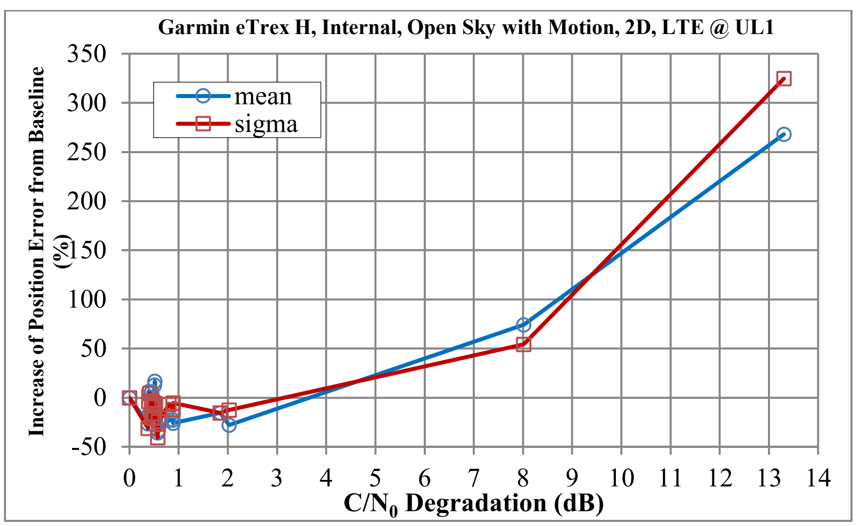
D.B.2 GLN Receiver Category



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution



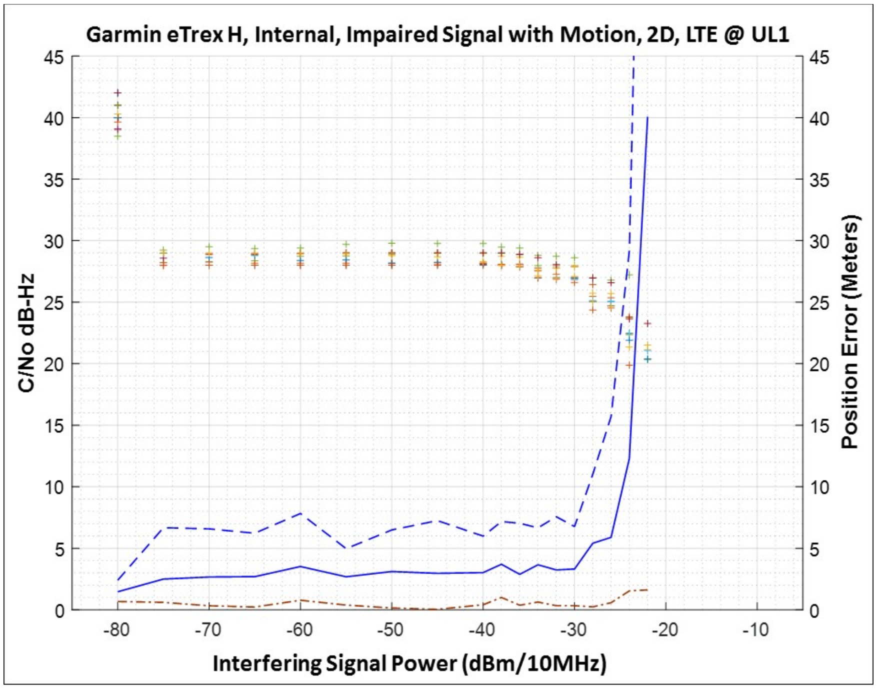
(c) Increase of Mean and Sigma of Position Error Distribution

Figure D.B.2.1. Position Error Distribution for Garmin eTrex H Interfering Signal in UL1 Band

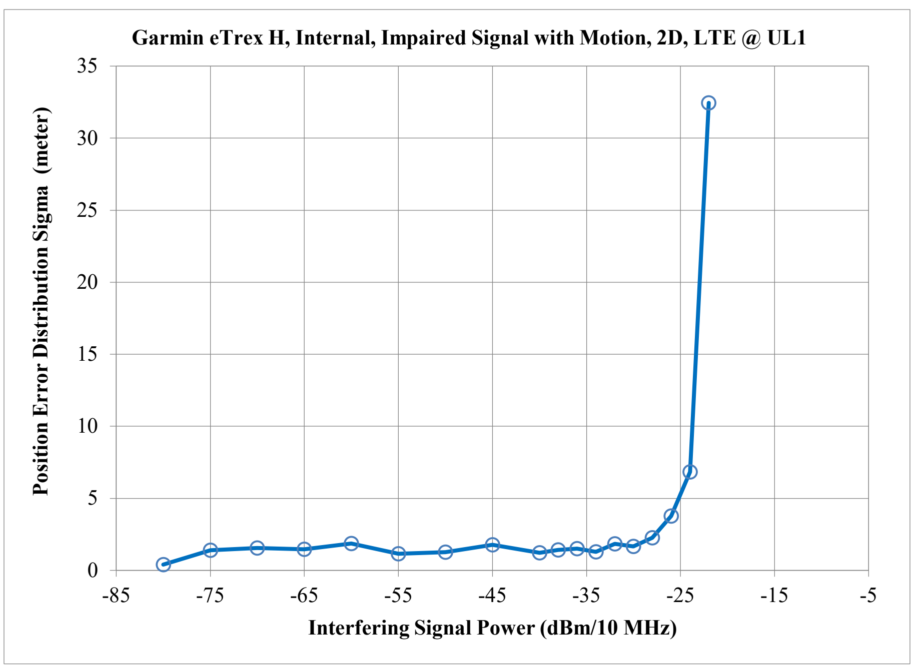
Table D.B.2.1. Position Error Distribution for Garmin eTrex H
Open Sky with Motion
Interfering Signal in UL1 Band

Interfering Signal Power (dBm/10 MHz)	C/N₀		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-80	40.0	Baseline	1.303	Baseline	0.553	Baseline
-75	39.5	0.52	1.522	16.7%	0.521	-5.7%
-70	39.5	0.51	1.162	-10.8%	0.464	-16.0%
-65	39.6	0.39	1.386	6.3%	0.532	-3.7%
-60	39.6	0.41	1.101	-15.5%	0.577	4.4%
-55	39.6	0.45	1.377	5.7%	0.512	-7.3%
-50	39.6	0.45	1.382	6.0%	0.443	-19.9%
-40	39.5	0.51	1.473	13.0%	0.506	-8.4%
-38	39.5	0.49	1.278	-1.9%	0.514	-7.0%
-36	39.5	0.50	1.211	-7.1%	0.439	-20.6%
-34	39.7	0.38	0.958	-26.5%	0.381	-31.1%
-32	39.6	0.45	1.067	-18.1%	0.536	-3.1%
-30	39.5	0.57	0.839	-35.6%	0.328	-40.7%
-28	39.4	0.59	0.874	-33.0%	0.419	-24.2%
-26	39.2	0.80	1.004	-23.0%	0.513	-7.2%
-24	39.1	0.88	1.009	-22.6%	0.486	-12.0%
-22	39.1	0.89	0.965	-26.0%	0.523	-5.3%
-20	38.2	1.85	1.101	-15.5%	0.467	-15.5%
-18	38.0	2.02	0.942	-27.7%	0.483	-12.6%
-16	34.9	5.11*	0.602	-53.8%*	0.092	-83.3%*
-14	32.0	8.01	2.270	74.2%	0.852	54.2%
-12	26.7	13.30	4.797	268.0%	2.346	324.7%
-10	20.9	19.12*	125.967	9565%**	52.613	9422%**

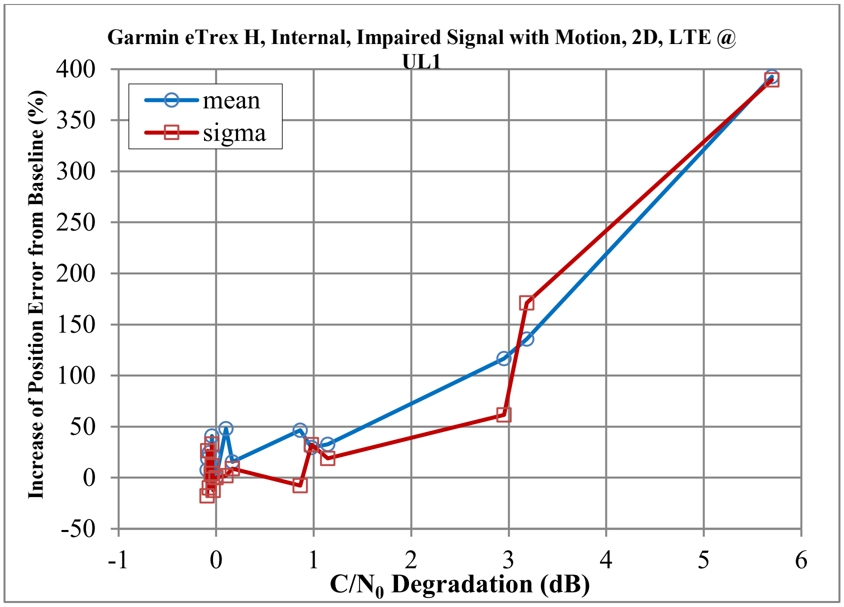
*: Data not included in figure (c) because there are only three measurement data points and not feasible for statistical application.
**: Data point was not included in figure (c) because the data appears to be unreliable.



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution



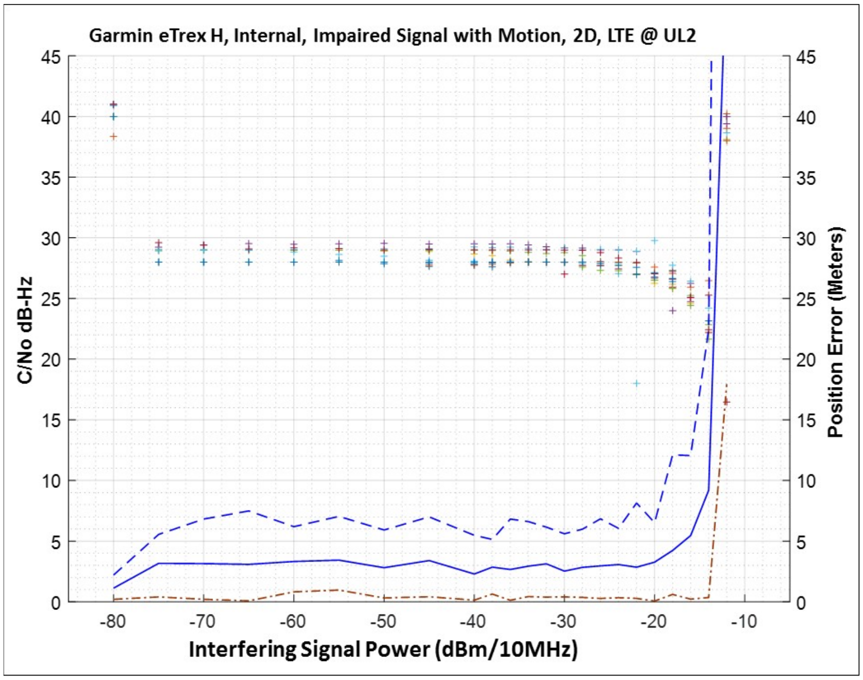
(c) Increase of Mean and Sigma of Position Error Distribution

Figure D.B.2.2. Position Error Distribution for Garmin eTrex H Interfering Signal in UL1 Band

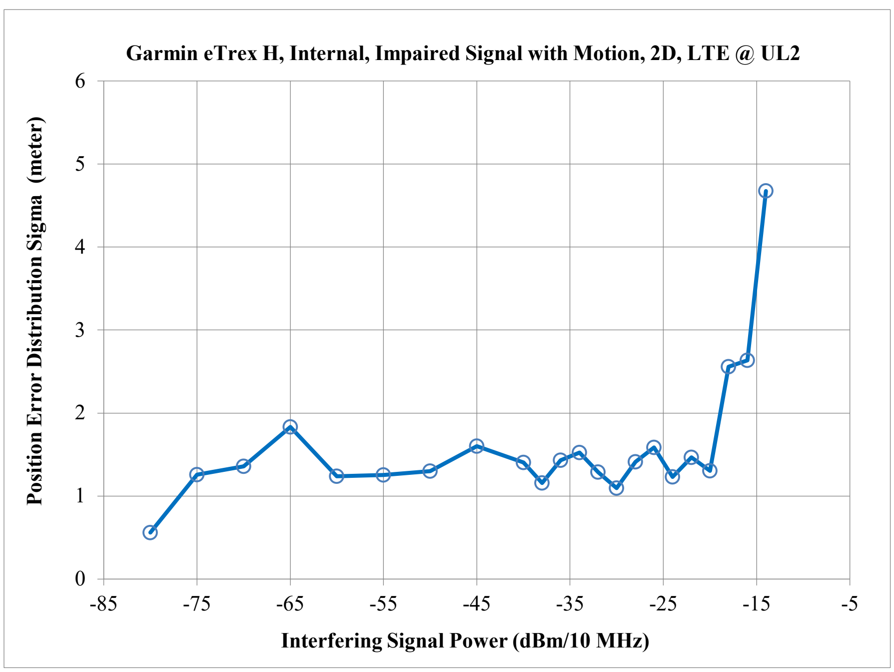
Table D.B.2.2. Position Error Distribution for Garmin eTrex H Impaired GPS Signal with Motion Interfering Signal in UL1 Band

Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-80	40.3	-	1.469	-	0.400	-
-75	28.6	Baseline	2.498	Baseline	1.394	Baseline
-70	28.6	-0.04	2.668	6.8%	1.559	11.8%
-65	28.6	-0.05	2.697	8.0%	1.454	4.3%
-60	28.6	-0.04	3.518	40.8%	1.856	33.1%
-55	28.7	-0.09	2.686	7.5%	1.147	-17.7%
-50	28.6	-0.07	3.112	24.6%	1.258	-9.8%
-45	28.7	-0.08	2.964	18.6%	1.765	26.5%
-40	28.6	-0.03	3.026	21.1%	1.222	-12.4%
-38	28.5	0.10	3.701	48.2%	1.422	2.0%
-36	28.4	0.17	2.883	15.4%	1.518	8.9%
-34	27.7	0.86	3.661	46.6%	1.286	-7.8%
-32	27.6	0.98	3.239	29.7%	1.845	32.3%
-30	27.4	1.14	3.317	32.8%	1.657	18.8%
-28	25.6	2.95	5.413	116.7%	2.253	61.5%
-26	25.4	3.19	5.887	135.6%	15.131	171.1%
-24	22.9	5.70	12.305	392.6%	27.645	389.6%
-22	21.3	7.29*	40.076	1504%*	92.785	2227%*

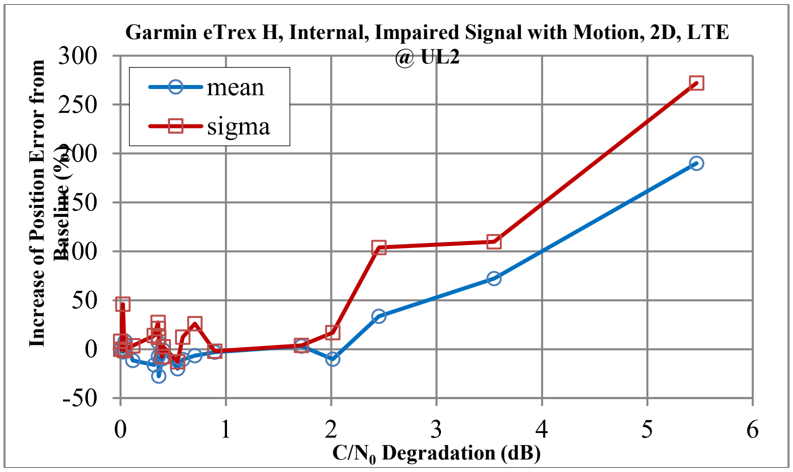
-: Not used as baseline because its sigma value appears to be unreliable.
*: Data point was not included in figure (c) because the data appears to be unreliable.



(a) C/N0 and Position Error Distribution



(b) Sigma of Position Error Distribution



(c) Increase of Mean and Sigma of Position Error Distribution

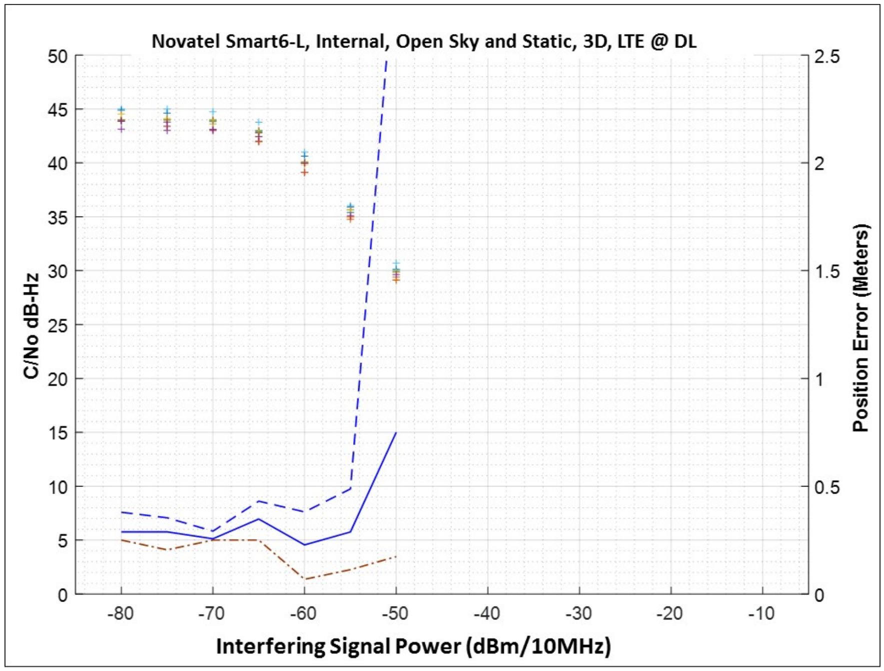
Figure D.B.2.3. Position Error Distribution for Garmin eTrex H Impaired GPS Signal with Motion Interfering Signal in UL2 Band

Table D.B.2.3. Position Error Distribution for Garmin eTrex H Interfering Signal in UL2 Band

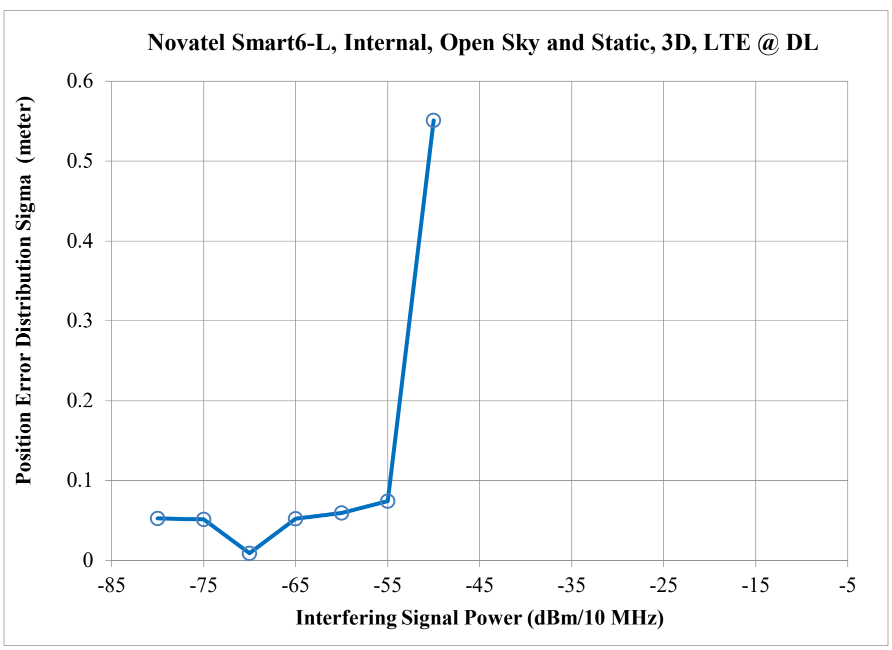
Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-80	40.4	-	1.126	-	0.561	-
-75	28.8	Baseline	3.174	Baseline	1.256	Baseline
-70	28.8	0.00	3.149	-0.8%	1.358	8.1%
-65	28.8	0.02	3.088	-2.7%	1.833	45.9%
-60	28.8	0.04	3.324	4.7%	1.237	-1.5%
-55	28.8	0.04	3.433	8.2%	1.255	-0.1%
-50	28.7	0.12	2.810	-11.5%	1.300	3.4%
-45	28.5	0.36	3.399	7.1%	1.601	27.4%
-40	28.5	0.36	2.294	-27.7%	1.406	11.9%
-38	28.5	0.40	2.857	-10.0%	1.158	-7.8%
-36	28.5	0.32	2.664	-16.0%	1.430	13.9%
-34	28.5	0.36	2.938	-7.4%	1.523	21.2%
-32	28.4	0.40	3.133	-1.3%	1.287	2.5%
-30	28.3	0.54	2.531	-20.2%	1.095	-12.8%
-28	28.3	0.59	2.839	-10.5%	1.411	12.3%
-26	28.1	0.71	2.960	-6.7%	1.585	26.1%
-24	28.0	0.89	3.071	-3.2%	1.232	-2.0%
-22	26.8	2.01	2.853	-10.1%	1.468	16.9%
-20	27.1	1.72	3.270	3.0%	1.305	3.9%
-18	26.4	2.45	4.234	33.4%	2.560	103.8%
-16	25.3	3.54	5.462	72.1%	2.634	109.7%
-14	23.4	5.47	9.205	190.1%	4.674	272.1%
-12	37.3	-8.41*	53.979	1600%*	44.200	3418%*

-: Not used as baseline because its sigma value appears to be unreliable.
*: Data point was not included in figures (b) and (c) because the data appears to be unreliable.

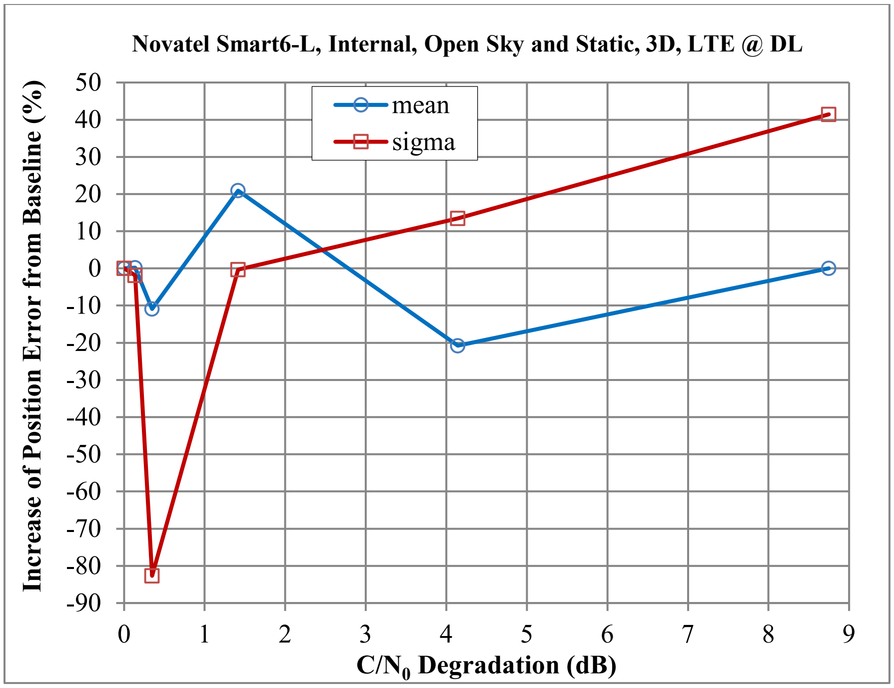
D.B.3 HP Receiver Category



(a) C/N0 and Position Error Distribution



(b) Sigma of Position Error Distribution



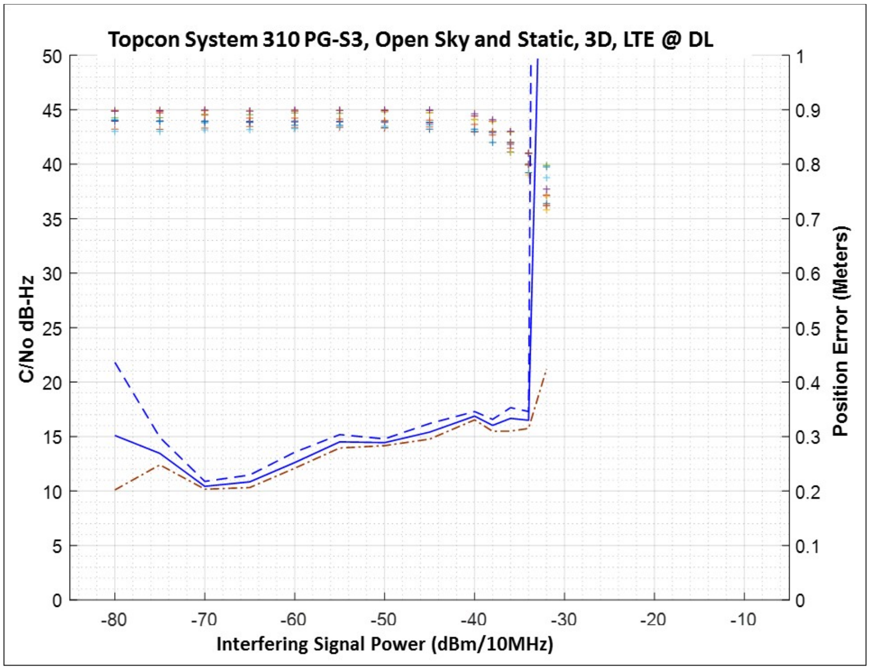
(c) Increase of Mean and Sigma of Position Error Distribution

Figure D.B.3.1. 3-D Position Error Distribution for Novatel Smart6-L Interfering Signal in DL Band

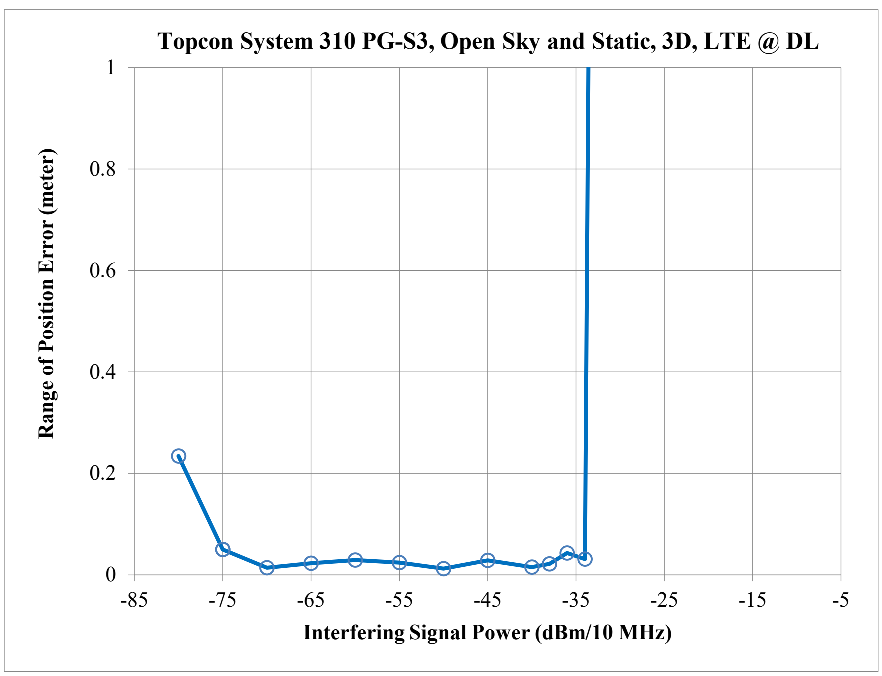
Table D.B.3.1. 3-D Position Error Distribution for Novatel Smart6-L Interfering Signal in DL Band

Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-80	44.1	0.00	0.288	0.0%	0.053	0.0%
-75	44.0	0.14	0.289	0.2%	0.052	-1.9%
-70	43.8	0.35	0.257	-10.9%	0.009	-82.7%
-65	42.7	1.42	0.348	20.9%	0.052	-0.3%
-60	40.0	4.14	0.228	-20.8%	0.060	13.4%
-55	35.4	8.75	0.288	0.0%	0.074	41.4%
-50	29.8	14.37*	0.751	160%*	0.551	948%*

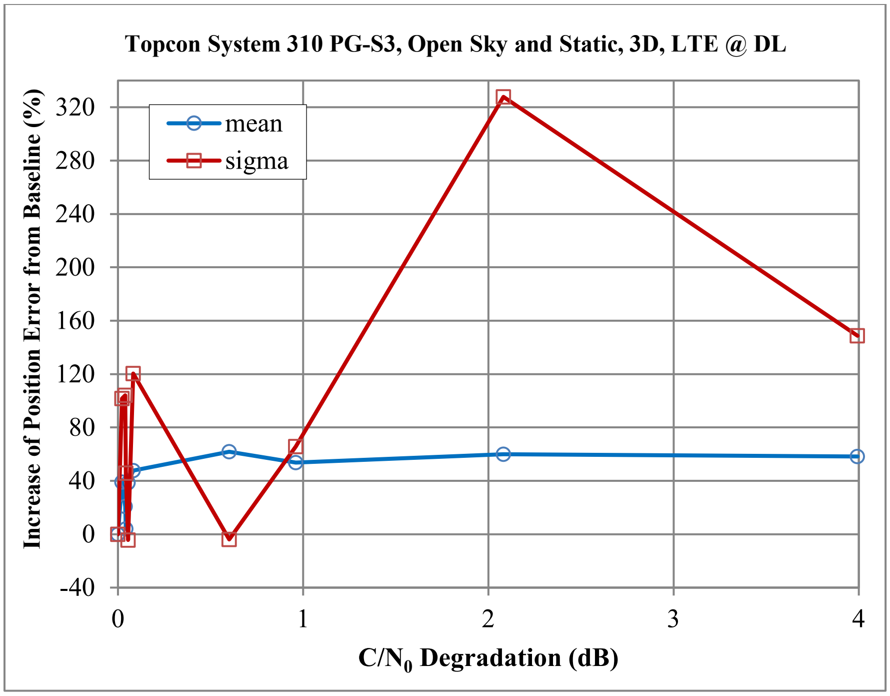
*: Data point was not included in figure (c) because the data appears to be unreliable.



(a) C/N$_0$ and Position Error Distribution



(b) Sigma of Position Error Distribution



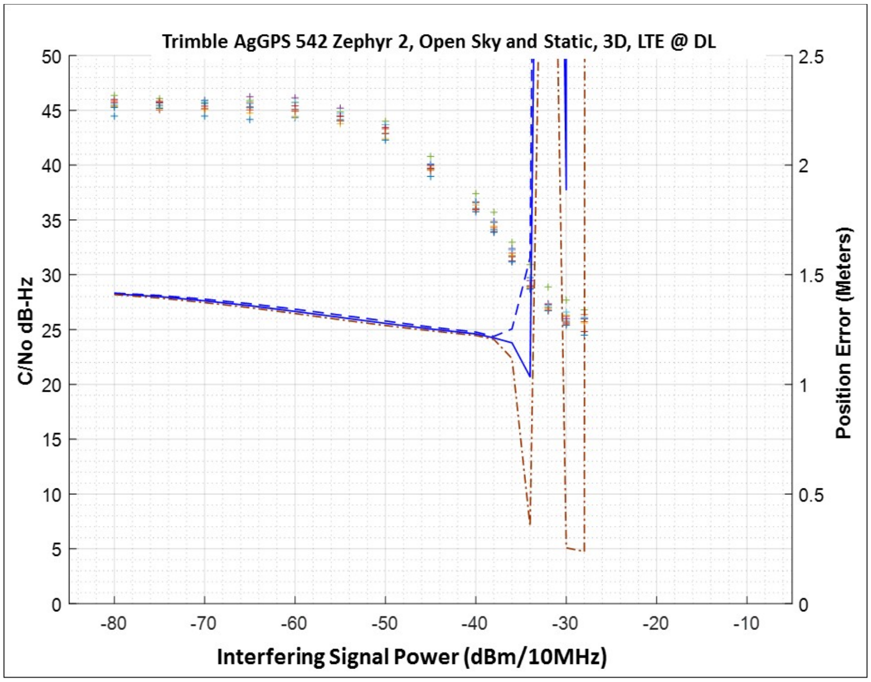
(c) Increase of Mean and Sigma of Position Error Distribution

Figure D.B.3.2. 3-D Position Error Distribution for Topcon System 310 Interfering Signal in DL Band

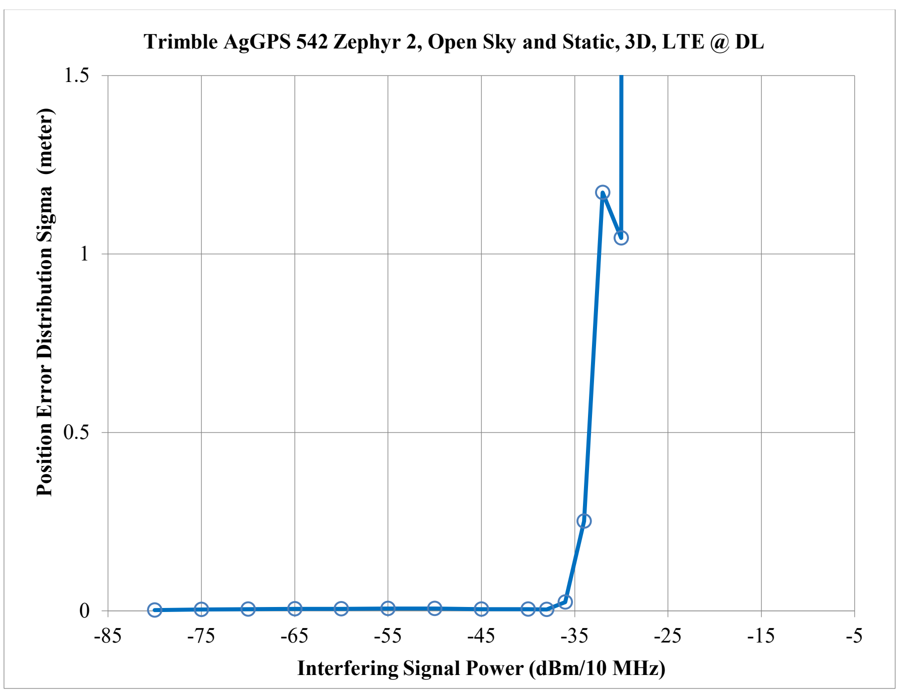
Table D.B.3.2. 3-D Position Error Distribution for Topcon System 310 Interfering Signal in DL Band

Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-80	44.2	-	0.302	-	0.064	-
-75	44.2	-	0.269	-	0.013	-
-70	44.2	Baseline	0.209	Baseline	0.004	Baseline
-65	44.2	0.04	0.217	4.0%	0.005	45.9%
-60	44.2	0.04	0.252	20.9%	0.007	104.2%
-55	44.2	0.02	0.290	39.2%	0.007	101.6%
-50	44.1	0.05	0.289	38.5%	0.003	-4.3%
-45	44.1	0.08	0.308	47.7%	0.008	120.4%
-40	43.6	0.60	0.337	61.8%	0.003	-4.0%
-38	43.2	0.96	0.320	53.7%	0.006	65.6%
-36	42.1	2.08	0.333	59.8%	0.015	327.8%
-34	40.2	3.99	0.330	58.2%	0.009	148.7%
-32	37.5	6.71*	1.636	684%*	0.8222	22800%*

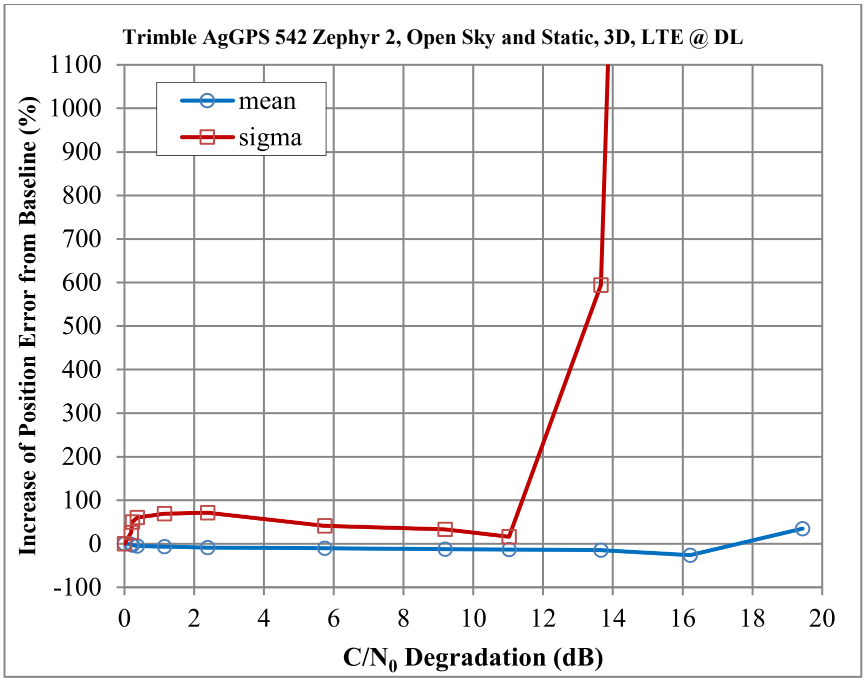
-: Not used as baseline because its sigma value appears to be unreliable.
*: Data point was not included in figure (c) because the data appears to be unreliable.



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution



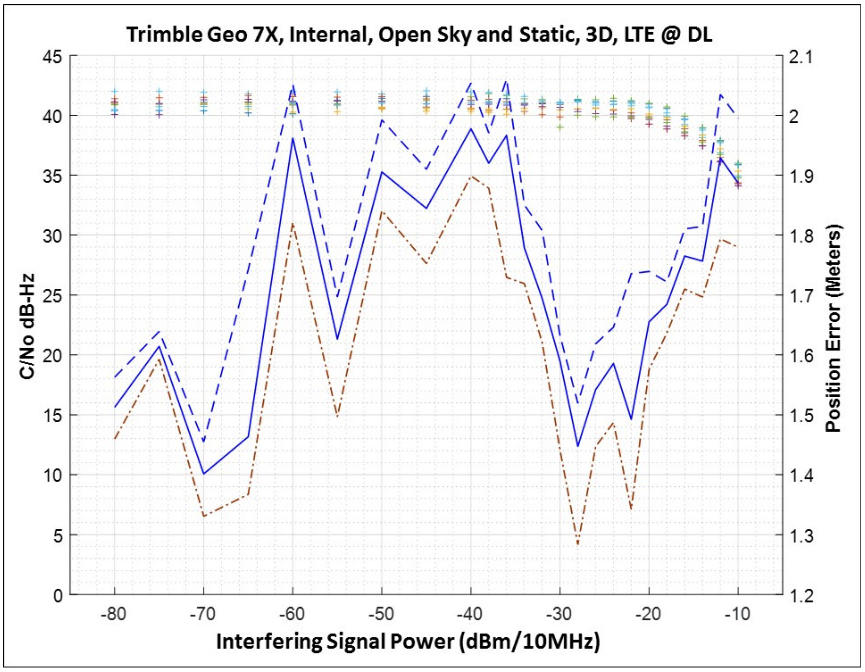
(b) Increase of Mean and Sigma of Position Error Distribution

Figure D.B.3.3. 3-D Position Error Distribution for Trimble AgGPS 542 with Zephyr Antenna Interfering Signal in DL Band

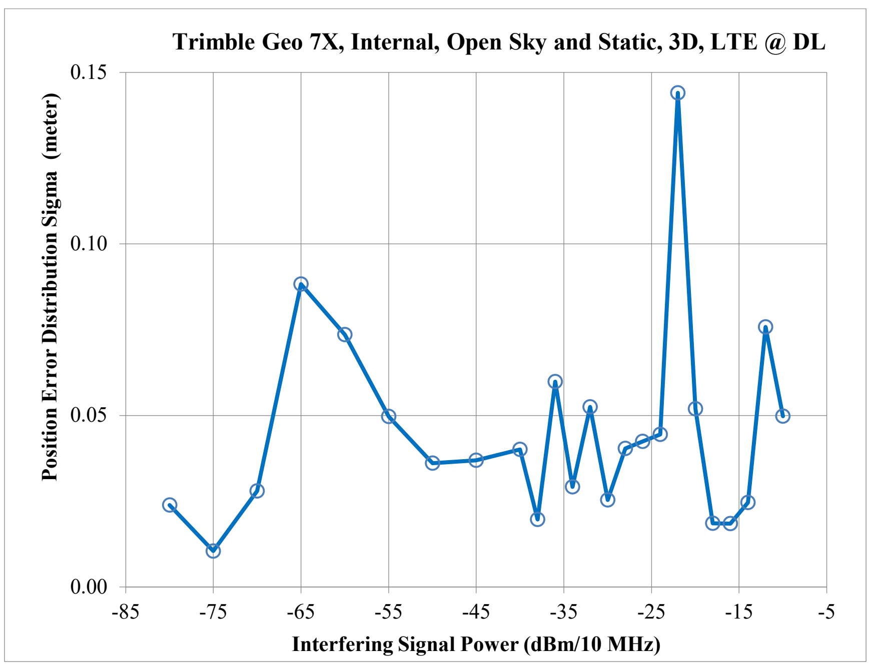
Table D.B.3.3. 3-D Position Error Distribution for Trimble AgGPS 542 with Zephyr Antenna Interfering Signal in DL Band

Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-80	45.5	-	1.413	-	0.0020	-
-75	45.6	Baseline	1.400	Baseline	0.0036	Baseline
-70	45.4	0.19	1.381	-1.4%	0.0045	25.5%
-65	45.3	0.23	1.359	-2.9%	0.0053	50.0%
-60	45.2	0.37	1.333	-4.8%	0.0057	60.3%
-55	44.4	1.15	1.306	-6.8%	0.0060	69.4%
-50	43.2	2.38	1.279	-8.7%	0.0061	71.2%
-45	39.8	5.74	1.253	-10.5%	0.0050	40.9%
-40	36.4	9.19	1.230	-12.1%	0.0047	33.4%
-38	34.5	11.03	1.212	-13.4%	0.0041	15.8%
-36	31.9	13.66	1.190	-15.0%	0.0247	593%
-34	29.3	16.21	1.035	-26.1%	0.2512	6966%
-32	27.2	18.33*	8.469*	504%*	1.1720	32872%*
-30	26.1	19.44	1.888	34.8%	1.0449	29296%
-28	25.8	19.79*	5294760.3	378116041%*	4381165.1	123256862775%*

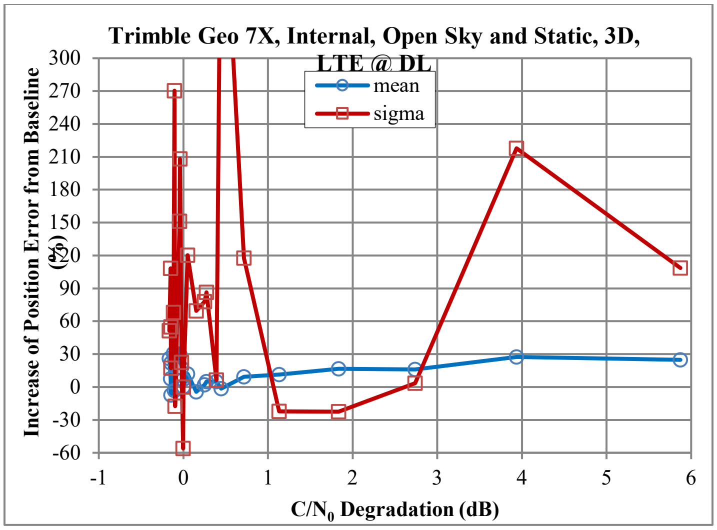
-: Not used as baseline because its sigma value appears to be unreliable.
*: Data point was not included in figure (c) because the data appears to be unreliable.



(a) C/N0 and Position Error Distribution



(b) Sigma of Position Error Distribution

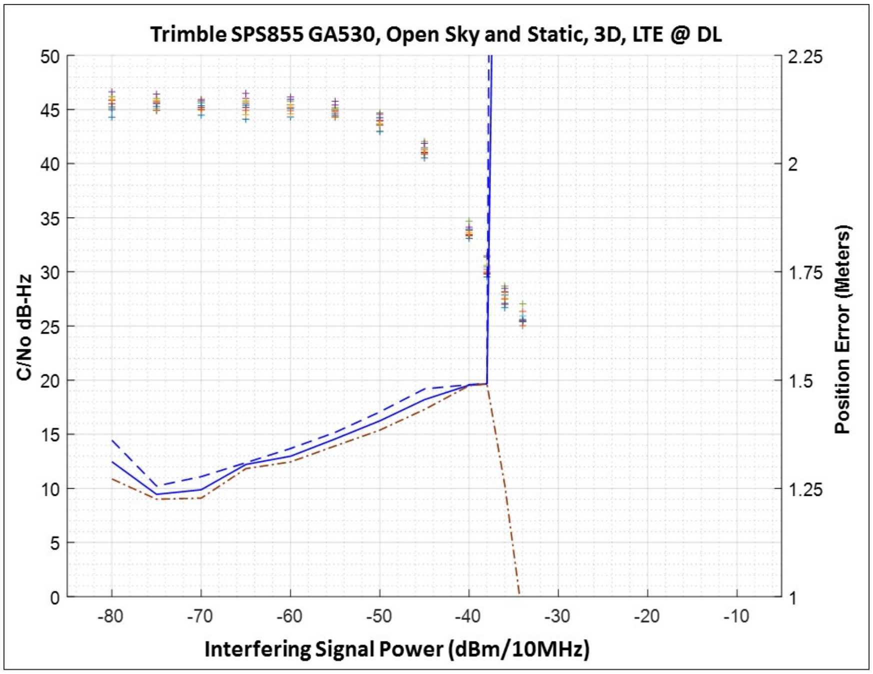


(c) Increase of Mean and Sigma of Position Error Distribution

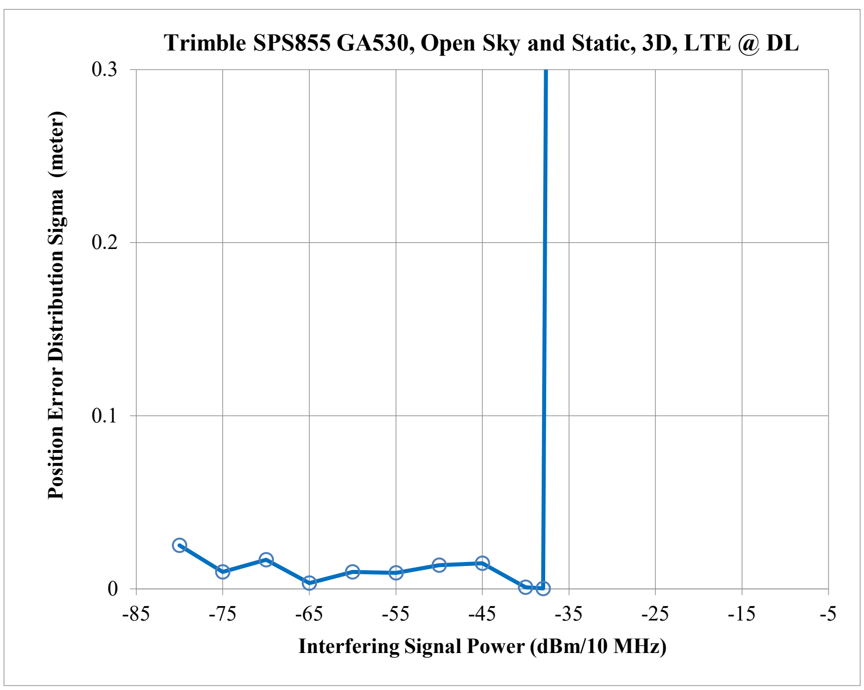
Figure D.B.3.4. 3-D Position Error Distribution for Trimble Geo 7X Interfering Signal in DL Band

Table D.B.3.4. 3-D Position Error Distribution for Trimble Geo 7X Interfering Signal in DL Band

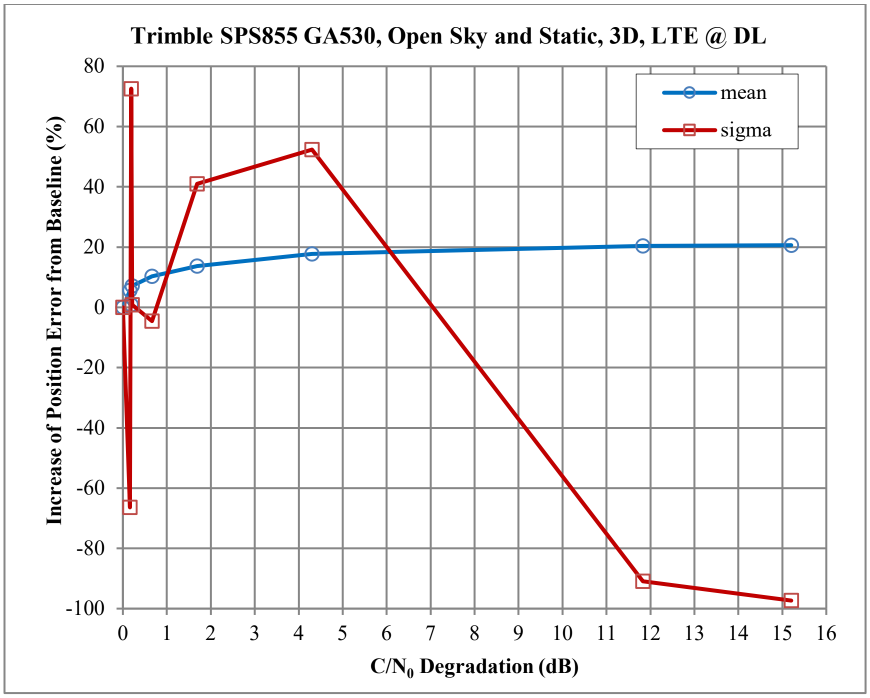
Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-80	40.9	0.00	1.513	0.0%	0.024	0.0%
-75	40.9	0.00	1.614	6.7%	0.010	-56.0%
-70	41.1	-0.15	1.401	-7.3%	0.028	17.3%
-65	41.0	-0.11	1.463	-3.3%	0.088	270.3%
-60	41.0	-0.04	1.962	29.7%	0.074	208.2%
-55	41.1	-0.15	1.626	7.5%	0.050	108.3%
-50	41.1	-0.17	1.905	26.0%	0.036	51.3%
-45	41.1	-0.15	1.845	22.0%	0.037	55.0%
-40	41.0	-0.12	1.978	30.7%	0.040	68.1%
-38	41.0	-0.10	1.920	26.9%	0.020	-17.4%
-36	41.0	-0.04	1.967	30.0%	0.060	151.1%
-34	41.0	-0.02	1.779	17.6%	0.029	22.5%
-32	40.9	0.05	1.694	12.0%	0.053	120.2%
-30	40.5	0.39	1.589	5.1%	0.025	6.3%
-28	40.8	0.15	1.447	-4.3%	0.040	69.4%
-26	40.7	0.25	1.542	2.0%	0.042	77.9%
-24	40.7	0.27	1.586	4.8%	0.044	86.6%
-22	40.5	0.45	1.492	-1.3%	0.144	504.0%
-20	40.2	0.72	1.655	9.4%	0.052	117.6%
-18	39.8	1.13	1.685	11.4%	0.019	-22.1%
-16	39.1	1.84	1.765	16.7%	0.018	-22.5%
-14	38.2	2.74	1.757	16.1%	0.025	3.4%
-12	37.0	3.94	1.929	27.5%	0.076	217.6%
-10	35.1	5.87	1.887	24.7%	0.050	108.6%



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution



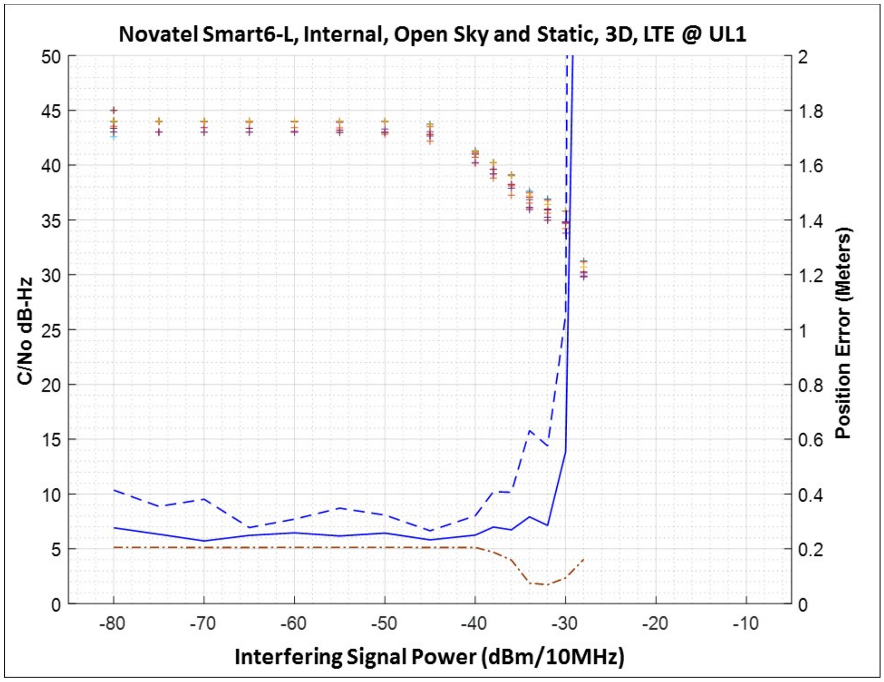
(c) Increase of Mean and Sigma of Position Error Distribution

Figure D.B.3.5. 3-D Position Error Distribution for Trimble SPS855 with GA530 Antenna Interfering Signal in DL Band

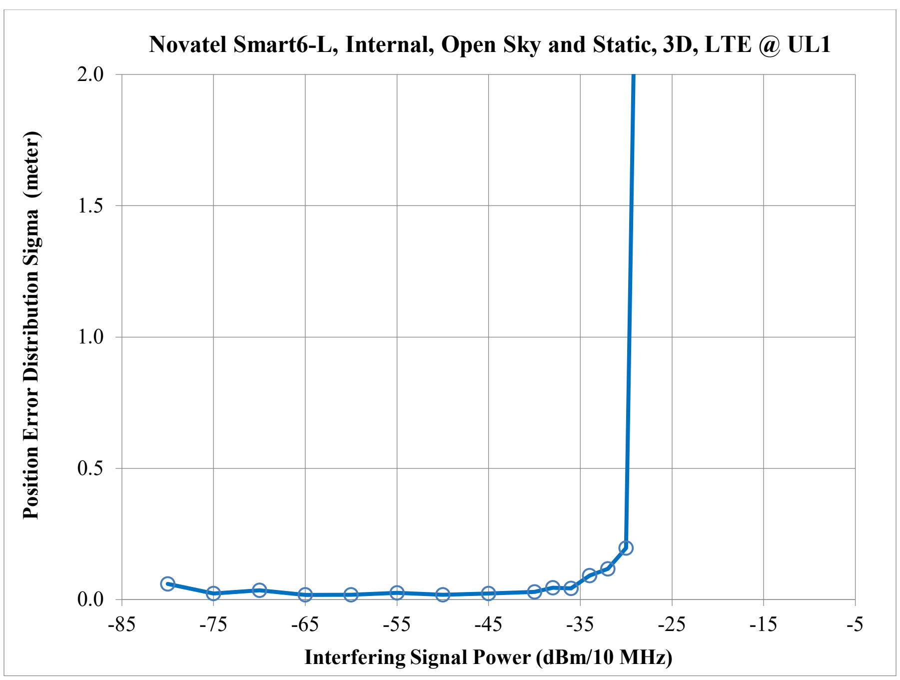
Table D.B.3.5. 3-D Position Error Distribution for Trimble SPS855 with GA530 Antenna Interfering Signal in DL Band

Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-80	45.5	-	1.312	-	0.025	-
-75	45.5	Baseline	1.236	Baseline	0.010	Baseline
-70	45.4	0.19	1.247	0.8%	0.017	72.6%
-65	45.4	0.16	1.305	5.6%	0.003	-66.4%
-60	45.3	0.21	1.324	7.1%	0.010	0.8%
-55	44.9	0.66	1.364	10.3%	0.009	-4.6%
-50	43.9	1.69	1.406	13.7%	0.014	40.9%
-45	41.2	4.30	1.455	17.7%	0.015	52.4%
-40	33.7	11.83	1.489	20.4%	0.001	-91.0%
-38	30.3	15.20	1.491	20.6%	0.000	-97.3%
-36	27.7	17.81*	4.396	255.5%*	1.835	18704%*
-34	25.8	19.79*	23.292	1783.8%*	21.140	216486%*

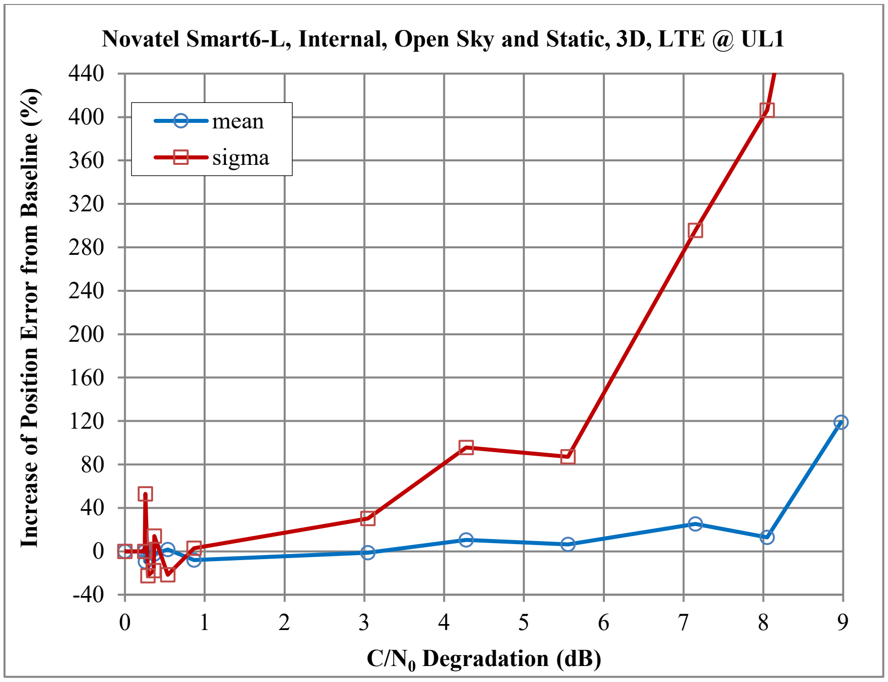
-: Not used as baseline because its sigma value appears to be unreliable.
*: Data point was not included in figure (c) because the data appears to be unreliable.



(a) C/N$_0$ and Position Error Distribution



(b) Sigma of Position Error Distribution



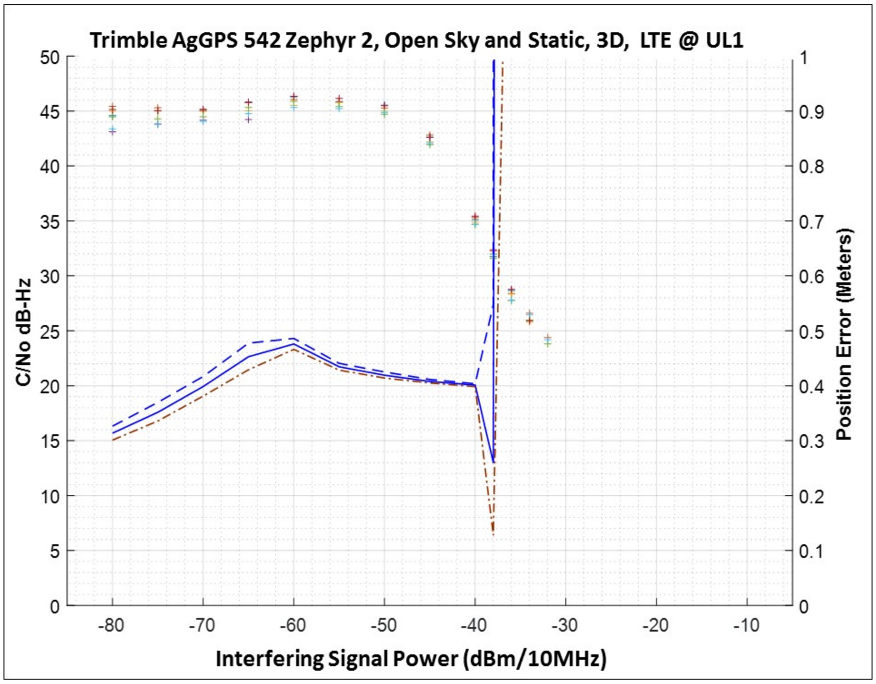
(c) Increase of Mean and Sigma of Position Error Distribution

Figure D.B.3.6. 3-D Position Error Distribution for Novatel Smart6-L Interfering Signal in UL1 Band

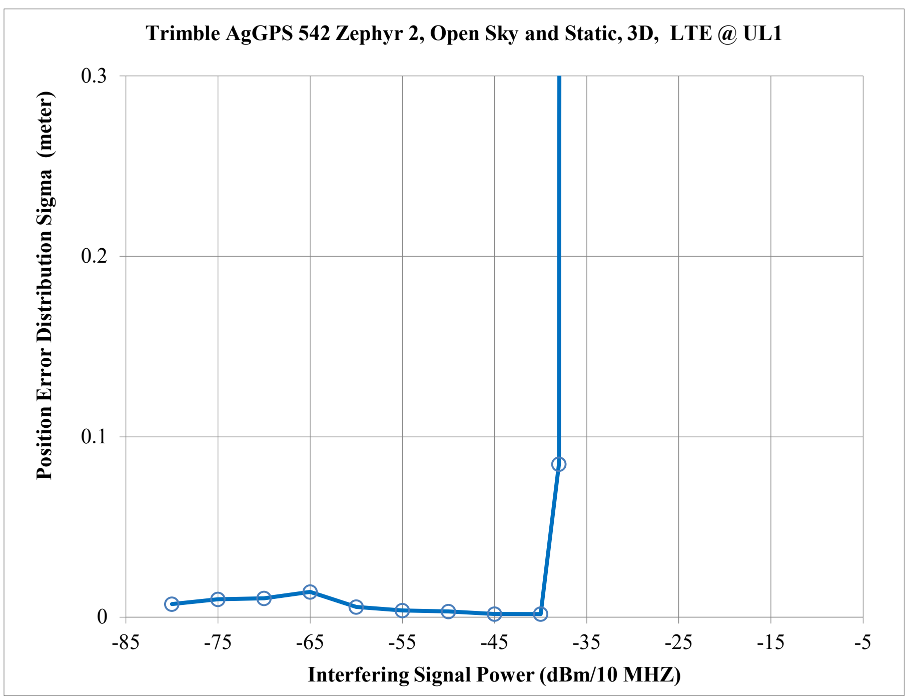
Table D.B.3.6. 3-D Position Error Distribution for Novatel Smart6-L Interfering Signal in UL1 Band

Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-80	43.9	0.00	0.277	-	0.060	-
-75	43.6	0.29	0.253	Baseline	0.023	Baseline
-70	43.7	0.25	0.229	-9.7%	0.035	52.8%
-65	43.7	0.26	0.249	-1.7%	0.018	-22.4%
-60	43.5	0.37	0.258	2.0%	0.019	-17.8%
-55	43.6	0.36	0.247	-2.5%	0.026	13.9%
-50	43.4	0.54	0.258	1.7%	0.018	-21.5%
-45	43.0	0.87	0.233	-8.1%	0.024	2.9%
-40	40.9	3.04	0.250	-1.2%	0.030	30.0%
-38	39.6	4.28	0.279	10.3%	0.045	95.5%
-36	38.4	5.55	0.269	6.3%	0.043	87.0%
-34	36.8	7.15	0.317	25.1%	0.091	295.7%
-32	35.9	8.05	0.286	12.7%	0.117	406.4%
-30	34.9	8.97	0.555	119.0%	0.197	752.9%
-28	30.4	13.53*	4.230	1570%*	4.651	20060%*

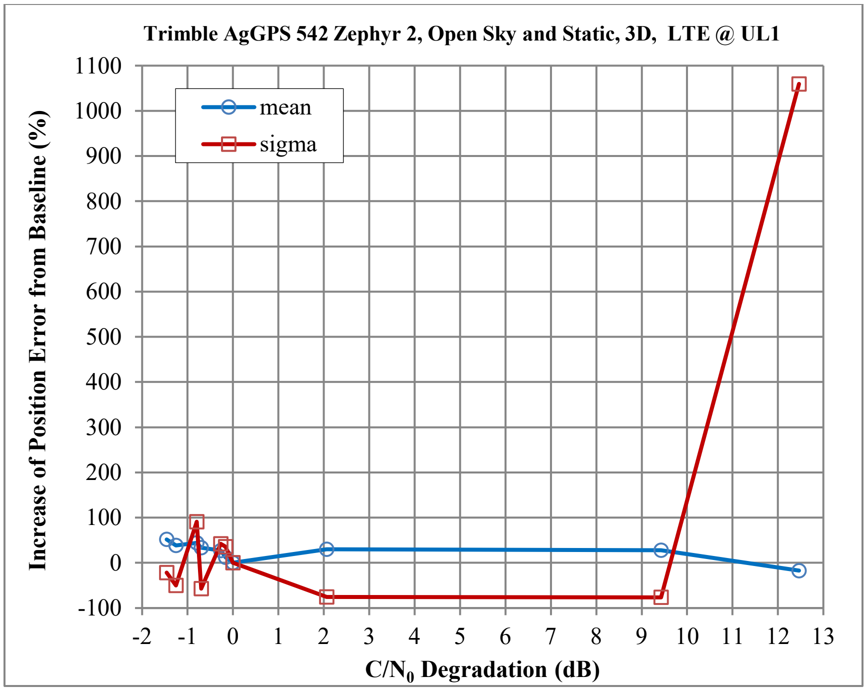
-: Not used as baseline because its sigma value appears to be unreliable.
*: Data point was not included in figure (c) because the data appears to be unreliable.



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution



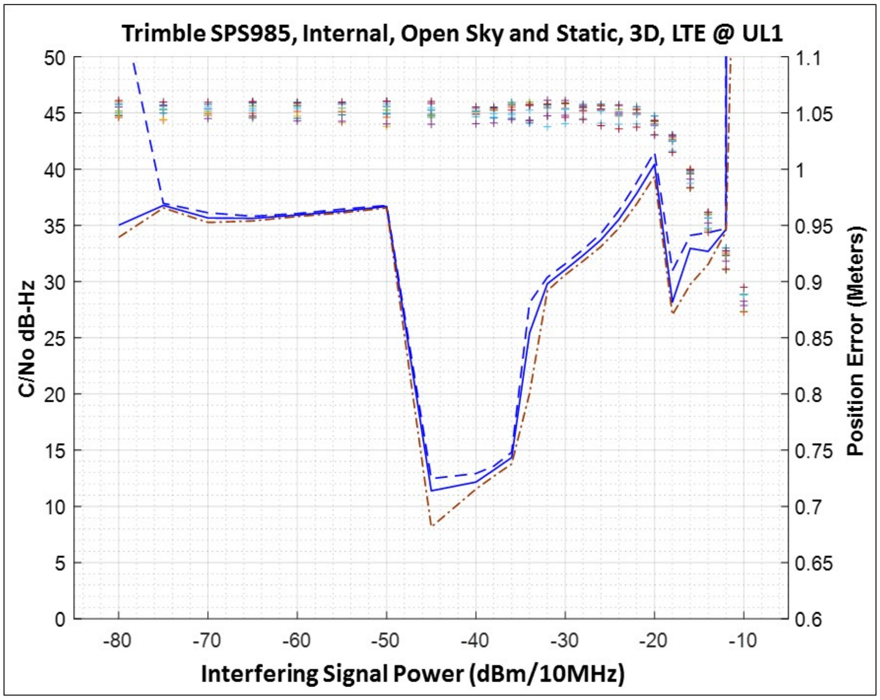
(c) Increase of Mean and Sigma of Position Error Distribution

Figure D.B.3.7. 3-D Position Error Distribution for Trimble AgGPS 542 with Zephyr Antenna Interfering Signal in UL1 Band

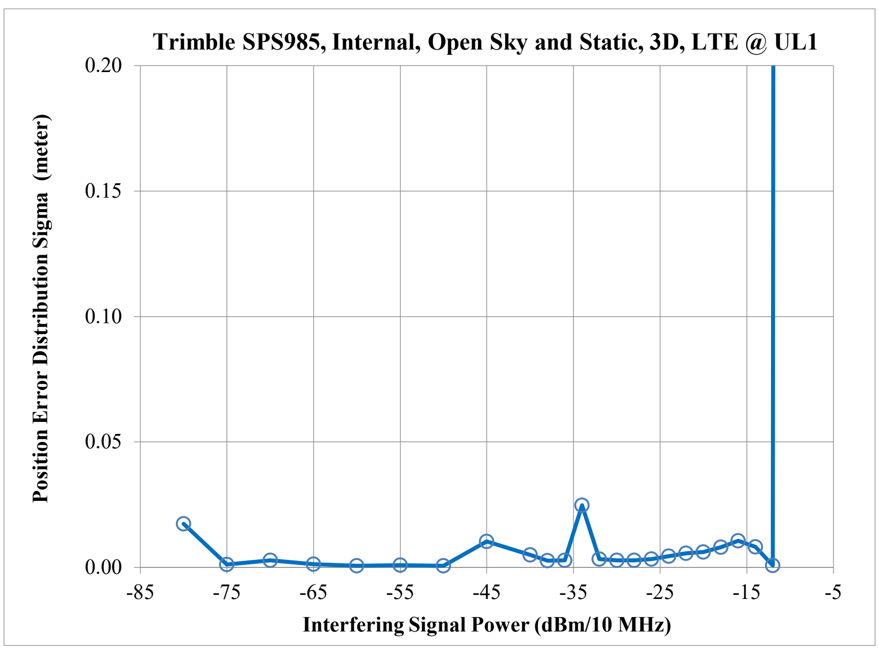
Table D.B.3.7. 3-D Position Error Distribution for Trimble AgGPS 542 with Zephyr Antenna Interfering Signal in UL1 Band

Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-80	44.4	0.00	0.314	Baseline	0.007	Baseline
-75	44.6	-0.16	0.352	12.1%	0.010	36.0%
-70	44.7	-0.27	0.399	27.1%	0.010	42.4%
-65	45.2	-0.80	0.453	44.4%	0.014	90.9%
-60	45.9	-1.46	0.476	51.8%	0.006	-21.8%
-55	45.7	-1.26	0.434	38.5%	0.004	-50.1%
-50	45.1	-0.70	0.419	33.7%	0.003	-57.2%
-45	42.4	2.06	0.408	30.0%	0.002	-75.6%
-40	35.0	9.42	0.401	27.9%	0.002	-76.4%
-38	32.0	12.46	0.260	-17.1%	0.085	1059%
-36	28.3	16.15*	14.790	4615%*	21.296	291282%*
-34	26.1	18.30*	16.001	5001%*	9.531	130303%*
-32	24.1	20.31*	6798480	2167606138%*	3797757	51962860982%*

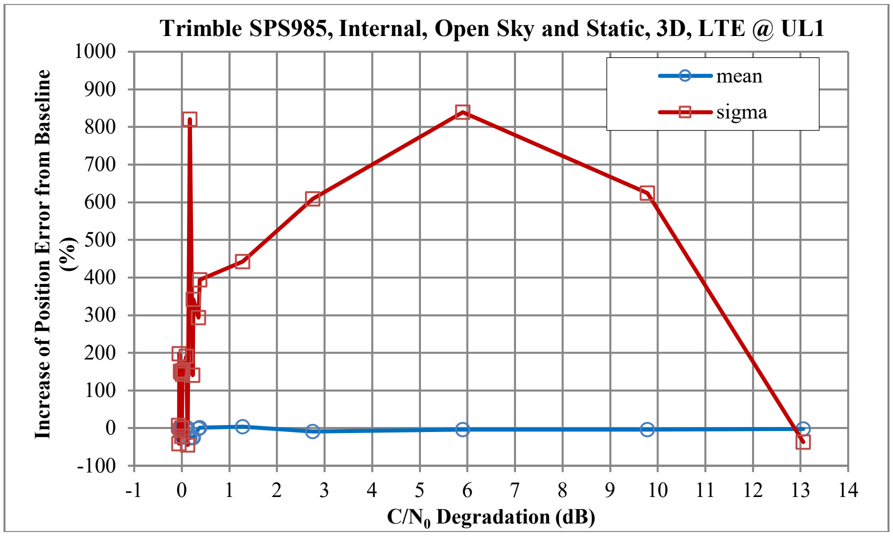
*: Data point was not included in figure (c) because the data appears to be unreliable.



(a) C/N_0 and Position Error Distribution



(b) Sigma of Position Error Distribution



(c) Increase of Mean and Sigma of Position Error Distribution

Figure D.B.3.8. 3-D Position Error Distribution for Trimble SPS985 Interfering Signal in UL1 Band

Table D.B.3.8. 3-D Position Error Distribution for Trimble SPS985 Interfering Signal in UL1 Band

Interfering Signal Power (dBm/10 MHz)	C/N_0		Position Error			
	Mean (dB-Hz)	Degradation (dB)	Mean (meter)	Increase of Mean	Sigma (meter)	Increase of Sigma
-75	45.2	Baseline	0.968	Baseline	0.001	Baseline
-70	45.2	0.02	0.957	-1.2%	0.003	142.9%
-65	45.3	-0.07	0.956	-1.2%	0.001	7.3%
-60	45.3	-0.06	0.959	-0.9%	0.001	-41.7%
-55	45.2	0.00	0.963	-0.5%	0.001	-21.5%
-50	45.1	0.12	0.967	-0.1%	0.001	-44.6%
-45	45.1	0.17	0.714	-26.2%	0.010	820.5%
-40	45.0	0.25	0.722	-25.4%	0.005	342.4%
-38	45.0	0.23	0.732	-24.3%	0.003	140.5%
-36	45.2	0.02	0.743	-23.2%	0.003	152.1%
-34	45.1	0.11*	0.854	-11.7%*	0.025	2094%*
-32	45.3	-0.05	0.898	-7.2%	0.003	197.9%
-30	45.3	-0.03	0.911	-5.9%	0.003	150.9%
-28	45.2	-0.01	0.923	-4.6%	0.003	149.4%
-26	45.1	0.10	0.937	-3.2%	0.003	190.7%
-24	44.9	0.35	0.955	-1.3%	0.004	293.2%
-22	44.9	0.38	0.978	1.1%	0.006	393.5%
-20	44.0	1.28	1.004	3.8%	0.006	442.4%
-18	42.5	2.75	0.882	-8.9%	0.008	609%
-16	39.3	5.90	0.930	-4.0%	0.011	839%
-14	35.4	9.78	0.927	-4.2%	0.008	624%
-12	32.2	13.06	0.946	-2.2%	0.001	-37.3%
-10	28.3	16.89*	10.884	1024%*	14.871	1317973%*

-: Not used as baseline because its sigma value appears to be unreliable.
*: Data point was not included in figure (c) because the data appears to be unreliable.

D.B.4 Summary

The interfering signal power and its corresponding C/N_0 and C/N_0 degradation when the mean and sigma show significant degradation are compared in Table D.B.4.1. All receivers in the General Aviation Receiver Category (GAV) category have virtually no change in C/N_0 for all interfering signal power and thus no C/N_0 degradation; therefore, they are not presented in Table D.B.4.1.

Table D.B.4.1. Threshold Interfering Signal Power, C/N_0, and C/N_0 Degradation Where Mean and Sigma Show Significant Degradation

(a) GLN Receiver Category

Interfering Signal Frequency Band	DUT	Threshold for Mean			Threshold for Sigma		
		LTE Power (dBm/10 MHz)	C/N_0 Mean (dB-Hz)	C/N_0 Degra-dation (dB)	LTE Power (dBm/10 MHz)	C/N_0 Mean (dB-Hz)	C/N_0 Degradation (dB)
UL 1	Garmin eTrex H under open sky with motion	-14	32.0	8.0	-14	32.0	8.0
	Garmin eTrex H under impaired GPS signal with motion	-28	25.6	3.0	-28	25.6	3.0
UL 2	Garmin eTrex H under impaired GPS signal with motion	-18	26.4	2.5	-22	26.8	2.0
The receivers in this category which were not analyzed have virtually no change in C/N_0 for all interfering signal power levels and thus no C/N_0 degradation.							

(b) HP Receiver Category

Interfering Signal Frequency Band	DUT	Threshold for Mean			Threshold for Sigma		
		LTE Power (dBm/10 MHz)	C/N_0 Mean (dB-Hz)	C/N_0 Degradation (dB)	LTE Power (dBm/10 MHz)	C/N_0 Mean (dB-Hz)	C/N_0 Degradation (dB)
DL	Novatel Smart6-L	-50	29.8	14.4	-60	40.0	4.1
	Topcon System 310	-32	37.5	6.7	-36	42.1	2.1
	Trimble AgGPS 542 with Zephyr Antenna	-32	27.2	18.3	-36	31.9	13.7
	Trimble Geo 7X	> -10	< 35.1	> 5.9	-12	37.0	3.9
	Trimble SPS855 with GA530 Antenna	-34	25.8	19.8	-45	41.2	4.3
UL 1	Novatel Smart6-L	-30	34.9	9.0	-38	39.6	4.3
	Trimble AgGPS 542 with Zephyr Antenna	-36	28.3	16.2	-38	32.0	12.5
	Trimble SPS985	-10	28.3	16.9	-18	42.5	2.8
The receivers in this category which were not considered or analyzed have virtually no change in C/N_0 for all interfering signal power levels and thus no C/N_0 degradation.							

Also, the C/N_0 degradations where the position error distribution sigma significantly deviates from the mean are shown in Table D.B.4.2. All receivers in the GAV category have virtually no change in C/N_0 for all LTE signal power and thus no C/N_0 degradation; therefore, they are presented in Table D.B.4.2.

Table D.B.4.2. C/N_0 Degradation Values Where Position Error Distribution Sigma Deviates Significantly from Mean

(a) GLN Receiver Category

DUT	Interfering Signal Frequency Band	C/N_0 Degradation (dB)
Garmin eTrex H under open sky with motion	UL 1	No significant deviation
Garmin eTrex H under impaired GPS signal with motion	UL 1	No significant deviation
Garmin eTrex H under impaired GPS signal with motion	UL 2	No significant deviation
The receivers in this category which were not considered or analyzed have virtually no change in C/N_0 for all interfering signal power levels and thus no C/N_0 degradation.		

(b) HP Receiver Category

DUT	Interfering Signal Frequency Band	C/N_0 Degradation (dB)
Novatel Smart6-L	DL	1.4
Topcon System 310	DL	2.1
Trimble AgGPS 542 with Zephyr Antenna	DL	13.7
Trimble Geo 7X	DL	3.9
Trimble SPS855 with GA530 Antenna	DL	4.3
Novatel Smart6-L	UL 1	4.3
Trimble AgGPS 542 with Zephyr Antenna	UL 1	12.5
Trimble SPS985	UL 1	2.8
The receivers in this category which were not considered or analyzed have virtually no change in C/N_0 for all interfering signal power levels and thus no C/N_0 degradation.		

APPENDIX E
SINGLE BASE STATION INTERFERENCE ANALYSIS

E.1 INTRODUCTION

This appendix summarizes the analysis conducted by the Technical Focus Group (TFG) to consider a single macro cell or Small Cell base station and Global Positioning System (GPS) receivers in the high precision, general location/navigation, timing and cellular categories. The following equation is used to calculate the received power at the output of a GPS receive antenna:[1]

$$P_R = EIRP - L_P - L_{GPS} - L_{BS}$$

where:

P_R: Received power (dBm/10 MHz);
$EIRP$: Equivalent isotropically radiated power of the base station (dBm/10 MHz);
L_P: Propagation loss from the base station antenna to the GPS antenna (dB);
L_{GPS}: Normalized, off-boresight loss of the GPS antenna (dB);[2] and
L_{BS}: Off-axis loss of the base station antenna (dB).[3]

In this analysis, a maximum equivalent isotropically radiated power (EIRP) of 62 Decibel (dB) relative to a milliwatt (dBm)/10 MHz is assumed for macro cell base stations and a maximum EIRP of 40 dBm/10 MHz is assumed for Small Cell base stations.

For separation distances of 100 meters or less, the free-space model is used to compute propagation loss:

$$L_P = 20 \text{ Log } (F) + 20 \text{ Log } (D) + 32.45$$

where

L_P: Propagation loss from the base station antenna to the GPS antenna (dB);
F : Frequency (MHz); and
D : Distance (km)

---

[1] The base station transmits dual orthogonal linear polarizations, where each orthogonal polarization is rotated 45 degrees. It is assumed that the signals transmitted in each diagonal polarization are mutually uncorrelated and have equal transmit EIRP. The analysis is simplified to calculate power as if all EIRP were transmitted from the vertical polarization. This assumption yields similar results as transmitting half of the total EIRP over each of the two orthogonal polarizations, where the signals transmitted on each polarization are mutually uncorrelated and are combined power-wise at the GPS receiver antenna input.

[2] Normalized off-boresight base station antenna loss is used because the base station transmit EIRP is specified in terms of maximum antenna gain.

[3] GPS off-boresight antenna loss is used because the test data was taken at the GPS antenna boresight.

For separation distances of 100 to 200 meters, a blended propagation model of Irregular Terrain Model (ITM) Area Mode and free space propagation loss is used.[4] The blending occurs from 100 to 200 meters because ITM Area Mode could be greater or less propagation loss due to the confidence level. The propagation loss difference between ITM Area Mode and free space propagation loss is calculated at 200 meters. For separation distances of less than or equal to 100 meters, free space path loss is used. For separation distances greater than 100 meters and less than or equal to 200 meters blended ITM is used. For separation distances greater than 200 meters, ITM Area Mode is used to compute propagation loss:

$$\mathrm{ITM_{Blend}} = \begin{matrix} \mathrm{FSPL} & \mathrm{d} \leq 100\mathrm{m} \\ \mathrm{FSPL} + \frac{\Delta \mathrm{L_P}}{100}(\mathrm{d} - 100) & 100\mathrm{m} < \mathrm{d} \leq 200\mathrm{m} \\ \mathrm{ITM} & 200\mathrm{m} > \mathrm{d} \end{matrix}$$

where:

$$\Delta \mathrm{L_P} = \mathrm{ITM_{200m}} - \mathrm{FSPL_{200m}}$$

Table E.1 provides the parameters used in the ITM Area Mode propagation loss calculations.

Table E.1. ITM Area Mode Parameters

Parameter	Value
Surface Refractivity	301 N-units
Conductivity of Ground	0.005 seimans per meter (S/m)
Dielectric Constant of Ground	15
Terrain Roughness Factor (Delta h)	30 meters
Polarization	Vertical
Mode of Variability	Single Message Mode
Percent Confidence (Time/Situation/Location Variability)	50 %
Frequency	1530 MHz
Transmitter Antenna Height	Variable 5 to 45 meters (macro cell) Variable 5 to 30 meters (Small Cell)
Receiver Antenna Height	1.5 meters
Site Criteria Transmitter	Careful
Site Criteria Receiver	Random
Radio Climate	Continental Temperate

[4] National Telecommunications and Information Administration, NTIA Report 82-100, *A Guide to the Use of the ITS Irregular Terrain Model in the Area Prediction Mode* (Apr. 1982), *available at* https://www.ntia.doc.gov/files/ntia/publications/ntia_82-100_20121129145031_555510.pdf.

The base station antenna gain reduction plots shown in Figure E.1 and Figure E.2 are used to compute the off-axis loss for down-tilt angles of 2, 4, and 6 degrees.[5]

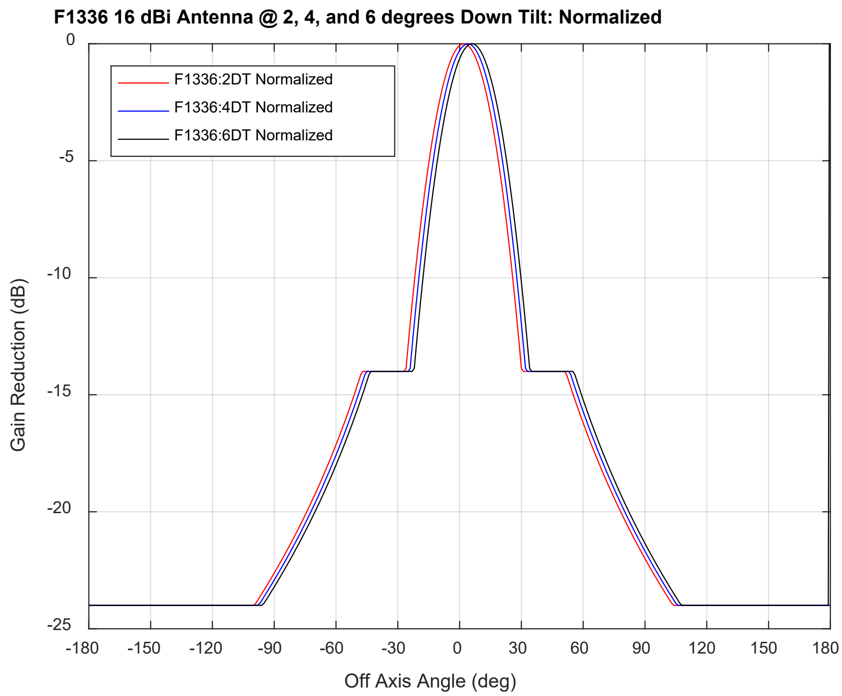


Figure E.1. Macro Cell Base Station Normalized Gain Plot

[5] Recommendation ITU-R F.1336-4, *Reference Radiation Patterns of Omnidirectional, Sectoral and Other Antennas for the Fixed and Mobile Services for Use in Sharing Studies in the Frequency Range from 400 MHz to About 70 GHz* (Feb. 2014), *available at*

https://www.itu.int/dms_pubrec/itu-r/rec/f/R-REC-F.1336-4-201402-S!!PDF-E.pdf. The antenna model is described in Recommends 3.1.

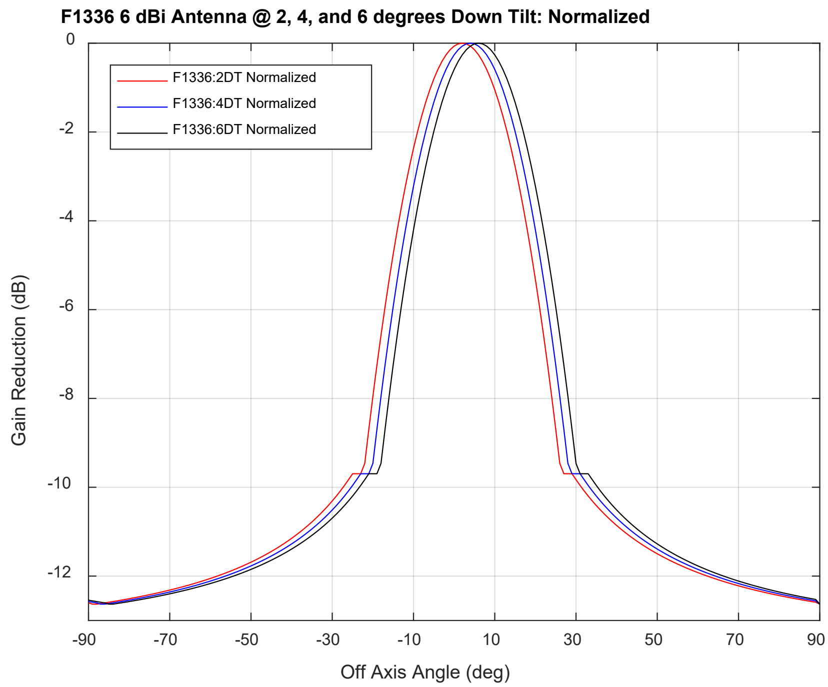


Figure E.2. Small Cell Base Station Normalized Gain Plot

E.2 HIGH PRECISION GPS RECEIVER CATEGORY

The GPS high precision receive antenna gain model is shown in Figure E.3.

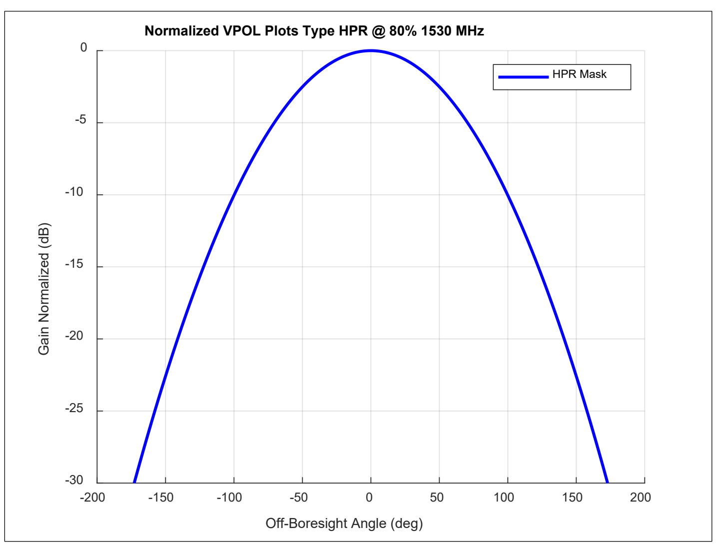


Figure E.3. GPS High Precision Receive Antenna Mask

The carrier-to-noise density ratio (C/N_0) degradation measurements from the Department of Transportation Adjacent Band Compatibility (DOT ABC), Department of Defense (DOD), Roberson and Associates (R&A), National Advanced Spectrum and Communications Test

Network (NASCTN), 2011 Federal Communications Commission Technical Working Group (TWG), and the 2012 National Positioning, Navigation, and Timing (PNT) Systems Engineering Forum (NPEF) test programs are used to establish the interference power levels for this analysis. The summary of interference power levels from the different test programs for a 1 dB, 3 dB, and 5 dB degradation in C/N_0 are shown in Tables E.2 through E.4 for high precision GPS receivers.

Table E.2. Summary of High Precision GPS Receiver Interference Power Levels
1 dB C/N_0 Degradation

Range of Interference Power Levels (dBm/10 MHz)	Number of Receivers				
	DOT ABC	DOD	R&A	NASCTN	TWG
-79 to -75					1
-74 to -70	1				1
-69 to -65			1	3	1
-64 to -60	1	1		1	1
-59 to -55	3				3
-54 to -50	1		2	2	3
-49 to -45		1			3
-44 to -40	7				6
-39 to -35	1	1	1		4
-34 to -30	2	1			3
-29 to -25	2				3
-24 to -20	6				4
-19 to -15	1				1
-14 to -10	4		4		
-9 to -5					
-4 to 0				1	
1 to 5				2	
Total Number of Receivers	29	4	8	9	34

Table E.3. Summary of High Precision GPS Receiver Interference Power Levels 3 dB C/N$_0$ Degradation

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers			
	DOT ABC	DOD	R&A	NASCTN
-64 to -60	1		1	3
-59 to -55	3	1		
-54 to -50	1			1
-49 to -45	1		2	2
-44 to -40	2	1		
-39 to -35	5			
-34 to -30	2	2	1	
-29 to -25	2			
-24 to -20	2			
-19 to -15	4			
-14 to -10	6		4	
-9 to -5				
-4 to 0				
1 to 5				3
Total Number of Receivers	29	4	8	9

Table E.4. Summary of High Precision GPS Receiver Interference Power Levels 5 dB C/N$_0$ Degradation

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers			
	DOT ABC	DOD	R&A	NASCTN
-64 to -60				2
-59 to -55	2		1	1
-54 to -50	2	1		
-49 to -45	2			3
-44 to -40	1	1	2	
-39 to -35	5			
-34 to -30	2		1	
-29 to -25	2	2		
-24 to -20	1			
-19 to -15	2			
-14 to -10	10		4	
-9 to -5				
-4 to 0				
1 to 5				3
Total Number of Receivers	29	4	8	9

E.2.1 Macro Cell Base Station Analysis

The analysis is used to determine the separation distances necessary to reduce the macro cell base station power level at the GPS receiver to below the interference power level based on a 1 dB, 3 dB, and 5 dB C/N_0 degradation. The analysis results are shown in Tables E.5 through E.7 for high precision GPS receivers. The macro cell base station-received power calculations for the GPS high precision receiver category are shown in Figures E.4 through E.6. The separation distance is varied in 1 meter steps from 1 to 20,000 meters. The base station antenna height is varied between 5, 10, 20, 30 and 45 meters. At each separation distance the maximum received power for all combinations of base station antenna height and down-tilt angle is determined. In addition, the calculated received power as a function of base station EIRP and separation distance is shown in Table E.8.

Table E.5. Percentage of High Precision GPS Receivers Impacted
1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -80	0	0 %	≥ 15217
≤ -75	1	1.2 %	≥ 11586
≤ -70	3	3.6 %	≥ 8463
≤ -65	8	9.5 %	≥ 5901
≤ -60	12	14.3 %	≥ 4024
≤ -55	18	21.4 %	≥ 2560
≤ -50	26	30.9 %	≥ 1608
≤ -45	30	35.7 %	≥ 979
≤ -40	43	51.2 %	≥ 582
≤ -35	50	59.5 %	≥ 348
≤ -30	56	66.7 %	≥ 195
≤ -25	61	72.6 %	≥ 130
≤ -20	71	84.5 %	≥86
≤ -15	73	86.9 %	≥ 49
≤ -10	81	96.4 %	≥ 28
≤ -5	81	96.4 %	≥ 15
≤ 0	82	97.6 %	≥ 5
≤ 5	84	100 %	< 5

Table E.6. Percentage of High Precision GPS Receivers Impacted
3 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -65	0	0 %	≥ 5901
≤ -60	5	10 %	≥ 4024
≤ -55	9	18 %	≥ 2560
≤ -50	11	22 %	≥ 1608
≤ -45	16	32 %	≥ 979
≤ -40	19	38 %	≥ 582
≤ -35	24	48 %	≥ 348
≤ -30	29	58 %	≥ 195
≤ -25	31	62 %	≥ 130
≤ -20	33	66 %	≥86
≤ -15	37	74 %	≥ 49
≤ -10	47	94 %	≥ 28
≤ -5	47	94 %	≥ 15
≤ 0	47	94 %	≥ 5
≤ 5	50	100 %	< 5

Table E.7. Percentage of High Precision GPS Receivers Impacted
5 dB C/N_0 Degradation

Interference Power Levels (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -65	0	0 %	≥ 5901
≤ -60	2	4 %	≥ 4024
≤ -55	6	12 %	≥ 2560
≤ -50	9	18 %	≥ 1608
≤ -45	13	26 %	≥ 979
≤ -40	18	36 %	≥ 582
≤ -35	23	46 %	≥ 348
≤ -30	26	52 %	≥ 195
≤ -25	30	60 %	≥ 130
≤ -20	31	62 %	≥86
≤ -15	33	66 %	≥ 49
≤ -10	47	94 %	≥ 28
≤ -5	47	94 %	≥ 15
≤ 0	47	94 %	≥ 5
≤ 5	50	100 %	< 5

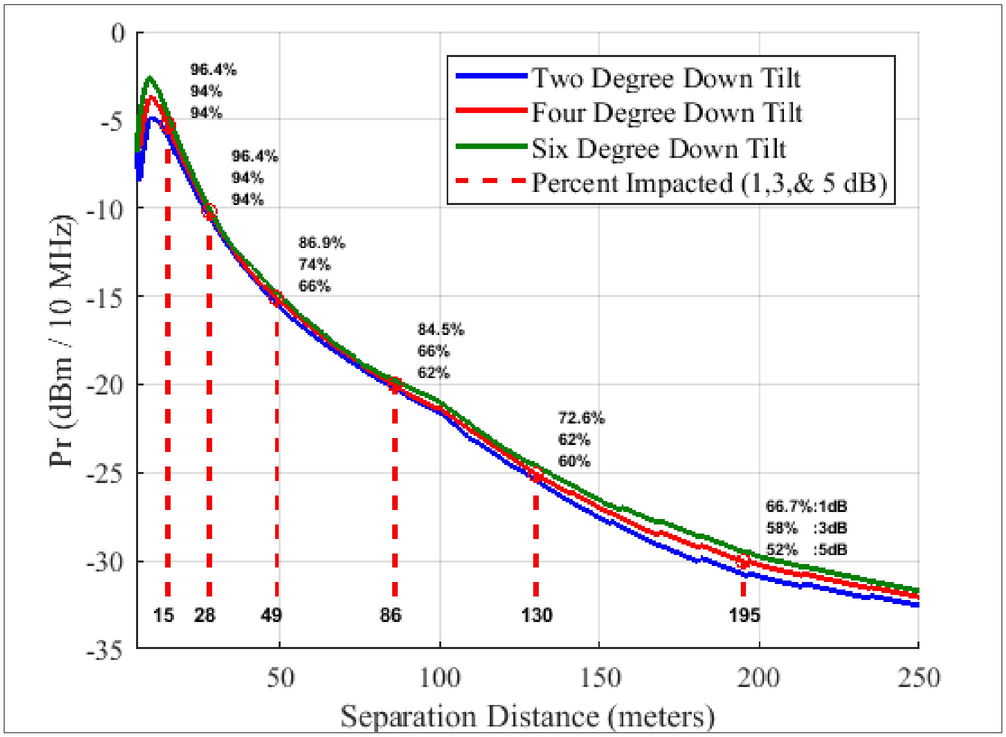


Figure E.4. Maximum Received Power as a Function of Separation Distance
High Precision Receiver
Macro Cell Base Station EIRP of 62 dBm/10 MHz

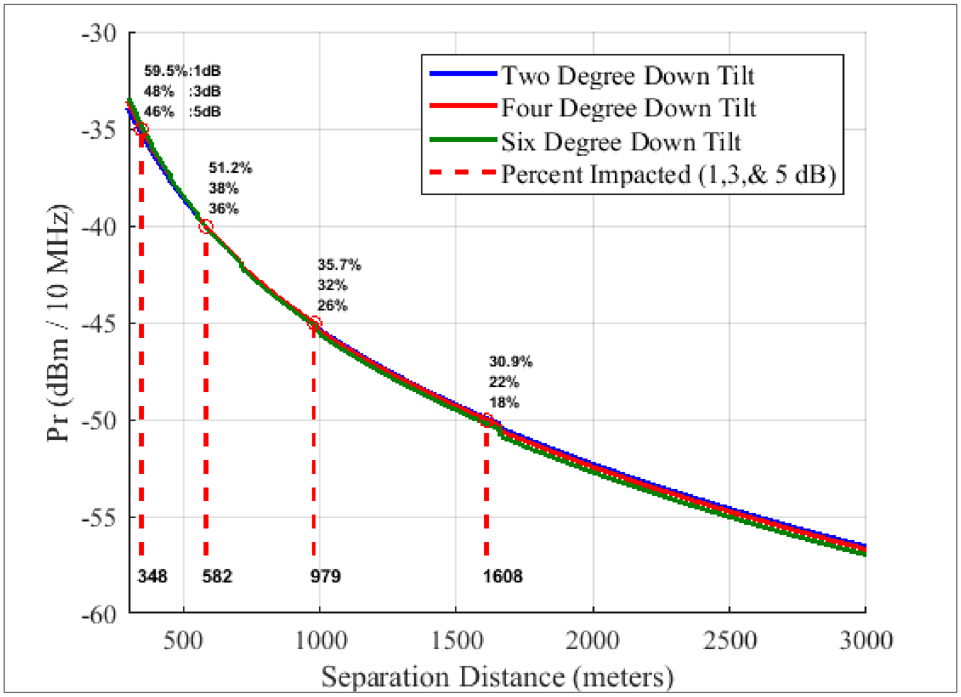


Figure E.5. Maximum Received Power as a Function of Separation Distance
High Precision Receiver
Macro Cell Base Station EIRP of 62 dBm/10 MHz

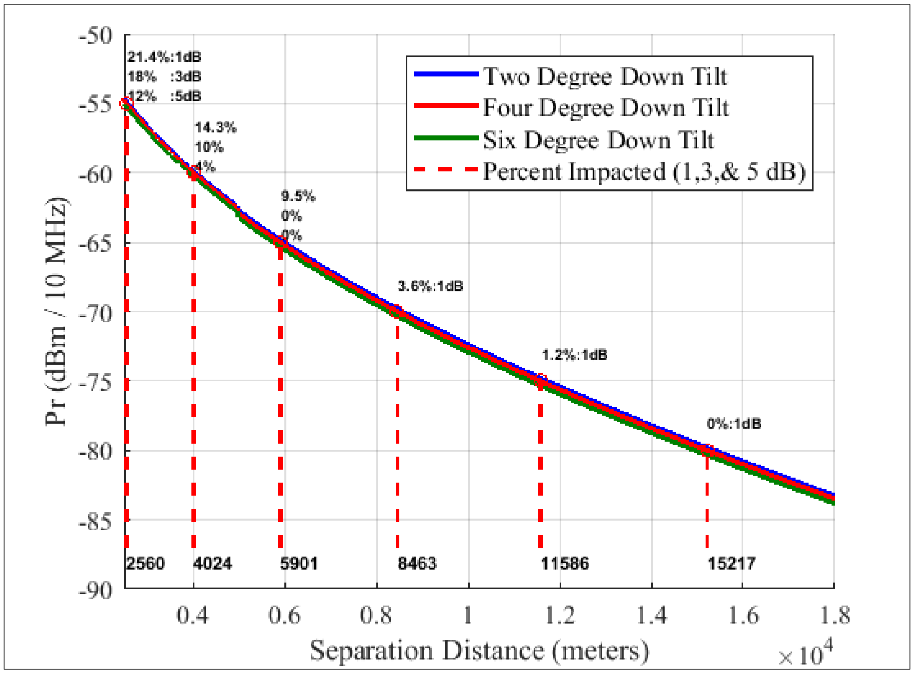


Figure E.6. Maximum Received Power as a Function of Separation Distance
High Precision Receiver
Macro Cell Base Station EIRP of 62 dBm/10 MHz

Table E.8. Power Received as a Function of EIRP and Separation Distance - Macro Cell

Base Station EIRP (dBm/10 MHz)	Received Power (dBm/10 MHz)									
	-75	-70	-65	-60	-55	-50	-45	-40	-35	-30
	Separation Distance (km)									
62	11.586	8.463	5.901	4.024	2.56	1.608	0.979	0.582	0.348	0.195
61	10.919	7.904	5.459	3.689	2.327	1.453	0.88	0.531	0.313	0.178
60	10.272	7.369	5.039	3.376	2.112	1.31	0.791	0.475	0.28	0.162
59	9.647	6.856	4.761	3.084	1.914	1.181	0.712	0.431	0.249	0.151
58	9.044	6.367	4.381	2.812	1.732	1.063	0.65	0.386	0.221	0.139
57	8.463	5.901	4.024	2.56	1.608	0.979	0.582	0.348	0.195	0.13
56	7.904	5.459	3.689	2.327	1.453	0.88	0.531	0.313	0.178	0.121
55	7.369	5.039	3.376	2.112	1.31	0.791	0.475	0.28	0.162	0.113
54	6.856	4.761	3.084	1.914	1.181	0.712	0.431	0.249	0.151	0.105
53	6.367	4.381	2.812	1.732	1.063	0.65	0.386	0.221	0.139	0.096
52	5.901	4.024	2.56	1.608	0.979	0.582	0.348	0.195	0.13	0.086
51	5.459	3.689	2.327	1.453	0.88	0.531	0.313	0.178	0.121	0.077
50	5.039	3.376	2.112	1.31	0.791	0.475	0.28	0.162	0.113	0.069
49	4.761	3.084	1.914	1.181	0.712	0.431	0.249	0.151	0.105	0.062
48	4.381	2.812	1.732	1.063	0.65	0.386	0.221	0.139	0.096	0.055
47	4.024	2.56	1.608	0.979	0.582	0.348	0.195	0.13	0.086	0.049
46	3.689	2.327	1.453	0.88	0.531	0.313	0.178	0.121	0.077	0.043
45	3.376	2.112	1.31	0.791	0.475	0.28	0.162	0.113	0.069	0.038

Base Station EIRP (dBm/10 MHz)	Received Power (dBm/10 MHz)									
	-75	-70	-65	-60	-55	-50	-45	-40	-35	-30
	Separation Distance (km)									
44	3.084	1.914	1.181	0.712	0.431	0.249	0.151	0.105	0.062	0.035
43	2.812	1.732	1.063	0.65	0.386	0.221	0.139	0.096	0.055	0.031
42	2.56	1.608	0.979	0.582	0.348	0.195	0.13	0.086	0.049	0.028
41	2.327	1.453	0.88	0.531	0.313	0.178	0.121	0.077	0.043	0.025
40	2.112	1.31	0.791	0.475	0.28	0.162	0.113	0.069	0.038	0.022
39	1.914	1.181	0.712	0.431	0.249	0.151	0.105	0.062	0.035	0.02
38	1.732	1.063	0.65	0.386	0.221	0.139	0.096	0.055	0.031	0.005
37	1.608	0.979	0.582	0.348	0.195	0.13	0.086	0.049	0.028	
36	1.453	0.88	0.531	0.313	0.178	0.121	0.077	0.043	0.025	
35	1.31	0.791	0.475	0.28	0.162	0.113	0.069	0.038	0.022	
34	1.181	0.712	0.431	0.249	0.151	0.105	0.062	0.035	0.02	
33	1.063	0.65	0.386	0.221	0.139	0.096	0.055	0.031	0.005	
32	0.979	0.582	0.348	0.195	0.13	0.086	0.049	0.028		
31	0.88	0.531	0.313	0.178	0.121	0.077	0.043	0.025		
30	0.791	0.475	0.28	0.162	0.113	0.069	0.038	0.022		
29	0.712	0.431	0.249	0.151	0.105	0.062	0.035	0.02		
28	0.65	0.386	0.221	0.139	0.096	0.055	0.031	0.005		
27	0.582	0.348	0.195	0.13	0.086	0.049	0.028			
26	0.531	0.313	0.178	0.121	0.077	0.043	0.025			
25	0.475	0.28	0.162	0.113	0.069	0.038	0.022			
24	0.431	0.249	0.151	0.105	0.062	0.035	0.02			
23	0.386	0.221	0.139	0.096	0.055	0.031	0.005			
22	0.348	0.195	0.13	0.086	0.049	0.028				
21	0.313	0.178	0.121	0.077	0.043	0.025				
20	0.28	0.162	0.113	0.069	0.038	0.022				
19	0.249	0.151	0.105	0.062	0.035	0.02				
18	0.221	0.139	0.096	0.055	0.031	0.005				
17	0.195	0.13	0.086	0.049	0.028					
16	0.178	0.121	0.077	0.043	0.025					
15	0.162	0.113	0.069	0.038	0.022					
14	0.151	0.105	0.062	0.035	0.02					
13	0.139	0.096	0.055	0.031	0.005					
12	0.13	0.086	0.049	0.028						
11	0.121	0.077	0.043	0.025						
10	0.113	0.069	0.038	0.022						
9	0.105	0.062	0.035	0.02						
8	0.096	0.055	0.031	0.005						
7	0.086	0.049	0.028							
6	0.077	0.043	0.025							
5	0.069	0.038	0.022							
1dB	1.2%	3.6%	9.5%	14.3%	21.4%	30.9%	35.7%	51.2%	59.5%	66.7%
3dB	0.0%	0.0%	0.0%	10.0%	18.0%	22.0%	32.0%	38.0%	48.0%	58.0%
5dB	0.0%	0.0%	0.0%	4.0%	12.0%	18.0%	26.0%	36.0%	46.0%	52.0%

E.2.2 Small Cell Base Station Analysis

The analysis is used to determine the separation distances necessary to reduce the Small Cell base station power level at the GPS receiver to below the interference power level based on a 1 dB, 3 dB, and 5 dB C/N_0 degradation. The analysis results are shown in Tables E.9 through Table E.11 for high precision GPS receivers. The Small Cell base station-received power calculations for the GPS high precision receiver category are shown in Figure E.7 and Figure E.8. The base station antenna height is varied between 5, 10, 20, and 30 meters. At each separation distance the maximum received power for all combinations of base station antenna height and down-tilt angle is determined. In addition, the calculated received power as a function of base station EIRP and separation distance is shown in Table E.13.

Table E.9. Percentage of High Precision GPS Receivers Impacted 1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -80	0	0 %	≥ 2697
≤ -75	1	1.2%	≥1690
≤ -70	3	3.6 %	≥ 1055
≤ -65	8	9.5 %	≥ 646
≤ -60	12	14.3 %	≥ 390
≤ -55	18	21.4 %	≥ 239
≤ -50	26	30.9 %	≥ 165
≤ -45	30	35.7 %	≥ 115
≤ -40	43	51.2 %	≥ 70
≤ -35	50	59.5 %	≥ 40
≤ -30	56	66.7 %	≥ 23
≤ -25	61	72.6 %	≥ 12
≤ -20	71	84.5 %	< 5

Table E.10. Percentage of High Precision GPS Receivers Impacted
3 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -65	0	0 %	≥ 646
≤ -60	5	10 %	≥ 390
≤ -55	9	18 %	≥ 239
≤ -50	11	22 %	≥ 165
≤ -45	16	32 %	≥ 115
≤ -40	19	38 %	≥ 70
≤ -35	24	48 %	≥ 40
≤ -30	29	58 %	≥ 23
≤ -25	31	62 %	≥ 12
≤ -20	33	66 %	< 5

Table E.11. Percentage of High Precision GPS Receivers Impacted
5 dB C/N_0 Degradation

Interference Power Levels (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -65	0	0 %	≥ 646
≤ -60	2	4%	≥ 390
≤ -55	6	12 %	≥ 239
≤ -50	9	18 %	≥ 165
≤ -45	13	26 %	≥ 115
≤ -40	18	36 %	≥ 70
≤ -35	23	46 %	≥ 40
≤ -30	26	52 %	≥ 23
≤ -25	30	60 %	≥ 12
≤ -20	31	62 %	< 5

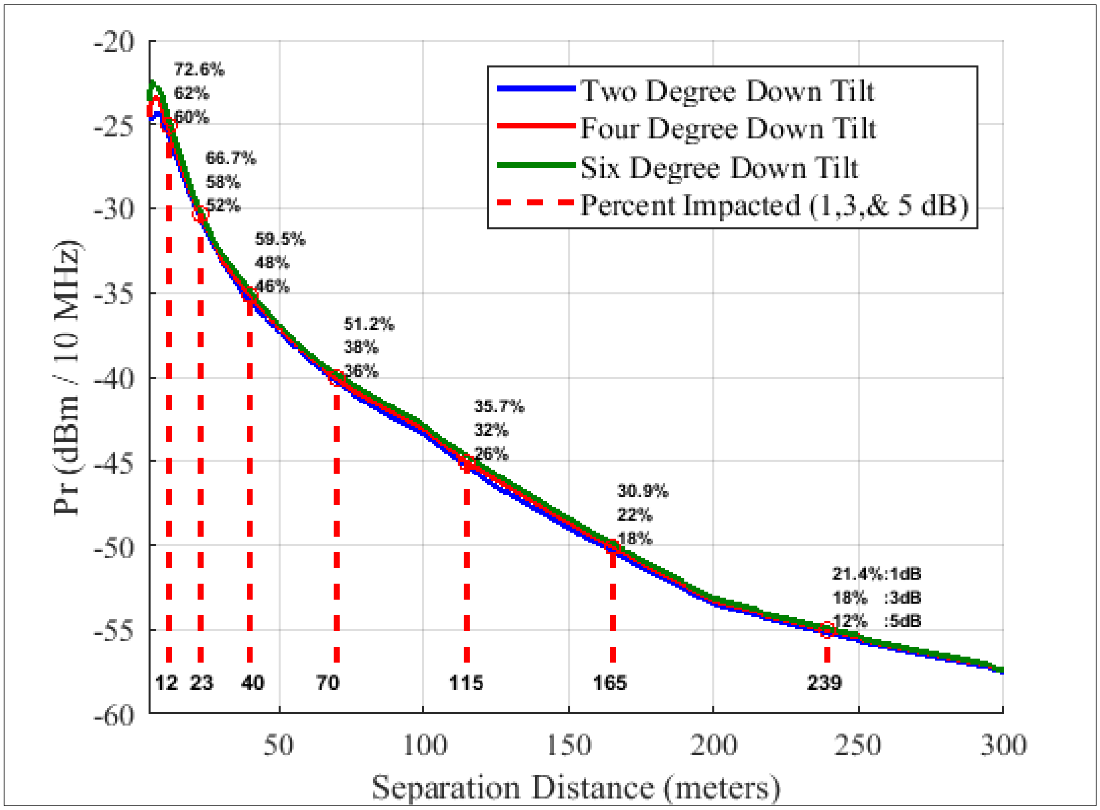


Figure E.7. Maximum Received Power as a Function of Separation Distance
High Precision Receiver
Small Cell Base Station EIRP of 40 dBm/10 MHz

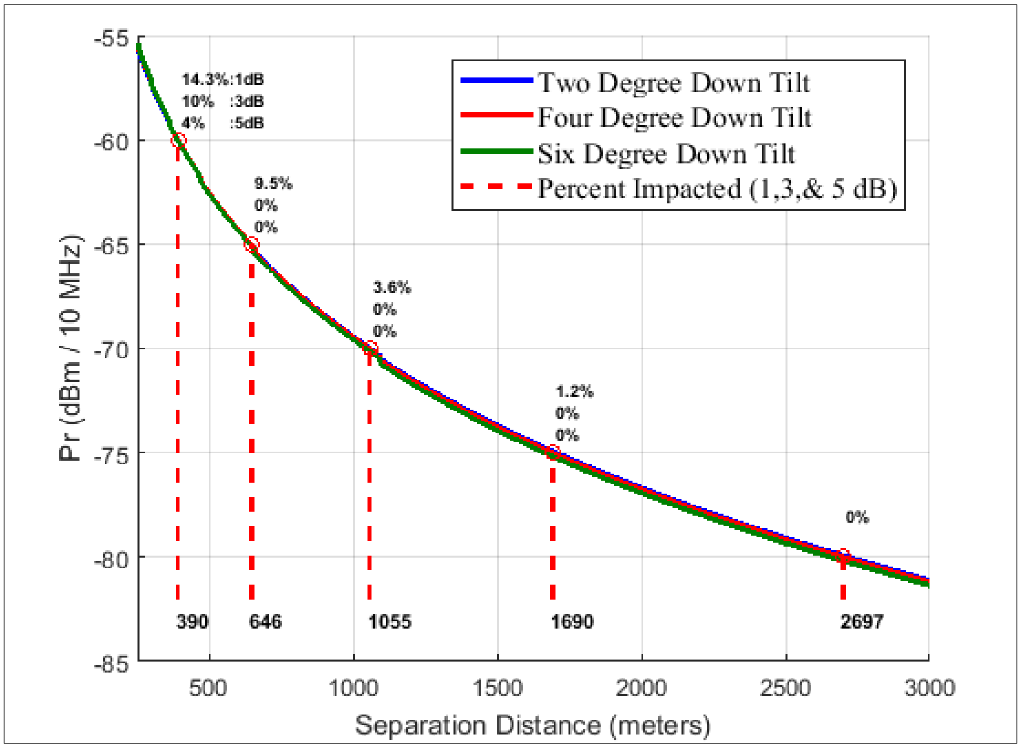


Figure E.8. Maximum Received Power as a Function of Separation Distance
High Precision Receiver
Small Cell Base Station EIRP of 40 dBm/10 MHz

For a 25 meter separation distance between a single base station and a GPS receiver, Table E.12 shows the additional attenuation needed to preclude a C/N_0 degradation all of the GPS high precision receivers measured in the different test programs.

Table E.12. Additional Attenuation needed for High Precision GPS Receivers

C/N_0 Degradation	Additional Attenuation (dB)
1 dB	48.9
3 dB	33.9
5 dB	33.9

The calculated received power, as a function of base station EIRP and separation distance are shown in table E.13.

Table E.13. Power Received as a Function of EIRP and Separation Distance - Small Cell

Base Station EIRP (dBm/10 MHz)	Received Power (dBm/10 MHz)									
	-75	-70	-65	-60	-55	-50	-45	-40	-35	-30
	Separation Distance (km)									
43	2.245	1.391	0.861	0.524	0.321	0.197	0.144	0.1	0.056	0.031
42	2.045	1.26	0.777	0.472	0.293	0.187	0.134	0.089	0.05	0.028
41	1.86	1.14	0.701	0.433	0.263	0.175	0.124	0.078	0.045	0.025
40	1.69	1.055	0.646	0.39	0.239	0.165	0.115	0.07	0.04	0.023
39	1.534	0.954	0.582	0.357	0.217	0.154	0.107	0.063	0.035	0.02
38	1.391	0.861	0.524	0.321	0.197	0.144	0.1	0.056	0.031	0.018
37	1.26	0.777	0.472	0.293	0.187	0.134	0.089	0.05	0.028	0.016
36	1.14	0.701	0.433	0.263	0.175	0.124	0.078	0.045	0.025	0.014
35	1.055	0.646	0.39	0.239	0.165	0.115	0.07	0.04	0.023	0.012
34	0.954	0.582	0.357	0.217	0.154	0.107	0.063	0.035	0.02	0.005
33	0.861	0.524	0.321	0.197	0.144	0.1	0.056	0.031	0.018	
32	0.777	0.472	0.293	0.187	0.134	0.089	0.05	0.028	0.016	
31	0.701	0.433	0.263	0.175	0.124	0.078	0.045	0.025	0.014	
30	0.646	0.39	0.239	0.165	0.115	0.07	0.04	0.023	0.012	
29	0.582	0.357	0.217	0.154	0.107	0.063	0.035	0.02	0.005	
28	0.524	0.321	0.197	0.144	0.1	0.056	0.031	0.018		
27	0.472	0.293	0.187	0.134	0.089	0.05	0.028	0.016		
26	0.433	0.263	0.175	0.124	0.078	0.045	0.025	0.014		
25	0.39	0.239	0.165	0.115	0.07	0.04	0.023	0.012		
24	0.357	0.217	0.154	0.107	0.063	0.035	0.02	0.005		
23	0.321	0.197	0.144	0.1	0.056	0.031	0.018			
22	0.293	0.187	0.134	0.089	0.05	0.028	0.016			
21	0.263	0.175	0.124	0.078	0.045	0.025	0.014			
20	0.239	0.165	0.115	0.07	0.04	0.023	0.012			
19	0.217	0.154	0.107	0.063	0.035	0.02	0.005			
18	0.197	0.144	0.1	0.056	0.031	0.018				
17	0.187	0.134	0.089	0.05	0.028	0.016				
16	0.175	0.124	0.078	0.045	0.025	0.014				
15	0.165	0.115	0.07	0.04	0.023	0.012				
14	0.154	0.107	0.063	0.035	0.02	0.005				
13	0.144	0.1	0.056	0.031	0.018					
12	0.134	0.089	0.05	0.028	0.016					
11	0.124	0.078	0.045	0.025	0.014					
10	0.115	0.07	0.04	0.023	0.012					
9	0.107	0.063	0.035	0.02	0.005					
8	0.1	0.056	0.031	0.018						
7	0.089	0.05	0.028	0.016						
6	0.078	0.045	0.025	0.014						
5	0.07	0.04	0.023	0.012						
1dB	1.2%	3.6%	9.5%	14.3%	21.4%	30.9%	35.7%	51.2%	59.5%	66.7%
3dB	0.0%	0.0%	0.0%	10.0%	18.0%	22.0%	32.0%	38.0%	48.0%	58.0%
5dB	0.0%	0.0%	0.0%	4.0%	12.0%	18.0%	26.0%	36.0%	46.0%	52.0%

E.3 GENERAL LOCATION/NAVIGATION GPS RECEIVER CATEGORY

The GPS general location/navigation receive antenna gain model is shown in Figure E.9.

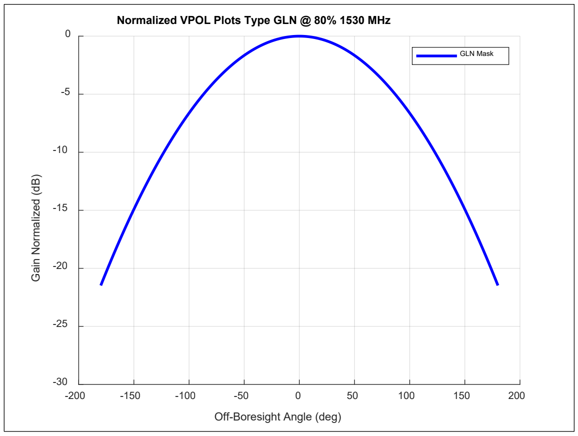


Figure E.9. GPS General Location/Navigation Receive Antenna Mask

The C/N_0 degradation measurements from the DOT ABC, DOD, R&A, NASCTN, TWG, and the NPEF test programs are used to establish the interference power levels. The summary of interference power levels from the different test programs for a 1 dB, 3 dB, and 5 dB degradation in C/N_0 are shown in Tables E.14 through E.16 for general location/navigation GPS receivers.

Table E.14. Summary of General Location/Navigation GPS Receiver Interference Power Levels 1 dB C/N_0 Degradation

Range of Interference Power Levels (dBm/10 MHz)	Number of Receivers					
	DOT ABC	DOD	R&A	NASCTN	NPEF	TWG
-69 to -65		1				
-64 to -60						
-59 to -55	2					
-54 to -50					1	
-49 to -45		1			2	
-44 to -40					2	
-39 to -35	1				3	
-34 to -30	7				8	3
-29 to -25	2				16	
-24 to -20					19	4
-19 to -15	1	1	1		20	
-14 to -10	4	1	7		23	4
-9 to -5				1		5
-4 to 0				1		4
1 to 5				2		9
Total Number of Receivers	17	4	8	4	94	29

Table E.15. Summary of General Location/Navigation GPS Receiver Interference Power Levels 3 dB C/N_0 Degradation

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers			
	DOT ABC	DOD	R&A	NASCTN
-64 to -60		1		
-59 to -55				
-54 to -50				
-49 to -45				
-44 to -40	2	1		
-39 to -35				
-34 to -30	1			
-29 to -25	7			
-24 to -20	2			
-19 to -15				
-14 to -10	5	2	8	
-9 to -5				1
-4 to 0				
1 to 5				3
Total Number of Receivers	17	4	8	4

Table E.16. Summary of General Location/Navigation GPS Receiver Interference Power Levels 5 dB C/N_0 Degradation

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers			
	DOT ABC	DOD	R&A	NASCTN
-59 to -55		1		
-54 to -50				
-49 to -45				
-44 to -40				
-39 to -35	1	1		
-34 to -30	1			
-29 to -25	4			
-24 to -20	5			
-19 to -15	1			
-14 to -10	5	2	8	
-9 to -5				1
-4 to 0				
1 to 5				3
Total Number of Receivers	17	4	8	4

E.3.1 Macro Cell Base Station Analysis

The analysis is used to determine the separation distances necessary to reduce the macro cell base station power level at the GPS receiver to below the interference power level based on a 1 dB, 3 dB, and 5 dB C/N_0 degradation. The analysis results are shown in Tables E.17 through E.19 for general location/navigation category of GPS receivers. The macro cell base station received power calculations for the GPS general location/navigation receiver category are shown in Figures E.10 through E.12. In addition, the calculated received power as a function of base station EIRP and separation distance is shown in Table E.20.

Table E.17. Percentage of General Location/Navigation GPS Receivers Impacted 1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -70	0	0 %	> 10110
≤ -65	1	0.6 %	≥ 7235
≤ -60	1	0.6 %	≥ 4985
≤ -55	3	1.9 %	≥ 3281
≤ -50	4	2.6 %	≥ 2047
≤ -45	7	4.5 %	≥ 1260
≤ -40	9	5.8 %	≥ 754
≤ -35	13	8.3 %	≥ 450
≤ -30	31	19.9 %	≥ 254
≤ -25	49	31.4 %	≥ 152
≤ -20	72	46.2 %	≥ 107
≤ -15	96	61.5 %	≥ 64
≤ -10	134	85.9 %	≥ 36
≤ -5	140	89.7 %	≥ 20
≤ 0	145	92.9 %	< 5

Table E.18. Percentage of General Location/Navigation GPS Receivers Impacted 3 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -65	0	0 %	≥ 7235
≤ -60	1	3 %	≥ 4985
≤ -55	1	3 %	≥ 3281
≤ -50	1	3 %	≥ 2047
≤ -45	1	3 %	≥ 1260
≤ -40	4	12.1 %	≥ 754
≤ -35	4	12.1 %	≥ 450
≤ -30	5	15.2 %	≥ 254
≤ -25	12	36.4 %	≥ 152
≤ -20	14	42.4 %	≥ 107
≤ -15	14	42.4 %	≥ 64
≤ -10	29	87.9 %	≥ 36
≤ -5	30	90.9 %	≥ 20
≤ 0	30	90.9 %	< 5

Table E.19. Percentage of General Location/Navigation GPS Receivers Impacted 5 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receiver Degraded	Separation Distance (meters)
≤ -60	0	0 %	≥ 4985
≤ -55	1	3 %	≥ 3281
≤ -50	1	3 %	≥ 2047
≤ -45	1	3 %	≥ 1260
≤ -40	1	3 %	≥ 754
≤ -35	3	9.1 %	≥ 450
≤ -30	4	12.1 %	≥ 254
≤ -25	8	24.2 %	≥ 152
≤ -20	13	39.4 %	≥ 107
≤ -15	14	42.4 %	≥ 64
≤ -10	29	87.9 %	≥ 36
≤ -5	30	90.9 %	≥ 20
≤ 0	30	90.9 %	< 5

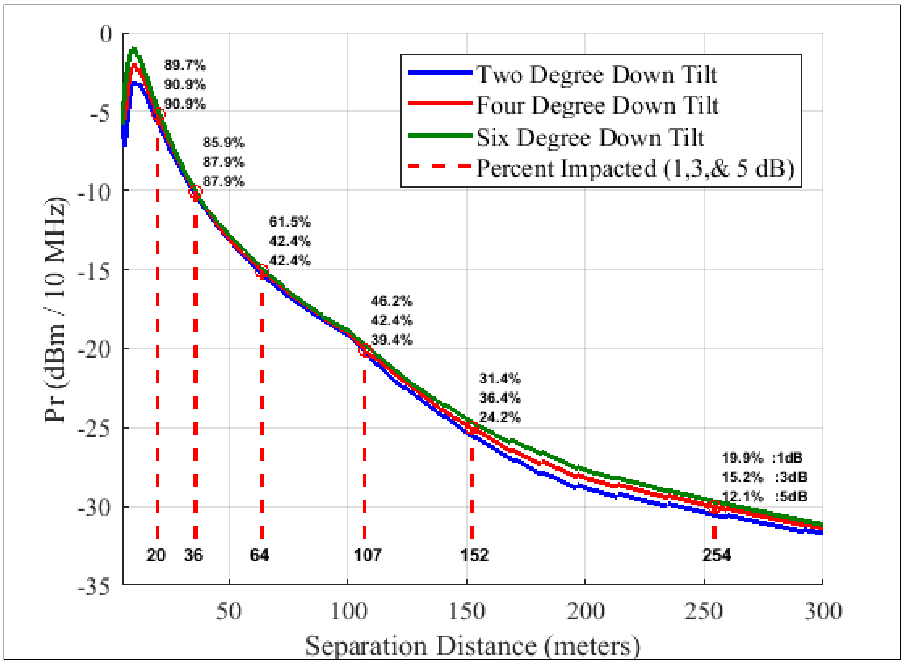


Figure E.10. Maximum Received Power as a Function of Separation Distance General Location/Navigation Receiver Macro Cell Base Station EIRP of 62 dBm/10 MHz

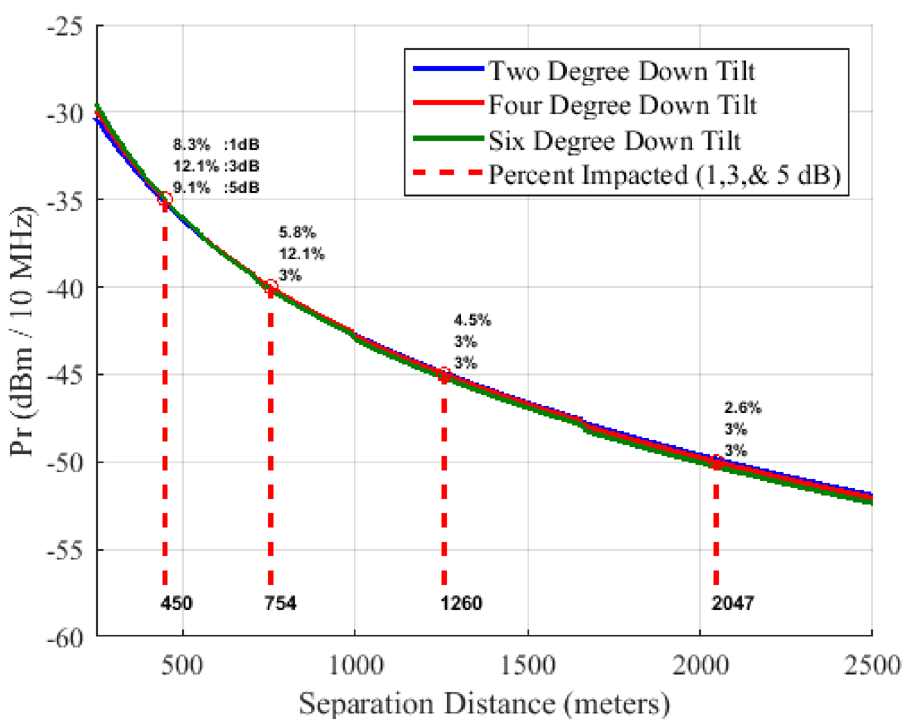


Figure E.11. Maximum Received Power as a Function of Separation Distance General Location/Navigation Receiver Macro Cell Base Station EIRP of 62 dBm/10 MHz

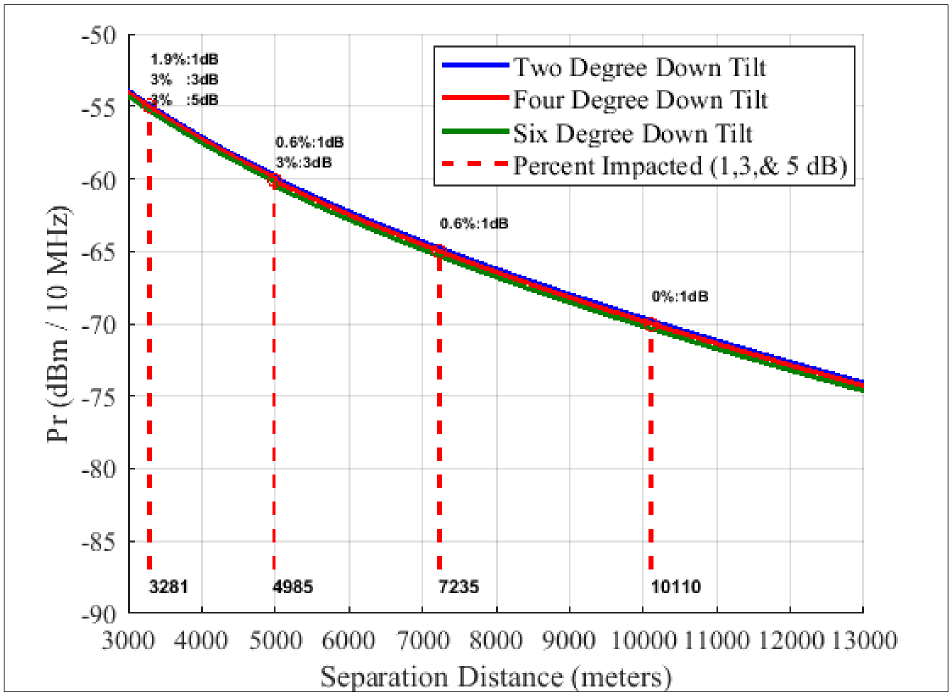


Figure E.12. Maximum Received Power as a Function of Separation Distance General Location/Navigation Receiver Macro Cell Base Station EIRP of 62 dBm/10 MHz

Table E.20. Power Received as a Function of EIRP and Separation Distance - Macro Cell

Base Station EIRP (dBm/10 MHz)	Received Power (dBm/10 MHz)									
	-70	-65	-60	-55	-50	-45	-40	-35	-30	-25
	Separation Distance (km)									
62	10.11	7.235	4.985	3.281	2.047	1.26	0.754	0.45	0.254	0.152
61	9.491	6.729	4.639	2.995	1.855	1.135	0.686	0.403	0.224	0.142
60	8.893	6.245	4.266	2.73	1.678	1.021	0.616	0.361	0.195	0.132
59	8.318	5.786	3.916	2.484	1.548	0.935	0.553	0.322	0.177	0.123
58	7.765	5.349	3.588	2.257	1.397	0.84	0.499	0.287	0.164	0.115
57	7.235	4.985	3.281	2.047	1.26	0.754	0.45	0.254	0.152	0.107
56	6.729	4.639	2.995	1.855	1.135	0.686	0.403	0.224	0.142	0.101
55	6.245	4.266	2.73	1.678	1.021	0.616	0.361	0.195	0.132	0.09
54	5.786	3.916	2.484	1.548	0.935	0.553	0.322	0.177	0.123	0.08
53	5.349	3.588	2.257	1.397	0.84	0.499	0.287	0.164	0.115	0.072
52	4.985	3.281	2.047	1.26	0.754	0.45	0.254	0.152	0.107	0.064
51	4.639	2.995	1.855	1.135	0.686	0.403	0.224	0.142	0.101	0.056
50	4.266	2.73	1.678	1.021	0.616	0.361	0.195	0.132	0.09	0.05
49	3.916	2.484	1.548	0.935	0.553	0.322	0.177	0.123	0.08	0.045
48	3.588	2.257	1.397	0.84	0.499	0.287	0.164	0.115	0.072	0.04
47	3.281	2.047	1.26	0.754	0.45	0.254	0.152	0.107	0.064	0.036
46	2.995	1.855	1.135	0.686	0.403	0.224	0.142	0.101	0.056	0.032
45	2.73	1.678	1.021	0.616	0.361	0.195	0.132	0.09	0.05	0.029
44	2.484	1.548	0.935	0.553	0.322	0.177	0.123	0.08	0.045	0.026
43	2.257	1.397	0.84	0.499	0.287	0.164	0.115	0.072	0.04	0.023
42	2.047	1.26	0.754	0.45	0.254	0.152	0.107	0.064	0.036	0.005

Base Station EIRP (dBm/10 MHz)	Received Power (dBm/10 MHz)									
	-70	-65	-60	-55	-50	-45	-40	-35	-30	-25
	Separation Distance (km)									
41	1.855	1.135	0.686	0.403	0.224	0.142	0.101	0.056	0.032	
40	1.678	1.021	0.616	0.361	0.195	0.132	0.09	0.05	0.029	
39	1.548	0.935	0.553	0.322	0.177	0.123	0.08	0.045	0.026	
38	1.397	0.84	0.499	0.287	0.164	0.115	0.072	0.04	0.023	
37	1.26	0.754	0.45	0.254	0.152	0.107	0.064	0.036	0.005	
36	1.135	0.686	0.403	0.224	0.142	0.101	0.056	0.032		
35	1.021	0.616	0.361	0.195	0.132	0.09	0.05	0.029		
34	0.935	0.553	0.322	0.177	0.123	0.08	0.045	0.026		
33	0.84	0.499	0.287	0.164	0.115	0.072	0.04	0.023		
32	0.754	0.45	0.254	0.152	0.107	0.064	0.036	0.005		
31	0.686	0.403	0.224	0.142	0.101	0.056	0.032			
30	0.616	0.361	0.195	0.132	0.09	0.05	0.029			
29	0.553	0.322	0.177	0.123	0.08	0.045	0.026			
28	0.499	0.287	0.164	0.115	0.072	0.04	0.023			
27	0.45	0.254	0.152	0.107	0.064	0.036	0.005			
26	0.403	0.224	0.142	0.101	0.056	0.032				
25	0.361	0.195	0.132	0.09	0.05	0.029				
24	0.322	0.177	0.123	0.08	0.045	0.026				
23	0.287	0.164	0.115	0.072	0.04	0.023				
22	0.254	0.152	0.107	0.064	0.036	0.005				
21	0.224	0.142	0.101	0.056	0.032					
20	0.195	0.132	0.09	0.05	0.029					
19	0.177	0.123	0.08	0.045	0.026					
18	0.164	0.115	0.072	0.04	0.023					
17	0.152	0.107	0.064	0.036	0.005					
16	0.142	0.101	0.056	0.032						
15	0.132	0.09	0.05	0.029						
14	0.123	0.08	0.045	0.026						
13	0.115	0.072	0.04	0.023						
12	0.107	0.064	0.036	0.005						
11	0.101	0.056	0.032							
10	0.09	0.05	0.029							
9	0.08	0.045	0.026							
8	0.072	0.04	0.023							
7	0.064	0.036	0.005							
6	0.056	0.032								
1dB	0.0%	0.6%	0.6%	1.9%	2.6%	4.5%	5.8%	8.3%	19.9%	31.4%
3dB	0.0%	0.0%	3.0%	3.0%	3.0%	3.0%	12.1%	12.1%	15.2%	36.4%
5dB	0.0%	0.0%	0.0%	3.0%	3.0%	3.0%	3.0%	9.1%	12.1%	24.2%

E.3.2 Small Cell Base Station Analysis

The analysis is used to determine the separation distances necessary to reduce the Small Cell base station power level at the GPS receiver to below the interference power level based on the 1 dB, 3 dB, and 5 dB C/N_0 degradation levels. The analysis results are shown in Tables E.21 through E.23 for general location/navigation category of GPS receivers. The Small Cell base station-received power calculations for the GPS general location/navigation receiver category are shown in Figure E.13 and Figure E.14.

Table E.21. Percentage of General Location/Navigation GPS Receivers Impacted 1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -70	0	0%	≥ 1348
≤ -65	1	0.6 %	≥ 829
≤ -60	1	0.6 %	≥ 501
≤ -55	3	1.9 %	≥ 302
≤ -50	4	2.6 %	≥ 189
≤ -45	7	4.5 %	≥ 135
≤ -40	9	5.8 %	≥ 90
≤ -35	13	8.3 %	≥ 51
≤ -30	31	19.9 %	≥ 29
≤ -25	49	31.4 %	≥ 16
≤ -20	72	46.2 %	< 5

Table E.22. Percentage of General Location/Navigation GPS Receivers Impacted 3 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -65	0	0 %	≥ 829
≤ -60	1	3 %	≥ 501
≤ -55	1	3 %	≥ 302
≤ -50	1	3 %	≥ 189
≤ -45	1	3 %	≥ 135
≤ -40	4	12.1 %	≥ 90
≤ -35	4	12.1 %	≥ 51
≤ -30	5	15.2 %	≥ 29
≤ -25	12	36.4 %	≥ 16
≤ -20	14	42.4 %	< 5

Table E.23. Percentage of General Location/Navigation GPS Receivers Impacted 5 dB C/N₀ Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receiver Degraded	Separation Distance (meters)
≤ -60	0	0 %	≥ 501
≤ -55	1	3 %	≥ 302
≤ -50	1	3 %	≥ 189
≤ -45	1	3 %	≥ 135
≤ -40	1	3 %	≥ 90
≤ -35	3	9.1 %	≥ 51
≤ -30	4	12.1 %	≥ 29
≤ -25	8	24.2 %	≥ 16
≤ -20	13	39.4 %	< 5

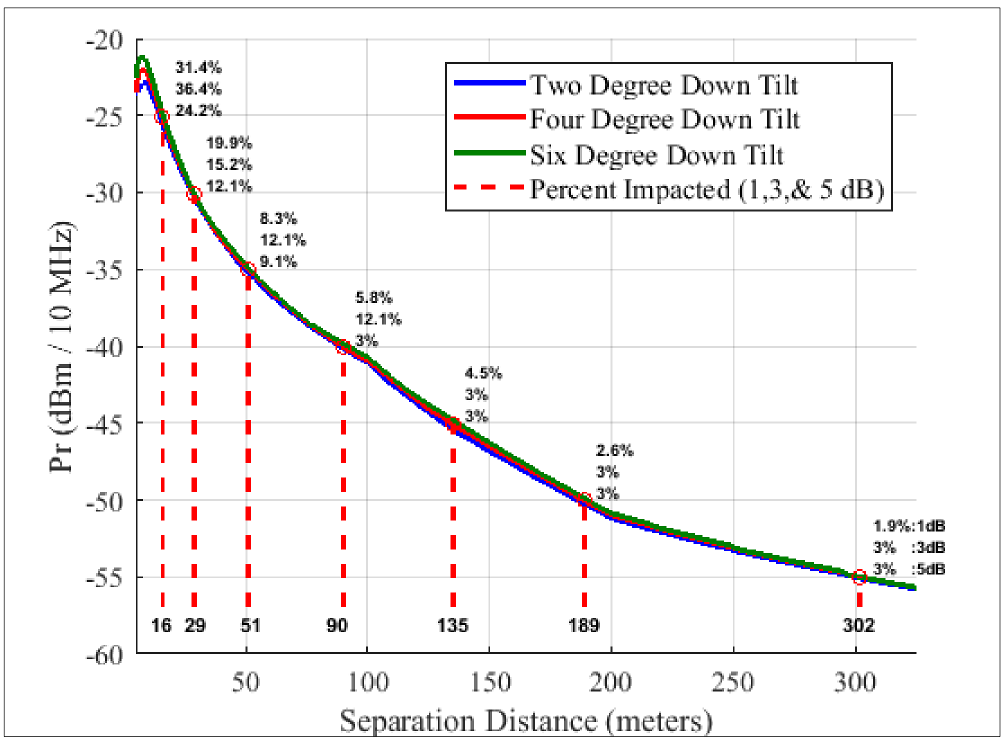


Figure E.13. Maximum Received Power as a Function of Separation Distance General Location/Navigation Receiver Small Cell Base Station EIRP of 40 dBm/10 MHz

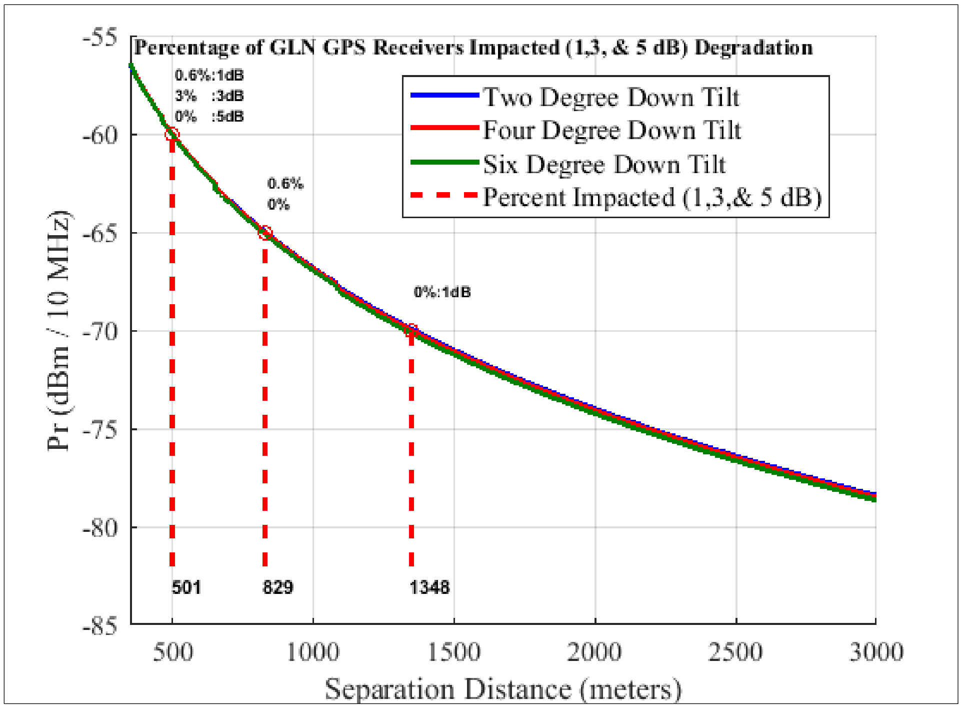


Figure E.14. Maximum Received Power as a Function of Separation Distance General Location/Navigation Receiver Small Cell Base Station EIRP of 40 dBm/10 MHz

For a 25-meter separation distance between a single base station and a GPS receiver, Table E.24 shows the additional attenuation needed to preclude a C/N_0 degradation for all of the GPS general location/navigation receivers measured in the different test programs. The calculated received power as a function of base station EIRP and separation distance is shown in Table E.25:

Table E.24. Additional Attenuation needed for General Location/Navigation GPS Receivers

C/N_0 Degradation	Additional Attenuation (dB)
1 dB	41.2
3 dB	36.2
5 dB	31.2

Table E.25. Power Received as a Function of EIRP and Separation Distance - Small Cell

Base Station EIRP (dBm/10 MHz)	Received Power (dBm/10 MHz)									
	-65	-60	-55	-50	-45	-40	-35	-30	-25	-20
	Separation Distance (km)									
43	1.105	0.674	0.411	0.248	0.167	0.117	0.072	0.04	0.023	< 0.005
42	1.016	0.617	0.37	0.223	0.156	0.109	0.065	0.036	0.021	< 0.005
41	0.918	0.556	0.336	0.201	0.145	0.101	0.058	0.032	0.018	0.005
40	0.829	0.501	0.302	0.189	0.135	0.09	0.051	0.029	0.016	
39	0.748	0.457	0.274	0.178	0.125	0.081	0.045	0.026	0.014	
38	0.674	0.411	0.248	0.167	0.117	0.072	0.04	0.023	0.005	
37	0.617	0.37	0.223	0.156	0.109	0.065	0.036	0.021		
36	0.556	0.336	0.201	0.145	0.101	0.058	0.032	0.018		
35	0.501	0.302	0.189	0.135	0.09	0.051	0.029	0.016		
34	0.457	0.274	0.178	0.125	0.081	0.045	0.026	0.014		
33	0.411	0.248	0.167	0.117	0.072	0.04	0.023	0.005		
32	0.37	0.223	0.156	0.109	0.065	0.036	0.021			
31	0.336	0.201	0.145	0.101	0.058	0.032	0.018			
30	0.302	0.189	0.135	0.09	0.051	0.029	0.016			
29	0.274	0.178	0.125	0.081	0.045	0.026	0.014			
28	0.248	0.167	0.117	0.072	0.04	0.023	0.005			
27	0.223	0.156	0.109	0.065	0.036	0.021				
26	0.201	0.145	0.101	0.058	0.032	0.018				
25	0.189	0.135	0.09	0.051	0.029	0.016				
24	0.178	0.125	0.081	0.045	0.026	0.014				
23	0.167	0.117	0.072	0.04	0.023	0.005				
22	0.156	0.109	0.065	0.036	0.021					
21	0.145	0.101	0.058	0.032	0.018					
20	0.135	0.09	0.051	0.029	0.016					
19	0.125	0.081	0.045	0.026	0.014					
18	0.117	0.072	0.04	0.023	0.005					
17	0.109	0.065	0.036	0.021						
16	0.101	0.058	0.032	0.018						
15	0.09	0.051	0.029	0.016						
14	0.081	0.045	0.026	0.014						
13	0.072	0.04	0.023	0.005						
12	0.065	0.036	0.021							
11	0.058	0.032	0.018							
10	0.051	0.029	0.016							
9	0.045	0.026	0.014							
8	0.04	0.023	0.005							
7	0.036	0.021								
6	0.032	0.018								
5	0.029	0.016								
1dB	0.6%	0.6%	1.9%	2.6%	4.5%	5.8%	8.3%	19.9%	31.4%	46.2%
3dB	0.0%	3.0%	3.0%	3.0%	3.0%	12.1%	12.1%	15.2%	36.4%	42.4%
5dB	0.0%	0.0%	3.0%	3.0%	3.0%	3.0%	9.1%	12.1%	24.2%	39.4%

E.4 TIMING GPS RECEIVER CATEGORY

The GPS timing receive antenna gain model is shown in Figure E.15.

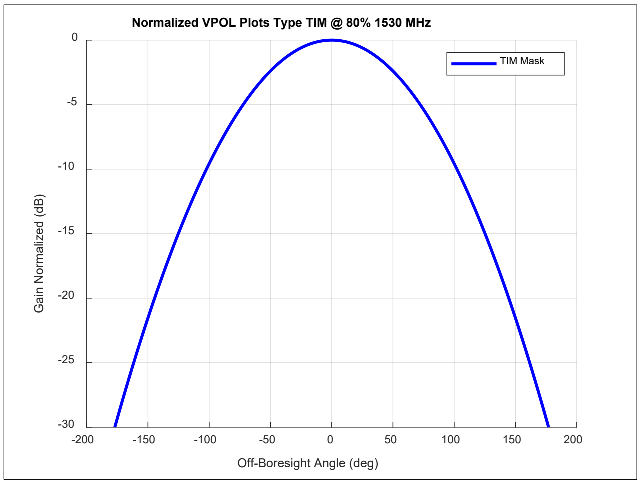


Figure E.15. GPS Timing Receive Antenna Mask

The C/N_0 degradation measurements from the DOT ABC, NASCTN, and TWG test programs are used to establish the interference power levels. The summary of interference power levels from the different test programs for a 1 dB, 3 dB, and 5 dB degradation in C/N_0 are shown in Tables E.26 through E.28 for timing GPS receivers.

Table E.26. Summary of Timing GPS Receiver Interference Power Levels 1 dB C/N_0 Degradation

Range of Interference Power Levels (dBm/10 MHz)	Number of Receiver		
	DOT ABC	NASCTN	TWG
-49 to -45	1		
-44 to -40			2
-39 to -35			1
-34 to -30	1		1
-29 to -25			3
-24 to -20	1	1	1
-19 to -15	2		4
-14 to -10	4		
-9 to -5			
-4 to 0			
1 to 5		2	
Total Number of Receivers	9	3	12

Table E.27. Summary of Timing GPS Receiver Interference Power Levels 3 dB C/N_0 Degradation

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers	
	DOT ABC	NASCTN
-44 to -40	1	
-39 to -35		
-34 to -30		
-29 to -25	1	
-24 to -20		
-19 to -15	2	1
-14 to -10	5	
-9 to -5		
-4 to 0		
1 to 5		2
Total Number of Receivers	9	3

Table E.28. Summary of Timing GPS Receiver Interference Power Levels 5 dB C/N_0 Degradation

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers	
	DOT ABC	NASCTN
-44 to -40	1	
-39 to -35		
-34 to -30		
-29 to -25	1	
-24 to -20		
-19 to -15	1	1
-14 to -10	6	
-9 to -5		
-4 to 0		
1 to 5		2
Total Number of Receivers	9	3

E.4.1 Macro Cell Base Station Analysis

The analysis is used to determine the separation distances necessary to reduce the macro cell base station power level at the GPS receiver to below the interference power level based on the 1 dB, 3 dB, and 5 dB C/N_0 degradation levels. The analysis results are shown in Tables E.29 through E.31 for timing category of GPS receivers. The macro cell base station-received power plots are shown in Figure E.16 and Figure E.17 for the timing GPS receiver category. In addition, the calculated received power as a function of base station EIRP and separation distance is shown in Table E.32.

Table E.29. Percentage of Timing GPS Receivers Impacted
1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -50	0	0 %	≥ 1662
≤ -45	1	4.2 %	≥ 997
≤ -40	3	12.5 %	≥ 606
≤ -35	4	16.7 %	≥ 361
≤ -30	6	25 %	≥ 201
≤ -25	9	37.5 %	≥ 133
≤ -20	12	50 %	≥ 89
≤ -15	18	75 %	≥ 51
≤ -10	22	91.7 %	≥ 29
≤ -5	22	91.7 %	≥ 16
≤ 0	22	91.7 %	< 5

Table E.30. Percentage of Timing GPS Receivers Impacted
3 dB C/N_0 Degradation

Interference Power Level (dBm/MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -45	0	0 %	≥ 997
≤ -40	1	8.3 %	≥ 606
≤ -35	1	8.3 %	≥ 361
≤ -30	1	8.3 %	≥ 201
≤ -25	2	16.7 %	≥ 133
≤ -20	2	16.7 %	≥ 89
≤ -15	5	41.7 %	≥ 51
≤ -10	10	83.3 %	≥ 29
≤ -5	10	83.3 %	≥ 16
≤ 0	10	83.3 %	< 5

Table E.31. Percentage of Timing GPS Receivers Impacted
5 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -45	0	0%	≥ 997
≤ -40	1	8.3 %	≥ 606
≤ -35	1	8.3 %	≥ 361
≤ -30	1	8.3 %	≥ 201
≤ -25	2	16.7 %	≥ 133
≤ -20	2	16.7 %	≥ 89
≤ -15	4	33.3 %	≥ 51
≤ -10	10	83.3 %	≥ 29
≤ -5	10	83.3 %	≥ 16
≤ 0	10	83.3 %	< 5

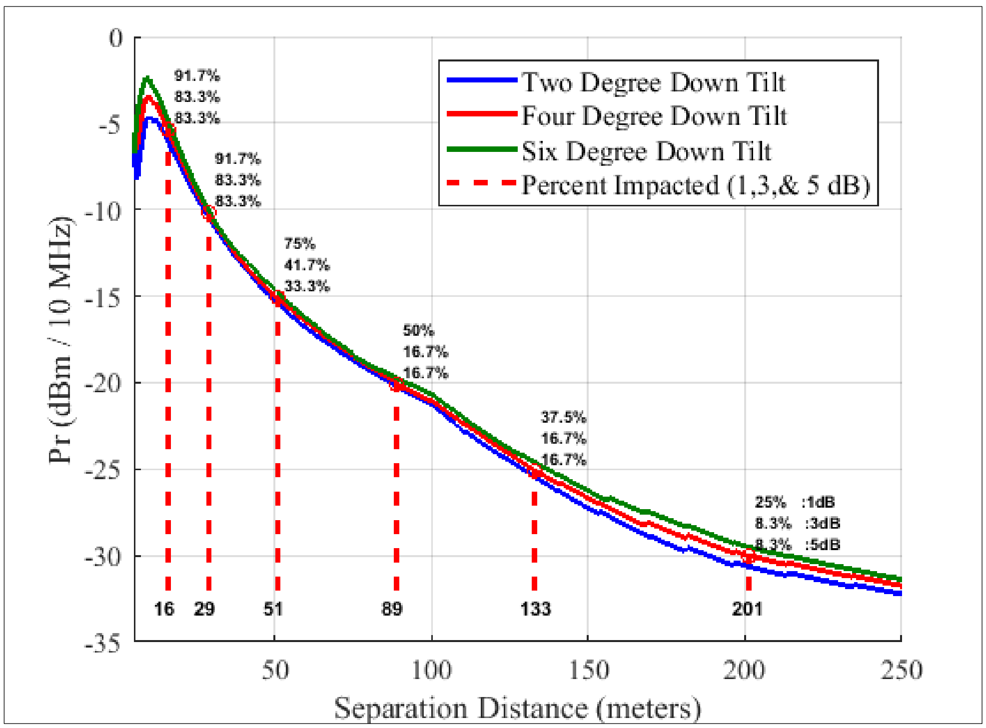


Figure E.16. Maximum Received Power as a Function of Separation Distance
Timing Receiver
Macro Cell Base Station EIRP of 62 dBm/10 MHz

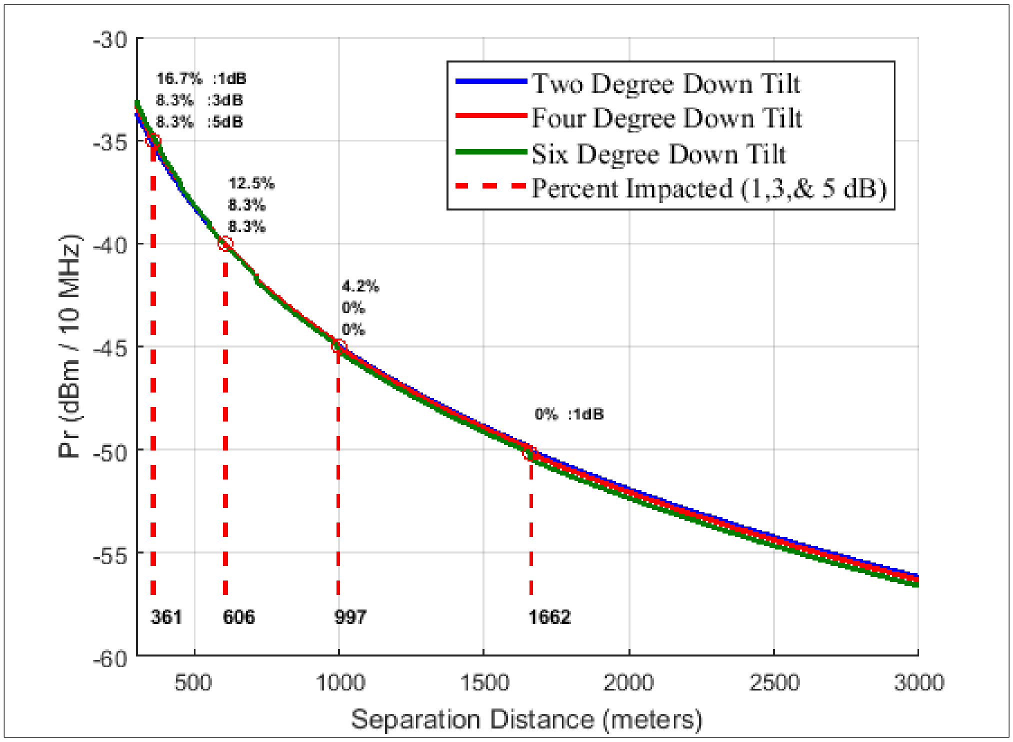


Figure E.17. Maximum Received Power as a Function of Separation Distance Timing Receiver Macro Cell Base Station EIRP of 62 dBm/10 MHz

Table E.32. Power Received as a Function of EIRP and Separation Distance - Macro Cell

Base Station EIRP (dBm/10 MHz)	Power Received (dBm/10 MHz)									
	-50	-45	-40	-35	-30	-25	-20	-15	-10	-5
	Separation Distance (km)									
62	1.662	0.997	0.606	0.361	0.201	0.133	0.089	0.051	0.029	0.016
61	1.511	0.916	0.552	0.324	0.185	0.124	0.08	0.045	0.026	0.005
60	1.363	0.823	0.494	0.29	0.165	0.116	0.072	0.04	0.023	
59	1.229	0.739	0.448	0.258	0.155	0.108	0.064	0.036	0.02	
58	1.107	0.676	0.401	0.228	0.144	0.1	0.057	0.032	0.005	
57	0.997	0.606	0.361	0.201	0.133	0.089	0.051	0.029		
56	0.916	0.552	0.324	0.185	0.124	0.08	0.045	0.026		
55	0.823	0.494	0.29	0.165	0.116	0.072	0.04	0.023		
54	0.739	0.448	0.258	0.155	0.108	0.064	0.036	0.02		
53	0.676	0.401	0.228	0.144	0.1	0.057	0.032	0.005		
52	0.606	0.361	0.201	0.133	0.089	0.051	0.029			
51	0.552	0.324	0.185	0.124	0.08	0.045	0.026			
50	0.494	0.29	0.165	0.116	0.072	0.04	0.023			
49	0.448	0.258	0.155	0.108	0.064	0.036	0.02			
48	0.401	0.228	0.144	0.1	0.057	0.032	0.005			
47	0.361	0.201	0.133	0.089	0.051	0.029				
46	0.324	0.185	0.124	0.08	0.045	0.026				
45	0.29	0.165	0.116	0.072	0.04	0.023				
44	0.258	0.155	0.108	0.064	0.036	0.02				
43	0.228	0.144	0.1	0.057	0.032	0.005				
42	0.201	0.133	0.089	0.051	0.029					
41	0.185	0.124	0.08	0.045	0.026					
40	0.165	0.116	0.072	0.04	0.023					
39	0.155	0.108	0.064	0.036	0.02					
38	0.144	0.1	0.057	0.032	0.005					
37	0.133	0.089	0.051	0.029						
36	0.124	0.08	0.045	0.026						
35	0.116	0.072	0.04	0.023						
34	0.108	0.064	0.036	0.02						
33	0.1	0.057	0.032	0.005						
32	0.089	0.051	0.029							
31	0.08	0.045	0.026							
30	0.072	0.04	0.023							
29	0.064	0.036	0.02							
28	0.057	0.032	0.005							
27	0.051	0.029								
26	0.045	0.026								
25	0.04	0.023								
24	0.036	0.02								
23	0.032	0.005								
22	0.029									
21	0.026									

Base Station EIRP (dBm/10 MHz)	Power Received (dBm/10 MHz)									
	-50	-45	-40	-35	-30	-25	-20	-15	-10	-5
	Separation Distance (km)									
20	0.023									
19	0.02									
18	0.005									
1 dB	0.0	4.2%	12.5%	16.7%	25%	37.5%	50%	75%	91.7%	91.7%
3 dB	0.0%	0.0%	8.3%	8.3%	8.3%	16.7%	16.7%	41.7%	83.3%	83.3%
5 dB	0.0%	0.0%	8.3%	8.3%	8.3%	16.7%	16.7%	33.3%	83.3%	83.3%

E.4.2 Small Cell Base Station Analysis

The analysis is used to determine the separation distances necessary to reduce the Small Cell base station power level at the GPS receiver to below the interference power level based on the 1 dB, 3 dB, and 5 dB C/N_0 degradation levels. The analysis results are shown in Tables E.33 through E.35 for timing category of GPS receivers. The Small Cell base station-received power calculations for the GPS timing receiver category are shown in Figure E.18. In addition, the calculated received power as a function of base station EIRP and separation distance is shown in Table E.37.

Table E.33. Percentage of Timing GPS Receivers Impacted 1 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -50	0	0 %	> 168
≤ -45	1	4.2 %	≥ 117
≤ -40	3	12.5 %	≥ 72
≤ -35	4	16.7 %	≥ 41
≤ -30	6	25 %	≥ 24
≤ -25	9	37.5 %	≥ 13
≤ -20	12	50 %	< 5

Table E.34. Percentage of Timing GPS Receivers Impacted 3 dB C/N_0 Degradation

Interference Power Level (dBm/MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -45	0	0 %	≥ 117
≤ -40	1	8.3%	≥ 72
≤ -35	1	8.3 %	≥ 41
≤ -30	1	8.3 %	≥ 24
≤ -25	2	16.7 %	≥ 13
≤ -20	2	16.7 %	< 5

Table E.35. Percentage of Timing GPS Receivers Impacted
5 dB C/N₀ Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -45	0	0 %	≥ 117
≤ -40	1	8.3 %	≥ 72
≤ -35	1	8.3 %	≥ 41
≤ -30	1	8.3 %	≥ 24
≤ -25	2	16.7 %	≥ 13
≤ -20	2	16.7 %	< 5

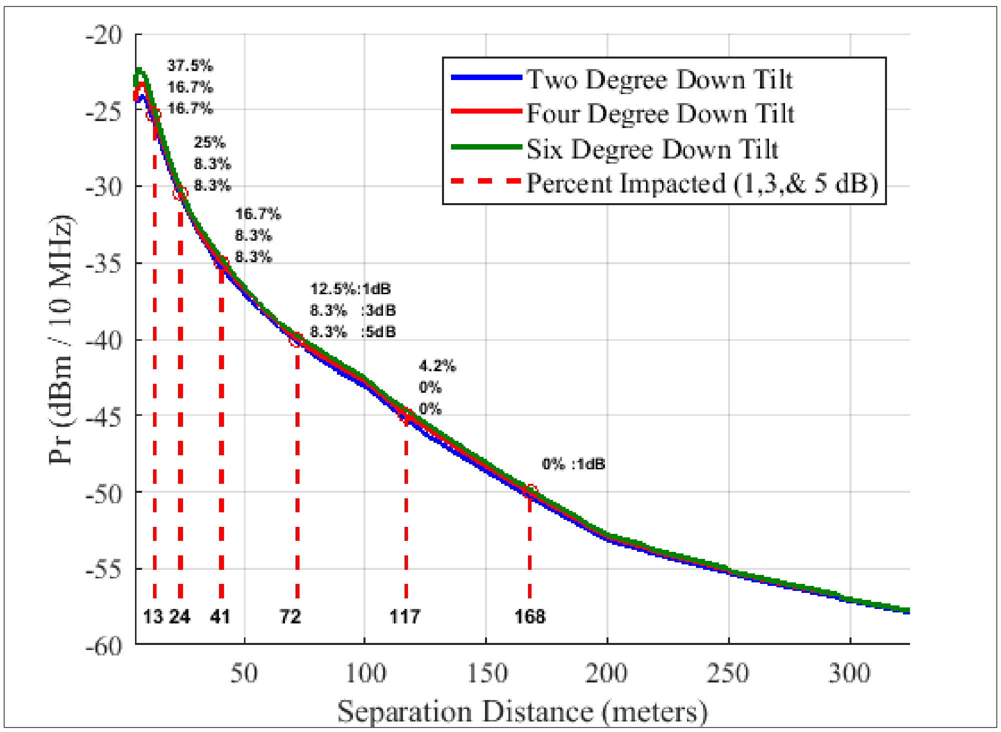


Figure E.18. Maximum Received Power as a Function of Separation Distance
Timing Receiver
Small Cell Base Station EIRP of 40 dBm/10 MHz

For a 25-meter separation distance between a single base station and a GPS receiver, Table E.36 shows the additional attenuation needed for all of the GPS timing receivers measured in the different test programs to preclude a C/N_0 degradation. The calculated received power as a function of base station EIRP and separation distance is shown in Table E.37.

Table E.36. Additional Attenuation Needed for Timing GPS Receivers

C/N_0 Degradation	Additional Attenuation (dB)
1 dB	19.24
3 dB	14.24
5 dB	14.24

Table E.37. Power Received as a Function of EIRP and Separation Distance - Small Cell

Base Station EIRP (dBm/10 MHz)	Power Received (dBm/10 MHz)									
	-60	-55	-50	-45	-40	-35	-30	-25	-20	-15
	Separation Distance (km)									
42	0.491	0.299	0.19	0.137	0.092	0.052	0.029	0.017	< 0.005	< 0.005
41	0.45	0.273	0.179	0.127	0.081	0.046	0.026	0.015	0.005	
40	0.405	0.248	0.168	0.117	0.072	0.041	0.024	0.013		
39	0.364	0.223	0.157	0.11	0.065	0.036	0.021	0.005		
38	0.333	0.202	0.147	0.102	0.058	0.032	0.019			
37	0.299	0.19	0.137	0.092	0.052	0.029	0.017			
36	0.273	0.179	0.127	0.081	0.046	0.026	0.015			
35	0.248	0.168	0.117	0.072	0.041	0.024	0.013			
34	0.223	0.157	0.11	0.065	0.036	0.021	0.005			
33	0.202	0.147	0.102	0.058	0.032	0.019				
32	0.19	0.137	0.092	0.052	0.029	0.017				
31	0.179	0.127	0.081	0.046	0.026	0.015				
30	0.168	0.117	0.072	0.041	0.024	0.013				
29	0.157	0.11	0.065	0.036	0.021	0.005				
28	0.147	0.102	0.058	0.032	0.019					
27	0.137	0.092	0.052	0.029	0.017					
26	0.127	0.081	0.046	0.026	0.015					
25	0.117	0.072	0.041	0.024	0.013					
24	0.11	0.065	0.036	0.021	0.005					
23	0.102	0.058	0.032	0.019						
22	0.092	0.052	0.029	0.017						
21	0.081	0.046	0.026	0.015						
20	0.072	0.041	0.024	0.013						
19	0.065	0.036	0.021	0.005						
18	0.058	0.032	0.019							
17	0.052	0.029	0.017							
16	0.046	0.026	0.015							
15	0.041	0.024	0.013							
14	0.036	0.021	0.005							
13	0.032	0.019								
12	0.029	0.017								
11	0.026	0.015								
10	0.024	0.013								
9	0.021	0.005								
1 dB	0.0%	0.0%	0.0%	4.2%	12.5%	16.7%	25%	37.5%	50%	75%
3 dB	0.0%	0.0%	0.0%	0.0%	8.3%	8.3%	8.3%	16.7%	16.7%	41.7%
5 dB	0.0%	0.0%	0.0%	0.0%	8.3%	8.3%	8.3%	16.7%	16.7%	33.3%

E.5 CELLULAR GPS RECEIVER CATEGORY

The GPS cellular receive antenna gain model is shown in Figure E.19.

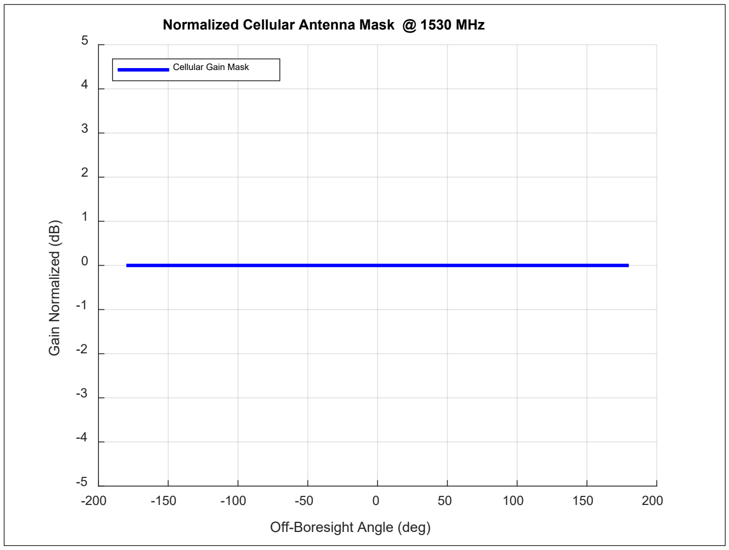


Figure E.19. GPS Cellular Receive Antenna Mask

The C/N_0 degradation measurements from the DOT ABC and TWG test programs are used to establish the interference power levels. The summary of interference power levels from the different test programs for a 1 dB, 3 dB, and 5 dB degradation in C/N_0 is shown in Tables E.38 through E.40 for cellular GPS receivers.

Table E.38. Summary of Cellular GPS Receiver Interference Power Levels 1 dB C/N_0 Degradation

Range of Interference Power Levels (dBm/10 MHz)	Number of GPS Receivers	
	DOT ABC	TWG
-34 to -30		1
-29 to -25		1
-24 to -20		1
-19 to -15		4
-14 to -10	2	4
-9 to -5		6
-4 to 0		23
Total Number of Receivers	2	40

Table E.39. Summary of Cellular GPS Receiver Interference Power Levels 3 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers
	DOT ABC
$\leq$ -10	2
Total Number of Receivers	2

Table E.40. Summary of Cellular GPS Receiver Interference Power Levels 5 dB C/N_0 Degradation

Interference Power Level (dBm/10 MHz)	Number of GPS Receivers
	DOT ABC
≤ -10	2
Total Number of Receivers	2

E.5.1 Macro Cell Base Station Analysis

The analysis is used to determine the separation distances necessary to reduce the macro base station power level at the GPS receiver to below the interference power level. The analysis results are shown in Table E.41 for the cellular category of GPS receivers. The macro base station-received power plot for the cellular GPS receiver category is shown in Figures E.20 and E.21.

Table E.41. Percentage of Cellular GPS Receivers Impacted

Interference Power Level (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -35	0	0 %	> 757
≤ -30	1	2.4 %	≥ 435
≤ -25	2	4.8 %	≥ 227
≤ -20	3	7.1 %	≥ 146
≤ -15	7	16.7 %	≥ 106
≤ -10	13	30.9 %	≥ 62
≤ -5	19	45.2 %	≥ 35
≤ 0	42	100 %	≥ 17

A separation distance of greater than 100 meters is necessary for the 3 dB and 5 dB degradations in C/N_0.

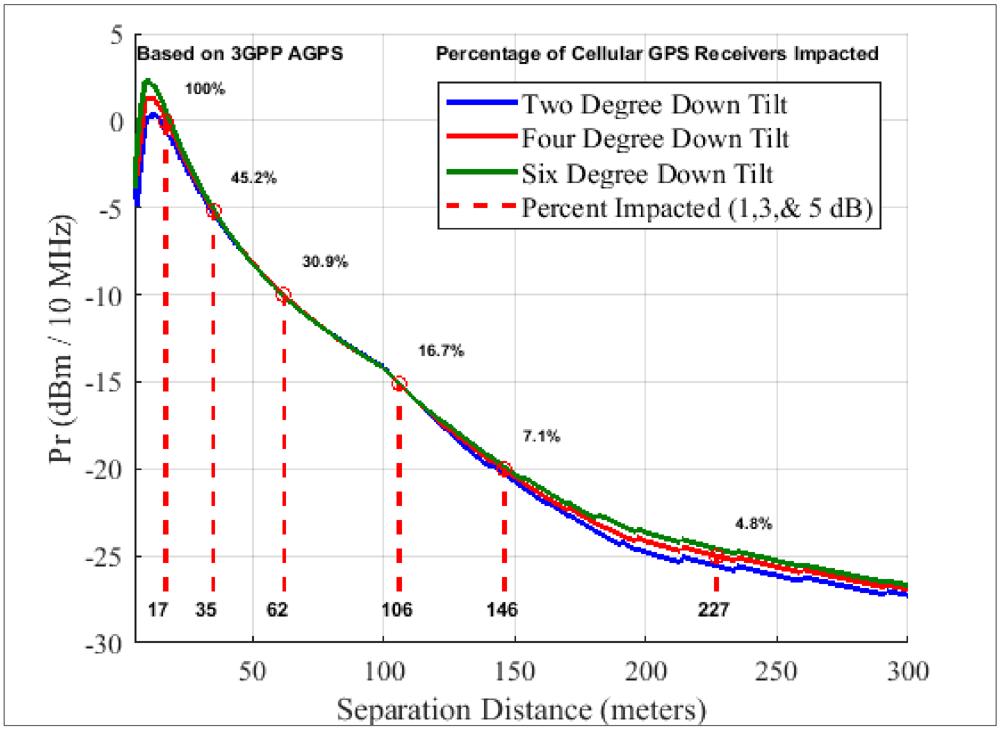


Figure E.20. Maximum Received Power as a Function of Separation Distance Cellular Receiver Macro Cell Base Station EIRP of 62 dBm/10 MHz

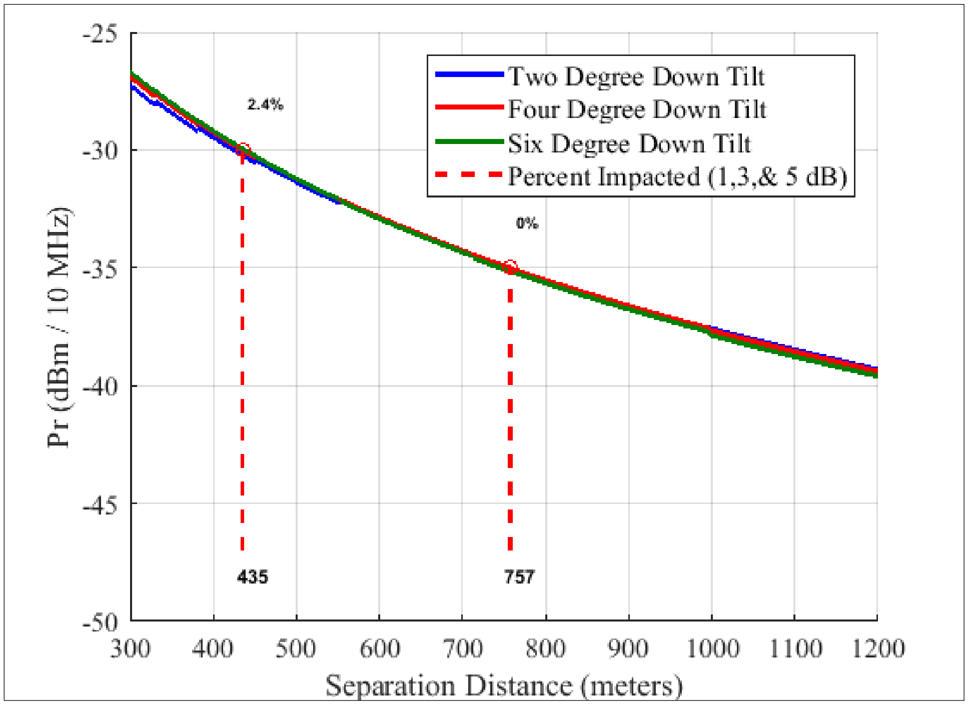


Figure E.21. Maximum Received Power as a Function of Separation Distance Cellular Receiver Macro Cell Base Station EIRP of 62 dBm/10 MHz

E.5.2 Small Cell Base Station Analysis

The analysis is used to determine the separation distances necessary to reduce the Small Cell base station power level at the GPS receiver to below the interference power level. The analysis results are shown in Table E.42 for the cellular category of GPS receivers. The Small Cell base station received power calculations for the GPS cellular receiver category are shown in Figure E.22.

Table E.42. Percentage of Cellular GPS Receivers Impacted

Interference Power Level (dBm/10 MHz)	Number of Receivers Degraded	Percentage of Receivers Degraded	Separation Distance (meters)
≤ -35	0	0 %	> 88
≤ -30	1	2.4 %	≥ 50
≤ -25	2	4.8 %	≥ 28
≤ -20	3	7.1 %	≥ 14
≤ -15	7	16.7 %	< 5

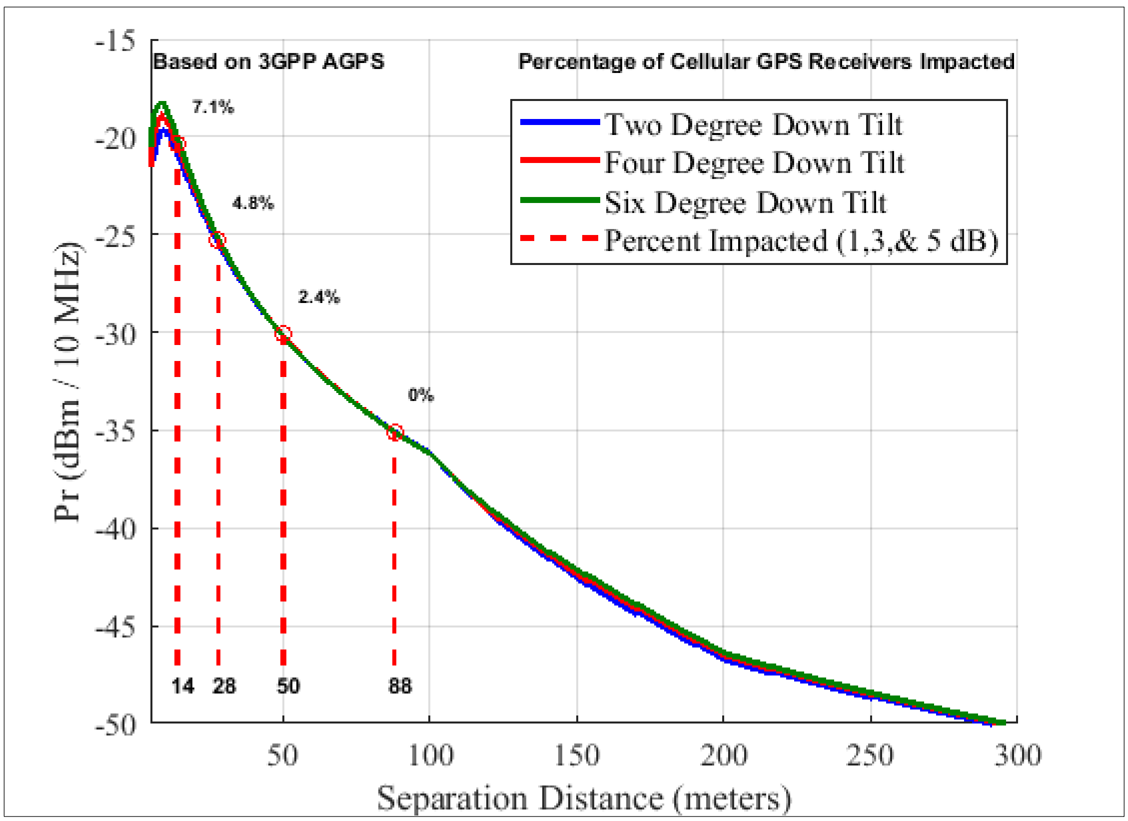


Figure E.22. Maximum Received Power as a Function of Separation Distance Cellular Receiver Small Cell Base Station EIRP of 40 dBm/10 MHz

ADDENDUM A GPS RECEIVE ANTENNA MASKS

The antenna masks for each of the Global Positioning System (GPS) receiver categories are provided in this addendum. The antenna masks are based on measurements performed for Department of Transportation Adjacent Band Compatibility (DOT ABC) test program and presented at their March, 30, 2017 Workshop.[6] The receive antenna masks were developed using the 80th percentile of the measured gain patterns, normalized, using the polarization set to maximize the receive antenna gain. The receive mask for the high precision GPS receiver category is shown in Figure E.A.1.

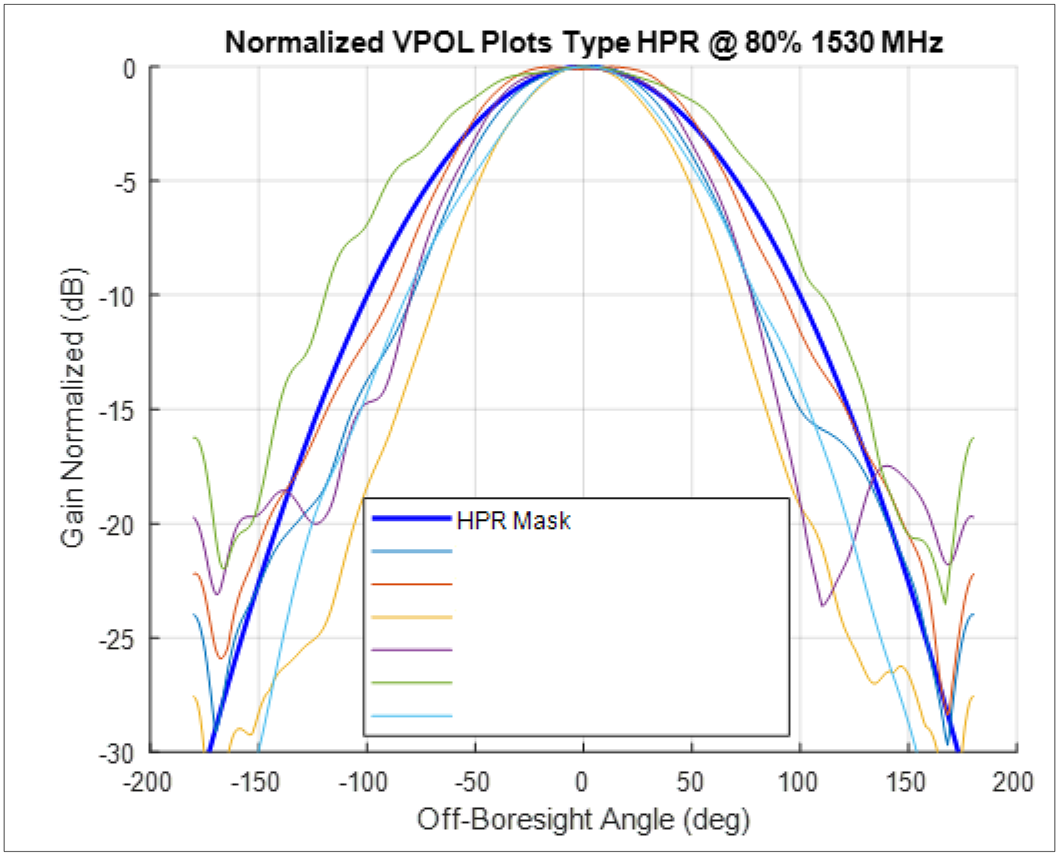


Figure E.A.1. Receive Mask for High Precision GPS Receiver

The receive mask for the timing GPS receiver category is shown in Figure E.A.2.

[6] United States Department of Transportation, Office of Research and Technology, *Inverse Modeling/Transmit Power Levels*, GPS-ABC Assessment Workshop VI, RTCA, Washington, DC (Mar. 30, 2017), *available at* https://www.transportation.gov/pnt/gps-adjacent-band-compatibility-assessment-workshop-vi.

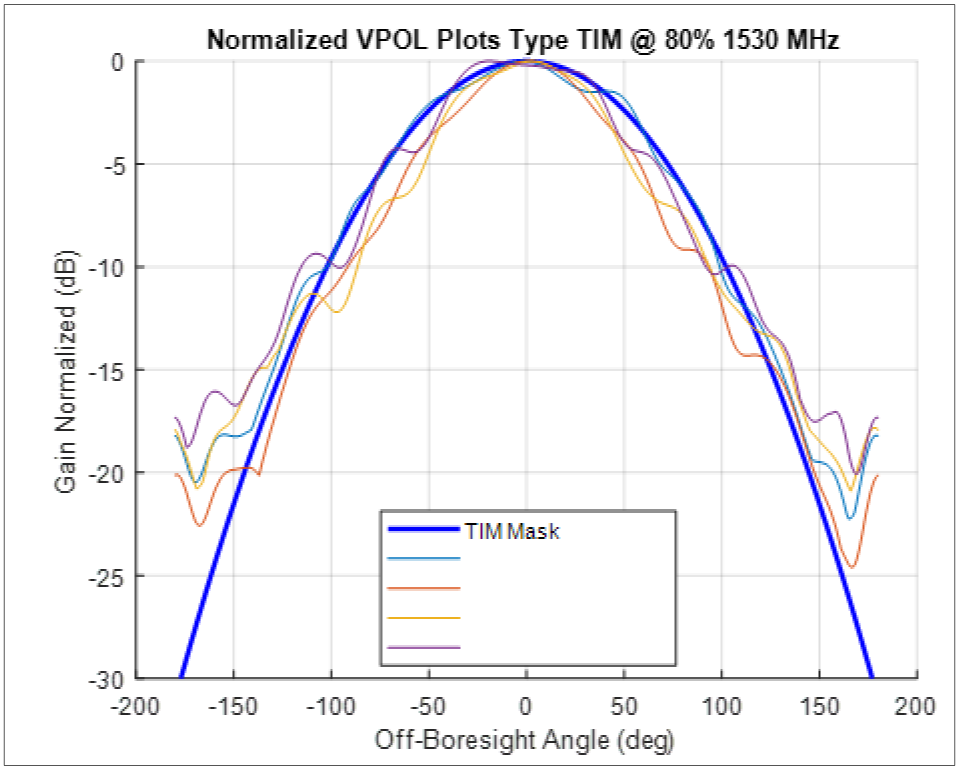


Figure E.A.2. Receive Mask for Timing GPS Receiver

The receive mask for the general location/navigation GPS receiver category is shown in Figure E.A.3.

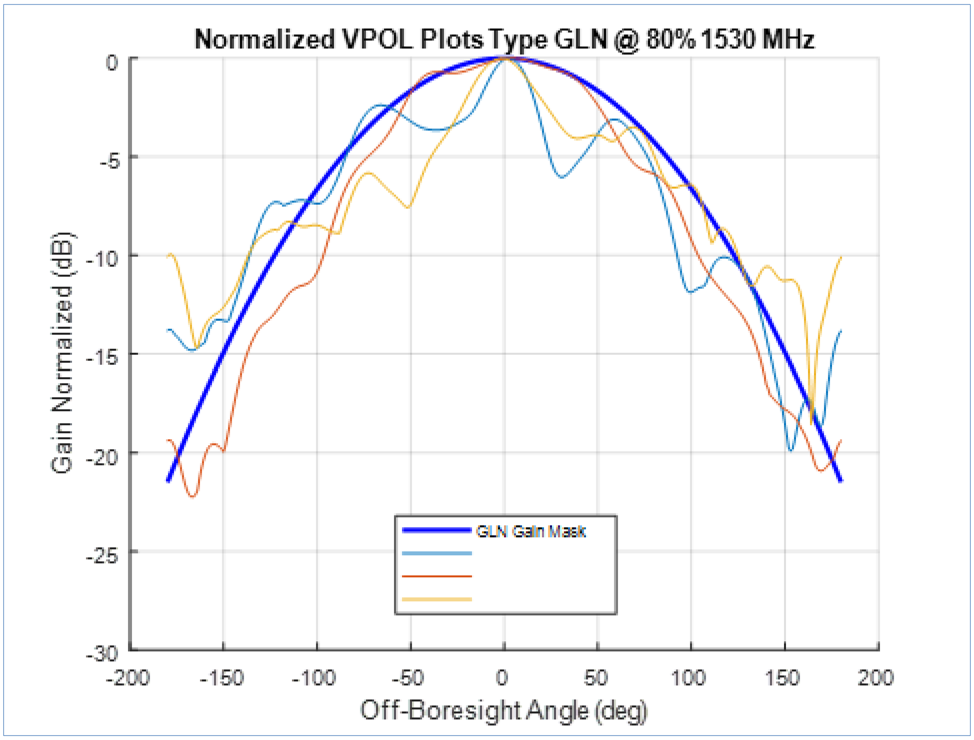


Figure E.A.3. Receive Mask for General Location/Navigation GPS Receiver

APPENDIX F
AGGREGATE BASE STATION ANALYSIS

F.1 INTRODUCTION

This appendix summarizes the Technical Focus Group (TFG)'s consideration of the aggregate power from base stations operating in the downlink band and statistically quantifies the probability and percentage of Global Positioning System (GPS) receivers, from all the measurement campaigns,[1] that will experience degradation. Four base station deployment types were based upon the deployment parameters in the Ligado aggregate report[2] and the Roberson and Associates aggregate report.[3] ITU-R M.2292-0[4] guided additional terrestrial mobile telecommunication simulation parameters. Table F.1 details the simulation parameters for the four deployment types.

[1] The measurements are from test programs performed by the Department of Transportation Adjacent Band Compatibility (DOT ABC), Department of Defense (DOD), Roberson and Associates (R&A), and National Advanced Spectrum and Communications Test Network (NASCTN). The measurement data is provided in Appendix A.

[2] RTCA Paper No. 333-16/SC159-1055, *Summary of Ligado Proposal Review by RTCA SC-159, WG6 as approved by RTCA SC-159* at 14 (Dec. 13, 2016), *available at* https://www.rtca.org/wp-content/uploads/2020/08/sc-159_wg6_response_ligado_with_tasking.pdf.

[3] Roberson and Associates, *Final Report: GPS and Adjacent Band Co-Existence Study* (June 10, 2016), *available at* https://ecfsapi.fcc.gov/file/60002112686.pdf.

[4] Report ITU-R M.2292-0, *Characteristics of terrestrial IMT-Advanced systems for frequency sharing/interference analyses* (Dec. 2013), *available at* https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2292-2014-PDF-E.pdf.

Table F.1. Simulation Parameters

Simulation Parameters	Macro Urban	Macro Suburban	Macro Rural	Micro Urban
Inter-Site Distance (km)	0.693	0.75	4.5	0.433
Propagation Model	Free Space Path Loss/Irregular Terrain Model (ITM) Area Mode			
Center Frequency (MHz)	1530 MHz[5]			
Base Station Height meters (m)	25m (ITU-R M.2292 Macro Urban)	30m (ITU-R M.2292 Macro Suburban)	30m (ITU-R M.2292 Macro Rural)	6m (ITU-R M.2292 Micro Urban)
Base Station Downtilt (deg)	10° (ITU-R M.2292 Macro Urban)	6° (ITU-R M.2292 Macro Suburban)	3° (ITU-R M.2292 Macro Rural)	0° (ITU-R M.2292 Micro Urban)
Base Station Antenna Pattern	ITU-R M.2292 Macro Urban, ITU-R F.1336	ITU-R M.2292 Macro Suburban, ITU-R F.1336	ITU-R M.2292 Macro Rural, ITU-R F.1336	ITU-R M.2292 Micro Urban, ITU-R F.1336
Base Station Sectors	3 Sectors	3 Sectors	3 Sectors	1 Sector[6]
GPS Height (m)	1.5m			

F.2 SIMULATION OVERVIEW

F.2.1 Simulation Geometry

Three base station/GPS receiver geometries were simulated.

1) For a GPS receiver operating within a cell, Figure F.1, GPS receiver locations were randomly distributed within the yellow highlighted, center cell/sector.
2) For a GPS receiver operating outside of a cell (exclusion zone), Figure F.2, the GPS receiver is located at the center and the separation distance is represented by the red line, which is a multiple of the inter-sight distance. This geometry was used to calculate the GPS receiver exclusion zone distance.
3) For a GPS receiver operating outside of a cell (offset), Figure F.3, the GPS receivers are located along the red line. The separation distance is found along the red line.

[5] R&A simulated aggregate power at 1531 MHz. A frequency of 1530 MHz was chosen because the MITRE empirical GPS antenna scans were at 1530MHz.

[6] A one sector, omni-directional antenna will create a higher aggregate power than a three-sector, 120° beamwidth antenna.

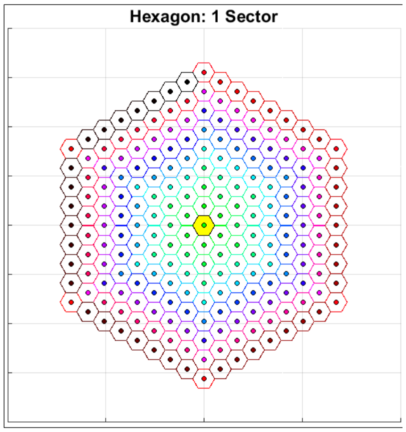


Figure F.1. GPS Receiver Operating Within a Cell

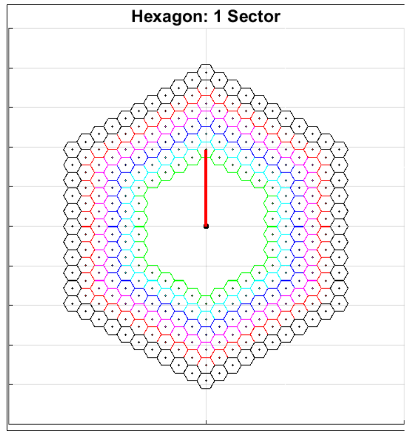


Figure F.2. GPS Receiver Operating Outside of a Cell (Exclusion Zone)

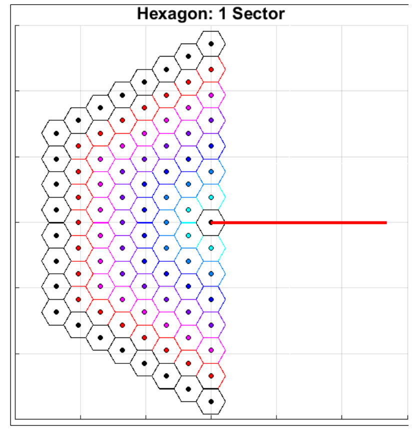


Figure F.3. GPS Receiver Operating Outside of a Cell (Offset)

F.2.2 Base Station Cell Structure

Figure F.4 and Figure F.5 show an example of the hexagonal cell structure for a base station with one and three sectors, with six additional surrounding base stations. Each base station cell is numbered and represented by a separate color. A frequency reuse factor of one was used for the base stations.

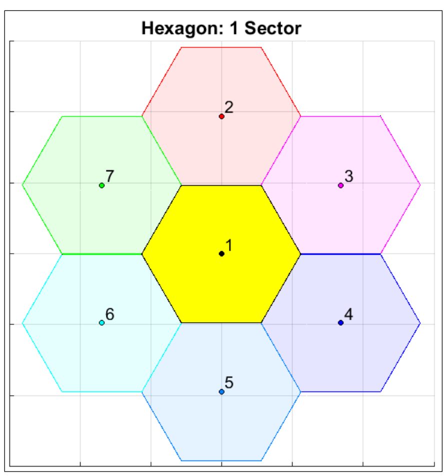


Figure F.4. One Sector Hexagonal Cell Structure

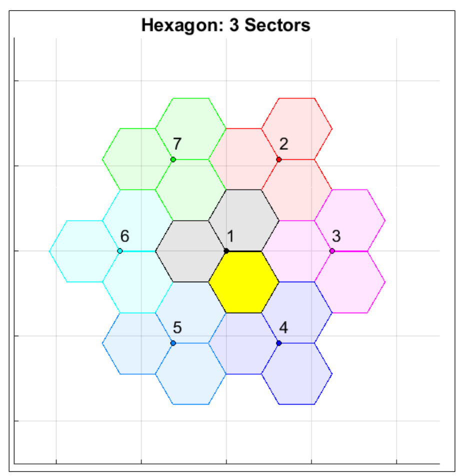


Figure F.5. Three Sector Hexagonal Cell Structure

F.2.3 Analysis Approach

The following equation was used to calculate the received power at the input of a GPS receiver:

$$P_R = EIRP - L_P - L_{GPS} - L_{BS}$$

where:

P_R: received power (dBm/10 MHz);

$EIRP$: equivalent isotropically radiated power of the LTE base station (dBm/10 MHz);
L_P: propagation loss from the base station antenna to the GPS antenna (dB);
L_{GPS}: off-boresight loss of the GPS antenna (dB);[7]
L_{BS}: the off-axis loss of the base station antenna (dB).[8]

The macro base station transmits dual orthogonal linear polarizations (ITU-R M.2292), where each orthogonal polarization is rotated 45 degrees. It is assumed that the signals transmitted in each diagonal polarization are mutually uncorrelated and have equal transmit Equivalently Isotropically Radiated Power (EIRP). The aggregate power was calculated for the horizontal and vertical polarization separately, converted to watts and summed, and converted back to dB relative to a milliwatt (dBm)/10 MHz.

$$P_{R_{Horizontal}} = (EIRP - 3dB) - L_{P_{Horizontal}} - L_{GPS_{Horizontal}} - L_{BS} \quad \text{(dBm/10 MHz)}$$

$$P_{R_{Vertical}} = (EIRP - 3dB) - L_{P_{Vertical}} - L_{GPS_{Vertical}} - L_{BS} \quad \text{(dBm/10 MHz)}$$

$$\mathrm{P}_{\mathrm{R}_{\mathrm{Watts}}} = \frac{10^{\left(\frac{\mathrm{P}_{\mathrm{R}_{\mathrm{Vertical}}}}{10}\right)}}{1000} + \frac{10^{\left(\frac{\mathrm{P}_{\mathrm{R}_{\mathrm{Horizontal}}}}{10}\right)}}{1000} \quad \text{(watts)}$$

$$\mathrm{P}_{\mathrm{R}_{dBm}} = 10Log\ \left(1000 * \mathrm{P}_{\mathrm{R}_{\mathrm{Watts}}}\right) \quad \text{(dBm/10 MHz)}$$

F.2.4 Propagation Loss

For separation distances greater than 200 meters, the Irregular Terrain Model (ITM) Area Prediction Mode is used to compute propagation loss.[9] Table F.2 provides the parameters used in the ITM Area Prediction Mode propagation loss calculations.

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[7] GPS off-boresight antenna loss is used because the test data was taken at the GPS antenna boresight.

[8] Normalized, off-boresight base station antenna loss is used because the base station transmit EIRP is specified in terms of the maximum antenna gain.

[9] National Telecommunications and Information Administration, NTIA Report 82-100, *A Guide to the Use of the ITS Irregular Terrain Model in the Area Prediction Mode* (Apr. 1982), *available at* https://www.ntia.doc.gov/files/ntia/publications/ntia_82-100_20121129145031_555510.pdf.

Table F.2. ITM Area Prediction Mode Parameters

Parameter	Value
Surface Refractivity	301 N-units
Conductivity of Ground	0.005 S/m
Dielectric Constant of Ground	15
Terrain Roughness Factor (Delta h)	30 meters
Polarization	Horizontal/Vertical
Mode of Variability	Mobile
Percent Confidence (Time/Situation/Location Variability)	50%
Frequency	1530 MHz
Site Criteria Transmitter	Careful
Site Criteria Receiver	Random
Radio Climate	Continental Temperate

For separation distances, less than or equal to 200 meters and based on the percent confidence of ITM, a blended model was used.

If $ITM_{100m} > FSPL_{100}$, (50% Confidence):

$$ITM_{Blend} = \begin{cases} FSPL & d \leq 100m \\ FSPL + \dfrac{\Delta L_P}{100}(d - 100) & 100m < d \leq 200m \\ ITM_{AreaMode} & d > 200m \end{cases}$$

where:

$$\Delta L_P = ITM_{200m} - FSPL_{200m}$$

Figure F.6 shows the comparison of ITM Area Mode (50% confidence) against free space propagation loss (FSPL).

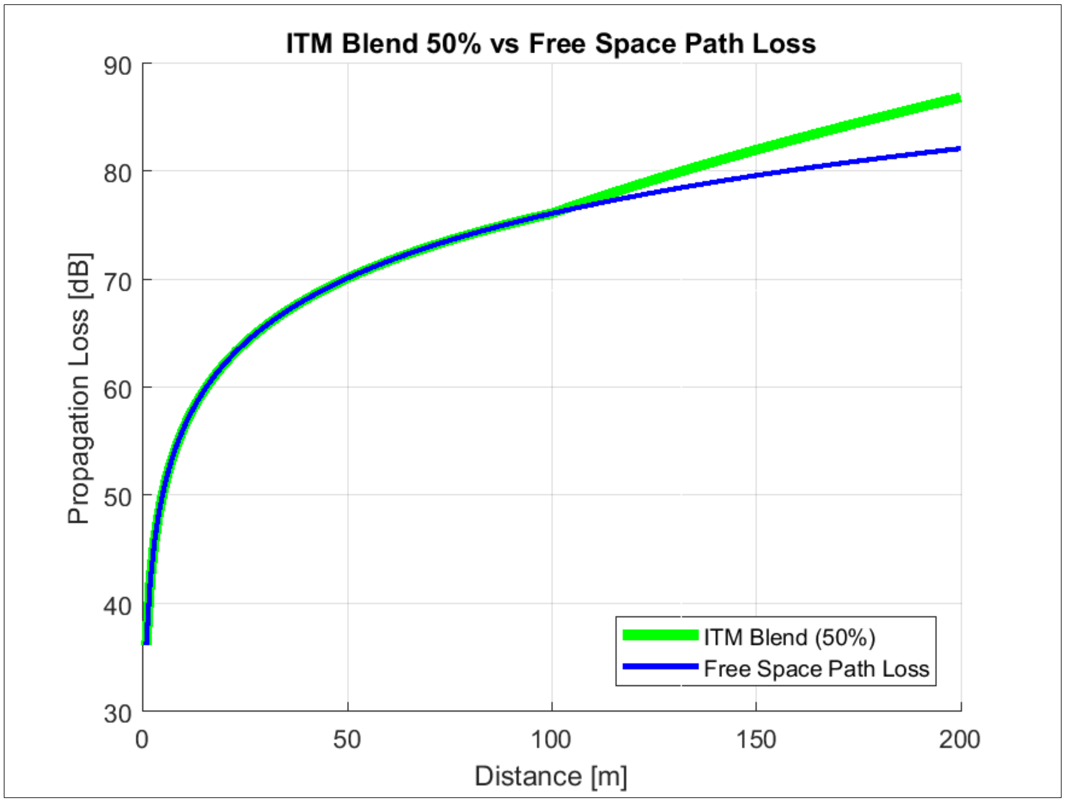

Figure F.6. ITM Blend 50% Confidence versus Free Space Propagation Loss

F.2.5 Normalized GPS Antenna Loss

The normalized, off-boresight loss of the GPS antenna was calculated for each GPS receiver category. MITRE provided empirical GPS antenna data of the vertical and horizontal polarization gain at specific frequencies.[10] The normalized gain was calculated for each category of GPS antenna. Each normalized antenna gain was then converted from decibel relative to an isotropic (dBi) to linear units, and averaged, from -180° to 0° and 0° to 180°, to make the GPS antenna gains symmetrical from -180° to 180°. The GPS antenna gains were then converted back to dBi. Figures F.7 through F.9 show the horizontal and vertical polarization antenna gain at 1530 MHz for each antenna type.

The angle of incident of the Long Term Evolution (LTE) signal was calculated between each base station and the GPS receiver locations. The normalized, off-boresight loss of the GPS antenna was then found for each antenna type.

[10] Antennas include: AeroAntenna AT575, AeroAntenna AT2775, Arbiter AS0087800, Garmin GA-25, Garmin GA-38, Hemisphere 804-3059-0, Leica AX1202GG, Navcom 82-001020-3001LF, PCTel 3977D, Trimble Bullet 360, Trimble Choke Ring, Trimble Zephyr, Trimble Zephyr Geodetic 2, and ublox ANN-MS-0-005.

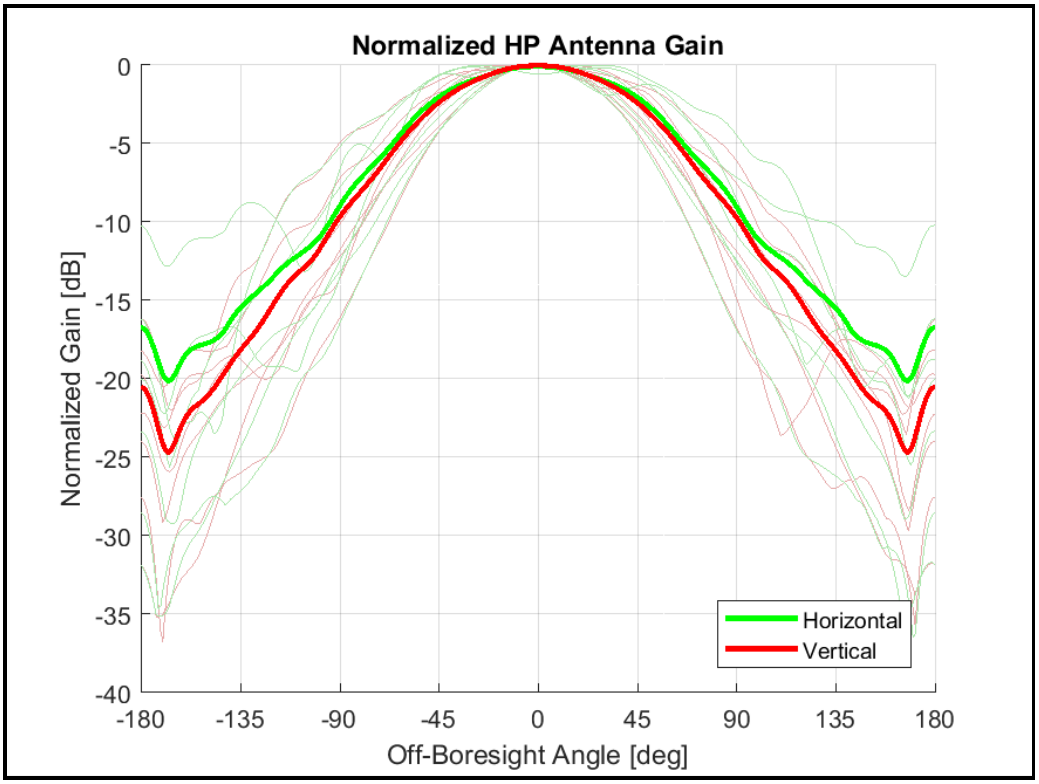

Figure F.7. Normalized HP Antenna Gain

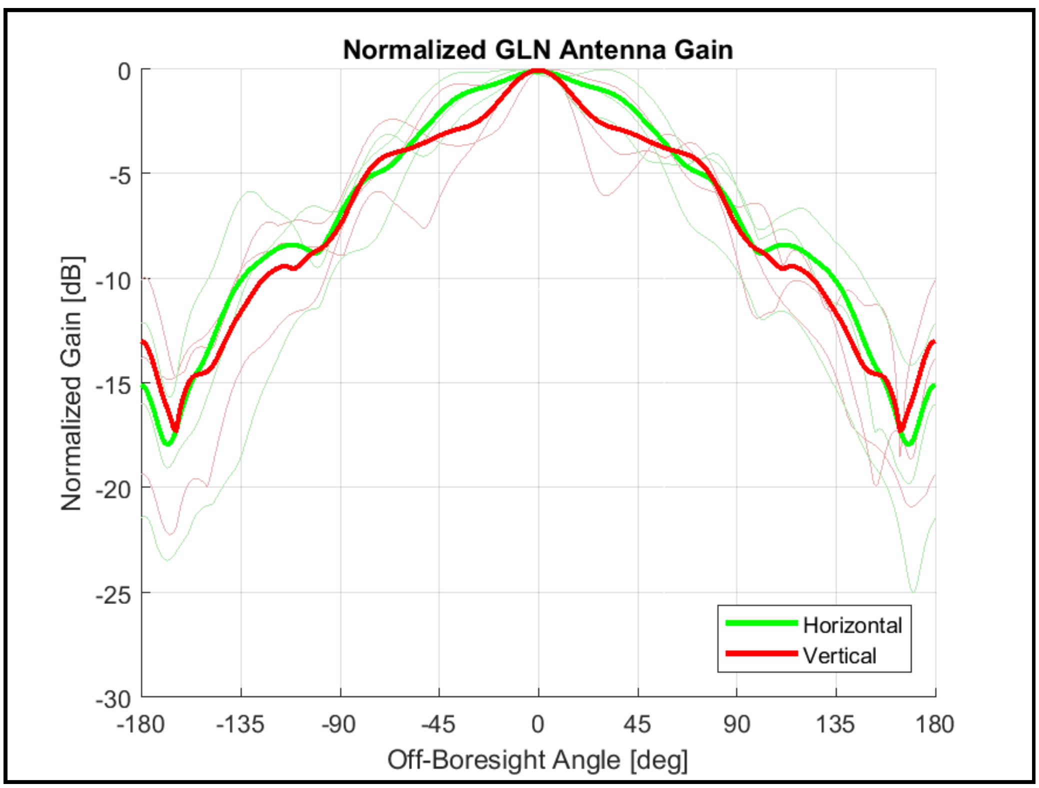

Figure F.8. Normalized GLN Antenna Gain

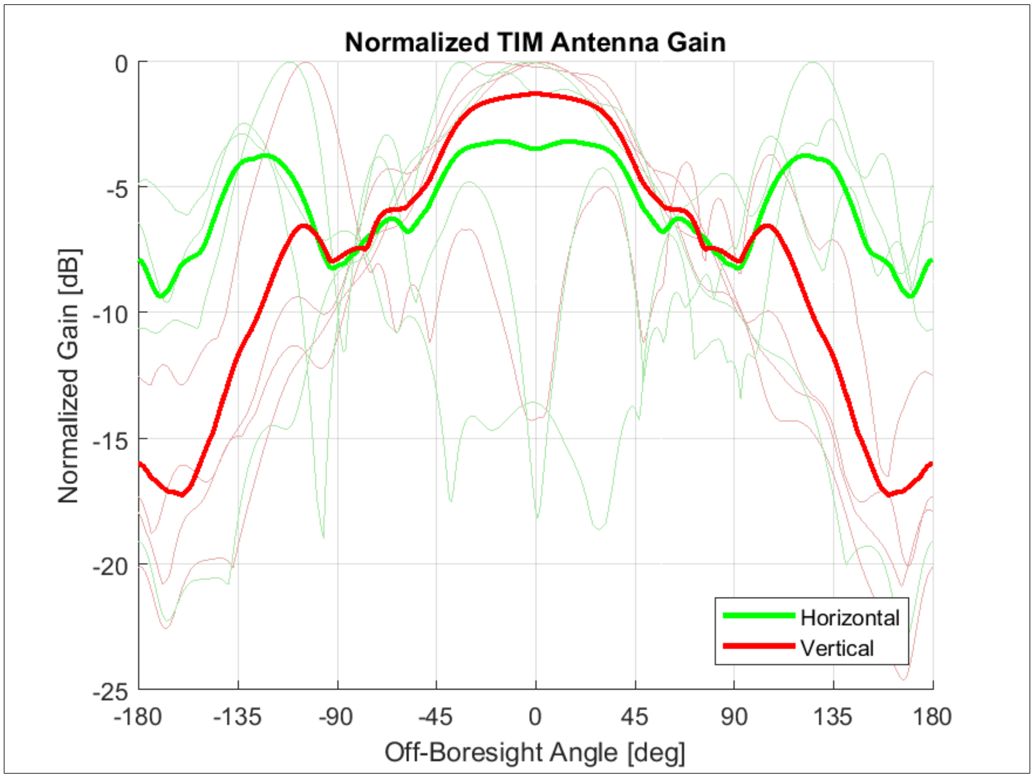

Figure F.9. Normalized TIM Antenna Gain

F.2.6 Base Station Antenna Loss

The off-axis loss of the base station antenna was calculated for each GPS receiver location. The base station antenna pattern was provided by Recommendation ITU-R F.1336-4.[11]

F.2.7 Aggregate Power

The power received, P_R (Watts), from all base stations was summed at each GPS receiver location to calculate the aggregate power. The summed powers were then converted to dBm/10 MHz.

[11] Recommendation ITU-R F.1336-4, *Reference Radiation Patterns of Omnidirectional, Sectoral and Other Antennas for the Fixed and Mobile Services for Use in Sharing Studies in the Frequency Range from 400 MHz to About 70 GHz* (Feb. 2014), *available at*

https://www.itu.int/dms_pubrec/itu-r/rec/f/R-REC-F.1336-4-201402-S!!PDF-E.pdf.

The antenna model is described in Recommends 3.1.

F.3 SIMULATION RESULTS

F.3.1 Simulation Geometry 1: GPS Receiver Operating Within a Cell

For a GPS receiver operating within a cell, Figure F.10 and Figure F.11, 50,000 GPS receiver locations were randomly distributed within the yellow highlighted, center cell/sector. Table F.3 to Table F.6 provide the percentage of GPS receiver, from all the measurement campaigns, that will experience 1 dB, 3 dB, and 5 dB C/N_0 degradation and loss of lock (LOL) within a cell for the four deployment types described in Table F.1. For each deployment type, the base station equivalent EIRP and the 99th percentile of the power received at the GPS receiver within a cell is calculated.

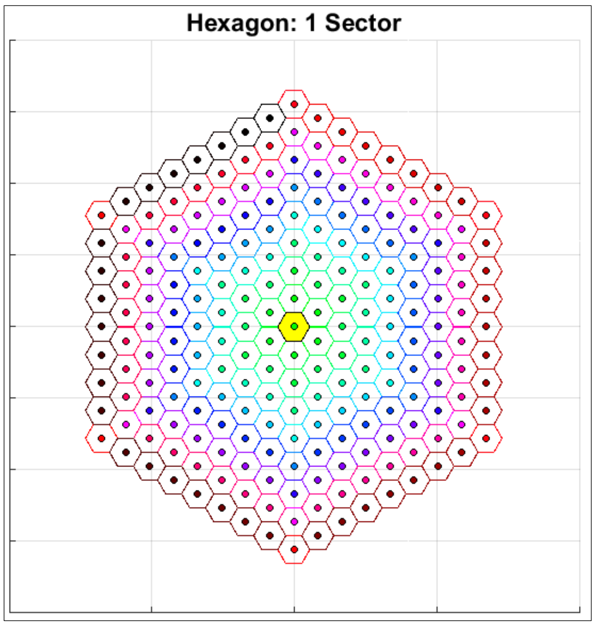

Figure F.10. One-Sector Hexagonal Cell

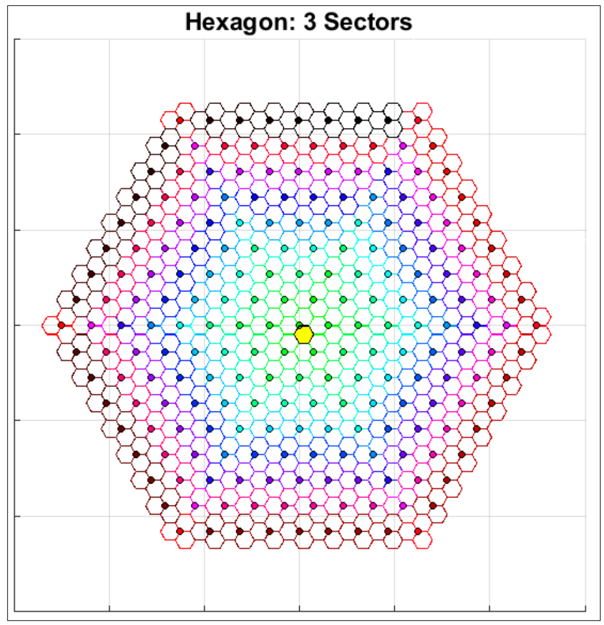

Figure F.11. Three-Sector Hexagonal Cell

The simulations results show that the 99th percentile for the four deployment types are within 0.4 dB when comparing the aggregate with no clutter loss, aggregate with clutter loss, and the single base station case. Most of the 99th percentile of the power received at the GPS receiver is within 100 meters of the base station, which means the propagation model to most of the 99th percentile power received is free space path loss.

Table F.3. Scenario 1: Macro Urban [693m ISD]
Summary of GPS Receiver Degradation

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands													
EIRP (dBm/10 MHz)	Power Received (dBm/10 MHz) 99th Percentile	Percentage of Receivers Impacted											
		1 dB			3 dB			5 dB			LOL		
		HP	GLN	TIM	HP	GLN	TIM	HP	GLN	TIM	HP	GLN	TIM
62	-22	80%	40%	42%	62%	39%	17%	62%	36%	17%	51%	3%	8%
60	-24	79%	34%	42%	62%	36%	17%	60%	36%	17%	47%	3%	8%
58	-26	71%	30%	38%	60%	36%	17%	58%	21%	8%	45%	3%	8%
56	-28	69%	26%	29%	58%	27%	17%	58%	12%	8%	45%	3%	
54	-30	67%	19%	25%	58%	15%	8%	52%	12%	8%	43%	3%	
52	-32	64%	13%	17%	52%	12%	8%	48%	12%	8%	41%	3%	
50	-34	62%	10%	17%	52%	12%	8%	46%	12%	8%	39%	3%	
48	-36	60%	8%	17%	48%	12%	8%	46%	9%	8%	24%	3%	
46	-38	56%	7%	17%	46%	12%	8%	38%	3%	8%	20%	3%	
44	-40	51%	6%	13%	38%	12%	8%	36%	3%	8%	18%	3%	
42	-42	44%	6%	8%	36%	9%	8%	26%	3%		18%	3%	
40	-44	40%	5%	8%	32%	9%	0%	26%	3%	0%	14%	3%	0%
38	-46	35%	3%	4%	28%	3%		24%	3%		6%		
36	-48	32%	3%	4%	28%	3%		22%	3%		6%		
34	-50	31%	3%		22%	3%		18%	3%		4%		
32	-52	27%	2%		20%	3%		18%	3%		2%		
30	-54	23%	2%		18%	3%		12%	3%		2%		
28	-56	20%	1%		14%	3%		10%	3%		2%		
26	-58	18%	1%		12%	3%		10%	3%		2%		
24	-60	14%	1%		10%	3%		4%	0%		2%		
22	-62	12%	1%		10%								
20	-64	12%	1%		4%								
18	-66	8%	1%										
16	-68	4%	1%										
14	-70	4%											
12	-72	2%											
10	-74	1%											

Table F.4. Scenario 2: Macro Suburban [750m ISD]
Summary of GPS Receiver Degradation

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands													
EIRP (dBm/10 MHz)	Power Received (dBm/10 MHz)99th Percentile	Percentage of Receivers Impacted											
		1 dB			3 dB			5 dB			LOL		
		HP	GLN	TIM	HP	GLN	TIM	HP	GLN	TIM	HP	GLN	TIM
62	-26	70%	26%	38%	60%	27%	17%	58%	12%	8%	45%	3%	8%
60	-28	69%	22%	29%	58%	21%	8%	54%	12%	8%	43%	3%	
58	-30	65%	16%	21%	54%	12%	8%	50%	12%	8%	43%	3%	
56	-32	63%	12%	17%	52%	12%	8%	48%	12%	8%	39%	3%	
54	-34	60%	8%	17%	48%	12%	8%	46%	9%	8%	31%	3%	
52	-36	57%	7%	17%	48%	12%	8%	40%	9%	8%	22%	3%	
50	-38	54%	6%	13%	44%	12%	8%	36%	3%	8%	18%	3%	
48	-40	50%	6%	8%	36%	9%	8%	26%	3%		18%	3%	
46	-42	42%	5%	8%	34%	9%	8%	26%	3%		16%	3%	
44	-44	36%	4%	4%	32%	3%		26%	3%		14%	3%	
42	-46	33%	3%	4%	28%	3%		22%	3%		6%		
40	-48	31%	3%	4%	26%	3%	0%	20%	3%	0%	6%	0%	0%
38	-50	29%	3%		22%	3%		18%	3%		2%		
36	-52	24%	2%		18%	3%		18%	3%		2%		
34	-54	21%	2%		18%	3%		12%	3%		2%		
32	-56	19%	1%		12%	3%		10%	3%		2%		
30	-58	18%	1%		10%	3%		6%			2%		
28	-60	13%	1%		10%			4%			2%		
26	-62	12%	1%		8%								
24	-64	10%	1%										
22	-66	8%	1%										
20	-68	4%											
18	-70	2%											
16	-72	1%											
14	-74	1%											

Table F.5. Scenario 3: Macro Rural [4.5km ISD]
Summary of GPS Receiver Degradation

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands													
EIRP (dBm/10 MHz)	**Power Received (dBm/10 MHz) 99th Percentile**	**Percentage of Receivers Impacted**											
		1 dB			**3 dB**			**5 dB**			**LOL**		
		HP	**GLN**	**TIM**	**HP**	**GLN**	**TIM**	**HP**	**GLN**	**TIM**	**HP**	**GLN**	**TIM**
62	-30	65%	16%	21%	54%	12%	8%	50%	12%	8%	43%	3%	0%
60	-32	63%	12%	17%	52%	12%	8%	48%	12%	8%	39%	3%	
58	-34	60%	8%	17%	48%	12%	8%	46%	9%	8%	31%	3%	
56	-36	57%	7%	17%	48%	12%	8%	40%	9%	8%	22%	3%	
54	-38	54%	6%	13%	44%	12%	8%	36%	3%	8%	18%	3%	
52	-40	50%	6%	8%	36%	9%	8%	26%	3%		18%	3%	
50	-42	42%	5%	8%	34%	9%	8%	26%	3%		16%	3%	
48	-44	36%	4%	4%	32%	3%		26%	3%		14%	3%	
46	-46	33%	3%	4%	28%	3%		22%	3%		6%		
44	-48	31%	3%	4%	26%	3%		20%	3%		6%		
42	-50	29%	3%		22%	3%		18%	3%		2%		
40	-52	24%	2%	0%	18%	3%	0%	18%	3%	0%	2%	0%	0%
38	-54	21%	2%		18%	3%		12%	3%		2%		
36	-56	19%	1%		12%	3%		10%	3%		2%		
34	-58	18%	1%		10%	3%		6%			2%		
32	-60	13%	1%		10%			4%			2%		
30	-62	12%	1%		8%								
28	-64	10%	1%										
26	-66	8%	1%										
24	-68	4%											
22	-70	2%											
20	-72	1%											
18	-74	1%											

Table F.6. Scenario 3: Micro Urban [433m ISD]
Summary of GPS Receiver Degradation

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands													
EIRP (dBm/10 MHz)	Power Received (dBm/10 MHz) 99th Percentile	Percentage of Receivers Impacted											
		1 dB			3 dB			5 dB			LOL		
		HP	GLN	TIM	HP	GLN	TIM	HP	GLN	TIM	HP	GLN	TIM
44	-28	69%	26%	29%	58%	27%	17%	58%	12%	8%	45%	3%	0%
43	-29	69%	22%	29%	58%	21%	8%	54%	12%	8%	43%	3%	
42	-30	67%	19%	25%	58%	15%	8%	52%	12%	8%	43%	3%	
40	-32	64%	13%	17%	52%	12%	8%	48%	12%	8%	41%	3%	
38	-34	62%	10%	17%	52%	12%	8%	46%	12%	8%	39%	3%	
36	-36	60%	8%	17%	48%	12%	8%	46%	9%	8%	24%	3%	
34	-38	56%	7%	17%	46%	12%	8%	38%	3%	8%	20%	3%	
32	-40	51%	6%	13%	38%	12%	8%	36%	3%	8%	18%	3%	
30	-42	44%	6%	8%	36%	9%	8%	26%	3%		18%	3%	
29	-43	42%	5%	8%	34%	9%	8%	26%	3%		16%	3%	
28	-44	40%	5%	8%	32%	9%		26%	3%		14%	3%	
27	-45	36%	4%	4%	32%	3%		26%	3%		14%	3%	
26	-46	35%	3%	4%	28%	3%		24%	3%		6%		
25	-47	33%	3%	4%	28%	3%		22%	3%		6%		
24	-48	32%	3%	4%	28%	3%		22%	3%		6%		
23	-49	31%	3%	4%	26%	3%		20%	3%		6%		
22	-50	31%	3%		22%	3%		18%	3%		4%		
21	-51	29%	3%		22%	3%		18%	3%		2%		
20	-52	27%	2%		20%	3%		18%	3%		2%		
19	-53	24%	2%		18%	3%		18%	3%		2%		
18	-54	23%	2%		18%	3%		12%	3%		2%		
17	-55	21%	2%		18%	3%		12%	3%		2%		
16	-56	20%	1%		14%	3%		10%	3%		2%		
15	-57	19%	1%		12%	3%		10%	3%		2%		
14	-58	18%	1%		12%	3%		10%	3%		2%		
13	-59	18%	1%		10%	3%		6%			2%		
12	-60	14%	1%		10%	3%		4%			2%		
11	-61	13%	1%		10%			4%			2%		
10	-62	12%	1%		10%								
9	-63	12%	1%		8%								
8	-64	12%	1%		4%								
7	-65	10%	1%										
6	-66	8%	1%										
5	-67	8%	1%										
4	-68	4%	1%										
3	-69	4%											
2	-70	4%											
1	-71	2%											
0	-72	2%											
-1	-73	1%											

F.3.2 Probability of C/N_0 Degradation and LOL in a Cell

For 50,000 randomized GPS receiver locations within a cell, the probability of 1 dB, 3 dB, and 5 dB C/N_0 degradation and LOL was calculated for each GPS receiver from all the measurement campaigns (Tables F.28 through F.30). Tables F.7 through F.10 provide the probability of 1 dB, 3 dB, and 5 dB C/N_0 degradation and LOL within a cell for each type of GPS receiver with the corresponding base station EIRP.

For example, there are 84 experimental measurements points for 1 dB C/N_0 degradation for GPS receivers in the HP category. Every HP receiver was checked for 1 dB C/N_0 degradation at each randomized location, totaling 4.2 million (50,000 x 84) calculations to find the probability of degradation for a single table entry for each deployment scenario. It should be noted that the 3 dB and 5 dB probability is higher than some 1 dB probability General Location/Receiver Navigation Category (GLN) GPS receiver category. This discrepancy is because of the number of measurement data points. Table F.30 provides the number of data measurements for 1 dB, 3 dB, and 5 dB and LOL.

Table F.7. Probability of GPS Degradation in a Cell: Macro Urban [693m ISD]

Interferring Signal in the 1525-1535 MHz/1526-1536 MHz Bands												
Base Station EIRP (dBm/10 MHz)	**HP**				**GLN**				**TIM**			
	1 dB	**3 dB**	**5 dB**	**LOL**	**1 dB**	**3 dB**	**5 dB**	**LOL**	**1 dB**	**3 dB**	**5 dB**	**LOL**
62	59.4%	49%	43%	27.2%	13.5%	16.3%	12.7%	3.1%	19.8%	9.4%	8.7%	0.9%
60	55.8%	43.8%	38.1%	24.4%	11.2%	15%	8.3%	3.1%	16.5%	8.9%	8.4%	0.4%
58	50.3%	40.5%	33.2%	22.4%	9.2%	13.3%	6.1%	3.1%	12.7%	8.6%	4.1%	0.1%
56	45.5%	37.4%	31%	19.5%	7.9%	11.1%	5%	3.1%	10.9%	6%	2.6%	
54	41.1%	33.8%	28.2%	13.8%	6.6%	9.1%	4.6%	3.1%	7.9%	3.1%	1.9%	
52	37.8%	31.5%	25.6%	11%	4.7%	6.2%	4.1%	1.7%	6.7%	2.2%	1.4%	
50	35.1%	27.7%	22.6%	7.8%	3.9%	5.3%	3.8%	1.1%	4.8%	1.6%	1.1%	
48	31.4%	24.3%	20.9%	5.8%	3.4%	4.7%	3.3%	0.8%	2.7%	1.3%	0.6%	
46	27.6%	22%	17%	4.7%	2.9%	4.3%	3.1%	0.6%	1.7%	0.9%	0.2%	
44	24.5%	18.3%	14.2%	3.9%	2.6%	3.9%	3%	0.5%	1.1%	0.4%		
42	22%	15.5%	11.9%	3.2%	2%	3.5%	3%	0.3%	0.7%	0.1%		
40	18.6%	13.6%	8.7%	2.7%	1.4%	3.2%	2.5%	0.2%	0.4%	0.0%	0.0%	0.0%
38	16.1%	12.0%	5.2%	1.3%	1.1%	2.5%	1.2%		0.2%			
36	14.2%	7.5%	3.6%	0.8%	1%	1.2%	0.9%		0.1%			
34	11.9%	4.6%	2.5%	0.5%	0.9%	0.9%	0.6%					
32	8.4%	3.1%	1.8%	0.4%	0.8%	0.6%	0.5%					
30	6.5%	2.2%	1.2%	0.3%	0.6%	0.5%	0.4%					
28	4.8%	1.6%	0.7%	0.2%	0.3%	0.4%	0.2%					
26	3.5%	1.1%	0.3%	0.1%	0.2%	0.2%	0.1%					
24	2.2%	0.6%	0.1%		0.1%	0.1%						
22	1.5%	0.2%			0.1%							
20	0.9%				0.1%							
18	0.6%											
16	0.3%											
14	0.2%											
12	0.1%											

Table F.8. Probability of GPS Degradation in a Cell: Macro Suburban [750m ISD]

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands												
Base Station EIRP (dBm/10 MHz)	**HP**				**GLN**				**TIM**			
	1 dB	**3 dB**	**5 dB**	**LOL**	**1 dB**	**3 dB**	**5 dB**	**LOL**	**1 dB**	**3 dB**	**5 dB**	**LOL**
62	61.5%	50.3%	47.3%	31.7%	14.1%	14.5%	12.3%	3.1%	18.2%	8.5%	8.3%	0.1%
60	58.4%	48.1%	41.9%	25.9%	10.8%	12.9%	10.3%	3.1%	17%	8.4%	8.3%	
58	54.6%	43.1%	38.7%	22%	8.6%	12.3%	7.2%	3.1%	14.7%	8.3%	8.3%	
56	49.4%	39.2%	31.1%	19.9%	7%	12.2%	5.1%	3.1%	11.5%	8.3%	4.2%	
54	44.6%	35.5%	28.5%	16.7%	6.3%	10.3%	4%	3.1%	9.8%	8.3%	2%	
52	39%	31.8%	26.3%	11.7%	5.6%	9.7%	3.4%	3.1%	6.8%	2.8%	0.9%	
50	35.4%	29.8%	23.6%	8.9%	4.1%	5.7%	3.1%	1.8%	5.2%	1.4%	0.1%	
48	32.9%	25.8%	20.7%	6.6%	3.3%	4.3%	3%	0.9%	4.7%	0.5%		
46	29.7%	22.9%	19.3%	3.9%	3%	3.7%	3%	0.5%	1.5%	0.1%		
44	25.7%	20.2%	15.9%	2.9%	2.4%	3.1%	3%	0.2%	0.7%			
42	22.9%	17.2%	12.9%	2.4%	2.1%	3.1%	3%		0.2%			
40	20.2%	14.2%	11.5%	2.1%	1.8%	3%	3%	0%	0%	0%	0%	0%
38	17.3%	11.9%	7.3%	2.1%	1.2%	3%	3%					
36	14.4%	10.9%	3.7%	1.1%	0.9%	3%	1.2%					
34	13.2%	7.3%	1.9%	0.5%	0.8%	1.2%	0.6%					
32	10.4%	3%	0.8%	0.3%	0.7%	0.6%	0.3%					
30	7.1%	1.7%	0.3%	0.1%	0.6%	0.3%						
28	5.3%	0.7%	0.1%		0.6%							
26	3.7%	0.2%			0.2%							
24	2.2%	0.1%			0.1%							
22	1.1%				0.1%							
20	0.5%											
18	0.2%											
16	0.1%											

Table F.9. Probability of GPS Degradation in a Cell: Macro Rural [4.5km ISD]

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands												
Base Station EIRP (dBm/10 MHz)	**HP**				**GLN**				**TIM**			
	1 dB	**3 dB**	**5 dB**	**LOL**	**1 dB**	**3 dB**	**5 dB**	**LOL**	**1 dB**	**3 dB**	**5 dB**	**LOL**
62	34.4%	27.6%	22.2%	8%	3.9%	5%	3.6%	1%	5.7%	1.3%	0.7%	0.1%
60	31.4%	24.3%	20.3%	5.1%	3.4%	4.3%	3.4%	0.6%	2.9%	0.8%	0.4%	
58	27.3%	21.3%	17.8%	3.9%	3%	3.8%	3.3%	0.4%	1.7%	0.5%	0.3%	
56	24.3%	18.9%	14.2%	3.3%	2.5%	3.6%	3.2%	0.2%	1%	0.3%	0.2%	
54	21.6%	15.4%	12.4%	2.9%	2.2%	3.4%	3.2%	0.2%	0.7%	0.2%	0.1%	
52	19%	12.9%	8.6%	2.6%	1.6%	3.3%	3.1%	0.1%	0.4%	0.1%	0.1%	
50	15.7%	11.8%	5.4%	1.8%	1.1%	3.2%	1.4%	0.1%	0.3%	0.1%	0.1%	
48	14.1%	8.9%	2.8%	0.9%	1%	1.5%	0.8%		0.2%	0.1%		
46	11.6%	4.2%	1.8%	0.6%	0.8%	0.8%	0.5%		0.1%			
44	8.8%	2.5%	1.1%	0.4%	0.8%	0.5%	0.3%		0.1%			
42	6.2%	1.6%	0.8%	0.2%	0.7%	0.3%	0.2%		0.1%			
40	4.6%	1%	0.5%	0.2%	0.4%	0.2%	0.1%	0%	0%	0%	0%	0%
38	3%	0.7%	0.3%	0.1%	0.2%	0.1%	0.1%					
36	2%	0.5%	0.2%	0.1%	0.1%	0.1%	0.1%					
34	1.1%	0.3%	0.2%	0.1%	0.1%	0.1%						
32	0.7%	0.2%	0.1%		0.1%							
30	0.5%	0.1%	0.1%									
28	0.3%	0.1%	0.1%									
26	0.2%	0.1%										
24	0.1%	0.1%										
22	0.1%											
20	0.1%											
18	0.1%											

Table F.10. Probability of GPS Degradation in a Cell: Micro Urban [433m ISD]

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands												
Base Station EIRP (dBm/10 MHz)	**HP**				**GLN**				**TIM**			
	1 dB	**3 dB**	**5 dB**	**LOL**	**1 dB**	**3 dB**	**5 dB**	**LOL**	**1 dB**	**3 dB**	**5 dB**	**LOL**
42	31.2%	25%	19.8%	7.1%	3.8%	5.4%	3.7%	0.9%	3.7%	1.8%	1%	
40	28%	21.4%	17%	5.9%	3.3%	4.7%	3.4%	0.8%	2.8%	1.3%	0.6%	0%
38	25.1%	18.5%	14.7%	4.6%	2.7%	4.2%	3.3%	0.6%	1.9%	0.8%	0.4%	
36	21.7%	16.3%	11.4%	3.9%	2%	3.8%	3.1%	0.4%	1.4%	0.5%	0.2%	
34	19%	14.4%	8.1%	2.4%	1.6%	3.4%	1.8%	0.3%	0.9%	0.3%	0.1%	
32	16.9%	10.4%	6.2%	1.7%	1.4%	2%	1.3%	0.2%	0.6%	0.2%	0.1%	
30	14.3%	7.5%	4.6%	1.2%	1.2%	1.5%	1%	0.1%	0.3%	0.1%		
28	11%	5.6%	3.4%	0.9%	1%	1.1%	0.8%	0.1%	0.2%			
26	9%	4.2%	2.6%	0.6%	0.9%	0.9%	0.7%		0.1%			
24	7%	3.1%	1.8%	0.5%	0.5%	0.7%	0.5%					
22	5.4%	2.4%	1.1%	0.3%	0.4%	0.5%	0.3%					
20	3.9%	1.6%	0.7%	0.2%	0.3%	0.3%	0.2%					
18	2.9%	1.0%	0.4%	0.1%	0.2%	0.2%	0.1%					
16	2.0%	0.6%	0.2%	0.1%	0.2%	0.1%	0.1%					
14	1.4%	0.4%	0.1%		0.1%	0.1%						
12	1%	0.2%	0.1%		0.1%							
10	0.7%	0.1%										
8	0.4%	0.1%										
6	0.2%											
4	0.1%											
2	0.1%											

F.3.3 Simulation Geometry 2: GPS Receiver Operating Outside a Cell (Exclusion Zone)

For a GPS receiver operating outside of a cell (exclusion zone), Figure F.12 and Figure F.13, the GPS receiver is located at the center and the separation distance is represented by the red line, which is a multiple of the inter-sight distance. This geometry was used to calculate the GPS receiver exclusion zone distance.

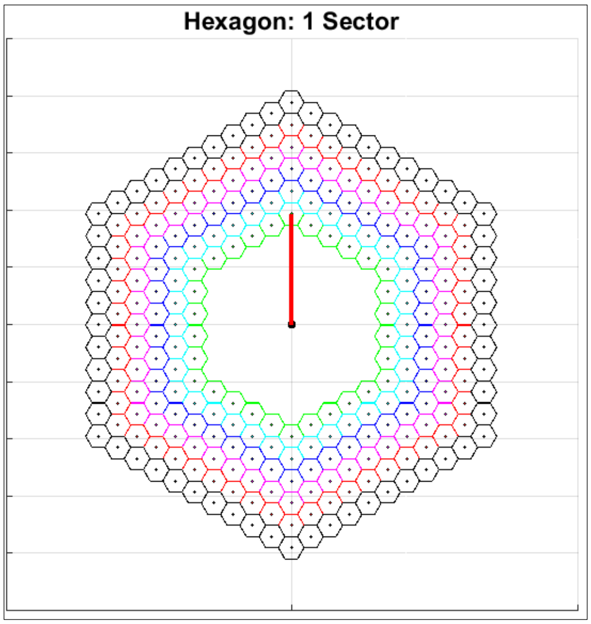

Figure F.12. One-Sector Hexagonal Cell

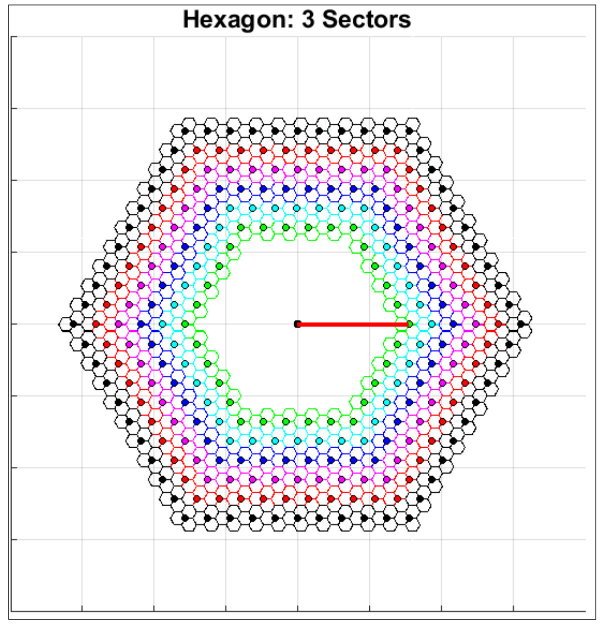

Figure F.13. Three-Sector Hexagonal Cell

Tables F.11 F.13 provide the 1 dB C/N_0 degradation exclusion zone separation distance for HP, GLN, and Timing Receiver Category (TIM) receivers, from all the measurement campaigns, for a base station EIRP of 62 dBm/10 MHz. Tables F.14 through F.16 provide the 1 dB C/N_0 degradation exclusion zone separation distance for HP, GLN, and TIM receivers, from all the measurement campaigns, for a base station EIRP of 40 dBm/10 MHz.

Table F.11. Exclusion Zone Separation Distance (km) HP GPS Receivers

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands				
Interference Power Level (dBm/10 MHz)	1 dB Degradation in C/N_0			
	Macro Urban 62 dBm (0.693 km)	Macro Suburban 62 dBm (0.75 km)	Macro Rural 62 dBm (4.5 km)	Percentage of Receivers
≤-75	33.957	39.75	18	1.2%
≤-72	29.106	34.5	13.5	2.4%
≤-70	26.334	31.5	13.5	3.6%
≤-67	22.176	27	9	8.3%
≤-65	19.404	24	9	9.5%
≤-64	18.018	23.25	4.5	11.9%
≤-61	14.553	19.5	4.5	13.1%
≤-60	13.167	18	4.5	14.3%
≤-59	12.474	16.5	<4.5	17.9%
≤-57	10.395	14.25	<4.5	19%
≤-56	9.009	13.5	<4.5	20.2%
≤-55	8.316	12	<4.5	21.4%
≤-54	7.623	11.25	<4.5	22.6%
≤-53	6.237	10.5	<4.5	23.8%
≤-52	5.544	9	<4.5	27.4%
≤-51	4.851	8.25	<4.5	28.6%
≤-50	4.158	7.5	<4.5	31%
≤-48	2.772	5.25	<4.5	32.1%
≤-47	2.079	4.5	<4.5	33.3%
≤-46	2.079	3.75	<4.5	34.5%
≤-45	1.386	3.75	<4.5	35.7%
≤-44	1.386	3	<4.5	40.5%
≤-43	0.693	2.25	<4.5	41.7%
≤-42	0.693	1.5	<4.5	44%
≤-41	0.693	1.5	<4.5	50%
≤-40	<0.693	0.75	<4.5	51.2%
≤-39	<0.693	0.75	<4.5	53.6%
≤-38	<0.693	0.75	<4.5	56%
≤-37	<0.693	<0.75	<4.5	57.1%
≤-36	<0.693	<0.75	<4.5	59.5%
≤-34	<0.693	<0.75	<4.5	61.9%
≤-33	<0.693	<0.75	<4.5	63.1%
≤-32	<0.693	<0.75	<4.5	64.3%
≤-31	<0.693	<0.75	<4.5	65.5%
≤-30	<0.693	<0.75	<4.5	66.7%
≤-29	<0.693	<0.75	0	69%
≤-27	<0.693	<0.75	0	70.2%
≤-26	<0.693	<0.75	0	71.4%
≤-25	<0.693	0	0	72.6%
≤-24	<0.693	0	0	78.6%
≤-23	<0.693	0	0	79.8%
≤-21	0	0	0	82.1%

Table F.12. Exclusion Zone Separation Distance (km) GLN GPS Receivers

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands				
Interference Power Level (dBm/10 MHz)	1 dB Degradation in C/N_0			
	Macro Urban 62 dBm (0.693 km)	Macro Suburban 62 dBm (0.75 km)	Macro Rural 62 dBm (4.5 km)	Percentage of Receivers
-68	26.334	31.5	13.5	0.6%
-57	12.474	17.25	<4.5	1.3%
-55	10.395	15	<4.5	1.9%
-51	6.237	10.5	<4.5	2.6%
-45	2.079	5.25	<4.5	4.5%
-44	2.079	4.5	<4.5	5.1%
-42	1.386	3	<4.5	5.8%
-40	0.693	1.5	<4.5	5.8%
-39	0.693	1.5	<4.5	6.4%
-38	<0.693	0.75	<4.5	7.1%
-37	<0.693	0.75	<4.5	7.1%
-36	<0.693	0.75	<4.5	8.3%
-34	<0.693	<0.75	<4.5	10.3%
-33	<0.693	<0.75	<4.5	11.5%
-32	<0.693	<0.75	<4.5	13.5%
-31	<0.693	<0.75	<4.5	16%
-30	<0.693	<0.75	<4.5	19.2%
-29	<0.693	<0.75	0	22.4%
-28	<0.693	<0.75	0	25.6%
-27	<0.693	<0.75	0	26.3%
-26	<0.693	<0.75	0	30.1%
-25	<0.693	0	0	31.4%
-24	<0.693	0	0	34%
-23	<0.693	0	0	35.3%
-22	<0.693	0	0	39.7%
-21	0	0	0	42.9%

Table F.13. Exclusion Zone Separation Distance (km) TIM GPS Receivers

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands				
Interference Power Level (dBm/10 MHz)	1 dB Degradation in C/N_0			
	Macro Urban 62 dBm (0.693 km)	Macro Suburban 62 dBm (0.75 km)	Macro Rural 62 dBm (4.5 km)	Percentage of Receivers
-49	4.158	7.5	<4.5	4.2%
-44	1.386	3.75	<4.5	8.3%
-40	0.693	1.5	<4.5	12.5%
-38	<0.693	0.75	<4.5	16.7%
-31	<0.693	<0.75	<4.5	20.8%
-30	<0.693	<0.75	<4.5	25%
-29	<0.693	<0.75	0	29.2%
-27	<0.693	<0.75	0	37.5%
-24	<0.693	0	0	41.7%
-20	0	0	0	50%

Table F.14. Exclusion Zone Separation Distance (km) HP GPS Receivers

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands					
Interference Power Level (dBm/10 MHz)	1 dB Degradation in C/N_0				
	Macro Urban 40 dBm (0.693 km)	Macro Suburban 40 dBm (0.75 km)	Macro Rural 40 dBm (4.5 km)	Micro Urban 40 dBm (0.433 km)	Percentage of Receivers
≤-75	8.316	10.5	<4.5	11.691	1.2%
≤-72	5.544	7.5	<4.5	8.66	2.4%
≤-70	4.158	5.25	<4.5	6.495	3.6%
≤-67	2.079	3.75	<4.5	3.897	8.3%
≤-65	1.386	2.25	<4.5	2.598	9.5%
≤-64	1.386	1.5	<4.5	2.165	11.9%
≤-61	0.693	0.75	<4.5	0.866	13.1%
≤-60	<0.693	0.75	<4.5	0.866	14.3%
≤-59	<0.693	<0.75	<4.5	0.433	17.9%
≤-57	<0.693	<0.75	<4.5	<0.433	19%
≤-56	<0.693	<0.75	<4.5	<0.433	20.2%
≤-55	<0.693	<0.75	<4.5	<0.433	21.4%
≤-54	<0.693	<0.75	<4.5	<0.433	22.6%
≤-53	<0.693	<0.75	<4.5	<0.433	23.8%
≤-52	<0.693	<0.75	<4.5	<0.433	27.4%
≤-51	<0.693	<0.75	0	<0.433	28.6%
≤-50	<0.693	<0.75	0	<0.433	31%
≤-48	<0.693	<0.75	0	<0.433	32.1%
≤-47	<0.693	0	0	<0.433	33.3%
≤-46	<0.693	0	0	<0.433	34.5%
≤-45	<0.693	0	0	<0.433	35.7%
≤-44	<0.693	0	0	<0.433	40.5%
≤-43	0	0	0	<0.433	41.7%
≤-42	0	0	0	<0.433	44%
≤-41	0	0	0	<0.433	50%
≤-40	0	0	0	<0.433	51.2%
≤-39	0	0	0	<0.433	53.6%
≤-38	0	0	0	<0.433	56%
≤-37	0	0	0	<0.433	57.1%
≤-36	0	0	0	<0.433	59.5%
≤-34	0	0	0	<0.433	61.9%
≤-33	0	0	0	<0.433	63.1%
≤-32	0	0	0	<0.433	64.3%
≤-31	0	0	0	0	65.5%

Table F.15. Exclusion Zone Separation Distance (km) GLN GPS Receivers

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands					
Interference Power Level (dBm/10 MHz)	1 dB Degradation in C/N_0				
	Macro Urban 40 dBm (0.693 km)	Macro Suburban 40 dBm (0.75 km)	Macro Rural 40 dBm (4.5 km)	Micro Urban 40 dBm (0.433 km)	Percentage of Receivers
-68	2.772	6	<4.5	6.928	0.6%
-57	<0.693	<0.75	<4.5	0.433	1.3%
-55	<0.693	<0.75	<4.5	<0.433	1.9%
-51	<0.693	<0.75	0	<0.433	2.6%
-45	<0.693	0	0	<0.433	4.5%
-44	<0.693	0	0	<0.433	5.1%
-42	0	0	0	<0.433	5.8%
-40	0	0	0	<0.433	5.8%
-39	0	0	0	<0.433	6.4%
-38	0	0	0	<0.433	7.1%
-36	0	0	0	<0.433	8.3%
-34	0	0	0	<0.433	10.3%
-33	0	0	0	<0.433	11.5%
-32	0	0	0	<0.433	13.5%
-31	0	0	0	0	16%

Table F.16. Exclusion Zone Separation Distance (km) TIM GPS Receivers

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands					
Interference Power Level (dBm/10 MHz)	1 dB Degradation in C/N_0				
	Macro Urban 40 dBm (0.693 km)	Macro Suburban 40 dBm (0.75 km)	Macro Rural 40 dBm (4.5 km)	Micro Urban 40 dBm (0.433 km)	Percentage of Receivers
≤-49	<0.693	<0.75	0	<0.433	4.2%
≤-44	<0.693	0	0	<0.433	8.3%
≤-40	0	0	0	<0.433	12.5%
≤-38	0	0	0	<0.433	16.7%
≤-31	0	0	0	0	20.8%

Additional exclusion zone analysis was calculated using ITM in the Point-to-Point Mode, which uses terrain data, to calculate the propagation loss.[12]

ITM is a general purpose radio propagation prediction algorithm intended for use on tropospheric radio circuits utilizing frequencies in the range 20 MHz to 20 GHz. The model is based on electromagnetic theory and statistical analyses of terrain features and radio measurements. The model predicts the median signal strength as a function of distance and the variability of the signal strength in time (because of changing atmospheric conditions) and space (because of changes in terrain). The model does not include the fine details of channel

[12] The only change was that ITM Point-to-Point Mode replaced ITM Area Mode as the propagation model. Additionally, elevation data was added to calculate the angle of the normalized, off-boresight loss of the GPS antenna and the off-axis loss of the base station antenna.

characterization (e.g., fast fading). For distances less than 1 kilometer (km), propagation loss is calculated as free space path loss. Table F.17 provides the ITM Point-to-Point simulation inputs.

Table F.17. ITM Point-to-Point Simulation Variables

ITM Point-to-Point Input Parameters	Values
Dielectric	15.0
Conductivity	0.005 S/m
Refractivity	301.0
Radio Climate	Continental temperate
Polarity	Horizontal/vertical
Reliability Percentage	50%
Confidence Percentage	50%

Over 7,000 fixed GPS receiver infrastructure locations were used as inputs to the simulation.[13] Figure F.14 shows the distribution of exclusion zone distances (macro urban, EIRP: 62 dBm) for a 1 dB C/N_0 degradation for all GPS receivers, specifically HP receivers at an interference power level of -75 dBm/10 MHz. The figure also shows that the mode of the histogram is approximately the same exclusion zone distance (33.957 km from Table F.11) when using 50% confidence and terrain roughness factor (Delta H) of 30 meters as input parameters for ITM Area Mode. This reinforces the validity of the parameters for ITM Area Mode in this simulation geometry.

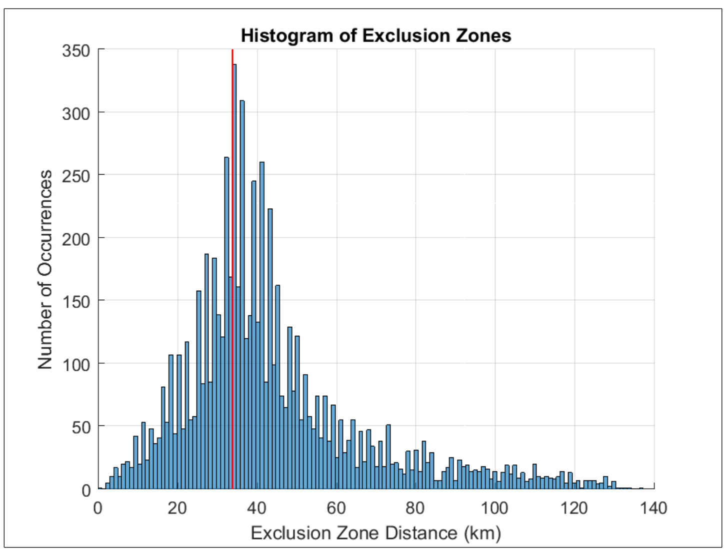

Figure F.14. Histogram of Exclusion Zone Distances for Fixed GPS Receivers

Figure F.15 shows the GPS receiver location and represents the exclusion zone distance as a color. For example, dark blue represents exclusion zone distances less than 20 km and dark red represents exclusion zone distances greater than 120 km.

[13] *See* Appendix G: Fixed GPS Infrastructure – Exclusion Zone Analysis for GPS receiver locations.

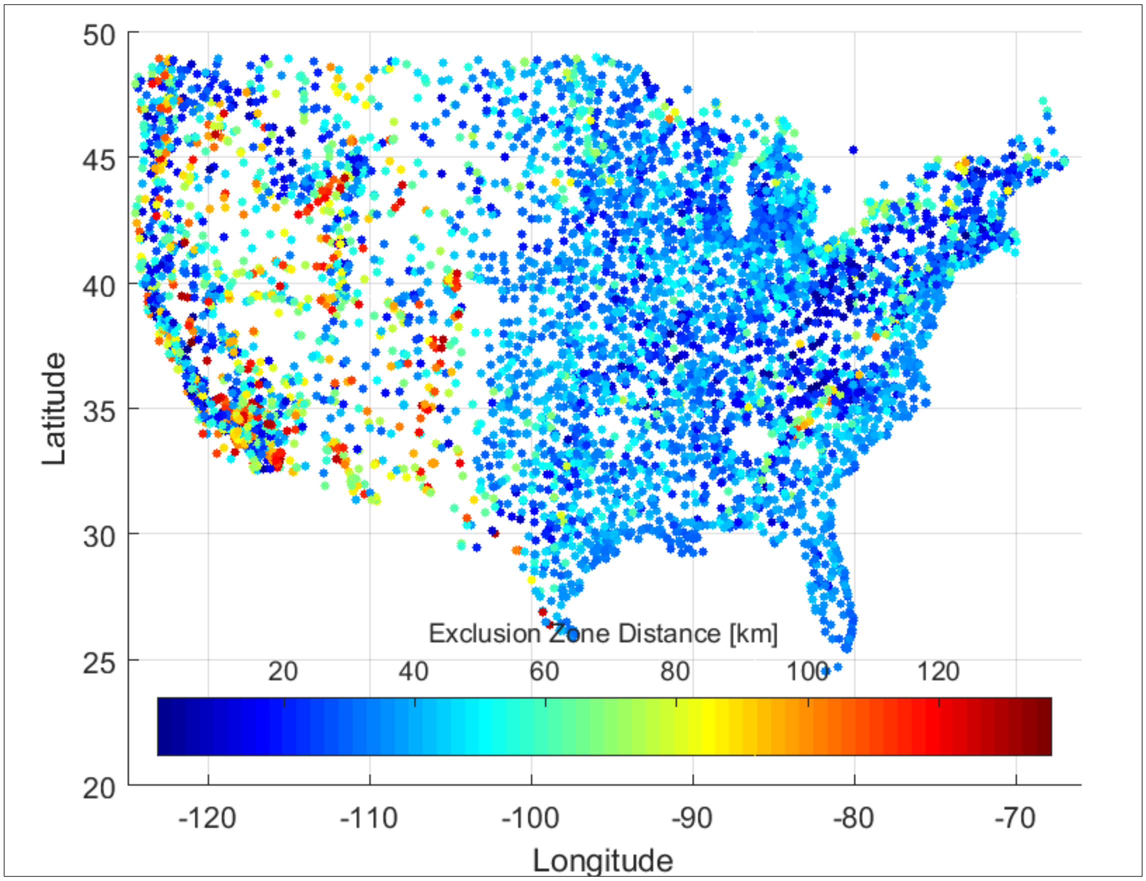

Figure F.15. Exclusion Zone Distances for Fixed GPS Receivers Locations

F.3.4 Simulation Geometry 3: GPS Receiver Operating Outside a Cell (Offset)

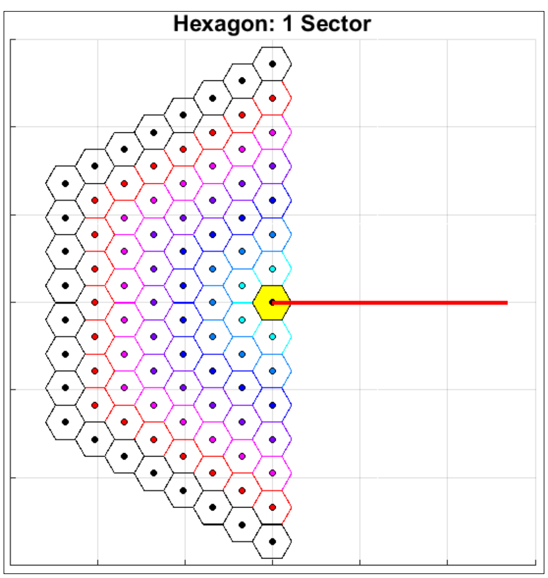

Figure F.16. One-Sector Hexagonal Cell

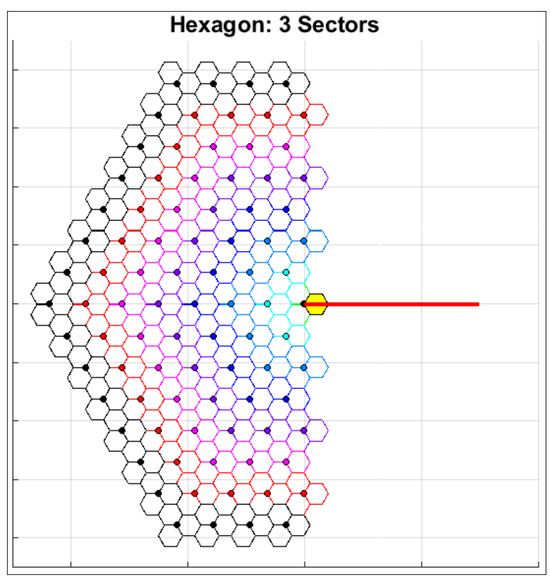

Figure F.17. Three-Sector Hexagonal Cell

For a GPS receiver operating outside of a cell (offset), Figure F.16 and Figure F.17, the GPS receivers are located along the red line. The separation distance is found along the red line.

Tables F.18 through F.27 provides the minimum separation distance needed from the closest base station to a GPS receiver. Each table has a varying base station EIRP along the top row and the power received at the GPS receiver along the left column. Each table shows the percentage of GPS receivers, from all the measurement campaigns, which will experience 1 dB, 3 dB, and 5 dB C/N_0 degradation and LOL for the power received at the GPS receiver. Separation distances less than the cell radius of the deployment are excluded.

Table F.18. Macro Urban: Percentage of HP Receivers Impacted vs Separation Distance (km)

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands Cell Radius: 462 meters																					
Power Received at GPS (dBm/10 MHz)	**Base Station EIRP (dBm/10 MHz)**																**Percentage of Receivers**			
	62	**60**	**58**	**56**	**54**	**52**	**50**	**48**	**46**	**44**	**42**	**40**	**38**	**36**	**34**	**32**	**30**	**1 dB**	**3 dB**	**5 dB**	**LOL**
-75	21.3	19.0	16.8	14.8	12.8	11.0	9.2	7.6	6.1	4.8	3.6	2.6	1.8	1.2	0.8	0.6	0.5	1.2%	0.0%	0.0%	0.0%
-72	17.9	15.8	13.8	11.9	10.1	8.4	6.9	5.5	4.2	3.1	2.2	1.5	1.0	0.7	0.5			2.4%	0.0%	0.0%	0.0%
-70	15.8	13.8	11.9	10.1	8.4	6.9	5.5	4.2	3.1	2.2	1.5	1.0	0.7	0.5				3.6%	0.0%	0.0%	0.0%
-67	12.8	11.0	9.2	7.6	6.1	4.8	3.6	2.6	1.8	1.2	0.8	0.6	0.5					8.3%	0.0%	0.0%	0.0%
-65	11.0	9.2	7.6	6.1	4.8	3.6	2.6	1.8	1.2	0.8	0.6	0.5						9.5%	0.0%	0.0%	0.0%
-64	10.1	8.4	6.9	5.5	4.2	3.1	2.2	1.5	1.0	0.7	0.5							11.9%	4.0%	0.0%	0.0%
-63	9.2	7.6	6.1	4.8	3.6	2.6	1.8	1.2	0.8	0.6	0.5							11.9%	8.0%	0.0%	0.0%
-62	8.4	6.9	5.5	4.2	3.1	2.2	1.5	1.0	0.7	0.5								11.9%	10.0%	0.0%	0.0%
-61	7.6	6.1	4.8	3.6	2.6	1.8	1.2	0.8	0.6	0.5								13.1%	10.0%	4.0%	2.0%
-60	6.9	5.5	4.2	3.1	2.2	1.5	1.0	0.7	0.5									14.3%	10.0%	4.0%	2.0%
-59	6.1	4.8	3.6	2.6	1.8	1.2	0.8	0.6	0.5									17.9%	10.0%	6.0%	2.0%
-58	5.5	4.2	3.1	2.2	1.5	1.0	0.7	0.5										17.9%	12.0%	10.0%	2.0%
-57	4.8	3.6	2.6	1.8	1.2	0.8	0.6	0.5										19.0%	12.0%	10.0%	2.0%
-56	4.2	3.1	2.2	1.5	1.0	0.7	0.5											20.2%	14.0%	10.0%	2.0%
-55	3.6	2.6	1.8	1.2	0.8	0.6	0.5											21.4%	18.0%	12.0%	2.0%
-54	3.1	2.2	1.5	1.0	0.7	0.5												22.6%	18.0%	12.0%	2.0%
-53	2.6	1.8	1.2	0.8	0.6	0.5												23.8%	18.0%	18.0%	2.0%
-52	2.2	1.5	1.0	0.7	0.5													27.4%	20.0%	18.0%	2.0%
-51	1.8	1.2	0.8	0.6	0.5													28.6%	22.0%	18.0%	2.0%
-50	1.5	1.0	0.7	0.5														31.0%	22.0%	18.0%	4.1%
-49	1.2	0.8	0.6	0.5														31.0%	26.0%	20.0%	6.1%
-48	1.0	0.7	0.5															32.1%	28.0%	22.0%	6.1%
-47	0.8	0.6	0.5															33.3%	28.0%	22.0%	6.1%
-46	0.7	0.5																34.5%	28.0%	24.0%	6.1%
-45	0.6	0.5																35.7%	32.0%	26.0%	14.3%
-44	0.5																	40.5%	32.0%	26.0%	14.3%

Table F.19. Macro Suburban: Percentage of HP Receivers Impacted vs Separation Distance (km)

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands
Cell Radius: 500 meters

Power Received at GPS (dBm/10 MHz)	Base Station EIRP (dBm/10 MHz)																		Percentage of Receivers			
	62	60	58	56	54	52	50	48	46	44	42	40	38	36	34	32	30	28	1 dB	3 dB	5 dB	LOL
-75	26.4	23.8	21.4	19.2	17.1	15.0	13.1	11.2	9.4	7.8	6.3	4.9	3.7	2.6	1.8	1.2	0.8	0.6	1.2%	0.0%	0.0%	0.0%
-72	22.6	20.3	18.1	16.0	14.0	12.1	10.3	8.6	7.0	5.6	4.3	3.1	2.2	1.5	1.0	0.7	0.5		2.4%	0.0%	0.0%	0.0%
-70	20.3	18.1	16.0	14.0	12.1	10.3	8.6	7.0	5.6	4.3	3.1	2.2	1.5	1.0	0.7	0.5			3.6%	0.0%	0.0%	0.0%
-67	17.1	15.0	13.1	11.2	9.4	7.8	6.3	4.9	3.7	2.6	1.8	1.2	0.8	0.6					8.3%	0.0%	0.0%	0.0%
-65	15.0	13.1	11.2	9.4	7.8	6.3	4.9	3.7	2.6	1.8	1.2	0.8	0.6						9.5%	0.0%	0.0%	0.0%
-64	14.0	12.1	10.3	8.6	7.0	5.6	4.3	3.1	2.2	1.5	1.0	0.7	0.5						11.9%	4.0%	0.0%	0.0%
-63	13.1	11.2	9.4	7.8	6.3	4.9	3.7	2.6	1.8	1.2	0.8	0.6							11.9%	8.0%	0.0%	0.0%
-62	12.1	10.3	8.6	7.0	5.6	4.3	3.1	2.2	1.5	1.0	0.7	0.5							11.9%	10.0%	0.0%	0.0%
-61	11.2	9.4	7.8	6.3	4.9	3.7	2.6	1.8	1.2	0.8	0.6								13.1%	10.0%	4.0%	2.0%
-60	10.3	8.6	7.0	5.6	4.3	3.1	2.2	1.5	1.0	0.7	0.5								14.3%	10.0%	4.0%	2.0%
-59	9.4	7.8	6.3	4.9	3.7	2.6	1.8	1.2	0.8	0.6									17.9%	10.0%	6.0%	2.0%
-58	8.6	7.0	5.6	4.3	3.1	2.2	1.5	1.0	0.7	0.5									17.9%	12.0%	10.0%	2.0%
-57	7.8	6.3	4.9	3.7	2.6	1.8	1.2	0.8	0.6										19.0%	12.0%	10.0%	2.0%
-56	7.0	5.6	4.3	3.1	2.2	1.5	1.0	0.7	0.5										20.2%	14.0%	10.0%	2.0%
-55	6.3	4.9	3.7	2.6	1.8	1.2	0.8	0.6											21.4%	18.0%	12.0%	2.0%
-54	5.6	4.3	3.1	2.2	1.5	1.0	0.7	0.5											22.6%	18.0%	12.0%	2.0%
-53	4.9	3.7	2.6	1.8	1.2	0.8	0.6												23.8%	18.0%	18.0%	2.0%
-52	4.3	3.1	2.2	1.5	1.0	0.7	0.5												27.4%	20.0%	18.0%	2.0%
-51	3.7	2.6	1.8	1.2	0.8	0.6													28.6%	22.0%	18.0%	2.0%
-50	3.1	2.2	1.5	1.0	0.7	0.5													31.0%	22.0%	18.0%	4.1%
-49	2.6	1.8	1.2	0.8	0.6														31.0%	26.0%	20.0%	6.1%
-48	2.2	1.5	1.0	0.7	0.5														32.1%	28.0%	22.0%	6.1%
-47	1.8	1.2	0.8	0.6															33.3%	28.0%	22.0%	6.1%
-46	1.5	1.0	0.7	0.5															34.5%	28.0%	24.0%	6.1%
-45	1.2	0.8	0.6																35.7%	32.0%	26.0%	14.3%
-44	1.0	0.7	0.5																40.5%	32.0%	26.0%	14.3%
-43	0.8	0.6																	41.7%	34.0%	26.0%	16.3%
-42	0.7	0.5																	44.0%	36.0%	26.0%	18.4%
-41	0.6																		50.0%	36.0%	26.0%	18.4%
-40	0.5																		51.2%	38.0%	36.0%	18.4%

Table F.20. Macro Rural: Percentage of HP Receivers Impacted vs Separation Distance (km)

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands Cell Radius: 3 km															
Power Received at GPS (dBm/10 MHz)	**Base Station EIRP (dBm/10 MHz)**											**Percentage of Receivers**			
	62	**60**	**58**	**56**	**54**	**52**	**50**	**48**	**46**	**44**	**42**	**1 dB**	**3 dB**	**5 dB**	**LOL**
-75	18.0	16.0	14.0	12.2	10.5	8.8	7.4	6.0	4.9	3.9	3.2	1.2%	0.0%	0.0%	0.0%
-72	15.0	13.1	11.3	9.6	8.1	6.7	5.4	4.4	3.5			2.4%	0.0%	0.0%	0.0%
-70	13.1	11.3	9.6	8.1	6.7	5.4	4.4	3.5				3.6%	0.0%	0.0%	0.0%
-67	10.5	8.8	7.4	6.0	4.9	3.9	3.2					8.3%	0.0%	0.0%	0.0%
-65	8.8	7.4	6.0	4.9	3.9	3.2						9.5%	0.0%	0.0%	0.0%
-64	8.1	6.7	5.4	4.4	3.5							11.9%	4.0%	0.0%	0.0%
-63	7.4	6.0	4.9	3.9	3.2							11.9%	8.0%	0.0%	0.0%
-62	6.7	5.4	4.4	3.5								11.9%	10.0%	0.0%	0.0%
-61	6.0	4.9	3.9	3.2								13.1%	10.0%	4.0%	2.0%
-60	5.4	4.4	3.5									14.3%	10.0%	4.0%	2.0%
-59	4.9	3.9	3.2									17.9%	10.0%	6.0%	2.0%
-58	4.4	3.5										17.9%	12.0%	10.0%	2.0%
-57	3.9	3.2										19.0%	12.0%	10.0%	2.0%
-56	3.5											20.2%	14.0%	10.0%	2.0%
-55	3.2											21.4%	18.0%	12.0%	2.0%

Table F.21. Micro Urban: Percentage of HP Receivers Impacted vs Separation Distance (km)

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands Cell Radius: 250 meters													
Power Received at GPS (dBm/10 MHz)	Base Station EIRP (dBm/10 MHz)									Percentage of Receivers			
	42	40	38	36	34	32	30	28	26	1 dB	3 dB	5 dB	LOL
-75	6.0	5.3	4.1	3.0	2.1	1.4	0.9	0.5	0.3	1.2%	0.0%	0.0%	0.0%
-72	4.7	3.5	2.5	1.7	1.1	0.7	0.4	0.3		2.4%	0.0%	0.0%	0.0%
-70	3.5	2.5	1.7	1.1	0.7	0.4	0.3			3.6%	0.0%	0.0%	0.0%
-67	2.1	1.4	0.9	0.5	0.3					8.3%	0.0%	0.0%	0.0%
-65	1.4	0.9	0.5	0.3						9.5%	0.0%	0.0%	0.0%
-64	1.1	0.7	0.4							11.9%	4.0%	0.0%	0.0%
-63	0.9	0.5	0.3							11.9%	8.0%	0.0%	0.0%
-62	0.7	0.4								11.9%	10.0%	0.0%	0.0%
-61	0.5	0.3								13.1%	10.0%	4.0%	2.0%
-60	0.4									14.3%	10.0%	4.0%	2.0%
-59	0.3									17.9%	10.0%	6.0%	2.0%

Table F.22. Macro Urban: Percentage of GLN Receivers Impacted vs Separation Distance (km)

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands Cell Radius: 462 meters																		
Power Received at GPS (dBm/10 MHz)	Base Station EIRP (dBm/10 MHz)														Percentage of Receivers			
	62	60	58	56	54	52	50	48	46	44	42	40	38	36	1 dB	3 dB	5 dB	LOL
-68	15.9	13.9	12.0	10.2	8.5	7.0	5.5	4.3	3.2	2.3	1.5	1.0	0.7	0.5	0.6%	0.0%	0.0%	0.0%
-60	8.5	7.0	5.5	4.3	3.2	2.3	1.5	1.0	0.7	0.5					0.6%	3.0%	0.0%	0.0%
-58	7.0	5.5	4.3	3.2	2.3	1.5	1.0	0.7	0.5						0.6%	3.0%	3.0%	0.0%
-57	6.2	4.9	3.7	2.7	1.9	1.3	0.9	0.6							1.3%	3.0%	3.0%	0.0%
-55	4.9	3.7	2.7	1.9	1.3	0.9	0.6	0.5							1.9%	3.0%	3.0%	0.0%
-51	2.7	1.9	1.3	0.9	0.6	0.5									2.6%	3.0%	3.0%	0.0%
-45	0.9	0.6	0.5												4.5%	3.0%	3.0%	3.1%
-44	0.7	0.5													5.1%	9.1%	3.0%	3.1%
-42	0.5														5.8%	9.1%	3.0%	3.1%

Table F.23. Macro Suburban: Percentage of GLN Receivers Impacted vs Separation Distance (km)

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands
Cell Radius: 500 meters

Power Received at GPS (dBm/10 MHz)	Base Station EIRP (dBm/10 MHz)																Percentage of Receivers			
	62	60	58	56	54	52	50	48	46	44	42	40	38	36	34	32	1 dB	3 dB	5 dB	LOL
-68	20.5	18.3	16.2	14.2	12.3	10.4	8.7	7.1	5.7	4.3	3.2	2.2	1.5	1.0	0.7	0.5	0.6%	0.0%	0.0%	0.0%
-60	12.3	10.4	8.7	7.1	5.7	4.3	3.2	2.2	1.5	1.0	0.7	0.5					0.6%	3.0%	0.0%	0.0%
-58	10.4	8.7	7.1	5.7	4.3	3.2	2.2	1.5	1.0	0.7	0.5						0.6%	3.0%	3.0%	0.0%
-57	9.6	7.9	6.4	5.0	3.7	2.7	1.9	1.2	0.8	0.6							1.3%	3.0%	3.0%	0.0%
-55	7.9	6.4	5.0	3.7	2.7	1.9	1.2	0.8	0.6	0.5							1.9%	3.0%	3.0%	0.0%
-51	5.0	3.7	2.7	1.9	1.2	0.8	0.6	0.5									2.6%	3.0%	3.0%	0.0%
-45	1.9	1.2	0.8	0.6	0.5												4.5%	3.0%	3.0%	3.1%
-44	1.5	1.0	0.7	0.5													5.1%	9.1%	3.0%	3.1%
-42	1.0	0.7	0.5														5.8%	9.1%	3.0%	3.1%
-40	0.7	0.5															5.8%	12.1%	3.0%	3.1%
-39	0.6																6.4%	12.1%	3.0%	3.1%
-38	0.5																7.1%	12.1%	3.0%	3.1%

Table F.24. Macro Rural: Percentage of GLN Receivers Impacted vs Separation Distance (km)

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands Cell Radius: 3 km													
Power Received at GPS (dBm/10 MHz)	Base Station EIRP (dBm/10 MHz)									Percentage of Receivers			
	62	60	58	56	54	52	50	48	46	1 dB	3 dB	5 dB	LOL
-68	13.2	11.4	9.8	8.2	6.8	5.5	4.5	3.6	2.9	0.6%	0.0%	0.0%	0.0%
-60	6.8	5.5	4.5	3.6						0.6%	3.0%	0.0%	0.0%
-58	5.5	4.5	3.6							0.6%	3.0%	3.0%	0.0%
-57	5.0	4.0	3.2							1.3%	3.0%	3.0%	0.0%
-55	4.0	3.2								1.9%	3.0%	3.0%	0.0%
-51	2.6									2.6%	3.0%	3.0%	0.0%

Table F.25. Micro Urban: Percentage of GLN Receivers Impacted vs Separation Distance (km)

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands Cell Radius: 250 meters											
Power Received at GPS (dBm/10 MHz)	Base Station EIRP (dBm/10 MHz)							Percentage of Receivers			
	42	40	38	36	34	32	30	1 dB	3 dB	5 dB	LOL
-68	3.6	2.6	1.8	1.1	0.7	0.4	0.3	0.6%	0.0%	0.0%	0.0%
-60	0.7	0.4	0.3					0.6%	3.0%	0.0%	0.0%
-58	0.4	0.3						0.6%	3.0%	3.0%	0.0%
-57	0.3							1.3%	3.0%	3.0%	0.0%

Table F.26. Macro Urban: Percentage of TIM Receivers Impacted vs Separation Distance (km)

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands Cell Radius: 462 meters								
Power Received at GPS (dBm/10 MHz)	Base Station EIRP				Percentage of Receivers			
	62	60	58	56	1 dB	3 dB	5 dB	LOL
-49	1.6	1.1	0.7	0.5	4.2%	0.0%	0.0%	0.0%
-44	0.6	0.5			8.3%	0.0%	0.0%	0.0%
-43	0.5				8.3%	8.3%	0.0%	0.0%

Table F.27. Macro Suburban: Percentage of TIM Receivers Impacted vs Separation Distance (km)

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands Cell Radius: 500 meters										
Power Received at GPS (dBm/10 MHz)	Base Station EIRP						Percentage of Receivers			
	62	60	58	56	54	52	1 dB	3 dB	5 dB	LOL
-49	3.3	2.3	1.6	1.0	0.7	0.5	4.2%	0.0%	0.0%	0.0%
-44	1.3	0.8	0.6				8.3%	0.0%	0.0%	0.0%
-43	1.0	0.7	0.5				8.3%	8.3%	0.0%	0.0%
-40	0.6						12.5%	8.3%	8.3%	0.0%

F.4 GPS MEASUREMENT DATA

Table F.28. Summary of HP GPS Receivers Impacted

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands								
Interference Power Level (dBm/10 MHz)	Number of Receivers				Percentage of Receivers			
	Degradation in C/N_0							
	1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
≤-75	1	0	0	0	1.2%	0.0%	0.0%	0.0%
≤-72	2	0	0	0	2.4%	0.0%	0.0%	0.0%
≤-70	3	0	0	0	3.6%	0.0%	0.0%	0.0%
≤-67	7	0	0	0	8.3%	0.0%	0.0%	0.0%
≤-65	8	0	0	0	9.5%	0.0%	0.0%	0.0%
≤-64	10	2	0	0	11.9%	4.0%	0.0%	0.0%
≤-63	10	4	0	0	11.9%	8.0%	0.0%	0.0%
≤-62	10	5	0	0	11.9%	10.0%	0.0%	0.0%
≤-61	11	5	2	1	13.1%	10.0%	4.0%	2.0%
≤-60	12	5	2	1	14.3%	10.0%	4.0%	2.0%
≤-59	15	5	3	1	17.9%	10.0%	6.0%	2.0%
≤-58	15	6	5	1	17.9%	12.0%	10.0%	2.0%
≤-57	16	6	5	1	19.0%	12.0%	10.0%	2.0%
≤-56	17	7	5	1	20.2%	14.0%	10.0%	2.0%
≤-55	18	9	6	1	21.4%	18.0%	12.0%	2.0%
≤-54	19	9	6	1	22.6%	18.0%	12.0%	2.0%
≤-53	20	9	9	1	23.8%	18.0%	18.0%	2.0%
≤-52	23	10	9	1	27.4%	20.0%	18.0%	2.0%
≤-51	24	11	9	1	28.6%	22.0%	18.0%	2.0%
≤-50	26	11	9	2	31.0%	22.0%	18.0%	4.1%
≤-49	26	13	10	3	31.0%	26.0%	20.0%	6.1%
≤-48	27	14	11	3	32.1%	28.0%	22.0%	6.1%
≤-47	28	14	11	3	33.3%	28.0%	22.0%	6.1%
≤-46	29	14	12	3	34.5%	28.0%	24.0%	6.1%
≤-45	30	16	13	7	35.7%	32.0%	26.0%	14.3%
≤-44	34	16	13	7	40.5%	32.0%	26.0%	14.3%
≤-43	35	17	13	8	41.7%	34.0%	26.0%	16.3%
≤-42	37	18	13	9	44.0%	36.0%	26.0%	18.4%
≤-41	42	18	13	9	50.0%	36.0%	26.0%	18.4%
≤-40	43	19	18	9	51.2%	38.0%	36.0%	18.4%
≤-39	45	22	18	9	53.6%	44.0%	36.0%	18.4%
≤-38	47	23	19	10	56.0%	46.0%	38.0%	20.4%
≤-37	48	24	20	11	57.1%	48.0%	40.0%	22.4%
≤-36	50	24	23	12	59.5%	48.0%	46.0%	24.5%
≤-35	50	24	23	15	59.5%	48.0%	46.0%	30.6%
≤-34	52	26	23	19	61.9%	52.0%	46.0%	38.8%
≤-33	53	26	24	19	63.1%	52.0%	48.0%	38.8%
≤-32	54	26	24	20	64.3%	52.0%	48.0%	40.8%
≤-31	55	27	25	21	65.5%	54.0%	50.0%	42.9%
≤-30	56	29	26	21	66.7%	58.0%	52.0%	42.9%
≤-29	58	29	27	21	69.0%	58.0%	54.0%	42.9%
≤-28	58	29	29	22	69.0%	58.0%	58.0%	44.9%

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands								
Interference Power Level (dBm/10 MHz)	Number of Receivers				Percentage of Receivers			
	Degradation in C/N_0							
	1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
≤-27	59	30	29	22	70.2%	60.0%	58.0%	44.9%
≤-26	60	30	29	22	71.4%	60.0%	58.0%	44.9%
≤-25	61	31	30	22	72.6%	62.0%	60.0%	44.9%
≤-24	66	31	30	23	78.6%	62.0%	60.0%	46.9%
≤-23	67	31	31	24	79.8%	62.0%	62.0%	49.0%
≤-22	67	31	31	25	79.8%	62.0%	62.0%	51.0%
≤-21	69	33	31	25	82.1%	66.0%	62.0%	51.0%
≤-20	71	33	31	26	84.5%	66.0%	62.0%	53.1%
≤-19	72	33	31	27	85.7%	66.0%	62.0%	55.1%
≤-18	72	33	32	27	85.7%	66.0%	64.0%	55.1%
≤-17	72	34	33	27	85.7%	68.0%	66.0%	55.1%
≤-16	72	36	33	27	85.7%	72.0%	66.0%	55.1%
≤-15	73	37	33	28	86.9%	74.0%	66.0%	57.1%
≤-14	74	38	35	28	88.1%	76.0%	70.0%	57.1%
≤-13	74	39	35	28	88.1%	78.0%	70.0%	57.1%
≤-12	75	41	37	30	89.3%	82.0%	74.0%	61.2%
≤-11	75	41	38	31	89.3%	82.0%	76.0%	63.3%
≤-10	81	47	47	46	96.4%	94.0%	94.0%	93.9%
≤0	82	47	47	46	97.6%	94.0%	94.0%	93.9%
≤1	83	48	48	47	98.8%	96.0%	96.0%	95.9%
≤2	83	49	49	48	98.8%	98.0%	98.0%	98.0%
≤3	84	50	50	49	100.0%	100.0%	100.0%	100.0%

Table F.29. Summary of TIM GPS Receivers Impacted

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands								
Interference Power Level (dBm/10 MHz)	Number of Receivers				Percentage of Receivers			
	Degradation in C/N_0							
	1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
≤-49	1	0	0	0	4.2%	0.0%	0.0%	0.0%
≤-44	2	0	0	0	8.3%	0.0%	0.0%	0.0%
≤-43	2	1	0	0	8.3%	8.3%	0.0%	0.0%
≤-40	3	1	1	0	12.5%	8.3%	8.3%	0.0%
≤-38	4	1	1	0	16.7%	8.3%	8.3%	0.0%
≤-31	5	1	1	0	20.8%	8.3%	8.3%	0.0%
≤-30	6	1	1	0	25.0%	8.3%	8.3%	0.0%
≤-29	7	1	1	0	29.2%	8.3%	8.3%	0.0%
≤-28	7	2	1	0	29.2%	16.7%	8.3%	0.0%
≤-27	9	2	1	1	37.5%	16.7%	8.3%	8.3%
≤-25	9	2	2	1	37.5%	16.7%	16.7%	8.3%
≤-24	10	2	2	1	41.7%	16.7%	16.7%	8.3%
≤-20	12	2	2	1	50.0%	16.7%	16.7%	8.3%
≤-19	13	2	2	1	54.2%	16.7%	16.7%	8.3%
≤-18	13	3	2	1	54.2%	25.0%	16.7%	8.3%
≤-17	14	3	2	1	58.3%	25.0%	16.7%	8.3%
≤-16	14	3	3	1	58.3%	25.0%	25.0%	8.3%
≤-15	18	4	4	1	75.0%	33.3%	33.3%	8.3%

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands								
Interference Power Level (dBm/10 MHz)	Number of Receivers				Percentage of Receivers			
	Degradation in C/N_0							
	1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
≤-14	18	5	4	1	75.0%	41.7%	33.3%	8.3%
≤-12	18	6	4	1	75.0%	50.0%	33.3%	8.3%
≤-10	22	10	10	10	91.7%	83.3%	83.3%	83.3%
≤0	22	10	10	11	91.7%	83.3%	83.3%	91.7%
≤1	23	11	11	12	95.8%	91.7%	91.7%	100.0%
≤2	24	12	12	12	100.0%	100.0%	100.0%	100.0%

Table F.30. Summary of GLN GPS Receivers Impacted

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands								
Interference Power Level (dBm/10 MHz)	Number of Receivers				Percentage of Receivers			
	Degradation in C/N_0							
	1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
≤-68	1	0	0	0	0.6%	0.0%	0.0%	0.0%
≤-60	1	1	0	0	0.6%	3.0%	0.0%	0.0%
≤-58	1	1	1	0	0.6%	3.0%	3.0%	0.0%
≤-57	2	1	1	0	1.3%	3.0%	3.0%	0.0%
≤-55	3	1	1	0	1.9%	3.0%	3.0%	0.0%
≤-51	4	1	1	0	2.6%	3.0%	3.0%	0.0%
≤-45	7	1	1	1	4.5%	3.0%	3.0%	3.1%
≤-44	8	3	1	1	5.1%	9.1%	3.0%	3.1%
≤-42	9	3	1	1	5.8%	9.1%	3.0%	3.1%
≤-40	9	4	1	1	5.8%	12.1%	3.0%	3.1%
≤-39	10	4	1	1	6.4%	12.1%	3.0%	3.1%
≤-38	11	4	1	1	7.1%	12.1%	3.0%	3.1%
≤-37	11	4	3	1	7.1%	12.1%	9.1%	3.1%
≤-36	13	4	3	1	8.3%	12.1%	9.1%	3.1%
≤-34	16	4	4	1	10.3%	12.1%	12.1%	3.1%
≤-33	18	4	4	1	11.5%	12.1%	12.1%	3.1%
≤-32	21	4	4	1	13.5%	12.1%	12.1%	3.1%
≤-31	25	4	4	1	16.0%	12.1%	12.1%	3.1%
≤-30	30	5	4	1	19.2%	15.2%	12.1%	3.1%
≤-29	35	7	4	1	22.4%	21.2%	12.1%	3.1%
≤-28	40	9	4	1	25.6%	27.3%	12.1%	3.1%
≤-27	41	9	4	1	26.3%	27.3%	12.1%	3.1%
≤-26	47	12	7	1	30.1%	36.4%	21.2%	3.1%
≤-25	49	12	8	1	31.4%	36.4%	24.2%	3.1%
≤-24	53	12	12	1	34.0%	36.4%	36.4%	3.1%
≤-23	55	13	12	1	35.3%	39.4%	36.4%	3.1%
≤-22	62	13	12	1	39.7%	39.4%	36.4%	3.1%
≤-21	67	13	13	1	42.9%	39.4%	39.4%	3.1%
≤-20	70	14	13	1	44.9%	42.4%	39.4%	3.1%
≤-19	74	14	13	1	47.4%	42.4%	39.4%	3.1%
≤-18	79	14	14	1	50.6%	42.4%	42.4%	3.1%
≤-17	84	14	14	1	53.8%	42.4%	42.4%	3.1%
≤-16	93	14	14	1	59.6%	42.4%	42.4%	3.1%
≤-15	95	14	14	2	60.9%	42.4%	42.4%	6.3%
≤-14	102	14	14	2	65.4%	42.4%	42.4%	6.3%
≤-13	108	14	14	2	69.2%	42.4%	42.4%	6.3%

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands								
Interference Power Level (dBm/10 MHz)	**Number of Receivers**				**Percentage of Receivers**			
	Degradation in C/N₀							
	1 dB	**3 dB**	**5 dB**	**LOL**	**1 dB**	**3 dB**	**5 dB**	**LOL**
≤-12	112	17	14	4	71.8%	51.5%	42.4%	12.5%
≤-10	133	29	29	29	85.3%	87.9%	87.9%	90.6%
≤-9	135	30	29	29	86.5%	90.9%	87.9%	90.6%
≤-8	136	30	30	30	87.2%	90.9%	90.9%	93.8%
≤-7	138	30	30	30	88.5%	90.9%	90.9%	93.8%
≤-5	140	30	30	30	89.7%	90.9%	90.9%	93.8%
≤-4	141	30	30	30	90.4%	90.9%	90.9%	93.8%
≤-3	144	30	30	30	92.3%	90.9%	90.9%	93.8%
≤-2	145	30	30	30	92.9%	90.9%	90.9%	93.8%
≤0	154	30	30	30	98.7%	90.9%	90.9%	93.8%
≤3	156	33	33	32	100.0%	100.0%	100.0%	100.0%

F.5 CLUTTER LOSS

Additional analysis was done with clutter loss for Simulation Geometry 1 (GPS receivers operating within a cell). Clutter loss calculations were performed using the methodology in Recommendation ITU-R P.2108-0, Section 3.2, for terrestrial terminals within clutter.[94] Clutter loss was not applied to the center base station in which the GPS receivers were randomly distributed. Clutter loss was applied to base stations that were outside the center cell and only applied to one end of the path.

The clutter loss in decibels was calculated by:

$$L_{ctt} = -5\text{Log}(10^{-0.2L_l} + 10^{-0.2L_s}) + normrnd(mean, sigma)$$

where the $normrnd(mean, sigma)$ is a normal distribution of numbers with a mean of zero, and a standard deviation of 6 dB.

The parameters L_l and L_s are computed using the equations below:

$$L_l = 23.5 + 9.6\text{Log}(F) \qquad \text{dB}$$

$$L_s = 32.98 + 23.9\text{Log}(D) + 3\text{Log}(F) \qquad \text{dB}$$

where F is frequency in gigahertz and D is separation distance in kilometers.

Figure F.18 shows the mean clutter loss applied to the 50,000 individual propagation paths. For the micro urban base station deployment scenario, 0 dB clutter loss was applied to the center base station, and then the mean clutter loss was 22 dB to 25 dB (black curve in Figure F.18) for the surrounding base stations.

[94] Recommendation ITU-R P.2108-0, *Prediction of Clutter Loss* (June 2017), *available at* https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.2108-0-201706-I!!PDF-E.pdf.

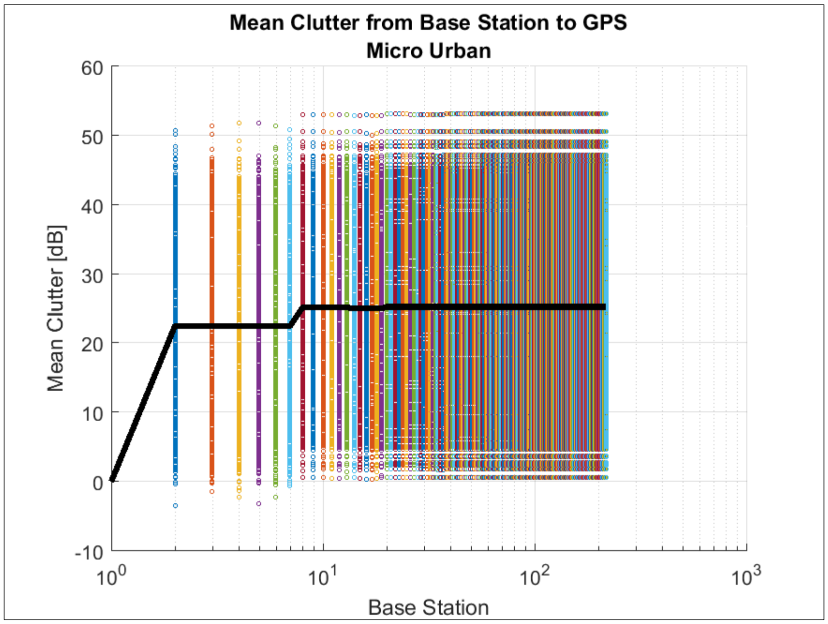

Figure F.18. Mean Clutter from Micro Urban Base Station to GPS

The 99th percentile of the power received (similar to Table F.3-Table F.6) was calculated with clutter loss applied. The results show that the 99th percentile is approximately the same for the single base station case scenario, aggregate with no clutter, and aggregate with clutter. The 99th percentile locations are within 100 meters of each base station, which means that the propagation model used to compute the 99th percentile is free space path loss and clutter loss is not applied.

APPENDIX G
FIXED GPS INFRASTRUCTURE – EXCLUSION ZONE ANALYSIS

G.1 INTRODUCTION

This appendix summarizes the Technical Focus Groups (TFG)'s analysis of the concept of exclusion zones around fixed Global Positioning System (GPS) receiver infrastructure, providing the percentage of population, outside of the exclusion zone, that is available to be provided coverage in the 1526-1536 MHz base station band. The following fixed GPS applications are included in the analysis:[1]

- National Oceanic and Atmospheric Administration (NOAA) - Continuously Operating Reference Stations (CORS)[2]
- United States Coast Guard - Differential Global Positioning System (DGPS)[3]
- Federal Railroad Administration (FRA) - Positive Train Control (PTC)
  - Amtrak[4]
- National Science Foundation (NSF) [awarded] - UNAVCO Geodesy Advancing Geosciences and EarthScope (GAGE) Facility[5]
  - Plate Boundary Observatory (PBO)
  - National Aeronautics and Space Administration's (NASA) Global GNSS Network (GGN)
    - International Global Navigation Satellite System (GNSS) Service (IGS) stations
    - NASA's Space Geodesy Project (SGP)
  - NSF-funded community GPS networks for Earth, atmospheric, and polar science applications
- Federal Aviation Administration (FAA) - Wide Area Augmentation System (WAAS).[6]

G.2 ANALYSIS OVERVIEW

For the analysis, exclusion zones were drawn around each high precision (HP) GPS receiver location, and the percentage of population outside of the exclusion zones was calculated. 2010 Census data and boundaries were used to determine the population percentage outside of the exclusion zones.[7] Figure G.1 and Figure G.2 show the simulation geometry for the exclusion zone calculation. The GPS receiver is located at the center and the separation distance is represented by the red line, which is a multiple of the inter-site distance.

[1] These applications do not represent all the applications of federal fixed GPS receivers.

[2] GPS receiver locations *available at* https://www.ngs.noaa.gov/CORS_Map/.

[3] GPS receiver locations *available at* https://www.navcen.uscg.gov/?pageName=dgpsSiteInfo&All.

[4] GPS receiver locations *available at* http://fragis.fra.dot.gov/GISFRASafety/.

[5] GPS receiver locations *available at* https://www.unavco.org/.

[6] GPS receiver locations *available at* https://en.wikipedia.org/wiki/List_of_WAAS_reference_stations.

[7] GPS receiver locations *available at* https://www.census.gov/geographies/reference-files/2010/geo/2010-centers-population.html.

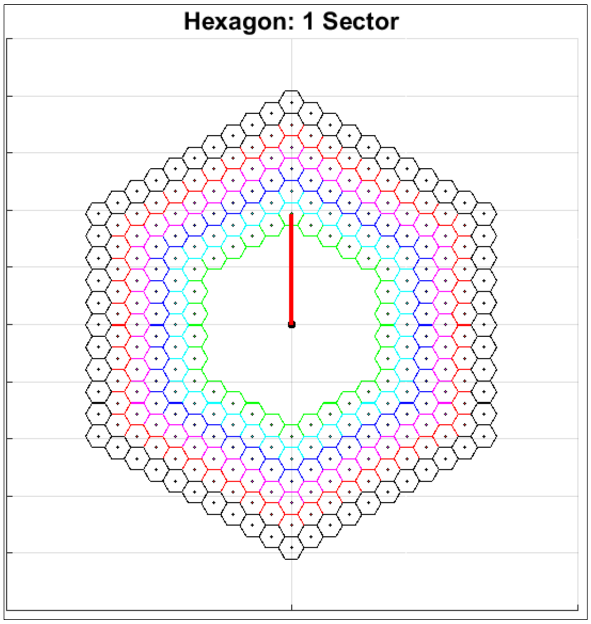

Figure G.1. One-Sector Hexagonal Cells

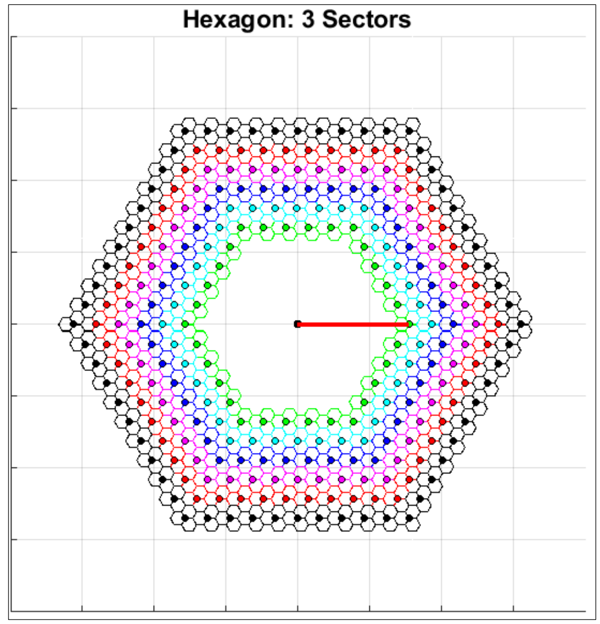

Figure G.2. Three-Sector Hexagonal Cell

Four base station deployment types were based upon the deployment parameters in the Ligado aggregate report[8] and the Roberson and Associates aggregate report.[9] ITU-R M.2292-0[10] guided additional base station simulation parameters. Table G.1 summarizes the simulation parameters for the four base station deployment types. For additional technical details, refer to Appendix F: Aggregate Base Station Analysis.

[8] RTCA Paper No. 333-16/SC159-1055, *Summary of Ligado Proposal Review by RTCA SC-159, WG6 as approved by RTCA SC-159* at 14 (Dec. 13, 2016), *available at* https://www.rtca.org/wp-content/uploads/2020/08/sc-159_wg6_response_ligado_with_tasking.pdf.

[9] Roberson and Associates, *Final Report: GPS and Adjacent Band Co-Existence Study* (June 10, 2016), *available at* https://ecfsapi.fcc.gov/file/60002112686.pdf.

[10] Report ITU-R M.2292-0, *Characteristics of terrestrial IMT-Advanced systems for frequency sharing/interference analyses* (Dec. 2013), *available at* https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2292-2014-PDF-E.pdf (ITU-R M.2292).

Table G.1: Summary of Simulation Parameters

Simulation Parameters	Macro Urban	Macro Suburban	Macro Rural	Micro Urban
Inter-Site Distance (km)	0.693	0.75	4.5	0.433
Propagation Model	Free Space Path Loss/ITM Area Mode			
Center Frequency (MHz)	1530 MHz[11]			
Base Station Height (m)	25m (ITU-R M.2292 Macro Urban)	30m (ITU-R M.2292 Macro Suburban)	30m (ITU-R M.2292 Macro Rural)	6m (ITU-R M.2292 Micro Urban)
Base Station Downtilt (deg)	10° (ITU-R M.2292 Macro Urban)	6° (ITU-R M.2292 Macro Suburban)	3° (ITU-R M.2292 Macro Rural)	0° (ITU-R M.2292 Micro Urban)
Base Station Antenna Pattern	ITU-R M.2292 Macro Urban, ITU-R F.1336	ITU-R M.2292 Macro Suburban, ITU-R F.1336	ITU-R M.2292 Macro Rural, ITU-R F.1336	ITU-R M.2292 Micro Urban, ITU-R F.1336
Base Station Sectors	3 Sectors	3 Sectors	3 Sectors	1 Sector[12]
GPS Height (m)	1.5m			

For the Macro (Urban/Suburban/Rural) base station deployment, the classification around each GPS receiver location was determined from the National Land Cover Database (NLCD) 2011.[13] Table G.2 provides association between base station deployment type and the NCLD classification. The base station equivalent isotropically radiated power (EIRP) is 62 dBm/10 MHz for Table G.3 and the base station EIRP is 40 dBm/10 MHz for Table G.4.

[11] Roberson and Associates simulated aggregate power at 1531 MHz. A frequency of 1530 MHz was chosen because the MITRE empirical GPS antenna scans were performed at 1530 MHz.

[12] A one sector, omni-directional antenna will create a higher aggregate power than a three-sectored, 120 degree beamwidth antenna.

[13] The NLCD database is *available at* https://www.mrlc.gov/data/nlcd-2011-land-cover-conus-0.

Table G.2. Base Station Deployment and NCLD Classification Descriptions

Base Station Deployment	Description of NCLD Classification
Macro Rural	21-Developed, Open Space-areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
Macro Suburban	22-Developed, Low Intensity-areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units. 23-Developed, Medium Intensity-areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.
Macro Urban	24-Developed High Intensity-highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover.

Figure G.3 through Figure G.7 show the exclusion zones drawn around each GPS receiver location for a base station EIRP of 62 dBm/10 MHz.

For Table G.5, a Micro Urban deployment exclusion zone, with a base station EIRP of 40 dBm/10 MHz, was drawn around every GPS receiver location.

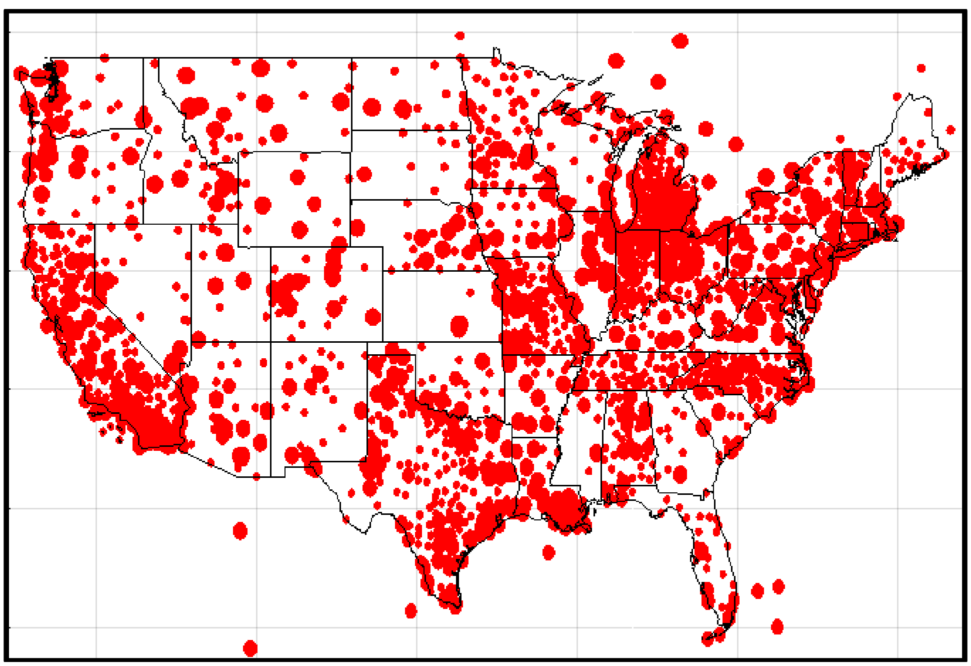

Figure G.3. CORS GPS Receiver Exclusion Zones-EIRP 62 dBm/10 MHz

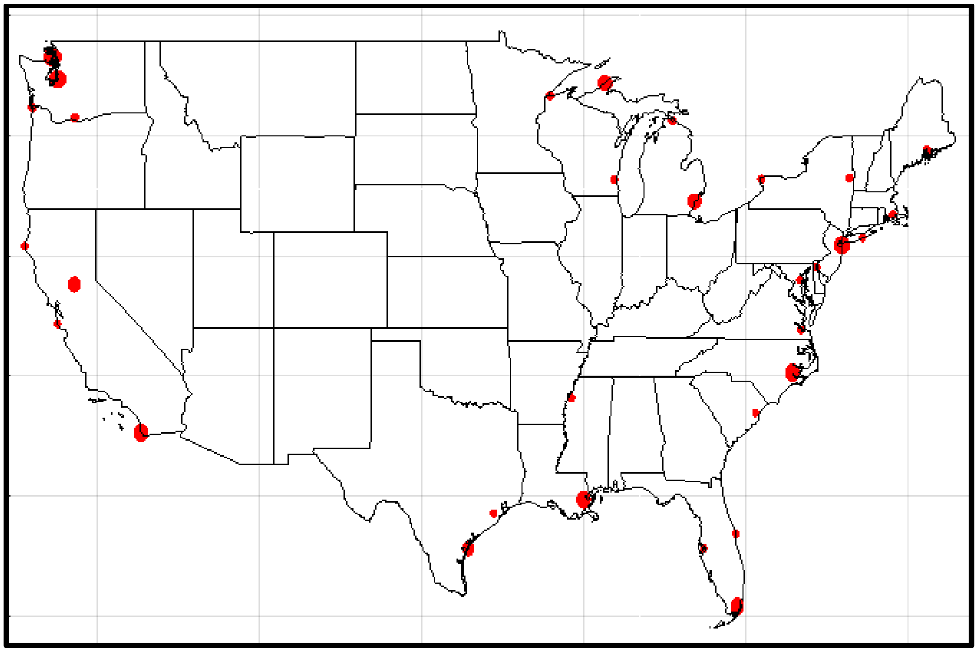

Figure G.4. NDGPS GPS Receiver Exclusion Zones-EIRP 62 dBm/10 MHz

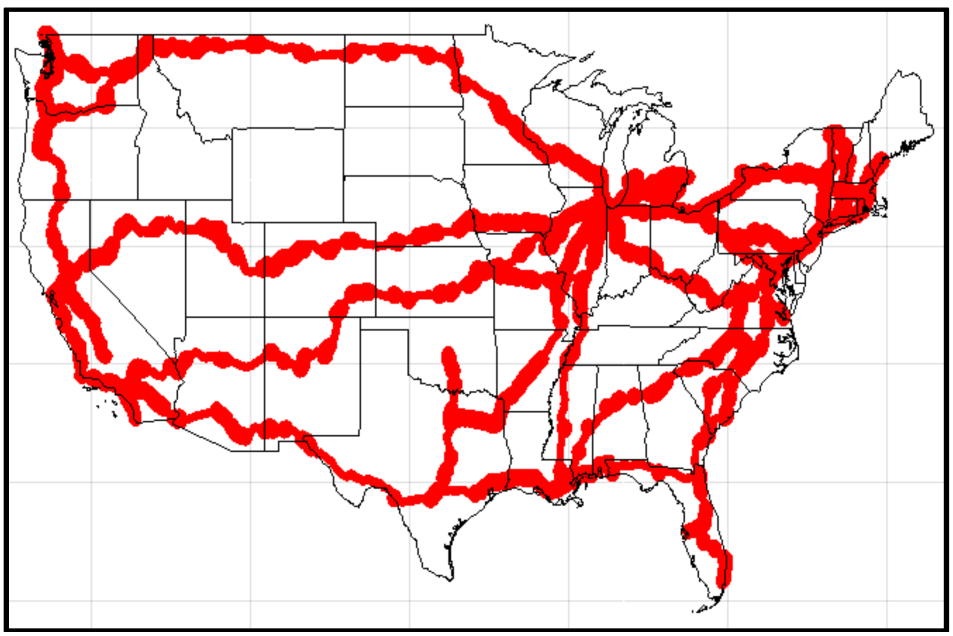

Figure G.5. AMTRAK GPS Receiver Exclusion Zones-EIRP 62 dBm/10 MHz

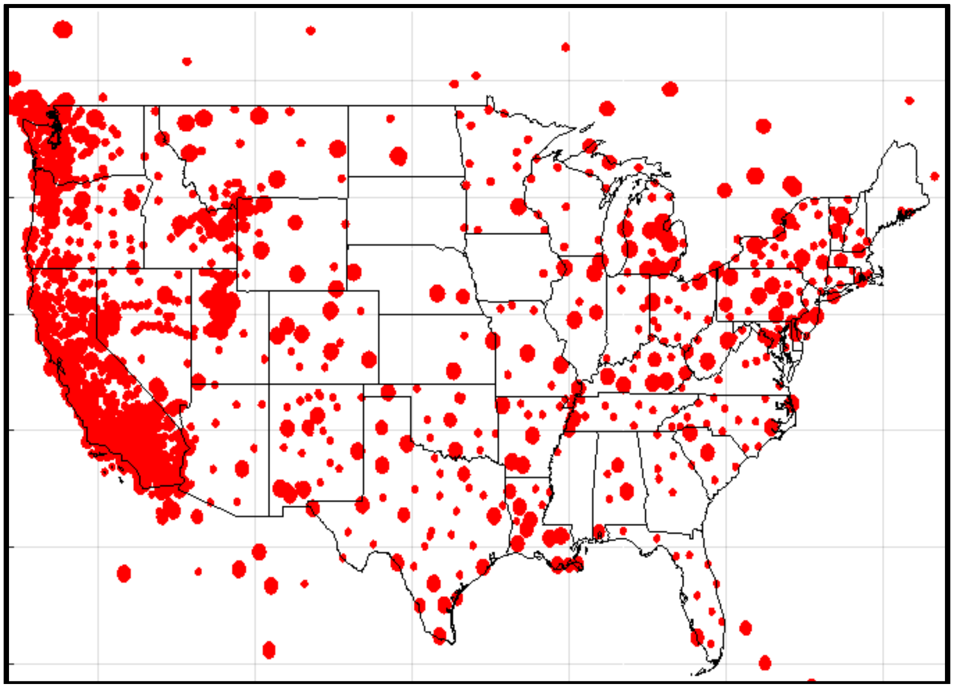

Figure G.6. GAGE GPS Receiver Exclusion Zones-EIRP 62 dBm/10 MHz

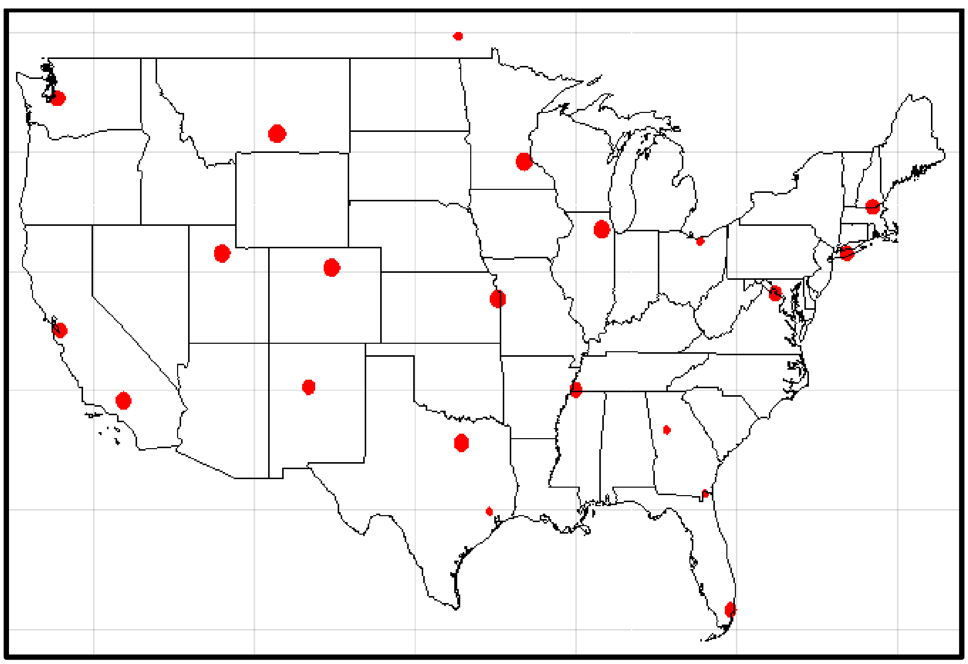

Figure G.7. WAAS GPS Receiver Exclusion Zones-EIRP 62 dBm/10 MHz

Table G.3. Available Percentage of Population

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands EIRP 62 dBm/10 MHz: Macro Urban/Suburban/Rural						
STATE	1 dB Degradation in C/N_0					
	CORS	NDGPS	PTC (Amtrak)	GAGE	WAAS	Combined Applications
TOTAL	26%	92%	34%	62%	91%	15%
Alabama	24%	100%	60%	64%	100%	20%
Arizona	15%	100%	64%	91%	100%	12%
Arkansas	46%	100%	63%	57%	99%	28%
California	12%	91%	11%	7%	91%	5%
Colorado	33%	100%	40%	72%	81%	27%
Connecticut	19%	100%	6%	88%	100%	4%
Delaware	4%	78%	41%	23%	100%	3%
District of Columbia	5%	100%	6%	5%	100%	5%
Florida	52%	92%	34%	91%	84%	24%
Georgia	83%	100%	46%	93%	97%	34%
Idaho	39%	100%	88%	83%	100%	26%
Illinois	15%	100%	17%	62%	81%	8%
Indiana	18%	100%	40%	92%	100%	12%
Iowa	58%	100%	85%	94%	100%	50%
Kansas	47%	100%	43%	53%	74%	28%
Kentucky	45%	100%	87%	53%	100%	43%
Louisiana	14%	82%	48%	55%	100%	13%
Maine	57%	99%	67%	96%	100%	40%
Maryland	16%	92%	14%	33%	93%	9%
Massachusetts	14%	97%	11%	73%	89%	3%
Michigan	7%	74%	23%	52%	100%	7%
Minnesota	36%	98%	36%	68%	72%	21%
Mississippi	82%	99%	47%	94%	95%	41%
Missouri	16%	100%	34%	84%	90%	9%
Montana	43%	100%	84%	53%	85%	35%
Nebraska	27%	100%	33%	76%	100%	22%
Nevada	11%	100%	78%	14%	100%	7%
New Hampshire	22%	100%	34%	47%	64%	14%
New Jersey	9%	67%	22%	70%	100%	8%
New Mexico	36%	100%	48%	37%	64%	25%
New York	16%	64%	15%	73%	92%	7%
North Carolina	14%	99%	35%	85%	100%	9%
North Dakota	56%	100%	52%	83%	100%	32%
Ohio	19%	100%	45%	69%	98%	11%
Oklahoma	39%	100%	68%	69%	100%	35%
Oregon	26%	99%	28%	22%	100%	8%
Pennsylvania	25%	100%	31%	46%	100%	12%
Rhode Island	47%	100%	4%	51%	100%	4%
South Carolina	42%	99%	28%	67%	100%	20%
South Dakota	53%	100%	99%	96%	100%	53%
Tennessee	22%	100%	83%	78%	86%	21%
Texas	16%	99%	34%	78%	80%	10%
Utah	45%	100%	33%	12%	52%	11%
Vermont	12%	100%	21%	44%	100%	6%
Virginia	18%	97%	23%	69%	91%	12%
Washington	31%	58%	14%	28%	76%	10%
West Virginia	45%	100%	53%	77%	99%	25%
Wisconsin	56%	90%	53%	86%	100%	43%
Wyoming	63%	100%	100%	73%	100%	59%

Table G.4. Available Percentage of Population

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands EIRP 40 dBm/10 MHz: Macro Urban/Suburban/Rural						
	1 dB Degradation in C/N_0					
STATE	CORS	NDGPS	PTC (Amtrak)	GAGE	WAAS	Combined Applications
TOTAL	79%	100%	62%	89%	99%	50%
Alabama	83%	100%	80%	92%	100%	69%
Arizona	70%	100%	83%	98%	100%	62%
Arkansas	83%	100%	80%	90%	100%	67%
California	79%	99%	45%	46%	99%	22%
Colorado	86%	100%	75%	95%	98%	65%
Connecticut	80%	100%	44%	99%	100%	40%
Delaware	71%	100%	50%	77%	100%	36%
District of Columbia	20%	100%	6%	21%	100%	6%
Florida	90%	99%	64%	99%	98%	59%
Georgia	96%	100%	78%	99%	100%	74%
Idaho	70%	100%	95%	92%	100%	64%
Illinois	62%	100%	42%	94%	98%	30%
Indiana	83%	100%	67%	100%	100%	59%
Iowa	89%	100%	92%	100%	100%	83%
Kansas	78%	100%	73%	87%	93%	51%
Kentucky	86%	100%	95%	91%	100%	83%
Louisiana	62%	97%	65%	87%	100%	48%
Maine	95%	100%	83%	100%	100%	77%
Maryland	85%	100%	47%	94%	100%	42%
Massachusetts	88%	100%	46%	99%	100%	40%
Michigan	68%	98%	60%	93%	100%	43%
Minnesota	87%	100%	66%	98%	99%	59%
Mississippi	96%	100%	71%	100%	100%	70%
Missouri	77%	100%	66%	99%	100%	50%
Montana	67%	100%	94%	76%	89%	61%
Nebraska	57%	100%	53%	86%	100%	43%
Nevada	51%	100%	87%	81%	100%	44%
New Hampshire	85%	100%	82%	91%	92%	69%
New Jersey	75%	99%	61%	95%	100%	53%
New Mexico	79%	100%	64%	84%	91%	53%
New York	72%	100%	53%	97%	99%	39%
North Carolina	82%	100%	68%	98%	100%	60%
North Dakota	67%	100%	62%	88%	100%	46%
Ohio	79%	100%	69%	96%	100%	56%
Oklahoma	87%	100%	86%	94%	100%	77%
Oregon	78%	100%	52%	85%	100%	38%
Pennsylvania	82%	100%	59%	93%	100%	53%
Rhode Island	91%	100%	32%	95%	100%	27%
South Carolina	89%	100%	66%	94%	100%	62%
South Dakota	85%	100%	100%	100%	100%	85%
Tennessee	87%	100%	93%	96%	97%	81%
Texas	73%	100%	68%	94%	99%	53%
Utah	86%	100%	51%	86%	92%	41%
Vermont	72%	100%	57%	82%	100%	50%
Virginia	74%	100%	58%	94%	99%	48%
Washington	80%	96%	40%	81%	98%	36%
West Virginia	90%	100%	75%	95%	100%	68%
Wisconsin	95%	99%	72%	99%	100%	69%
Wyoming	74%	100%	100%	85%	100%	74%

Table G.5. Available Percentage of Population

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands EIRP 40 dBm/10 MHz: Micro Urban						
STATE	1 dB Degradation in C/N_0					
	CORS	NDGPS	PTC (Amtrak)	GAGE	WAAS	Combined Applications
TOTAL	66%	99%	57%	83%	98%	39%
Alabama	69%	100%	75%	86%	100%	56%
Arizona	57%	100%	82%	96%	100%	51%
Arkansas	75%	100%	77%	86%	100%	58%
California	63%	99%	35%	30%	98%	12%
Colorado	82%	100%	68%	91%	98%	58%
Connecticut	67%	100%	38%	94%	100%	30%
Delaware	56%	95%	48%	66%	100%	30%
District of Columbia	11%	100%	6%	12%	100%	6%
Florida	79%	99%	57%	96%	95%	48%
Georgia	91%	100%	73%	96%	99%	66%
Idaho	66%	100%	93%	90%	100%	59%
Illinois	55%	100%	39%	93%	97%	27%
Indiana	67%	100%	64%	98%	100%	47%
Iowa	80%	100%	91%	98%	100%	73%
Kansas	73%	100%	70%	83%	92%	45%
Kentucky	74%	100%	92%	80%	100%	70%
Louisiana	53%	97%	63%	82%	100%	40%
Maine	79%	100%	81%	99%	100%	63%
Maryland	54%	97%	41%	74%	100%	32%
Massachusetts	76%	99%	40%	97%	100%	30%
Michigan	43%	96%	53%	89%	100%	27%
Minnesota	81%	100%	61%	97%	98%	49%
Mississippi	93%	100%	63%	99%	99%	59%
Missouri	66%	100%	62%	98%	100%	39%
Montana	61%	100%	91%	71%	89%	52%
Nebraska	49%	100%	49%	82%	100%	38%
Nevada	36%	100%	86%	73%	100%	31%
New Hampshire	73%	100%	79%	81%	90%	59%
New Jersey	52%	99%	55%	91%	100%	38%
New Mexico	67%	100%	60%	73%	83%	45%
New York	53%	99%	43%	91%	98%	27%
North Carolina	61%	100%	62%	93%	100%	42%
North Dakota	64%	100%	60%	87%	100%	42%
Ohio	69%	100%	66%	91%	99%	47%
Oklahoma	77%	100%	83%	88%	100%	68%
Oregon	73%	100%	48%	75%	100%	28%
Pennsylvania	70%	100%	54%	90%	100%	43%
Rhode Island	89%	100%	25%	94%	100%	20%
South Carolina	79%	100%	58%	93%	100%	50%
South Dakota	63%	100%	100%	99%	100%	63%
Tennessee	67%	100%	91%	90%	94%	62%
Texas	57%	100%	63%	91%	97%	41%
Utah	83%	100%	46%	73%	90%	37%
Vermont	49%	100%	44%	69%	100%	30%
Virginia	59%	100%	53%	92%	98%	36%
Washington	73%	95%	36%	68%	96%	26%
West Virginia	82%	100%	69%	93%	100%	57%
Wisconsin	89%	96%	70%	95%	100%	64%
Wyoming	70%	100%	100%	82%	100%	69%

G.3 EXCLUSION ZONE SEPARATION DISTANCE FOR HP GPS RECEIVERS

HP GPS receiver exclusion zone separation distances for base station, EIRP values of 62 dBm/10 MHz and 40 dBm/10 MHz are provided in Table G.6.

Table G.6. HP Receiver Exclusion Zone Distances

Interference Power Level (dBm/10 MHz)	Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands		
	EIRP 62 dBm/10 MHz	EIRP 40 dBm/10 MHz	Percentage of Receivers
	Exclusion Zone Separation Distance (km)		
≤-75	33.957	6.237	1.2%
≤-72	29.106	4.158	2.4%
≤-70	26.334	2.772	3.6%
≤-67	22.176	1.386	8.3%
≤-65	19.404	0.693	9.5%
≤-64	18.018	0.693	11.9%
≤-61	14.553	<0.693	13.1%
≤-60	13.167	<0.693	14.3%
≤-59	12.474	<0.693	17.9%
≤-57	10.395	<0.693	19.0%
≤-56	9.009	<0.693	20.2%
≤-55	8.316	<0.693	21.4%
≤-54	7.623	<0.693	22.6%
≤-53	6.237	<0.693	23.8%
≤-52	5.544	<0.693	27.4%
≤-51	4.851	<0.693	28.6%
≤-50	4.158	<0.693	31.0%
≤-48	2.772	<0.693	32.1%
≤-47	2.079	<0.693	33.3%
≤-46	2.079	<0.693	34.5%
≤-45	1.386	<0.693	35.7%
≤-44	1.386	<0.693	40.5%
≤-43	0.693	<0.693	41.7%
≤-42	0.693	<0.693	44.0%
≤-41	0.693	<0.693	50.0%
≤-40	<0.693	<0.693	51.2%
≤-39	<0.693	<0.693	53.6%
≤-38	<0.693	<0.693	56.0%
≤-37	<0.693	<0.693	57.1%
≤-36	<0.693	<0.693	59.5%
≤-34	<0.693	<0.693	61.9%
≤-33	<0.693	<0.693	63.1%
≤-32	<0.693	0	64.3%
≤-31	<0.693	0	65.5%
≤-30	<0.693	0	66.7%
≤-29	<0.693	0	69.0%
≤-27	<0.693	0	70.2%
≤-26	<0.693	0	71.4%
≤-25	<0.693	0	72.6%
≤-24	<0.693	0	78.6%
≤-23	<0.693	0	79.8%
≤-21	0	0	82.1%

APPENDIX H
USER EQUIPMENT ANALYSIS

H.1 INTRODUCTION

This appendix summarizes the Technical Focus Group (TFG)'s analysis of the single transmitter case and the aggregate power from user equipment operating in the Uplink 1 band (1627.5-1637.5 MHz) and Uplink 2 band (1646.5-1656.5 MHz) and statistically quantifies the percentage of Global Positioning System (GPS) receivers that will experience a 1 dB, 3 dB, and 5 dB carrier to noise (C/N_0) degradation and loss of lock (LOL) with a corresponding minimum separation distance. The simulation scenarios were based upon the deployment parameters in the Ligado aggregate report.[1] ITU-R M.2292-0[2] and ITU-R M.2101-0[3] guided additional terrestrial mobile telecommunication simulation parameters. Table H.1 summarizes the simulation parameters.

[1] *See* Reply Comments of Ligado Networks LLC, *Comment Sought on Ligado's Modification Applications*, IB Docket No. 11-109, at Attachment A at 17 (June 6, 2016), *available at* https://ecfsapi.fcc.gov/file/60002097963.pdf (*Ligado Reply Comments*).

[2] Report ITU-R M.2292-0, *Characteristics of terrestrial IMT-Advanced systems for frequency sharing/interference analyses* (Dec. 2013), *available at* https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2292-2014-PDF-E.pdf.

[3] Recommendation ITU-R M.2101-0, *Modelling and simulation of IMT networks and systems for use in sharing and compatibility studies* (Feb. 2017), *available at* https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2101-0-201702-I!!PDF-E.pdf.

Table H.1. Summary of Simulation Parameters

Simulation Parameters	Within a Cell	Outside of a Cell
Inter-Site Distance	433 meters	
Maximum User Equipment equivalent isotropically radiated power (EIRP)	23 dBm/10 MHz	
Minimum User Equipment EIRP	-40 dBm/10 MHz	
User Equipment Antenna Gain	0 dBi[4]	
Propagation Model	Single Case: Free Space Path Loss Aggregate: Free Space Path Loss/Irregular Terrain Model (ITM) Area Mode	
Number of User Equipment	30 per cell: [180/km^2] [5, 6]	
Minimum Distance between User Equipment and serving cell	10 meters (Urban Micro)[7]	
Minimum Distance between User Equipment and GPS receiver	2 meters	
User Equipment Height	1.5 meters	
GPS Height	1.5 meters	
GPS Antenna Pattern	MITRE Empirical Scans: High Precision, General Location/ Navigation, and Timing	
Number of Simulations (Aggregate) for each Uplink Band	250 Simulations per uplink frequency (10,000 GPS placements per iteration)	500 Simulations per uplink frequency (1-meter resolution)

H.2 SIMULATION OVERVIEW

H.2.1 Simulation Geometry

Three user equipment/GPS receiver geometries were simulated:

1) Single User Equipment: the minimum separation distance was calculated between a single user equipment transmitter and a GPS receiver.
2) Aggregate User Equipment: for a GPS receiver operating within a cell, shown in Figure H.1, GPS receiver locations were randomly distributed within the yellow highlighted, center cell. The black dots represent an example of the user equipment distribution.

[4] Recommendation ITU-R M.2292-0 recommends an antenna gain of -3 dBi.

[5] *Ligado Reply Comments* user equipment surface densities of 30, 75, and 180 per square kilometer were used, citing an RTCA Markup, Section 3.5.1.

[6] 3rd Generation Partnership Project (3GPP) ETSI Technical Report TR 136-942, *LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Frequency (RF) system scenarios* (3GPP TR 36.942 version 10.2.0 Release 10) recommends 8 resource blocks per user equipment, which is 6 user equipment for a 10 MHz channel, *available at*

http://www.etsi.org/deliver/etsi_tr/136900_136999/136942/10.02.00_60/tr_136942v100200p.pdf.

[7] Report ITU-R M.2135-1, *Guidelines for evaluation of radio interface technologies for IMT-Advanced* (Dec. 2009), *available at*

https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2135-1-2009-PDF-E.pdf.

3) Aggregate User Equipment: for a GPS receiver operating outside of a cell (offset), shown in Figure H.2, the minimum separation distance was calculated between the cell edge and GPS receivers (located along the red line). For the simulation, more than 20,000 user equipments were randomly generated across the simulation geometry.

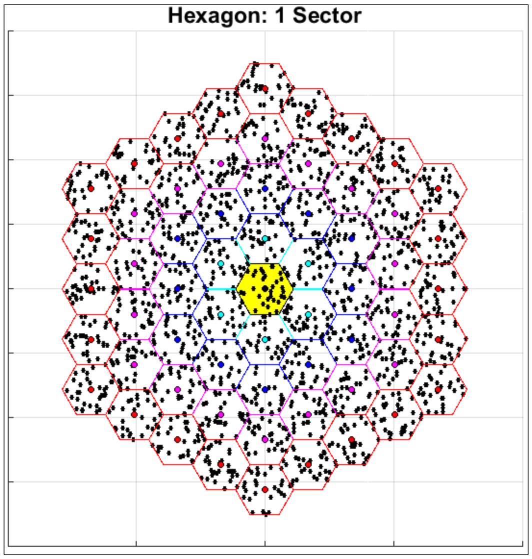

Figure H.1. GPS Receiver Operating Within a Cell

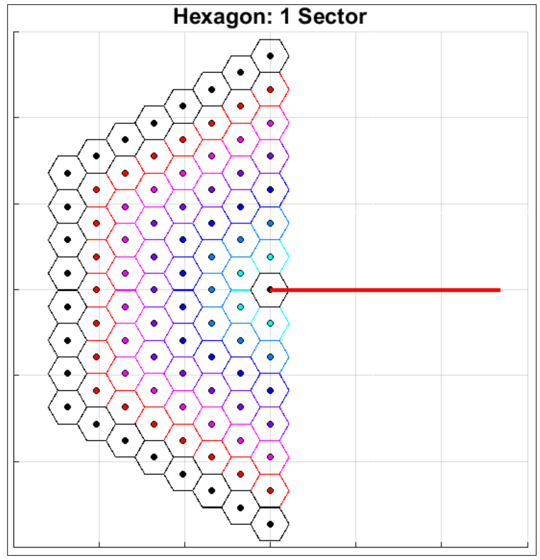

Figure H.2. GPS Receiver Operating Outside of a Cell (Offset)

H.2.2 Description of Cell Structure

Figure H.3 shows an example of the hexagonal cell structure for a base station with one sector, with six additional surrounding base stations. Each cell is numbered and represented by a separate color. After the base stations are deployed in a hexagonal grid, user equipment is randomly distributed in each cell with a surface density of 180 per square kilometer, which equates to 30 user equipments per urban microcell. For GPS receivers operating within a cell, 10,000 GPS receiver locations were randomly distributed within the center cell (yellow), where a separation of at least 2 meters was kept between the user equipment and the GPS receiver locations. A frequency reuse factor of one was used for the user equipment. For example, Figure H.4 shows the aggregate power at the GPS receiver. The heat map shows an example of one user equipment distribution and the aggregate power received at the GPS receiver locations.

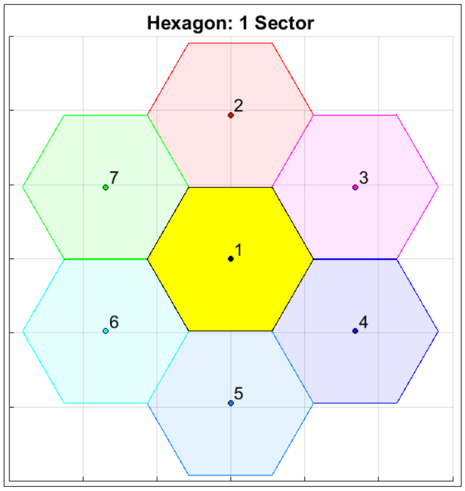

Figure H.3. One Sector Hexagonal Cell Structure

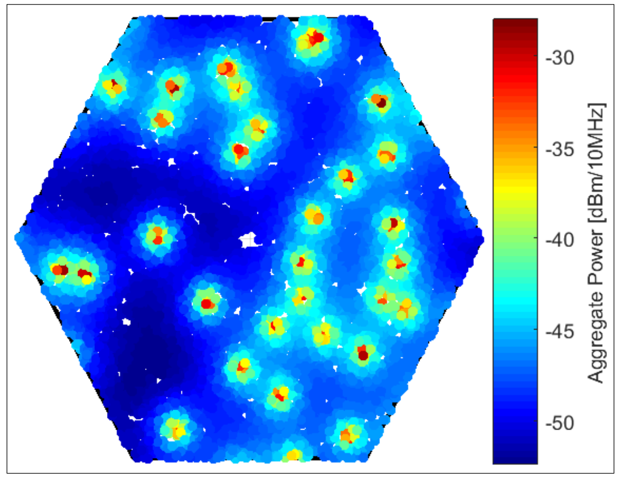

Figure H.4. One Set of User Equipment Randomized Placements with Corresponding Aggregate Power at the GPS Receiver

Figure H.5 shows the distribution of separation distance between the randomized GPS receiver locations in the center cell and surrounding user equipment. For this simulation geometry and number of user equipment, the separation distance fits a Weibull distribution and a GPS receiver within a cell will not be more than 150 meters away from user equipment.

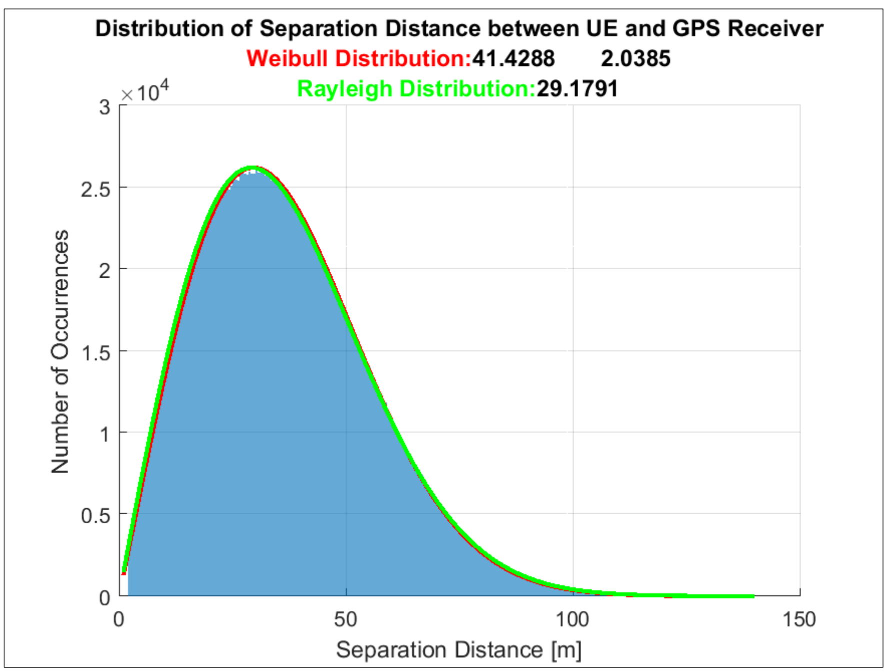

Figure H.5. Histogram of the Separation Distances Between the Randomized GPS Receiver Locations and the Nearest Randomized User Equipment, Fit to a Weibull Distribution[8]

[8] The Rayleigh distribution is a special case of the Weibull distribution. If A and B are the parameters of the Weibull distribution, then the Rayleigh distribution with parameter b is equivalent to the Weibull distribution with parameters $\boldsymbol{A} = \sqrt{2}\boldsymbol{b}$ and $\boldsymbol{B} = 2$.

H.2.3 Analysis Approach

The following equation was used to calculate the received power at the input of a GPS receiver:

$$P_R = EIRP - L_P - L_{GPS}$$

where:

P_R: received power (dBm/10 MHz);
$EIRP$: equivalent isotropically radiated power of the user equipment (dBm/10 MHz);
L_P: propagation loss from the user equipment antenna to the GPS antenna (dB); and
L_{GPS}: the off-boresight loss of the GPS antenna (dB).[9]

H.2.4 Single Transmitter Case Propagation Loss

Free-space loss was used to calculate the propagation loss from the user equipment to the GPS receiver for the single transmitter case.

H.2.5 Aggregate Propagation Loss

For separation distances greater than 200 meters, the Irregular Terrain Model (ITM) Area Prediction Mode is used to compute propagation loss.[10] Table H.2 provides the parameters used in the ITM Area Prediction Mode propagation loss calculations.

Table H.2. ITM Area Prediction Mode Parameters

Parameter	Value
Surface Refractivity	301 N-units
Conductivity of Ground	0.005 S/m
Dielectric Constant of Ground	15
Terrain Roughness Factor (Delta h)	30 meters
Polarization	Horizontal/Vertical
Mode of Variability	Mobile Mode
Percent Confidence (Time/Situation/Location Variability)	50%
Frequency	1630 MHz and 1645 MHz[11]
Site Criteria Transmitter	Random
Site Criteria Receiver	Random
Radio Climate	Continental Temperate

For separation distances, less than or equal to 200 meters, and based on the percent confidence of ITM, a blended model was used.

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[9] GPS off-boresight antenna loss is used because the test data was taken at the GPS antenna boresight.

[10] National Telecommunications and Information Administration, NTIA Report 82-100, *A Guide to the Use of the ITS Irregular Terrain Model in the Area Prediction Mode* (Apr. 1982), *available at* https://www.ntia.doc.gov/files/ntia/publications/ntia_82-100_20121129145031_555510.pdf.

[11] 1630 MHz and 1645 MHz was chosen because the empirical GPS antenna data was closest to the Uplink 1 and Uplink 2 bands.

If $ITM_{100m} > FSPL_{100}$, (50% Confidence):

$$ITM_{Blend} = \begin{cases} FSPL & d \leq 100m \\ FSPL + \frac{\Delta L_P}{100}(d-100) & 100m < d \leq 200m \\ ITM_{AreaMode} & d > 200m \end{cases}$$

where:

$$\Delta L_P = ITM_{200m} - FSPL_{200m}$$

Figure H.6 shows the comparison of ITM Blend (50%) versus free space propagation loss (FSPL).

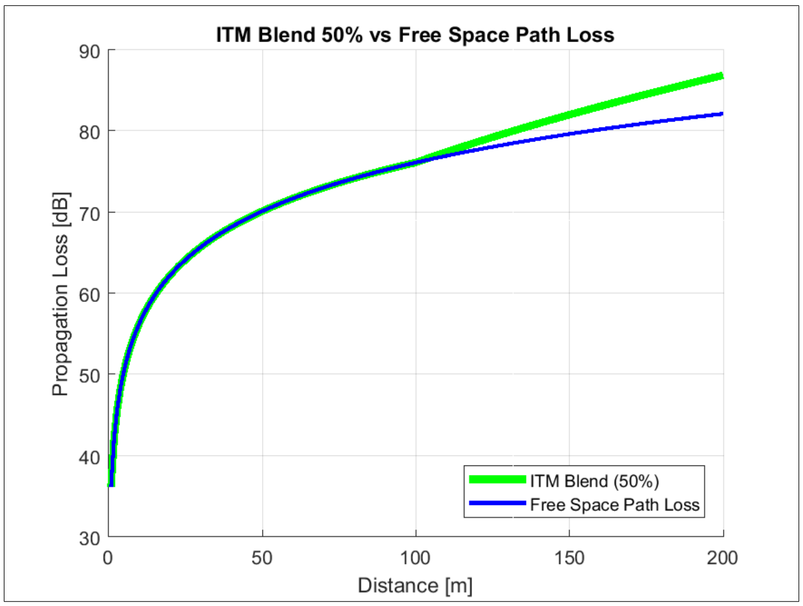

Figure H.6. ITM Blend 50% versus Free Space Path Loss

H.2.6 Normalized GPS Antenna Loss

The normalized, off-boresight loss of the GPS antenna was calculated for each GPS receiver category. MITRE provided empirical GPS antenna data of the vertical and horizontal polarization gain at specific frequencies.[12] The normalized gain was calculated for each category of GPS antenna. Each normalized antenna gain was then converted from Decibel relative to an isotropic antenna (dBi) to linear units, and averaged, from -180° to 0° and 0° to 180°, to make the GPS antenna gains symmetrical from -180° to 180°. The GPS antenna gains were then converted back to dBi. Figures H.7 through H.9 show the horizontal and vertical polarization antenna gain at 1630 MHz and 1645 MHz for each antenna type.

[12] Antennas include: AeroAntenna AT575, AeroAntenna AT2775, Arbiter AS0087800, Garmin GA-25, Garmin GA-38, Hemisphere 804-3059-0, Leica AX1202GG, Navcom 82-001020-3001LF, PCTel 3977D, Trimble Bullet 360, Trimble Choke Ring, Trimble Zephyr, Trimble Zephyr Geodetic 2, and ublox ANN-MS-0-005.

The angle of incident of the Long Term Evolution (LTE signal was calculated between each user equipment and randomized GPS locations. The normalized, off-boresight loss of the GPS antenna was then found for each antenna type.

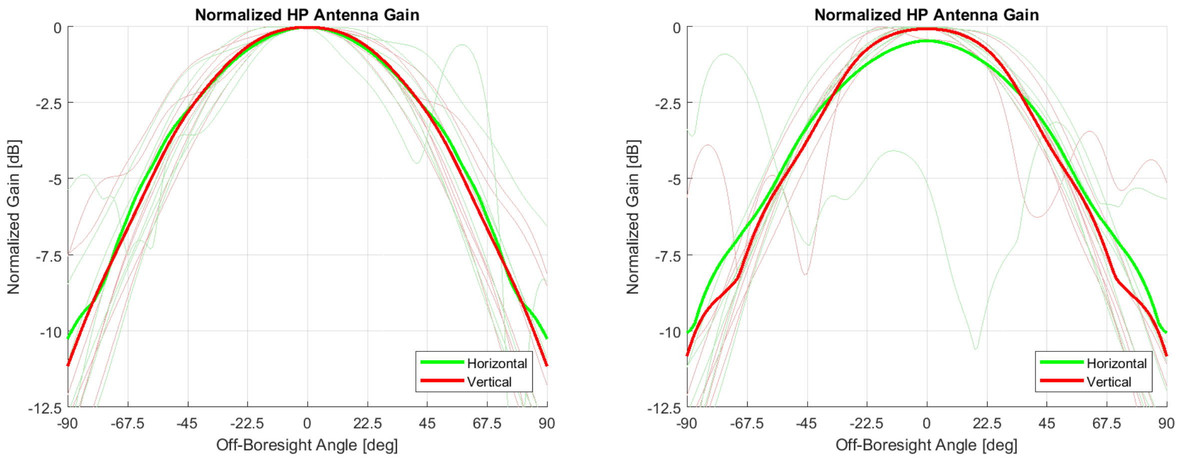

Figure H.7. Normalized HP Antenna Gain: 1630 MHz/1645MHz

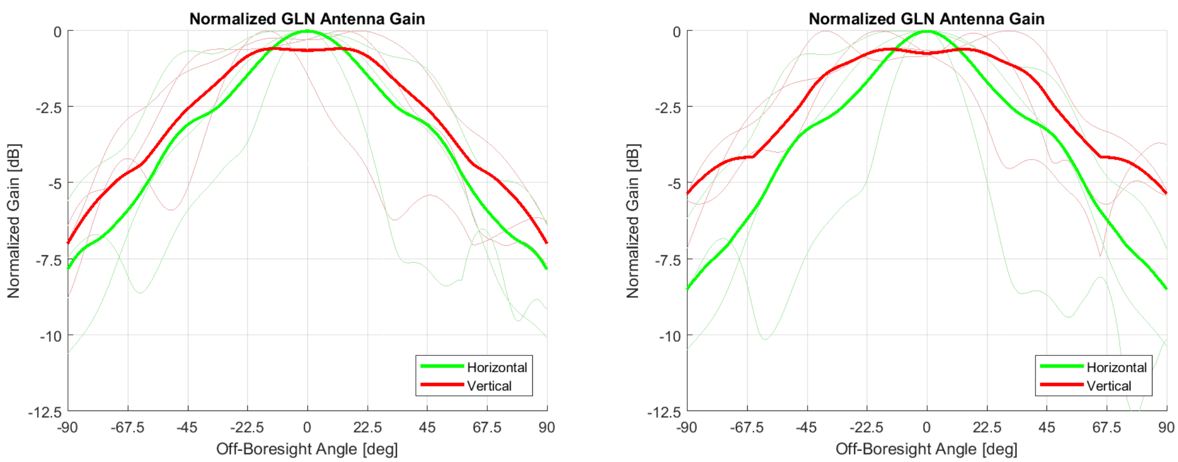

Figure H.8. Normalized GLN Antenna Gain: 1630 MHz/1645MHz

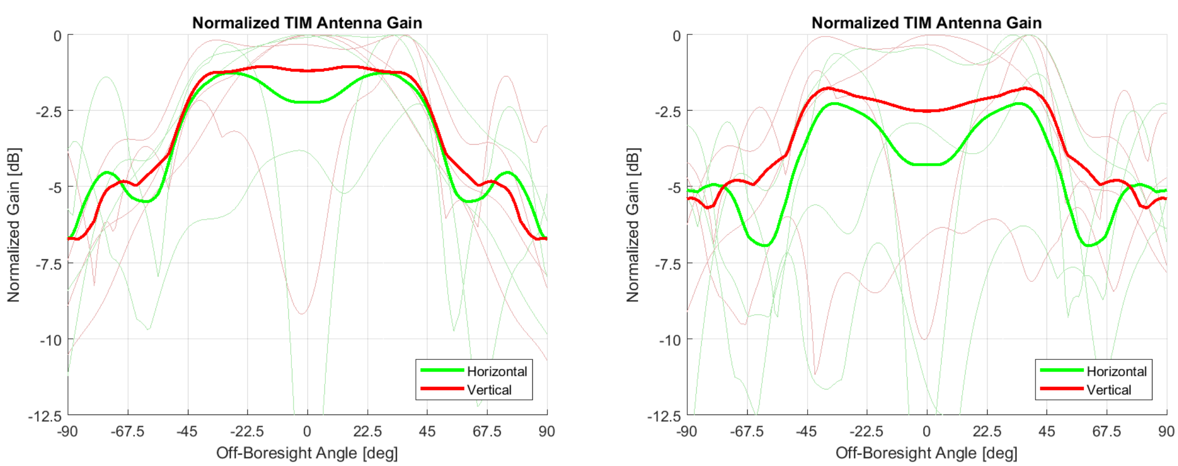

Figure H.9. Normalized TIM Antenna Gain: 1630 MHz/1645MHz

H.2.7 Base Station Antenna Loss

The normalized off-axis loss of the base station antenna was calculated for the randomized user equipment locations. The base station antenna pattern was provided by ITU-R F.1336. The off-axis base station antenna loss was used for the user equipment power control algorithm.

H.2.8 Power Control Algorithm for User Equipment (Open Loop)

The user equipment power control algorithm was implemented from Recommendation ITU-R M.2101-0.[13]

$$P_{PUSCH} = min\left(P_{CMAX}, P_{calc\ open\ loop}\right)$$

$$P_{calc\ open\ loop} = max\left(P_{CMIN}, 10log_{10}(M_{PUSCH}) + P_{0\_PUSCH} + \alpha \cdot PL\right)$$

where:

P_{PUSCH}: transmit power of the user equipment (dBm);
P_{CMAX}: maximum user equipment transmit power (23 dBm/10 MHz);
P_{CMIN}: minimum user equipment transmit power (-40 dBm/10 MHz);
M_{PUSCH}: number of allocation resource blocks for the user equipment;
P_{0_PUSCH}: power per resource block target value (dBm);
$Alpha\ (\alpha)$: balancing factor for user equipment with bad channels and with good channels; and
PL: propagation loss for the user equipment from its serving base station (dB).

H.2.9 Example Power Control Calculation

Resource blocks were distributed among the user equipment in each cell, with an assumption of 50 resource blocks for 10 MHz, where user equipment were given 1 or 2 resource blocks.[14] The resource block distribution was identical for each cell, which means the same set of allocated resources blocks for each cell is identical. This means that in every cell, a single user equipment is using the same set of resource blocks. M_{PUSCH} is then calculated.

$$M_{PUSCH} = \frac{50\ Resource\ Blocks}{30\ Handsets}$$

For parameters α and P_{0_PUSCH}, recommendations were taken from Commerce Spectrum Management Advisory Committee (CSMAC) Working Group 5 and 3GPP, where:

[13] Recommendation ITU-R M.2101-0, Section 4.

[14] 3GPP ETSI TR 136-942 recommends 8 resource blocks per user equipment, which is 6 user equipment for a 10 MHz channel.

$$\alpha = 0.8 \text{ and } P_{0\_PUSCH} = -90 \text{ dBm}^{15}$$

For the open loop power control algorithm, the transmission power of the user equipment is proportional to the path loss (propagation loss and base station antenna loss) from the user equipment to the serving base station. Specifically, the propagation loss from the base station to the user equipment is a large part of the path loss. Propagation loss is proportional to the distance between the base station and the user equipment. To show this relationship, Figure H.10 shows the relationship between the user equipment transmission power and the distance from the base station. When alpha equals 0, the user equipment does not have power control and is operating at the maximum EIRP of 23 dB relative to a milliwatt (dBm)/10 MHz (blue horizontal line across the top). When alpha equals 0.8, this denotes that the user equipment uses the open loop power control algorithm.

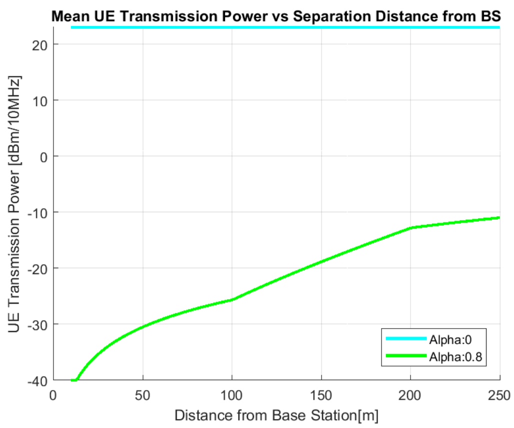

Figure H.10. Transmission Power of User Equipment Versus Distance from Base Station

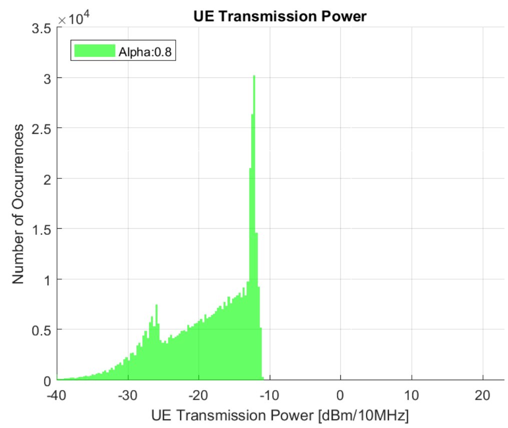

Figure H.11. Histogram of User Equipment Transmission Power with Power Control

Figure H.11 shows the distribution of transmission power for the user equipment. Since there is a higher probability that user equipment will be placed further away from the base station, there is a larger number of user equipment transmitting at a higher power. The small peak of the histogram around -25 dBm/10 MHz is due to propagation loss, specifically, free space loss is used to calculate the propagation loss for separation distances less than 100 meters.

H.2.10 Aggregate Power

The power received, P_R (Watts), from all base stations were summed at each GPS receiver location to calculate the aggregate power. The summed powers were then converted to dBm/10 MHz.

H.3 SINGLE USER EQUIPMENT RESULTS

Tables H.3 through H.8 provide the separation distance, power received at the GPS receiver, the number and percentage of GPS receivers that will experience 1 dB, 3 dB, and 5 dB

[15] CSMAC WG5, *1755-1850 MHz Airborne Operations: Sub-Working Group Report* (Mar. 4, 2014), *available at* https://www.ntia.doc.gov/files/ntia/publications/suas_swg_final_report_posted_03042014.pdf. 3GPP ETSI-TR-136-942 recommends $\alpha = 0.8$, and $P_{0\_PUSCH} = -90$ dBm.

C/N_0 degradation and LOL**.** It should be noted that the interference power in Tables H.3 through H.8 are different for similar distances. For example, a 1 meter separation distance equates to power levels that can cause LOL in the range of -24.4 dBm/10 MHz to approximately -19 dBm/10 MHz due to the GPS antenna loss for the different antenna types and different frequencies. For example, the General Location/Navigation Receiver Category (GLN) and Timing Receiver Category (TIM) antenna loss is greater at 1630 MHz than 1645 MHz (see Figure H.8 and Figure H.9).

Table H.3. Single User Equipment: Separation Distance and Received Power at the HP Receiver EIRP 23 dBm/10 MHz

Uplink 1 Band: Interfering Signal in the 1625-1635 MHz/1627.5-1637.5 MHz										
Separation Distance (meters)	Interference Power Level (dBm/10 MHz)	Degradation in C/N_0								
		Number of Receivers				Percentage of Receivers				
		1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
1	-24.4	39	38	35	27	73.6%	71.7%	66.0%	50.9%
2	-30.4	38	32	25	22	71.7%	60.4%	47.2%	41.5%
3	-33.9	35	24	24	18	66.0%	45.3%	45.3%	34.0%
4	-36.4	28	22	20	13	52.8%	41.5%	37.7%	24.5%
5	-38.3	25	19	16	10	47.2%	35.8%	30.2%	18.9%
6	-39.9	23	17	14	8	43.4%	32.1%	26.4%	15.1%
7	-41.3	19	15	11	7	35.8%	28.3%	20.8%	13.2%
11	-45.2	17	13	9	3	32.1%	24.5%	17.0%	5.7%
13	-46.6	16	9	7	1	30.2%	17.0%	13.2%	1.9%
16	-48.4	15	9	5		28.3%	17.0%	9.4%	
18	-49.5	14	9	5		26.4%	17.0%	9.4%	
22	-51.2	12	7	3		22.6%	13.2%	5.7%	
25	-52.3	11	7	2		20.8%	13.2%	3.8%	
31	-54.2	10	4	1		18.9%	7.5%	1.9%	
35	-55.2	7	3	1		13.2%	5.7%	1.9%	
49	-58.2	5	1			9.4%	1.9%		
54	-59.0	3	1			5.7%	1.9%		
68	-61.0	2				3.8%			
96	-64.0	1				1.9%			

Table H.4. Single User Equipment: Separation Distance and Received Power at the GLN Receiver EIRP 23 dBm/10 MHz

Uplink 1 Band: Interfering Signal in the 1625-1635 MHz/1627.5-1637.5 MHz									
Separation Distance (meters)	Interference Power Level (dBm/10 MHz)	Degradation in C/N_0							
		Number of Receivers				Percentage of Receivers			
		1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
1	-21.1	22	10	9	5	64.7%	29.4%	26.5%	14.7%
2	-27.1	9	8	6	2	26.5%	23.5%	17.6%	5.9%
4	-33.1	6	4	4	2	17.6%	11.8%	11.8%	5.9%
5	-35.0	4	4	3	1	11.8%	11.8%	8.8%	2.9%
13	-43.3	3	3	1		8.8%	8.8%	2.9%	
32	-51.2	2				5.9%			
45	-54.1	1				2.9%			

Table H.5. Single User Equipment: Separation Distance and Received Power at the TIM Receiver EIRP 23 dBm/10 MHz

Uplink 1 Band : Interfering Signal in the 1625-1635 MHz/1627.5-1637.5 MHz									
Separation Distance (meters)	Interference Power Level (dBm/10 MHz)	Degradation in C/N_0							
		Number of Receivers				Percentage of Receivers			
		1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
1	-20.4	5	2	1	0	45.5%	18.2%	9.1%	0.0%
2	-26.4	2				18.2%			
5	-34.4	1				9.1%			

Table H.6. Single User Equipment: Separation Distance and Received Power at the HP Receiver EIRP 23 dBm/10 MHz

Uplink 2 Band: Interfering Signal in the 1640-1650 MHz/1646.5-1656.5 MHz Band									
Separation Distance (meters)	Interference Power Level (dBm/10 MHz)	Degradation in C/N_0							
		Number of Receivers				Percentage of Receivers			
		1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
1	-24.2	29	23	19	14	53.7%	42.6%	35.2%	29.2%
2	-30.2	21	18	17	11	38.9%	33.3%	31.5%	22.9%
3	-33.7	19	17	15	6	35.2%	31.5%	27.8%	12.5%
4	-36.2	16	12	8	1	29.6%	22.2%	14.8%	2.1%
5	-38.2	14	7	4	1	25.9%	13.0%	7.4%	2.1%
6	-39.7	12	4	3		22.2%	7.4%	5.6%	
7	-41.1	9	3	1		16.7%	5.6%	1.9%	
8	-42.2	7	3	1		13.0%	5.6%	1.9%	
11	-45.0	5	2	1		9.3%	3.7%	1.9%	
13	-46.5	3	2	1		5.6%	3.7%	1.9%	
22	-51.0	2	2	1		3.7%	3.7%	1.9%	
62	-60.0	1				1.9%			

Table H.7. Single-Case: Separation Distance and Received Power at the GLN Receiver EIRP 23 dBm/10 MHz

Uplink 2 Band: Interfering Signal in the 1640-1650 MHz/1646.5-1656.5 MHz Band									
Separation Distance (meters)	Interference Power Level (dBm/10 MHz)	Degradation in C/N_0							
		Number of Receivers				Percentage of Receivers			
		1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
1	-20.4	8	4	3	0	23.5%	11.8%	8.8%	0.0%
2	-26.4	5	2	2		14.7%	5.9%	5.9%	
3	-29.9	4	1	1		11.8%	2.9%	2.9%	
7	-37.3	1	1	1		2.9%	2.9%	2.9%	

Table H.8. Single-Case: Separation Distance and Received Power at the TIM Receiver EIRP 23 dBm/10 MHz

Uplink 2 Band: Interfering Signal in the 1640-1650 MHz/1646.5-1656.5 MHz Band									
Separation Distance (meters)	Interference Power Level (dBm/10 MHz)	Degradation in C/N_0							
		Number of Receivers				Percentage of Receivers			
		1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
1	-19.0	4	0	0	0	36.4%	0.0%	0.0%	0.0%
2	-25.0	3				27.3%			
8	-37.1	1				9.1%			

H.4 AGGREGATE USER EQUIPMENT RESULTS

H.4.1 Simulation Geometry 2: GPS Receiver Operating Within a Cell

Figure H.12 shows that the GPS receiver locations were randomized within the yellow highlighted, center cell. The black dots represent an example user equipment distribution.[16]

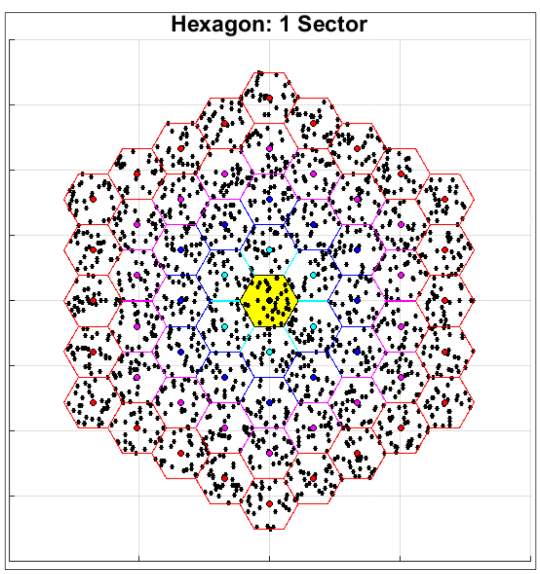

Figure H.12. GPS Receiver Operating Within a Cell

[16] It should be noted that more cells and user equipment were simulated than Figure H.12 depicts.

Figure H.13 shows the cumulative distribution function (CDF) of the aggregate power at the GPS receiver for user equipment operating in Uplink 1 band. When alpha equals 0, the user equipment does not have power control and is operating at the maximum EIRP of 23 dBm/10 MHz. When alpha equals 0.8, this denotes that the user equipment uses an open loop power control. The CDF for user equipment operating in the Uplink 2 band is similar.

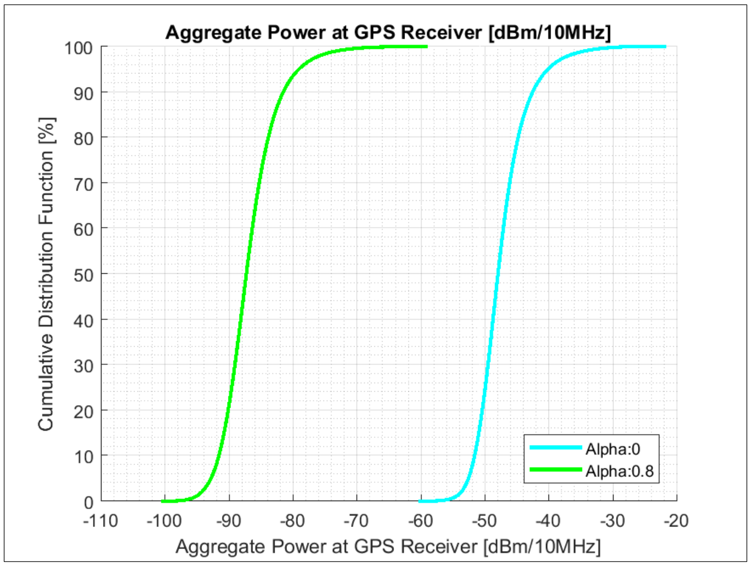

Figure H.13. Cumulative Distribution Function of the Aggregate Power at a GPS Receiver for User Equipment Operating in Uplink 1 Band

Figure H.14 shows the aggregate power at the GPS receiver operating within a cell versus the separation distance from the user equipment (Uplink 1 band). The red line denotes the 99th percentile of the aggregate power at each separation distance. Table H.9 and Table H.10 provide the numerical values from Figure H.14.

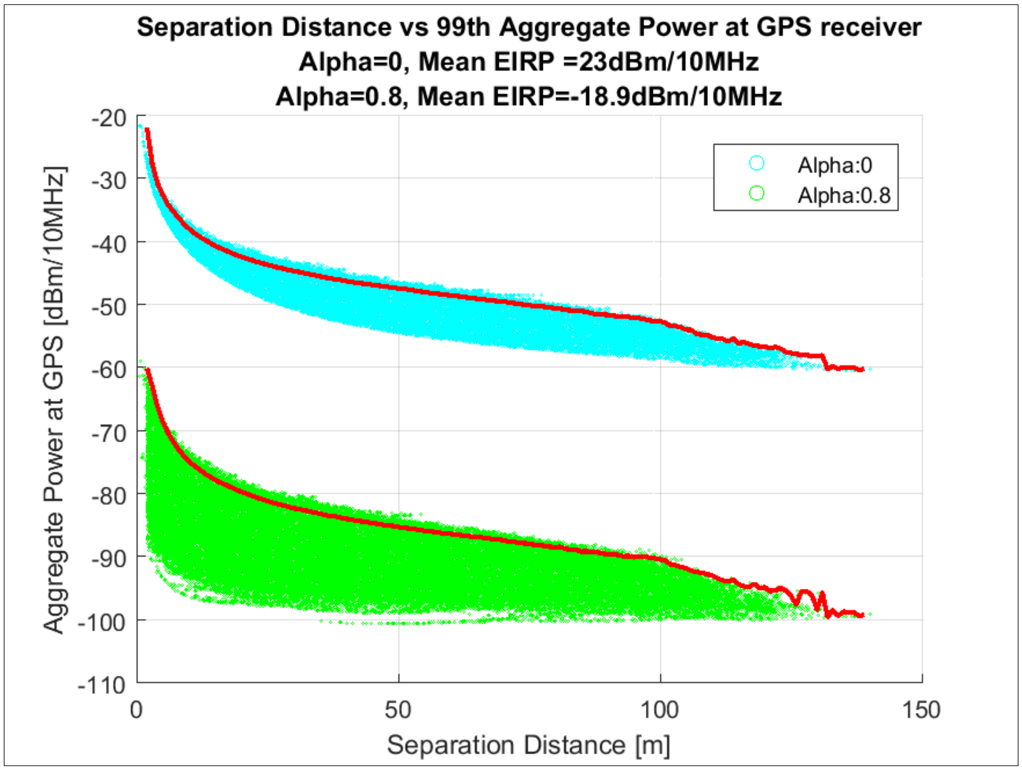

Figure H.14. Scatter Plot of the Aggregate Power (99th Percentile in Red) at a GPS Receiver versus the Separation Distance from the User Equipment Operating in Uplink 1 Band

In Table H.9 and Table H.10, the separation distance[17] between user equipment and a GPS receiver has the corresponding 99th percentile of aggregate power for that separation distance. The percentage of GPS receivers that will experience 1 dB C/N_0 degradation is provided for the corresponding separation distance and aggregate power. In Table H.9, the user equipment has an EIRP of 23 dBm/10 MHz (no power control). In Table H.10, the user equipment has the power control algorithm applied. It should be noted that the interference power in Table H.9 and Table H.10 are different for similar distances. This is due to the GPS antenna loss for the different antenna types and different frequencies. For example, the GLN and TIM antenna loss is greater at 1630 MHz than at 1645 MHz (see Figure H.8 and Figure H.9).

[17] Figure H.5 shows the distribution of separation distance between the user equipment and the randomized GPS receiver locations. The separation distance fits a Weibull distribution. For this simulation geometry, a GPS receiver is not more than 150 meters away from user equipment.

Table H.9. Separation Distance versus Aggregate Power at the GPS Receiver Within a Cell [EIRP 23 dBm/10 MHz, No Power Control]

99th Percentile Aggregate Power at the GPS Receiver within a Cell								
Closest Minimum Separation Distance from UE (meters)	Percentage of GPS Receivers with 1 dB C/N_0 Degradation							
	Uplink Band 1				Uplink Band 2			
	Aggregate Power (dBm/10 MHz)	HP	GLN	TIM	Aggregate Power (dBm/10 MHz)	HP	GLN	TIM
2	-21.8	75.5%	44.1%	36.4%	-20.8	57.4%	20.6%	27.3%
3	-27.6	73.6%	26.5%	9.1%	-24.1	53.7%	14.7%	9.1%
4	-30.7	69.8%	23.5%	9.1%	-27.5	44.4%	11.8%	9.1%
5	-32.5	66.0%	17.6%	9.1%	-29.7	38.9%	2.9%	9.1%
6	-34.0	58.5%	11.8%		-31.0	37.0%	2.9%	9.1%
7	-35.1	52.8%	11.8%		-32.5	35.2%	2.9%	9.1%
8	-36.2	49.1%	11.8%		-33.7	35.2%	2.9%	9.1%
9	-37.1	47.2%	11.8%		-34.1	33.3%	2.9%	9.1%
10	-37.9	47.2%	11.8%		-35.6	29.6%	2.9%	9.1%
11	-38.5	43.4%	11.8%		-35.8	29.6%	2.9%	9.1%
13	-39.6	39.6%	11.8%		-36.9	29.6%	2.9%	
15	-40.6	35.8%	11.8%		-37.8	25.9%	2.9%	
18	-41.7	35.8%	11.8%		-38.9	22.2%	2.9%	
21	-42.7	35.8%	8.8%		-40.0	20.4%	2.9%	
25	-43.6	35.8%	8.8%		-40.9	16.7%	2.9%	
26	-43.8	35.8%	8.8%		-41.1	13.0%	2.9%	
30	-44.6	32.1%	8.8%		-42.0	13.0%	2.9%	
32	-44.9	32.1%	8.8%		-42.6	9.3%	2.9%	
36	-45.6	30.2%	8.8%		-42.9	9.3%	2.9%	
46	-46.9	30.2%	8.8%		-44.6	9.3%		
49	-47.2	28.3%	8.8%		-44.9	9.3%		
55	-47.9	28.3%	8.8%		-45.7	5.6%		
56	-48.1	26.4%	8.8%		-46.0	5.6%		
65	-49.0	26.4%	8.8%		-46.7	3.7%		
74	-49.9	26.4%	5.9%		-48.2	3.7%		
85	-51.0	22.6%	5.9%		-48.6	3.7%		
101	-52.9	20.8%	2.9%		-51.7	3.7%		
106	-54.0	18.9%	2.9%		-53.0	3.7%		
123	-56.9	13.2%			-56.3	3.7%		
126	-57.8	9.4%			-56.3	3.7%		
128	-58.0	9.4%			-57.8	1.9%		
130	-58.1	5.7%			-57.8	1.9%		
139	-60.1	3.8%			-59.9	1.9%		

Table H.10. Separation Distance versus Aggregate Power at the GPS Receiver within a cell [Power Control Employed]

Separation Distance (meters)	99th Percentile Aggregate Power at the GPS Receiver within a cell — Percentage of GPS Receivers with 1 dB C/N_0 Degradation — Uplink 1 Band: Aggregate Power (dBm/10 MHz)	HP	GLN	TIM	Uplink 2 Band: Aggregate Power (dBm/10 MHz)	HP	GLN	TIM
2	-60.0	5.7%	0%	0%	-58.8	1.9%	0%	0%
3	-62.8	1.9%	0%	0%	-62.0	0%	0%	0%

Table H.11 provides a summary of the percentage of GPS receivers, from all the measurement campaigns, that will experience 1 dB, 3 dB, and 5 dB C/N_0 degradation and LOL within a cell with the corresponding the 99th percentile of the aggregate power for the Uplink 1 and Uplink 2 bands when the user equipment has an EIRP of 23 dBm/10 MHz (no power control) and power control.[18]

For Timing GPS receivers, the 9% in Uplink 2 band (23 dBm/10 MHz no power control) represent a single GPS receiver. For Timing GPS receivers in the Uplink 1 band (23 dBm/10 MHz no power control), the 99th percentile of aggregate power received is within 0.5 dB to cause interference to a single Timing GPS receiver (or 9%). For GLN GPS receivers, the 3% in Uplink 1 band (23 dBm/10 MHz no power control) represents a single GPS receiver.

Table H.11. Summary of GPS Receiver Degradation Within a Cell

Interfering Signal	Power Received (dBm/10 MHz) 99th Percentile	HP				GLN				TIM			
		1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
Uplink 1 23 dBm/10 MHz	-34.5	58%	45%	42%	28%	12%	12%	9%	3%	0%	0%	0%	0%
Uplink1 Power Control	-73.3	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Uplink 2 23 dBm/10 MHz	-33.6	35%	28%	22%	8%	3%	3%	3%	0%	9%	0%	0%	0%
Uplink 2 Power Control	-72.4	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

H.4.2 Probability of C/N_0 Degradation and Loss of Lock in a Cell

For 250 simulations per uplink frequency and 10,000 randomized GPS receiver locations within a cell per simulation, the probability of 1 dB, 3 dB, and 5 dB C/N_0 degradation and LOL was calculated for each GPS receiver from all the measurement campaigns (Tables H.18 through H.23). Table H.12 provides the probability of GPS receiver degradation within a cell for Uplink

[18] Table H.11, Table H.12, Table H.13, Table H.14, Table H.15, and Table H.16 provide the 1 dB, 3 dB, and 5 dB C/N_0 degradation and loss of lock data from all the measurement campaigns.

1 and Uplink 2 when the user equipment has an EIRP of 23 dBm/10 MHz (no power control) and power control.

For example, there are 43 experimental measurements points for 1 dB C/N_0 degradation for HP GPS receivers. Every HP receiver was checked for a 1 dB C/N_0 degradation at each randomized location, totaling in 107.5 million (10,000 x 43 x 250) calculations to find the probability of degradation for a single table entry for each scenario.

Table H.12. Probability of GPS Receiver Degradation Within a Cell

Interfering Signal	HP				GLN				TIM			
	1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
Uplink 1 23 dBm/10 MHz	30.1%	19.8%	12.2%	3.6%	8.8%	3.6%	1.0%	0.1%	9.2%	0.0%	0.0%	0.0%
Uplink 1 Power Control	1.9%	0.0%	0.0%	0.0%	2.9%	0.0%	0.0%	0.0%	9.1%	0.0%	0.0%	0.0%
Uplink 2 23 dBm/10 MHz	9.2%	5.0%	2.6%	0.3%	3.2%	0.5%	0.1%	0.0%	9.5%	0.0%	0.0%	0.0%
Uplink 2 Power Control	1.9%	0.0%	0.0%	0.0%	2.9%	0.0%	0.0%	0.0%	9.1%	0.0%	0.0%	0.0%

H.4.3 Simulation Geometry 3: GPS Receiver Operating Outside a Cell (Offset)

Figure H.15 shows the simulation geometry for a GPS receiver operating outside of a cell (offset). The minimum separation distance was calculated between the nearest base station and the GPS receivers (located along the red line). For the simulation, more than 20,000 user equipment locations were randomly generated across the simulation geometry.

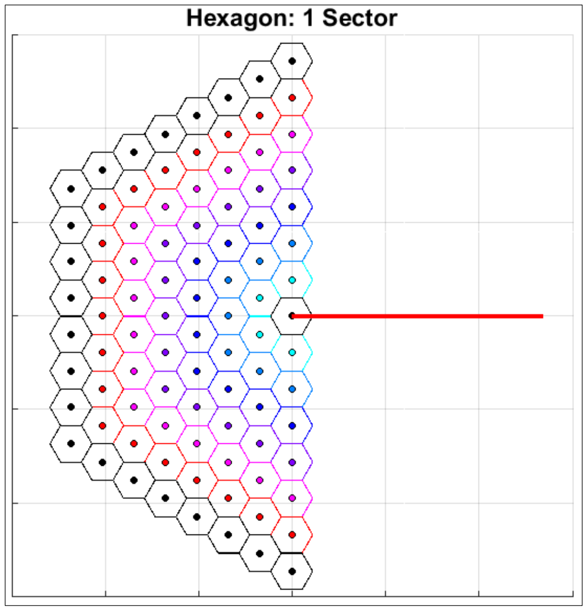

Figure H.15. GPS Receiver Operating Outside of a Cell (Offset)

Figure H.16 shows the maximum aggregate power, for 500 randomized user equipment locations, for a GPS receiver operating inside and outside of a cell, with the separation distance specified as the distance from the base station. The GPS receiver is placed along the red line in Figure H.15.

For the simulation, the cell radius/edge is 250 meters, which is denoted by a vertical red line in Figure H.16. When alpha equals 0, the user equipment does not have power control and is operating at the maximum EIRP of 23 dBm/10 MHz. When alpha equals 0.8, this denotes that the user equipment uses an open loop power control. When the user equipment has power control, no GPS receivers are degraded outside of a cell.

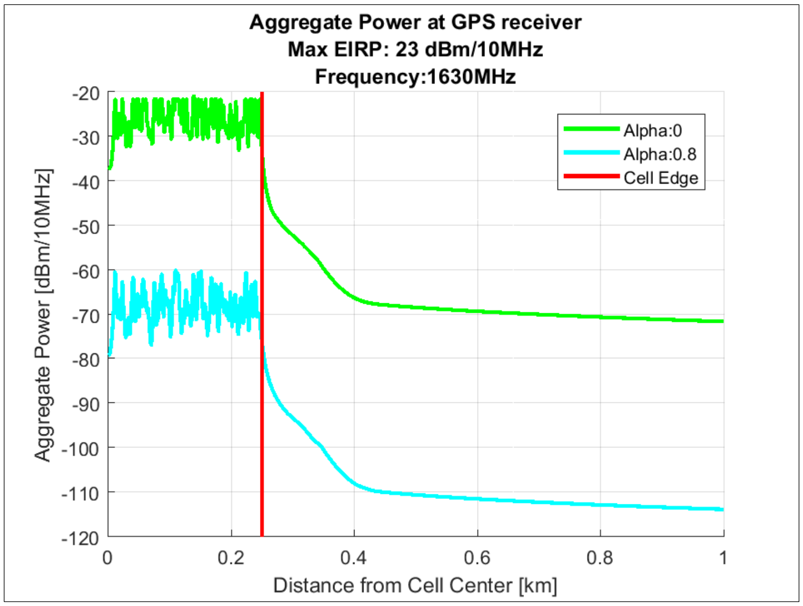

Figure H.16. Maximum Aggregate Power at GPS Receiver Versus Separation Distance

For a GPS receiver operating outside of a cell, Tables H.13 through H.17 provide the separation distance from the base station and the corresponding 99th percentile of the aggregate power for Uplink 1 and Uplink 2 bands when the user equipment has an EIRP of 23 dBm/10 MHz (no power control). The percentage of GPS receivers impacted is provided for each distance. For the simulation, the cell radius was 250 meters. GPS receivers within 250 meters of the base station would be operating within the cell. It should be noted that there was no TIM degradation outside of a cell for Uplink 1 band. It should be noted that the interference power in Tables H.13 through H.17 are different for similar distances. This is due to the GPS antenna loss for the different antenna types and different frequencies. For example, the GLN and TIM antenna loss is greater at 1630 MHz than 1645 MHz (see Figure H.8 and Figure H.9).

Table H.13. Separation Distance Versus Aggregate Power at the HP Receiver Outside a Cell

Aggregate Power at the GPS Receiver Outside of a Cell Uplink 1 Band: EIRP 23 dBm/10 MHz					
Separation Distance from Base Station (meters) [Cell Edge: 250 meters]	Aggregate Power (dBm/10 MHz)	Percentage of GPS Receivers with C/N_0 Degradation			
		1 dB	3 dB	5 dB	LOL
251	-37	49%	38%	30%	21%
252	-38	47%	36%	30%	19%
253	-39	43%	32%	26%	15%
254	-40	40%	30%	26%	15%
255	-41	36%	28%	21%	13%
256	-42	36%	28%	19%	11%
257	-43	36%	26%	17%	9%
259	-44	36%	26%	17%	6%
261	-45	32%	25%	17%	6%
263	-46	30%	17%	13%	2%
266	-47	30%	17%	9%	2%
271	-48	28%	17%	9%	
276	-49	26%	17%	9%	
282	-50	26%	17%	8%	
289	-51	23%	13%	6%	
297	-52	21%	13%	4%	
305	-53	21%	11%	2%	
313	-54	19%	8%	2%	
320	-55	13%	6%	2%	
327	-56	13%	6%		
333	-57	13%	4%		
340	-58	9%	2%		
345	-59	6%	2%		
350	-60	6%			
356	-61	4%			
376	-64	2%			

Table H.14. Separation Distance Versus Aggregate Power at the GLN Receiver Outside a Cell

Aggregate Power at the GPS Receiver Outside of a Cell Uplink 1 Band: EIRP 23 dBm/10 MHz					
Separation Distance from Base Station (meters) [Cell Edge: 250 meters]	Aggregate Power (dBm/10 MHz)	Percentage of GPS Receivers with C/N_0 Degradation			
		1 dB	3 dB	5 dB	LOL
251	-54	12%	12%	9%	
253	-55	12%	9%	9%	
256	-56	12%	9%	3%	
257	-57	9%	9%	3%	
259	-58	9%	6%		
266	-59	9%	3%		
276	-60	9%			
289	-61	6%			
313	-64	3%			

Table H.15. Separation Distance Versus Aggregate Power at the HP Receiver Outside a Cell

Aggregate Power at the GPS Receiver Outside of a Cell Uplink 2 Band: EIRP 23 dBm/10 MHz					
Separation Distance from Base Station (meters) [Cell Edge: 250 meters]	Aggregate Power (dBm/10 MHz)	Percentage of GPS Receivers with C/N_0 Degradation			
		1 dB	3 dB	5 dB	LOL
251	-35	33%	26%	15%	6%
252	-36	30%	22%	15%	2%
254	-37	30%	17%	11%	2%
255	-38	26%	13%	7%	2%
256	-39	22%	7%	6%	
258	-40	20%	6%	4%	
260	-41	17%	6%	2%	
263	-42	13%	6%	2%	
272	-45	9%	4%	2%	
276	-46	6%	4%	2%	
305	-51	4%	4%	2%	
313	-52	4%	2%	2%	
331	-54	4%	2%		
350	-57	4%			
366	-60	2%			

Table H.16. Separation Distance Versus Aggregate Power at the GLN Receiver Outside a Cell

Aggregate Power at the GPS Receiver Outside of a Cell Uplink 2 Band: EIRP 23 dBm/10 MHz					
Separation Distance from Base Station (meters) [Cell Edge: 250 meters]	Aggregate Power (dBm/10 MHz)	Percentage of GPS Receivers with C/N_0 Degradation			
		1 dB	3 dB	5 dB	LOL
254	-54	3%	3%	3%	
256	-57	3%	3%		
265	-60	3%			

Table H.17. Separation Distance Versus Aggregate Power at the TIM Receiver Outside a Cell

Aggregate Power at the GPS Receiver Outside of a Cell Uplink 2 Band: EIRP 23 dBm/10 MHz					
Separation Distance from Base Station (meters) [Cell Edge: 250 meters]	Aggregate Power (dBm/10 MHz)	Percentage of GPS Receivers with C/N_0 Degradation			
		1 dB	3 dB	5 dB	LOL
252	-60	9%			

H.5 GPS MEASUREMENT DATA

H.5.1 Summary of Uplink 1 Band C/N_0 Measurement Data

Tables H.19 through H.20 summarize the C/N_0 data for HP, TIM, and GLN receivers when an interfering signal is in the Uplink 1 band.

Table H.18. Summary of HP GPS Receivers Impacted

Uplink 1 Band: Interfering Signal in the 1625-1635/1627.5-1637.5 MHz								
Interference Power Level (dBm/10 MHz)	Number of Receivers				Percentage of Receivers			
	Degradation in C/N_0							
	1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
≤-64	1	0	0	0	1.9%	0.0%	0.0%	0.0%
≤-61	2	0	0	0	3.8%	0.0%	0.0%	0.0%
≤-60	3	0	0	0	5.7%	0.0%	0.0%	0.0%
≤-59	3	1	0	0	5.7%	1.9%	0.0%	0.0%
≤-58	5	1	0	0	9.4%	1.9%	0.0%	0.0%
≤-57	7	2	0	0	13.2%	3.8%	0.0%	0.0%
≤-56	7	3	0	0	13.2%	5.7%	0.0%	0.0%
≤-55	7	3	1	0	13.2%	5.7%	1.9%	0.0%
≤-54	10	4	1	0	18.9%	7.5%	1.9%	0.0%
≤-53	11	6	1	0	20.8%	11.3%	1.9%	0.0%
≤-52	11	7	2	0	20.8%	13.2%	3.8%	0.0%
≤-51	12	7	3	0	22.6%	13.2%	5.7%	0.0%
≤-50	14	9	4	0	26.4%	17.0%	7.5%	0.0%
≤-49	14	9	5	0	26.4%	17.0%	9.4%	0.0%
≤-48	15	9	5	0	28.3%	17.0%	9.4%	0.0%
≤-47	16	9	5	1	30.2%	17.0%	9.4%	1.9%
≤-46	16	9	7	1	30.2%	17.0%	13.2%	1.9%
≤-45	17	13	9	3	32.1%	24.5%	17.0%	5.7%
≤-44	19	14	9	3	35.8%	26.4%	17.0%	5.7%
≤-43	19	14	9	5	35.8%	26.4%	17.0%	9.4%
≤-42	19	15	10	6	35.8%	28.3%	18.9%	11.3%
≤-41	19	15	11	7	35.8%	28.3%	20.8%	13.2%
≤-40	21	16	14	8	39.6%	30.2%	26.4%	15.1%
≤-39	23	17	14	8	43.4%	32.1%	26.4%	15.1%
≤-38	25	19	16	10	47.2%	35.8%	30.2%	18.9%
≤-37	26	20	16	11	49.1%	37.7%	30.2%	20.8%
≤-36	28	22	20	13	52.8%	41.5%	37.7%	24.5%
≤-35	31	24	22	15	58.5%	45.3%	41.5%	28.3%
≤-34	32	24	23	18	60.4%	45.3%	43.4%	34.0%
≤-33	35	24	24	18	66.0%	45.3%	45.3%	34.0%
≤-32	37	27	24	19	69.8%	50.9%	45.3%	35.8%
≤-31	37	32	24	21	69.8%	60.4%	45.3%	39.6%
≤-30	38	32	25	22	71.7%	60.4%	47.2%	41.5%
≤-29	39	35	30	22	73.6%	66.0%	56.6%	41.5%
≤-28	39	36	31	24	73.6%	67.9%	58.5%	45.3%
≤-27	39	36	34	26	73.6%	67.9%	64.2%	49.1%
≤-25	39	37	34	27	73.6%	69.8%	64.2%	50.9%
≤-24	39	38	35	27	73.6%	71.7%	66.0%	50.9%
≤-23	40	38	35	28	75.5%	71.7%	66.0%	52.8%
≤-22	40	38	38	29	75.5%	71.7%	71.7%	54.7%
≤-21	43	38	38	32	81.1%	71.7%	71.7%	60.4%
≤-20	43	39	38	33	81.1%	73.6%	71.7%	62.3%
≤-19	43	39	38	34	81.1%	73.6%	71.7%	64.2%
≤-18	45	39	39	34	84.9%	73.6%	73.6%	64.2%

Uplink 1 Band: Interfering Signal in the 1625-1635/1627.5-1637.5 MHz								
Interference Power Level (dBm/10 MHz)	Number of Receivers				Percentage of Receivers			
	Degradation in C/N_0							
	1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
≤-17	46	41	39	35	86.8%	77.4%	73.6%	66.0%
≤-16	46	42	40	35	86.8%	79.2%	75.5%	66.0%
≤-15	47	43	40	36	88.7%	81.1%	75.5%	67.9%
≤-14	47	43	42	37	88.7%	81.1%	79.2%	69.8%
≤-13	47	44	42	37	88.7%	83.0%	79.2%	69.8%
≤-12	47	45	43	37	88.7%	84.9%	81.1%	69.8%
≤-11	47	45	43	38	88.7%	84.9%	81.1%	71.7%
≤-10	52	52	52	52	98.1%	98.1%	98.1%	98.1%
≤-9	53	53	53	52	100.0%	100.0%	100.0%	98.1%
≤2	53	53	53	53	100.0%	100.0%	100.0%	100.0%

Table H.19. Summary of TIM GPS Receivers Impacted

Uplink 1 Band : Interfering Signal in the 1625-1635/1627.5-1637.5 MHz								
Interference Power Level (dBm/10 MHz)	Number of Receivers				Percentage of Receivers			
	Degradation in C/N_0							
	1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
≤-34	1	0	0	0	9.1%	0.0%	0.0%	0.0%
≤-25	2	0	0	0	18.2%	0.0%	0.0%	0.0%
≤-24	3	0	0	0	27.3%	0.0%	0.0%	0.0%
≤-22	4	2	0	0	36.4%	18.2%	0.0%	0.0%
≤-21	5	2	0	0	45.5%	18.2%	0.0%	0.0%
≤-20	5	2	1	0	45.5%	18.2%	9.1%	0.0%
≤-17	5	3	2	1	45.5%	27.3%	18.2%	9.1%
≤-15	7	4	2	1	63.6%	36.4%	18.2%	9.1%
≤-13	7	4	3	1	63.6%	36.4%	27.3%	9.1%
≤-12	8	4	4	1	72.7%	36.4%	36.4%	9.1%
≤-10	11	10	9	9	100.0%	90.9%	81.8%	81.8%
≤-9	11	11	9	9	100.0%	100.0%	81.8%	81.8%
≤-8	11	11	10	9	100.0%	100.0%	90.9%	81.8%
≤-6	11	11	11	11	100.0%	100.0%	100.0%	100.0%

Table H.20. Summary of GLN GPS Receivers Impacted

Uplink 1 Band: Interfering Signal in the 1625-1635/1627.5-1637.5 MHz								
Interference Power Level (dBm/10 MHz)	Number of Receivers				Percentage of Receivers			
	Degradation in C/N_0							
	1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
≤-54	1	0	0	0	2.9%	0.0%	0.0%	0.0%
≤-51	2	0	0	0	5.9%	0.0%	0.0%	0.0%
≤-49	3	0	0	0	8.8%	0.0%	0.0%	0.0%
≤-47	3	1	0	0	8.8%	2.9%	0.0%	0.0%
≤-44	3	2	0	0	8.8%	5.9%	0.0%	0.0%
≤-43	3	3	1	0	8.8%	8.8%	2.9%	0.0%
≤-42	4	3	1	0	11.8%	8.8%	2.9%	0.0%
≤-39	4	3	3	0	11.8%	8.8%	8.8%	0.0%
≤-37	4	4	3	0	11.8%	11.8%	8.8%	0.0%
≤-35	4	4	3	1	11.8%	11.8%	8.8%	2.9%
≤-34	5	4	3	1	14.7%	11.8%	8.8%	2.9%
≤-33	6	4	4	2	17.6%	11.8%	11.8%	5.9%
≤-32	7	4	4	2	20.6%	11.8%	11.8%	5.9%
≤-31	8	4	4	2	23.5%	11.8%	11.8%	5.9%
≤-29	9	6	4	2	26.5%	17.6%	11.8%	5.9%
≤-28	9	7	5	2	26.5%	20.6%	14.7%	5.9%
≤-27	9	8	6	2	26.5%	23.5%	17.6%	5.9%
≤-25	13	8	7	2	38.2%	23.5%	20.6%	5.9%
≤-24	14	8	8	2	41.2%	23.5%	23.5%	5.9%
≤-22	15	10	8	3	44.1%	29.4%	23.5%	8.8%
≤-20	22	10	9	5	64.7%	29.4%	26.5%	14.7%
≤-19	24	11	9	5	70.6%	32.4%	26.5%	14.7%
≤-18	24	12	9	5	70.6%	35.3%	26.5%	14.7%
≤-17	24	12	10	5	70.6%	35.3%	29.4%	14.7%
≤-16	25	13	10	5	73.5%	38.2%	29.4%	14.7%
≤-15	26	16	12	8	76.5%	47.1%	35.3%	23.5%
≤-14	26	16	13	8	76.5%	47.1%	38.2%	23.5%
≤-13	26	17	14	8	76.5%	50.0%	41.2%	23.5%
≤-12	27	20	15	11	79.4%	58.8%	44.1%	32.4%
≤-11	27	22	15	11	79.4%	64.7%	44.1%	32.4%
≤-10	34	34	32	32	100.0%	100.0%	94.1%	94.1%
≤-9	34	34	33	32	100.0%	100.0%	97.1%	94.1%
≤-8	34	34	34	32	100.0%	100.0%	100.0%	94.1%
≤-7	34	34	34	33	100.0%	100.0%	100.0%	97.1%
≤-6	34	34	34	34	100.0%	100.0%	100.0%	100.0%

H.5.2 Summary of Uplink 2 Band C/N_0 Measurement Data

Tables H.21 through H.23 summarize the C/N_0 data for HP, TIM, and GLN receivers when an interfering signal is in the Uplink 2 band.

Table H.21. Summary of HP GPS Receivers Impacted

Uplink 2 Band: Interfering Signal in the 1640-1650 MHz/1646.5-1656.5 MHz Band								
Interference Power Level (dBm/10 MHz)	Number of Receivers				Percentage of Receivers			
	Degradation in C/N_0							
	1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
≤-60	1	0	0	0	1.9%	0.0%	0.0%	0.0%
≤-57	2	0	0	0	3.7%	0.0%	0.0%	0.0%
≤-54	2	1	0	0	3.7%	1.9%	0.0%	0.0%
≤-52	2	1	1	0	3.7%	1.9%	1.9%	0.0%
≤-51	2	2	1	0	3.7%	3.7%	1.9%	0.0%
≤-46	3	2	1	0	5.6%	3.7%	1.9%	0.0%
≤-45	5	2	1	0	9.3%	3.7%	1.9%	0.0%
≤-42	7	3	1	0	13.0%	5.6%	1.9%	0.0%
≤-41	9	3	1	0	16.7%	5.6%	1.9%	0.0%
≤-40	11	3	2	0	20.4%	5.6%	3.7%	0.0%
≤-39	12	4	3	0	22.2%	7.4%	5.6%	0.0%
≤-38	14	7	4	1	25.9%	13.0%	7.4%	2.1%
≤-37	16	9	6	1	29.6%	16.7%	11.1%	2.1%
≤-36	16	12	8	1	29.6%	22.2%	14.8%	2.1%
≤-35	18	14	8	3	33.3%	25.9%	14.8%	6.3%
≤-34	19	15	12	4	35.2%	27.8%	22.2%	8.3%
≤-33	19	17	15	6	35.2%	31.5%	27.8%	12.5%
≤-32	20	17	15	9	37.0%	31.5%	27.8%	18.8%
≤-31	20	17	16	10	37.0%	31.5%	29.6%	20.8%
≤-30	21	18	17	11	38.9%	33.3%	31.5%	22.9%
≤-29	22	18	17	11	40.7%	33.3%	31.5%	22.9%
≤-28	24	19	18	13	44.4%	35.2%	33.3%	27.1%
≤-27	25	19	18	14	46.3%	35.2%	33.3%	29.2%
≤-26	26	21	18	14	48.1%	38.9%	33.3%	29.2%
≤-25	29	23	18	14	53.7%	42.6%	33.3%	29.2%
≤-24	29	23	19	14	53.7%	42.6%	35.2%	29.2%
≤-23	31	24	20	14	57.4%	44.4%	37.0%	29.2%
≤-22	31	25	23	14	57.4%	46.3%	42.6%	29.2%
≤-21	31	25	24	14	57.4%	46.3%	44.4%	29.2%
≤-20	32	25	24	15	59.3%	46.3%	44.4%	31.3%
≤-19	33	26	24	15	61.1%	48.1%	44.4%	31.3%
≤-18	34	26	25	16	63.0%	48.1%	46.3%	33.3%
≤-17	37	29	26	17	68.5%	53.7%	48.1%	35.4%
≤-16	37	29	26	18	68.5%	53.7%	48.1%	37.5%
≤-15	37	32	26	19	68.5%	59.3%	48.1%	39.6%
≤-13	37	32	29	19	68.5%	59.3%	53.7%	39.6%
≤-12	39	32	29	19	72.2%	59.3%	53.7%	39.6%
≤-11	41	35	34	20	75.9%	64.8%	63.0%	41.7%
≤-10	54	54	54	46	100.0%	100.0%	100.0%	95.8%
≤-6	54	54	54	47	100.0%	100.0%	100.0%	97.9%

Table H.22. Summary of TIM GPS Receivers Impacted

Uplink 2 Band: Interfering Signal in the 1640-1650 MHz/1646.5-1656.5 MHz Band								
Interference Power Level (dBm/10 MHz)	Number of Receivers				Percentage of Receivers			
	Degradation in C/N_0							
	1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
≤-36	1	0	0	0	9.1%	0.0%	0.0%	0.0%
≤-21	3	0	0	0	27.3%	0.0%	0.0%	0.0%
≤-18	4	0	0	0	36.4%	0.0%	0.0%	0.0%
≤-17	4	1	1	0	36.4%	9.1%	9.1%	0.0%
≤-16	5	2	1	0	45.5%	18.2%	9.1%	0.0%
≤-15	6	2	1	0	54.5%	18.2%	9.1%	0.0%
≤-12	6	2	2	0	54.5%	18.2%	18.2%	0.0%
≤-11	6	3	2	0	54.5%	27.3%	18.2%	0.0%
≤-10	11	11	9	8	100.0%	100.0%	81.8%	80.0%
≤-6	11	11	11	10	100.0%	100.0%	100.0%	100.0%

Table H.23. Summary of GLN GPS Receivers Impacted

Uplink 2 Band: Interfering Signal in the 1640-1650 MHz/1646.5-1656.5 MHz Band								
Interference Power Level (dBm/10 MHz)	Number of Receivers				Percentage of Receivers			
	Degradation in C/N_0							
	1 dB	3 dB	5 dB	LOL	1 dB	3 dB	5 dB	LOL
≤-43	1	0	0	0	2.9%	0.0%	0.0%	0.0%
≤-39	1	1	0	0	2.9%	2.9%	0.0%	0.0%
≤-37	1	1	1	0	2.9%	2.9%	2.9%	0.0%
≤-29	4	1	1	0	11.8%	2.9%	2.9%	0.0%
≤-28	4	2	1	0	11.8%	5.9%	2.9%	0.0%
≤-27	4	2	2	0	11.8%	5.9%	5.9%	0.0%
≤-26	5	2	2	0	14.7%	5.9%	5.9%	0.0%
≤-24	6	2	2	0	17.6%	5.9%	5.9%	0.0%
≤-21	7	4	3	0	20.6%	11.8%	8.8%	0.0%
≤-20	8	4	3	0	23.5%	11.8%	8.8%	0.0%
≤-19	8	5	3	0	23.5%	14.7%	8.8%	0.0%
≤-18	9	6	4	0	26.5%	17.6%	11.8%	0.0%
≤-17	10	6	4	0	29.4%	17.6%	11.8%	0.0%
≤-16	10	7	5	0	29.4%	20.6%	14.7%	0.0%
≤-15	13	7	6	0	38.2%	20.6%	17.6%	0.0%
≤-14	13	7	7	0	38.2%	20.6%	20.6%	0.0%
≤-13	13	7	7	1	38.2%	20.6%	20.6%	3.6%
≤-12	14	8	8	1	41.2%	23.5%	23.5%	3.6%
≤-11	14	10	8	1	41.2%	29.4%	23.5%	3.6%
≤-10	34	34	31	25	100.0%	100.0%	91.2%	89.3%
≤-8	34	34	33	25	100.0%	100.0%	97.1%	89.3%
≤-6	34	34	34	28	100.0%	100.0%	100.0%	100.0%

APPENDIX I
GPS RECEIVER LOSS-OF-LOCK ANALYSIS

I.1 INTRODUCTION

This appendix documents the Technical Focus Group (TFG)'s analysis of Global Positioning System (GPS) receiver loss-of-lock (LOL) based on a single and aggregate macro cell and small cell base station interference. For the purpose of this analysis, LOL occurs when the interfering signal causes the GPS receiver to stop reporting carrier-to-noise density values for each satellite. Base station equivalent isotropically radiated power (EIRP) values of 62 dB relative to a milliwatt (dBm)/10 MHz (macro cell) and 40 dBm/10 MHz (small cell) are used in the analysis.

I.2 MEASURED LOL INTERFERENCE POWER LEVELS

Tables I.1 I.3 summarize the number and percentage of high precision (HP), general location/navigation (GLN), and timing (TIM) categories of GPS receivers and the interfering signal power level that cause an LOL condition to occur.

Table I.1. Summary of HP GPS Receiver LOL Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Band

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤-63	0	0 %
≤-61	1	2.0%
≤-50	2	4.1%
≤-49	3	6.1%
≤-45	7	14.3%
≤-43	8	16.3%
≤-42	9	18.4%
≤-38	10	20.4%
≤-37	11	22.4%
≤-36	12	24.5%
≤-35	15	30.6%
≤-34	19	38.8%
≤-32	20	40.8%
≤-31	21	42.9%
≤-28	22	44.9%
≤-24	23	46.9%
≤-23	24	49.0%
≤-22	25	51.0%
≤-20	26	53.1%
≤-19	27	55.1%
≤-15	28	57.1%
≤-12	30	61.2%
≤-11	31	63.3%
≤-10	46	93.9%
≤1	47	95.9%
≤2	48	98.0%
≤3	49	100.0%

Table I.2. Summary of GLN GPS Receivers LOL Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Band

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤-48	0	0 %
≤-45	1	3.1%
≤-15	2	6.3%
≤-12	4	12.5%
≤-10	29	90.6%
≤-8	30	93.8%
≤3	32	100.0%

Table I.3. Summary of TIM GPS Receiver LOL Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Band

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers
≤-30	0	0 %
≤-27	1	8.3%
≤-10	10	83.3%
≤0	11	91.7%
≤1	12	100.0%

I.3 SINGLE BASE STATION LOL ANALYSIS

The single base station interference analysis methodology in this appendix will be used to perform the LOL analysis to determine the separation distances necessary to reduce the base station power level at the GPS receiver to below the interference power level based on LOL. The analysis results are shown in Tables I.4 through I.6. The base station-received power calculations for each GPS receiver category are shown in Figures I.1 through I.6.

Table I.4. Percentage of HP GPS Receivers Impacted LOL Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers	Separation Distance (meters)	
			Macro Cell Base Station	Small Cell Base Station
≤-63	0	0 %	5518	562
≤-61	1	2.0%	4817	458
≤-50	2	4.1%	1765	166
≤-49	3	6.1%	1636	155
≤-45	7	14.3%	1085	114
≤-43	8	16.3%	897	97
≤-42	9	18.4%	805	86
≤-38	10	20.4%	541	54
≤-37	11	22.4%	484	49
≤-36	12	24.5%	439	44
≤-35	15	30.6%	395	39
≤-34	19	38.8%	355	34
≤-32	20	40.8%	285	27
≤-31	21	42.9%	254	24
≤-28	22	44.9%	175	18
≤-24	23	46.9%	122	11
≤-23	24	49.0%	113	9
≤-22	25	51.0%	104	5
≤-20	26	53.1%	84	< 5
≤-19	27	55.1%	75	< 5
≤-15	28	57.1%	47	< 5
≤-12	30	61.2%	33	< 5
≤-11	31	63.3%	29	< 5
≤-10	46	93.9%	27	< 5
≤1	47	95.9%	< 5	< 5
≤2	48	98.0%	< 5	< 5
≤3	49	100.0%	< 5	< 5

Table I.5. Percentage of GLN GPS Receivers Degraded LOL Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers	Separation Distance (meters)	
			Macro Cell Base Station	Small Cell Base Station
≤-48	0	0 %	1885	169
≤-45	1	3.1%	1425	135
≤-15	2	6.3%	62	< 5
≤-12	4	12.5%	43	< 5
≤-10	29	90.6%	35	< 5
≤-8	30	93.8%	28	< 5
≤3	32	100.0%	< 5	< 5

Table I.6. Percentage of TIM GPS Receiver Degraded LOL Degradation

Interference Power Level (dBm/10 MHz)	Number of Receivers	Percentage of Receivers	Separation Distance (meters)	
			Macro Cell Base Station	Small Cell Base Station
≤-30	0	0%	235	23
≤-27	1	8.3%	160	16
≤-10	10	83.3%	28	< 5
≤0	11	91.7%	< 5	< 5
≤1	12	100.0%	< 5	< 5

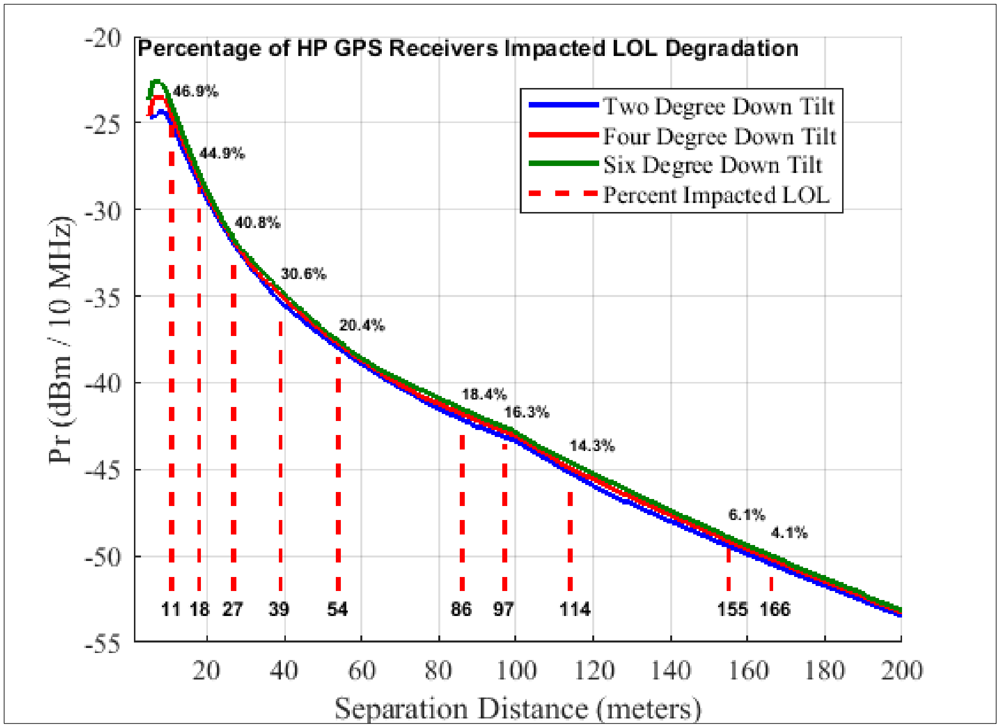

Figure I.1a. Maximum Received Power as a Function of Separation Distance Base Station EIRP of 40 dBm/10 MHz

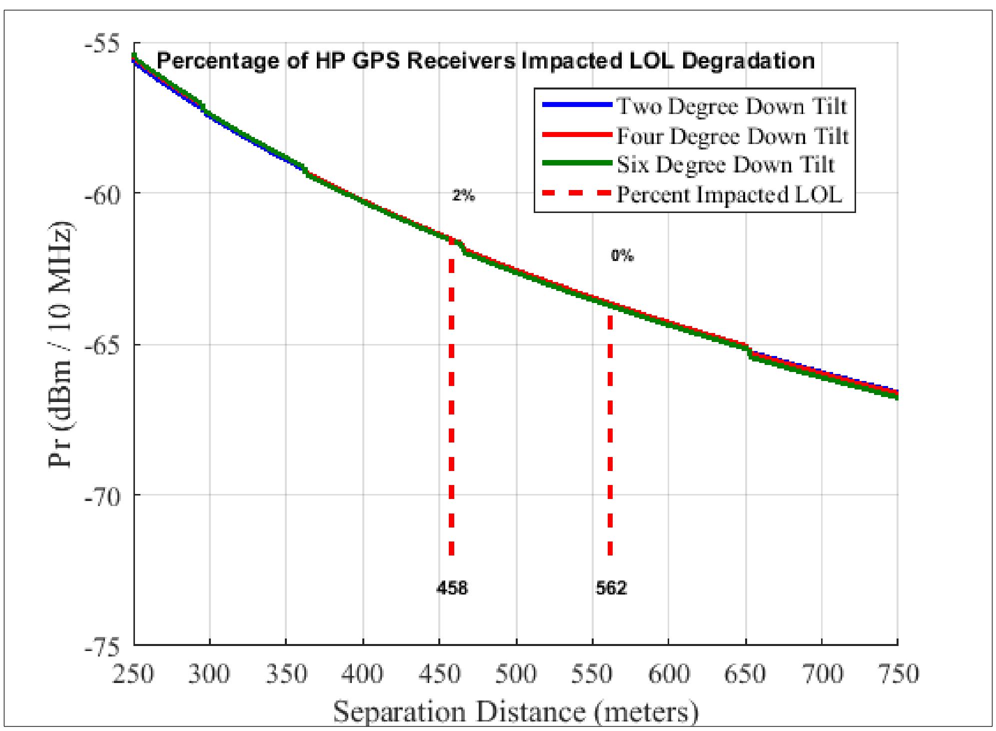

Figure I.1b. Maximum Received Power as a Function of Separation Distance Base Station EIRP of 40 dBm/10 MHz

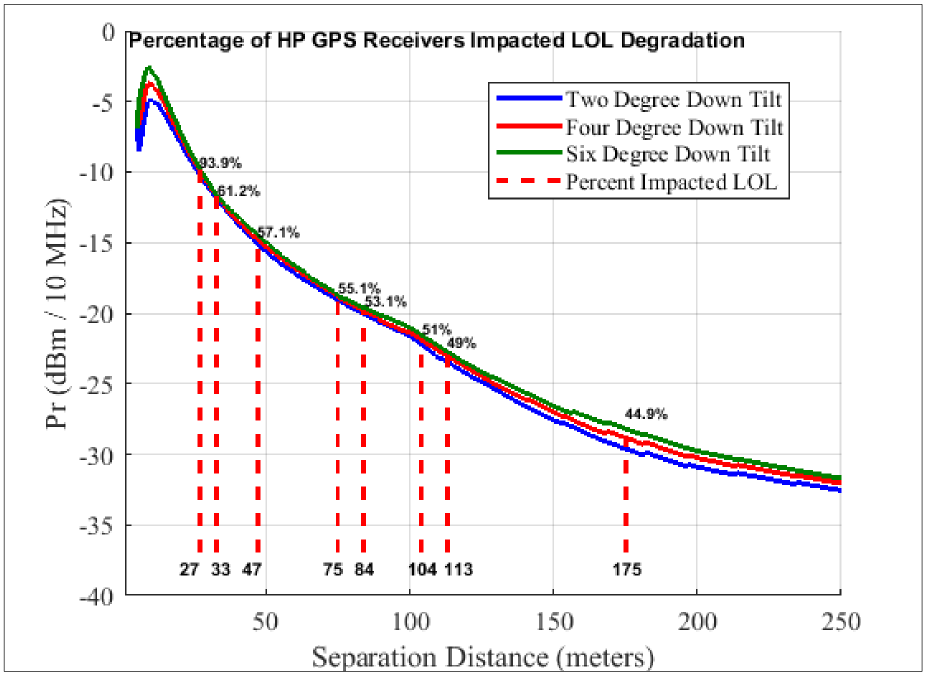

Figure I.2a. Maximum Received Power as a Function of Separation Distance Base Station EIRP of 62 dBm/10 MHz

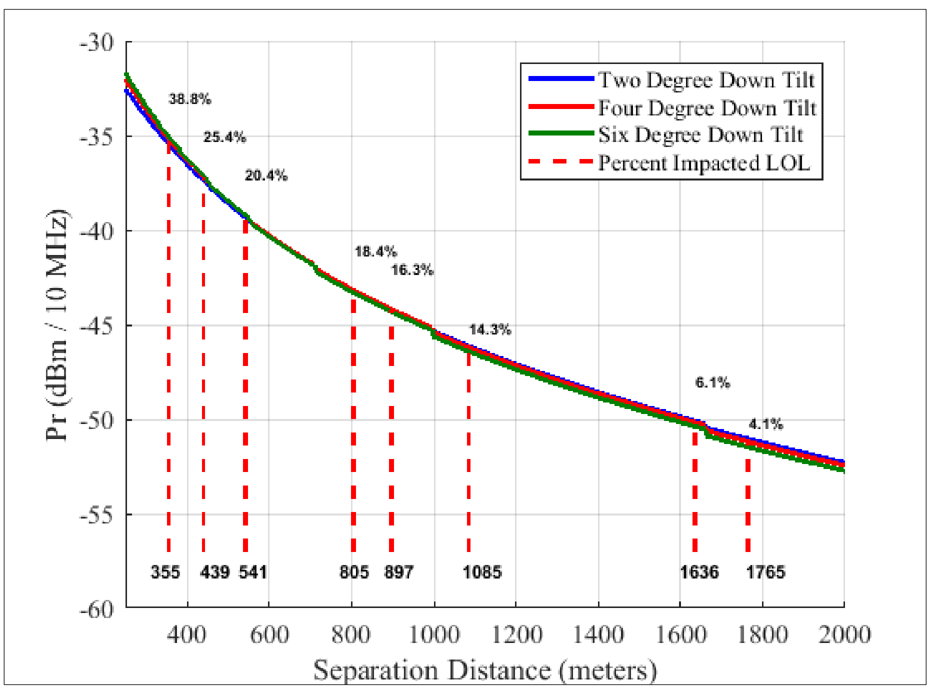

Figure I.2b. Maximum Received Power as a Function of Separation Distance Base Station EIRP of 62 dBm/10 MHz

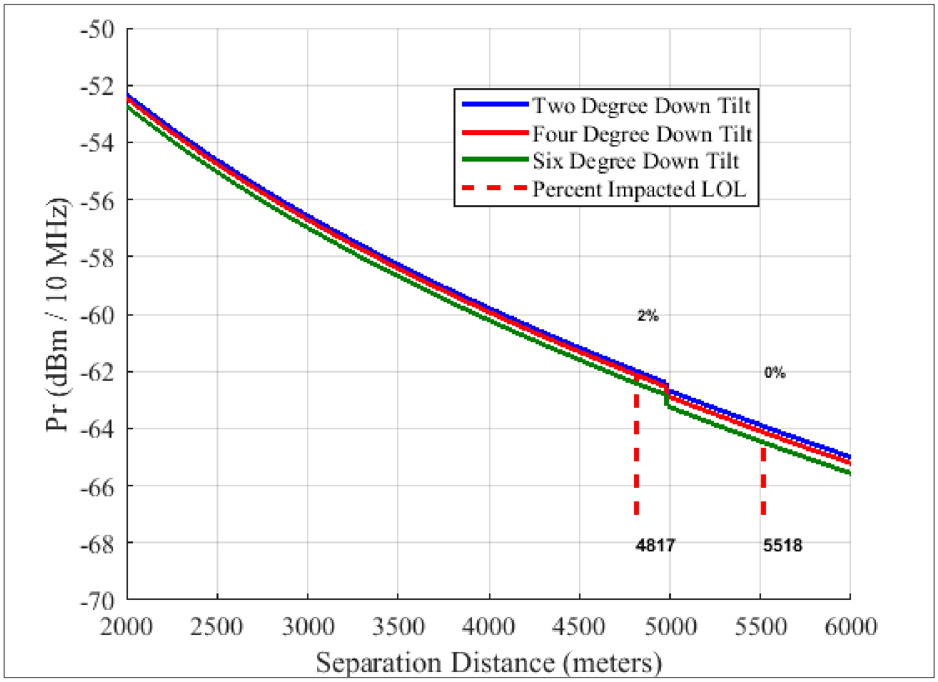

Figure I.2c. Maximum Received Power as a Function of Separation Distance Base Station EIRP of 62 dBm/10 MHz

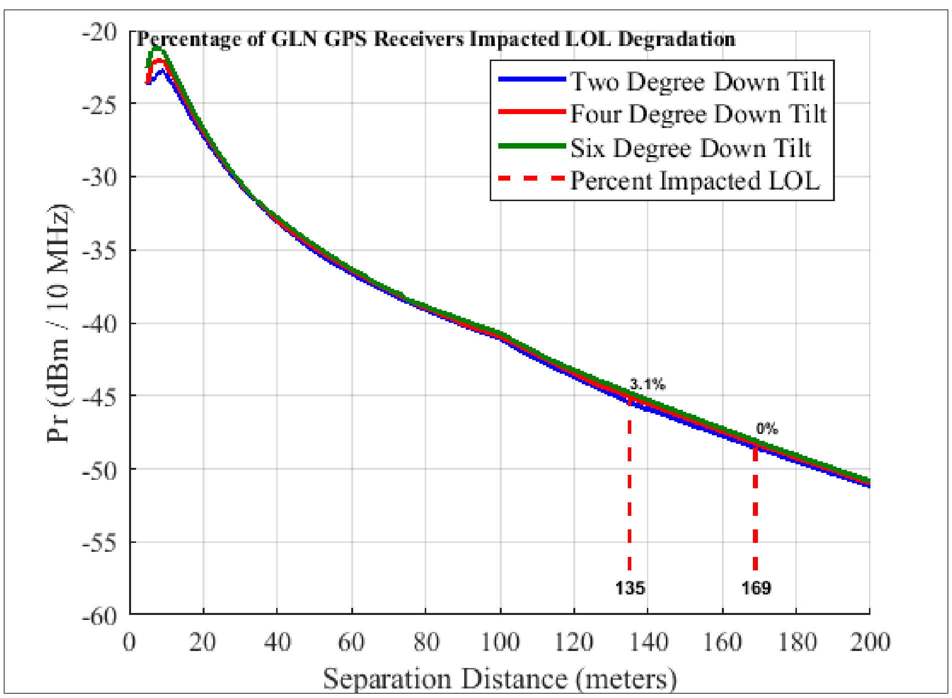

Figure I.3. Maximum Received Power as a Function of Separation Distance Base Station EIRP of 40 dBm/10 MHz

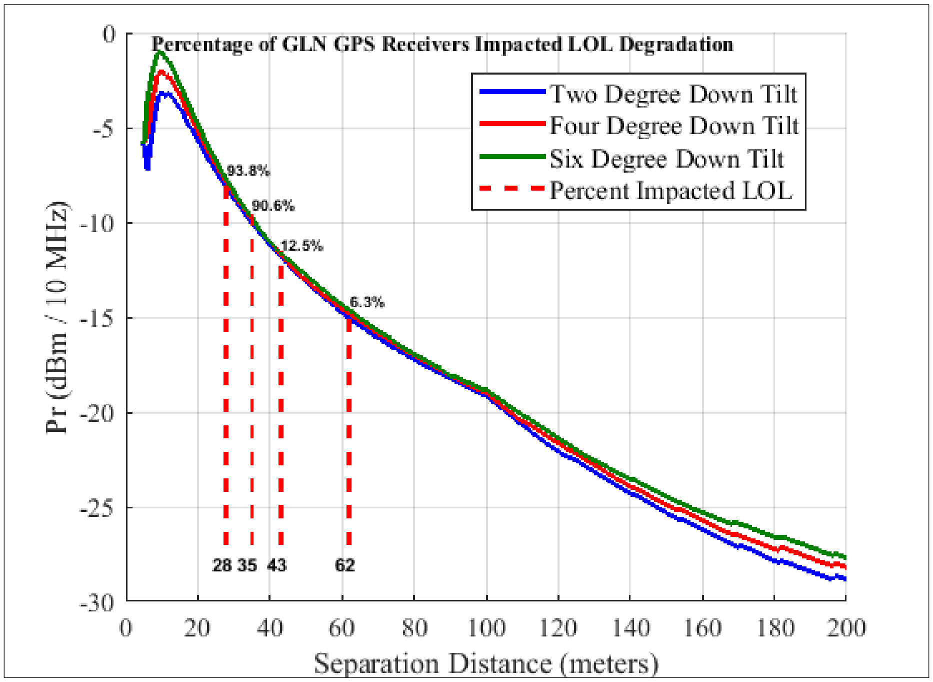

Figure I.4a. Maximum Received Power as a Function of Separation Distance Base Station EIRP of 62 dBm/10 MHz

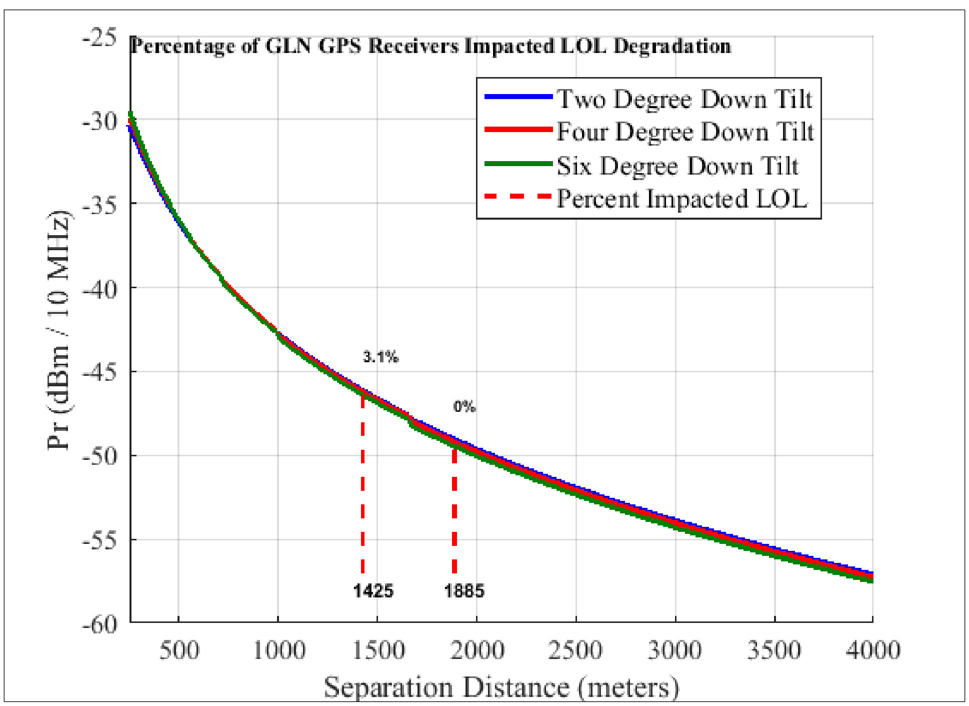

Figure I.4b. Maximum Received Power as a Function of Separation Distance Base Station EIRP of 62 dBm/10 MHz

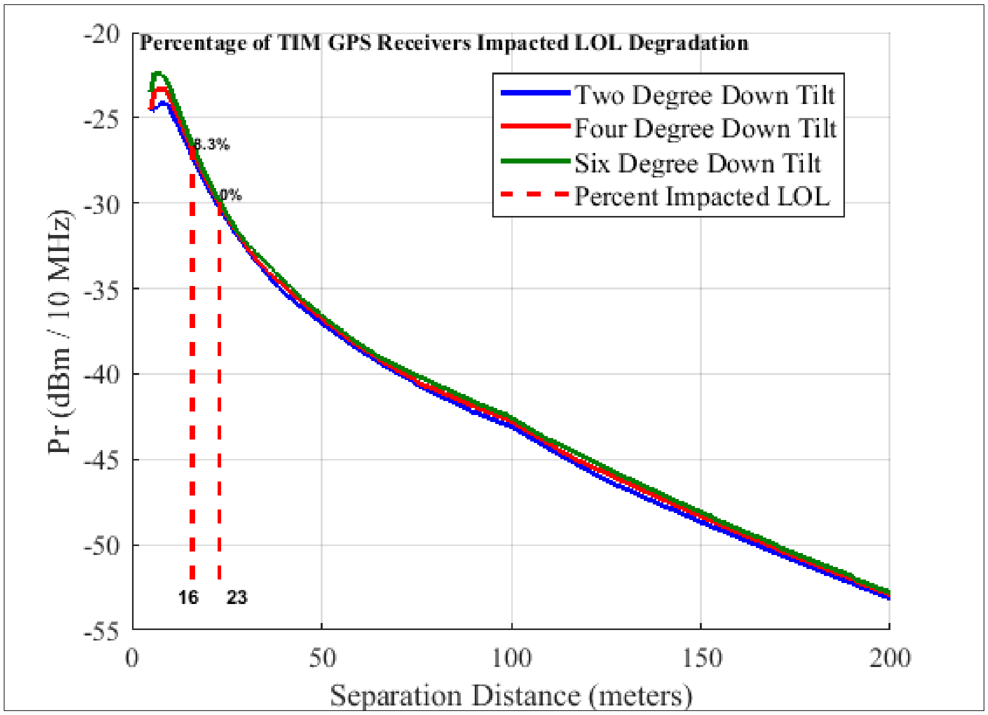

Figure I.5. Maximum Received Power as a Function of Separation Distance Base Station EIRP of 40 dBm/10 MHz

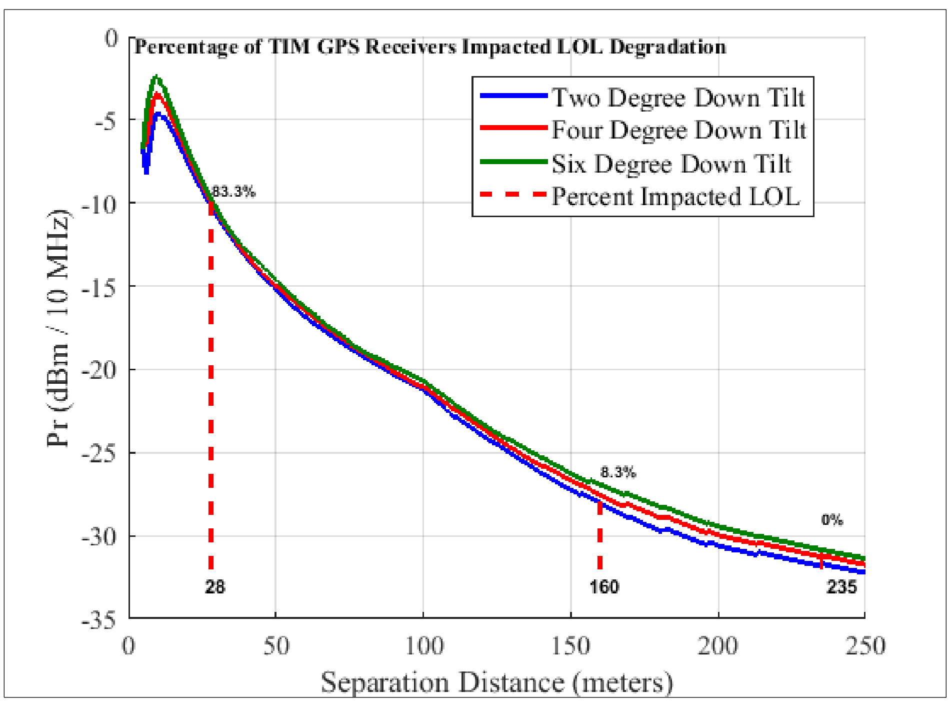

Figure I.6. Maximum Received Power as a Function of Separation Distance Base Station EIRP of 62 dBm/10 MHz

I.4 AGGREGATE BASE STATION LOL ANALYSIS

The simulation scenarios described in Appendix F will be used to assess the potential LOL based on aggregate base station interference. Tables I.1 through I.4 provide the percentage of GPS receivers with each category that will experience LOL. The 99th percentile of the power received at the GPS receiver is calculated for 50,000 locations within a cell. The propagation model used to compute the 99th percentile is free space, because the 99th percentile locations are all within 100 meters of the base station. From the received power calculations, the percentage of GPS receivers from all of the measurement programs is provided that will experience an LOL. The simulation results are contained in Tables I.7 through I.10.

Table I.7. Scenario 1: Macro Suburban [693m ISD]
Summary of GPS Receiver LOL Degradation

EIRP (dBm/10 MHz)	Power Received (dBm/10 MHz) 99th Percentile	Percentage of Receivers with LOL		
		HP	GLN	TIM
62	-25	45%	3%	8%
60	-27	45%	3%	
58	-29	43%	3%	
56	-31	41%	3%	
54	-33	39%	3%	
52	-35	24%	3%	
50	-37	20%	3%	
48	-39	18%	3%	
46	-41	18%	3%	
44	-43	14%	3%	
42	-45	6%		
40	-47	6%		
38	-49	4%		
36	-51	2%		
34	-53	2%		
32	-55	2%		
30	-57	2%		
28	-59	2%		

Table I.8. Scenario 2/3: Macro Urban [693m ISD]
Summary of GPS Receiver LOL Degradation

EIRP (dBm/10 MHz)	Power Received (dBm/10 MHz) 99th Percentile	Percentage of Receivers with LOL		
		HP	GLN	TIM
62	-22	51%	3%	8%
60	-24	47%	3%	8%
58	-26	45%	3%	8%
56	-28	45%	3%	
54	-30	43%	3%	
52	-32	41%	3%	
50	-34	39%	3%	
48	-36	24%	3%	
46	-38	20%	3%	
44	-40	18%	3%	
42	-42	18%	3%	
40	-44	14%	3%	0%
38	-46	6%		
36	-48	6%		
34	-50	4%		
32	-52	2%		
30	-54	2%		
28	-56	2%		
26	-58	2%		
24	-60	2%		

Table I.9. Scenario 4: Macro Urban [433m ISD]
Summary of GPS Receiver LOL Degradation

EIRP (dBm/10 MHz)	Power Received (dBm/10 MHz) 99th Percentile	Percentage of Receivers with LOL		
		HP	GLN	TIM
62	-21	51%	3%	8%
60	-23	47%	3%	8%
58	-25	45%	3%	8%
56	-27	45%	3%	
54	-29	43%	3%	
52	-31	41%	3%	
50	-33	39%	3%	
48	-35	24%	3%	
46	-37	20%	3%	
44	-39	18%	3%	
42	-41	18%	3%	
40	-43	14%	3%	0%
38	-45	6%		
36	-47	6%		
34	-49	4%		
32	-51	2%		
30	-53	2%		
28	-55	2%		
26	-57	2%		
24	-59	2%		

Table I.10. Scenario 5: Micro Urban [433m ISD]
Summary of GPS Receiver LOL Degradation

EIRP (dBm/10 MHz)	Power Received (dBm/10 MHz) 99th Percentile	Percentage of Receivers with LOL		
		HP	GLN	TIM
42	-30	43%	3%	
40	-32	41%	3%	0%
38	-34	39%	3%	
36	-36	24%	3%	
34	-38	20%	3%	
32	-40	18%	3%	
30	-42	18%	3%	
29	-43	16%	3%	
28	-44	14%	3%	
27	-45	14%	3%	
26	-46	6%		
25	-47	6%		
24	-48	6%		
23	-49	6%		
22	-50	4%		
21	-51	2%		
20	-52	2%		
19	-53	2%		
18	-54	2%		
17	-55	2%		
16	-56	2%		
15	-57	2%		
14	-58	2%		
13	-59	2%		
12	-60	2%		
11	-61	2%		

APPENDIX J
CERTIFIED AVIATION USE CASE[1]

J.1 INTRODUCTION

This appendix provides a summary of the analyses that were performed as part of the Department of Transportation (DOT) Adjacent Band Compatibility (ABC) effort regarding certified aviation Global Positioning System (GPS) receivers. These receivers operate in accordance with internationally-accepted standards, so testing against Ligado-type signals was not required. Full details on the analysis approach and results can be found in the DOT ABC final report.[2]

J.2 CERTIFIED AVIATION RECEIVER STANDARDS

Certified GPS, GPS/Satellite-based Augmentation System (SBAS) and GPS/ground-based augmentation system (GBAS) airborne equipment will meet their performance requirements when operating within the radio frequency (RF) interference (RFI) environment defined in appropriate Federal Aviation Administration (FAA) Technical Standard Orders (TSO). These technical standard orders invoke industry Minimum Operational Performance Standards (MOPS) developed through RTCA (RTCA/DO-229, RTCA/DO-253 and RTCA/DO-316). Additionally, Sections 3.7.2 and 3.7.3 of the International Civil Aviation Organization (ICAO) Global Navigation satellite System (GNSS) Standards and Recommended Practices (SARP)[3] also contain continuous wave (CW) and band limited noise interference levels, respectively, for which these receivers must satisfy their performance specifications and operational objectives.

This analysis addresses all receivers compliant with the requirements of:[4]

- Technical Standard Order (TSO)-C145(),[5] *Airborne Navigation Sensors Using The Global Positioning System Augmented By The Satellite Based Augmentation System*. This standard invokes RTCA/DO-229, *Minimum Operational Performance Standards for GPS/Wide Area Augmentation System Airborne Equipment*.
- TSO-C146(), *Stand-Alone Airborne Navigation Equipment Using The Global Positioning System Augmented By The Satellite Based Augmentation System.* This standard invokes RTCA/DO-229, *Minimum Operational Performance Standards for GPS/Wide Area Augmentation System Airborne Equipment*.

[1] This appendix was prepared by the FAA.

[2] United States Department of Transportation, *Global Positioning System (GPS) Adjacent Band Compatibility Assessment Final Report* (Apr. 2018) *available at* https://www.transportation.gov/sites/dot.gov/files/docs/subdoc/186/dot-gps-adjacent-band-final-reportapril2018.pdf.

[3] ICAO Standards and Recommended Practices (SARPs) Annex 10 Volume I Appendix B.

[4] Where specifications are referenced, the latest version is assumed.

[5] "()" encompasses all versions.

- TSO-C161(), *Ground Based Augmentation System Positioning and Navigation Equipment.* This standard invokes RTCA/DO-253, *Minimum Operational Performance Standards for GPS/Local Area Augmentation System Airborne Equipment*.
- TSO-C196(), *Airborne Supplemental Navigation Sensor for Global Positioning System Equipment Using Aircraft-Based Augmentation*. This standard invokes RTCA/DO-316, *Minimum Operational Performance Standards for GPS/Aircraft-Based Augmentation System Airborne Equipment*.
- TSO-C204(), *Circuit Card Assembly Functional Sensors using Satellite-Based Augmentation System (SBAS) for Navigation and Non-Navigation Position/Velocity/Time Output.* This standard invokes RTCA/DO-229, *Minimum Operational Performance Standards for GPS/Wide Area Augmentation System Airborne Equipment*.
- TSO-C205(), *Circuit Card Assembly Functional Class Delta Equipment Using The Satellite-Based Augmentation System For Navigation Applications.* This standard invokes RTCA/DO-229, *Minimum Operational Performance Standards for GPS/Wide Area Augmentation System Airborne Equipment*.
- TSO-C206(), *Circuit Card Assembly Functional Sensors using Aircraft-Based Augmentation for Navigation and Non-Navigation Position/Velocity/Time Output.* This standard invokes RTCA/DO-316, *Minimum Operational Performance Standards for Global Positioning System/Aircraft Based Augmentation System Airborne Equipment.*

J.2 AREA OF AVIATION OPERATION

The analysis for certified aviation receivers is based on the concept of a "standoff cylinder", inside of which, GPS performance may be compromised or unavailable. In this region, GPS based instrument flight rules (IFR) operations will be restricted (Figure J.1) due to the elevated levels of RFI. The dimensions of the cylinder used in this analysis were proposed by Ligado.

The approach for certified aviation GPS receivers is based on the assumption that those receivers do not need to enter a 250 foot (75.2 meters) radius cylinder around a base station. The derivation of the standoff cylinder concept was based on engineering and operational assumptions where helicopter operations using certified avionics are the limiting factor. The FAA has not completed an exhaustive evaluation of the operational scenarios in developing this standoff cylinder. Further, the current analyses do not include an operational assessment of the impact of the standoff cylinder in densely populated areas. For example, the risk posed to people and property for operations such as unmanned aircraft systems (UAS) using certified avionics may be significant as such aircraft may be required to operate within the standoff cylinder.

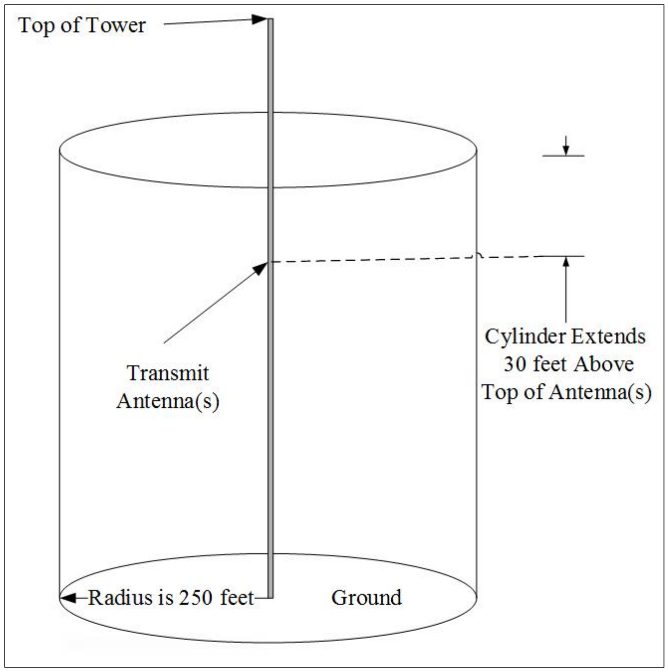

Figure J.1. Candidate Standoff Cylinder

J.3 TRACKING AND ACQUISITION THRESHOLDS

The tracking and acquisition performance requirements for GPS airborne receivers are defined in FAA TSO-C145, TSO-C146, TSO-C161, TSO-C196, TSO-C204, TSO-C205 and TSO-C206. The RFI aspects of these standards are identical. The relevant characteristics were first published in 1996 and invoked by the FAA in May 1998. The same requirements have been harmonized internationally since 2001.[6] The passband for this equipment is from 1565.42 MHz to 1585.42 MHz.[7]

J.4 RECEIVER TRACKING LIMIT CRITERIA FOR ADJACENT BAND RFI

MOPS adjacent- and in-band RFI rejection requirements are specified for CW, narrowband radio frequency interference for the GPS band. All TSO (and European TSO) approved equipment is designed and tested to ensure that these requirements are satisfied. For convenience, the CW susceptibility limit curve for receiver tracking mode is shown in Figure J.2. The adjacent band susceptibility limits will be applied in the RFI impact analysis of the broadband wireless handset and base station emissions. Adjacent band base station broadband emission RFI effects are modelled as if the entire fundamental emission power is concentrated at the emission center frequency.[8]

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[6] ICAO Standards and Recommended Practices (SARP) Annex 10 Volume I Appendix B at paragraph 3.7.4.

[7] A passband is the range of frequencies that can pass through a filter.

[8] This assumption was validated during the Federal Communications Commission LightSquared Technical Working Group activities performed in 2011.

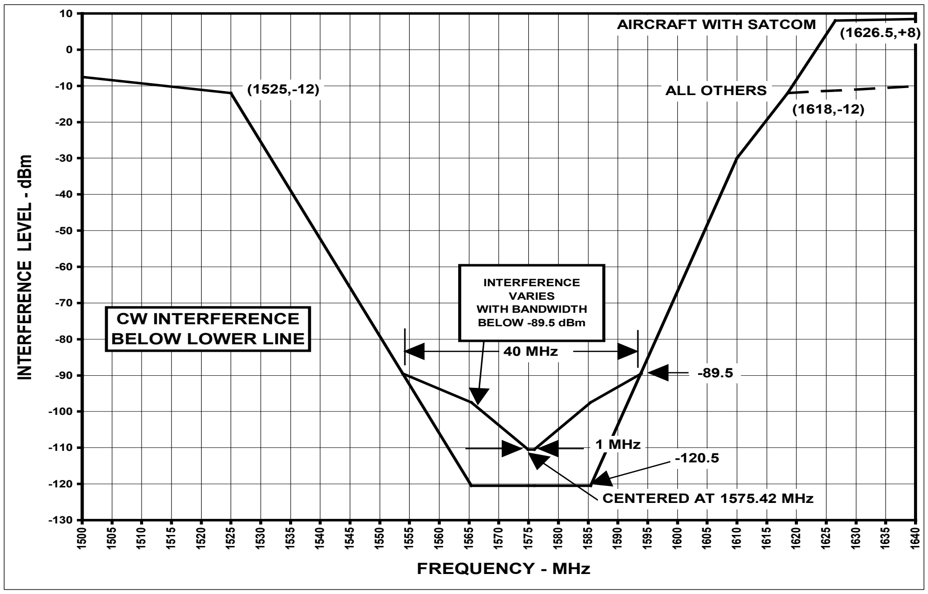

Figure J.2. CW Interference Susceptibility as a Function of Frequency, Tracking Mode

To preserve the aeronautical safety margin, the maximum mean aggregate RFI power must be kept at least 6 Decibel(s) (dB) below the curves at any center frequency point.[9] An additional constraint on the aggregate RFI is that the probability that the received RFI exceeds a value 2 dB below the limit curve is less than 10^{-6}/hour. The 10^{-6}/hour probability represents a 1/10 portion of the overall continuity requirement for aircraft operations from en route to non-precision approach.[10] This 10^{-6}/hour limit is understood as the probability of a single disruptive RFI event. As with previous analyses, the frequency point for limit determination is the emission center frequency. For any aircraft attitude under study, the aggregate mean and rare (10^{-6}) limits apply simultaneously.

J.5 RECEIVER ACQUISITION LIMIT CRITERIA FOR ADJACENT BAND RFI

Numerous flight circumstances require GPS acquisition while airborne such as power interruptions on the aircraft or loss of GPS due to aggregate RF interference. Since acquisition is more demanding than tracking, the receiver standards require operation with a 6 dB lower interference test condition than in the tracking case. As a result, the acquisition test threshold is -64.1 dB relative to a Watt (dBW) and applying a safety margin would then result in an interference threshold at -70.1 dBW. Rather than applying this limit directly, the FAA previously determined in the 2012 Interim FAA Study Report[11] that the analysis should account for a maximum probability of 10^{-3} that the interference exceeds -64.1 dBW. The assessment

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9 This safety margin applies for aircraft airborne and ground operations.

10 The reliability of the positioning service is specified in terms of continuity (see Section 2.3.3 of the Wide Area Augmentation System (WAAS) Performance Standard [4]). The more stringent requirement is for en route through non-precision approach where the service is defined from the surface of the earth to 100,000 feet. The associated continuity requirement is 10^{-5} per hour.

11 Status Report: Assessment of Compatibility of Planned LightSquared Ancillary Terrestrial Component Transmissions in the 1526-1536 MHz Band with Certified Aviation GPS Receivers, FAA Report PR 25, January 25, 2012.

concluded that this particular threshold was not the limiting condition, so for all the certified aviation use cases/interaction scenarios in this analysis only the tracking mode was considered.

J.6 RECEIVER TRACKING LIMIT CRITERIA FOR BROADBAND HANDSET RFI IN-BAND TO GPS

In this analysis, all of the scenarios associated with additional broadband handset unwanted RFI to certified GPS aviation receivers assume operation in the presence of a baseline non-aeronautical noise-like RFI environment within the receiver passband (i.e., in-band RFI to the receiver). The in-band susceptibility for broad band non-aeronautical RFI is specified as -110.5 dBm/MHz in a ±10 MHz band centered on 1575.42 MHz.[12] As with the adjacent band susceptibility, this limit represents an airborne receiver test condition limit and, for aviation safety considerations, the mean environment aggregate RFI power spectral density (PSD) must be kept at least 6 dB[13] below the test limit. Recent studies[14] have shown that an existing baseline environment[15] results in an aggregate received RFI whose probability distribution tail essentially reaches the operational probability limit for precision approach. As such, any additional aggregate impact from new broadband wireless source unwanted emission will need to be well below that of the baseline environment. The limit used for these analyses is that the aggregate effect from additional in-band RFI does not increase the exceedance probability by more than 6 percent.[16]

J.7 GPS RECEIVE ANTENNA GAIN

An FAA Federal Advisory Committee, RTCA Special Committee (SC-159), developed a representative lower hemisphere antenna gain pattern model for the GPS receive antenna mounted on the top of the aircraft fuselage. The vertical and horizontal polarization pattern models are assumed to be azimuthally symmetric and dependent solely on the elevation angle from the aircraft horizon and represent the maximum gain for the particular RFI signal polarization. The gain pattern model is dependent on the approach category for which the aircraft is certified.

The lower hemisphere aircraft receive antenna pattern model in terms of gain versus elevation angle (angle between the aircraft horizon and the line joining aircraft and RFI source) is shown in Figure J.3. This pattern is used for the broadband handsets and base stations unwanted emission analyses when the source antenna heights are below the aircraft antenna height.

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[12] *Minimum Operational Performance Standards for GPS/Wide Area Augmentation System Airborne Equipment*, RTCA/DO-229, Appendix C, Table C-2.

[13] This safety margin applies for aircraft airborne and ground operations.

[14] *Final Report: A Generalized Statistical Model for Aggregate Radio Frequency Interference to Airborne GPS Receivers from Ground Based Emitters* (DOT/FAA/TC-14/30), September 30, 2014.

[15] The unwanted emissions from cellular mobile handsets, unlicensed wireless network interface infrastructure emitters and unintentional emissions from FCC Part 15 Class B digital devices.

[16] *FAA GPS Adjacent-Band Compatibility Study Methodology and Assumptions with RTCA SC-159 mark-ups*, RTCA Paper No. 095-15/SC159-1040.

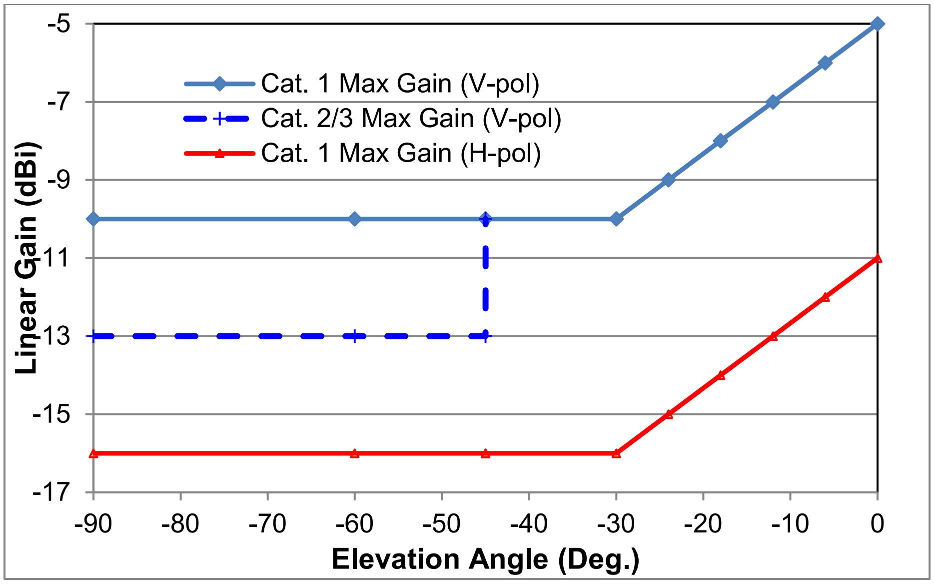

Figure J.3. Lower Hemisphere Installed V-Polarization and H-Polarization Receive Antenna Patterns Maximum Gain as a Function of Elevation Angle

The upper hemisphere aircraft installed receive antenna maximum gain pattern model for linear horizontal and vertical polarization is shown in Figure J.4. This pattern is used in cases when the source antennas are at, or above, the height of the aircraft antenna.

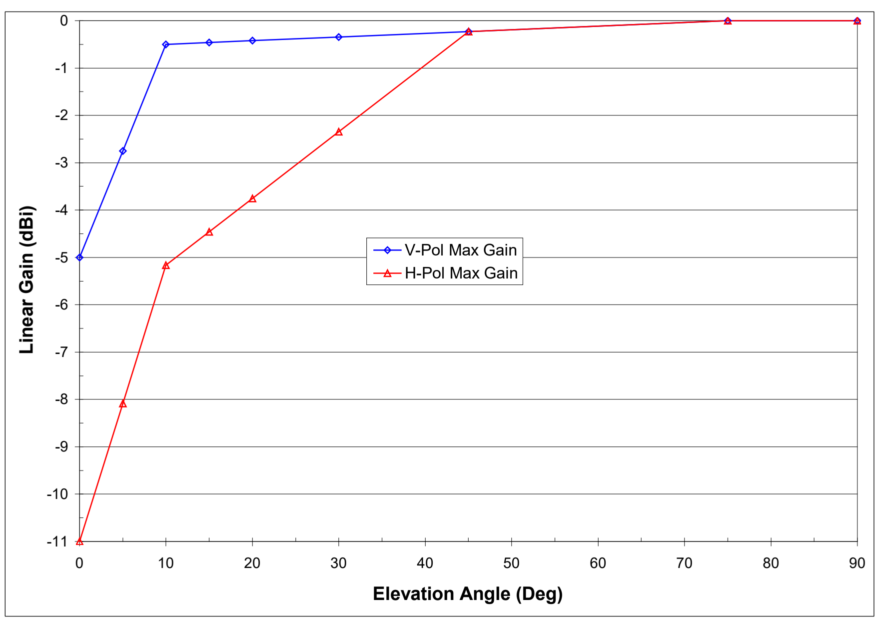

Figure J.4. Upper Hemisphere Installed V-Polarization and H-Polarization Receive Antenna Patterns Maximum Gain as a Function of Elevation Angle

In the analyses that follows, the aircraft antenna is either assumed to be boresighted at zenith (for an aircraft in level flight) or banked (for a banking aircraft) at a particular angle towards a particular azimuth bearing.

J.8 ANALYSIS RESULTS

The FAA's analysis defined and considered numerous conditions and scenarios as shown in Table J.1. The analysis showed that the helicopter terrain awareness warning system (HTAWS) case presents the most restrictive base station limits. Solution sensitivities to various parameters were assessed using examples from this case. The computed limit is also sensitive to the emitter polarization because, at some elevations, the aircraft antenna gains are larger for vertically polarized than for horizontally polarized signals. All analyses assumed an equal power combination of vertically and horizontally polarized waves (i.e., dual polarization).

The parameters varied during the HTAWS case study are listed below and after each parameter type the range of values explored are listed in parentheses. The computed maximum limit is sensitive to the following parameters and the interplay between these parameters:

- The heights of the emitter (10, 15, 20, 25 meters) and aircraft antennas (4 to 35 meters)
- The down tilt angle of the emitter antenna (2, 4, 6, and 8 degrees)
- The ground distance between the two antennas (100 feet versus 250 feet and vicinity)
- Flat ground versus Sloping ground (upward with a 10 milliradian slope)
- Level flight versus banking (at 25 degrees)
- Vertical versus dual polarization (equal power vertical and horizontal polarization)

In order to protect against all of the various permutations, the maximum base station equivalent isotropically radiated power must be limited to 9.8 dBW (39.8 dBm). It is very important to note that this result assumes (equal power split) dual polarization and highlights that a requirement for cross-polarization emissions from the base stations must be captured in any license application or issuance. A vertical polarization (only) based limit would be approximately 7.9 dBW (37.9 dBm).

Analysis has shown that the fundamental emission of the broadband wireless mobile handsets, at least up to the assumed 0 dBW (30 dBm) maximum power and operation above 1616 MHz, are not of concern for certified avionics. As a result, rather than determining an unknown fundamental power level of the base stations as described above, the broadband wireless handsets are assumed to operate with a specified unwanted emission limit (-95 dBW/MHz) within the aviation GPS receiver passband.

Table J.1. Summary of Scenarios and Findings

Scenario	Conditions	Comments
Inflight aircraft/ground-based handset	Final Approach Fix and Waypoint, Category I and Category II Decision Height.	Category II determined as most stringent case; Assessed, <6% threshold increase, not deemed a critical or limiting scenario
Inflight aircraft/ground base station	Random and discrete tower locations, aircraft level, and banking.	Assessed 1531 MHz at WIRSO location 125.64-meter altitude. Differences between 0^o, 25^o attitude as well as rare event attributed to tower distributions
Inflight aircraft/onboard handset	Aircraft at 10,000 ft. altitude.	Assessment premised on handset exhibiting characteristics of Wi-Fi at 2.45 GHz, no further assessment required
Aircraft on ground/onboard handset	Aircraft antenna at 4 meters.	Assessed, not deemed a critical or limiting scenario
Aircraft at Gate/Single Handset Source on or near Boarding Stairs or Jetway	0 dBW @ 1616 MHz.	Assessed, 3.5 meters minimum separation distance
Aircraft at gate/users inside airport	Random distribution of thirty handsets.	Assessed, not deemed critical or limiting scenario
Fixed-wing and helicopter terrain awareness warning system (TAWS/HTAWS) scenarios with ground-based mobile broadband handsets	Three handset surface concentrations with -95 dBW/MHz in the GPS L1 receiver passband, two aircraft antenna heights.	Assessed, found fundamental emission effects insignificant, no further assessment required
TAWS and HTAWS Scenarios with Broadband Base Station	Base stations located on a grid with 433 meters or 693 meters inter-site distance. Base station heights of 6, 10, 15 and 25 meters were considered, with 2, 4, 6, and 8-degree antenna down tilt. Aircraft was assumed at the worst-case location on the stand-off cylinder, both level flight and 25-degree bank toward the base station. Additional parameters including sloping ground were utilized as part of a sensitivity analysis,	Fixed location base stations in hexagonal grid with 433 meters and 693 meters inter-site distances, flat earth and funnel terrain, aircraft lateral distances of 15.2-76.2 meters, 25^o and 0^o banking. Both Monte Carlo and Analytic Statistical methods used for assessment. Assessment found HTAWS the most restrictive scenario

APPENDIX K
NON-CERTIFIED AVIATION GPS RECEIVER ANALYSIS

K.1 INTRODUCTION

This appendix describes the analysis performed by the Technical Focus Group (TFG) of GPS general aviation (GAV) and high precision (HP) receivers operating on an unmanned aerial vehicle (UAV). The following equation is used to calculate the received power:

$$P_R = EIRP - L_{GPS} - L_{BS} - L_P$$

where:

P_R: received power at GPS receiver input (dBm/10 MHz);
EIRP: equivalent isotropic-ally radiated power of the base station (dBm/10 MHz);
L_{GPS}: normalized, off-boresight loss of the GPS antenna (dB);[1]
L_{BS}: off-axis loss of the base station antenna (dB);[2] and
L_P: propagation loss (dB).

In this analysis, an equivalent isotropically radiated power (EIRP) of 40 dBm/10 MHz is used for small cell base stations and 62 dBm/10 MHz for macro cell base stations.

The propagation loss is calculated in the analysis for different UAV heights, separation distances, and base station antenna heights. The free-space model is used to compute propagation loss:

$$L_P = 20 \text{ Log } (F) + 20 \text{ Log } (D) - 27.55$$

where:
F: Frequency (MHz); and
D: Distance (meter).

For the small cell base station analysis, UAV heights are varied from 20 to 40 meters in 1-meter increments. For the macro cell base station analysis, UAV heights are varied from 35 to 55 meters in 1-meter increments. Level flight and banked (25 degrees) UAV operation is considered.

K.2 GPS RECEIVE ANTENNA MASK

The General Location/Navigator Receiver Category (GLN) and High Precision Receiver Category (HP) antenna masks used in the analysis are shown in Figure K.1 and Figure K.2. The receive antenna gain values assume GPS antenna positioned at incident angles. The different test programs radiated the interfering power at the zenith. The test programs did not adjust their measurement for the gain of the antenna for the GPS receiver under test. The GPS receiver gain

[1] GPS off-boresight antenna loss is used because the test data was taken at the GPS antenna boresight.

[2] Normalized, off-boresight base station antenna loss is used because the base station transmit EIRP is specified in terms of the maximum antenna gain.

was normalized at the zenith to 0 Decibel(s) (dB) because of the test setup used. The receive antenna masks were developed using the 80th percentile of the measured gain pattern.

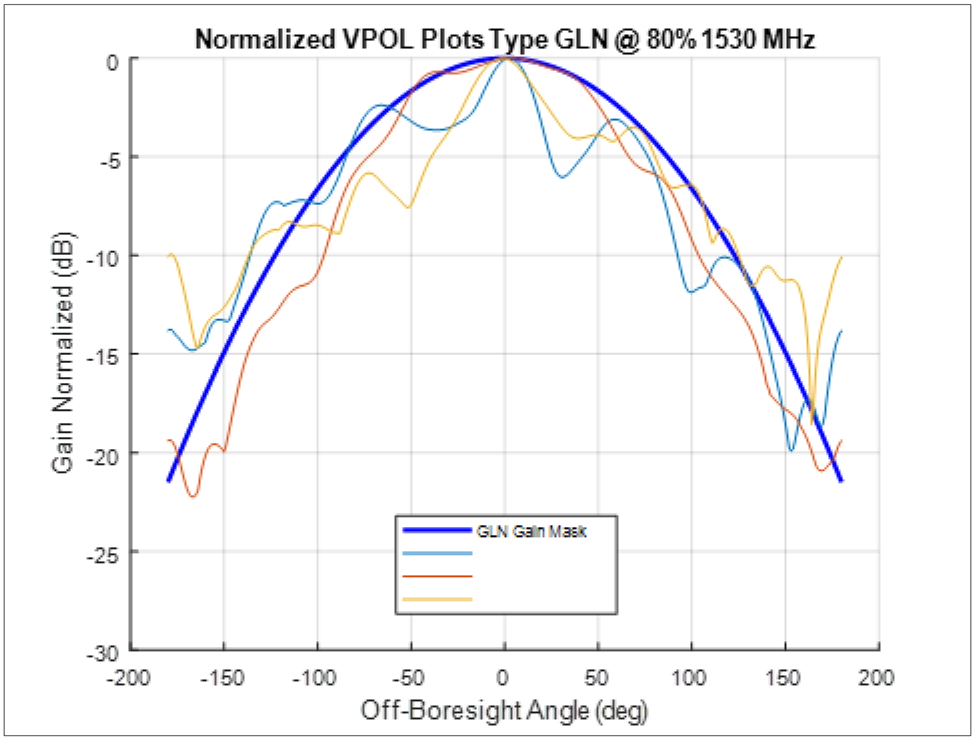

Figure K.1. Normalized GLN Antenna Gain

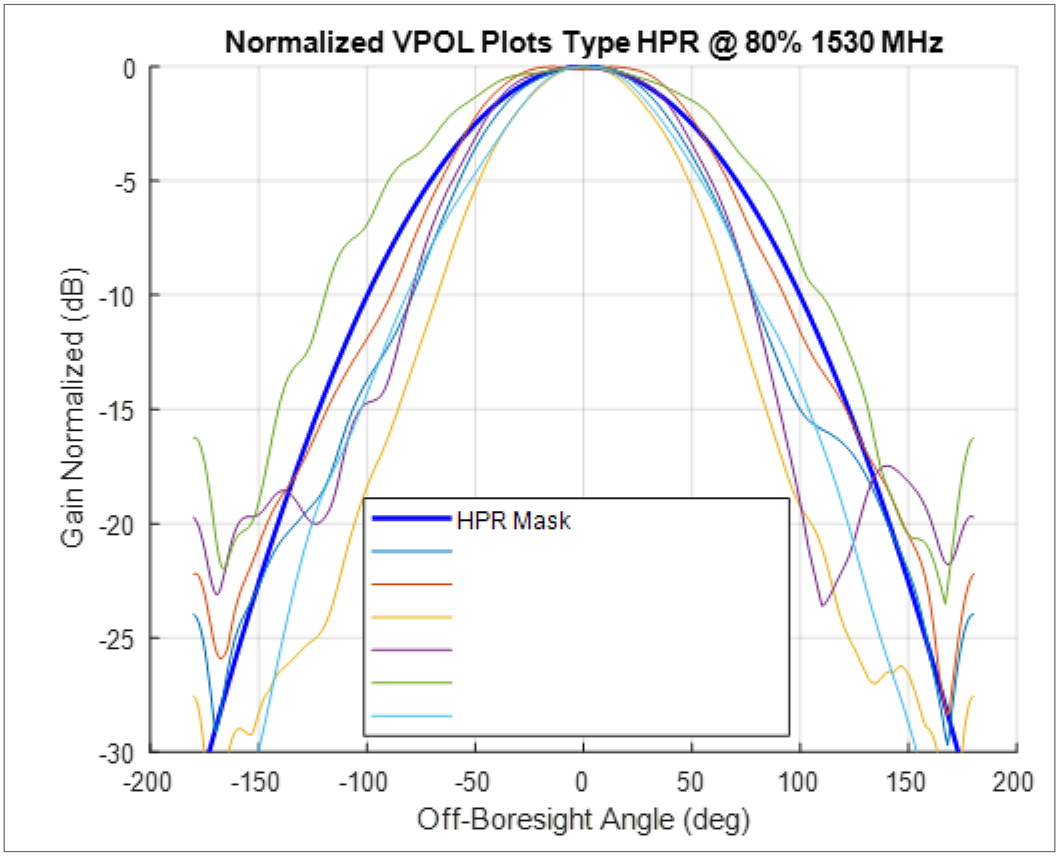

Figure K.2. Normalized HP Antenna Gain

K.3 GPS RECEIVER INTERFERENCE POWER LEVELS

The GPS receiver interference power levels for the HP and GLN receivers considered in this analysis are summarized in Table K.1 and Table K.2.

Table K.1. Summary of HP GPS Receiver Interference Power Levels

Interfering Signal in the 1525-1535 MHz/1526-1536 MHz Bands						
Interference Power Level (dBm/10 MHz)	Number of Receivers			Percentage of Receivers		
	Degradation in C/N_0					
	1 dB	3 dB	5 dB	1 dB	3 dB	5 dB
≤ -75	1			1.2 %		
≤ -70	3			3.6 %		
≤ -65	8			9.5 %		
≤ -60	12	5	2	14.3 %	10 %	4 %
≤ -55	18	9	6	21.4 %	18 %	12 %
≤ -50	26	11	9	30.9 %	22 %	18 %
≤ -45	30	16	13	35.7 %	32 %	26 %
≤ -40	43	19	18	51.2 %	38 %	36 %
≤ -35	50	24	23	59.5 %	48 %	46 %
≤ -30	56	29	26	66.7 %	58 %	52 %
≤ -25	61	31	30	72.6 %	62 %	60 %
≤ -20	71	33	31	84.5 %	66 %	62 %
≤ -15	73	37	33	86.9 %	74 %	66 %
≤ -10	81	47	47	96.4 %	94 %	94 %
≤ -5	81	47	47	96.4 %	94 %	94 %
≤ 0	82	47	47	97.6 %	94 %	94 %
≤ 5	84	50	50	100 %	100 %	100 %

Table K.2. Summary of GAV GPS Receiver Interference Power Levels

Interfering Signal in the 1525-1535 MHz Band						
Interference Power Level (dBm/10 MHz)	Number of Receivers			Percentage of Receivers		
	Degradation in C/N_0					
	1 dB	3 dB	5 dB	1 dB	3 dB	5 dB
≤ -55	2			18.2 %		
≤ -50	2			18.2 %		
≤ -45	3			27.3 %		
≤ -40	3	3	1	27.3 %	27.3 %	9.1 %
≤ -35	4	3	2	36.4 %	27.3 %	18.2 %
≤ -30	11	3	3	100 %	27.3 %	27.3 %
≤ -25		11	9		100 %	81.8 %
≤ -20			11			100

K.4 SMALL CELL BASE STATION ANALYSIS

The small cell base station antenna gain reduction plots shown in Figure K.3 are used to compute the off-axis loss for down-tilt angles of 2, 4, and 6 degrees.[3] The mainbeam antenna gain is 5 Decibel(s) relative to an isotropic antenna (dBi).

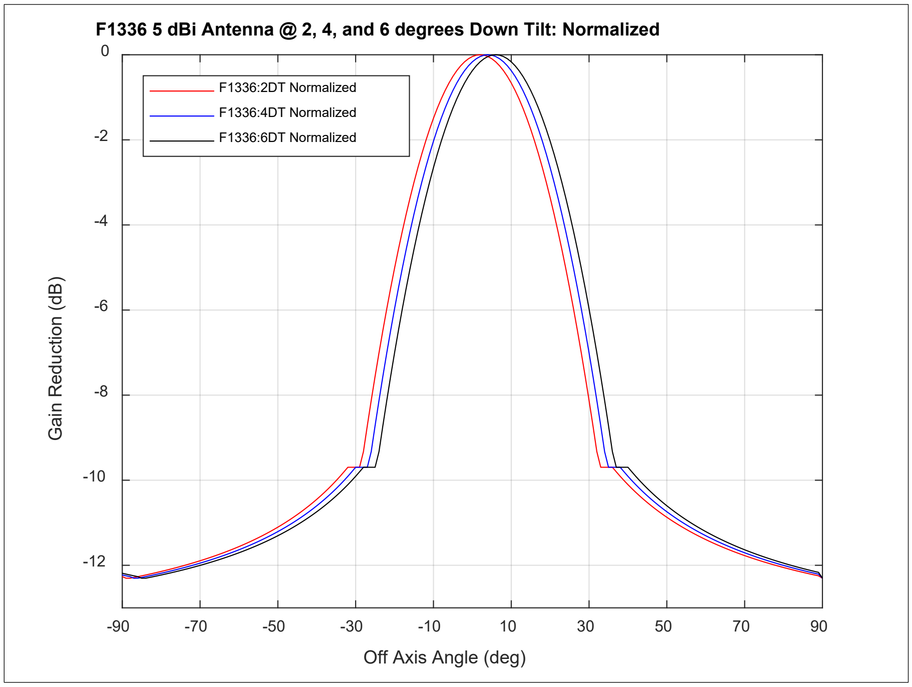

Figure K.3. Small Cell Base Station Normalized Gain Plot

The received power as a function of separation distance is shown in Figure K.4. The percentage of GAV receivers degraded based on a 1 dB, 3 dB, and 5 dB reductions in Carrier-to-Noise Density (C/N_0) are shown in Figure K.5.

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[3] Recommendation ITU-R F.1336-4, *Reference Radiation Patterns of Omnidirectional, Sectoral and Other Antennas for the Fixed and Mobile Services for Use in Sharing Studies in the Frequency Range from 400 MHz to About 70 GHz* (Feb. 2014), *available at* https://www.itu.int/dms_pubrec/itu-r/rec/f/R-REC-F.1336-4-201402-S!!PDF-E.pdf. The antenna model is described in Recommends 2.1 (*ITU-R F.1336-4*).

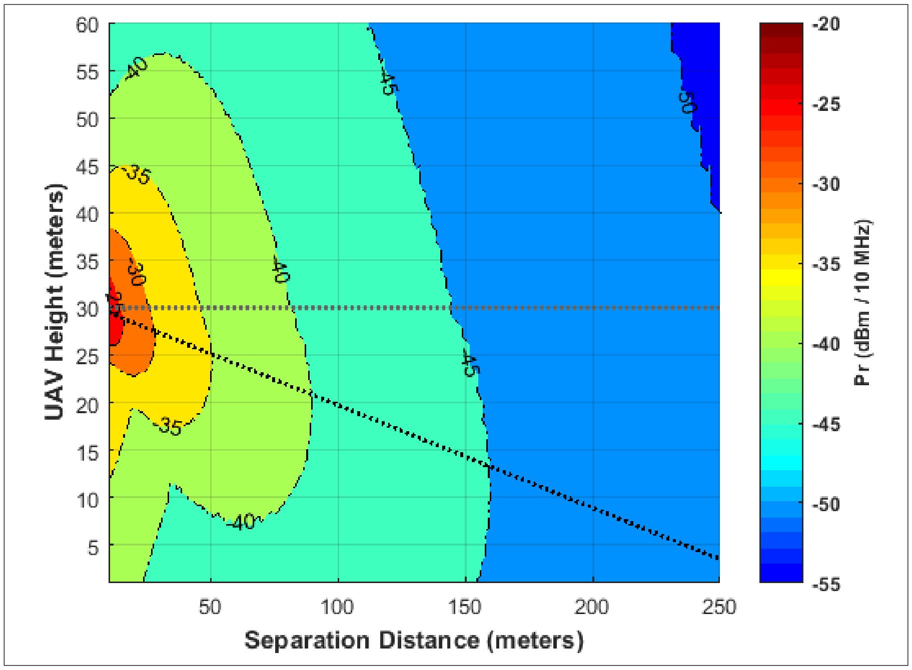

Figure K.4a. Received Power Contour – GAV/GLN Base Station EIRP of 40 dBm/10 MHz (UAV Un-Banked)

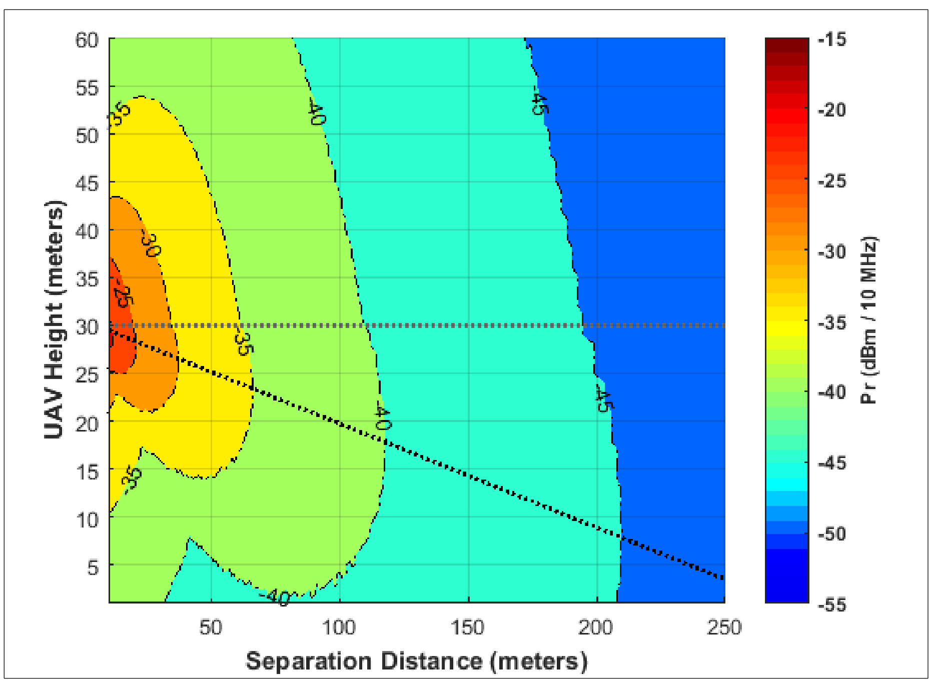

Figure K.4b. Received Power Contour – GAV/GLN Base Station EIRP of 40 dBm/10 MHz (UAV Banked 25 degrees)

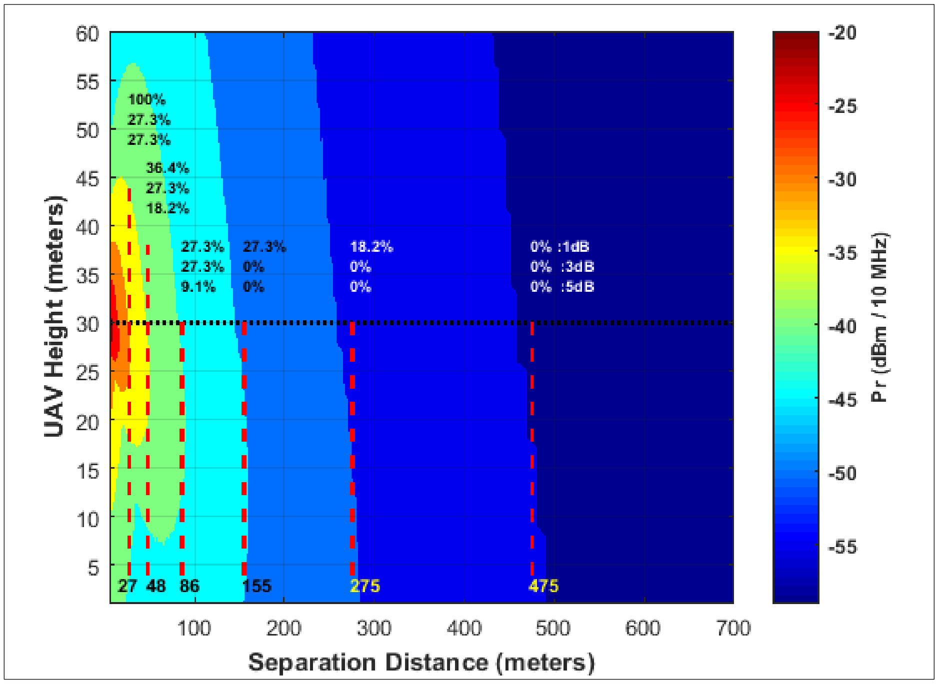

Figure K.5a. Percentage of GPS Receivers Degraded – GAV/GLN Base Station EIRP of 40 dBm/10 MHz (UAV Un-Banked)

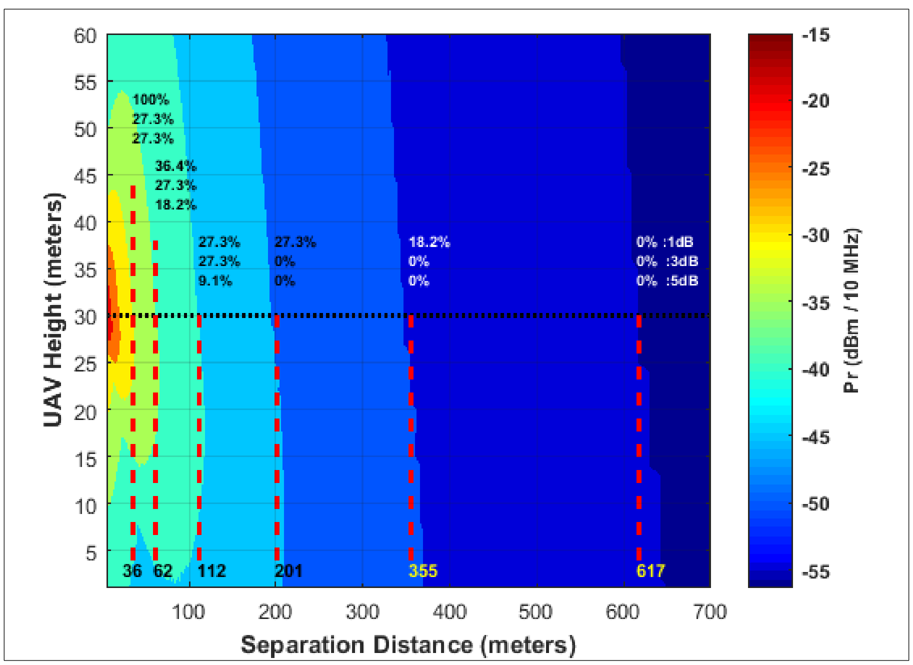

Figure K.5b. Percentage of GPS Receivers Degraded – GAV/GLN Base Station EIRP of 40 dBm/10 MHz (UAV Banked 25 Degrees)

The received power as a function of separation distance is shown in Figure K.6. The percentage of HP receivers degraded based on a 1 dB, 3 dB, and 5 dB reduction in C/N_0 is shown in Figure K.7.

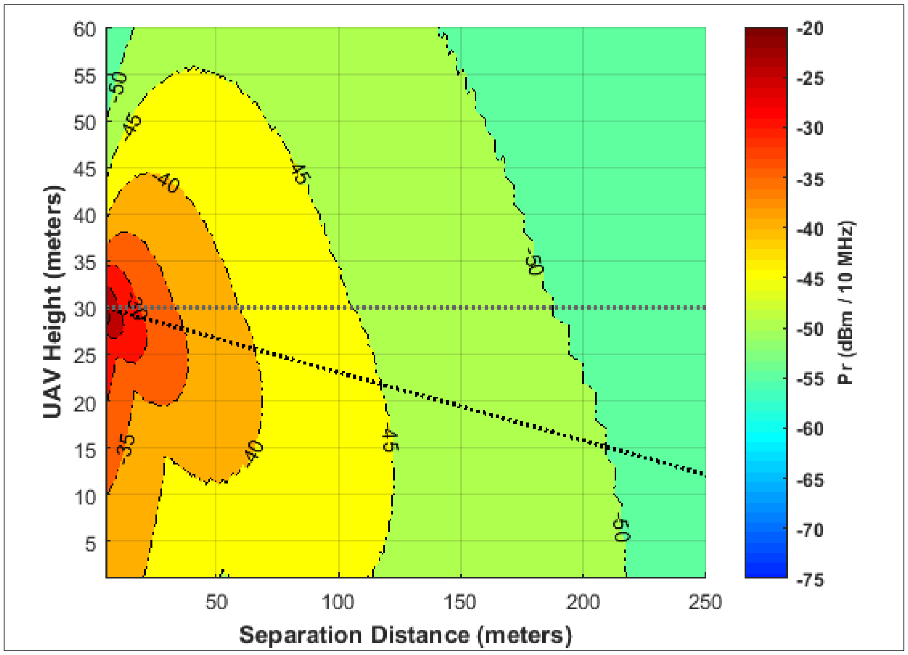

Figure K.6a. Received Power Contour – HP Base Station EIRP of 40 dBm/10 MHz (UAV Un-Banked)

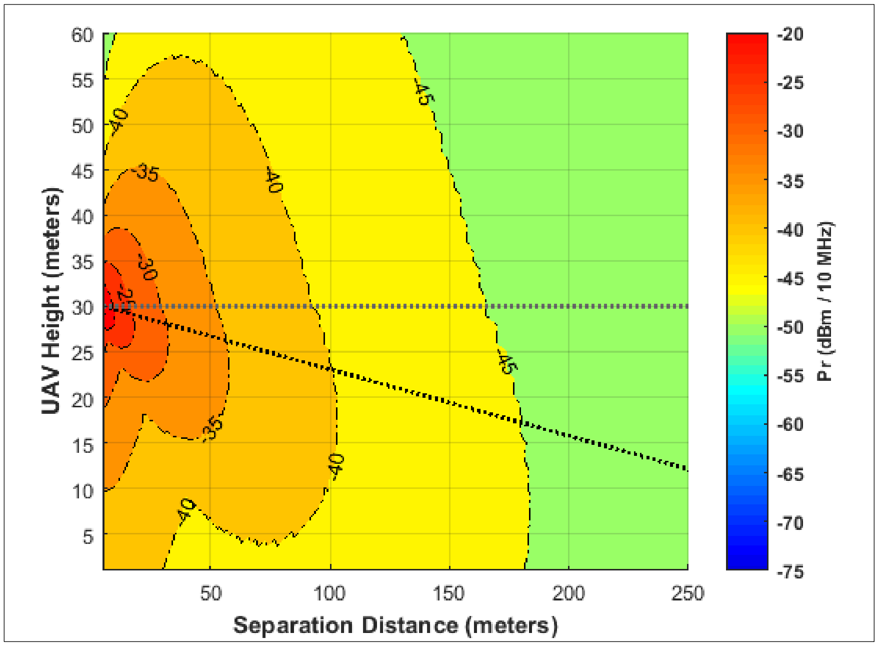

Figure K.6b. Received Power Contour – HP Base Station EIRP of 40 dBm/10 MHz (UAV Banked 25 degrees)

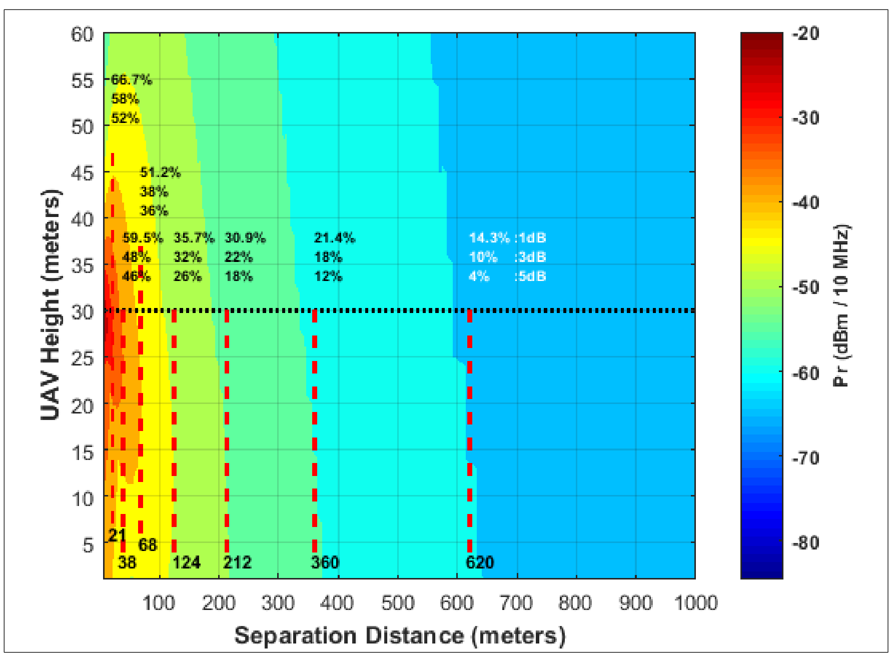

Figure K.7a. Percentage of GPS Receivers Degraded – HP Base Station EIRP of 40 dBm/10 MHz (UAV Un-Banked)

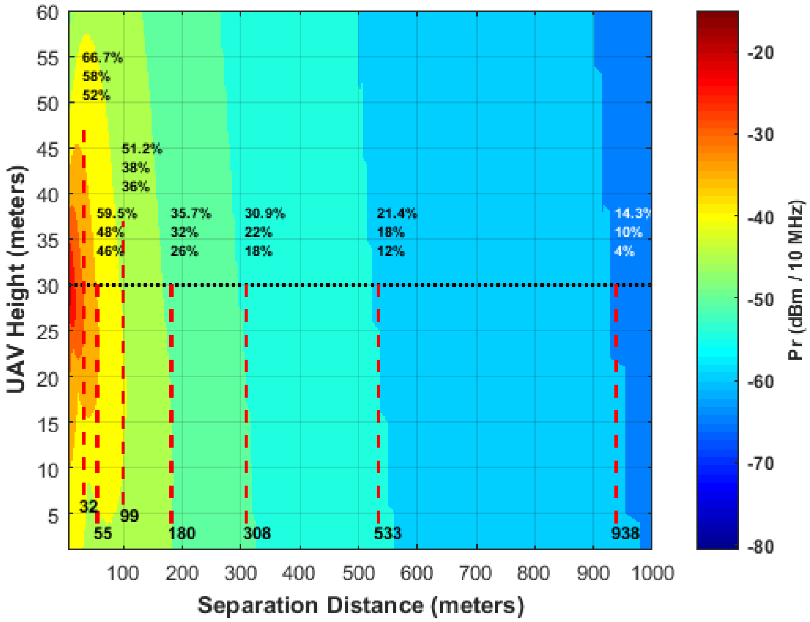

Figure K.7b. Percentage of GPS Receivers Degraded – HP Base Station EIRP of 40 dBm/10 MHz (UAV Banked 25 degrees)

K.5 MACRO CELL BASE STATION ANALYSIS

The macro cell base station antenna gain reduction plots shown in Figure K.8 are used to compute the off-axis loss for down-tilt angles of 2, 4, and 6 degrees.[4] The mainbeam antenna gain is 16 dBi.

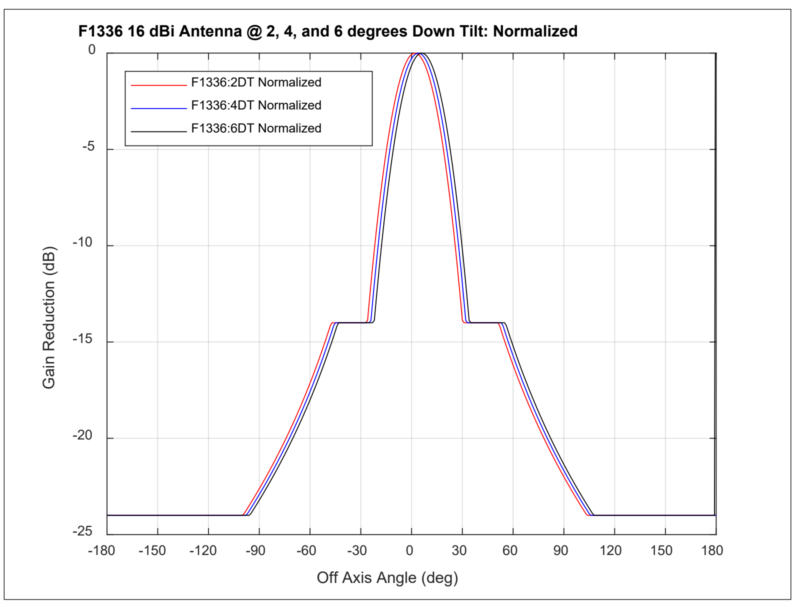

Figure K.8. Macro Cell Base Station Normalized Gain Plot

[4] *ITU-R F.1336-4.*

The received power as a function of separation distance is shown in Figure K.9. The percentage of GAV receivers degraded based on a 1 dB, 3 dB, and 5 dB reductions in C/N_0 are shown in Figure K.10 and Figure K.11.

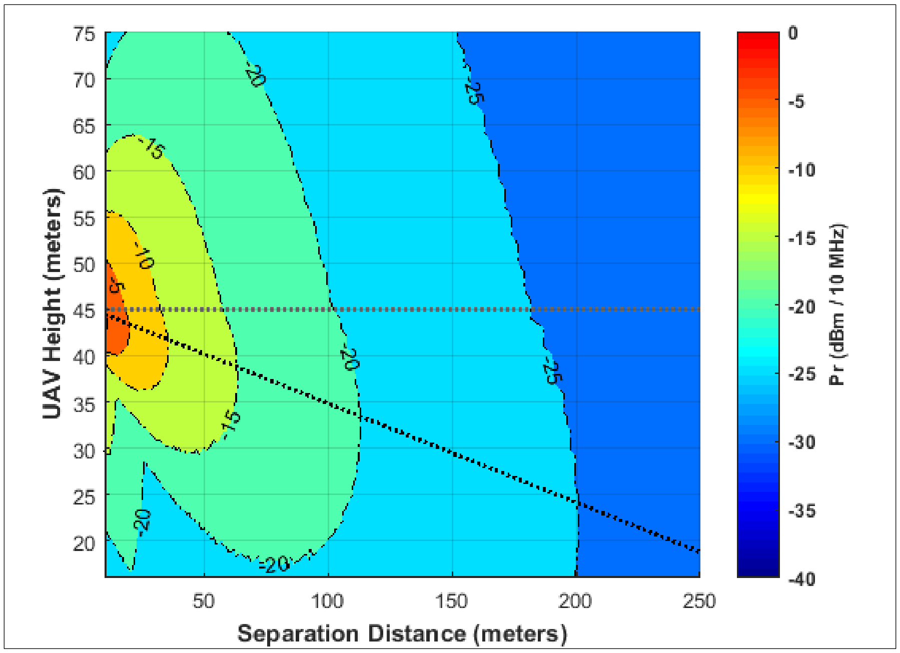

Figure K.9a. Received Power Contour – GAV/GLN Base Station EIRP of 62 dBm/10 MHz (UAV Un-Banked)

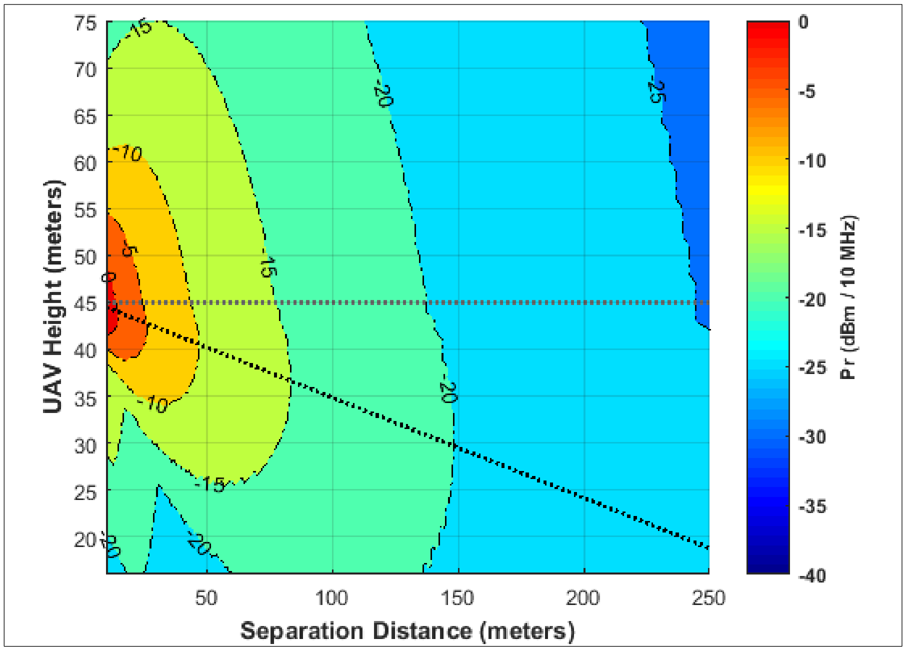

Figure K.9b. Received Power Contour – GAV/GLN
Base Station EIRP of 62 dBm/10 MHz
(UAV Banked 25 degrees)

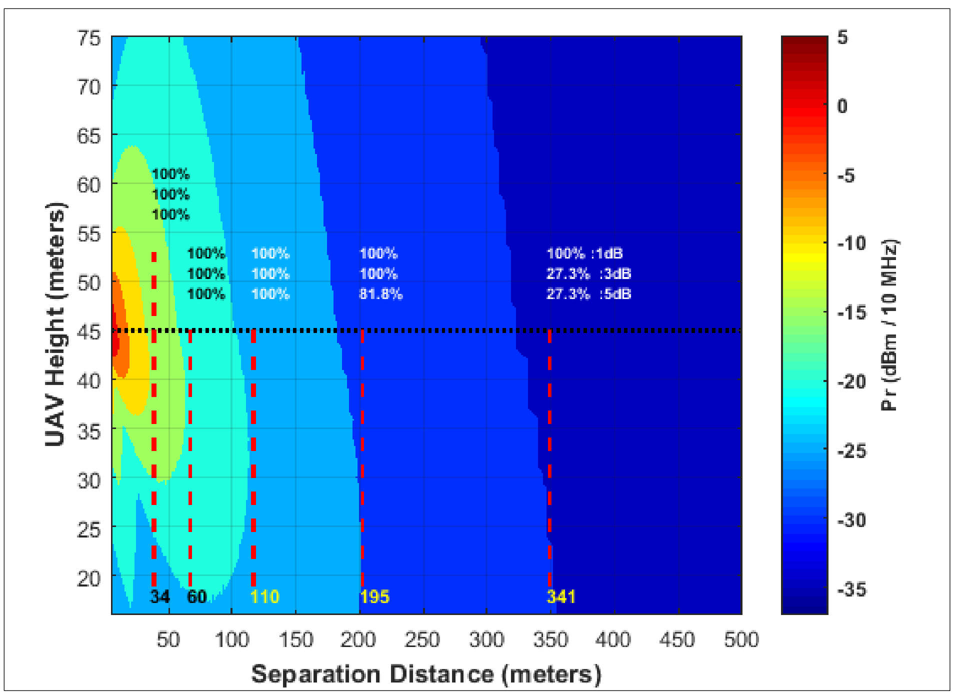

Figure K.10a. Percentage of GPS Receivers Degraded – GAV/GLN
Base Station EIRP of 62 dBm/10 MHz
(UAV Un-Banked)

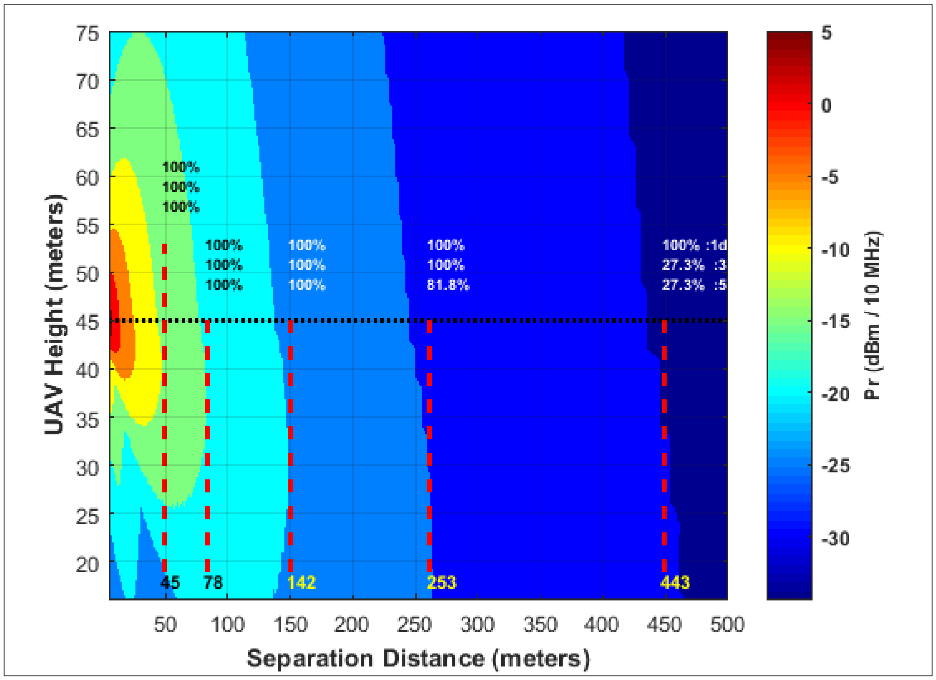

Figure K.10b. Percentage of GPS Receivers Degraded – GAV/GLN
Base Station EIRP of 62 dBm/10 MHz
(UAV Banked 25 Degrees)

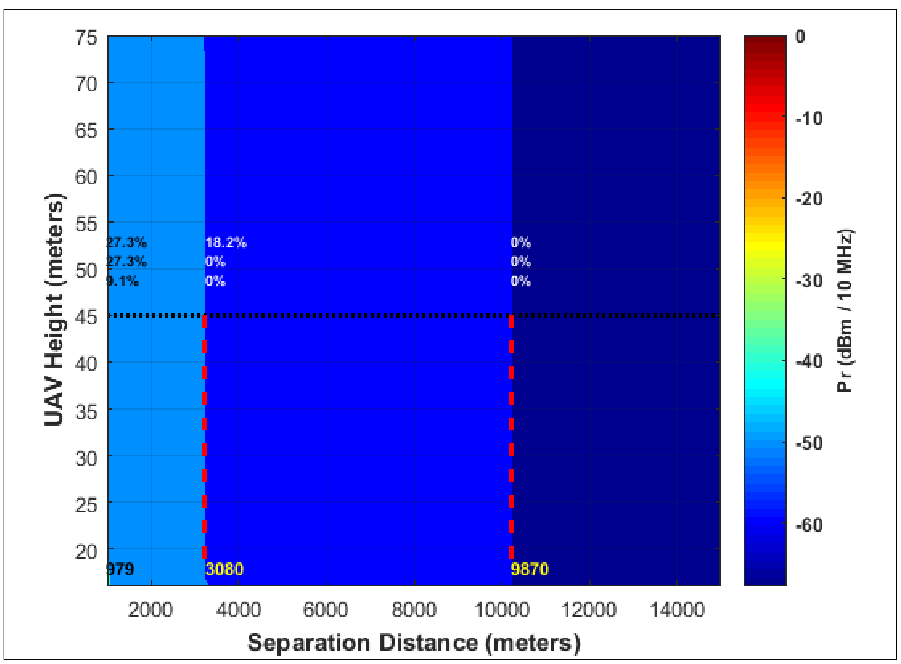

Figure K.11a. Percentage of GPS Receivers Degraded – GAV/GLN
Base Station EIRP of 62 dBm/10 MHz
(UAV Un-Banked)

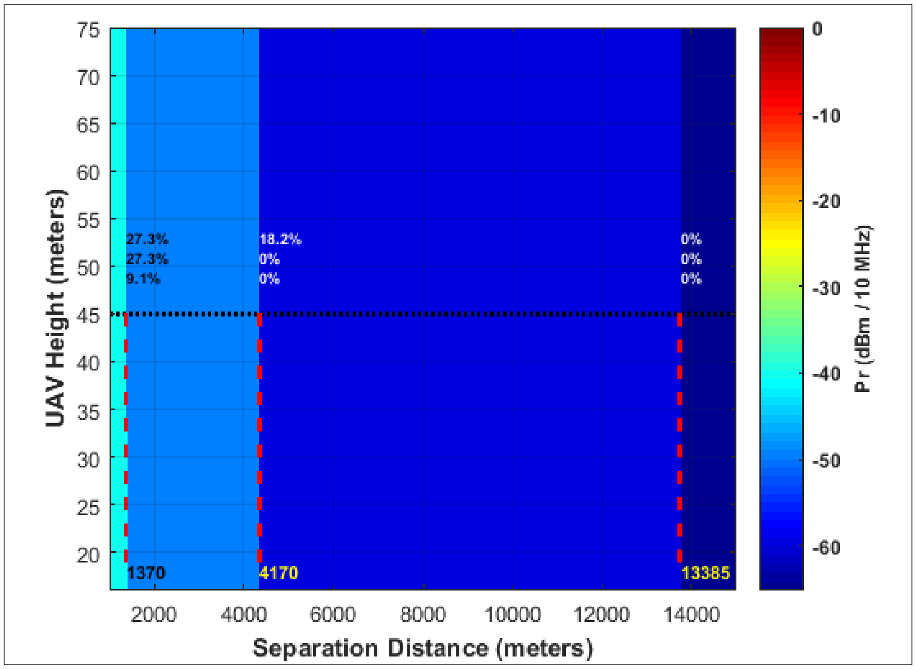

Figure K.11b. Percentage of GPS Receivers Degraded – GAV/GLN Base Station EIRP of 62 dBm/10 MHz (UAV Banked 25 Degrees)

The percentage of HP receivers degraded based on a 1 dB, 3 dB, and 5 dB reduction in C/N_0 are shown in Figures K.12 through K.14.

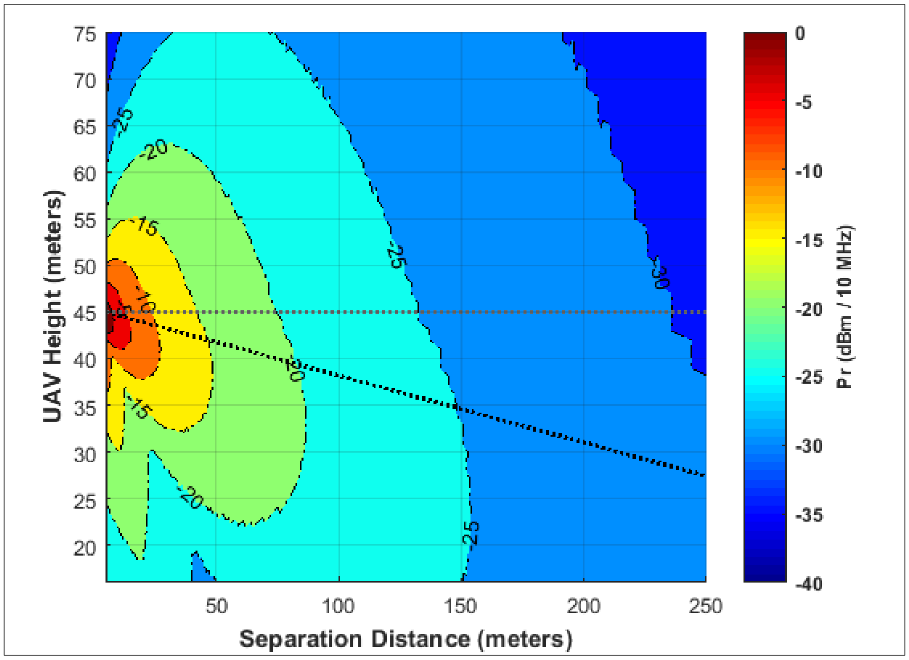

Figure K.12a. Received Power Contour – HP Base Station EIRP of 62 dBm/10 MHz (UAV Un-Banked)

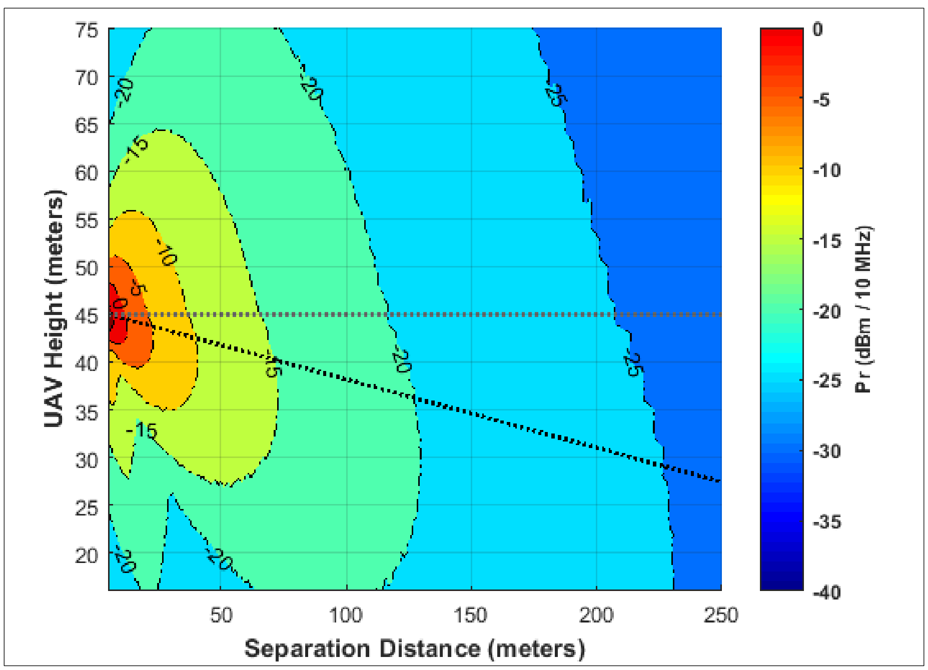

Figure K.12b. Received Power Contour – HP Base Station EIRP of 62 dBm/10 MHz (UAV Banked 25 Degrees)

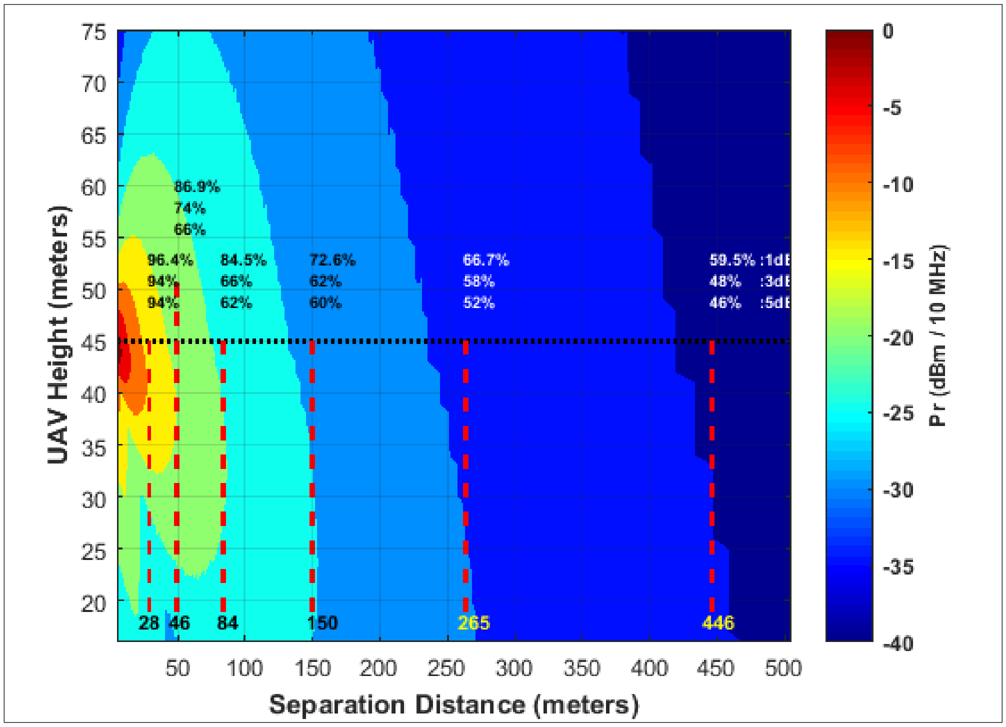

Figure K.13a. Percentage of GPS Receivers Degraded – HP Base Station EIRP of 62 dBm/10 MHz (UAV Un-Banked)

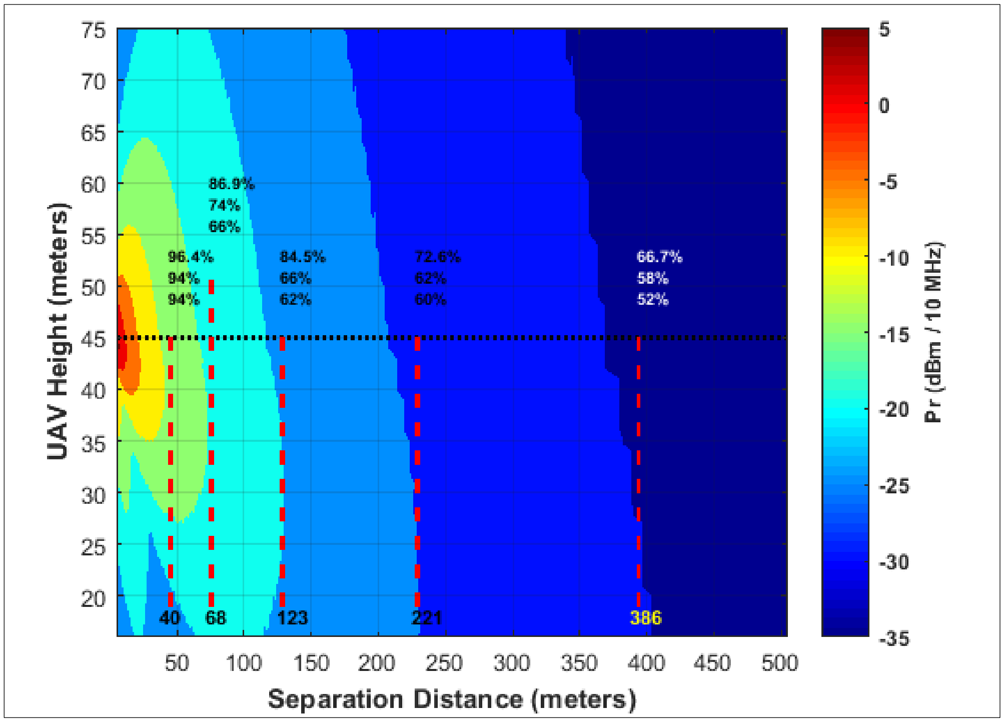

Figure K.13b. Percentage of GPS Receivers Degraded – HP Base Station EIRP of 62 dBm/10 MHz (UAV Banked 25 Degrees)

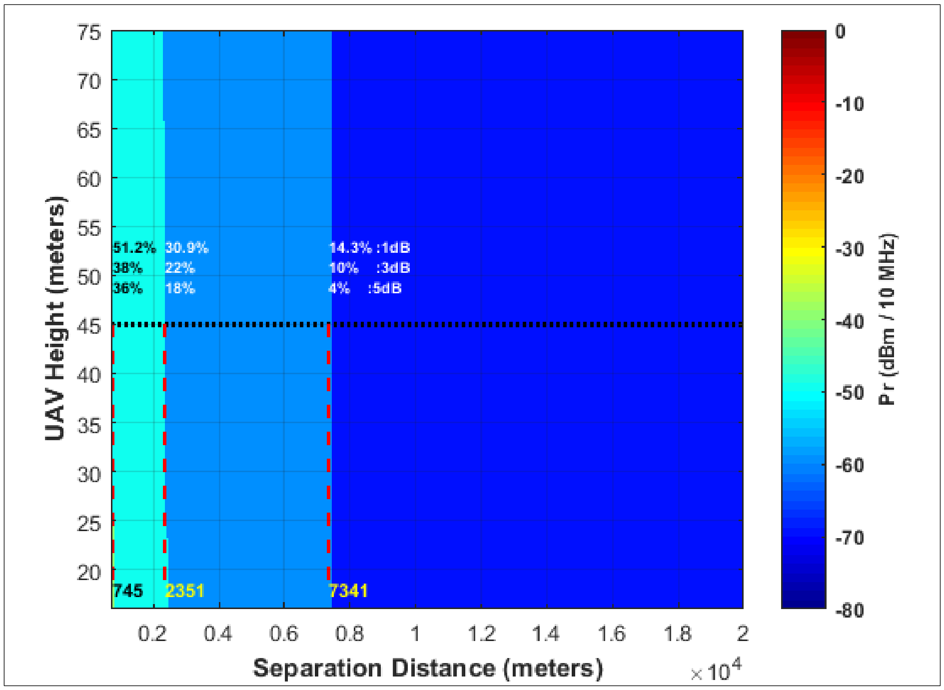

Figure K.14a. Percentage of GPS Receivers Degraded – HP Base Station EIRP of 62 dBm/10 MHz (UAV Un-Banked))

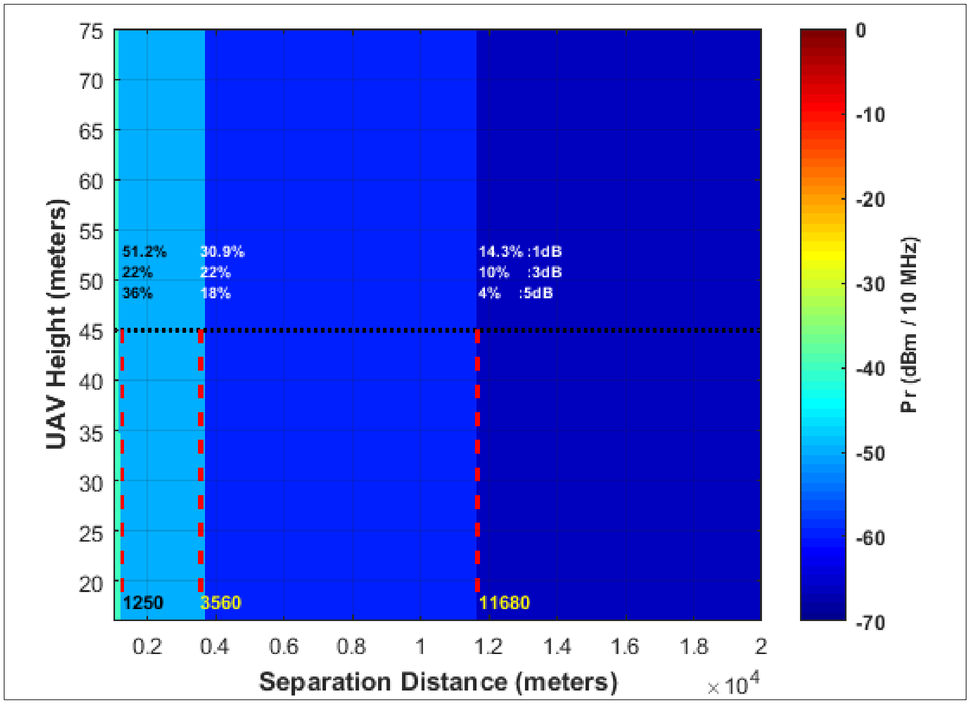

Figure K.14b. Percentage of GPS Receivers Degraded – HP Base Station EIRP of 62 dBm/10 MHz (UAV Banked 25 Degrees)

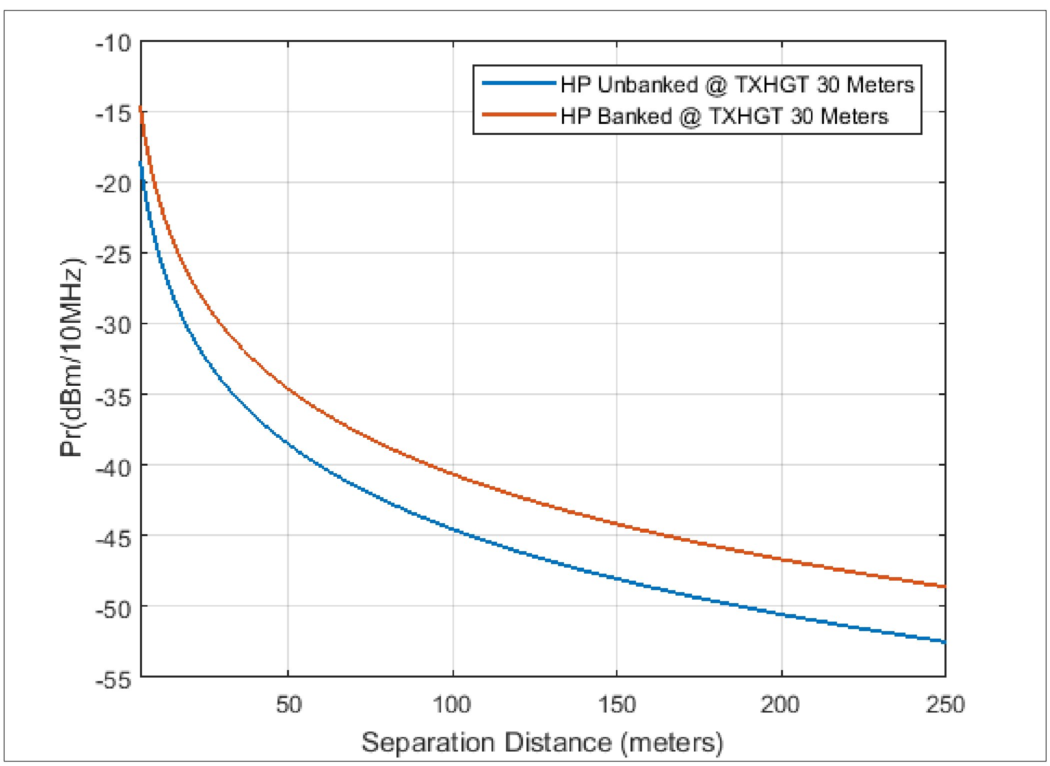

Figure K.15. Comparison of UAV Un-banked and Banked Received Power Levels

APPENDIX L
PSEUDORANGE AND POSITION RMS ERROR VERSUS C/N$_0$ FOR SIMPLE L1 C/A RECEIVER ARCHITECTURE

L.1 INTRODUCTION

This appendix was prepared by the Department of Transportation and has two main sections. Section L.2 discusses the relationship between pseudorange (PR) root-mean-square (RMS) error and carrier-to-noise-density ratio (C/N$_0$) by looking at the tracking loop errors assuming ionospheric and tropospheric corrections are applied and multipath is not present. Section L.3 discusses the position error dependence on PR RMS error (and therefore C/N$_0$).

L.2 PR RMS ERROR AND C/N$_0$

Measurable PR RMS error dependence on a particular C/N$_0$ degradation level (such as 1 dB) is a strong function of the baseline C/N$_0$ level. This can be illustrated by inspecting the non-linear dependence on C/N$_0$ of both the code tracking loop error (for medium accuracy applications), and the carrier tracking loop error (for high accuracy applications).

L.2.1 C/N$_0$ Degradation Effects on Code Tracking Loop Error and Pseudo-Range

The top plot in Figure L.1 is the RMS tracking loop error as a function of C/N$_0$ for a loop bandwidth of 1 Hertz (Hz) and a pre-detection integration time of 20 milliseconds. The lower plot in Figure L.1 is the change in RMS tracking loop error per 1 Decibel (dB) change in C/N$_0$ as a function of C/N$_0$. For example, with a baseline of 30 dB-Hz C/N$_0$ (representing stressed conditions) the RMS loop error changes approximately 55 centimeters (cm) with a change of 1 dB compared with approximately 10 cm when the baseline C/N$_0$ is 45 dB-Hz (direct overhead conditions).

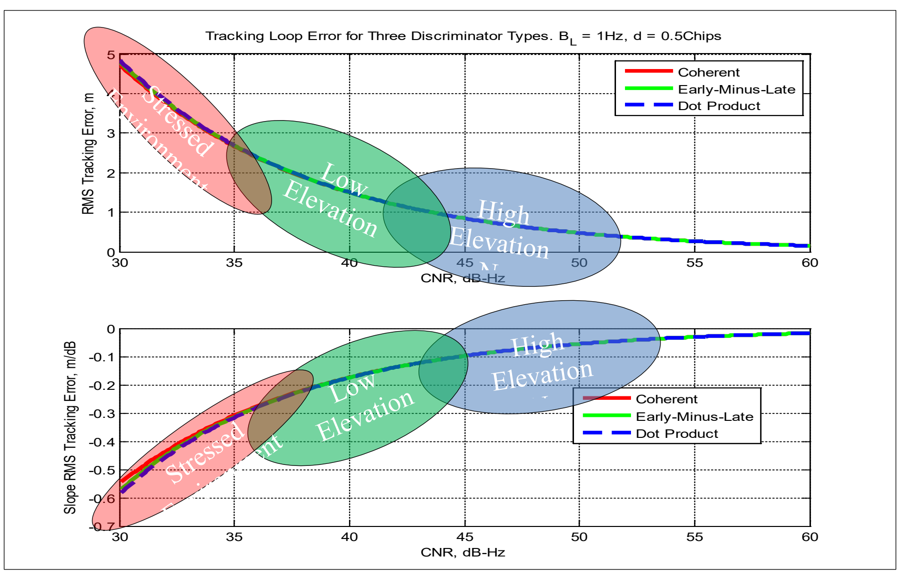

Figure L.1. Tracking Loop Error as a Function of C/N$_0$

Therefore, looking at 1 dB degradation effect on PR RMS error at a particular C/N_0 value is not representative for all receiver conditions. Furthermore, averaging of PRs over a large integration time (for example 1 second or more) will mask the effect on the tracking loop in high dynamic conditions.

Also it is important to note that the low C/N_0 values ($\leq$ 30dB-Hz) are not uncommon, as discussed later in this appendix.

L.2.2 C/N_0 Degradation Effects on Carrier Tracking Loop Error and Pseudo Range for High Accuracy Applications

High accuracy applications typically utilize some form of carrier aiding, and often ultimately use carrier phase measurements for ranging (e.g., in real-time kinematic (RTK) systems). Therefore, the carrier tracking loop RMS errors become significant for such applications. The theoretical approximation of Costas carrier tracking error as a function of C/N_0 is shown in Figure L.2.

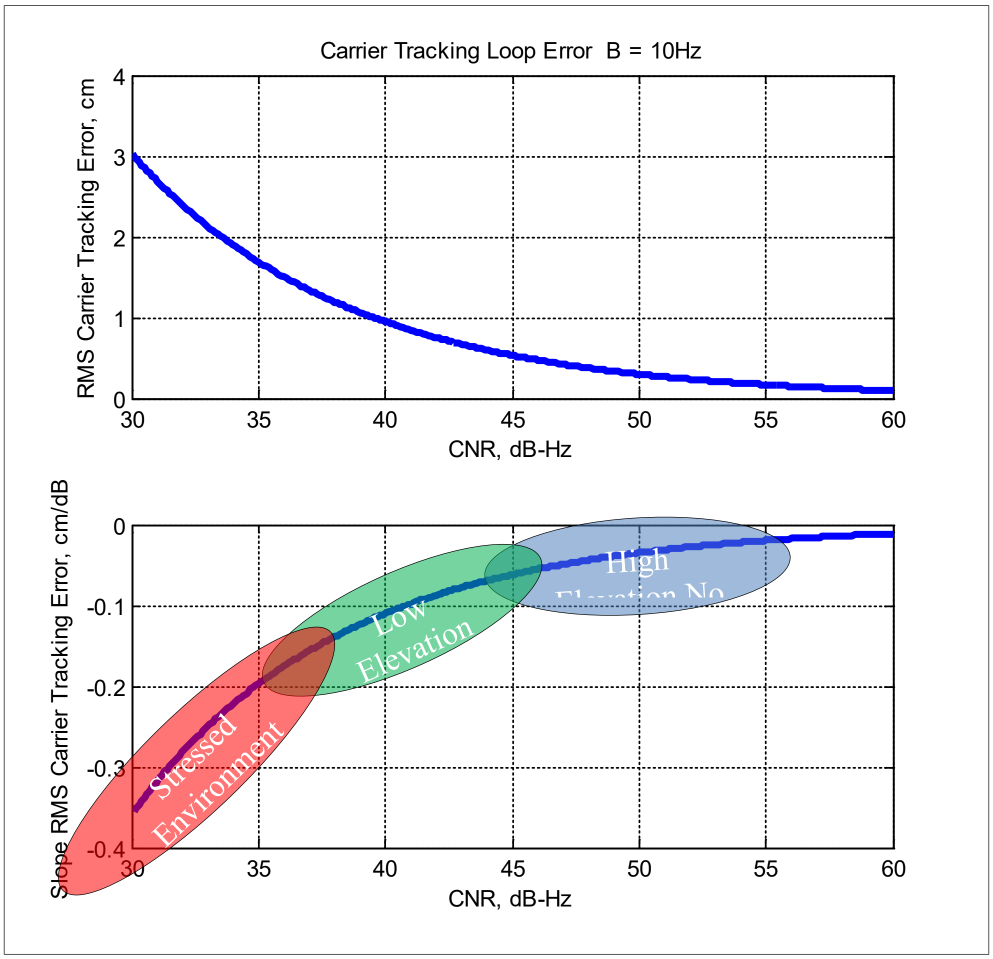

Figure L.2. Carrier Tracking Error as a function of C/N_0

Again the same C/N_0 degradation amount under stressed conditions corresponds to significantly larger carrier tracking error than for the case of a clear line-of-sight and high elevation Satellite Vehicle (SV) conditions. For example, a 1 dB degradation at a C/N_0 of 30 dB-Hz corresponds to approximately 36 millimeters RMS carrier tracking error compared to near 6 millimeters at 45 dB-Hz (a factor of 6 difference). Furthermore, many high precision receivers will abruptly cease carrier phase tracking at C/N_0 below 27 to 30 dB-Hz due to unreliable loop operation (and inability to read the broadcast navigation data) at lower C/N_0.

L.3 RELATION BETWEEN PR AND POSITION RMS ERRORS

The position error is directly dependent on the PR errors in the case of a frozen constellation. However, this is not the case for a moving constellation when satellites are dropped and others are acquired (due to setting of some SVs and/or rising of others) creating fast changes in the direction cosines between the receiver and the SVs involved in the solution for the receiver's location.

The differential position and clock correction vector (Δx) relation to the differential vector of PRs (ΔPR) is:

$$\Delta PR = G.\Delta x + \epsilon$$

where G (nx4) is the Jacobian of PR with respect to x. The first three elements of each row are the direction cosines from the receiver to each of the SVs and the last element reflects the one-to-one mapping of receiver clock errors into pseudorange.

For a least squares solution and assuming independent identically distributed PR errors for all satellites, the position and clock error covariance matrix ($C_{\Delta x}$) is related to the PR RMS error (σ_R) as follows:

$$C_{\Delta x} = (G^T G)^{-1}\sigma_R^2 = D.\sigma_R^2 \quad .$$

The total position error standard deviation is: $\sigma_P = \sqrt{D_{11} + D_{22} + D_{33}}.\sigma_R = PDOP.\sigma_R$

The position dilution of precision (PDOP) is solely a function of the relative geometry between the receiver and SVs involved in calculating the position solution. PDOP is unitless and typically ranges between values of 1 and 6 as can be seen in Figure L.3 (along with other dilutions of precision); this figure is taken from an older *GPS World* article.[1] Therefore, for the same PR error the variation in PDOP will act to mask the effects of changes in PR due to C/N_0 degradation.

---

[1] Richard B. Langley, "Dilution of Precision", *GPS World* May 1999 at 59. In addition to PDOP, vertical dilution of precision (VDOP), horizontal dilution of precision (HDOP), and time dilution of precision (TDOP) are shown.

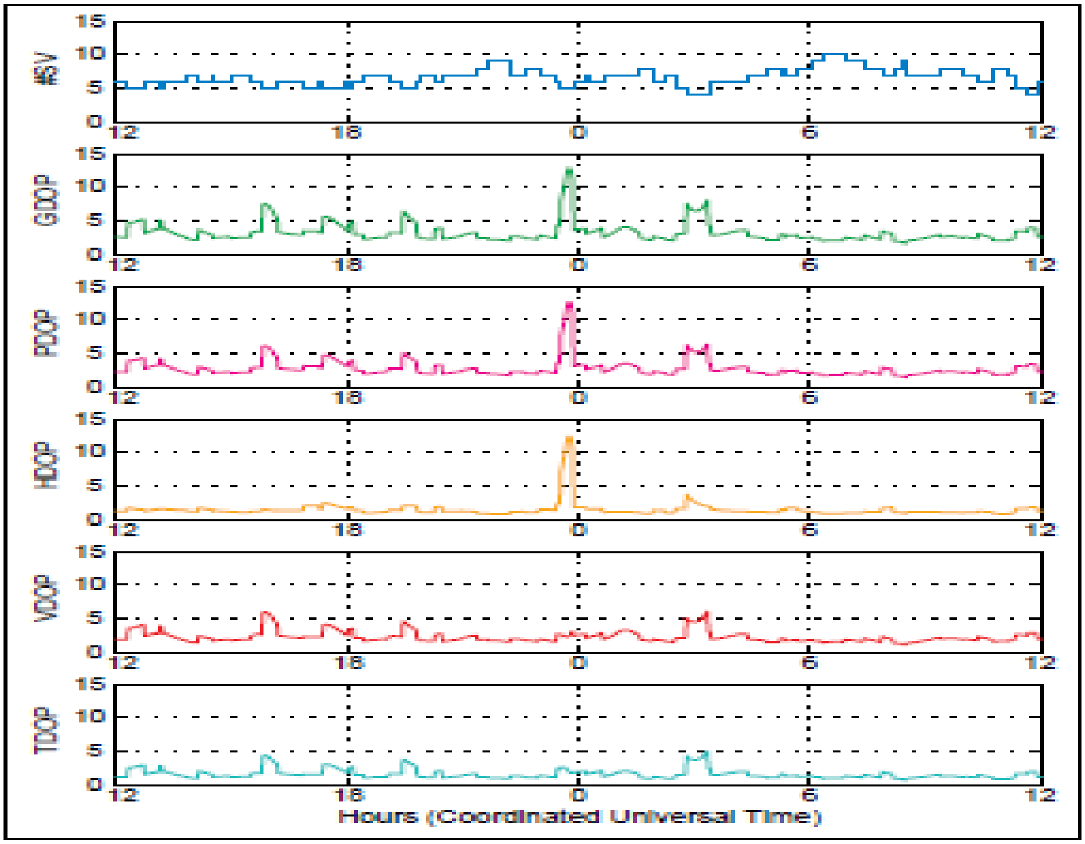

Figure 3. DOP values at Fredericton, New Brunswick, Canada, — computed from broadcast satellite ephemerides using a 15-degree elevation mask angle — are sufficiently small except just before 0000 hours when HDOP, PDOP, and GDOP increase to more than 12 (#SV represents the number of visible satellites [space vehicles]).

Figure L.3. Example of Dilution of Precision

Figure L.4 shows additional PDOP/VDOP/HDOP/TDOP plots for the 27-satellite expanded GPS constellation for a location in Bedford, Massachusetts showing more typical values.

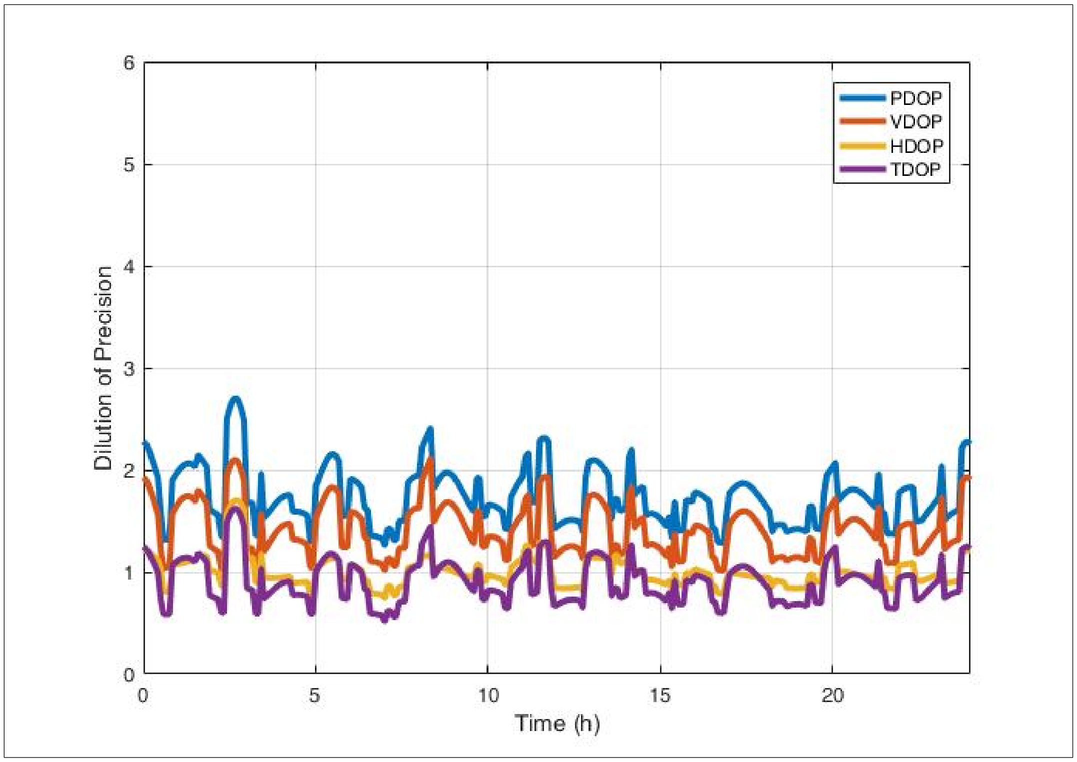

Figure L.4. Typical Values of Dilution of Precision

L.4 C/N_0 VALUES OBSERVED IN LIVE SKY MEASUREMENTS

The theoretical analysis performed in Sections L.2 and L.3 considered C/N_0 values down to 30. Live sky measurements confirm that C/N_0 values can go even below this level even in clear sky conditions due to high directivity in some receivers, low gain in others among other reasons. This is shown in Figure L.5 and Figure L.6. Figure L.5 is for live sky measurements performed using three General Location/Navigation Receiver Category (GLN) and one High Precision (HP) receiver with integrated antennas. The legend indicates the receiver category and the measured antenna number. This data is available in an October 2016 Workshop V presentation on Antenna data.

Figure L.6 is for the GPS L1 C/N_0 data reported by the receiver as a function of elevation angle for PRN-17 and PRN-18 SVs recorded by the Chicago Air Route Traffic Control Center WAAS reference station in Aurora, Illinois, for a single day in April 2014. The large variation in C/N_0 relative to elevation angle is caused mostly by the gain pattern of this antenna (not atypical of what was measured for other HP antennas by MITRE). The large variation in C/N_0 at low elevations is largely due to site multipath.

Both plots show that, even with direct line of site to an SV, C/N_0 values below 35 dB-Hz are not uncommon for low elevation satellites. These plots taken with the analysis above further illustrate the difficulties in attempting to accurately reflect the impacts of 1 dB degradation in C/N_0 with a metric like position accuracy given the multitude of variables that need to be carefully considered.

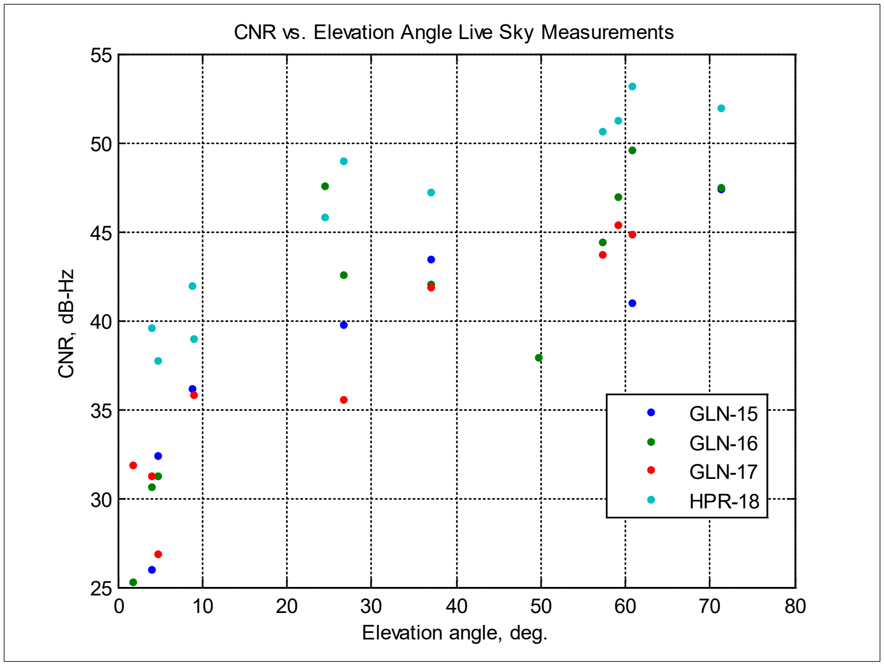

Figure L.5. Live Sky Measurements

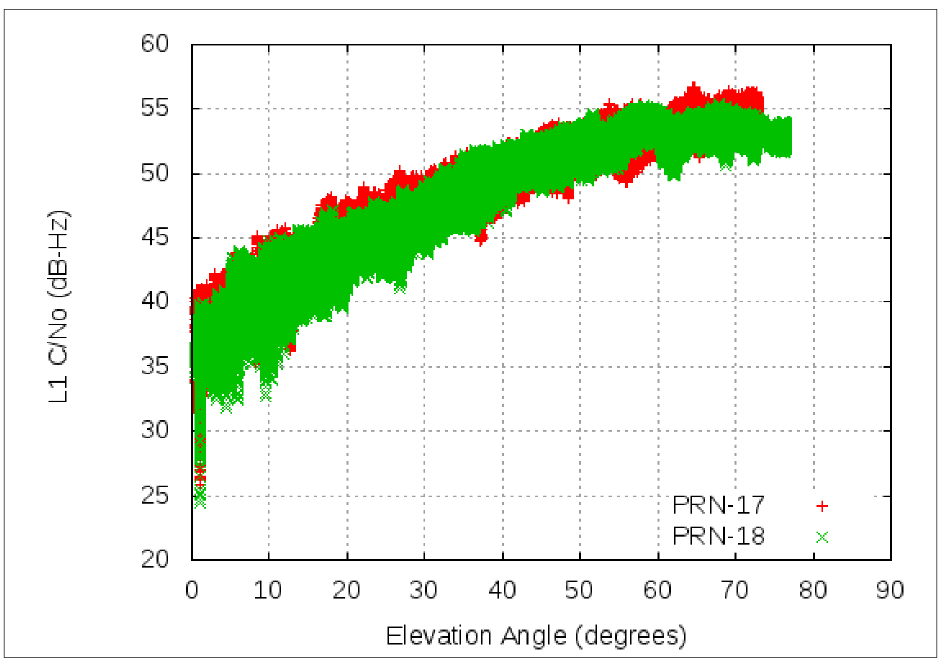

Figure L.6. ZAU PRN-17 and PRN-18 Reported L1 C/N$_0$ vs. Elevation Angle (April 2014)

APPENDIX M
ANALYSIS OF GNSS RECEIVERS SPACEBORNE AND SCIENCE APPLICATIONS

M.1 OVERVIEW

This appendix provides the results of assessments conducted by the National Aeronautics and Space Administration (NASA) and describes the analysis and evaluation of a proposed Long Term Evolution (LTE) base station network operating on adjacent radio frequency bands to space-based receivers. A comprehensive assessment on Global Navigation Satellite System (GNSS) receivers, used in various applications, supporting NASA's portfolio of missions, is also addressed. However, the emphasis of this section is on the assessment to GNSS receivers used as a science application.

The following evaluation assesses the impact to space-based GNSS receivers performing radio occultation (RO) measurements (a scientific application of GNSS) of the stratosphere and the troposphere. RO measurements, coupled with traditional methodologies for weather prediction, provide weather and science data observations from ocean areas, the atmosphere, and other natural phenomena, which has improved accuracy and predictability of weather forecasts by as much as 2 days.

Specifically, NASA's assessment focuses on the most recent developed RO receiver, called the TriG, developed by the NASA/Jet Propulsion Laboratory (JPL). The TriG is the newest RO receiver of the BlackJack class of GNSS receivers. The increase in performance by these receivers is partially due to the TriG's ability to receive all GNSS signals: GPS, Galileo, GLONASS, Compass, as well as other future navigation signals (QZSS, DORIS, etc.).

Radio Frequency Interference (RFI) is an utmost problem when GNSS signals are being used for science applications. When RFI occurs, the GNSS signal is defocused by tens of Decibel(s) (dB) at low ray heights, where the signal-to-noise ratio (SNR) is already being measured in a marginal zone. In fact, in this already marginal zone, tracking loops cannot be closed and the captured data is running open loop. The spatially correlated noise can bias the captured data and affect the recent climate record, thus providing incorrect weather phenomena predictions.

This assessment demonstrates the effect of RFI generated by the ground-based LTE network. Several iterations of the modeling and simulation (M&S) runs were performed to more accurately model the presumed network deployment of the interfering network. The M&S scenarios estimate the receive interference levels to the TriG, utilizing specific mission parameters, and comparing them against interference limits/thresholds obtained through anechoic chamber testing described under the Department of Transportation (DOT) Adjacent Band Compatibility (ABC) Assessment.

M.2 BACKGROUND

M.2.1 Radio Occultation (GNSS-RO)

RO/GNSS-RO is the disruption/interruption of GNSS signals from a spacecraft by the intervention of a celestial body. RO is a relatively new method for the indirect measurement of temperature, pressure, and water vapor in the stratosphere and the troposphere. These measurements are made from specifically designed GNSS receivers on-board a Low-Earth-Orbit (LEO) satellite. The techniques utilize the unique radio signals continuously transmitted by the GNSS satellites (GPS, GLONASS, Galileo, etc.) orbiting the Earth at an approximate altitude of 20,000 kilometers (km) above the surface. The GNSS radio signals are influenced both by the electron density in the ionosphere and by the variations of temperature, pressure, and water vapor in the atmosphere which are used in meteorology and climate science. RO measurements are also used to derive various ionospheric parameters (Total Electron Content (TEC), Electron Density Profiles (EDP), L-band scintillation, etc.) for understanding earth and space weather dynamics.

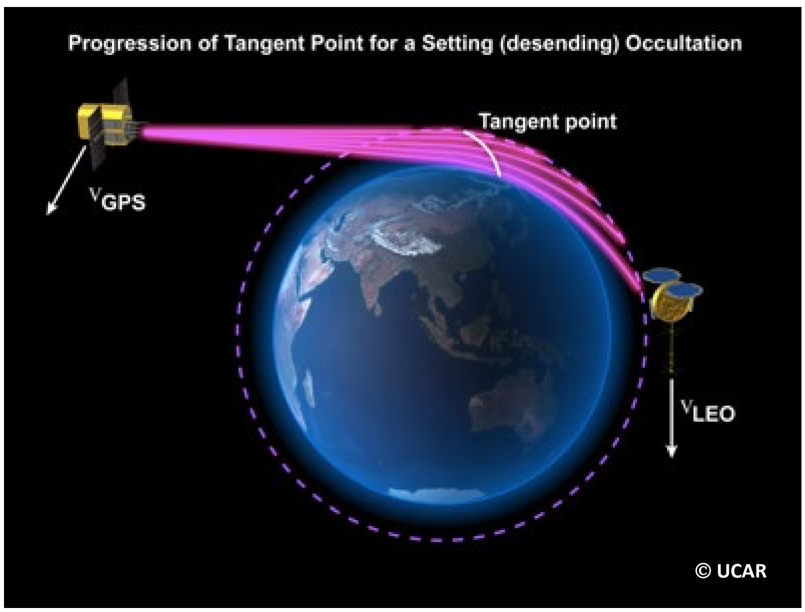

Figure M.1: Progression of Tangent Point for a Setting (Descending) Occultation

From the point of view of an LEO satellite (at an altitude of 700-800 km), the GNSS satellites continually rise above, or set behind, the horizon of the Earth. During these so-called "radio occultations", where the GNSS and the LEO satellite are just able to "see" each other through the atmosphere, the GNSS signals will be slightly delayed and their ray path slightly bent (refracted) on the way through the layers of the atmosphere (see Figure M.1). The excess range increases as the ray propagates through denser mediums at lower altitudes (e.g., moisture in the atmosphere). This delay is a function of density (n/V), which is related to temperature by the ideal gas law. Equation M.1 is used to determine Radio Occultation delays

$$P*V = n*R*T \quad \text{(M.1)}$$

A typical occultation sounding will last 1 to 2 minutes, and during this time the LEO satellite will receive signals where the ray paths have different minimum distances to the surface of the Earth, from 0 up to approximately 100 km. The GNSS satellites transmit on multiple frequencies, and with a receiver rate of 50 Hz this will yield around 6,000 rays, making up 2 profiles of phase residuals up/down through the lowest 100 km of the atmosphere and the ionosphere.

The residual positioning error and determination of time delays (see Figure M.2), derived from the measurements taken during an RO event, are key parameters in the obtaining the temperature, pressure, and water vapor characteristics of the atmosphere at different heights. Given sub-millimeter (mm) measurement precision, RO can determine atmospheric temperature profiles to 0.1 – 0.5 Kelvin (K) accuracy from 8 - 25 km height levels.

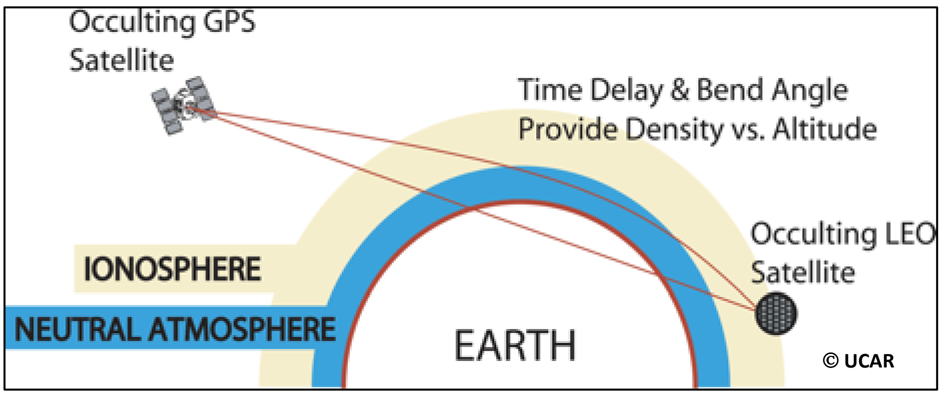

Figure M.2: Straight Line Versus Actual Path of GNSS Signal

NASA has several radio occultation receivers in its portfolio, including the Integrated GPS Occultation Receiver (IGOR), the IGOR+, and a more recently developed receiver called the TriG receiver.

M.2.2 NASA/JPL TriG Receiver Overview

The NASA/JPL developed TriG receiver functions as a multi-function GNSS receiver. This single receiver has multiple antenna inputs and can be configured to operate in a navigation capacity, as well as, simultaneously, in a scientific measurement role.

In its traditional function, coupled with a choke ring antenna (see Table M.3), the TriG serves as a device for space vehicle navigation and precise orbit determination (POD). The receiver provides accurate information to space vehicle operators on position, velocity, time, and attitude. A high level of accuracy is important, especially when docking with other spacecraft or the International Space Station (ISS).

Figure M.3: Typical Choke Ring Antenna

Configured in a scientific measurement mode, the TriG, coupled with a series of specially designed antenna arrays, performs RO measurements of GNSS signals. TriG receivers are able to receive all GNSS signals: GPS, Galileo, GLONASS, and Compass, as well as other navigation signals (QZSS, DORIS, etc.). This capability increases the number of RO measurements that can be made during any given orbit.

Additional information on TriG can be found in a document titled, "TriG - A GNSS Precise Orbit and Radio Occultation Space Receiver", written by the JPL and California Institute of Technology.[1]

M.2.2.1 TriG Pre-Select Filter

Much akin to high-precision (HP) GPS receivers, the TriG has been designed with a wide front-end receiver filter. This wider pre-select filter can be derived from the interference tolerance masks developed by the DOT (see section 3 of the DOT ABC Assessment Report). Although the DOT developed interference tolerance masks for each of the six categories of GPS receivers using bounding results, NASA specifically tested two spaced-based receivers during the anechoic chamber tests.

The wide pre-select filter (i.e., 3 dB bandwidth from 1100 MHz to 1660 MHz) allows the receiver to be reprogrammed in flight to different frequencies over the full range of GNSS signals. The TriG also has second stage narrow band filters that are centered around the GPS L1 Channel at 1575.42 (L1) and GPS L1 channel at 1227.60 MHz (L2) bands.

Receivers are purposely designed to have a wider bandwidth for both HP and the TriG receivers. The wider bandwidth front-end filter takes advantage of:

- The ability to track all current and future GNSS:
  - GPS
  - Galileo (Europe)
  - GLONASS (Russia)
  - Compass/BeiDou (China)
  - QZSS (Japan)
  - NaVIC (formerly, IRNSS) (India)
  - DORIS (France)
  - GPS augmentation systems operating on mobile satellite service (MSS) frequency allocations, and
  - Other future GNSS constellations.
- Exploiting modern techniques such as narrow-lag correlators and on-receiver multipath suppression.
- Avoiding the disadvantages that narrow filters with sharp cutoffs produce, such as:
  - Distorted ranging code transitions
  - Introduction of inter-signal biases which vary with temperature and Doppler
  - Increased insertion loss that cause lower SNR, and
  - Phase and delay distortion across signal band.

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[1] 22nd International Meeting of the Satellite Division of The Institute of Navigation, Savannah, GA, Jet Propulsion Laboratory and California Institute of Technology, *TriG - A GNSS Precise Orbit and Radio Occultation Space Receiver*, (Sept. 22-25, 2009), *available at* http://authors.library.caltech.edu/21729/1/Esterhuizen2009p12347Proceedings_Of_The_22Nd_International_Technical_Meeting_Of_The_Satellite_Division_Of_The_Institute_Of_Navigation_(Ion_Gnss_2009).pdf.

In addition to the typical advantages afforded to HP receivers that are designed with wider front-end bandwidth filters, the TriG gains additional benefits for employing wide bandwidth filters by:

- Avoiding extensive development cost and time,
- Avoiding the additional cost for pre-flight testing,
- Avoiding the additional costs associated with size and mass restrictions of flight instrument, and
- Leveraging advanced techniques such as:
  - Oversampling the GNSS signal and use of narrow-lag correlators for better precision, and
  - On-receiver multipath mitigation techniques.

M.2.2.2 Upcoming TriG Missions

TriG receivers will be flown on the next generation radio occultation capable satellites as part of the COSMIC-2[2] mission, which is sponsored by several U.S. federal agencies and NASA international partners. The COSMIC-2 mission is broken down into two sub-missions, which will deploy six satellites each. Table M.1 displays the upcoming missions where the TriG receiver will be deployed.

Note: The list of missions in Table M.1 depicts the known missions, as of 2018. As NASA continues to develop partnerships with other International Space Agencies and other U.S. federal partners, coupled with the success of integrating RO measurements into the weather prediction models, it should be noted that this list may change in the future.

[2] Reference: http://www.cosmic.ucar.edu/cosmic2/.

Table M.1. TriG Mission List (as of May 2017)

Mission	Launch Date	TriG Function
Deep Space Atomic Clock (DSAC)	Sep-18	Precise clock validation
		Timing
		POD
Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC)-2 (A) - 6 satellites	Sep-18	RO
		SWO
Gravity Recovery and Climate Experiment (GRACE) Follow-On	Dec-17	Micron ranging
		POD
		RO
COSMIC-2 (B) - 6 satellites	2019*	RO
		SWO
Sentinel-6 / Jason-CS (A)[3]	2020*	RO
		POD
Surface Water and Ocean Topography (SWOT)	2021*	POD
NASA-ISRO Synthetic Aperture Radar (NISAR)	2021*	POD
Table Legend: POD – Precision Orbit Determination RO – Radio Occultation SWO – Space Weather Observation * Tentative mission launch year		

M.2.3 Other Scientific Applications of GNSS

GNSS technology has become an essential tool to monitor and improve our understanding of earth systems, including weather monitoring and solid earth hazards such as earthquakes and volcanic activity. This knowledge of our environment and its changes is also used for resource management, protection, and environmental impact mitigation. Some examples of the use of GNSS to improve our knowledge of the Earth are determining the atmosphere's water content, improving the accuracy of weather forecasts, enabling ocean topography measurements to determine currents and secular changes in sea height. Ground-based GNSS networks are also playing an increasingly prominent role to monitor ground movement to identify potential conditions that may precede earthquakes and volcanic activity. In addition, some insurance companies use GNSS-based maps of accumulated tectonic strain to predict risk. The same data are used by other government agencies beyond NASA. GNSS technology assists NASA scientists in understanding the physical characteristics of the earth and its atmosphere, and changes over time. NASA scientists use GPS science receivers, in combination with other measurement techniques such as laser ranging and radar altimeters, to monitor the changes in Earth's surface, sea level height, and atmospheric measurements and provide precise knowledge of Earth's shape and rotation.

[3] A description of the Jason-CS (Sentinel-6) mission is *available at* https://sealevel.jpl.nasa.gov/missions/jasoncs/.

As the scientific community continues to embrace leveraging on GNSS, additional techniques have been developed to measure and monitor earth and space weather phenomena. These techniques take advantage of:

- Existing development and deployment of satellite constellations, thereby, saving money in developing and deploying a separate constellation for science signals;
- Existing satellite constellations providing signals known and consistent position determinations all around the Earth; and
- GNSS signals transmit precise time and positioning information continuously in all weather conditions.

M.2.3.1 Ground-based GNSS Receivers Used for Integrated Precipitable Water Measurements

This recently developed technique in performing atmospheric observations utilizes ground-based GNSS receivers that employ zenith (away from earth) pointing antennas to measure GNSS signals. As the GNSS satellite comes into view of the antenna overhead, the amount of measured delay of the signal due to water vapor in the atmosphere can be measured and attributed to specific weather conditions. As a meteorological application, ground-based GNSS receiver data is used to derive the Integrated Precipitable Water which is fed into the Numerical Weather Prediction model. This data is complementary to the space-based data (RO), and together, they provide valuable ionospheric information for space weather specification and forecasting.

In this system, commercially available HP GPS/GNSS receivers are typically utilized and the data is fed into post-processing algorithms to determine or estimate the precipitable water vapor content of the atmosphere.

Although NASA utilizes such systems to correlate the water vapor data with RO measurements to more accurately predict weather phenomena, NASA did not perform any specific assessments to these systems under the DOT ABC Assessment. Since NASA leverages commercial HP GPS/GNSS receivers to perform these measurements, any such protection criteria and separation distances afforded to the HP category of receivers under Section 3 of the DOT ABC Assessment Report will be applicable to locations where ground-based GPS/GNSS receivers are used for metrology.

M.2.3.2 Reflectometry (GNSS-R)

In addition to radio occultation and ground-based GNSS measurements, measuring the characteristics of Earth and bodies of water through a technique called “reflectometry” (GNSS-R) is also valuable application for science and weather.

For example, NASA’s Cyclone Global Navigation Satellite System (CYGNSS) mission, consisting of eight small satellite observatories, which was launched in 2016, will make frequent and accurate measurements of ocean surface winds throughout the life cycle of tropical storms and hurricanes. In addition to using GNSS signals for satellite navigation, each satellite observatory can measure four separate GNSS signals at the specular reflection points on the ocean to obtain information about ocean surface roughness. Ocean surface roughness is correlated to surface wind speed. The CYGNSS data will enable scientists to probe key air-sea interaction processes that take place near the core of storms, which are rapidly changing and play a critical role in the genesis and intensification of hurricanes.

Spacecraft equipped with GNSS-R systems receive a direct GNSS signal, as well as a "reflected" GNSS signal from the Earth's surface. The direct signal is transmitted from a GNSS satellite and received by a zenith pointing antenna onboard the spacecraft, while the reflected signal is received by the two nadir (towards the earth) pointing antennas. If the surface is perfectly smooth, the specular reflection point is the location on the surface where all of the scattering originates. In comparison, if the surface is roughened (e.g., due to over the surface wind speed), the scattering of the GNSS signal originates from a diffuse region called the glistening zone around the specular point. Figure M.4 demonstrates a pictorial of the GNSS-R concept of operations.

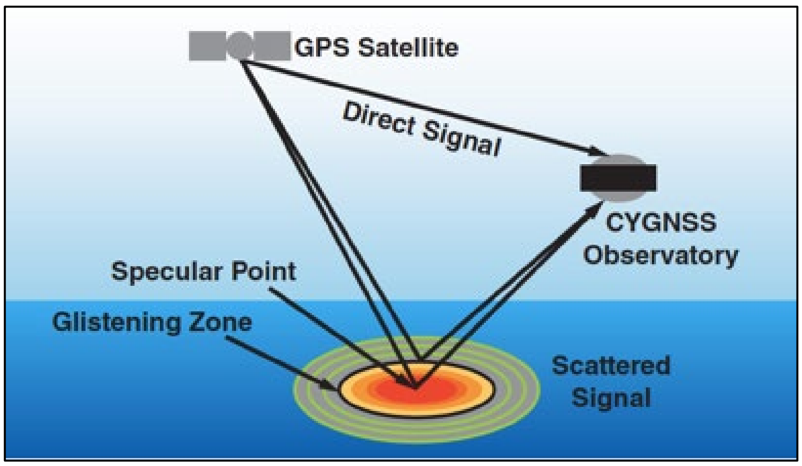

Figure M.4: GNSS-R Concept of Operations (Image Credit – University of Michigan)

Algorithms measure the amplitude of the reflected signal versus delay and Doppler shift. If the surface is smooth, nearly all power originates at the specular reflection point. If the surface is rough, there are reflections from facets separated from the specular points. Those reflections have more delay, and a spread of Doppler shifts. An example of Delay Doppler Maps for 2, 7, and 10 meter per second (m/s) wind speeds [*top to bottom*] is shown in Figure M.5.

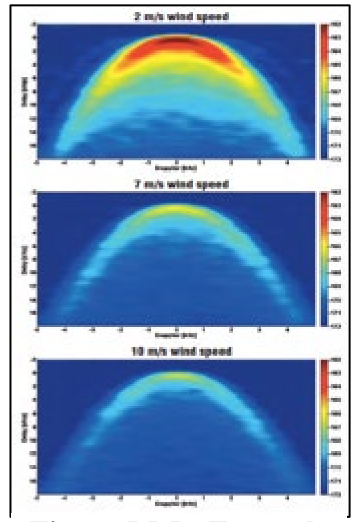

Figure M.5: Example Delay Doppler Maps

[Illustration Note: The images show how progressively stronger wind speeds, and therefore progressively rougher sea surfaces, produce a weaker maximum signal (at the top of the "arch") and a scattered signal along the arch that is closer in strength to the maximum. A perfectly smooth surface would produce a single red spot at the top of the arch.[4] Image credit: University of Michigan.]

In addition to weather forecasting (e.g., cyclonic and hurricane activity), GNSS-R has shown promises to predict other Earth surface phenomena relating to bodies of water. NASA scientists are exploring the capability of GNSS-R receivers to monitor and anticipate:

- Coastal tidal surges,
- River and lake overflows,
- Flood plains,
- Water surges beneath foliage canopies (e.g., swamps and mangroves),
- Potential dyke, reservoir, and dam exceedances, and
- Many more areas that may be impacted due to watershed anomalies.

Since GNSS-R is a relatively new technique used as a scientific application of GNSS, NASA was unable to obtain a GNSS-R receiver to be tested during the testing phases (anechoic chamber or conducted) of the DOT ABC Assessment. Therefore, the effects of adjacent band LTE operations to GNSS-R are currently unknown.

M.2.3.3 Geodesy/Geodetics

Geodesy or geodetics is the science of accurately measuring and obtaining data to understand the properties of the Earth. In this scientific discipline, observations are performed to obtain information on the Earth's geometric shape, orientation (relative to Earth's axis and the sun), crustal motion, oceanic tides, and Earth's gravitational field. Since these Earth properties are continuously changing, measurements are taken with respect to time. To ensure stability and consistency in these measurements, scientists leverage on a known and constant signal source,

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[4] Additional information on CYGNSS can be found at the NASA CYGNSS Mission site *available at* https://www.nasa.gov/cygnss/overview.

like GPS and other GNSS signals, where accurate three-dimensional positioning attributes and timing can be obtained.

In order to accurately measure these Earth properties, commercially available HP GPS/GNSS receivers are typically utilized at fixed locations on the Earth's surface. Scientifically measured data is fed into post-processing algorithms to determine the three-dimensional positioning (in some cases such earthquake monitoring, accuracy levels must be down to millimeters) and variances in time, and compared to the historical record.

Since NASA leverages on commercial HP GPS/GNSS receivers to perform these scientific measurements, any such protection criteria and separation distances afforded to the HP category of receivers under Section 3 of the DOT ABC Assessment Report will be applicable to locations where ground-based GPS/GNSS receivers are used for geodesy/geodetic science.

M.2.4 Other NASA Applications of GNSS Receivers

Statistically, nearly 60% of projected worldwide space missions from the present through 2027 will operate in LEO. Additionally, 35% of space missions that will operate at higher altitudes will remain at or below Geostationary-Earth-Orbit (GEO). Therefore, approximately 95% of projected worldwide space missions over the next 20 years will operate within the GNSS service envelope and will rely on GNSS for space activities associated with navigation, POD, science, and other applications.

The following sections describe the uses of GNSS receivers that support various NASA missions.

Note: Although the following applications, coupled with the science applications of GNSS (in above sections) provide for a comprehensive list of NASAs' uses of GNSS, it should be noted that this does not provide a full complement of NASA's uses of GNSS receivers. Other uses for day-to-day operations, NASA security, fire and rescue, etc., typically utilize General Location/Navigation Receiver Category (GLN) receivers, which are addressed in Section 3 of the DOT ABC Assessment Report. Therefore, any constraints to LTE operations required to protect GLN devices will be applicable to these NASA functions.

Figure M.6: NASA Security Vehicle

M.2.4.1 Aviation Systems

NASA's Aeronautical Research Mission Directorate operates NASA owned, maintained, and operated aircraft, which are certified by the Federal Aviation Administration (FAA) to operate in the National Airspace System. If such NASA aircraft are equipped with Global Positioning System (GPS) receivers, they are required to be compliant with FAA Certification Regulations and are equipped with FAA-certified GPS receivers.

Figure M.7: Example of NASA Aircraft Fleet

Moreover, NASA also possesses and operates several Unmanned Aerial Systems (UAS) that are equipped with GPS receivers. Some of the UAS are designed and developed by NASA Program Offices, while other UAS are operated under a leasing contract with the UAS developer. UAS are used by NASA in various manners, from developing UAS Traffic Management policies and procedures–to performing airborne science measurements–to performing research and development of new aircraft materials and aircraft designs. Regardless what mission or function the UAS is supporting, if required and necessary for flight in the National Airspace System, UAS will be equipped with certified aviation receivers or with general aviation (GAV) receivers.

Figure M.8: Example of NASA UAS

M.2.4.2 Spacecraft

Spacecraft, as defined by the International Telecommunication Union (ITU),[5] is a man-made vehicle which is intended to go beyond the major portion of the Earth's atmosphere. NASA's spacecraft portfolio consists of, but not limited to:

- Space vehicles,
- Space stations,
- Space platforms, and
- Satellites.

The orbital mechanics and flight operation of spacecraft, including navigation, POD, metrics tracking, timing, velocity, and attitude, rely on GNSS signals for accuracy. During development, spacecraft are typically fitted with either commercially available HP GPS/GNSS receivers or NASA developed GNSS receivers.

Throughout the years, NASA has developed and continues to develop GNSS receivers that meet specific mission requirements and are designed with the robustness to withstand the harsh elements of space.

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[5] International Telecommunication Union, Radiocommunication Sector, (ITU-R), Radio Regulations, Edition 2016, Volume 1, Chapter I – Terminology and technical characteristics, *available at*

http://www.itu.int/pub/R-REG-RR-2016.

Some of these devices are the:

- TurboRouge,
- IGOR and IGOR+,
- Navigator, and
- TriG.

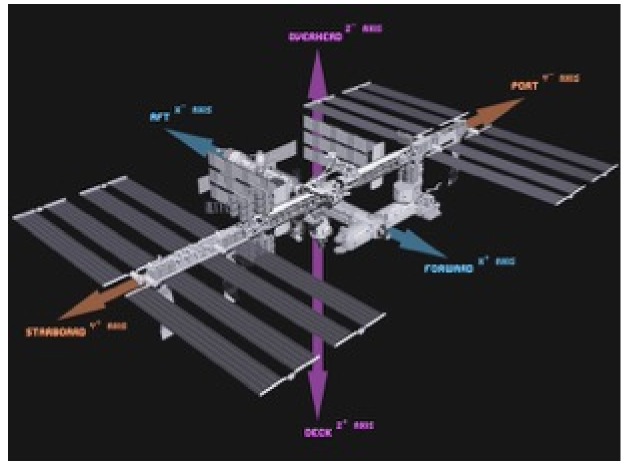

Figure M.9: Orientation Designations of Spacecraft

Employed to perform orbital mechanics and flight operations, GNSS receivers (commercial or NASA-developed) are unlikely to be significantly affected by the ground-based LTE broadband operations in adjacent bands. NASA has previously studied the IGOR, TriG,[6] and Navigator[7] in this mode of operation. This is due to the configuration and placement of the antenna. Since most spacecraft operate within GNSS constellation orbits to operate inside their space service volumes, antennae are located in the zenith (away from earth) position of the spacecraft.

M.2.4.3 Launch Vehicles

Launch vehicles are rockets used to propel a payload from the Earth's surface to outer space. In some cases (e.g., sounding rockets), the rockets are designed to carry a scientific measuring device into sub-orbital altitudes; while some rockets are designed with enough inertia and thrust to enable its payload to entirely escape Earth orbit.

Through the past two decades, the design and development of launch vehicles include the equipage of HP GNSS receivers. The use of these receivers facilitates ground control operators by providing key metric tracking and inertial measurements of launch vehicles. Integrated metric tracking units provide accurate and stable positioning, attitude, and inertial measurements on high dynamic platforms.

More recently, NASA has implemented an Autonomous Flight Safety System (AFSS)[8], which is a real-time safety system comprised of the ground software used to write mission rules and convert the mission rules into a mission data load. Coupled with the ground system, the AFSS includes on-board hardware and software. Specifically, the launch vehicle is equipped with an Automated Flight Termination Unit (AFTU) used for the Automated Flight Termination System (AFTS) of the Autonomous Flight Safety System (AFSS).

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[6] 2011 National Space-Based Positioning, Timing, and Navigation Systems Engineering Forum Report, Subtask 6, NASA Simulations.

[7] GPS Navigator (Nav) Near-band and In-band RFI Susceptibility Report (461-NAV-ANYS-0256), NASA Goddard Space Flight Center.

[8] James B. Bull and Raymond J. Lanzi, NASA Goddard Space Flight Center and NASA Wallops Flight Facility, *An Autonomous Flight Safety System* (Sept. 24, 2007), *available at* https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080044860.pdf.

Figure M.10: Antares Rocket Launch, Wallops Island, Oct. 2016 (Photo Credit: NASA/Joel Kowsky)

The AFTS augments or replaces the functions of the traditional human-in-the-loop (HITL) process and procedures. Redundant AFTS processors evaluate data from onboard AFTUs, which include GNSS receivers and other navigation sensors, and are used to make flight termination decisions. The mission rules are developed by the local Range Safety Authorities using the inventory of rule types taken from current HITL operational flight safety practices.[9] HP GNSS receivers are typically configured in the AFTUs to achieve the high-level of accuracy necessary to track the position of the launch vehicle within the projected launch path safety boundary.

NASA employs commercial HP GNSS as a part of the AFTU and any such protection criteria and separation distances afforded to the HP category of receivers under Section 3 of the DOT ABC Assessment Report will be applicable to locations where these receivers are used on launch vehicles as part of the AFSS.

M.2.4.4 Spaceborne Receiver Assessment for Science-Based Applications

NASA has performed an assessment of the potential impacts caused by a proposed terrestrial LTE network operating in the adjacent band to GPS L1. Two future science missions, COSMIC-2 and Sentinel-6 (formerly, Jason Continuity of Service (Jason-CS)), were used as the basis for these assessments. NASA's assessment is to have the TriG receiver performing a science application using the RO technique.

To determine the impact to the TriG receiver, the aggregate interference power at the output of the TriG receiver antenna was calculated using MATLAB to model the interference scenario, as well as the TriG receiver system, and simulate the interference effects to the satellites in orbit. Satellites operating in LEO gain a much broader view of the earth (dependent

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[9] Lisa Valencia, Robert Morrison, and Roger Zoerner, NASA Kennedy Space Center, FL, *Autonomous Flight Termination System Reference Design Hardware* (Mar. 1, 2016), *available at* http://www.techbriefs.com/component/content/article/ntb/tech-briefs/machinery-and-automation/24084.

upon antenna characterizations and operating parameters), which must be accounted for in performing the analysis.

Unlike the assessments performed in Section 3 of the DOT ABC Assessment Report, in-orbit satellites will see a greater number of potential interference sources (e.g., increased number of terrestrial earth stations (ES) and the aggregate of those interference sources will be the major contributing factor in the assessment, see Figure M.11.

Figure M.11: Example Satellite View of the U.S. Cities

This section describes the modeling and simulation (M&S) for a variety of terrestrial LTE base station deployment scenarios. Further, this section will also describe, where applicable, assumptions made in the M&S, population density of the LTE network, and other dependent parameters or characteristics. Finally, this section will also provide the results and NASA's assessment on impacts/effects on TriG mission performance.

M.2.5 Assumptions

M.2.5.1 Interference Protection Threshold (TriG)

NASA participated during the DOT ABC Testing of various GPS/GNSS receivers at the Army Research Laboratory facility in White Sands Missile Range (WSMR), New Mexico. One of the various systems NASA tested was the TriG receiver (see Section 3 of the DOT ABC Assessment Report). The results of the testing produced an interference protection threshold of -73 dB relative to a milliwatt (dBm). This protection threshold value is based upon the interference protection criteria of -1 dB Carrier to Noise Density (C/N_0) for LTE signals being present in the 1526-1536 MHz band.

Furthermore, the testing produced a loss-of-lock threshold down to -59 dBm.

Table M.2. TriG Interference Protection Threshold

Parameter	Threshold	Effect on TriG
-1 dB C/N_0	-73 dBm	Degraded performance, inaccurate measurements
Loss-of-Lock	-59 to -35 dBm	Saturated/jammed (no longer able to receive signals)

M.2.5.2 Impacted Receiver Satellite Orbit Specifications

The impacted receiver, in the context herein, is referred to at the receiver system that will be impacted by interference from the interfering source (e.g., terrestrial LTE broadband network).

Typical TriG receiver specifications have been previously described in this appendix. The following provides the satellite-specific parameters for each of the assessed missions.

Table M.3. Simulation Parameters - Satellite Orbit Parameters

Orbit Characteristic	COSMIC-2	Sentinel-6
Altitude	800 km	1330 km
Inclination Angle	72°	66°

M.2.5.3 TriG Receiver Antenna

The TriG receiver system can be configured to use a variety of NASA/JPL developed antennas to meet its mission needs. The following provides a description of the antenna configurations used to support COSMIC-2 and Sentinel-6.

M.2.5.3.1 Antenna Configuration for COSMIC-2 Mission

The antenna configuration to support COSMIC-2 utilizes a set of 2 proprietary beam forming 12-element subarrays each with +13.4 dBi for a circularly polarized receive antenna (dBic) peak gain at 1530 MHz. The 12 elements of each subarray are on a 60 centimeter (cm) tall x 40 cm wide mounting plate and mounted on the spacecraft so that the plate is vertical and the outward normal to the plate is parallel to the spacecraft's velocity vector (assuming circular orbit). The first antenna subarray is mounted in the forward direction of a satellite (to receive rising GNSS satellite signals) and the second subarray is mounted in the aft direction (to receive setting GNSS satellite signals). The TriG receiver has the capability of eight independent antenna inputs (three inputs from each of the two subarrays and two inputs from the antennas performing POD and space weather data acquisition functions.) Three subarrays (performing the RO technique) are combined for the fore and aft antennas, increasing the gains by approximately 4.8 dB to a total main beam gain of +18.2 dBic. Note that the gain and beam shape used for the simulation is from the 4-element subarray. Since each subarray has its own filter/low noise amplifier (LNA) chain, the effects of RFI apply at the subarray level.

Based on the satellite altitude (for COSMIC-2 altitude = 800 km), the receiver main-beam is directed towards the earth limb (approximately 26.2° below the satellite velocity vector). Figure M.12 demonstrates an example of an in-orbit satellite with the forward antenna subarray with its down-tilt.[10] Consequently, the potential interfering signals from terrestrial LTE ES will be in view of the receive antenna array main beams.

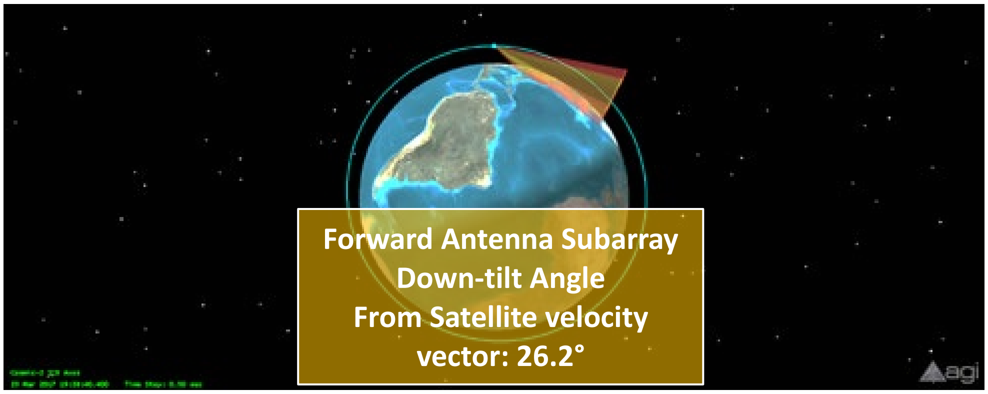

Figure M.12: TriG RO Antenna Array Main-Beam Down-tilt (26.2°)

The antenna subarrays are designed to receive right-hand circular polarized signals from the GNSS satellites. For the analysis, an antenna coupling mismatch (cross-polarization loss) of -3 dB is used (assuming a typical vertically polarized LTE signal).

Figure M.13 and Figure M.14 show the gain pattern for the forward antenna with the main-beam directed 26.2° below the satellite velocity vector towards earth limb.

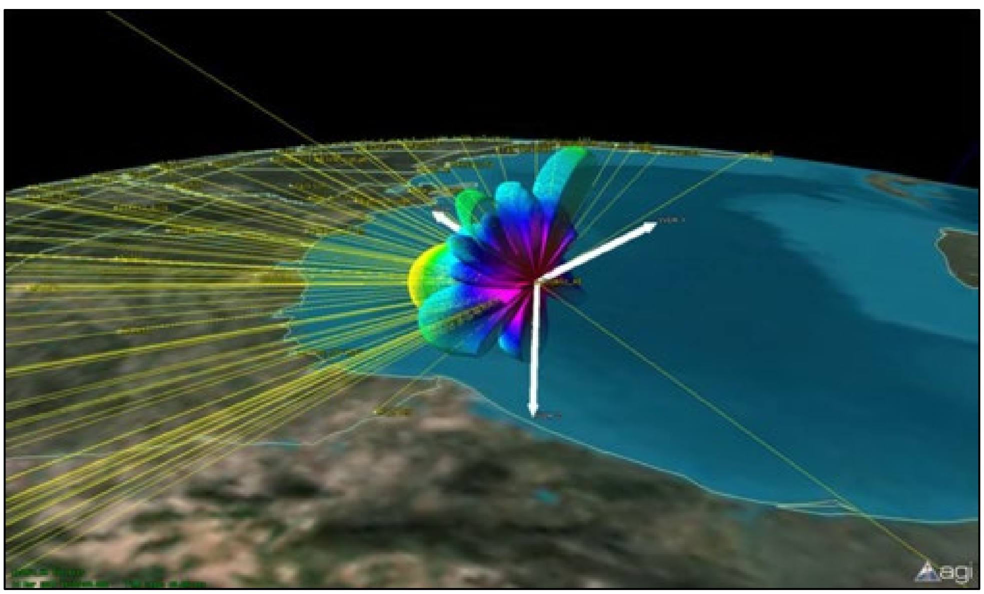

Figure M.13: Forward Direction Antenna Array (12-Element, 13.4 dBic @ 1530 MHz, Main Beam Pointed Towards Earth Limb)

[10] For graphical simplicity, the aft subarray is not pictured.

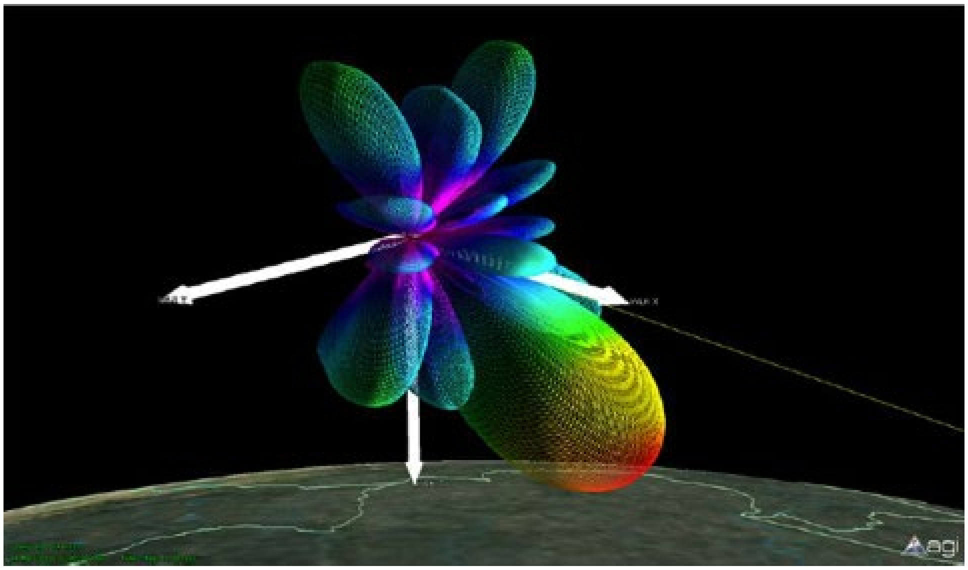

Figure M.14: Aft Direction Antenna Array (12-Element, 13.4 dBic @ 1530 MHz, Main Beam Pointed Towards Earth Limb)

Based upon the antenna array specifications and operational parameters, above, the 3 dB antenna beamwidth coverage footprint from COSMIC-2 is approximately 1.6 million square miles. The yellow shaded area over the United States (U.S.) in Figure M.15 displays the footprint for the forward antenna array. [*Note*: It should be noted that a similar area of coverage (mirror-image in the horizontal plane) would also be succeeding the satellite.]

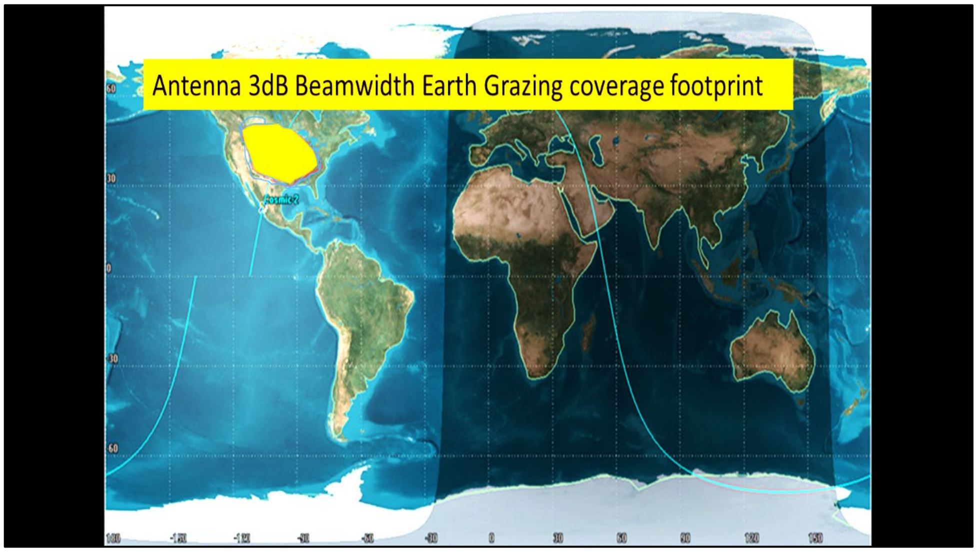

Figure M.15: COSMIC-2 Antenna 3 dB Beamwidth Coverage Footprint

M.2.5.3.2 COSMIC-2 Antenna Configuration Used for M&S Analysis

Although the COSMIC-2 Antenna has two beamforming arrays the M&S was configured to model only the forward subarray since the aft subarray model parameters where not available at simulation time.

The effects of this modification are discussed in the results section for COSMIC-2.

M.2.5.3.3 Antenna Configuration for Sentinel-6 Mission

Similar to the COSMIC-2 antenna configuration, the antenna configuration to support Sentinel-6 utilizes a set of two proprietary beam forming subarrays. However, the mission requirements for Sentinel-6 call for a different array configuration, as well as, a difference of subarrays on the forward and aft directions of the spacecraft.

The forward antenna array is comprised of a 6 element array in a 2 x 3 configuration. This array will nominally produce a main beam gain of approximately +15.5 dBic at 1530 MHz. Based on the orbit altitude of Sentinel-6 (1330 km), the forward antenna is mechanically down-tilted so that the main beam is 34.2° below the satellite velocity vector towards earth limb.

The aft antenna array is comprised of a 12-element array in a 4 x 3 configuration. This array will nominally produce a main beam gain of approximately +17.5 dBic at 1530 MHz. Based on the orbit altitude of Sentinel-6 (1330 km), the aft antenna is electrically phased down (down-tilted) by 22°, as well as mechanically down-tilted an additional 12.0° below the satellite velocity vector towards earth limb.

M.2.5.3.4 Sentinel-6 Antenna Configuration Used for M&S Analysis

The Sentinel-6 antenna will digitally combine the outputs of each of the subarrays on the fore and aft antenna. Because each Radio Frequency (RF) front end is separate for each subarray, the effect on a single subarray was analyzed for degradation and saturation. For the forward subarray, a 2-element array (2 x 1 configuration) with a peak main beam gain of +10.5 dBic at 1530 MHz was modeled for the simulation. In the aft subarray, a 4-element array (4 x 1 configuration) with a peak main beam gain of +12.5 dBic at 1530 MHz was modeled for the simulation.

The effects of this modification are discussed in the results section for Sentinel-6.

M.2.6 Summary of TriG Receiver System Characteristics Used for Analyses

Table M.4 summarizes the satellite TriG receiver system characteristics for the analyses performed on COSMIC-2 and Sentinel-6. The interference threshold in this table is the RFI power at the output of the flight RO antenna which causes a -1 dB C/N_0 degradation in the TriG receiver as used in the COSMIC2-A mission. It was derived from the power density observed by the 0 dBi standard gain horn used in during the DOT ABC test at an RFI power level causing a 1 dB C/N_0 degradation. Since the TriG choke ring antenna was located at a different spot, it actually received about 3.2 dB more RFI power per meter squared (m^2). In addition, the choke ring antenna had about +3.7 dBi linear gain toward the RFI source, adding 3.7 dB to the threshold power. After these corrections, the LTE power at 1530 MHz that causes a 1 dB C/N_0 degradation is -78.2 dBm + 3.2 dB + 3.7 dB = -71.3 dBm, defined at the output of the receive antenna.

Another adjustment that was made to estimate the effect on the flight receiver is the difference in noise floors due to the extra antenna temperature from black body radiation coming from the ceiling and walls of the WSMR anechoic chamber. During the test, the noise floor is estimated to be 349 Kelvin (K). This is based on preamplifier (Preamp) noise of 51 K, antenna temperature of 300 K, and filter loss of 0.8 dB. The noise floor in flight is estimated to be 224 K based on Preamp noise of 51 K, antenna temperature of 150 K, and filter loss of 0.8 dB. This difference shows an adjustment to lower the 1 dB threshold by 1.9 dB. Therefore, the normalized in-flight RFI power of is calculated to be approximately -73 dBm (-71.3 dBm – 1.9 dB = -73.2 dBm) from the antenna corresponding to a -1 dB degradation of C/N_0.

Table M.4. Summary Table of Satellite TriG Receiver Characteristics Used for M&S

Receiver Characteristic	COSMIC-2	Sentinel-6
Satellite Orbit Altitude	800 km	1330 km
Satellite Orbit Inclination Angle	72°	66°
TriG Forward Receive Antenna Type	12-Element Array	6-Element Array
TriG Forward Receive Antenna Downtilt (relative to satellite velocity vector)	26.2°	34.2°
TriG Forward Receiver Antenna Main-Beam Gain @ 1530 MHz (single array)	+ 13.4 dBic	+ 10.5 dBic
TriG Aft Receive Antenna Type	Not modeled	12-Element Array
TriG Aft Receive Antenna Downtilt (relative to satellite velocity vector)	Not modeled	34.0°
TriG Aft Receiver Antenna Main-Beam Gain @ 1530 MHz (single array)	Not modeled	+ 12.5 dBic
Interference Threshold (-1 dB C/N_0)	- 73 dBm	- 73 dBm
Loss-of-Lock (*Note*: The LOL value ranged from a low of -59 dBm for Test 04 at 1525 MHz to a high of -35 dBm for Test 04 at 1530 MHz, all corrected for antenna location and gain)	- 59 to -35 dBm	- 59 to -35 dBm
Antenna Coupling Mismatch (Cross-Polarization Loss)	- 3 dB	- 3 dB

M.3 TERRESTRIAL LTE DEPLOYMENT SCENARIOS

The aggregate interference is dependent upon several factors. A few of those factors are the satellite related, to include, orbital parameters and receiver system characteristics. The other determining factor comes from the interference sources. Most importantly, the transmitter characteristics and the total number of sources (e.g., LTE ES). Since TriG receiver systems (performing the RO technique) operate in LEO, they have a direct line-of-sight to a broad area of the U.S., and the aggregate interference is dependent upon the long-term deployment scenario of the LTE operator.

The following describes the LTE parameters and the developed scenarios used during M&S.

M.3.1 Earth Stations Used for LTE Deployment

To model the terrestrial LTE base station deployment, the analyses used ES macro and microcell parameters, which are primarily derived from ITU-R M.2292.

For this analysis, the following ES macro and microcell antenna bore sites with respect to True North were assumed:

- Macrocell Sector-1 bore-site: 0°
- Macrocell Sector-2 bore-site: 120°
- Macrocell Sector-3 bore-site: 240°
- Microcell Sector bore-site: Randomly selected from (0°, 120°, 240°)

NASA used two different methodologies to determine the total number of ES that could be deployed to support the LTE network. The assumptions used for each of the methodologies are described below and resulted in a different number of cell sites.

M.3.2 City Zone Model

The City Zone model was used to determine the physical area around a city center location that the simulated LTE network would be deployed over. The baseline City Zone model was chosen to conform to the only available accepted model given in ITU Report ITU-R SA.2325-0[11] (International Mobile Telecommunication (IMT) sharing at 2GHz) for an ES deployment based on three zones (e.g., urban, suburban, and rural) with given radial distances from a city center latitude/longitude location. Figure M.16 demonstrates an example of the City Zone model with the typical macro cellular hexagonal grid layout deployed about a city center.

Because the LTE services to be provided by the proposed and analyzed network may not be as widespread in terms of city area as the conventional LTE deployment described in SA.2325-0, a second City Zone model with a smaller Suburban and Rural zone size was analyzed. Parameters for both the City Zone models are listed in Table M.5.

[11] Report ITU-R SA.2325-0, *Sharing between space-to-space links in space research, space orientation and Earth exploration-satellite services and IMT systems in the frequency bands 2025-2110 MHz and 2200-2290 MHz* (Nov. 2014), *available at*

https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-SA.2325-2014-PDF-E.pdf.

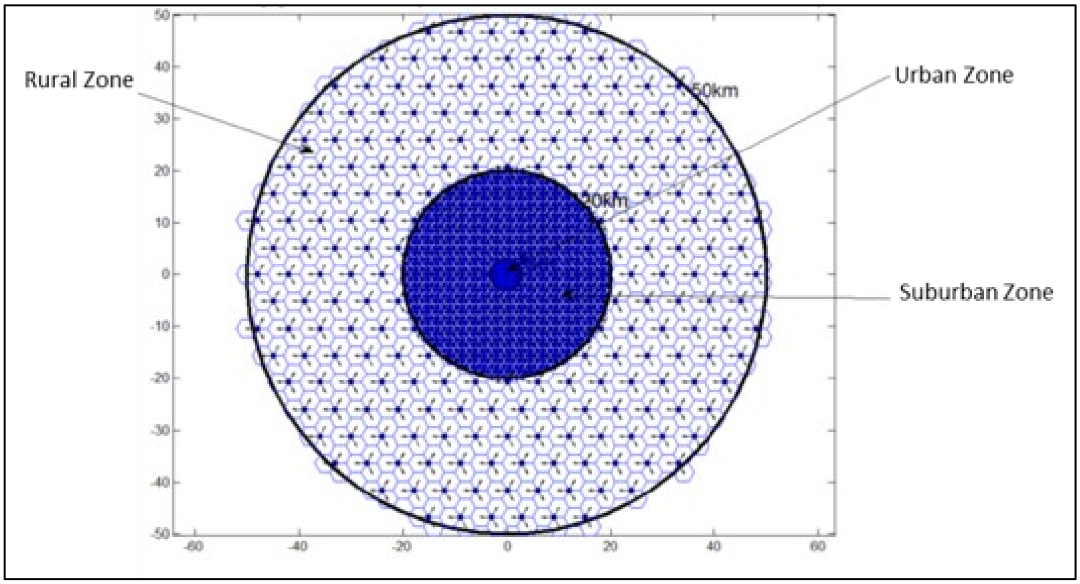

Figure M.16: Earth Station Deployment Zone Model (Report ITU-R SA. 2325-0)

Table M.5. Zone Model - ES Zone-specific Radial Distance from City Center

Zone Model	Urban Zone (km)	Suburban Zone (km)	Rural Zone (km)
1	0 – 3	3 – 20	20 – 50
2	0 – 3	3 – 10	10 – 30

M.3.3 City Population Size / Earth Station Cell Radius

In addition to a City Zone model, it was necessary to define the ES cell radius (CR) parameter in order to determine the ES grid layout within each City Zone. The typical ITU-R M.2292 zone values listed in Table M.6 were used as the baseline CR in the simulation.

Table M.6. Typical CR - ITU-R M.2292

Zone type	City Population	CR (km)
Urban	All	0.5
Suburban	All	1.0
Rural	All	5.0

In consideration to the where the proposed LTE network is to be deployed, the size of the city population was an additional parameter that was included in the simulations. If a U.S. city had a population of greater than 125,000, but less than 250,000, it was included in the analyses for half of the simulations. Cities with populations of over 250,000 were included in all simulations.

Accordingly, the number of assumed cities included in each simulation was chosen from:

- City Population > 125K: 225 cities or
- City Population > 250K: 82 cities

Additionally, since a smaller population city could have a smaller amount of Earth Stations with a larger CR, then the typical M.2292 CR values where scaled by the city population and included in the set of simulation runs. Table M.7 shows the addition inclusion of the largest M.2292 CR Table values.

Table M.7. CR Scaled by City Population Density (ITU-R M.2292)

Zone type	City Population (in 1000s)	CR (km)
Urban	> 125 > POP < 250 > 250 > POP < 500 POP > 500	1.0 0.75 0.5 (Typical)
Suburban	> 125 > POP < 250 > 250 > POP <500 POP > 500	2.0 1.5 1.0 (Typical)
Rural	> 125 > POP < 250 > 250 > POP < 500 POP > 500	10.0 10.0 5.0 (Typical)

M.3.4 Total Number of Earth Stations in Simulations

Using the set of Zone Model, City Population and CR parameters, NASA calculated the total number of ES required for deployment for each simulation run. Table M.8 depicts the number of Earth stations for the set of three parameters for a LTE network deployment consisting of only macrocells. Table M.9 accounts for microcells to be included in the LTE network deployment.

Table M.8. Total # of ES (Macrocell Deployment Only)

Zone Model	City Population (in 1000s)	Cell Radius	Number of ES			
			Urban	Suburban	Rural	Total
1	> 125	Table M.6	11,700	143,100	29,700	184,500
1	> 250	Table M.6	4,264	52,152	10,824	67,240
1	> 125	Table M.7	5,330	58,962	10,320	74,612
1	> 250	Table M.7	3,024	35,796	6030	44,868
2	> 125	Table M.6	11,700	33,750	12,150	57,600
2	> 250	Table M.6	4,264	12,300	4,428	20,992
2	> 125	Table M.7	5,330	13,500	5,310	24,140
2	> 250	Table M.7	3,042	8352	2,736	14,130

Table M.9. Total # of ES (Macro + Microcells)

Zone Model	City Population (in 1000s)	Cell Radius	Number of ES		
			Macrocells	Microcells	Total
1	> 125	Table M.6	184,500	97,686	282,186
1	> 250	Table M.6	67,240	35,601	102,841
1	> 125	Table M.7	74,612	41,014	115,626
1	> 250	Table M.7	44,868	24,609	69,477
2	> 125	Table M.6	57,600	36,450	94,050
2	> 250	Table M.6	20,992	13,284	34,276
2	> 125	Table M.7	24,140	15,555	39,695
2	> 250	Table M.7	14,130	9,240	23,370

M.3.5 Additional LTE Network Deployment Assumptions for Analysis

In addition to the parameters described above, the following simulation parameters were considered and chosen by NASA for the analysis performed.

- Since specific latitude and longitude locations for the ES in each city were not available, ES are placed at respective city center latitude/longitude and ES power aggregated for urban, suburban, and rural ES transmitters to get single equivalent urban, suburban, rural and microcell ES.
  Rationale 1: The angular separation between 2 ES separated by 10 km is only 0.7°, assuming a TriG receiver at 800 km altitude. This angular separation is relatively small with respect to the transmitter and receiver antenna gain patterns.
  Rational 2: The time and resources required to model separate ES locations for each city would be exhaustive. Further, the computational time to run the simulations and amount of processing power would be extensive.
- ES antenna side-lobe pattern:
  - ITU-R F.1336-4 Recommends 3.1. (Macro)
  - ITU-R F.1336-4 Recommends 3.2. (Micro)
- Per M.2292, 30% of the macrocell, ES are below rooftop and the simulation considered half of the 30% blocked from contributing interference and have already been excluded in the total ES calculations in Table M.8.
- Per M.2292, microcell ES antennas are below rooftop with 50% of the microcells in the urban zone and 30% of the microcells in the suburban zone considered blocked. These ES have already been excluded in the total ES calculations in Table M.9.
- Elevation Mask:
  Consideration given to blockage from terrain, vegetation, and additional man-made structures. This was simulated by providing a 5° transmitter elevation mask in the vertical plane of the transmitter, 360° around the ES in the horizontal plane.
  Two ES mask angles are utilized for the analysis:

- A 0° elevation mask on the ES so that all ES which see the satellite above 0° elevation angle are included in the aggregate interference calculation, and
- A 5° mask angle so that only ES which see the satellite above 5° elevation angle contribute to the aggregate interference.

- One 10 MHz LTE channel per sector.
- Propagation Loss: Free space
- ES Activity Factor (AF):
  An AF of 3 dB, corresponding to 50% of the earth stations transmitting simultaneously, is used throughout the analysis.
  Note: If 100% of the earth stations are transmitting simultaneously, the peak interference levels in the results will be 3 dB higher. This will also hold true for other resultant statistics, as well.
- ES Transmitter Power (EIRP):
  Table M.10 depicts the nominal transmit power used for some of the simulations (as per ITU-R M.2292). Considerations were also given to the maximum transmit powers of +10 dBW/10 MHz[12] and +32 dBW/10 MHz[13] EIRP per channel per sector.

Table M.10. Assumed Maximum Transmitter Levels per Sector (Typical per ITU-R M.2292)

ES Type	Typical Max. Transmit Power/Channel/Sector (EIRP)
Macrocell - Urban	26 dBW
Macrocell - Suburban	26 dBW
Macrocell - Rural	28 dBW
Microcell (any zone)	7 dBW

M.4 TRIG RECEIVER ANALYSIS

Two NASA missions (COSMIC-2 and Sentinel-6) that include the TriG receiver, as a science-based function (e.g., RO technique) were utilized for analysis. A MATLAB simulation program was developed to model the receiver on-board a satellite, using mission-specific parameters, and interference statistics were calculated for an LTE network deployment of ES distributed in U.S. cities.

M.4.1 MATLAB Simulation

For the spaceborne receiver analysis, the aggregate interference power at the output of the GPS receiver antenna is calculated at 10-second time steps in the satellite orbit from ES distributed among U.S. cities. The MATLAB program was setup to model a 10-day orbit of the satellite. Figure M.17 provides an example of the COSMIC-2 satellite simulation of a 10-day orbit.

[12] These simulations took place prior to the applicant amending its application to propose a maximum transmit power of 9.8 dB relative to a Watt (dBW).

[13] Maximum transmit power per channel per sector as proposed in initial applications.

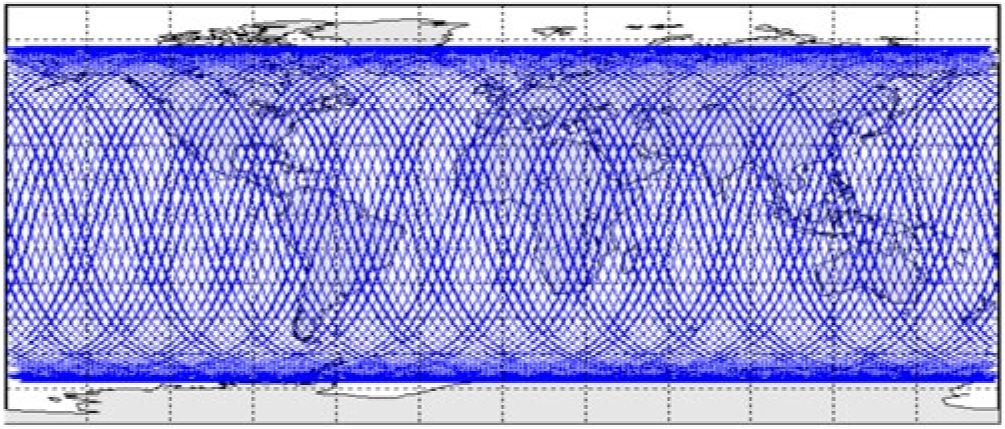

Figure M.17: Ground Track of COSMIC-2 Orbital Path (10-Day Simulation at 10-Second Time Steps)

M.4.2 Aggregate Interference Calculation

The analysis calculates the interference-to-noise ratio and is not dependent upon the carrier (C) signal. Thresholds for determining the saturation (-1 dB C/N_0) and jammed (loss-of-lock) values of the TriG are discussed in this appendix.

The aggregate interference to the receiver antenna output is calculated using a summation of the interference from each source. A simple link budget formula is used to calculate the interference received by a single source, LTE ES. The total aggregate interference is determined through the summation of interference from the individual sources, see Equation M.2.

Rx Int Pwragg = $\sum$(Int sources) Tx Pwr $(EIRP)_{off\text{-}boresite}$ – FSL – Pol Loss + Rx Ant Gain (M.1)

Where,

Rx Int Pwr_{agg} = Aggregate interference power level (dBm);
Tx Pwr $(EIRP)_{off\text{-}boresite}$ = Tx power output including antenna off-boresite calculations (dBm) (See below);
FSL = Free Space Loss (dB);
Pol Loss = Loss of dissimilar polarizations (Linear to RCHP Polarization = - 3 dB); and
Rx Ant Gain = Rx antenna gain (dBic).

The ES sector antenna gain towards the satellite is calculated by first determining the appropriate azimuth (AZ) (horizontal plane) and elevation (EL) (vertical plane) angles based on the ES and satellite geometry. The antenna off-boresite gain is calculated by, first, summing the AZ plane discrimination with the EL plane discrimination and, secondly, subtracting this total discrimination from the maximum sector gain[14] to get the net sector gain towards the satellite.

[14] As defined in ITU-R M.2292 and ITU.R F.1336-4.

Note: The maximum interference from an ES will occur when it sees the satellite at low elevation angles.

M.4.3 Simulation Runs

A total of 96 simulation runs were performed for COSMIC-2, while a lesser number, but still representative, number of runs (16 runs) were performed for Sentinel-6. Each of the simulation runs varied one or more LTE ES deployment parameters.

While it is unknown for how the LTE operator will be performing their network deployment, the variations in simulation runs should be demonstrative. Further, the variations in runs may be representative of an LTE network through its various phases of deployment (initial deployment through full deployment).

Table M.13 summarizes the various simulation runs.

Table M.13. Summary of Simulation Runs

Run	Sim No.	Run Designator	COSMIC-2	Sentinel-6	ES Tx Power	Zone Model	City Population	Cell Radius	Elevation Mask	Macrocell Only	Macro + Microcell	Total # of Earth Stations
1	1	a	X		M.2292 levels	1	> 125K	Typical	0°	X		184,500
2	1	b	X	X	M.2292 levels	1	> 125K	Typical	5°	X		184,500
3	1	c	X		32 dBW	1	> 125K	Typical	0°	X		184,500
4	1	d	X		32 dBW	1	> 125K	Typical	5°	X		184,500
5	1	e	X		10 dBW	1	> 125K	Typical	0°	X		184,500
6	1	f	X	X	10 dBW	1	> 125K	Typical	5°	X		184,500
7	2	a	X		M.2292 levels	1	> 250K	Typical	0°	X		67,240
8	2	b	X	X	M.2292 levels	1	> 250K	Typical	5°	X		67,240
9	2	c	X		32 dBW	1	> 250K	Typical	0°	X		67,240
10	2	d	X		32 dBW	1	> 250K	Typical	5°	X		67,240
11	2	e	X		10 dBW	1	> 250K	Typical	0°	X		67,240
12	2	f	X	X	10 dBW	1	> 250K	Typical	5°	X		67,240
13	3	a	X	X	M.2292 levels	1	> 125K	Scaled	0°	X		74,612
14	3	b	X	X	M.2292 levels	1	> 125K	Scaled	5°	X		74,612
15	3	c	X	X	32 dBW	1	> 125K	Scaled	0°	X		74,612
16	3	d	X	X	32 dBW	1	> 125K	Scaled	5°	X		74,612
17	3	e	X	X	10 dBW	1	> 125K	Scaled	0°	X		74,612
18	3	f	X	X	10 dBW	1	> 125K	Scaled	5°	X		74,612
19	4	a	X	X	M.2292 levels	1	> 250K	Scaled	0°	X		44,850
20	4	b	X	X	M.2292 levels	1	> 250K	Scaled	5°	X		44,850
21	4	c	X	X	32 dBW	1	> 250K	Scaled	0°	X		44,850
22	4	d	X	X	32 dBW	1	> 250K	Scaled	5°	X		44,850
23	4	e	X	X	10 dBW	1	> 250K	Scaled	0°	X		44,850

Run	Sim No.	Run Designator	COSMIC-2	Sentinel-6	ES Tx Power	Zone Model	City Population	Cell Radius	Elevation Mask	Macrocell Only	Macro + Microcell	Total # of Earth Stations
24	4	f	X	X	10 dBW	1	> 250K	Scaled	5°	X		44,850
25	5	a	X		M.2292 levels	2	> 125K	Typical	0°	X		57,600
26	5	b	X		M.2292 levels	2	> 125K	Typical	5°	X		57,600
27	5	c	X		32 dBW	2	> 125K	Typical	0°	X		57,600
28	5	d	X		32 dBW	2	> 125K	Typical	5°	X		57,600
29	5	e	X		10 dBW	2	> 125K	Typical	0°	X		57,600
30	5	f	X		10 dBW	2	> 125K	Typical	5°	X		57,600
31	6	a	X		M.2292 levels	2	> 250K	Typical	0°	X		20,992
32	6	b	X		M.2292 levels	2	> 250K	Typical	5°	X		20,992
33	6	c	X		32 dBW	2	> 250K	Typical	0°	X		20,992
34	6	d	X		32 dBW	2	> 250K	Typical	5°	X		20,992
35	6	e	X		10 dBW	2	> 250K	Typical	0°	X		20,992
36	6	f	X		10 dBW	2	> 250K	Typical	5°	X		20,992
37	7	a	X		M.2292 levels	2	> 125K	Scaled	0°	X		24,140
38	7	b	X		M.2292 levels	2	> 125K	Scaled	5°	X		24,140
39	7	c	X		32 dBW	2	> 125K	Scaled	0°	X		24,140
40	7	d	X		32 dBW	2	> 125K	Scaled	5°	X		24,140
41	7	e	X		10 dBW	2	> 125K	Scaled	0°	X		24,140
42	7	f	X		10 dBW	2	> 125K	Scaled	5°	X		24,140
43	8	a	X		M.2292 levels	2	> 250K	Scaled	0°	X		14,130
44	8	b	X		M.2292 levels	2	> 250K	Scaled	5°	X		14,130
45	8	c	X		32 dBW	2	> 250K	Scaled	0°	X		14,130
46	8	d	X		32 dBW	2	> 250K	Scaled	5°	X		14,130
47	8	e	X		10 dBW	2	> 250K	Scaled	0°	X		14,130
48	8	f	X		10 dBW	2	> 250K	Scaled	5°	X		14,130

Run	Sim No.	Run Designator	COSMIC-2	Sentinel-6	ES Tx Power	Zone Model	City Population	Cell Radius	Elevation Mask	Macrocell Only	Macro + Microcell	Total # of Earth Stations
49	9	a	X		M.2292 levels	1	> 125K	Typical	0°		X	282,186
50	9	b	X		M.2292 levels	1	> 125K	Typical	5°		X	282,186
51	9	c	X		32 dBW	1	> 125K	Typical	0°		X	282,186
52	9	d	X		32 dBW	1	> 125K	Typical	5°		X	282,186
53	9	e	X		10 dBW	1	> 125K	Typical	0°		X	282,186
54	9	f	X		10 dBW	1	> 125K	Typical	5°		X	282,186
55	10	a	X		M.2292 levels	1	> 250K	Typical	0°		X	102,841
56	10	b	X		M.2292 levels	1	> 250K	Typical	5°		X	102,841
57	10	c	X		32 dBW	1	> 250K	Typical	0°		X	102,841
58	10	d	X		32 dBW	1	> 250K	Typical	5°		X	102,841
59	10	e	X		10 dBW	1	> 250K	Typical	0°		X	102,841
60	10	f	X		10 dBW	1	> 250K	Typical	5°		X	102,841
61	11	a	X		M.2292 levels	1	> 125K	Scaled	0°		X	115,626
62	11	b	X		M.2292 levels	1	> 125K	Scaled	5°		X	115,626
63	11	c	X		32 dBW	1	> 125K	Scaled	0°		X	115,626
64	11	d	X		32 dBW	1	> 125K	Scaled	5°		X	115,626
65	11	e	X		10 dBW	1	> 125K	Scaled	0°		X	115,626
66	11	f	X		10 dBW	1	> 125K	Scaled	5°		X	115,626
67	12	a	X		M.2292 levels	1	> 250K	Scaled	0°		X	69,477
68	12	b	X		M.2292 levels	1	> 250K	Scaled	5°		X	69,477
69	12	c	X		32 dBW	1	> 250K	Scaled	0°		X	69,477
70	12	d	X		32 dBW	1	> 250K	Scaled	5°		X	69,477
71	12	e	X		10 dBW	1	> 250K	Scaled	0°		X	69,477
72	12	f	X		10 dBW	1	> 250K	Scaled	5°		X	69,477
73	13	a	X		M.2292 levels	2	> 125K	Typical	0°		X	94,050

Run	Sim No.	Run Designator	COSMIC-2	Sentinel-6	ES Tx Power	Zone Model	City Population	Cell Radius	Elevation Mask	Macrocell Only	Macro + Microcell	Total # of Earth Stations
74	13	b	X		M.2292 levels	2	> 125K	Typical	5°		X	94,050
75	13	c	X		32 dBW	2	> 125K	Typical	0°		X	94,050
76	13	d	X		32 dBW	2	> 125K	Typical	5°		X	94,050
77	13	e	X		10 dBW	2	> 125K	Typical	0°		X	94,050
78	13	f	X		10 dBW	2	> 125K	Typical	5°		X	94,050
79	14	a	X		M.2292 levels	2	> 250K	Typical	0°		X	34,276
80	14	b	X		M.2292 levels	2	> 250K	Typical	5°		X	34,276
81	14	c	X		32 dBW	2	> 250K	Typical	0°		X	34,276
82	14	d	X		32 dBW	2	> 250K	Typical	5°		X	34,276
83	14	e	X		10 dBW	2	> 250K	Typical	0°		X	34,276
84	14	f	X		10 dBW	2	> 250K	Typical	5°		X	34,276
85	15	a	X		M.2292 levels	2	> 125K	Scaled	0°		X	39,695
86	15	b	X		M.2292 levels	2	> 125K	Scaled	5°		X	39,695
87	15	c	X		32 dBW	2	> 125K	Scaled	0°		X	39,695
88	15	d	X		32 dBW	2	> 125K	Scaled	5°		X	39,695
89	15	e	X		10 dBW	2	> 125K	Scaled	0°		X	39,695
90	15	f	X		10 dBW	2	> 125K	Scaled	5°		X	39,695
91	16	a	X		M.2292 levels	2	> 250K	Scaled	0°		X	23,370
92	16	b	X		M.2292 levels	2	> 250K	Scaled	5°		X	23,370
93	16	c	X		32 dBW	2	> 250K	Scaled	0°		X	23,370
94	16	d	X		32 dBW	2	> 250K	Scaled	5°		X	23,370
95	16	e	X		10 dBW	2	> 250K	Scaled	0°		X	23,370
96	16	f	X		10 dBW	2	> 250K	Scaled	5°		X	23,370

M.5 RESULTS

The aggregate interference results for the TriG receiver, functioning as a science measurement instrument, are presented in the following sections.

The data collected for each simulation run for the received aggregate interference level is between -90 dBm to -40 dBm.

The interference data in the following results tables correspond to an aggregate interference signal strength of -73 dBm (threshold) in the 1526-1536 MHz band that causes the TriG RO receiver a 1 dB C/N_0 degradation.

It should be noted that the loss-of-lock threshold for the TriG receiver occurs between -59 to -35 dBm aggregate interference power in the 1526-1536 MHz band. Loss-of-Lock at -59 dBm was seen in Test 04 with RFI at 1525 MHz and LOL at -35 dBm was seen in Test 04 at 1530 MHz.

The entries in the results tables are interpreted as follows:

- Column 3: Max Int. Level (dBm)
  Indicates the maximum aggregate interference level that could be received at the receiver antenna output.
  Note: Any value ≥ -66 dBm in this column indicates that there is sufficient aggregate interference received from the terrestrial LTE network for the TriG receiver to lose lock.
- Column 4: % Time > Threshold
  Indicates the percent time, over the 10-day simulation period, where the aggregate interference at the TriG receiver antenna output exceeds the threshold level (-73 dBm).
  As an example, if the value is about 10% of the time, the TriG receiver will be receiving aggregate interference for a cumulative of 24 hours. This is calculated by, as an example:
  Ten days (total period of simulation run) = 240 hours
  % Time > Threshold = 10%
  Ten percent of 10 days (240 hours) = 0.10 x 240 = 24 hours.
  Note: The value reported represents the Percentage of Time > Threshold for the entire 10 days of the simulation, to include the time and instances where the continental U.S. is not within the field-of-view of the satellite. Consideration must be taken based on this. If the master time schedule only included the instances where the continental U.S. (and surrounding bodies of water) were in the field-of-view of the satellite, these values would increase.
- Column 5: # of Int Events
  Indicates that over the 10-day period, the total number of interference events in which interference exceed the -73 dBm threshold.
  Note: The interference time intervals for each interference occurrence may be short or long depending on how many interfering ES the satellite sees on the particular orbit

pass over the U.S. The sum duration of all of the interference events (provided in this column) is the reported in column 4 (%Time > Threshold). Furthermore, it should be noted that there can be multiple interference events for a single satellite pass, as different ES pass through the field-of-view of the TriG receiver antenna.

- Column 6: Avg Dur Int Event (min)
  Indicates the mean average duration (in minutes) of an interference event for the entire 10-day period.
  Note: As previously discussed above, the duration of an atmospheric occultation (as the signal path moves from skimming the Earth's surface to an altitude of about 100 km) is 1 to 2 minutes.
- Column 7: Max Int Event (min)
  Indicates the maximum duration (in minutes) that was recorded for a single interference event over the 10-day period.
- Column 8: Max Allow EIRP Level (dBW/10 MHz)
  Indicates a reverse-engineered maximum ES transmitter power level (in dBW) distributed across a 10 MHz bandwidth per channel per sector. The calculated level is based on the maximum interference level received during the 10-day period.
  Note 1: The reverse-engineered value calculated in this column would bring the interference level below the -73 dBm threshold value. However, it should be also noted that interference to the TriG receiver occurs well before the -73 dBm threshold value occurs, which causes degradation in scientific measurements (e.g., interference occurs at interference levels -90 dBm to -73 dBm (threshold).
  Note 2: Where applicable (i.e., simulations that utilized variable maximum transmitter power levels), the maximum allowable EIRP level is linearly calculated for each zonal category of ES sector.
  As an example, if the maximum interference level (column 3) indicates -70 dBm, the ES transmitter power needs to be reduced by 3.1 dBm in order for the received interference to be below the -73 dBm threshold. The 3.1 dBm reduction in power is linearly attributed to each of the maximum transmitter power for the urban/suburban (+26 dBW/10 MHz), rural (+28 dBW/10 MHz), and microcells (+7 dBW/10 MHz). The resulting maximum allowable transmitter power is calculated for the urban/suburban zone as +22.9 dBW/10 MHz, rural zone as +24.9 dBW/10 MHz, and microcells as +3.9 dBW/10 MHz.

M.5.1 Results Caveats

Caveat 1:
The results are only for the LTE deployment scenarios derived from parameters outlined. Deviation of such LTE system characteristics from ITU-R M.2292 may adversely impact the interference received at the satellite. This is especially true if the typical ES antennas vary in the vertical plane from what was defined in ITU-R F.1336-4, or if the nominal down-tilt angles, as defined in ITU-R M.2292, are deployed at 0 degrees or with an up-tilt (e.g., more LTE ES signal energy pointing directly over the horizon or into the atmosphere).

Caveat 2:
The results presented in the following sections are intended to draw no conclusions or make any recommendations as to what level of interference may be tolerated by the other missions

employing the TriG receiver for science applications. Aggregate interference received by the TriG receiver system in-orbit is dependent upon the satellite orbit parameters and receive antenna configurations.

Caveat 3:
The results are for the simulated operational use of the TriG receiver while in-orbit. It should be noted that the TriG receivers are currently researched, developed, and tested (RD&T) in facilities that are not electromagnetically shielded from the existing RF environment. As such, the TriG receivers may be impacted by LTE ES sites located within close proximity. The effects to the RD&T facilities have not been studied and additional analyses would be required to further understand the impacts to the TriG receivers at the RD&T facilities.

M.5.2 Results for COSMIC-2

Tables M.14 through M.19 provide a results summary of the analyses performed for the TriG receiver simulated aboard a single COSMIC-2 satellite, and for all simulation parameters shown in Table M.13. (The COSMIC-2 mission is comprised of six total satellites.)

[*Note*: Only the forward antenna array was used in the M&S. In reality, COSMIC-2 will utilize two sets of subarrays on the forward and aft of the satellite. These 2 subarrays (each having a property of +13.4 dBic main beam gain at 1530 MHz) will be digitally combined in the TriG receiver to achieve a total of +16.7 dBic antenna gain at 1530 MHz.

Although the difference between the total array gain (+16.7 dBic) and each individual subarray (+13.4 dBic) is +3.3 dBic, the reported results in the following tables cannot be linearly modified to include the +3.3 dBic difference to demonstrate the impact to the TriG receiver.

Further, it must be noted that the results in the following (e.g., # of int events) cannot be simply doubled to account for the aft antenna.

The reason these additional calculations cannot be done is based on the locations of the subarray antennas (forward and aft). The geometry between the forward subarray and the LTE ES will be slightly different than the geometry between the aft subarray and the LTE ES. Even if both subarrays see the same ES in the field-of-view of the antenna, the azimuthal properties of the ES sector antennas will provide a slight difference.

Therefore, as reported, the results depict a representative, but not exact, impact of the LTE ES to the TriG receiver in orbit. Additional consideration must be given to the aft antenna while reviewing the results.]

Table M.14. COSMIC-2 Interference Results (Macro ES Only, Urban/Suburban: Tx Power +26 dBW/10 MHz, Rural Tx Power: +28 dBW/10 MHz)

Sim No.	Run Designator	Max int. Level (dBm)	% Time > Thresh	# of Int Events	Avg Dur Int. Event (min)	Max Int Event (min)	Max Allow EIRP Level (dBW/10 MHz)	
							Urban/ Suburban ES	Rural ES
1	a	-57	3.3	83	5.5	11.0	10	12
1	b	-62	2.1	61	4.8	8.8	15	17
2	a	-62	1.8	59	4.1	9.0	15	17
2	b	-67	1.1	43	3.4	6.3	20	22
3	a	-62	1.9	62	4.3	9.0	15	17
3	b	-66	1.2	40	4.0	7.0	19	21
4	a	-64	1.3	44	3.9	7.7	17	19
4	b	-68	0.6	31	2.8	4.8	21	23
5	a	-63	1.6	52	4.2	8.5	16	18
5	b	-67	0.9	32	3.7	6.7	20	22
6	a	-68	0.7	43	2.2	5.5	21	23
6	b	-72	0.1	10	1.9	2.7	25	27
7	a	-67	0.8	32	3.4	6.0	20	22
7	b	-71	0.2	19	1.4	3.0	24	26
8	a	-69	0.4	31	1.6	4.2	22	24
8	b	-74	0.0	0	0.0	0.0	27	29

Table M.15. COSMIC-2 Interference Results (Macro ES Only, All ES Tx Power +32 dBW/10 MHz)

Sim No.	Run Designator	Max int. Level (dBm)	% Time > Thresh	# of Int Events	Avg Dur Int. Event (min)	Max Int Event (min)	Max Allow EIRP Level (dBW/10 MHz)
1	c	-52	5.4	137	5.5	13.2	11
1	d	-56	3.7	84	6.2	10.7	15
2	c	-57	3.7	115	4.5	10.7	16
2	d	-61	2.3	67	4.9	9.3	20
3	c	-57	3.9	93	5.8	11.5	16
3	d	-61	2.5	70	5.1	9.5	20
4	c	-58	3.1	87	5.0	10.5	17
4	d	-63	2.0	57	4.8	8.0	22
5	c	-57	3.4	83	5.7	11.2	16
5	d	-61	2.2	57	5.4	8.8	20
6	c	-62	1.9	62	4.2	9.2	21
6	d	-66	1.2	47	3.5	6.5	25
7	c	-62	2.1	66	4.4	9.2	21
7	d	-66	1.3	47	3.9	7.3	25
8	c	-64	1.4	44	4.3	7.8	23
8	d	-68	0.7	32	3.2	5.3	27

Table M.16. COSMIC-2 Interference Results
(Macro ES Only, All ES Tx Power +10 dBW/10 MHz)

Sim No.	Run Designator	Max int. Level (dBm)	% Time > Thresh	# of Int Events	Avg Dur Int. Event (min)	Max Int Event (min)	Max Allow EIRP Level (dBW/10 MHz)[161]
1	e	-74	0.0	0	0.0	0.0	10
1	f	-78	0.0	0	0.0	0.0	10
2	e	-79	0.0	0	0.0	0.0	10
2	f	-83	0.0	0	0.0	0.0	10
3	e	-79	0.0	0	0.0	0.0	10
3	f	-83	0.0	0	0.0	0.0	10
4	e	-80	0.0	0	0.0	0.0	10
4	f	-85	0.0	0	0.0	0.0	10
5	e	-79	0.0	0	0.0	0.0	10
5	f	-83	0.0	0	0.0	0.0	10
6	e	-84	0.0	0	0.0	0.0	10
6	f	-88	0.0	0	0.0	0.0	10
7	e	-84	0.0	0	0.0	0.0	10
7	f	-88	0.0	0	0.0	0.0	10
8	e	-86	0.0	0	0.0	0.0	10
8	f	-90	0.0	0	0.0	0.0	10

[161] Based on the assumption that the maximum transmitter power level is limited to +10 dBW/10 MHz.

Table M.17. COSMIC-2 Interference Results (Macro + Microcells, Urban/Suburban: Tx Power +26 dBW/10 MHz, Rural Tx Power: +28 dBW/10 MHz, Microcell Tx Power +7 dBW/10 MHz)

Sim No.	Run Designator	Max int. Level (dBm)	% Time > Thresh	# of Int Events	Avg Dur Int. Event (min)	Max Int Event (min)	Max Allow EIRP Level (dBW/10 MHz)		
							Urban/ Suburban ES	Rural ES	Microcell
9	a	-57	3.3	81	5.8	11.2	10	12	-9
9	b	-62	2.1	60	5.0	8.8	15	17	-4
10	a	-62	1.8	59	4.3	9.0	15	17	-4
10	b	-66	1.1	42	3.8	6.3	19	21	0
11	a	-62	2.0	62	4.5	9.0	15	17	-4
11	b	-66	1.2	43	3.9	7.0	19	21	0
12	a	-64	1.3	44	4.1	7.8	17	19	-2
12	b	-68	0.7	30	3.1	5.0	21	23	2
13	a	-63	1.7	52	4.5	8.7	16	18	-3
13	b	-67	1.0	43	3.1	6.8	20	22	1
14	a	-68	0.7	40	2.5	5.5	21	23	2
14	b	-71	0.2	15	1.4	2.8	24	26	5
15	a	-67	0.8	33	3.4	6.2	20	22	1
15	b	-71	0.2	18	1.8	3.0	24	26	5
16	a	-69	0.4	35	1.5	4.3	22	24	3
16	b	-73	0.0	4	0.1	0.2	26	28	7

Table M.18. COSMIC-2 Interference Results (Macro + Microcells, All ES Tx Power +32 dBW/10 MHz)

Sim No.	Run Designator	Max int. Level (dBm)	% Time > Thresh	# of Int Events	Avg Dur Int. Event (min)	Max Int Event (min)	Max Allow EIRP Level (dBW/10 MHz)
9	c	-49	8.5	160	7.5	15.5	8
9	d	-50	6.3	136	6.5	13.5	9
10	c	-53	7.0	147	6.7	13.5	12
10	d	-54	5.2	128	5.6	11.5	13
11	c	-53	6.9	137	7.0	14.3	12
11	d	-54	5.1	111	6.5	11.8	13
12	c	-55	6.4	135	6.7	13.2	14
12	d	-56	4.6	132	4.9	11.2	15
13	c	-53	6.5	128	7.2	13.8	12
13	d	-54	4.9	111	6.2	11.7	13
14	c	-58	4.9	119	5.7	11.8	17
14	d	-59	3.5	97	5.0	10.2	18
15	c	-57	4.8	95	7.1	12.3	16
15	d	-58	3.5	86	5.7	10.5	17
16	c	-59	3.8	91	5.9	11.0	18
16	d	-61	2.7	71	5.3	9.5	20

Table M.19. COSMIC-2 Interference Results (Macro + Microcells, All ES Tx Power +10 dBW/10 MHz)

Sim No.	Run Designator	Max int. Level (dBm)	% Time > Thresh	# of Int Events	Avg Dur Int. Event (min)	Max Int Event (min)	Max Allow EIRP Level (dBW/10 MHz)[162]
9	e	-71	0.5	32	1.9	3.8	7
9	f	-72	0.1	12	1.0	2.2	8
10	e	-75	0.0	0	0.0	0.0	10
10	f	-76	0.0	0	0.0	0.0	10
11	e	-75	0.0	0	0.0	0.0	10
11	f	-76	0.0	0	0.0	0.0	10
12	e	-77	0.0	0	0.0	0.0	10
12	f	-78	0.0	0	0.0	0.0	10
13	e	-75	0.0	0	0.0	0.0	10
13	f	-76	0.0	0	0.0	0.0	10
14	e	-80	0.0	0	0.0	0.0	10
14	f	-81	0.0	0	0.0	0.0	10
15	e	-79	0.0	0	0.0	0.0	10
15	f	-80	0.0	0	0.0	0.0	10
16	e	-81	0.0	0	0.0	0.0	10
16	f	-83	0.0	0	0.0	0.0	10

[162] Based on the assumption that the maximum transmitter power level is limited to +10 dBW/10 MHz.

M.5.3 Results for Sentinel-6

Tables M.20 through M.22 report the results of the analyses performed for the TriG receiver simulated aboard the Sentinel-6 satellite.

[*Note*: A 2-element array (2 x 1 configuration) with a peak main beam gain of +10.5 dBic at 1530 MHz was modeled for the forward subarray, and a 4-element array (4 x 1 configuration) with a peak main beam gain of +12.5 dBic at 1530 MHz was modeled for the aft subarray. In reality, Sentinel-6 will be comprised of a 6-element forward subarray (2 x 3 configuration) with a main beam gain of +15.5 dBic at 1530 MHz, and a 12-element aft subarray (4 x 3 configuration) with a main beam gain of +17.5 dBic at 1530 MHz.

The main beam gain difference between the modeled antenna arrays (forward and aft) versus the actual arrays are +5.0 dBic and +5.0 dBic, respectively. The total main beam gain for the RO segment of the system is approximately +3.3 dBic. As previously noted for the COSMIC-2 results, the reported results for Sentinel-6 in the following tables cannot be linearly modified to include the +3.3 dBic difference to demonstrate the impact to the TriG receiver.

Therefore, as reported, the results depict a representative, but not exact, impact of the LTE ES to the TriG receiver in-orbit for Sentinel-6. Additional consideration must be given to the actual antenna configuration while reviewing the results.]

Table M.20. Sentinel-6 Interference Results (Macro ES Only, Urban/Suburban: Tx Power +26 dBW/10 MHz, Rural Tx Power: +28 dBW/10 MHz)

Sim No.	Run Designator	Max int. Level (dBm)	% Time > Thresh	Max Allow EIRP Level (dBW/10 MHz)	
				Urban/ Suburban ES	Rural ES
1	b	-66	3.7	19	21
2	b	-70	1.9	23	25
3	b	-72	0.6	25	27
4	b	-76	0	29	31
3	a	-70	2.1	23	25
4	a	-74	0.2	27	29

Table M.21. Sentinel-6 Interference Results (Macro ES Only, All ES Tx Power +32 dBW/10 MHz)

Sim No.	Run Designator	Max int. Level (dBm)	% Time > Thresh	Max Allow EIRP Level (dBW/10 MHz)
3	c	-64	5.8	23
3	d	-66	3.7	25
4	c	-68	3.4	27
4	d	-70	1.9	29

Table M.22. Sentinel-6 Interference Results (Macro ES Only, All ES Tx Power +10 dBW/10 MHz)

Sim No.	Run Designator	Max int. Level (dBm)	% Time > Thresh	Max Allow EIRP Level (dBW/10 MHz)[163]
1	f	-76	0	10
2	f	-76	0	10
3	f	-78	0	10
4	f	-82	0	10
3	e	-76	0	10
4	e	-80	0	10

M.5.4 Results Summary

The results tables represent a myriad of LTE ES deployment scenarios and reports the maximum allowable EIRP levels for the terrestrial LTE ES sectors per channel.

In the case of the COSMIC-2, for the simple scenario of macro cell ES at 32 dBW EIRP, as the number of stations decreases from simulation 1 to 2 for the zone-1 model, and from simulation 5 to 6 for the zone-2 model, there is about 5 dB less interference in zone-2 compared to zone-1, which is expected because the zone-2 model uses about 3 times fewer stations. There is about 4 dB less interference in models using transmitter elevation mask of 5^{o} (run d) compared to the 0^{o} mask (run c), indicating that less than half of the available stations affect the satellite in the 5^{o} mask case.

For the most challenging model (1c), using 184,500 macro cell stations, the tolerable EIRP is 11 dBW/10 MHz (i.e., 12.6 Watts). For a deployment of macro and microcells, utilizing the same transmitter power, the maximum tolerable EIRP is approximately 8 dBW/10 MHz (i.e., 6.3 Watts).

In the case of the Sentinel-6, for the simple scenario of macro cell ES at 32 dBW EIRP, as the number of stations decreases from simulation 3 to 4 for the zone-1 model, there is about 2 dB less interference in models using transmitter elevation mask of 5° (run d) compared to the 0° mask (run c). For the most challenging model (3c), using 74,612 macro cell stations, the tolerable EIRP is 23 dBW.

It should be noted that simulations 3 and 4 use the aforementioned variation of the cell model, referred to as ‘scaled’ model, in which the cell radius increases up to double its typical value, as the city population decreases; this results in fewer stations, and less interference, compared to simulations 1 and 2.

These tolerances only predict the impact to two NASA Missions (COSMIC-2 and Sentinel-6), and the results from these simulations cannot be used to deduce the impacts of other missions where the TriG receiver will be employed for science applications. Specific orbit and

[163] Based on the assumption that the maximum transmitter power level is limited to +10 dBW/10 MHz.

antenna configuration for other TriG missions will need to be considered in order to make a holistic determination of the maximum tolerance values (e.g., maximum transmitter power and total number of LTE ES) for the terrestrial LTE network.

As an example of this, while the maximum antenna gain for Sentinel-6 is lower than the antenna configuration used for COSMIC-2, the percent time above the threshold (-73 dBm) is greater. This is due to the higher orbit altitude of the Sentinel-6 providing more distance; however, also due to the increased distance, Sentinel-6 will have a much larger field-of-view of the U.S. and the total number of LTE ES. This results in a lower received peak interference power, but greater average power.

Also, consideration needs to be given to the reported results on TIME, when assessing the overall impact of the scientific measurements. The typical duration for an atmospheric sounding using RO is only 1 to 2 minutes. In certain modeled LTE ES deployment scenarios, the average duration of an interference event may be well above the 1 or 2 minutes needed perform an occultation measurement. In these situations, the TriG receiver will be unable to perform the necessary measurements required to provide enhanced weather phenomenon predictions.

Further, in conjunction with the TIME aspect, the time associated when a satellite in-orbit has the continental U.S. (and adjacent areas in surrounding bodies of water – Atlantic Ocean, Pacific Ocean, and Gulf of Mexico) within its field-of-view needs to be considered. As the reported results under the % Time > Threshold are referenced to a timeframe that is representative of a satellite orbiting the entire Earth, the deduced interference time to occultations performed over the continental U.S. will be significant. The results tables indicate that the TriG receiver will effectively be degraded (> threshold) up to 9.6% of the time during a 10-day orbit. Since the continental U.S. (and surrounding bodies of water) represent approximately 2.5% of the surface of the Earth, this represents a significant degradation to the ability for the TriG receiver in providing valuable scientific data.

M.5.5 Impact Plots

It is important to provide a visual representation of the areas affected by the aggregate interference received by the terrestrial LTE ES network. Figure M.18 through Figure M.20 depict the areas where the TriG receiver will be impacted for COSMIC-2 and Sentinel-6, respectively. These figures are provided as a sample - additional impact plots for all of the simulations ran for COSMIC-2 and a majority of the simulations for Sentinel-6 are provided at the end of this section.

M.5.5.1 COSMIC-2 Impact Plots

Figure M.18 demonstrates the locations of where the TriG receiver will receiver various levels of interference. In the COSMIC-2 plots, below, the colored levels are defined as:

Table M.23. COSMIC-2 Impact Plot Threshold Levels

Received Interference Level (dBm)	Color	Comment
< -90	None	Below simulation parameters. No interference recorded.
≤ -90 < -73	YELLOW	Interference received, but below -73 dBm (-1 dB C/N_0) threshold
≤ -73 < -66	ORANGE	Interference received above -73 dBm (-1 dB C/N_0) threshold, but below -66 dBm (loss-of-lock) threshold
≥ -66	RED	Interference received causes TriG to lose lock

Although the impact plots provide an honest representation of the areas where degraded performance of the TriG receiver will occur, it must be noted that the position of the degradation signifies the location of the actual satellite and not where the occultation measurement is taking place.

The plots demonstrate the received interference levels based on the simulation parameters. Therefore, the plots for COSMIC-2 depict simulations with the forward antenna subarray. RO measurements from the forward array will slightly skew the overlaid interference plots toward the equator, while the satellite is traversing in the southwest to northeast direction. In converse, the RO measurements from the forward array while traversing over the U.S. in a northwest to southeast direction will skew the overlaid interference plots toward the North Pole.

Additional consideration must be given to the aft antenna array for COSMIC-2, in combination with these plots.

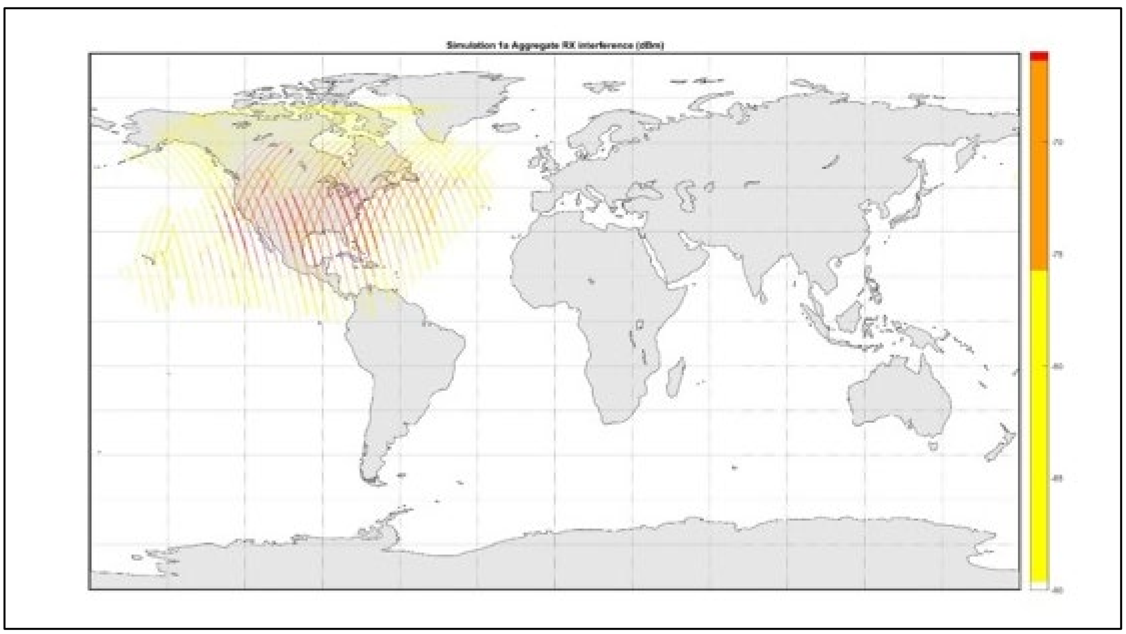

Figure M.18: COSMIC-2 Interference Impact Plot for Simulation 1a (Sample Plot)

M.5.5.2 Sentinel-6 Impact Plots

Figure M.19 and Figure M.20 demonstrate the interference impacts to Sentinel-6. Figure M.19 depicts the positions where the RO measurements will be taken. Each red dot represents one occultation. When an occultation occurs during the simulation, the location of the occultation (referenced to the Earth's surface). Coupled with Figure M.19, Figure M.20 depicts the satellite position and the level of received interference from the LTE ES network. These two plots have been performed for each of the Sentinel-6 simulation runs performed.

For the Sentinel-6 plots, consideration must be given to the received interference levels, as the simulations modeled antenna systems with less overall main beam gain. In reality, the received interference levels will be increased and the impact areas in the plots will likely increase and cover a larger area.

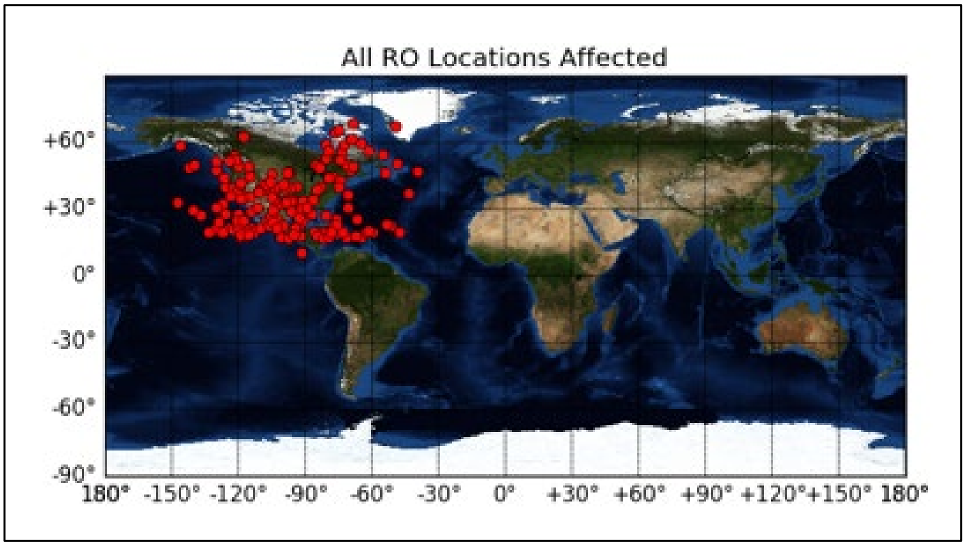

Figure M.19: Sentinel-6 Plot of RO Locations for Simulation 3b (Sample Plot)

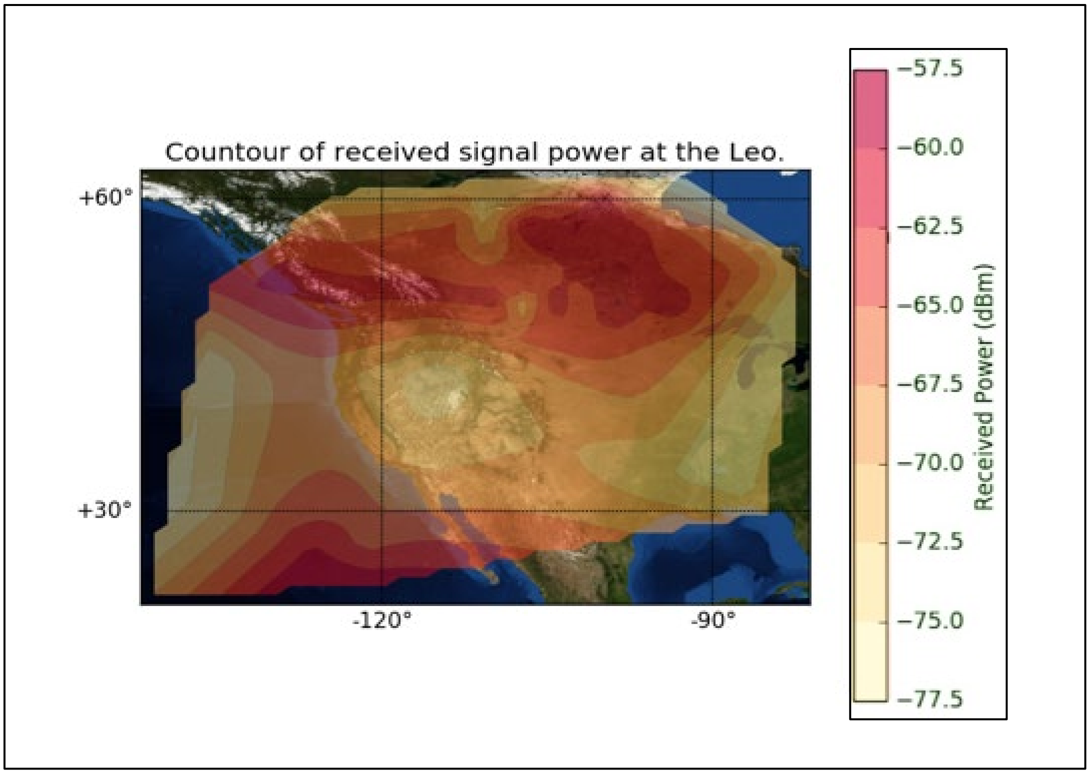

Figure M.20: Sentinel-6 Interference Impact Plot of Simulation 3b (Sample Plot)