Determination of Tolerable Transmitter EIRP Levels for High Precision GNSS Receivers

57th Meeting of the CGSIC at the ION GNSS+ 2017 Conference
Portland, Oregon
September 25, 2017

Hadi Wassaf, Stephen Mackey, Karen Van Dyke

U.S. Department of Transportation
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Advancing transportation innovation for the public good

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Acknowledgement

- George Dimos
- Pratik Gandhi
- Chris Hegarty
- Karl Shallberg

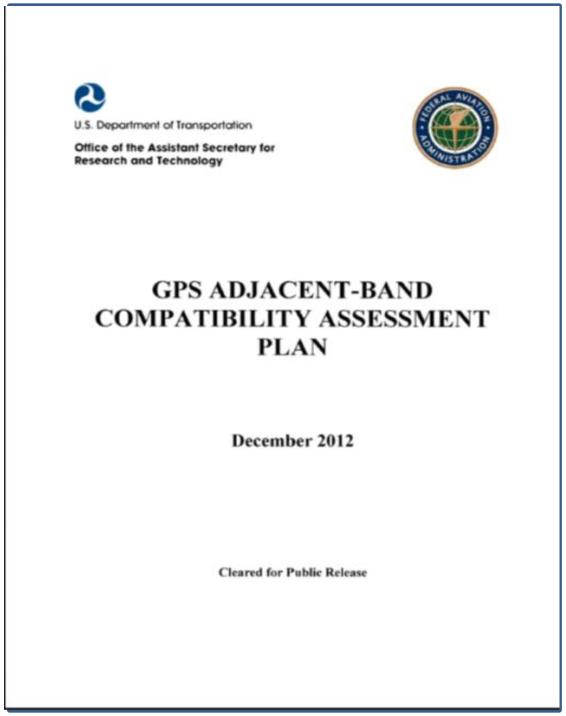
Outline

- GPS Adjacent Band Compatibility Assessment Background
- Technical approach
- Receiver testing and results for high precision (HPR) receivers
- HPR example use case
- Transmit network and handset/mobile device parameters
- Receive antenna patterns
- Results and sensitivity analysis
- Summary and Conclusion

GPS Adjacent Band Compatibility Assessment Background

- Propose adjacent band transmit power levels that can be tolerated by existing GNSS receivers for civil applications [excluding certified aviation applications - those are considered in a parallel FAA effort]

- Accomplish this through:
  - Seeking users, manufacturers, and other stakeholders' inputs and feedback throughout the planning, testing and analysis phases of this effort
  - Investigating use cases to determine practical limiting scenarios
  - GNSS receiver testing and antenna characterization
  - Data analysis to develop 1 dB CNR degradation interference tolerance masks (ITMs) for each GNSS receiver
  - Development of generic transmitter (base station and handheld) scenarios
  - Analysis and modeling to determine tolerable transmit power levels and regions of impact


U.S. Department of Transportation
Office of the Assistant Secretary for Research and Technology

GPS ADJACENT-BAND COMPATIBILITY ASSESSMENT PLAN

December 2012

Cleared for Public Release

Technical Approach

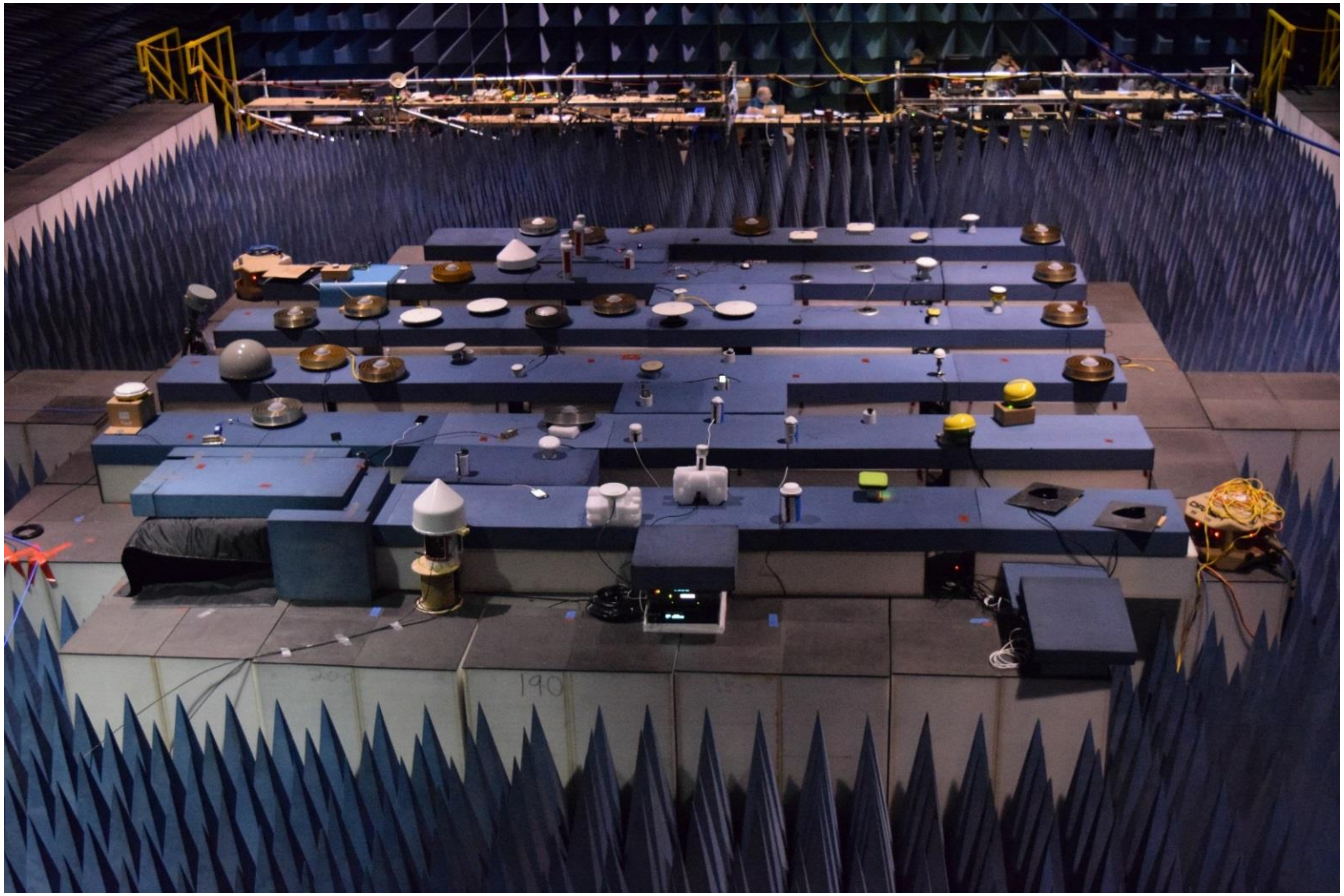
- Interference Criterion: 1-dB CNR degradation
- Anechoic chamber testing of receivers to determine the receive interference power (IP*) threshold level for each receiver according to the above criterion
  - The minimum IP* threshold across a category of GNSS receivers is used to determine ITM(f) for that category
- Transmitter parameters, receiver parameters, and antenna characteristics are then used to determine tolerable transmit power levels for each category.
- This presentation addresses the HPR category

***IP is referenced to the output of a hypothetical ideal isotropic antenna collocated with the receiver antenna, and having a polarization matching that of the radiated interference signal. It is essentially a measure of the intensity of the electromagnetic wave impinging on the receiver antenna**

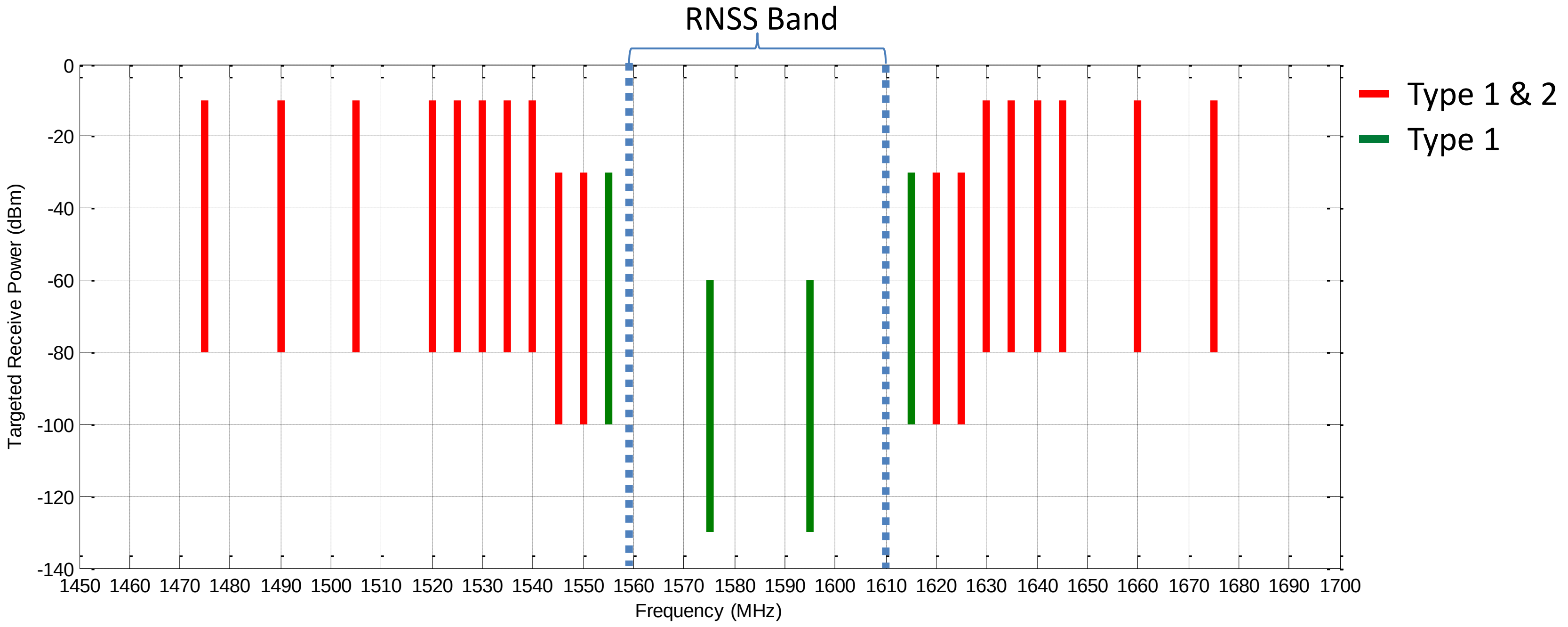
Receiver Testing : Overview

- GNSS receiver testing was carried out April 25-29, 2016 at the Army Research Laboratory's (ARL) Electromagnetic Vulnerability Assessment Facility (EMVAF), White Sands Missile Range (WSMR), NM
- Participation included DOT's federal partners/agencies (USCG, NASA, NOAA, USGS, and FAA) and GPS manufacturers
  - Air Force/GPS Directorate conducted testing week of April 18th
- 80 receivers were tested representing six categories of GPS/GNSS receivers: General Aviation (non certified), General Location/Navigation, **High Precision & Networks**, Timing, Space Based, and Cellular
- Tests performed in the anechoic chamber:
  - Linearity (receivers CNR estimators are operating in the linear region)
  - 1 MHz Bandpass Noise (Type 1)
  - 1 MHz In-Band Noise (Type 1)
  - 10 MHz Long Term Evolution (LTE) (Type 2)
  - Intermodulation (effects of 3rd order intermodulation)

Receiver Testing: Chamber Test Grid and Setup



Receiver Testing: Interference Test Signal Frequencies and Power Profiles



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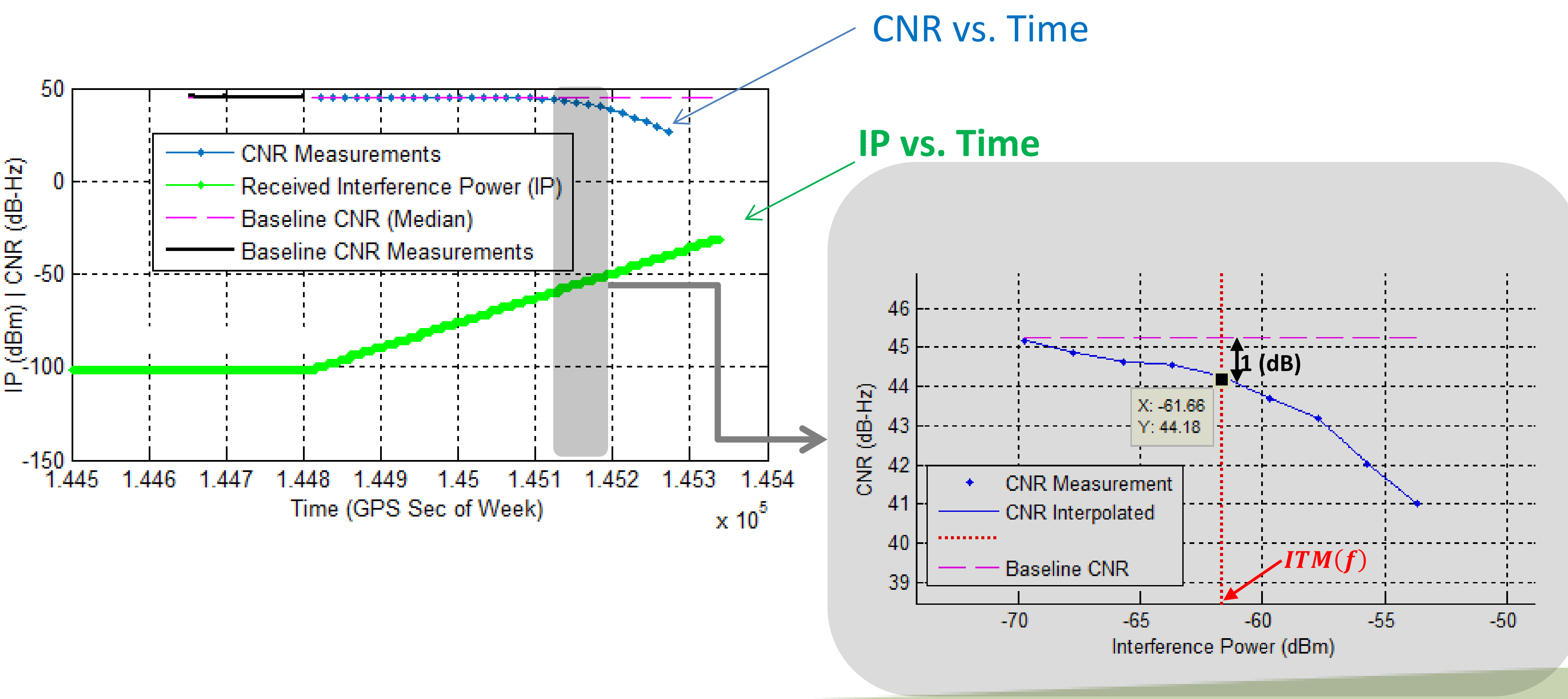
Receiver Testing: GNSS Signals Used in Testing

Signal
GPS 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
Galileo E1 B/C

Receiver Testing: Data Processed to Produce a 1 dB Interference Tolerance Mask

- Example for determining ITM(f) for 1 frequency (f=1545) for PRN 31 for one of the Devices Under Test (DUT)



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Receiver Testing: Determination of Tolerable EIRP levels

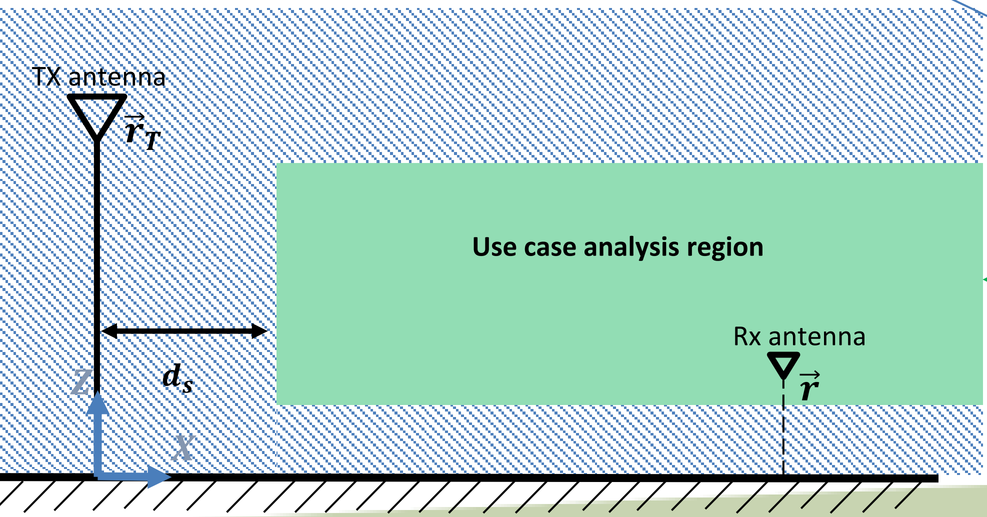
- It can be shown that the tolerable EIRP of a transmitter radiating a +/- 45^{o} cross polarized interference signal can be determined according to the following equation

$$EIRP(\vec{r},f) = \frac{ITM(f)}{L_p(\vec{r}_T,\vec{r}).\, g_{Td}\,(\vec{r}_T,\vec{r}).\frac{1}{2}\,(g_{Rdv}(\vec{r}_T,\vec{r},f) + g_{Rdh}(\vec{r}_T,\vec{r},f))}$$

Free Space Path Loss (FSPL)

Normalized H-pol and V-pol receiver antenna patterns

Normalized transmitter antenna pattern assumed to be the same for H an V polarized radiations



$$EIRP(d_s,f) = Min_{\vec{r}\epsilon R_{uc}}\{\,EIRP(\vec{r}_T,\vec{r},f)\}$$

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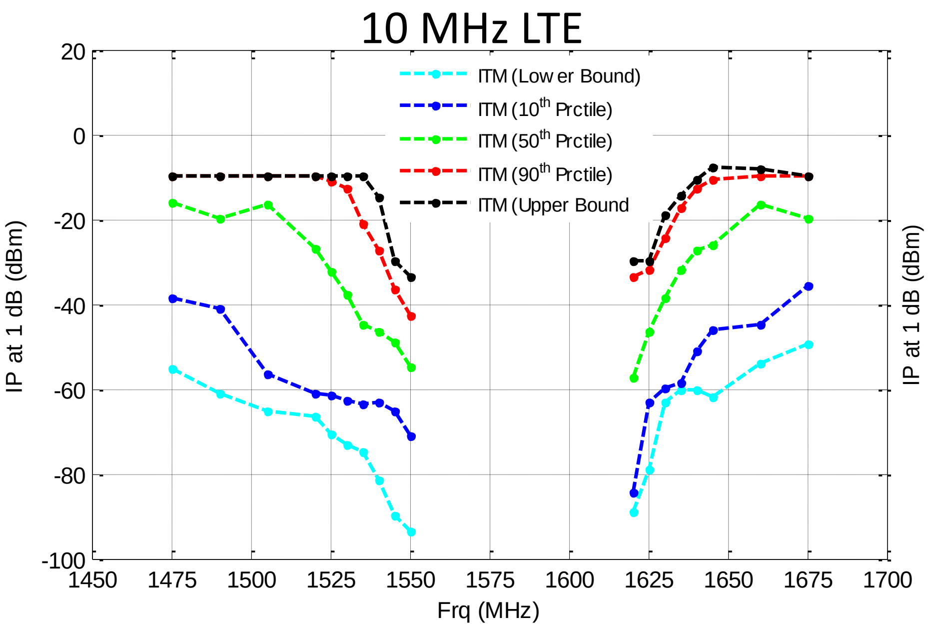
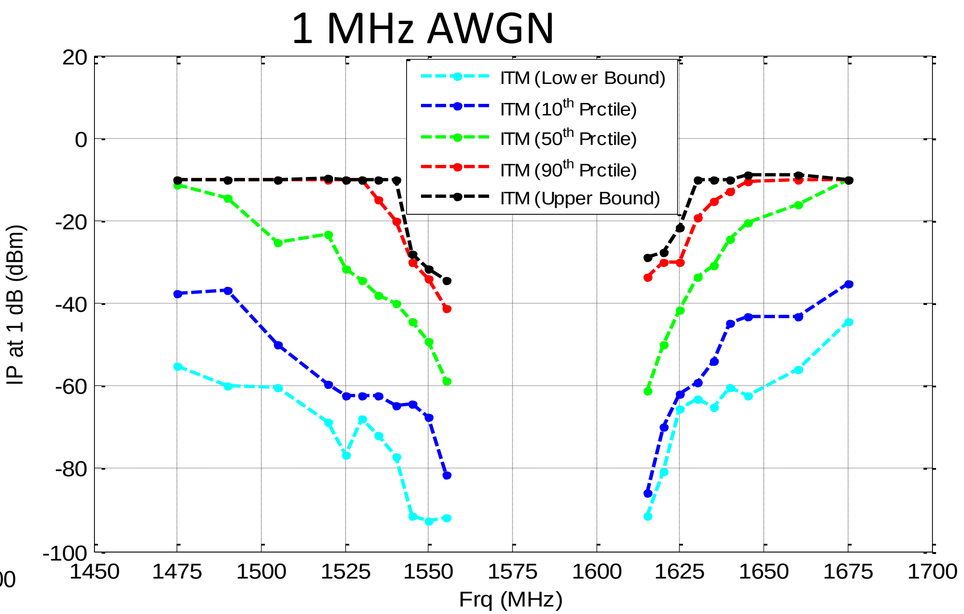
HPR Test Results: L1 C/A Statistical Mask Results for HPR Receivers





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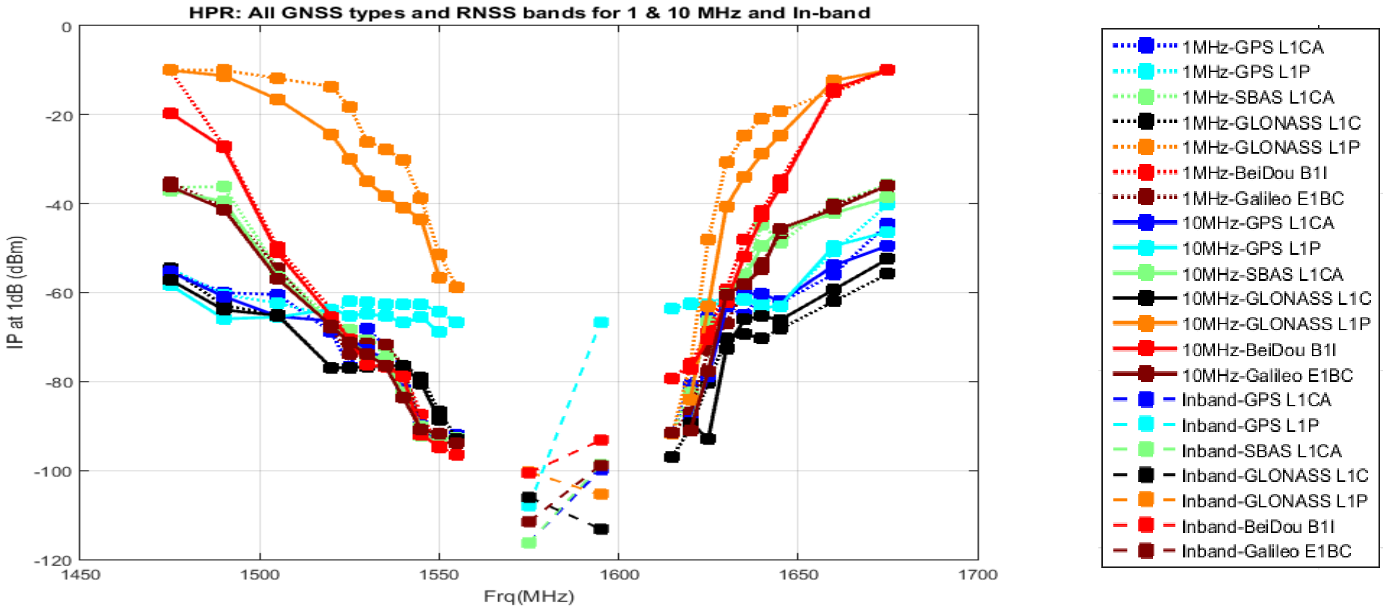
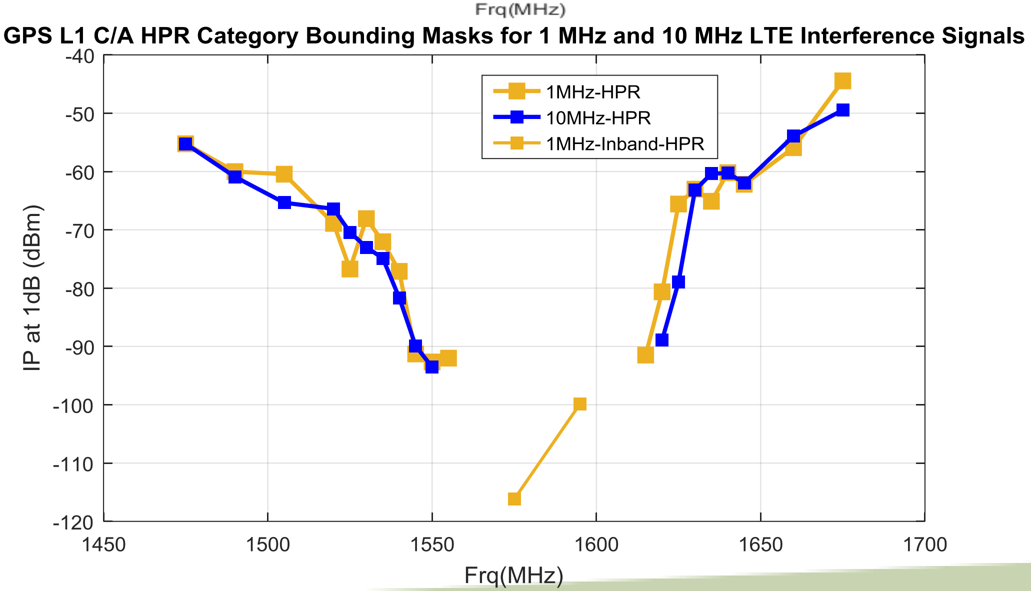
HPR Test Results: Summary of 1&10 MHz and In-band Bounding Masks - HPR





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HPR Example Use Case: Construction and Machine Control

Photo courtesy of WSP Canada Inc

Photo courtesy ThinkStock

Photo courtesy of WSP Canada Inc

Photo courtesy Medvedkov/ThinkStock

Surveying

Photo courtesy Kadmy/ThinkStock

HPR Example Use Case: GNSS Receiver Proximity to Interfering Transmitter(s)

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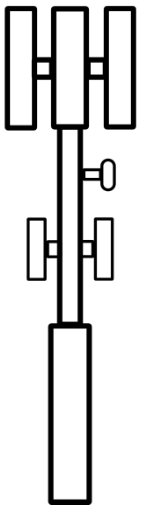
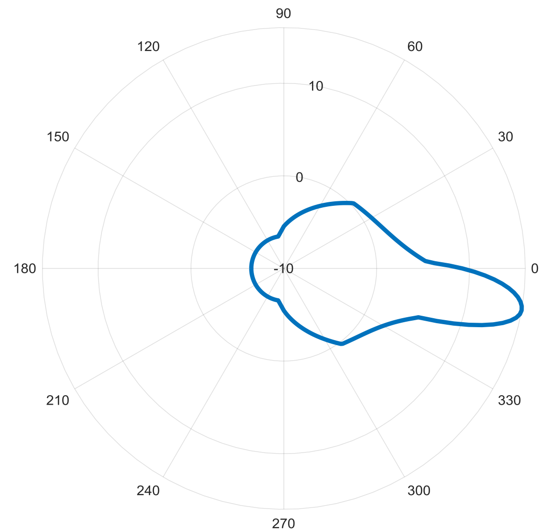
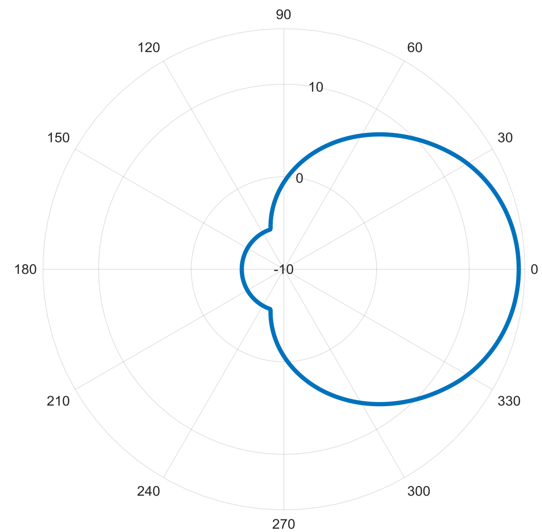
Transmit Network Parameters: ITU-R M.2292 Macro Base Stations





Elevation Cut

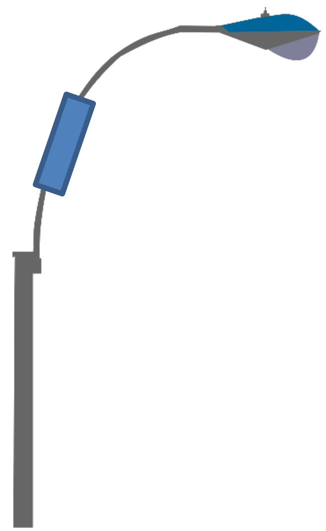


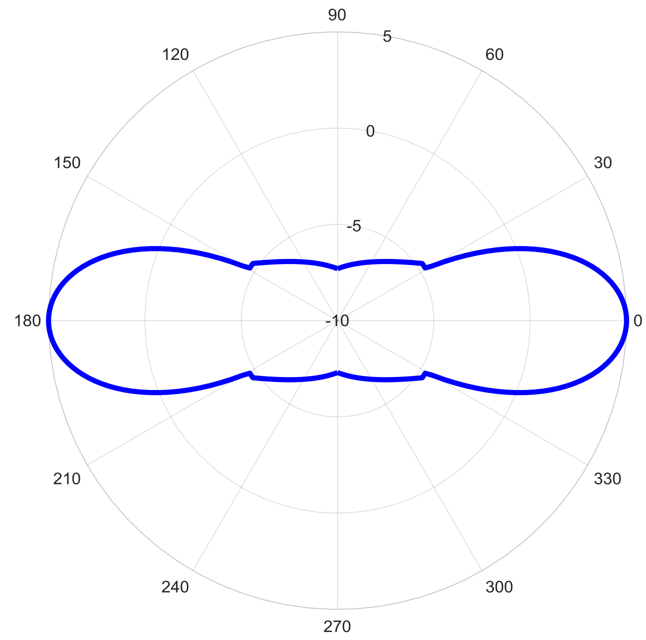
Azimuth Cut (1 Sector)

Macro Urban

- 16 dBi antenna gain
- +/-45° polarization
- 3 sectors
- EIRP: 59 dBm
- 25 m height
- 10 deg downtilt
- 0.25 – 1 km cell radius

Transmit Network Parameters: ITU-R M.2292 Small Cell Base Stations





Small cell outdoor/ Micro urban

- 5 dBi antenna gain
- Linear polarization
- Single sector
- No downtilt
- EIRP: 40 dBm
- 6 m height
- 1 – 3 per Urban macro cell

- Azimuth pattern is omnidirectional
- Plot above is an elevation cut

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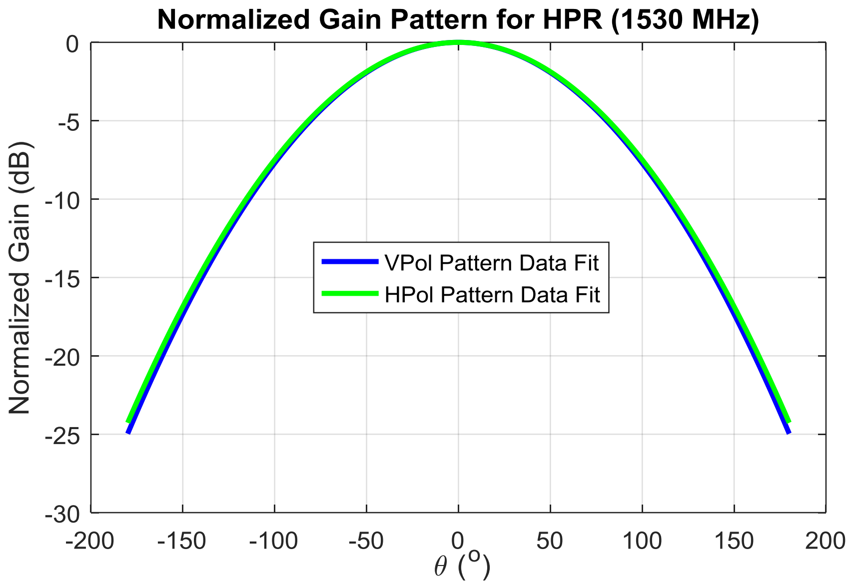
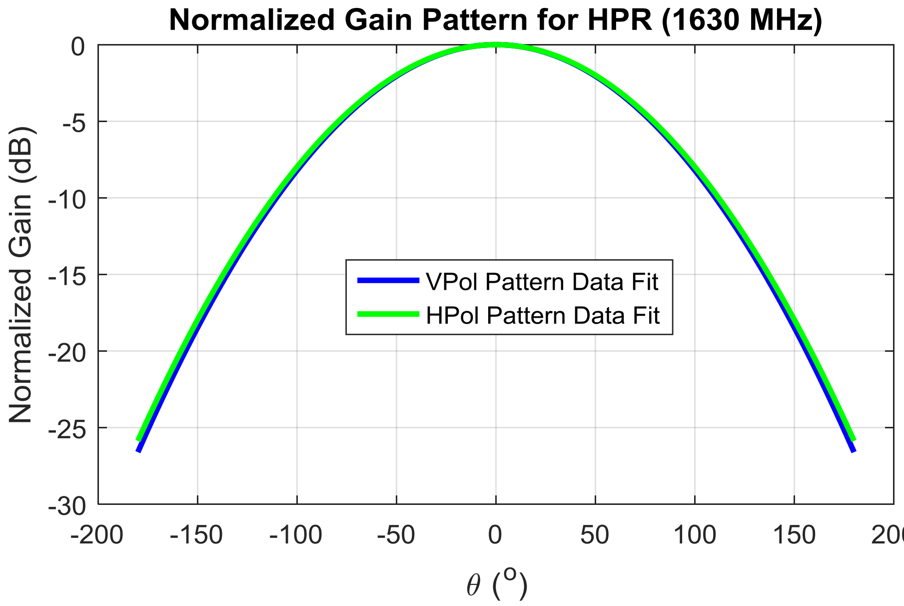
Handset/Mobile Device Parameters

- 23 dBm EIRP (assumes 0 dBi antenna gain and no body loss)
- Isotropic transmit antenna gain
- Vertical polarization
- Assumed to be at 2 m height above ground

Receive Antenna Characteristics: VPOL and HPOL Patterns

- Antenna patterns are generated by a parabolic fit to average gain patterns of a representative set of HPR antennas measured in an anechoic chamber
- Averaging across antenna patterns is performed separately for each frequency and polarization combination prior to fitting
- Below are example antenna patterns used in the tolerable EIRP analysis for one downlink frequency (1530 MHz) and one uplink frequency (1630 MHz)





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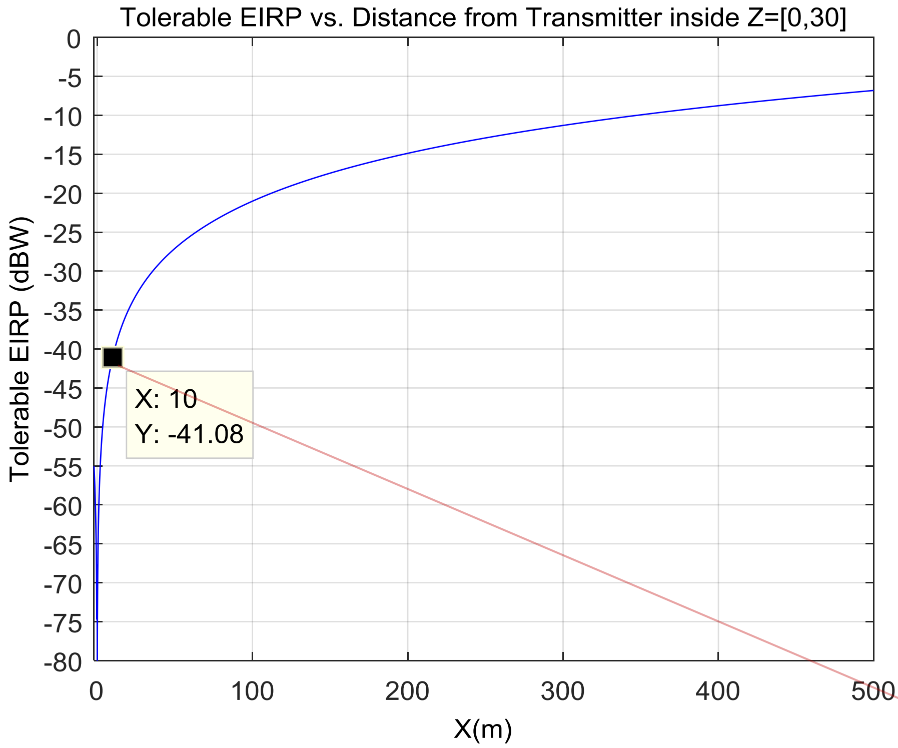
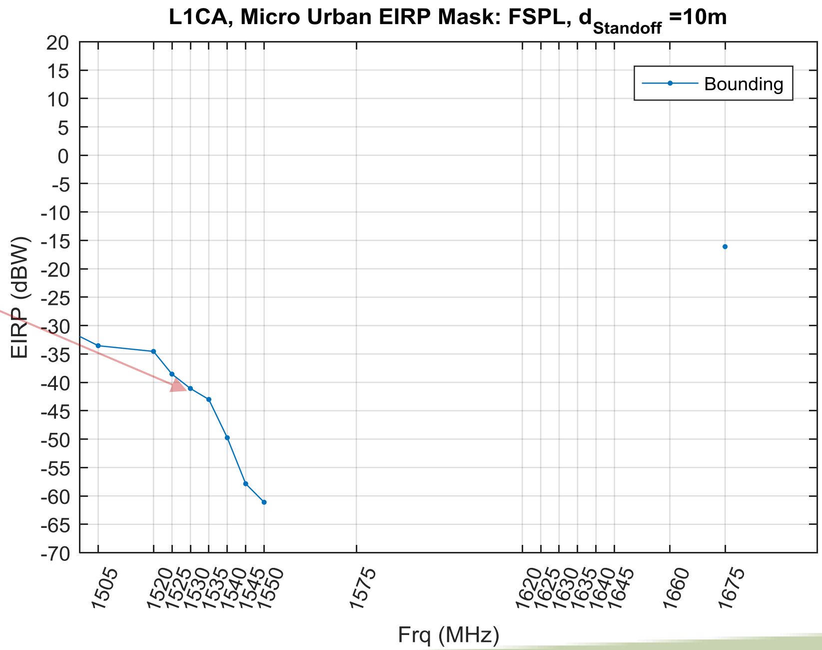
Results: Tolerable EIRP Levels: Single Base Station Transmitter, FSPL



- For a 1530 MHz interference signal, the tolerable EIRP Levels are below 0.25 watts at a standoff distance of ½ km
- At 10m stand-off distance the tolerable EIRP ranges from 1 μW to 1 mW for interference for an interference signal with center frequency in the 1500 to 1550 frequency range
- For a 1675 MHz interference signal the tolerable EIRP is on the order of 30 mW for the same 10m stand-off distance



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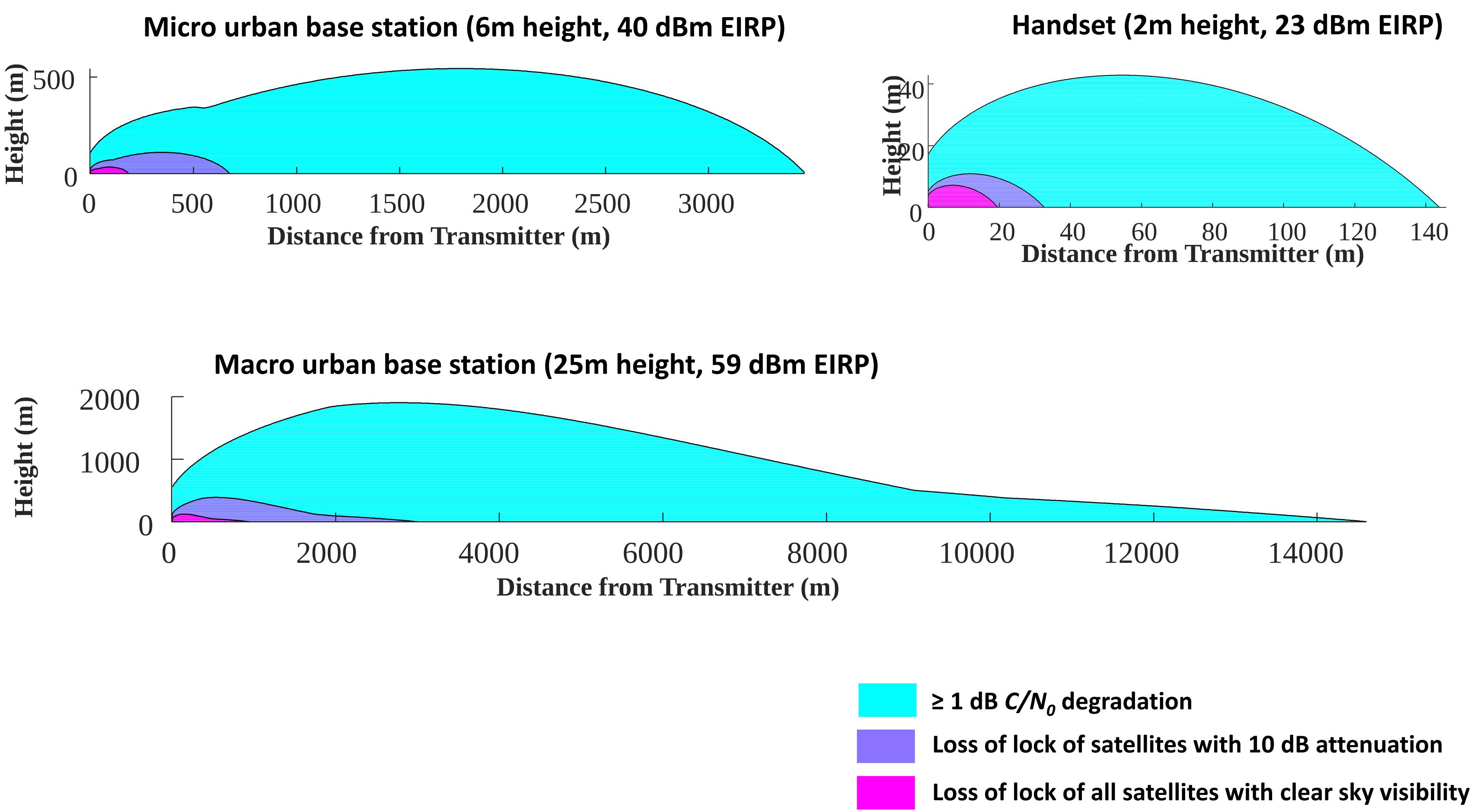
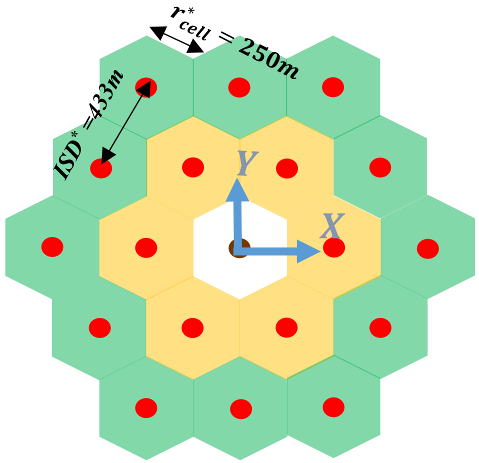
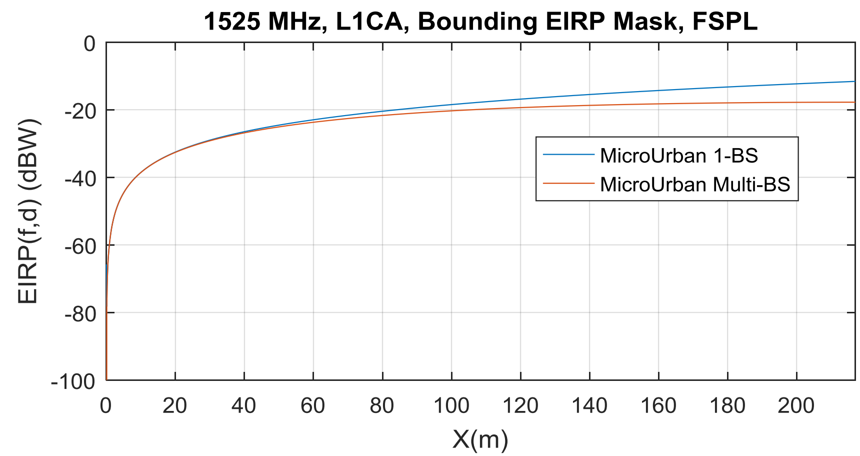
Results: Region of Impact for ITU Recommended Power Levels Discussed in Previous Slides

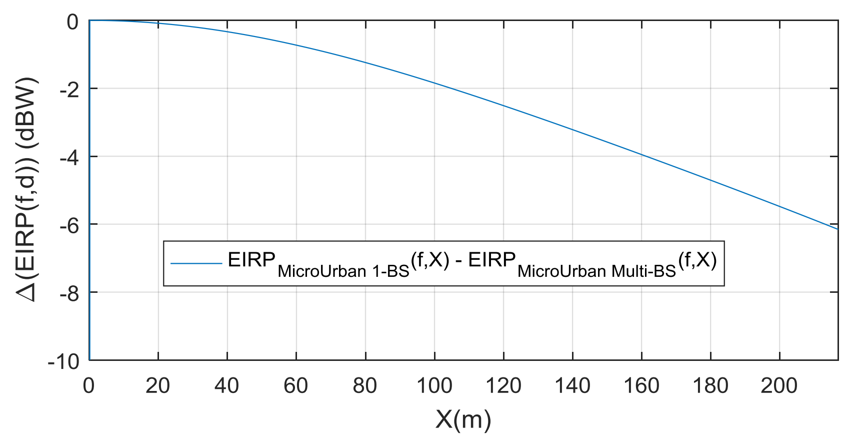


Sensitivity Analysis: Aggregation Effects (Micro Urban Deployment)





$\frac{ISD}{2}$



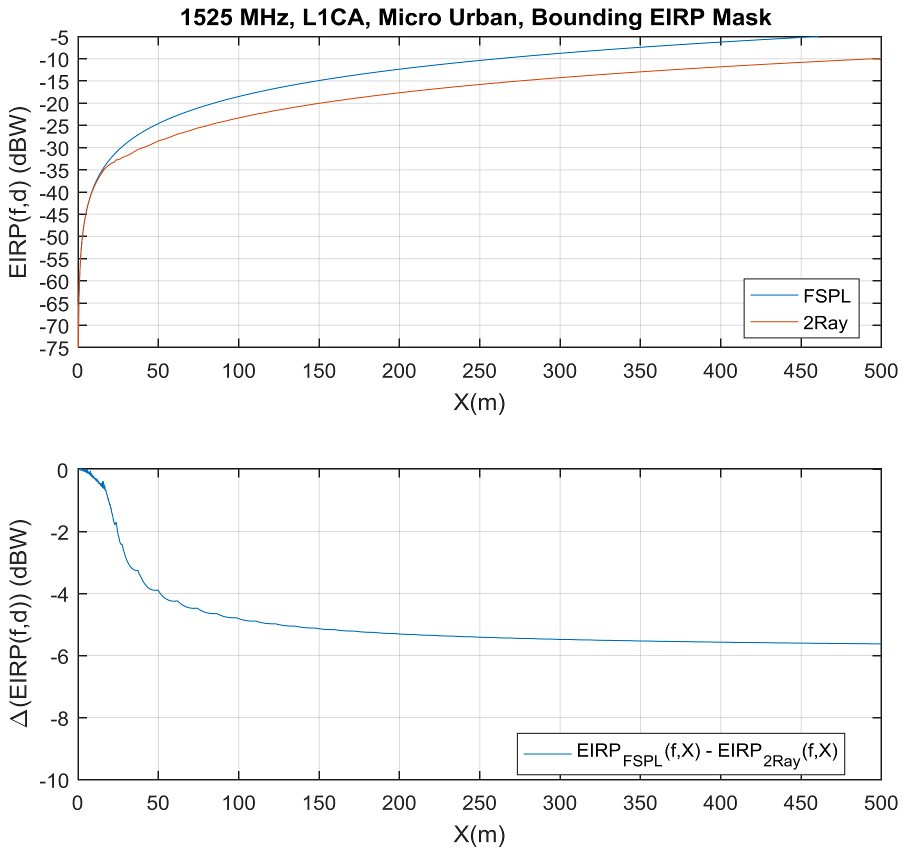
- Due to the periodicity of transmitter placement, the vertical analysis plane (y=0) need to extend only up to X=ISD/2.
- Interference is dominated by a single transmitter for standoff distances less than 20m
- The aggregate tolerable EIRP decreases monotonically relative to the single transmitter case to a maximum reduction of 6 dB at the mid-point location between two consecutive transmitters

* Inter-site distance (ISD) Based on ITU-R M.2292 TABLE-3 typical cell radius/cell density to be used in sharing studies. See appendix B

Sensitivity Analysis: Sensitivity to Propagation Loss Models

- Two-ray path loss model* reduces the tolerable EIRP levels by up to 6 dB

- Difference is less significant for small distances due to the combined effects of transmit/receive (T/R) antenna patterns



* See appendix C for two-ray path loss model equations

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Summary and Conclusion

- Inverse modeling allows determination of tolerable EIRP levels when the receiver tolerable IP levels are known
- Model takes into account the polarization dependent gain pattern of T/R antennas and is capable of considering aggregation and propagation model effects from multiple transmitters
- For a micro-urban base station radiating a 10 MHz LTE signal, the tolerable transmit EIRP levels ranges from $1\mu W\ to\ 1mW$ for center frequencies between 1500 and 1550, and is $30\ mW$ for the 1675 center frequency
- Sensitivity analysis results for micro urban network configuration:
  - Aggregation effects will limit the maximum tolerable power at larger distances up to the maximum distance of ISD/2
  - Two ray path loss model results in a reduction of up to 6 dB at the maximum distance of ISD/2
- When the recommended ITU power levels for transmitters are used, the maximum extent of the impact regions are

Transmitter type	Extent of impact Region
Macro urban base station	**14.5 km**
Micro Urban base station	**3.5 km**
Mobile transmitter	**140 m**

Appendices

Appendix A: Receiver Test List (1/2)

No.	Receiver
1	Trimble SPS461
2	Furuno GP-33
3	TriG
4	TriG V2
5	Septentrio PolaRx4TR Pro
6	Ashtech Z-12
7	Javad Delta-3
8	Ashtech uZ-CGRS
9	Javad EGGDT-160
10	Novatel OEM628V-G1S-B0G-TTN-H
11	Javad Delta II
12	Septentrio PolaRx4Pro
13	Trimble NETR5
14	Trimble NETR5
15	Trimble NETR9
16	Leica GRX1200GGPRO
17	Trimble 5700
18	Leica GRX1200GGPRO
19	Trimble NETRS
20	Trimble NETRS

No.	Receiver
21	Trimble NETRS
22	Topcon Net-G3A Sigma
23	Garmin GPSMap 295
24	Garmin - GPSMap 696
25	Garmin - Area 560
26	Garmin - GLOGPS (GPS & GLONASS)
27	Dual Electronics - SkyPro XGPS 150
28	EVA-7M EVK-7EVA-0
29	MAX-7C EVK-7C-0
30	MAX-7Q EVK-7N-0
31	EVA-M8M EVK-M8EVA-0
32	LEA-M8F EVK-M8F-0
33	MAX-M8Q EVK-M8N-0
34	LEA-M8S EVK-M8N-0
35	uBlox EVU-6P-0-001
36	SiRF III
37	Trimble NETR5
38	Symmetricom Xli
39	Symmetricom-GPS
40	Trimble SMT360 GPS receiver

Receivers included in the wired/conducted test

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Appendix B: Receiver Test List (2/2)

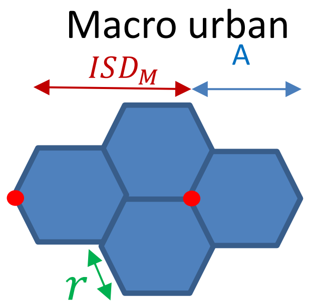
No.	Receiver
41	Dynon 250
42	Dynon 2020
43	Garmin EDGE 1000
44	Garmin GPSMAP 64
45	Garmin ETREX 20x
46	Garmin FORERUNNER 230
47	Garmin GPSMAP 741
48	Symmetricom Xli
49	JAVAD Triumph-1
50	Hemisphere R330
51	NAVCOM SF3050
52	Symmetricom SyncServer S350
53	Arbiter Systems 1088B
54	Arbiter Systems 1094B
55	Schweitzer Eng. Labs SEL-2401
56	Android S5
57	Android S6
58	Android S7
59	Supercruise "VCP"
60	Supercruise "VCP"

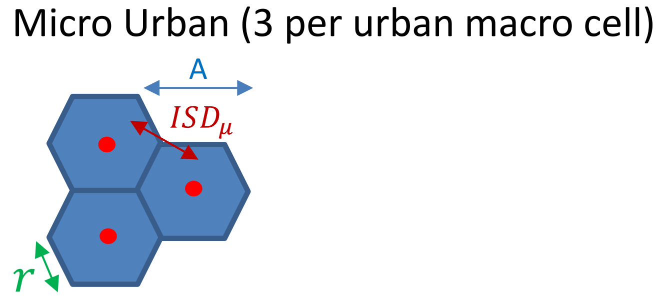
No.	Receiver
61	EVK-M8N
62	EVK-M8T
63	MAX-M8Q
64	EVK-7P
65	EVK-6n
66	NovAtel 628 Card w/ Flex pack
67	Trimble Ag-382
68	Trimble Geo 7X
69	Trimble Bison III
70	Trimble R8
71	Trimble SPS985
72	Trimble SPS855
73	Trimble Acutime 360
74	Trimble Ag-382
75	SF3000
76	SF3000
77	Septentrio PolaRx5TR Pro
78	Septentrio PolaRx5TR Pro
79	Trimble NetRS
80	Trimble NETR9

Receivers included in the wired/conducted test

Appendix B: Inter-Site Distance

- ITU-R M.2292, Table 3: Recommend A=500 m for urban macro cell sharing studies. Recommends up to 3 times the density for a urban micro cell.





- Cell radius $r = \frac{A}{2} = 250m$, resulting in inter-site distances of $\mathrm{ISD}_\mu = \sqrt{3}.r = \sqrt{3} \times 250 = 433\ m$ and ISD_M= 3x250 = 750 m

Appendix C: 2-Ray Path-Loss

$$EIRP(\vec{r}, f) = \frac{ITM(f)}{\frac{1}{2} \cdot g_{Td}(\vec{r}).\left(g_{Rdv}(\vec{r}, f) \,.\, PF_v(\vec{r}, f) + g_{Rdh}(\vec{r}, f).\, PF_h(\vec{r}, f)\right)}$$

$$PF_{h,v}(\vec{r}, f) = \left(\frac{\lambda}{4\pi R_d}\right)^2 . \left|1 + F_{h,v}(\vec{r}, f)\right|^2$$

$$\mathrm{F}_{\mathrm{h,v}}(\vec{r}, f) = \rho_{h,v} \cdot \frac{R_d}{R_r} \cdot \sqrt{\frac{g_{Tr}(\vec{r}).\, g_{Rrh,v}(\vec{r}_T, \vec{r}, f)}{g_{Td}(\vec{r}).\, g_{Rdh,v}(\vec{r}, f)}}\, e^{j2\pi\frac{R_r - R_d}{\lambda}}$$

$$\rho_h(r, f_c) = \frac{\sin(\theta_{GR}(r)) - \sqrt{(\varepsilon_r - i \cdot x(f_c)) - \cos^2(\theta_{GR}(r))}}{\sin(\theta_{GR}(r)) + \sqrt{(\varepsilon_r - i \cdot x(f_c)) - \cos^2(\theta_{GR}(r))}}$$

$$\rho_v(r, f_c) = \frac{(\varepsilon_r - i \cdot x(f_c))\sin(\theta_{GR}(r)) - \sqrt{(\varepsilon_r - i \cdot x(f_c)) - \cos^2(\theta_{GR}(r))}}{(\varepsilon_r - i \cdot x(f_c))\sin(\theta_{GR}(r)) + \sqrt{(\varepsilon_r - i \cdot x(f_c)) - \cos^2(\theta_{GR}(r))}}$$

$$x(f_c) = \frac{\sigma_c}{2\pi.\, fc.\, d.\, \epsilon_o}$$

$\theta_{GR}(\vec{r})$: Grazing angle of reflected ray