CARMEN: Center for Automated Vehicle Research with Multimodal Assurred Navigation

A USDOT Tier-1 University Transportation Center

RF and Antenna Threats, Risks, and Mitigations for GNSS Receivers

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Final Report for CARMEN UTC Project 4: RF and Antenna Threats, Risks, and Mitigations for GNSS Receivers

PI: Teh-Hong Lee (previously Andrew O'Brien until 10/5/2021)

Project Duration: 11/1/2020 – 8/31/2023

Introduction:

Under this project, we were responsible for two subtasks 3.1 and 4.1. The final report for each of these tasks is provided below.

Task 3.1- RF PNT Threat Scenario Evaluation

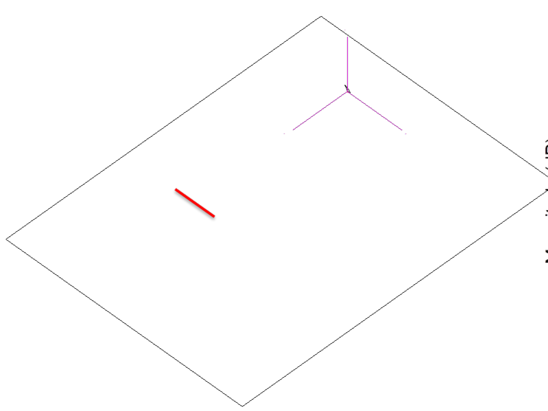
GPS/GNSS systems have been a very critical element to the operation of various modern vehicles as knowing the position of vehicles is very important for many reasons, such as the safety of the vehicles. As an example, the precise GNSS positioning requires receiving clear signals from many satellites over the sky for an automobile at any given location on the ground. Unfortunately, the urban environment in many major cities can cause degradation in GNSS position information due to blockage of the satellite signals and signal scatters from buildings.

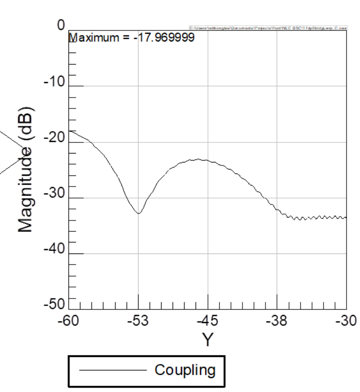
Since GNSS signals are weak and require a line-of-sight (LOS) to the satellite to be trackable by a receiver. The tall buildings in urban canyon environment block this LOS, limiting the number of visible satellites. In addition, the GNSS signals that reflect and diffract from nearby buildings distorting the signal and altering its polarization as well as have additional delay in time of arrival that makes estimation of precise time and direction of arrival more difficult. Knowing the characteristics of the multipath signals, it will be advantageous to have ways from receiver to reduce the threat caused by the multipath signals.

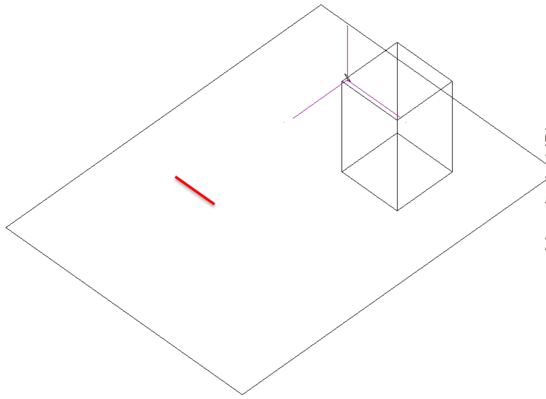
The traditional automotive GNSS antennas can be quite simple. It will be of interest to learn how advanced antenna designs could improve positioning accuracy in under urban canyon conditions although the cost of such antennas as well as their physical sizes can become an issue. The potential goals of advanced antenna design include higher gain, more directive as well as better cross-polarization performance. By characterizing the multipath effects as well as antenna characteristics on the signal propagation in the urban environment, accurate system requirements can be generated.

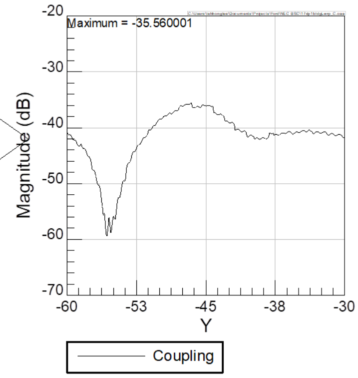
It has been done in the past to use numerical ray tracing approach to study the fading issues associated with mobile communication. In house or commercial ray tracing solutions, based on Uniform Geometrical Theory, have been used in the past for such study. Similar software can be used to simulate the urban propagation environment for vehicles moving under open sky, suburban and urban canyon environments. The received signals will then be used in GNSS/GPS receiver models to quantify the expected positioning accuracy.

A quick example to demonstrate the multipath with wave propagation model is shown below where a dipole antenna was setup on top of a structure while a receiver is moving along a given path. The NEC-Basic Scattering Code (NEC-BSC) was used for this simulation. Structures were added one at a time and one can see the impact of each additional structure to the received signal along the path (red straight line). The open space result with no structure present (first chart) and the result with 6 structures (last chart) are totally different due to the scattering from the structures.





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-53
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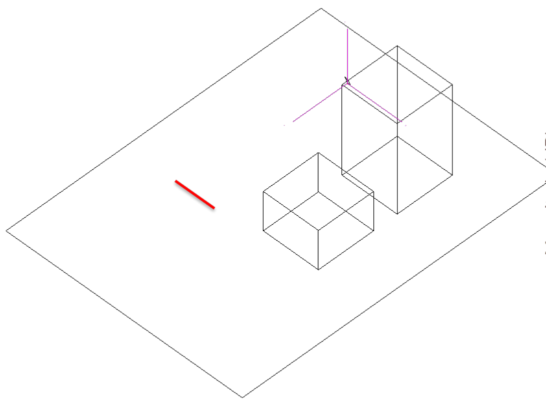
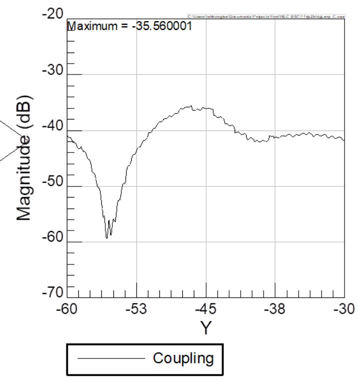
Y
Coupling

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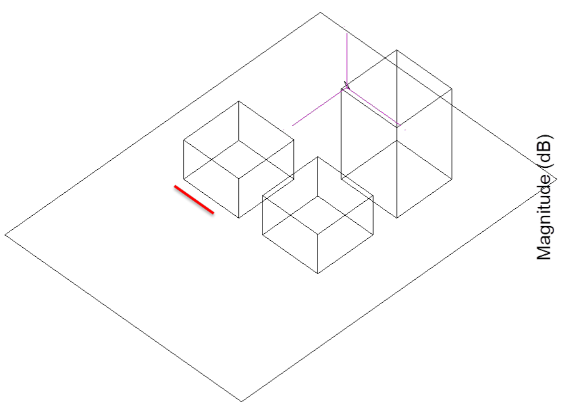

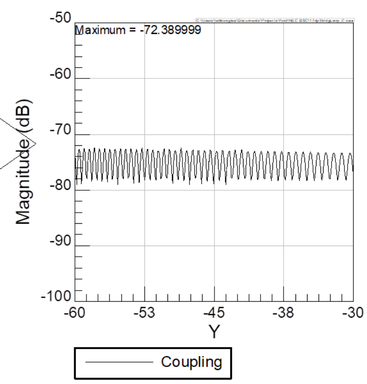
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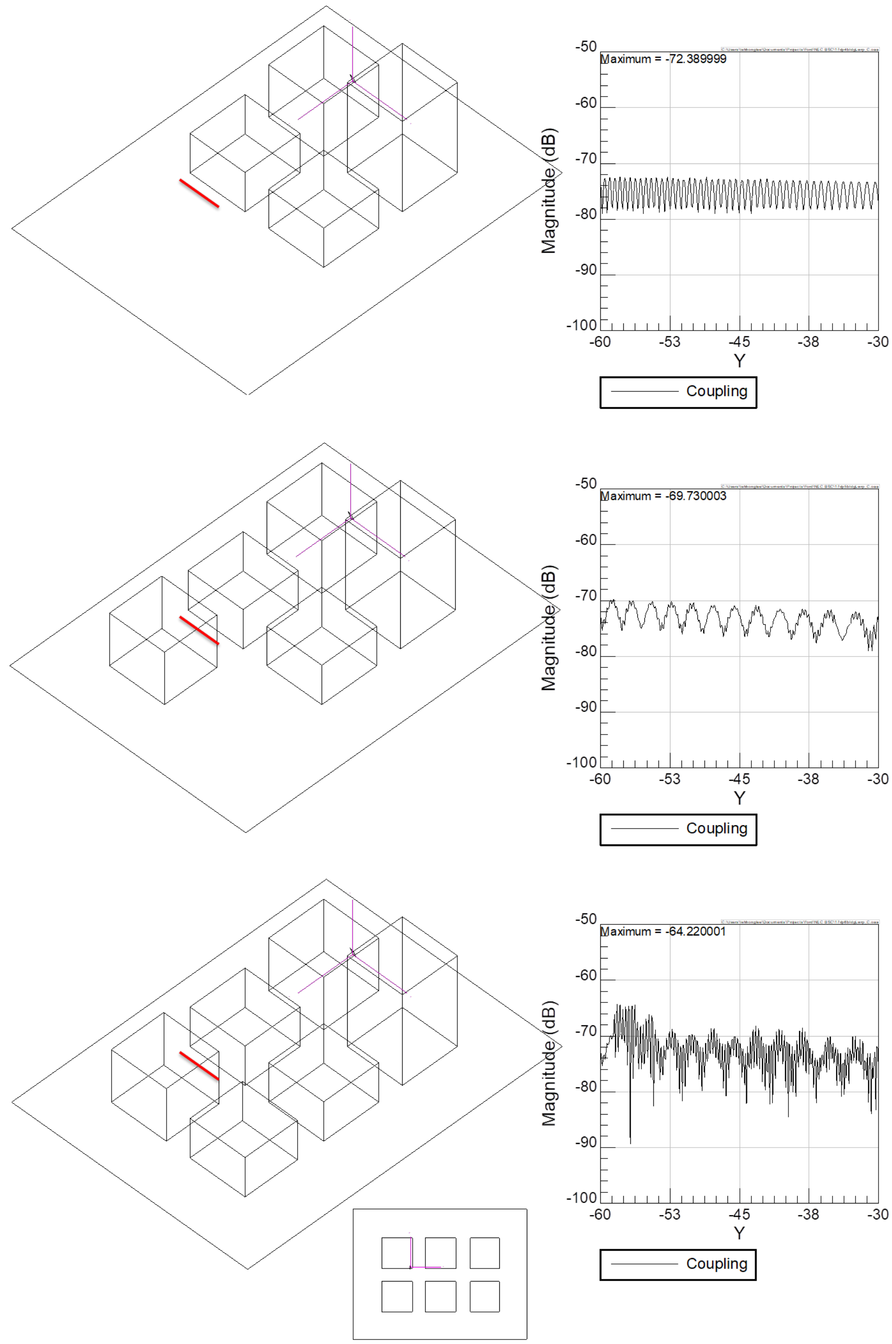
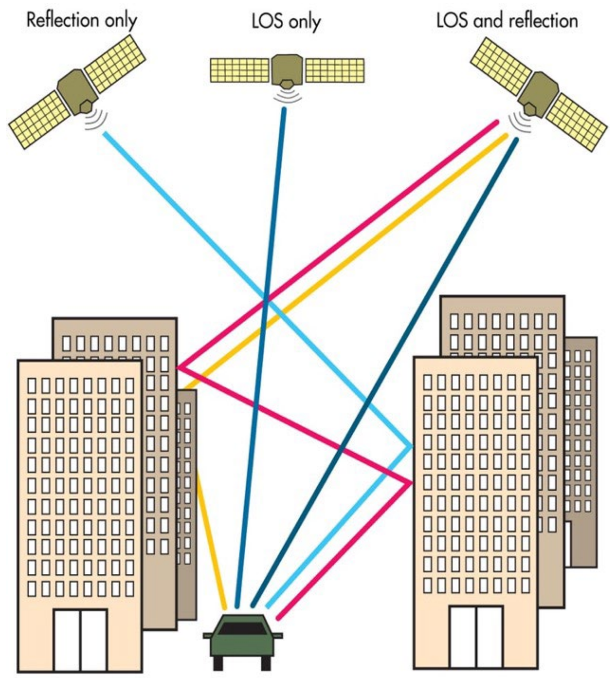
Coupling



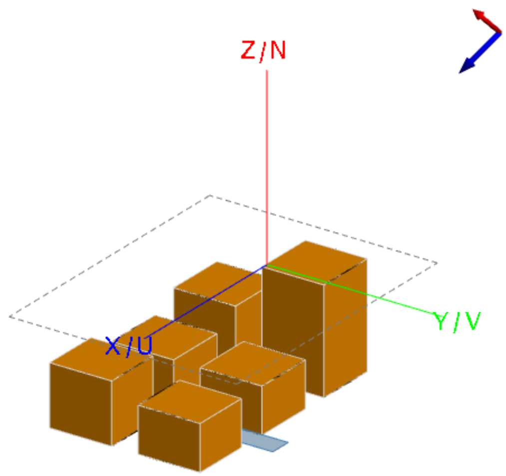
One of the main GNSS threats in urban environments is multipath signals received by the receiver that cause error in positioning and the loss of position when moving in urban canyons. The blockage of direct line of sight (LOS) signal means the loss of the signal from the satellite. Furthermore, the multi-reflection of GNSS signal through the walls of buildings in the canyon adds the delay and polarization diversity of the received signal. There should be an interest in how to reduce the impact of positioning error under a heavy multipath environment. It is a question whether more advanced antenna pattern and receiver designs could improve positioning accuracy in these conditions. We have evaluated commercially available advanced wave propagation software that can be used to simulate the urban propagation environment for vehicles moving under open sky, suburban and urban canyon environments. With the simulated results, we are hoping the simulated results can help us understand the threat impact due to multipath threat and help in future antenna and receiver design.

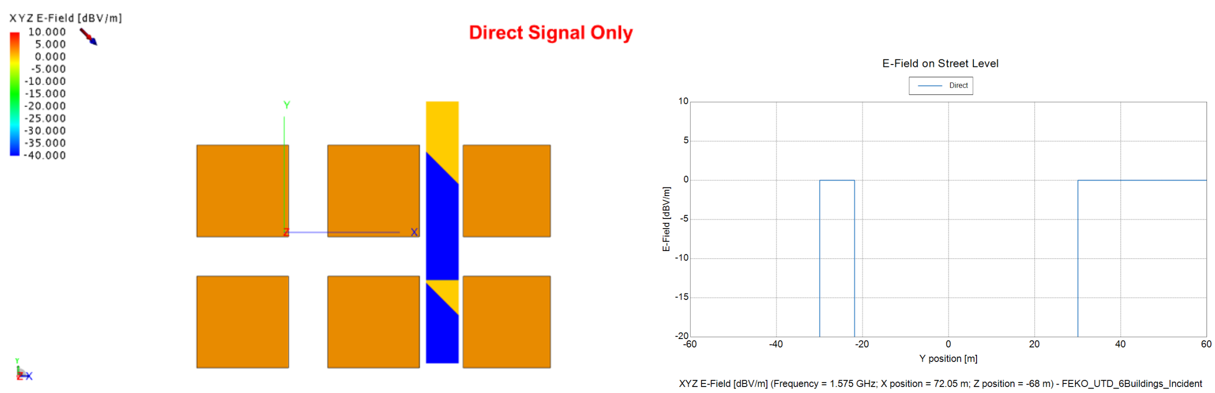


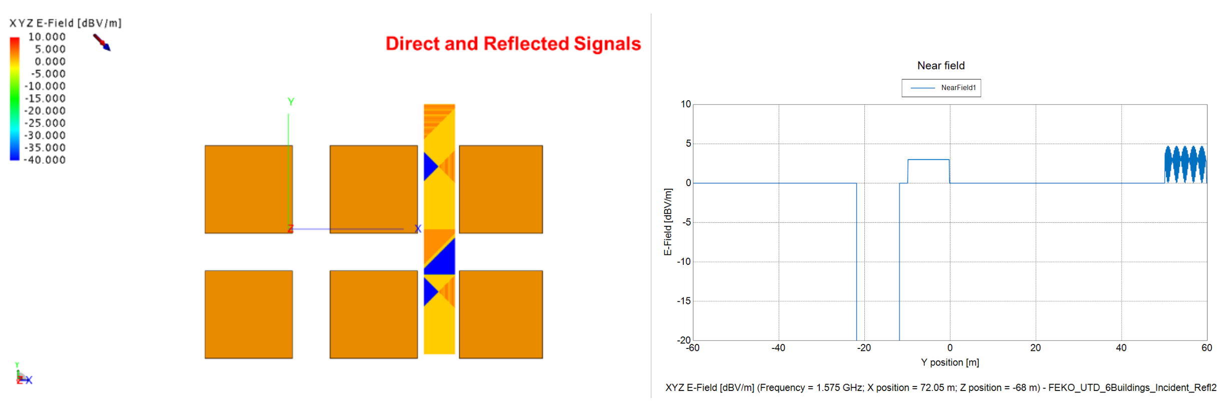
PNT threats due to multipath in urban environment.

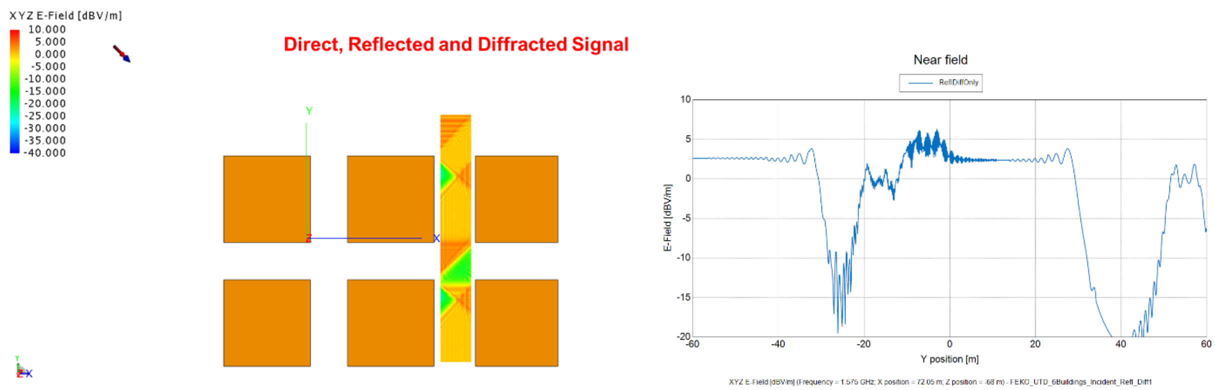
Commercial software Altaire FEKO has been chosen for this study as it has built-in wave propagation model based on Uniform Geometrical Theory of Diffractions (UTD). With the taller structure blocking the light of sight signal from satellites, the multiple reflections and diffractions occur and create error in received signal. Since GNSS is a circularly polarized signal, any single reflection will reverse the polarization, as has been shown in the previous report. In addition, any diffraction through edges depolarizes the signal and results in both right and left circular polarizations. Consequently, how to minimize impact of the multi path signals is very critical in antenna and receiver designs. Note that another feature using UTD for this study is that it allows the option of selecting how many of multi path signal terms between a given incident signal and a receiving antenna position such that each multipath signal and its impact can be analyzed independently if needed.

The pervious example of 6 structures can also be modeled by Altaire FEKO and for a given incident plane wave direction from space, each signal path can be calculated separately as shown below:

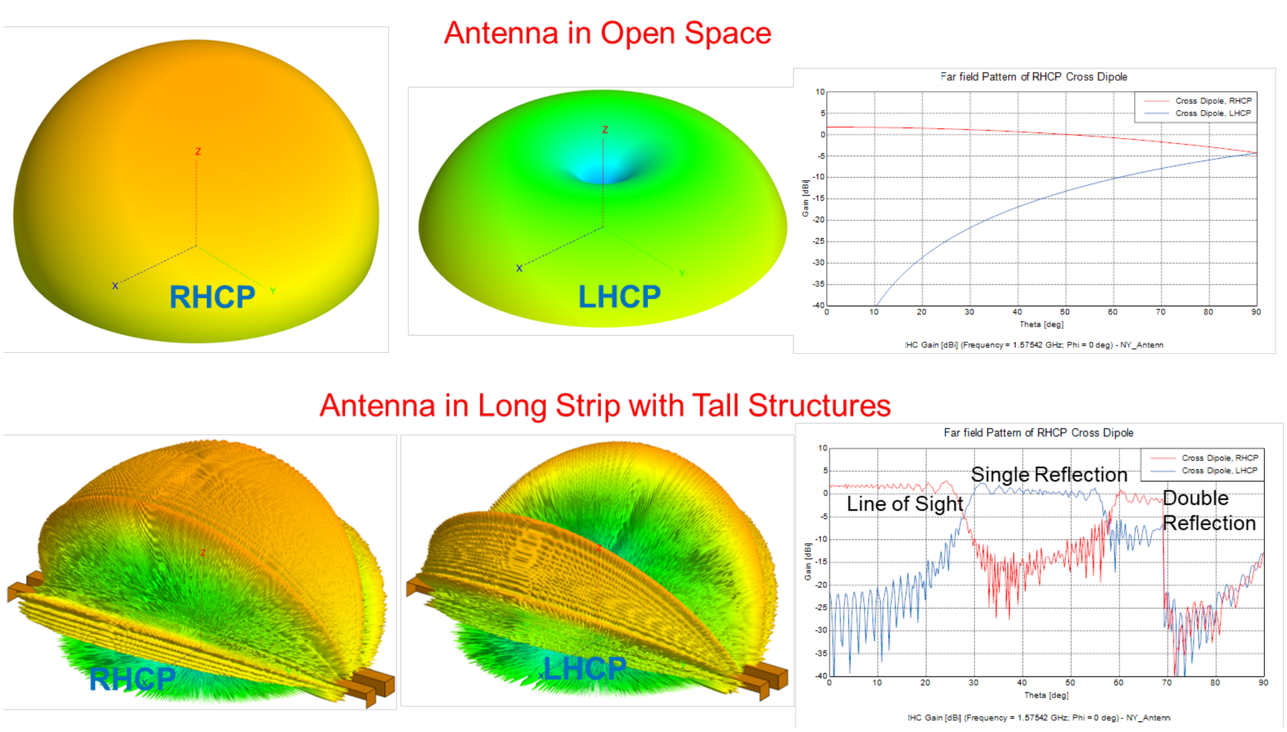




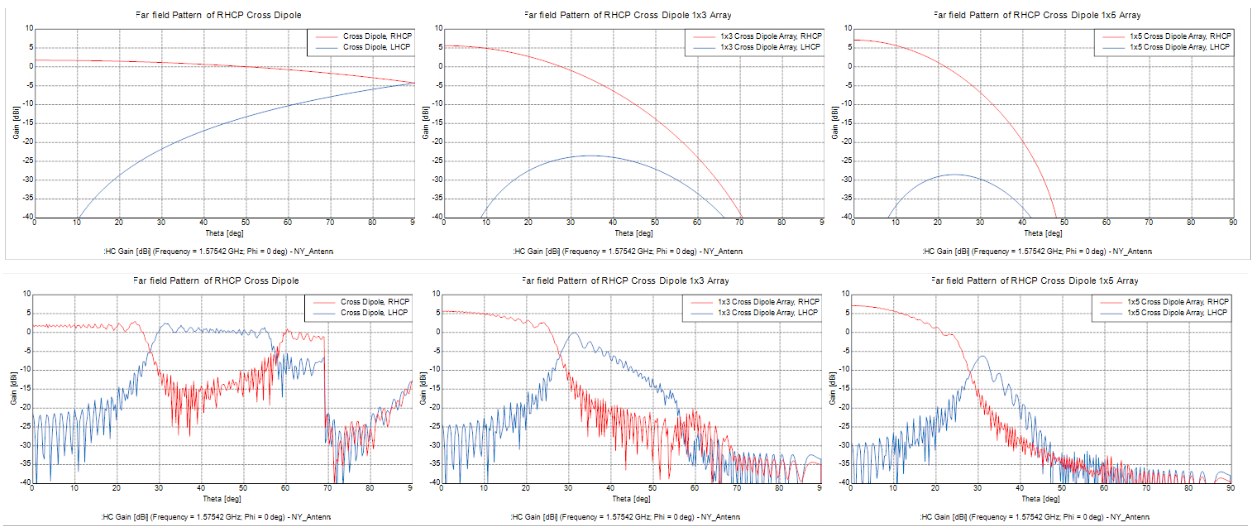




A simple example to study the multipath effect is using a typical GNSS antenna pattern moving along a narrow street lined with tall building on both sides. The results from this simplified model are shown below. The behavior of each multipath is shown from the crosscut of the simulated antenna patterns along the narrow street where one can observe the polarization change due to reflection as well as de-polarization impact of diffractions. Note that the ripples shown in the results are caused by diffractions from the edges of the structure.

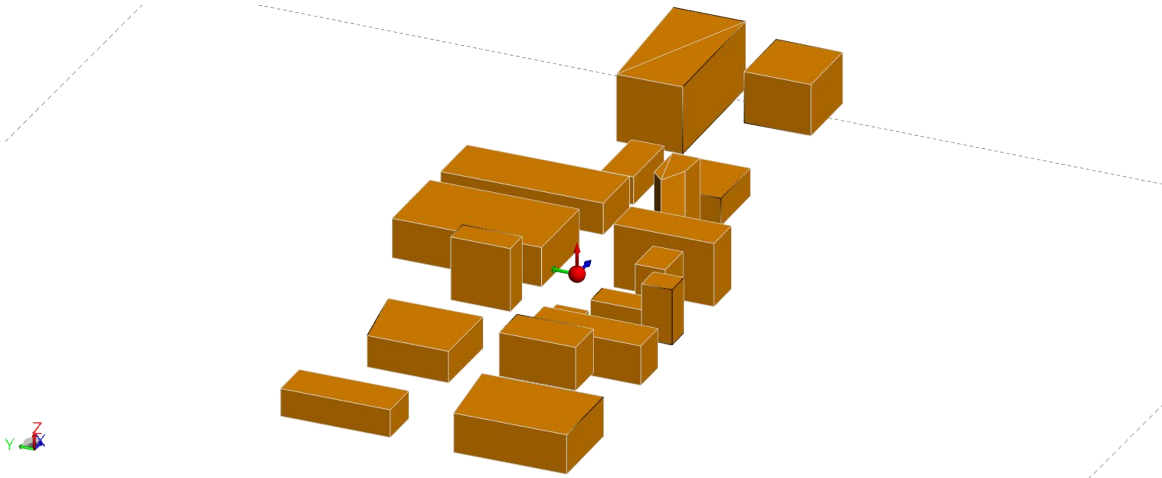


To reduce the impact of multipath and diffractions, one potential solution is to narrow the antenna pattern to reduce the receive signal from the wall and edges. We used simplified antenna model of using cross dipole to simulate the GNSS antenna. To narrow the antenna pattern in one direction, we added additional cross dipoles, so the GNSS antenna becomes a simple 1x3 and 1x5 linear array. The results are shown below:

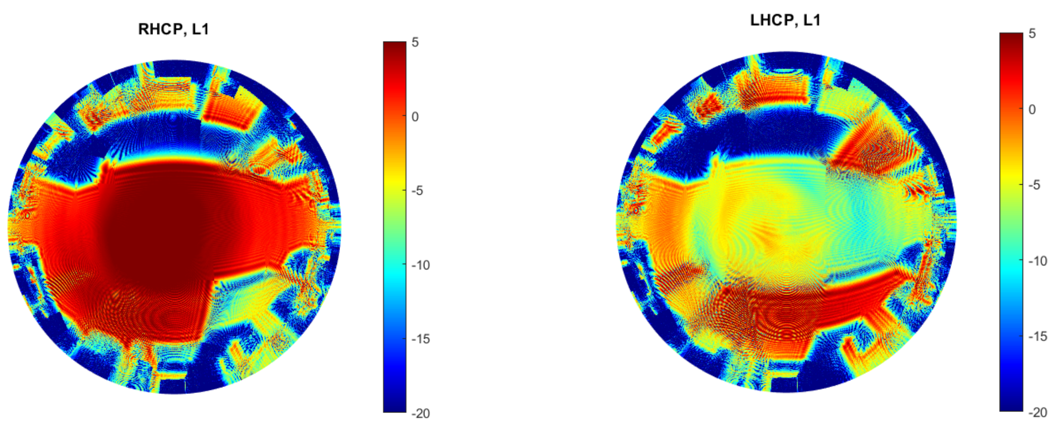


As can be seen from these results that the use of array clearly reduces the diffraction and multi reflections within the structure. However, if the same antenna is used in open sky, it will also reduce the received signal from various available GNSS satellite due to the taper of the antenna patterns.

We had also investigated multipath impact on the GNSS receiving antenna performance when the vehicle is moving along urban environments where buildings along the street have various heights. The line of sight (LOS) region within the view of the GNSS antenna changes as the position of the antenna moves. One such example is shown below where the GNSS receiver/antenna is indicated by the red dot in the figure below.



If a GNSS satellite is present in any direction of the upper hemisphere, the typical signal received by the antenna, simulated by FEKO, is shown below:

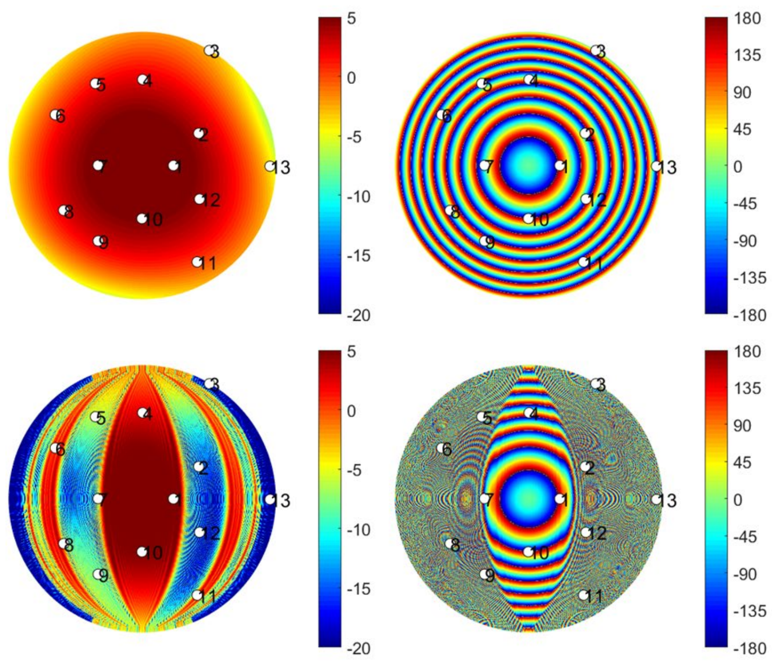


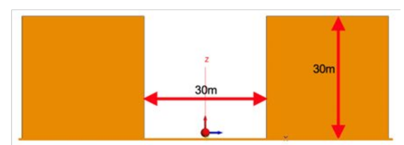
When a satellite is present within the LOS of the receiver, there is a strong GNSS signal received by the receiver as shown in the figure on the left. However, if there is no direct LOS between the satellite and the receiver, there is still some signal received by the receiver due to the reflection and diffractions from the satellite to the receiver. In addition, due to the polarization reversal of circularly polarized signal as well as depolarization effects caused by diffractions, there are signals entering the receiving antenna as LHCP components. Note that the multipath signals also include multiple reflections, diffractions, reflection/diffractions of the signal between the satellite and the receiver. All these multipath signals can potentially degrade the performance of the GNSS positioning.

Note that for any urban environment, if a CAD data for the city is available, it can be converted to simplified models accepted by FEKO. We can then use various GNSS antenna patterns to study how antenna design can improve the multipath scenarios in the urban environment. We believe the simulation of the urban environment with commercially available software is a valid solution for future PNT threats if the environment can be an issue. The tool can also help to design a better GNSS antenna if one must deal with very complex environment.

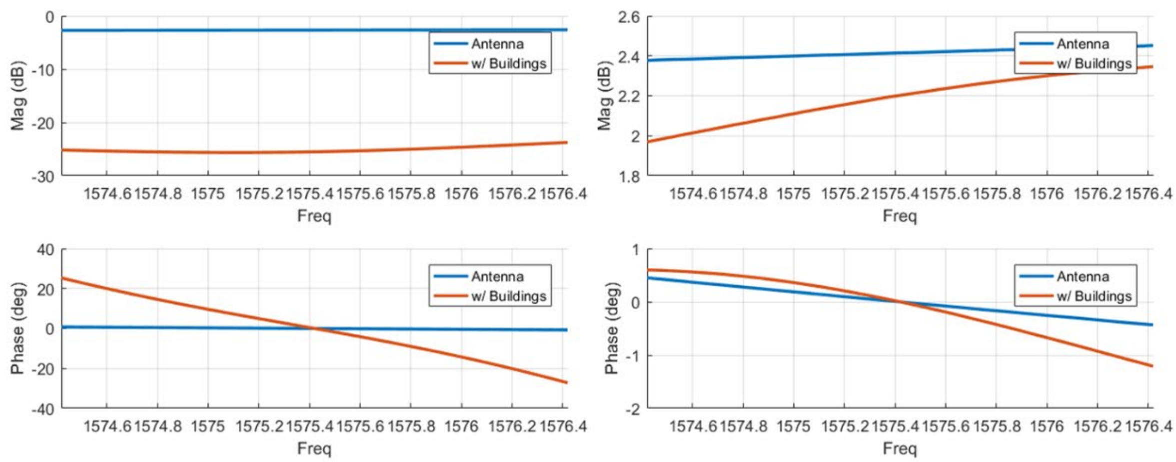
The knowledge of the received antenna response can be used to quantify GNSS receiver metrics. This approach has been applied to a different research project in that receiver responses were estimated based on the antenna response under urban environment. The complex antenna response simulated using FEKO can be used to estimate the Carrier to Noise ratio (C/N) and also antenna-induced biases on different GNSS signals caused by the multipath signals. If one can incorporate a large set of GNSS satellite distributions, one can then calculate the statistics of performance for a given antenna and environment. Note that the GNSS satellite distribution changes as time change so it is possible to create a large set of satellite distribution. One can use the antenna response to quantify receiver metrics, including RMS position error, DOP, number of satellites available, average C/N, and several GNSS receiver PVT solution models (single-frequency standard positioning, dual-frequency, rejection of worst-case satellites, etc.

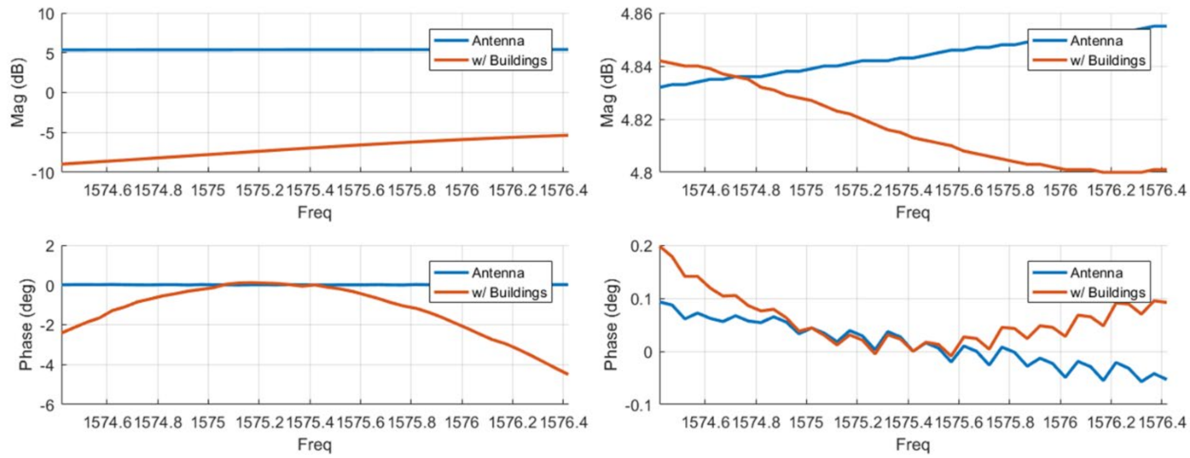
The simulation from FEKO outputs a complex antenna pattern as a function of frequency for each direction which forms an antenna response (i.e., linear transfer function) that can be applied to the GNSS signal. As an example, the figure below shows an open sky antenna response with GNSS satellite distribution (marked as circles) and when the antenna is inside a street with tall structures on its sides.





The antenna responses for satellite #3, #4, #7 and #10 are shown below:





These plots show the magnitude and phase for the antenna-only (blue) and the response that includes the effects of the multipath in the environment (red). Note that a linear change in phase with frequency as shown in the responses for satellite #3 and #4 corresponds to a delay (caused by multipath). On the other hand, the effects can be complex and non-linear and will have non-trivial effect on the received GNSS signal as shown in the responses for satellite #7 and # 10. The antenna responses from the simulation can then be used to model the multipath effects on the GNSS receiver.

The operation of GNSS receiver is that it cross-correlates signals received from an antenna with locally generated reference signals. The signal received by the antenna passes through the complex channel of the multipath environment and the antenna (as represented by the in-situ antenna response). The received antenna response shifts, delays, and otherwise distorts the correlation function in the receiver, resulting in biases in the code delay and carrier phase measurements, and increase/decrease in C/N. It can be shown that the multipath signal can cause significant delay and biases.

From current and past studies based on simulation of urban environment, we observed how multipath caused by the diffractions off edges and corners to produce linear- or mixed-polarized signals. Every reflection from a face of buildings will reverse the circularly polarized signal. Therefore, an antenna with good axial ratio is not going to have much improvement in the canyon environments, especially if the multipath error is caused by the diffractions from the edges of building. Antenna with excellent axial ratio certainly can reduce the impact of odd number of reflections through the faces of the building due to the polarization change of incoming RHCP signal.

If the GNSS antenna's gain is improved upwards toward the sky in the canyon, there is an improvement in gain, but not a significant reduction in the multipath. While this would provide a modest improvement in C/N, however, it can reduce the ability to acquire additional satellites when the vehicle is located at more open space. Furthermore, antenna with higher gain will have narrower beam width but its size can be physically large and heavy which may not be feasible to be installed in the consumer vehicles.

We have also found from the past receiver metrics study that utilizing more satellite constellations clearly can improve the positioning accuracy. However, it will require antennas to cover the frequency from L5 to L1 bands as well as good receiver design to acquire the signals from the satellites.

References:

"Influence of multi path on positioning accuracy in a low sky view factor environment", S. Tatsuguchi, Y. Oshima, H. Oguma, S. Kameda, N. Suematsu, 2017 International Conference on Information and Communication Technology Convergence (ICTC).

"Effect of Antenna Performance on the GPS Signal Accuracy", Waldemar Kunysz, Proceedings of the 1998 National Technical Meeting of The Institute of Navigation
January 21 - 23, 1998.

"Comparative Studies of GPS Multipath Mitigation Methods Performance", Xin Chen, Fabio Dovis, Senlin Peng, Yu Morton, IEEE Transactions on Aerospace and Electronic Systems, Issue 3, July-2013.

Task 4.1- Resilient Receiver Antenna Validation (standards and guidelines)

Background:

The properties of GNSS antenna and RF components within the GNSS receiver front-end electronics are expected to be critical to the protection efficacy against PNT threats. Therefore, testing standards will necessarily involve characterization of these components at an RF level in order to establish PNT risks in relevant threat scenarios. We will develop and formalize the RF testing standards of GNSS antenna and front-end electronics. Mitigation methods for RF signal threats (jammers and spoofers) will involve specialized antennas with multiple modes or elements to support identification of threats via direction of arrival, polarization, etc. It will also involve front-end filtering, limiting, enhanced dynamic-range, and blanking techniques. Testing standards for these mitigation systems will require characterization of the efficacy of these approaches at an RF level. Furthermore, it is expected that testing standards will involve creation or simulation of RF signal environments focusing on transportation modalities. We will apply our team's extensive understanding of RF testing chambers (see Figure 7, Page 16) and simulated RF signal injection (using software-defined radios (SDRs) and lab RF equipment) as a key component of RF testing standard development.

Progress:

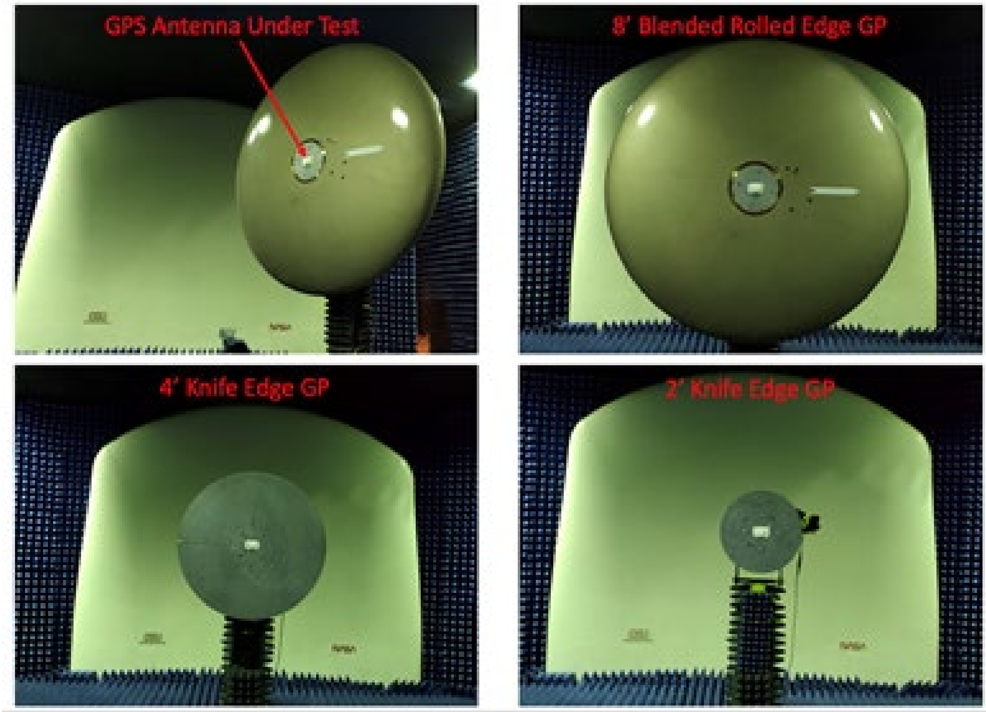
The properties of GNSS antenna and RF components within the GNSS receiver front-end electronics are expected to be critical to the protection efficacy against PNT threats. One of the key elements in PNT threat is how accurate one can predict the performance of the antenna and receiver such that various threats can be estimated based on the antenna and receiver performance. Consequently, knowledge of radiation patterns of GNSS antenna mounted on vehicles is a critical element to evaluate potential RF PNT Threat Scenario. Once the in-situ antenna pattern is fully characterized, it can be used for study in (1) physical arrangement and design of jamming and spoofing; (2) RF propagation environment and (3) RF component design in the receiver front-end.

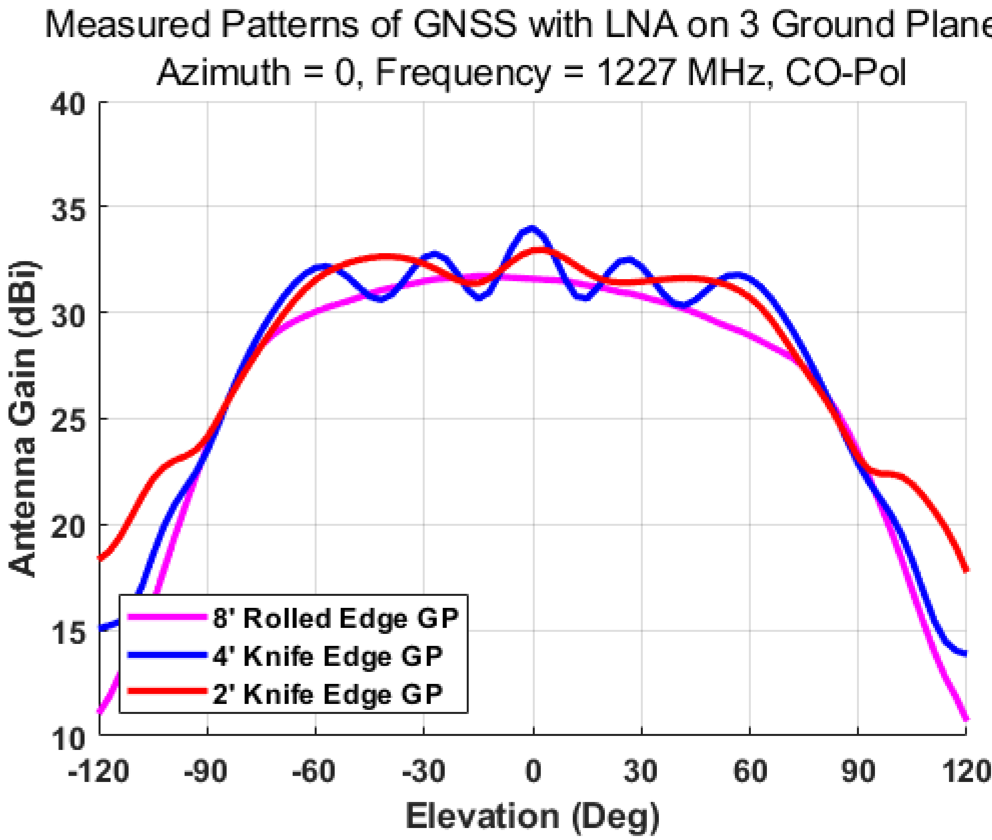
As previously reported, most GNSS antenna for vehicle applications are designed based on infinite ground to simulate the mounting of the antenna on conformal vehicle surface. However, common practice to validate the antenna design is to measure the actual GNSS antenna on a finite circular plate which introduces errors caused by the scattering of the edges of the ground plane. The edge scattering does not exist if the antenna is mounted on a conformal surface such as automobiles, UAV and aircraft, etc. If the measured antenna patterns on the finite plane are used for additional studies on navigation, the edge diffraction can create additional signals that do not exist in the real scenario and results in error in positioning.

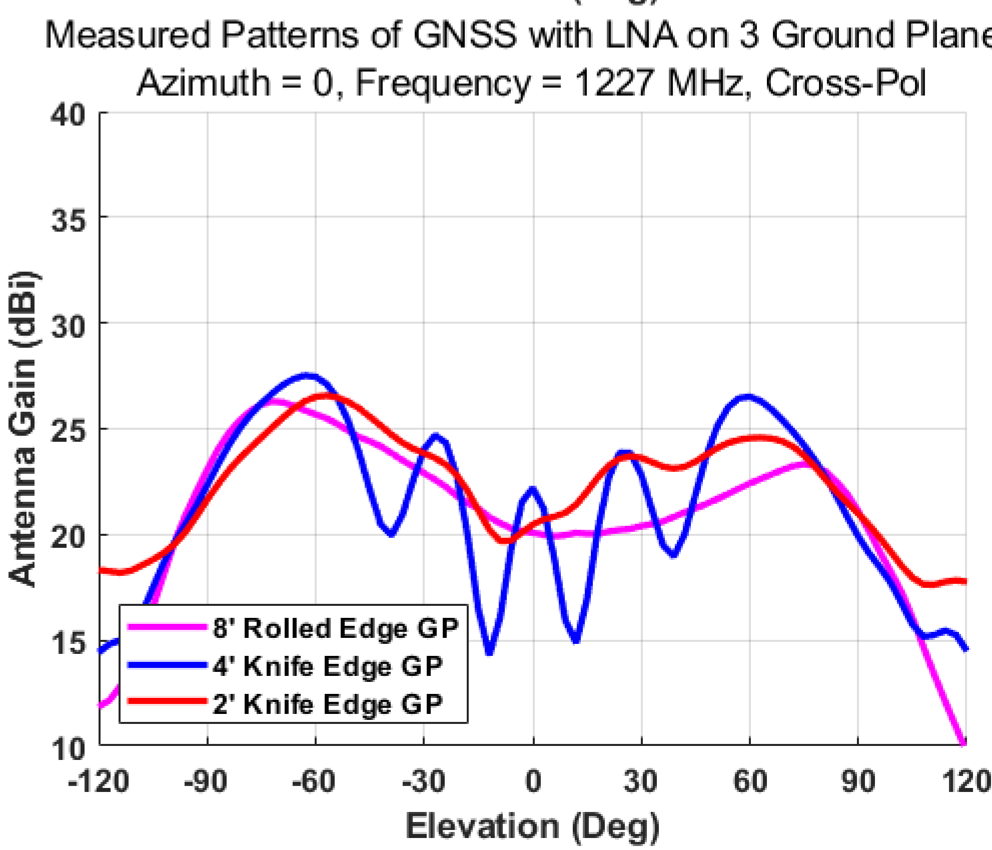
At OSU-ESL, a specially constructed ground plane with continuously rolled surface is available at for pattern measurement of GNSS antennas mounted on conformal surface that avoid the diffraction caused by the finite flat ground plane. We have presented the comparison between measurement using finite circular ground plane with sharp edge and the one using the specially designed rolled edge ground plane in earlier report. We have suggested to UTC community the availability of this ground plane for any member who would like to learn the in-situ performance of their antennas so accurate antenna data can be used in their future analysis of any potential PNT threat.

Reference:

"A Novel Structure for Accurate Measurement of Antennas Mounted on Ground Planes", I.J. Gupta, W.D. Burnside, J.-F. Lee andR.C. Flippo, Proceeding of Antenna Measurement Techniques Association, November 2003.


GPS Antenna Under Test
8' Blended Rolled Edge GP
4' Knife Edge GP
2' Knife Edge GP


Measured Patterns of GNSS with LNA on 3 Ground Planes
Azimuth = 0, Frequency = 1227 MHz, CO-Pol
Antenna Gain (dBi)
Elevation (Deg)
8' Rolled Edge GP
4' Knife Edge GP
2' Knife Edge GP
40
35
30
25
20
15
10
-120
-90
-60
-30
0
30
60
90
120


Measured Patterns of GNSS with LNA on 3 Ground Planes
Azimuth = 0, Frequency = 1227 MHz, Cross-Pol
Antenna Gain (dBi)
Elevation (Deg)
8' Rolled Edge GP
4' Knife Edge GP
2' Knife Edge GP
40
35
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25
20
15
10
-120
-90
-60
-30
0
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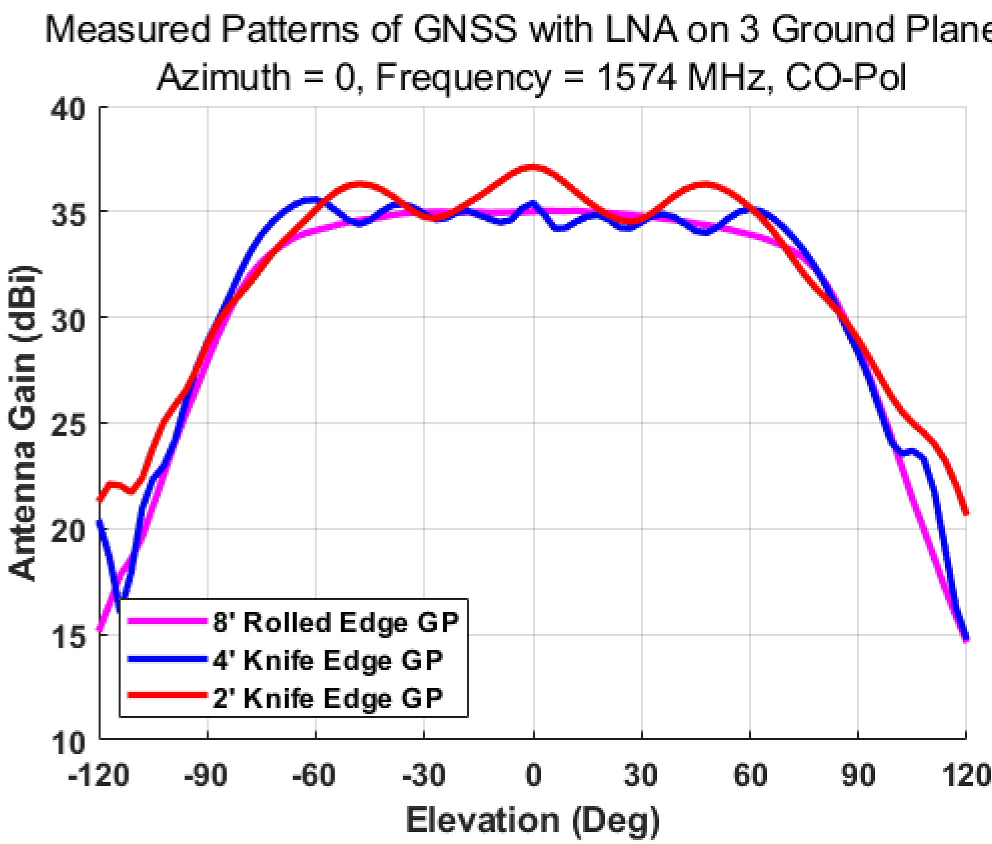
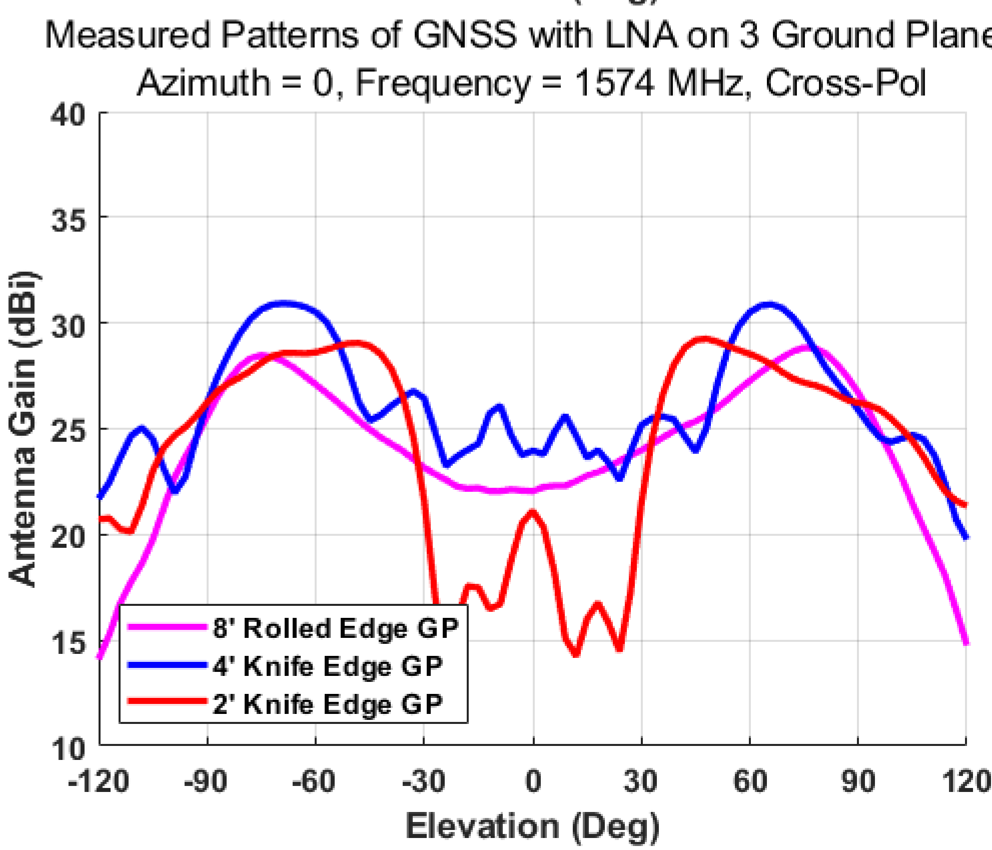
60
90
120


Measured Patterns of GNSS with LNA on 3 Ground Planes
Azimuth = 0, Frequency = 1574 MHz, CO-Pol
Antenna Gain (dBi)
40
35
30
25
20
15
10
-120
-90
-60
-30
0
30
60
90
120
Elevation (Deg)
8' Rolled Edge GP
4' Knife Edge GP
2' Knife Edge GP


Measured Patterns of GNSS with LNA on 3 Ground Planes
Azimuth = 0, Frequency = 1574 MHz, Cross-Pol
Antenna Gain (dBi)
40
35
30
25
20
15
10
-120
-90
-60
-30
0
30
60
90
120
Elevation (Deg)
8' Rolled Edge GP
4' Knife Edge GP
2' Knife Edge GP