



**AN ANALYSIS OF CONUS BASED DEPLOYMENT OF PSEUDOLITES FOR  
POSITIONING, NAVIGATION AND TIMING (PNT) SYSTEMS**

THESIS

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AFIT-ENV-MS-15-S-37

**DEPARTMENT OF THE AIR FORCE  
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POSITIONING, NAVIGATION AND TIMING (PNT) SYSTEMS

THESIS

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Degree of Master of Science in Systems Engineering

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### **Abstract**

The Global Positioning System (GPS) developed and operated by the United States Air Force (USAF) provides a way for users to determine position, navigation and timing (PNT). GPS provides an extraordinary capability that has become instrumental in all aspects of our day to day lives. As new technologies such as automated vehicles and unmanned aircraft continue to be developed, a reliable back up to GPS is required to ensure the PNT data generated in these systems is accurate.

This research studies a potential architecture for deploying a nationwide network of ground based pseudolites that would act to supplement and backup GPS for US operations. In addition this research develops a tailorable model for determining pseudolite coverage based on currently available ground infrastructure, varied transmit power levels, and different frequencies.

## **Acknowledgments**

We would like to thank Dr. David Jacques for his mentorship as our advisor. In addition we would like to thank the men and women of the GPS Directorate for providing us technical mentorship and expertise through the course of our assignment within the program office. Finally, we would like to thank our families for the love and support.

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# AN ANALYSIS OF CONUS BASED DEPLOYMENT OF PSEUDOLITES FOR POSITIONING, NAVIGATION AND TIMING (PNT) SYSTEMS

## I. Introduction

### General Issue

Navigation technologies go back thousands of years in human history. One of the earliest forms of navigation, celestial, used stars to determine position. The Global Positioning System (GPS) is one of the more recent technologies for navigation and timing. GPS began development in 1973 as a solution to the Department of Defense's (DoD's) desire for precise positioning anywhere throughout the globe. Over the course of the following 15 years, prototype satellites were developed and launched. These prototype satellites, known as Block-I GPS, validated the concept of providing space-based Positioning, Navigation and Timing (PNT) on a global scale. Soon after, the United States Air Force (USAF) GPS program office began launching the Block-IIA GPS satellites to achieve an Initial Operational Capability (IOC). In 1993, 20 years after program initiation the GPS program was able to achieve IOC and in 1995 the program reached Full Operational Capability (FOC). Since achieving FOC, GPS has had more than the minimum of 24 satellites available for global PNT.

Over the previous 40 years, GPS has evolved in both complexity and usage. The vast use of GPS has created an environment where GPS receivers are embedded into all aspects of our daily lives. GPS receivers are utilized in banking systems, farming equipment, transportation, logistics systems and in cell phone networks. Due to the limitless usage of GPS, it has become a critical element of our national infrastructure.

Currently, other countries are also building similar satellite based constellations that will increase the availability of satellite based navigation signals.

GPS and similar space based PNT systems are able to provide continuous global PNT; however, due to the low received signal power and lack of encryption they are extremely susceptible to both jamming and spoofing. In addition, GPS receivers typically perform poorly in mountainous terrain, canyons (both natural and man-made) and under dense foliage. This is due to signal attenuation, multipath, poor geometric conditions between the satellite and receiver and in extreme cases the lack of the minimum number of satellites in view of a receiver for position determination.

Due to these limitations, a robust alternative to space based navigation will be required in the future to protect national infrastructure and to expand the current positioning and timing capability that GPS provides. New requirements are already emerging as possible alternatives to GPS. For instance, by 2025 the Federal Aviation Administration (FAA) is planning to implement Next Generation (NextGen) upgrades to the National Airspace (NAS), with a key to those upgrades being alternate PNT solutions near the busiest airports. In addition to NextGen FAA requirements, future technologies such as unmanned aircraft and autonomous cars will also require a robust alternative for PNT throughout the U.S.

While many potential solutions exist to be the “backup” to GPS, this research will primarily focus on pseudolite networks that could be deployed in the United States to act as a ground based PNT network. A pseudolite solution should be less susceptible to jamming and spoofing due to the fact that ground based solutions provide increased power (as compared to space based solutions) and therefore perform better in harsh,

naturally occurring and man-made situations in which GPS currently performs poorly. However, questions exist over the feasibility of developing such a large nationwide network of pseudolites to accomplish this task.

### **Problem Statement**

A suitable alternative to GPS for nationwide coverage has not been identified.

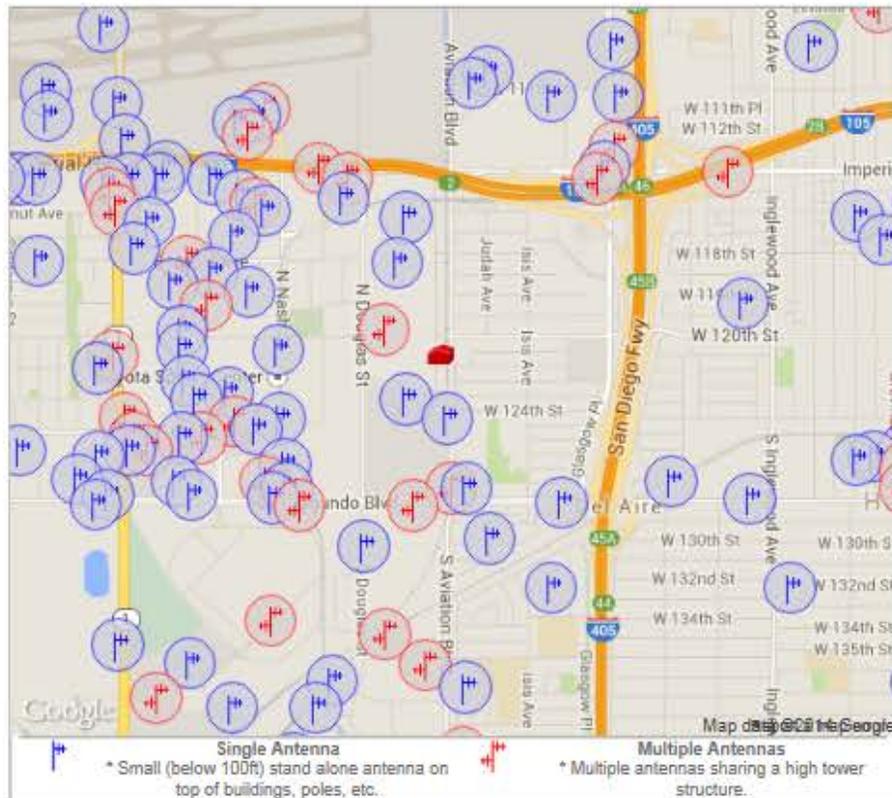
### **Research Objectives and Methodology**

This research seeks to determine how a pseudolite network can be developed and deployed to meet the needs for a robust alternative to space based PNT. This objective for a robust terrestrial alternative to PNT will be developed in four parts. The first part of this research is to develop and analyze the projected architecture which could be deployed for our proposed pseudolite network. This architecture will take into account the fact that this architecture must exist separate from space based PNT systems, but should act complementary to space based systems.

The second part of this research will provide a simulation capability to model pseudolite networks. The models will vary based on geographic conditions such as; mountainous terrain, canyons, suburban sprawl and urban canyons. These models will use specific propagation models based on the area being simulated. As an example, in large open spaces it is most likely that the free-space propagation model will apply, where as in densely populated urban environments, models for radio propagation such as the Hata model for urban areas may be more appropriate.

The third objective will be to model a theoretical ground network for Continental U.S. (CONUS) operations utilizing PNT signals. For this part of the research the

simulation will utilize actual U.S. cell tower infrastructure to determine the network's feasibility. Figure 1 below provides a pictorial sample of potential locations based on current antenna locations.



**Figure 1. Sample Antenna Location**

**(Created using General Data Resources, Inc)**

This simulation will then utilize Google Earth and MatLab to generate overlay maps of signal power and availability. The models developed in part one and two in conjunction with the antenna location models will be utilized to generate the theoretical CONUS terrestrial deployment model.

The fourth and final objective will be to analyze methods for synchronizing time for the ground network. This analysis will assume that GPS is not available as a primary

source for time synchronization. Precise synchronization of the entire network and receivers is essential to ensure that the pseudolite receivers are capable of determining extremely precise locations.

### **Research Focus**

This research will focus on developing and generating models for a future pseudolite network. In general this research will:

- Develop a systems architecture for a pseudolite network
- Develop a model for deployment of a pseudolite network.
- Develop a cursory level requirements set for both transmitters and receivers using the data outputs of the terrestrial model.
- Analyze the feasibility of the pseudolite network to meet the requirements as a viable alternative to GPS, and
- Research options for time synchronization of a pseudolite network and provide proposed solutions and recommendations.

### **Investigative Questions**

In order to meet the research objectives the following questions will be answered to help build the terrestrial based model for pseudolites as well as the options for time synchronization of the network.

- What is a proposed architecture for a pseudolite solution that would provide CONUS PNT coverage?
- What are the candidate frequencies for deployment of a pseudolite network, based on spectrum that could realistically be allocated in the future?
- What are suitable ranges for transmit and received power to make a pseudolite network viable?

- How will a pseudolite deployment differ based on different geographically developed environments (e.g. mountainous, canyon, rural, urban, suburban, etc.)?
- Do certain propagation models apply more locally to specific locations? If so which models should be applied?
- What is the deployment for different geographical development environments?
- What are options for time synchronization between pseudolites?
- What is the recommended solution for synchronization of time between pseudolites?

### **Assumptions/Limitations**

This thesis is written in the context of developing an alternative to GPS that is robust and feasible for CONUS based deployment. The following forms the key assumptions and limitations of this thesis:

- The performance of GPS will not be analyzed in this thesis. Data for GPS comparison will be derived from the Standard Positioning Service Standard for GPS which is published by the Office of the Secretary of Defense.
- Limited to a CONUS based deployment of a pseudolite network.
- A similar Code Division Multiple Access (CDMA) signal structure that GPS utilizes to acquire and track signals.
- The pseudolite signal will be encrypted and the receivers will be capable of processing the encrypted signal.
- Analysis of various propagation models will occur but testing of those models will not occur.
- Relative costs between options will not be investigated.

## **Implications**

This research defines the feasibility of being able to deploy a robust alternative to GPS. This has the potential to improve the future of NextGen for the FAA, improve the reliability of navigation and timing services in support of critical U.S. national infrastructure and finally provide a new technology that could be utilized by autonomous vehicles and aircraft.

## **Document Overview**

This thesis is organized into five chapters. Chapter II provides a foundation of literature and equations required to accomplish the objectives of this research. Chapter III provides the methodology that will be followed to develop an alternate PNT architecture and model. The fourth chapter will describe a potential architecture for an alternate PNT system based on pseudolites. Chapter V develops anticipated coverage models for a pseudolite network.

## **II. Literature Review**

### **Chapter Overview**

The literature review covers the topics that are the foundation for this research. Each topic provides key insight into a specific area essential to development of this thesis. The first key area will be a review of current space based positioning systems. Next, a review of potential frequencies to be considered in the pseudolite model development will be performed. After review of the various available frequencies, this chapter will then review current and future pseudolite solutions. The fourth area will be a comprehensive review of propagation models. This review is essential to developing aggregate transmission models in future sections. Finally, clock technologies are reviewed and presented to gain a better understanding of potential future time synchronization solutions for pseudolite networks.

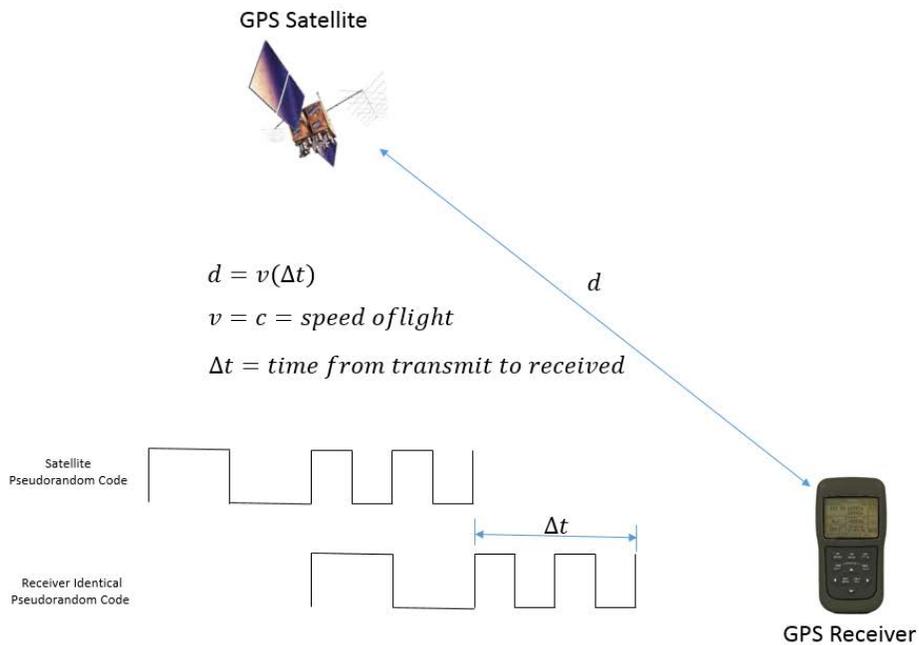
### **Global Navigation Satellite Service (GNSS) Systems**

#### *GNSS Background*

GNSS systems began development in the 1970s primarily as a means for the military to precisely determine location. The first GNSS system, developed by the United States, is currently known as the Global Positioning System (GPS). GPS has become a staple in everyday life for billions of users around the globe. GPS reached full operational capability in 1995 with the launch of the twenty-fourth GPS satellite and placement of that satellite into operations.

GPS, similar to other GNSS systems, works by ranging from the satellite to the receiver. The distance between the satellite and the receiver is known as the

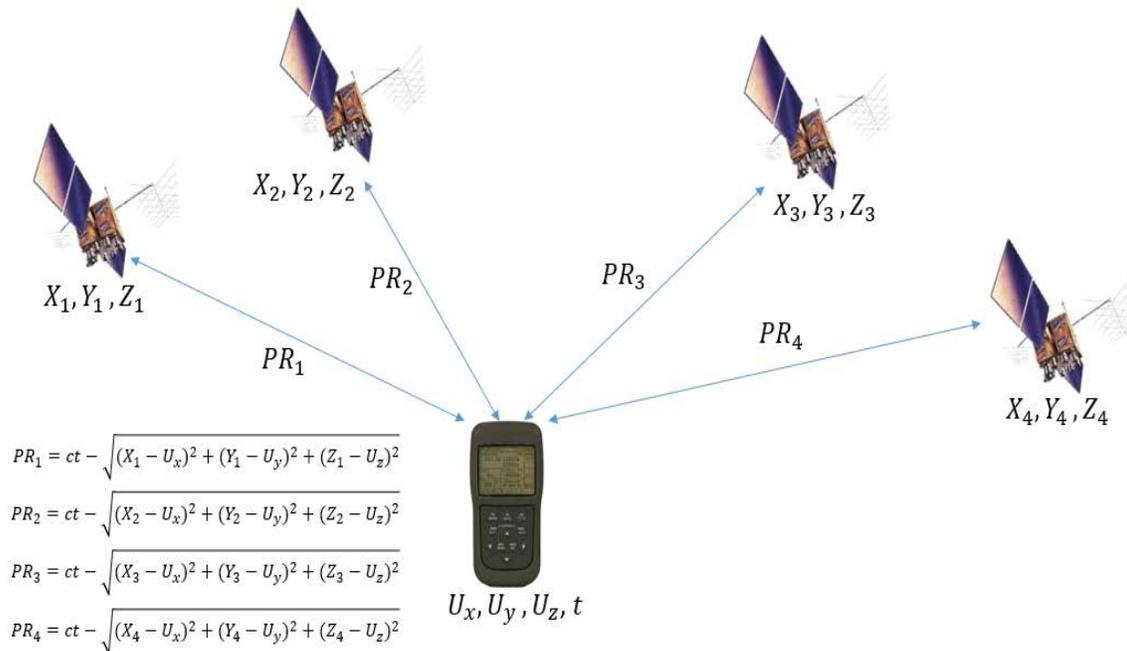
pseudorange. The term “pseudo” in “pseudorange” stems from the fact that there is error between the actual geometric range and the range calculated by the receiver. This error is from factors such as atmospheric delay on the signal. Figure 2 below provides a simplistic view of how a receiver determines pseudorange from a GPS satellite. Every GPS satellite has extremely precise atomic clocks which are accurate to around one nanosecond (one billionth of a second). Also each satellite transmits a unique pseudorandom number (PRN) which is a specific combination of binary ones and zeros. The satellite continually broadcasts its PRN. The pseudorange is determined by the receiver by correlating satellite PRN with the PRN generated by the receiver. The receiver then determines how long it took the signal to travel from the satellite to the receiver. Once time is known the pseudorange is determined by multiplying the speed of light by the time it took the signal to travel to the receiver.



**Figure 2. Determining Pseudorange**

The explanation of pseudorange above ignores factors such as ionospheric delay of signals and how those are modeled. But for the purposes of this discussion the simplistic view is sufficient.

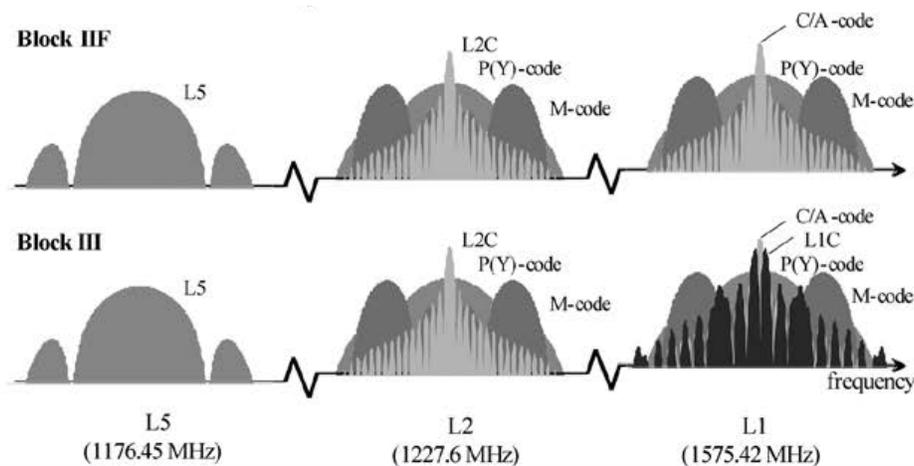
Knowing the distance to a single satellite only provides the user part of the answer in determining their location. In three dimensional space the receiver is required to know the pseudorange to three satellites to determine its precise location. GPS also requires a fourth satellite to determine time since receiver clocks are not as accurate as atomic clocks used by GPS satellites. This means that four equations and four unknowns are required. These four unknowns are the X, Y, Z position of the receiver and time in GPS seconds (t). Figure 3 provides a pictorial representation of how a receiver determines its location utilizing a minimum of four satellites.



**Figure 3. Determining Receiver Position with GPS**

## GPS Specifications

Modern GPS satellites such as GPS IIF and soon GPS III, transmit on three frequency bands. These bands are L1 (center frequency 1575.42 MHz), L2 (center frequency 1227.60 MHz) and L5 (center frequency 1176.45 MHz). Figure 4 shows the GPS signals for the IIF and III satellites. On L1, GPS broadcasts a Coarse Acquisition (C/A) code that allows users to easily correlate and acquire GPS. In the future, L1C will provide a common signal between the GPS system and the European Galileo GNSS system. Also on L1 is the Precision User (P(Y)) signal which is reserved for military use. This signal provides a secure encrypted signal for military users. Finally, residing on L1 is the M-Code signal. This is the future military signal that provides increased power and encryption security for military use. GPS L2 provides a military signal spectrally separated from L1. This allows military users to correct for ionospheric delay of the transmit signals, and also provides a back up to L1 in the case that it is jammed or otherwise unavailable. Finally, the L5 signal was developed specifically as the “safety of life” signal for use by the FAA. All IIF and III GPS satellites can transmit this signal.



**Figure 4. GPS Signals Broadcast by GPS IIF and III Satellites [1]**

GPS satellites operate in Medium Earth Orbits (MEO) at an altitude of 20,200 km. This altitude provides an orbital period of approximately 12 hours. Operating in MEO, GPS satellites are able to provide global coverage of 4 or more satellites in view with a constellation size of twenty-four satellites. Table 1 provides the specified received power level of a GPS receiver measured at a 5 degree elevation angle from a transmitting satellite [2]. These power levels will increase as a satellite rises over the receiver.

**Table 1. GPS Specified Power Levels at 5 degrees Elevation**

<b>Signal</b>	<b>Power in Decibel-Watts (dBW)</b>
L1 C/A	-158.5
L1C	-155.5
L1 P(Y)	-161.5
L2C	-160
L2 P(Y)	-161.5
L5	-157.9

*GNSS Vulnerabilities*

While GPS has been an instrumental part of our society for the past 20 years, it is quickly becoming a single point of failure. In today’s society GPS is used for determining position and providing accurate time to critical infrastructure. The two major concerns with GPS are jamming and spoofing of its signals.

GPS satellites transmit an extremely weak signal as measured on the surface of the Earth. As shown in Table 1, GPS L1 C/A has a specified power level of -158.5dBW.

Due to the low power level of the signal it is extremely easy to jam the signal by broadcasting noise in any GPS transmitted frequency band. For example, in 2013 a truck driver utilizing a GPS jammer to mask his location from his employer accidentally jammed Newark Airport[3]. The GPS program office has looked into increasing power in space, but for all practical purposes it is not possible to transmit a signal from 20,200 km that cannot be jammed.

The second concern with GPS is the ability to spoof the unencrypted signal. Currently, the majority of civilian user equipment utilizes the unencrypted L1 C/A code. This signal structure is publically available and therefore anyone with knowledge and ability can easily create a GPS C/A spoofer. The ability to spoof a GPS transmitted signal to cause a user to think they are in a location that they are not was brought to the forefront when a group of Texas college students spoofed a luxury yacht. The students were able to create a GPS spoofer that transmitted signals and made the yacht think it was over 30 miles away from where it actually was located[4].

The vulnerabilities associated with GPS jamming and spoofing establish the need for a robust and reliable back up to GPS to support future aircraft navigation, unmanned aircraft and automobiles as well as a future intelligent highway system.

## **Radio Navigation Spectrum**

### *Radio Frequency Spectrum*

The selection of a viable frequency for use in our pseudolite network requires careful thought to minimize terrestrial effects near the surface of the Earth where the system will operate. The Ultra-High Frequency (UHF) band offers many benefits for use

in a communication network such as this pseudolite network. Some benefits are that frequencies in this band are not susceptible to weather effects due to rain, sleet and snow where some attenuation in a transmitted signal may occur. Additionally, this frequency band offers a large foot-print due to a longer wavelength when compared to other frequency bands such as the Extremely-High Frequency (EHF) and other higher frequency bands. One major concern for systems operating in the UHF band, however, is the possibility of jamming. Within all communication networks, signal jamming is a major concern due to operation of other systems that are utilizing similar frequencies and which are at relatively higher power levels at the receiver. The National Telecommunications and Information Administration (NTIA) maintains a table of frequency allocations which must be followed by anyone wishing to use a specific frequency for their system or network. Since GPS signals are very weak at the receiver input, the likelihood of intentional and unintentional jamming is very high if other systems are using a frequency that is near any of the current GPS frequency bands in use today.

For this thesis a specific frequency band was not selected; advantages and disadvantages of using a few bands that may be sufficient for use in a pseudolite network was discussed. In previous research, a system named Locata was investigated as a possible solution to providing a pseudolite network for the FAA [5]. The frequency band proposed by Locata is in the 2.4 GHz band which is located within the UHF region. According to Locata's Interface Control Document (ICD), the 2.4 GHz frequency was issued since it is license-free and interference-free from GPS[6]. Mitigating interference as much as possible is a top priority in any communication network and will be the main

focus of the thesis. According to Title 47 of the Code of Federal Regulations (CFR), Part 15.5, low power communication devices must accept interference from licensed users of that frequency band, and the Part 15 device must not cause interference to licensed users. An example of a technology that operates in the 2.4 GHz band is a Bluetooth which emits low power and will only work at short distances, thereby reducing the possibility of causing interference to other devices or systems that also operate in this band. Other wireless systems that operate in the 2.4 GHz band are modems and routers which provide home internet access. Since Locata is already utilizing 2.4GHz and the fact that other systems are also utilizing this frequency, we do not propose that the pseudolite system use 2.4GHz to minimize interference from those other systems.

Ideally the pseudolite network would utilize two frequencies spectrally separated to allow for error correction. Having multiple ranging signals transmitted at different frequencies provides the benefit of removing errors from signal propagation delays, and also provides a redundant signal source for any durable system.

Since this is a hypothetical network, three frequencies were chosen to develop the models. The frequencies that were utilized are 700 MHz, 900MHz and 1765MHz. The 700MHz and 1765MHz frequencies will be or have recently been proposed for auction by the Federal Communications Commission (FCC). In addition, the 900MHz band is currently used for special mobile radio service which provides land mobile communications on a commercial basis. It is assumed this spectrum could be converted for use in a pseudolite network. This research assumes similar frequency bands will be available for a pseudolite network.

## **Pseudolites**

### *Background*

The proof of concept for the GPS system has roots in ground based pseudolites. The name “pseudolite” was shortened from “pseudo-satellites.” During the development of GPS these “pseudo-satellites” acted as ground based satellites for testing. Prior to launching the first GPS satellites, the Navstar Joint Program Office (JPO), tested the concept of positioning using these ground based pseudolites. The success of this testing led to the development of GPS [7].

Pseudolites work on the same basic concept as satellite based PNT systems. These devices calculate position based off the ability to range from a transmitted signal. Pseudolites provide a means for determining precise position from a ground based transmitted signal. In the past, pseudolites were used to prove the concept of how a satellite based navigation system would operate. After the GPS successfully reached Full Operation Capability (FOC) pseudolites were primarily viewed as an efficient way to augment the GPS system to provide more precise positioning solutions in challenging environments.[8]

### *Current Pseudolite Technology*

This research found that one of the most prevalent technologies on the market today for pseudolites is Locata. This technology was developed to augment GPS by providing precise location in conditions where GPS is either unavailable or unreliable. Situations where Locata may be beneficial include mountainous regions, urban canyons, in buildings or even in mines. Locata’s pseudolite technology operates very similar to GPS and, therefore, the basic premise is the same as discussed in the GPS section of this

chapter. Locata, like other current pseudolite technologies utilizes precise timing and the knowledge of the transmitter's location to determine a user's position.

The Locata-ICD-100E specification [6], in conjunction with specifications calculated by the AFIT thesis *Pseudolite Architecture and Performance Analysis for the FAA's NextGen Airspace* [5], are used as the basis for developing the ground based pseudolite requirements for this thesis.

Table 2 and Figure 5 provide the data presented in the ICD and thesis that will form the foundation for aggregate ground based pseudolite networks developed in Chapter V.

**Table 2. Proposed Pseudolite Transmitter Values [5]**

Variable	UHARS	Proposed Value
<b><i>Frequency Bandwidth(<math>f_B</math>)</i></b>	10.23 MHz	10.23MHz
<b><i>Center Frequency (<math>f_C</math>)</i></b>	2241 & 2465 MHz	971.85 MHz
<b><i>Chip Rate</i></b>	10.23 MCps	5.115MCps
<b><i>Code Length</i></b>	1023	1023
<b><i>TDMA Slot Duration</i></b>	100 $\mu$ s	100 $\mu$ s
<b><i>Data Bit Rate</i></b>	100	100
<b><i>Transmitted Power</i></b>	10W	20W
<b><i>Transmitter Antenna Gain</i></b>	N/A	2.3dB
<b><i>Receiver Antenna Gain</i></b>	N/A	5.162dB
<b><i>User Range</i></b>	15 nmi	130 nmi
<b><i>Transmission Mask</i></b>	20MHz Bandpass	6MHz Bandpass
<b><i><math>N_0</math> – Noise background</i></b>	N/A	-150dBW/Hz
<b><i>Maximum PDOP</i></b>	2.838	2.838
<b><i>Max Correlator Spacing</i></b>	N/A	1
<b><i>Minimum Received Code Power</i></b>	-135dBW	-132dBW

<u>Element</u>	<u>GPS</u>	<u>LocataNet</u>
Transmitter Location	Medium Earth Orbit (1/2 geosynchronous)	Terrestrial
Transmitter Name	Space Vehicle (SV)	LocataLite
Control Segment	Earth based control station	Master LocataLite within network
Transmit Antennas per LocataLite	1	2
Signals per Transmitting Antenna	4 (counting L1 and L2 only)	2
Carrier Frequencies	L <sub>1</sub> = 1575.42 MHz L <sub>2</sub> = 1227.60 MHz	S <sub>02</sub> = 2411.211 MHz S <sub>05</sub> = 2414.280 MHz S <sub>52</sub> = 2462.361 MHz S <sub>55</sub> = 2465.430 MHz S <sub>82</sub> = 2472.591 MHz
Ranging Codes	C/A, P, P(Y)	C/A
Code Frequency	C/A = 1.023 MHz	C/A = 10.23 MHz
NAV Data	<u>D(t)</u> 50 bps 5 Subframes of 10 30-bit words each 1 page of SF 1, 2, 3 25 pages of SF 4, 5	<u>D(t)</u> 100 bps (50 bps optional) 2 Subframes of 20 30-bit words each 1 page of SF 1 2 pages of SF 2
Maximum Transmitters in Network	32	undefined
TDMA Scheme	None	10 x 100µs slots per TDMA frame. 200 Frames per TDMA super-frame.
Diversity Schemes at Transmitter	Frequency	Frequency, Spatial
Transmitter Power	≤ 50W	≤ 1W
Assured Minimum RF Signal Strength	-128.5 dBm	N/A

**Figure 5. Locata vs GPS Specifications [6]**

## NextGen and Intelligent Highway

Many ideas have been researched to describe what an intelligent highway could look like or how it would operate. One such idea proposed is to use a triple redundancy navigation system using magnetometer, inertial, and carrier phase differential GPS measurements [9]. The idea of a triple redundancy system is attractive since each one of the components separately does not provide the reliability required for a nationwide safe highway system. With the employment of this system the vehicle trajectory and vehicle yaw can be determined and monitored. The yaw is simply the measure of a vehicle's

distance off center when traveling in a straight line. Implementation of this system was tested in 2001 with using a test vehicle, two magnetometers, a control law and actuators. The magnetometers were placed in the front and rear of the vehicle, with magnets embedded into the test road to create a magnetic field for the magnetometers to sense. Multiple scenarios were then tested with GPS on and off to gather data on the reliability of the system to monitor vehicle trajectory and yaw rate. The results showed that with only magnetometer measurements, the system was able to maintain an accurate estimate of position lateral to the trajectory of the vehicle which could aide in lane departure warning for the driver or to assist the vehicle to remain in a specific lane for future “smart-car” technology. This technology by itself could keep a vehicle in its lane but adding a PNT signal would allow the vehicle to arrive at its final destination just like GPS is able to assist people with getting from point A to point B. Built in receivers would need current GPS and future pseudolite signals to be able to operate in either configuration. Therefore, the receivers in use today that rely solely on GPS would need to be upgraded to be able to also read the new frequencies that were proposed earlier in the UHF band.

The FAA is trying to implement a pseudolite system which would have similar capabilities as the proposed system. This system was developed to assist aircraft with landing and departing from certain airports with or without GPS capabilities. The similarities with the system that we are proposing is that pseudolites are also being utilized as the main technology driver.

## Propagation Models

### *Free Space Path-loss Model*

This thesis relies completely on empirical models to develop the propagation of Radio Frequency (RF) waves through open space. The first model reviewed is the Free Space Path-loss (FSPL) model. The FSPL model is considered an ideal model for radio wave propagation since it assumes the Power Flux Density (PFD) of a wave expands radially with no obstructions [10]. This means that the transmitted power ( $P_T$ ) fills an area based on the waves distance ( $d$ ) from the source. As the wave travels farther from the source the area increases. The FSPL model is expressed as:

$$PFD = \frac{P_T}{4\pi d^2} \quad (1)$$

Note:  $P_T$  is in watts ( $W$ ) and  $d$  is in kilometers ( $km$ )

The FSPL model is a good starting point for estimating the power lost between two isotropic antennas at a given distance [11]. The received power ( $P_R$ ) is a function of the wavelength ( $\lambda$ ) of the signal, transmitter gain ( $G_T$ ), and receiver gain ( $G_R$ ). When  $P_T$ ,  $P_R$ ,  $G_T$ ,  $G_R$  are expressed in decibels (dB), this simplifies to:

$$P_R = G_T + P_T + 20 \log\left(\frac{\lambda}{4\pi d}\right) + G_R \quad (2)$$

Equation 2 gives that the power at the receiver as function of the distance and wavelength; the rest of the variables are constants based on the design of the system. Another valuable way to express the free-space model is based on the pathloss ( $L_{FS}$ ). This is the loss in decibels (dB) between the transmit antenna and the receive antenna. When distance ( $d$ ) is expressed in kilometers and frequency ( $f$ ) is expressed in megahertz (MHz), the constant in the path-loss equation simplifies to 32.45.

$$L_{FS} = 32.45 + 20 \log(d) + 20 \log(f) - (G_R) - (G_T) \quad (3)$$

This expression will be utilized as the starting block for many of the empirical models that will be discussed later.

### *Empirical Models for Path-loss Models*

The FSPL model provides a lower bound for calculating path-loss of a radio wave. In most scenarios path-loss will exceed what is calculated using the FSPL, due to free space model failing to account for antenna height, the landscape (i.e. urban, suburban, rural), and other factors that could attenuate the signal, such as obstructions.

Overall, there are two categories of models for determining path-loss. The first is empirical models and the second is deterministic models. Empirical models provide a way of determining path-loss based on statistical estimations of how a wave propagates based on multiple input variables [11]. Deterministic models use data from actual sites and are therefore very accurate, but do not account for uncertainty. For the purposes of this research only empirical models will be used.

The first empirical model reviewed was the Okumura Model. The Okumura model was developed in Tokyo during the 1960s using radio-frequency (RF) data collected around the city. This model is one of the most widely used signal propagation models. It is a combination of the free-space analytical model but allows the user to model additional attenuation. Equation 4 is the equation for the path-loss in Okumura model ( $L_{OK}$ ) [10].

$$L_{OK} = L_{FS} + A_{MU} + H_{TX} + H_{RX} \quad (4)$$

In this equation  $L_{OK}$ , refers to the overall path-loss. The Okumura model uses free-space propagation path-loss ( $L_{FS}$ ) as the starting point for determining path-loss.

This was previously expressed in Equation (3). Based on the extensive measurement data received through experimentation, Okumura determined that transmit power decreased at a much greater rate than predicted by free-space propagation. To account for this additional attenuation, Okumura used the deterministic RF propagation data from around Tokyo to create a “Basic Median Attenuation” factor ( $A_{MU}$ ). This attenuation factor is the key difference between Okumura and free-space propagation models. Figure 6 below is one example of a look up curve that provides  $A_{MU}$  based on distance, frequency, receiver height ( $H_{RX}$ ) and transmitter height ( $H_{TX}$ ). While the Okumura model is very reliable it does have the limitations of being a look-up table approach to determining predicted signal propagation.

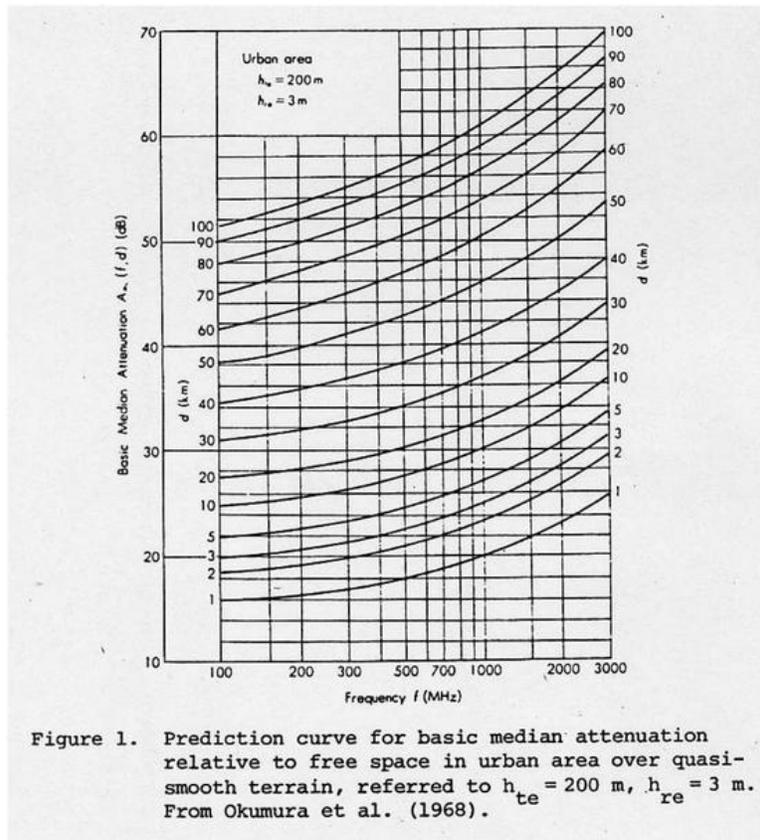


Figure 6. Sample of Basic Median Attenuation ( $A_{MU}$ ) from Okumura [10]

To overcome the limitations of look up tables with Okumura's model, Hata developed a computational representation of Okumura's model. Hata's model allows for simple input variables that translate directly to an output for path-loss between a transmitter and a receiver at a specific frequency and distance. This loss is designated  $L_{Hata}$  for the purposes of this research. Hata's simplified formula for propagation is represented in equation (5) below.

$$L_{Hata} = A + B * (10 \log(R)) \quad (5)$$

In Hata's equation, A and B are antenna height functions and R is the distance between the transmitter and receiver[12]. This equation allows for computational implementation of Okumara's model. Equations 6-9 below are the full representations of Hata's equations for Urban, Suburban, and Open areas. Equation 6 is Hata's model for urban areas.

$$L_{Urban} = 69.55 + 26.16 \log(f) - 13.82 \log(h_B) - C_H + [44.9 - 6.55 \log(h_B)] \log(d) \quad (6)$$

For this equation  $C_H$  is the antenna height correction factor. For a medium sized city  $C_H$  is represented in equation 7 and for a large city is equation 8.

$$C_H = 0.8 + (1.1 \log(f) - 0.78) h_M - 1.56 \log(f) \quad (7)$$

$$C_H = \begin{cases} 8.29(\log(1.54h_M))^2 - 1.1, & \text{if } 150 \leq f \leq 200 \\ 3.2(\log(11.75h_M))^2 - 4.97, & \text{if } 200 < f \leq 1500 \end{cases} \quad (8)$$

The Hata model for suburban areas simplifies to equation 9. This uses the Hata urban model plus an additional term to account for the fact that suburban areas that tend to attenuate the transmitted signal less in urban areas based on the Okumura model.

$$L_{Suburban} = L_{Urban} - 2(\log(\frac{f}{28}))^2 - 5.4 \quad (9)$$

It is important to note that the Hata equations are limited to a frequency range of 150-1500 MHz, a receiver height of 1-10 meters and a transmitter height 30-200 meters. For frequencies between 1500 MHz and 2000 MHz the COST231-Hata Model has been developed[13]. The COST231 model is represented by equations 10-12 below.

$$L_{Cost231} = 46.3 + 33.9 \log(f) - 13.82 \log(h_B) - a(h_B) + [44.9 - 6.55 \log(h_B)] \log(d) + C \quad (10)$$

$$a(h_B) = (1.1 \log(f) - 0.7)(h_B) - (1.56 \log(f) - 0.8) \quad (11)$$

$$C = \begin{cases} 0 \text{ dB for medium cities and suburban areas} \\ 3 \text{ dB for metropolitan areas} \end{cases} \quad (12)$$

For the purposes of this research the primary empirical models that will be used are the free-space propagation model and the Hata empirical model. These two models will form the basis for determining how the pseudolite network will propagate at different frequencies, transmit power levels and locations.

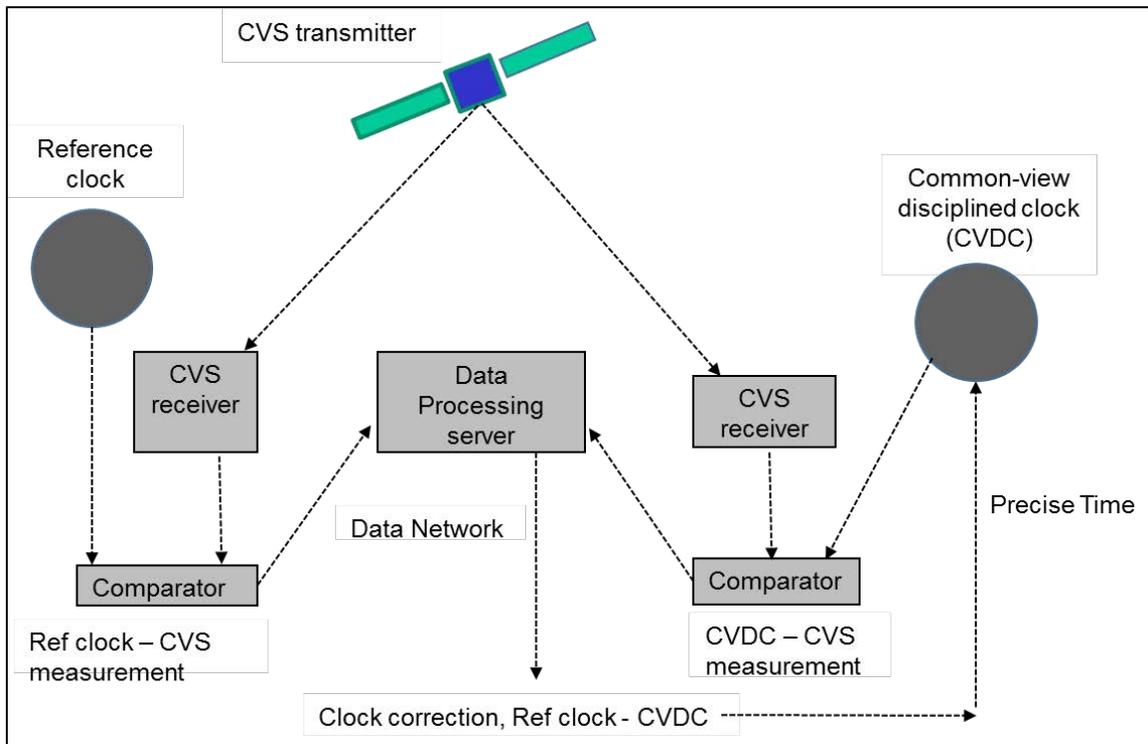
### **Precise Timing Synchronization**

Timing is a very important aspect of a PNT system like GPS because without precise timing GPS wouldn't be relied upon to provide that data to the many industries that use GPS on a daily basis. If timing were not synchronized properly amongst all the GPS satellites, receivers would have to vastly improve their internal clocks to be more accurate. Similar to the method used by GPS, this pseudolite system needs to incorporate a master "time-keeper" or reference transmitter that other receiver/transmitters can synchronize with. Currently, GPS provides about 1 m of accuracy for navigation purposes [14]. To be able to maintain this accuracy each GPS satellite clock needs to be within 3.3 nanoseconds (ns) for a period of up to one day otherwise, the timing accuracy will suffer and will not be as precise [14].

To be able to support critical infrastructure, it is important to achieve timing accuracy of at least one micro-second ( $\mu\text{s}$ ) to maintain the precise timing required by this infrastructure. GPS can meet this requirement and is the reason why it is relied upon by many industries to provide accurate timing. However, GPS isn't without vulnerabilities and a back-up system should be planned for in the near future since there are currently no other systems available today that can meet a 1- $\mu\text{s}$  timing requirement like GPS. In a situation where GPS is not available, GPS clocks on Earth must rely on less accurate quartz crystal oscillators to maintain synchronization until a satellite is in view to correct any errors from those less accurate oscillators. New timing technology aims to improve the clocks used today for small handheld devices that rely on GPS. Chip scale atomic clocks (CSAC) are becoming more widely used since first introduced in 2011. Deploying these at multiple sites can dramatically improve the tolerances in holdover capabilities when compared to current clocks but they still need to rely on GPS to be able to synchronize to a UTC source [14].

Another possible solution to provide accurate timing of 1- $\mu\text{s}$  or better at multiple sites is to use the common-view measurement technique as shown in Figure 7. This is a rather simple technique to implement but one that currently uses GPS satellites to provide the common-view signal (CVS). The idea behind this technique is to compare two clocks located at different sites with one clock being a reference clock. In theory, the CVS does not have to be accurate because a data server processes the received signal from both sites and subtracts the two measured data from each other. The result is the time difference from both sites that is used to constantly calibrate the non-reference clock. The CVS technique does rely on the use of an independent transmitter which could be

located on a communication satellite in orbit which has constant view over a specific region.



**Figure 7. A common-view disciplined clock (CVDC) system**

In Figure 7, a satellite transmits precise timing data to a CVS receiver which in conjunction with reference clock timing data is sent to a data processing server. The same satellite timing data is also sent to another CVS receiver located in a different location. The clock associated with that receiver sends its current timing information to the data processing server and the server compares the two clocks' timing offset, if any. If there is an offset, the server updates the common-view disciplined clock (CVDC) with the correct timing data. All other receivers within the network would also correct their clocks to the reference clock as just described. In terms of feasibility and technology

maturity, this technique offers the best overall solution to be able to provide accurate timing for a back-up system to GPS.

### **Summary**

Pseudolites provide a way to provide a back up to this critical capability to enable future technologies such as automated smart automobiles, fully autonomous aircraft, and numerous other technologies. GPS and pseudolites use the same basic concept of determining a precise range from a transmitter and determining position to the user based off that range. This thesis will leverage this knowledge, along with the various propagation models developed for wireless transmission networks to determine the feasibility of a ground based augmentation for GPS.

### **III. Methodology**

#### **Chapter Overview**

The primary goal of this research is to determine the feasibility of implementing a ground based pseudolite network for CONUS operations. To accomplish this goal the thesis is broken into two parts. The first part is developing the system architecture that will support a ground based pseudolite network. The second part is developing a model for the pseudolite transmitter and then creating an aggregate model of multiple ground based transmitters. This model will help in evaluating the feasibility of implementing this network on a scale to support CONUS operations.

#### **Pseudolite Architecture**

Chapter IV discusses the system architecture for the proposed pseudolite network. To develop the system architecture, basic requirements will be derived and developed to ensure similar functionality to GPS. This thesis uses the Department of Defense Architecture Framework Version 2.0 (DoDAF 2.0) [15], which is the current standard for DoD systems of systems architectures. To capture the Pseudolite Architecture and ensure proper linkages within the framework this thesis utilizes Enterprise Architecture as the primary tool for architecture development.

The architectural views to be developed in this thesis will be the All View (AV)-1, Operational View (OV)-1, OV-5a, Capability View (CV)-2 and the Systems View (SV)-1. The AV-1 describes the project's vision and objectives and sets the basis for the other views. Next, the OV-1 provides the top level graphical overview of how the pseudolite system will work. Third, the CV-2 provides the overall vision of the

capabilities to be provided in the Pseudolite System Architecture. Fourth, the SV-1 will show the interfaces and connections between system elements. Finally, the model to be used to provide a top level overview of the system and confirm that all activities are mapped appropriately to the capabilities will be the OV-5a model view.

Additional views that are generated to fully depict the Pseudolite System Architecture are listed and discussed in Chapter IV of this thesis.

### **Aggregate Modeling of the Pseudolite Network**

The methodology for developing the model for the pseudolite network involves multiple steps and calculations. The following is the detailed methodology for meeting the thesis objective of developing an aggregate model discussed in Chapter I. The analysis and results for the modeling are further discussed in Chapter V.

#### *Single Tower Modeling*

The initial step in developing the aggregate model is to develop the single antenna model for the omni-directional transmit antenna. This model represents a single transmitter at ideal conditions. To develop a single tower location model various frequencies discussed in Chapter II are applied to antenna patterns for a transmit power. Based on this research three separate frequencies will be applied to a standard pseudolite model at power levels between one and ten watts. Antenna height and propagation effects are taken into account later in the thesis when these models are applied to aggregate models for urban, suburban and rural locations.

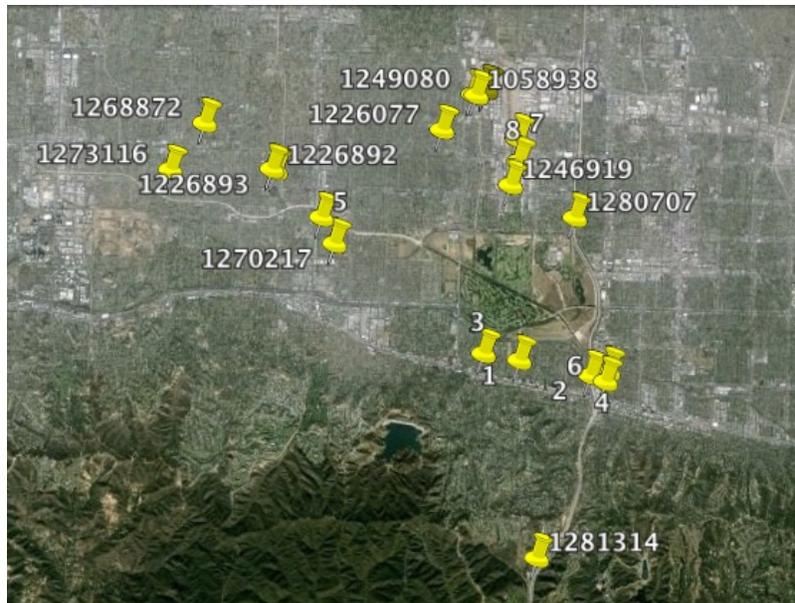
*Tower Location Models*

To determine placement of tower locations the model utilizes current United States data for cellular tower placement. This data is publically available through the Federal Communication Commission (FCC), and also available through multiple databases. Table 3 below provides an example output which is limited to tower heights greater than 50 meters.

<b>Registration</b>	<b>Latitude</b>	<b>Longitude</b>	<b>Antenna Height</b>
1	34.15725	-118.48758	51.8
2	34.1547222	-118.47061	53.6
3	34.1583333	-118.49617	54.9
1268872	34.2019722	-118.56411	55.1208
1270217	34.1790556	-118.53236	55.777
1246919	34.1916944	-118.49092	58.0737
1280707	34.1856667	-118.47542	59.058
1273116	34.1925556	-118.57189	59.7142
1293403	34.21025	-118.49753	59.7142
1226077	34.2021389	-118.50764	64.9638
1281314	34.1186111	-118.48228	65.9481
4	34.1555556	-118.46644	73.8
1249080	34.2092778	-118.50047	75.1349
1058938	34.2091667	-118.49972	76.1192
5	34.1841667	-118.53564	78.9
6	34.1536111	-118.467	92.4
1226892	34.1930556	-118.54694	124.678
1226893	34.1933333	-118.54778	180.455
7	34.2008611	-118.48958	234.7
8	34.1963056	-118.48919	244.4

**Table 3. Antenna Location Data**

The data in Table 3 provides a reference ID number for the tower, latitude and longitude in degrees, and the antenna height. It should be noted that the antenna height in above is in feet (ft) and is converted within the script to meters. This data is then plotted for each location. Figure 8 provides an example of tower locations for a suburban area.



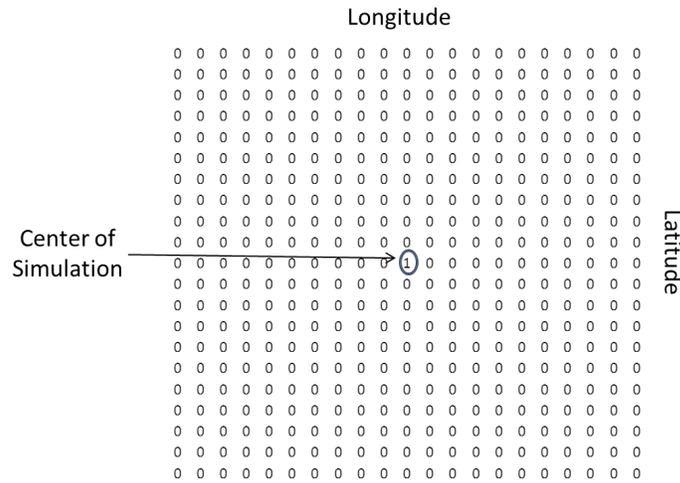
**Figure 8. Tower Locations Plotted**

The plotted tower locations above provide an approximation of tower locations for cellular networks in a densely populated suburban area. To model the aggregate ability of pseudolite towers across the US, tower location models will be developed for representative rural, urban and suburban locations and presented in Chapter V.

*Generating Aggregate Models*

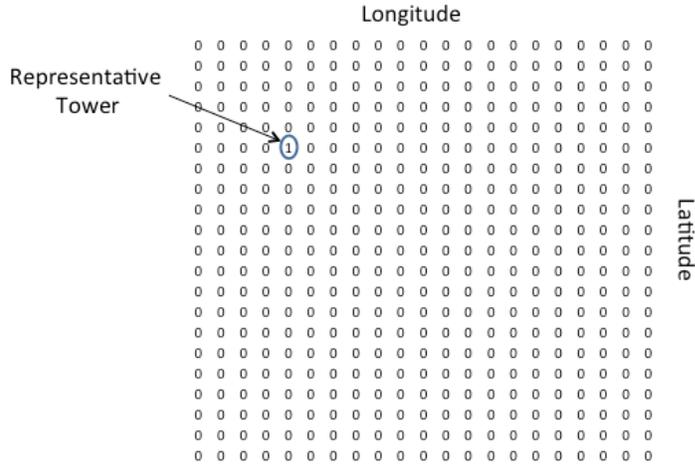
After developing the model of a single tower, and models for various population centers, an aggregate model can then be generated. The aggregate model is generated in MatLab<sup>™</sup> by overlaying each tower location onto a two-dimensional matrix. The first step in overlaying each location on a matrix is to generate a simulation size matrix. This matrix is based off the dimensions, resolution and geographical center of the simulation. Figure 9 is an example of the simulation size matrix. In this matrix the number one (1) represents the center of the matrix. The matrix boundaries and resolution can then be set in terms of kilometers within the script. To set the resolution each cell within the matrix

has the ability to be set to increments of between 0.1km and 10km depending on the size of the simulation area.



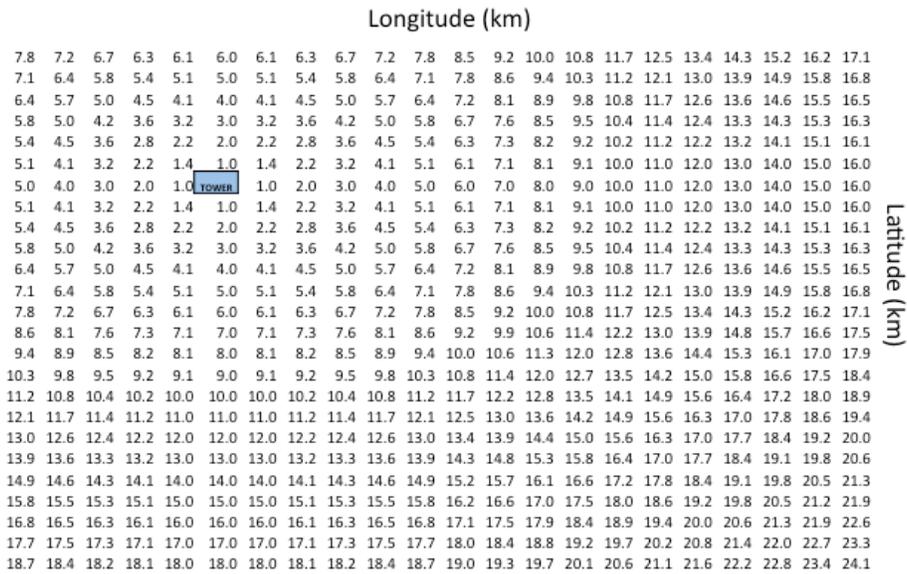
**Figure 9. Simulation Size Matrix**

The second step uses the antenna location data to develop a representative tower matrix for each location. This matrix is developed for every tower location (see Table 2) within the simulation. Figure 10 depicts a sample matrix for a single tower location. The number one (1) represents the tower location, which is calculated by taking the center of the simulation (Latitude and Longitude) and creating a vector from the center location to location of the tower. The number one (1) is then placed at the location of the tower relative to the center of the matrix.



**Figure 10. Representative Tower Matrix**

Before the power matrix can be determined, a distance matrix is developed for each representative tower matrix. The distance matrix utilizes the simulation resolution and creates a distance for each point on the matrix relative to the tower. Figure 11 below is an example distance matrix based of the Tower Matrix depicted in Figure 10.



Note: Distances are relative to a single tower

**Figure 11. Tower Distance Matrix**

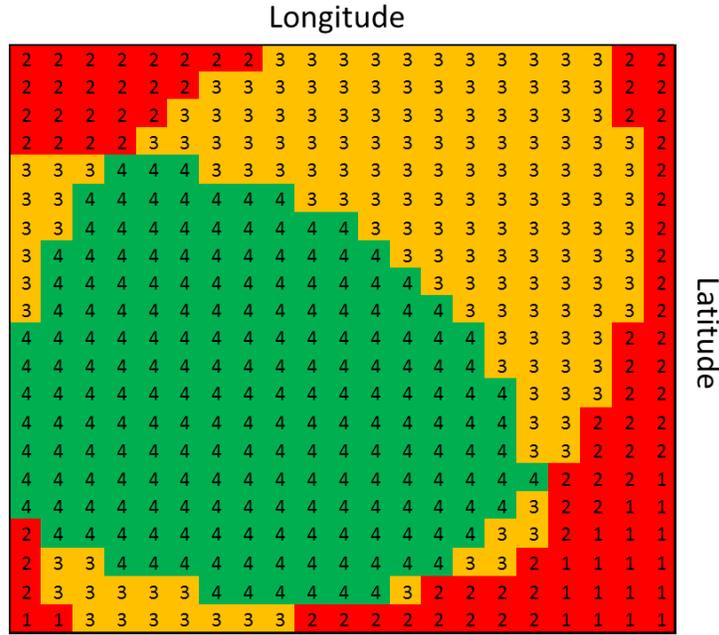
After the development of the distance matrix the power matrix can be developed. This matrix utilizes the antenna model Effective Isotropic Radiated Power (EIRP), tower location matrix (Figure 12), antenna heights (Table 3), distance matrix (Figure 11) and the propagation models (from Chapter II) to develop a composite power matrix for every tower matrix. Figure 12 provides the predicted power at every location in the simulation based off the transmission of a single tower.

																Longitude																
-117	-116	-115	-114	-114	-114	-114	-114	-115	-116	-117	-118	-119	-120	-121	-122	-123	-124															
-116	-114	-113	-112	-111	-111	-111	-112	-113	-114	-116	-117	-118	-119	-121	-122	-123	-124															
-114	-113	-111	-110	-109	-108	-109	-110	-111	-113	-114	-116	-117	-119	-120	-121	-122	-123															
-113	-111	-109	-107	-105	-105	-105	-107	-109	-111	-113	-115	-117	-118	-120	-121	-122	-123															
-112	-110	-107	-104	-101	-99	-101	-104	-107	-110	-112	-114	-116	-118	-119	-120	-122	-123															
-111	-109	-105	-101	-95	-90	-95	-101	-105	-109	-111	-114	-116	-117	-119	-120	-122	-123															
-111	-108	-105	-99	-90	<b>TOWER</b>	-90	-99	-105	-108	-111	-114	-116	-117	-119	-120	-121	-123															
-111	-109	-105	-101	-95	-90	-95	-101	-105	-109	-111	-114	-116	-117	-119	-120	-122	-123															
-112	-110	-107	-104	-101	-99	-101	-104	-107	-110	-112	-114	-116	-118	-119	-120	-122	-123															
-113	-111	-109	-107	-105	-105	-105	-107	-109	-111	-113	-115	-117	-118	-120	-121	-122	-123															
-114	-113	-111	-110	-109	-108	-109	-110	-111	-113	-114	-116	-117	-119	-120	-121	-122	-123															
-116	-114	-113	-112	-111	-111	-111	-112	-113	-114	-116	-117	-118	-119	-121	-122	-123	-124															
-117	-116	-115	-114	-114	-114	-114	-114	-115	-116	-117	-118	-119	-120	-121	-122	-123	-124															
-118	-117	-117	-116	-116	-116	-116	-116	-117	-117	-118	-119	-120	-121	-122	-123	-124	-124															
-119	-119	-118	-118	-117	-117	-117	-118	-118	-119	-119	-120	-121	-122	-123	-123	-124	-125															
-121	-120	-120	-119	-119	-119	-119	-120	-120	-121	-121	-122	-123	-123	-124	-125	-125	-125															
-122	-121	-121	-120	-120	-120	-120	-121	-121	-122	-122	-123	-123	-124	-125	-125	-125	-126															
-123	-122	-122	-122	-122	-122	-122	-122	-122	-123	-123	-124	-124	-125	-125	-126	-127	-127															
-124	-123	-123	-123	-123	-123	-123	-123	-123	-123	-124	-124	-125	-125	-126	-127	-127	-127															
-125	-124	-124	-124	-124	-124	-124	-124	-124	-125	-125	-125	-126	-126	-127	-127	-128	-128															
-125	-125	-125	-125	-125	-125	-125	-125	-125	-125	-125	-126	-126	-126	-127	-127	-128	-128															

**Figure 12. Power (dBm) from Tower Matrix**

The tower specific power data must then be compared to power matrices generated for all of the towers in the simulation. This is accomplished by making an aggregate tower matrix (Figure 13). This matrix provides the location of all towers in the simulation relative to the center of the simulation. This matrix is then used to determine which locations in the matrix have a power level that exceeds the minimum projected tracking power of the pseudolite receiver.





**Figure 14. Aggregate Receiver Tracking Matrix**

*Analysis of Aggregate Models*

After developing the aggregate receiver-tracking matrix the data is overlaid back into *Google Earth*. For the purposes of this thesis a color gradient between tracking and not tracking is provided as an overlay. Various plots are then generated for different transmit powers, propagation models and population centers. These results will be analyzed and compared to determine the feasibility of a proposed pseudolite network. In addition this data will be used to help optimize a pseudolite network based off existing infrastructure.

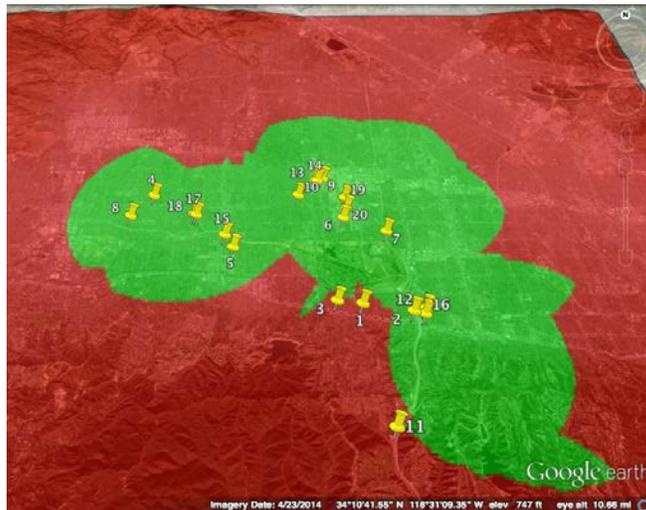
A Matlab script was developed that follows the above process. The script prompts the user to input simulation size (km<sup>2</sup>), simulation resolution (km), minimum pseudolites in-view of a receiver, receiver altitude (m), effective isotropic radiated power (EIRP) of the transmitter (watts), frequency of the transmitter (MHz), and minimum

received power of the receiver (dBm). Figure 15 below provides an example of the input script prompts.

```
Input Simulation Size(km): 50
Input Simulation Resolution (km): .1
Input Towers Required Inview of Location(#): 6
Input Receiver Altitude (m):3
Transmitter Power (W): 1
Simulation Frequency (MHz): 2414
Minimum Receiver Power (dBm): -100
```

**Figure 15. MatLab Script Command Prompts**

The MatLab script also takes into account additional factors including the curvature of the Earth, which is not accounted for in the simple example above. A copy of the Matlab script is available in Appendix A. Figure 16 provides an output from the Matlab script described above. For this simulation ‘green’ represents four or more transmitters provide adequate power (as defined by the user input) at a received location on the ground; and red represents that less than four towers are providing a solution. Chapter V provides multiple runs of the simulation based on the described methodology.



**Figure 16. Example Model Output**

## IV. Pseudolite Architecture

### Chapter Overview

To ensure a successful pseudolite system is in place, systems architecture must be defined due to the complexity and size of this system. In order to develop good architecting principles for our pseudolite system it's important to construct several viewpoints to represent the various subsystems in sufficient detail which are presented in this section. Developing good architectural models reduces risks for all stakeholders and enables communication with them on how the system should function and operate.

The purpose of this architecture is to achieve a land-based navigation and timing system. In order to accomplish this, several models described in the DoDAF 2.0 framework detail how the pseudolite system such as this may be architected. There are many models that may be used depending on the type of system that is being architected but this research will focus on a few. An important thing to note is that some of these models or diagrams rely on other models within an architecture viewpoint so they must agree or be concordant with each other.

The first view that we will look at is the All-View 1 or AV-1. An AV-1 helps to provide information about the pseudolite system that is being architected. Table 4 shows important information pertaining to a representative ground-based pseudolite system. Table 4 also shows some of the inputs that would be provided by the system owners and agreed upon by the stakeholders of the system. The system architect will then use this information to begin to frame the system from a very high level and then work down to the specifics by means of the requirements that are derived from this information. This

information could be represented in many ways but the current effort will utilize a particular format for the AV-1 example.

Architecture Identification	
Name	Ground Pseudolite System
Description	The purpose of this architecture is to achieve a ground-based navigation and timing system. This architecture would provide ground users an alternate means of timing and navigation in the event of a major disruption to the GPS space or control segments.
Architects	Justin Deifel and Albert Pena
Organization	Air Force Institute of Technology
Assumptions and Constraints	<p>Pseudolite System Architecture:</p> <ul style="list-style-type: none"> <li>- Will rely on timing provided by the United States Naval Observatory (USNO) and transmitted through a single satellite</li> <li>- Will only use ground based pseudolites</li> <li>- Will use frequencies that are out of band from GPS frequencies</li> <li>- Will provide an alternate means of acquiring position, navigation, and timing</li> <li>- Will only be used operationally in the continental U.S.</li> <li>- Will use current US Military data transfer methods</li> </ul>
Approval Authority	Dr. David Jacques
Date Completed	
Scope: Architecture View and Models Identification	
Views Developed	<ul style="list-style-type: none"> <li>- Overview and Summary (AV-1)</li> <li>- High Level Operational Concept Graphic (OV-1)</li> <li>- Capability Taxonomy (CV-2)</li> <li>- Operational Activity Decomposition Tree (OV-5a)</li> <li>- Systems Interface Description (SV-1)</li> </ul>
Capabilities	- Primary: Provide position, navigation, and timing (PNT) to ground users to include smart highway systems
Time Frames Addressed	A successful demonstration is desired by 2025 and fully fielded by 2035.
Organizations Involved	<ul style="list-style-type: none"> <li>- Air Force Institute of Technology (system architect)</li> <li>- Northern Command, civilians and smart highway systems (customer)</li> <li>- U.S. Department of Transportation</li> </ul>
Purpose and Viewpoint	
Purpose (Problems, Needs, Gaps)	GPS is the primary source for PNT in both the civilian and military world. However, in the event that GPS signals are not available, there is no existing rapidly deployable or permanent solution in place to provide PNT for ground users. In a complex urban environment with constantly changing city landscapes and few distinct terrain features, ground users will require precise coordinates for navigation.

Questions to be Answered	<ol style="list-style-type: none"> <li>1. What are the ideal frequency or frequencies for deployment of a pseudolite network, based off spectrum that could realistically be allocated in the future?</li> <li>2. What is a proposed architecture for a pseudolite solution that would provide CONUS PNT coverage?</li> <li>3. How will a pseudolite deployment differ based on different geographical developed environments (e.g. mountainous, canyon, rural, urban, suburban, etc.)?</li> <li>4. What is the deployment for different geographical development environments and how does this aggregate to a CONUS deployment model?</li> </ol>
Architecture Viewpoint	The Pseudolite System architecture will be developed from the perspective of the Air Force Institute of Technology (AFIT) and its feasibility as a future alternative or back-up to GPS.
Context	
Mission	To provide an alternate PNT system that will act as a back-up to the GPS system for ground users in the continental United States.
Doctrine, Goals, Vision	The Pseudolite system seeks to provide the US DoD, an alternate means to receive accurate PNT. Providing similar capabilities of GPS and to be able to operate concurrently with GPS.
Rules, Conventions, and Criteria	The Pseudolite System architectural data conforms to the DoD Architectural Framework (DoDAF) Version 2.0.
Linkages to Other Architectures	None.
Tools and File Formats to be Used	
Sparx Enterprise Architect V10.0, Microsoft Word & Microsoft Excel	

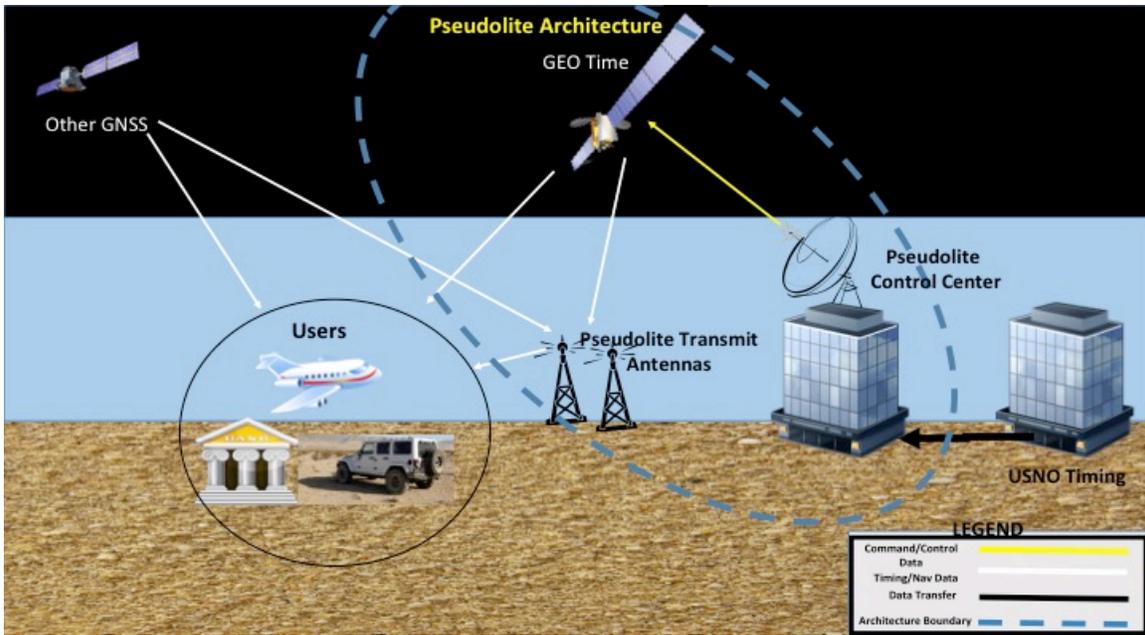
**Table 4. Overview and Summary Information (AV-1)**

### **Concept of Operations (CONOPS)**

Next, the Operational View 1 or OV-1 model is simply a high-level model used to describe the system. This is a graphical view of the proposed architecture which is used to depict the interactions between the architecture and its environment. The data shown on an OV-1 is determined by the type of system being represented and by the architect. Figure 17 depicts the four major elements of the Pseudolite Architecture. These elements are the (1) pseudolite ground transmitters, (2) a satellite in geosynchronous orbit which provides a continuous time reference, (3) a control center which monitors and controls

the system activity and finally, (4) the users' receiver which can read signals transmitted by the geosynchronous satellite and by other GNSS satellites developed by other countries. Another important aspect of the CONOPS is the USNO's timing source data. For a pseudolite to work properly it must know its position precisely. Therefore, each pseudolite will be precisely surveyed during installation to determine its precise location. The second main element is to ensure time synchronization between pseudolites. In this architecture, a satellite in geosynchronous (GEO) orbit will provide continuous time reference data for the entire network. The time reference will be continuously monitored by the control center which will receive precise timing from the USNO. Finally, the user receives the timing data from the satellite and from pseudolites using a receiver capable of reading the signals transmitted by the satellite and pseudolites. The received signals will then be processed to determine the receiver's pseudorange from a pseudolite just as GPS does with each satellite from which a signal was transmitted and presented in Chapter II, *GNSS Background*. When a receiver has the minimum number of pseudolites in view, it can then calculate its position based on multiple pseudorange and basic geometric calculations.

As depicted in the OV-1, the receivers will still have the capability to track GNSS signals as well as pseudolite signals. This feature allows a user's receiver to perform integrity checks on both the pseudolite and GNSS signals. The ability to perform these integrity checks is important to ensure future autonomous vehicles' positioning data is accurate. In an operational scenario, the user's experience with the pseudolite system will be very similar to what users of GPS experience today.



**Figure 17. High Level Operational Concept Graphic (OV-1)**

### **Timing Architecture**

In many systems that rely on precise timing synchronization, GPS is used as the source for this data. When architecting a system that does not rely on GPS it is important to separate GPS timing as a requirement for time synchronization. For this reason, the architecture presented utilizes a satellite system that provides timing from a geosynchronous orbit to provide continuous CONUS coverage for timing data to synchronize the pseudolites. In addition, this satellite could be used as another ranging source for the receivers to help improve accuracy. Depicted in Figure 18 the USNO initially provides the precise timing for the system to the Pseudolite Control Center which ensures that the data is in the proper format and that the information is capable to be received by the satellite. In conjunction with atomic clocks residing on the satellite, this timing data will then be transmitted to pseudolites located in CONUS. This entire

process repeats itself on a constant basis so that the data is updated in real time and users can benefit from using this system twenty-four hours a day and seven days a week just like GPS provides today. No timing analysis was conducted since the USNO will continue to be relied upon to provide precise timing data for the pseudolite system.

Another operational view that was developed is the Operational Activity Decomposition Tree or OV-5a shown in Figure 18. This model shows the hierarchical functional decomposition of operational activities for the pseudolite system. This model is often represented by three or more different levels with the lower the level, the more detailed in representing the various components of the system. As mentioned recently, some models provide information to other models within an architecture and this is especially true of the OV-5a model. Because the OV-5a model details the operational activities for all other models within the architecture, it helps to explain those operational activities and to support the functionality of those activities. Therefore, the OV-5a is one of the more important views within any system architecture, including the present one. The OV-5a model shown below is what was developed for the pseudolite system.

The OV-5a model shows several levels of operational activities with the lowest level of activities representing the lowest level of detail. This OV-5a model helps develop other models within the systems architecture and it is important that the other models also agree or are concordant with the OV-5a model. It's also important to note that not all branches in the OV-5a model will have the same number of levels. Some branches show more detail, while other activities have fewer levels of detail.

The top level operational activity shown in the model is "Provide PNT Services." The main purpose for the pseudolite system is to be a backup for GPS and therefore, to be

able to also perform the function of providing PNT service just like the GPS. The method of performing this activity is slightly different from how GPS provides position, navigation and timing as described in the OV-1. The further down the model you go, one can see the activities needed to be able to achieve “Provide PNT Services.” As can be seen in Figure 18, more sub-activities are associated with performing system command and control than the other second level activities. The third-level activities of “Provide Ground Based Signal” and “Provide Satellite Service” require even more detail to show how those activities are achieved. The OV-5a model serves as a great model to map out all the operational activities required for the pseudolite system. Capturing all the required activities properly will ensure that the system can indeed provide PNT services.

Name: Operational Activity Model  
 Author: Group 3  
 Version: 1.0  
 Created: 4/26/2014 6:22:34 PM  
 Updated: 5/16/2014 2:38:58 AM

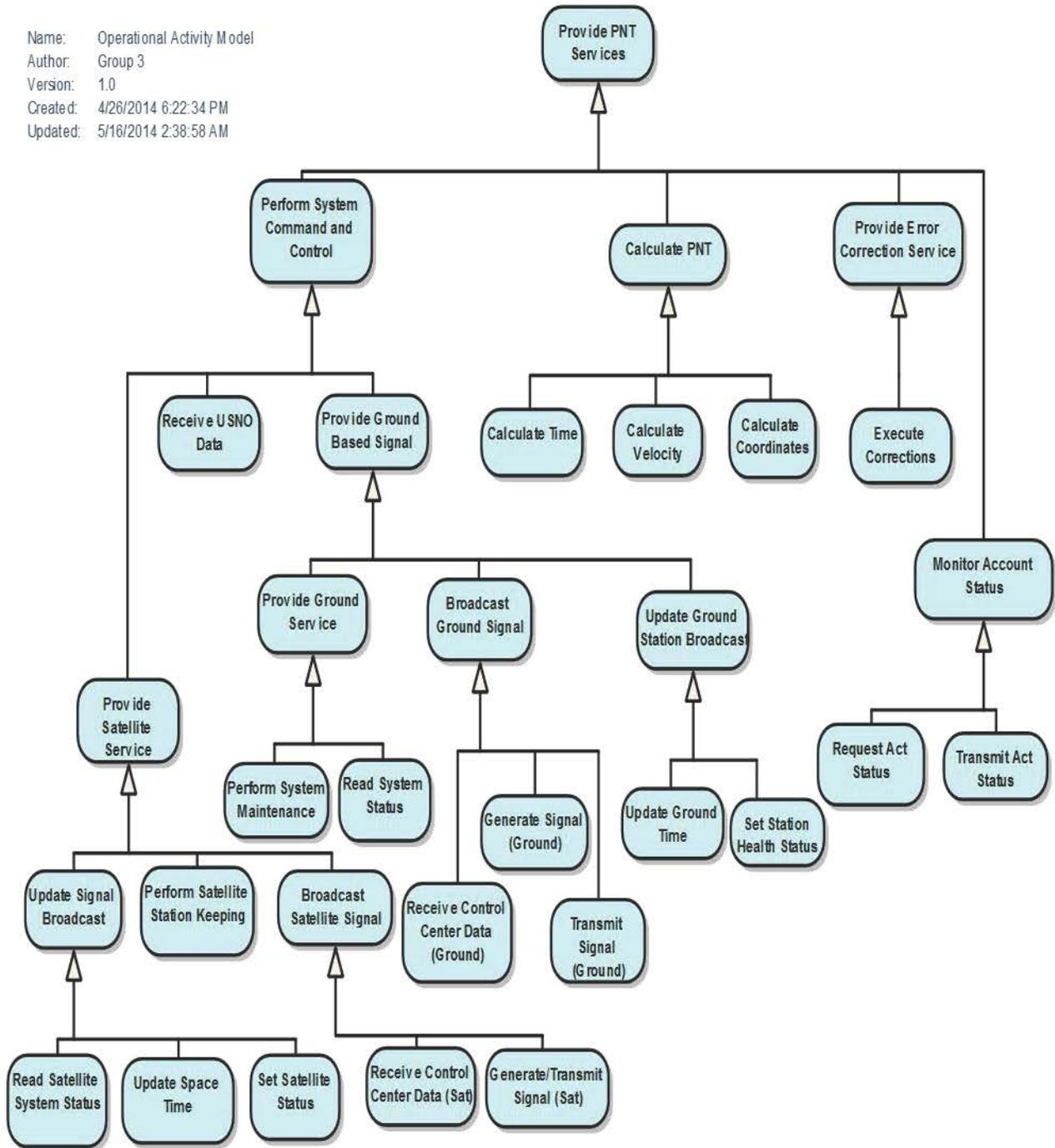
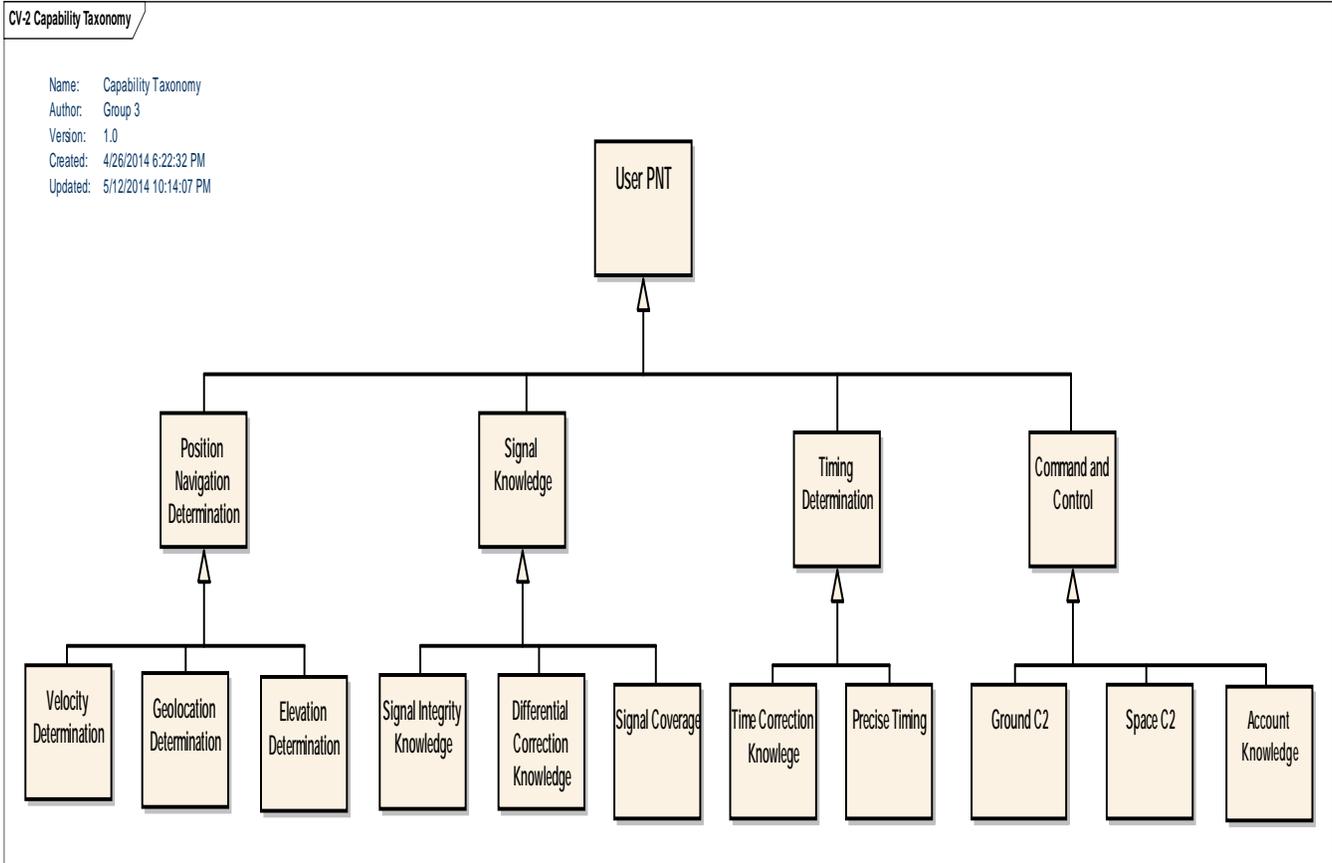


Figure 18. OV-5A, Operational Activity Model

One model that must be highly concordant with the OV-5a is the Capability Taxonomy or CV-2, which details the operational capabilities of the system. The CV-2 is contained within the capabilities viewpoint of DoDAF 2.0 and is shown in Figure 19. This model relies on the OV-5a because the leaves of the CV-2 are the roots of the OV-5a model. Once the capabilities for the system are identified they are further broken down into the activities that need to occur to ensure that particular capability of the system can occur. When developing the CV-2, one must also ensure that the AV-1 is concordant with the CV-2. The high-level “User PNT” capability further breaks down to lower level capabilities of “Position Navigation determination,” “Signal Knowledge,” “Timing Determination” and “Command and Control.”

Another important model developed for the system is the System Interface Description Model or SV-1 shown in Figure 20. This model describes all of the system interfaces or connections that must occur for the system to operate as intended. The important aspect of this model is to represent how data is transferred within the system and what type of connections must be used, including all wireless connections.



**Figure 19. CV-2, Capability Taxonomy**

The other major components of the SV-1 as shown in the model are nodes that are usually the main actors or system nodes associated with the system. In the model, it shows how PNT signals propagate through the system and are received by users by means of either a hand-held device or other receiver that can read the signals properly and use the data for PNT purposes. Other connections occur through hard-wired connections as shown in Figure 20.

Systems architecture of our pseudolite system is an important process that must take place due to the complexity and with the multiple components and subsystems that are involved with developing our system. The development of architectural models will

ensure that the pseudolite system is built soundly and incorporates all the capabilities that are identified for the system.

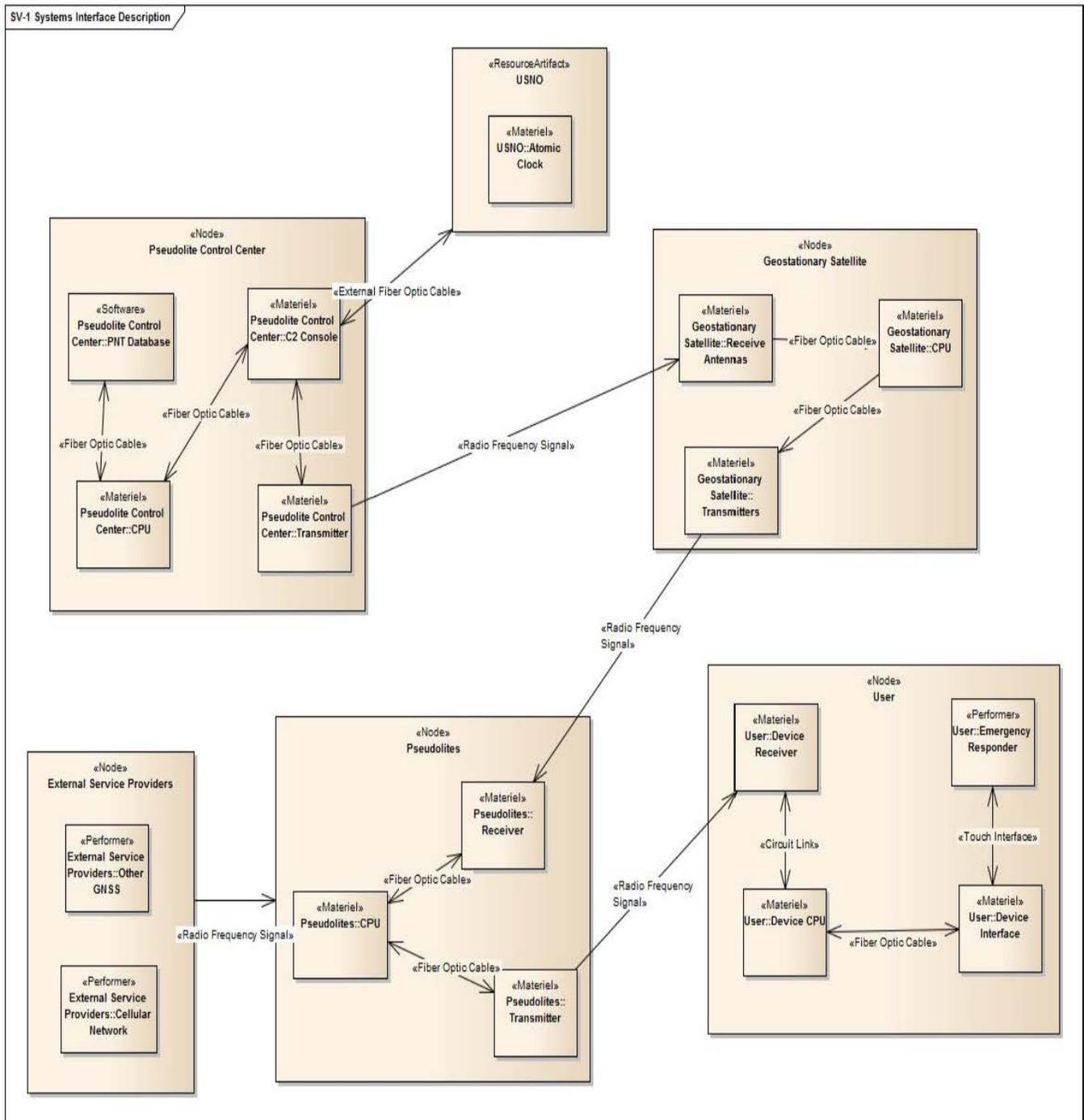


Figure 20. SV-1, System Interface Description

## V. Pseudolite Network Modeling

This chapter will provide various aggregate pseudolite models based on different frequencies, power levels, geographic regions and tower deployments. The ground work for this analysis is discussed throughout Chapter II and III. The first step in the model is to develop the propagation models, followed by implementing these models to aggregate a pseudolite model for different regions.

### Propagation Model Analysis

The models in this research rely heavily on propagation models discussed in Chapter II. Equations 1-12 are the foundation for determining how the pseudolite signal will propagate over various geographical and man-made terrains. Using the FSP model and the Hata-Model for urban, suburban and open space, Figure 21-Figure 23 were generated. Based on the discussion in Chapter II this analysis uses the assumption that 700, 900 and 1765 MHz are available in the future for utilization by this network.

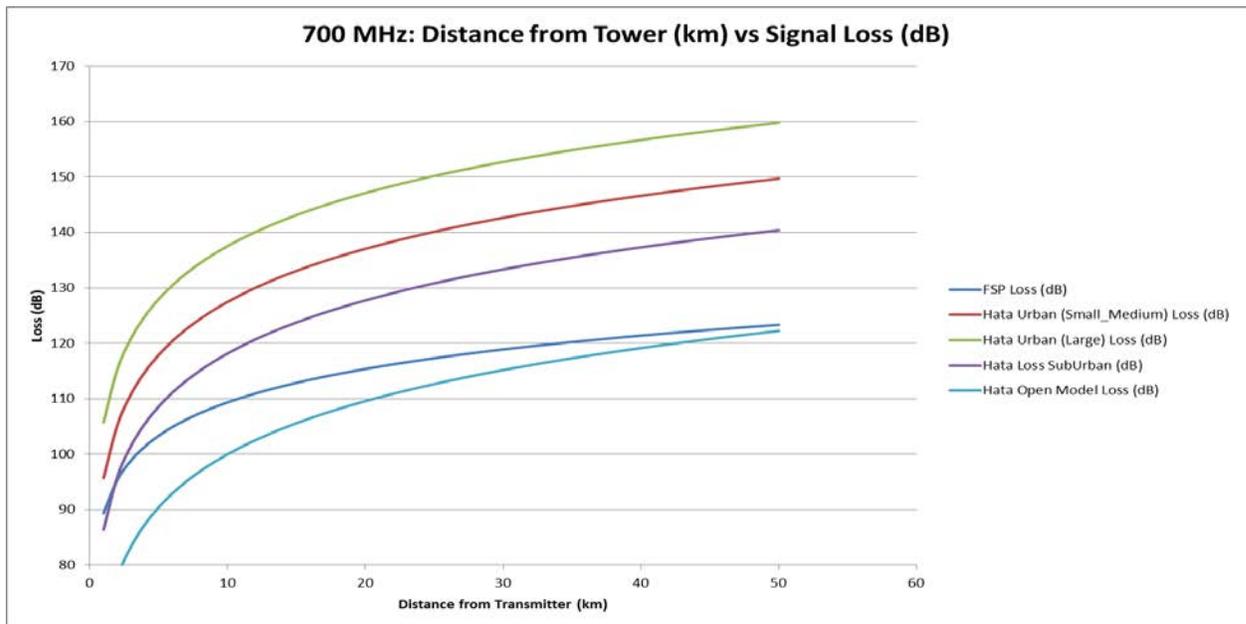
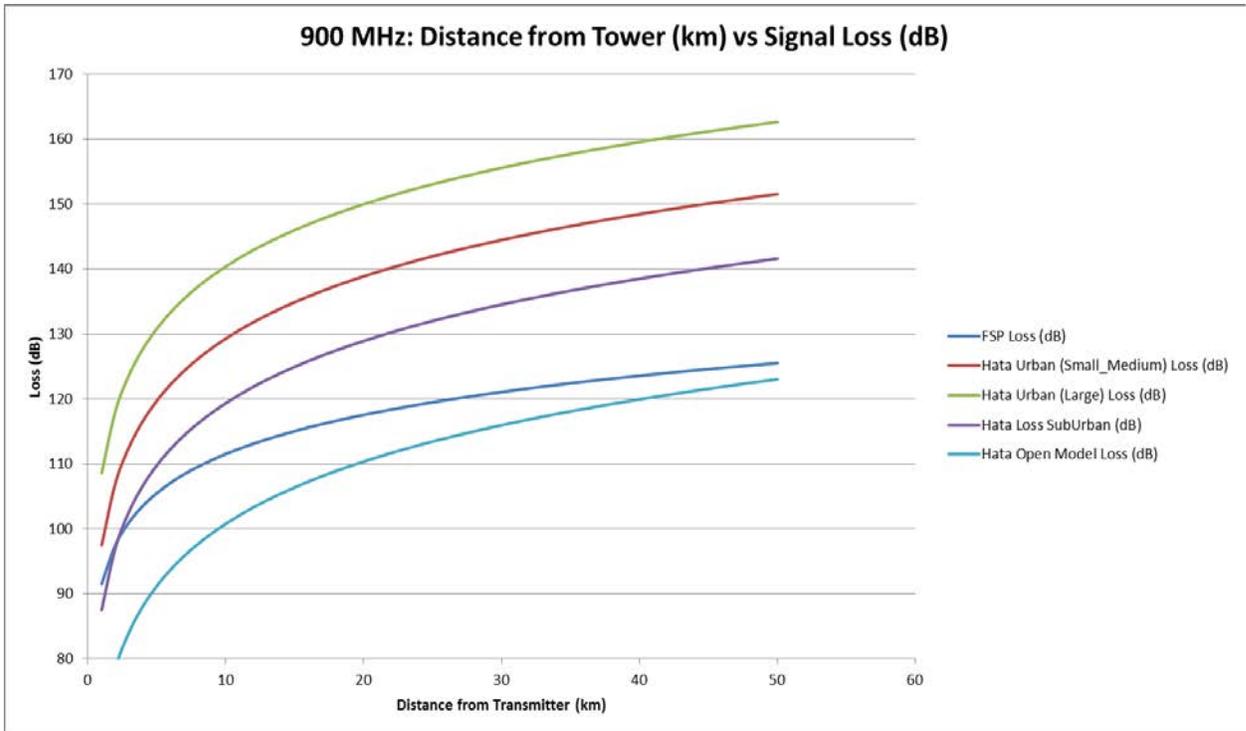
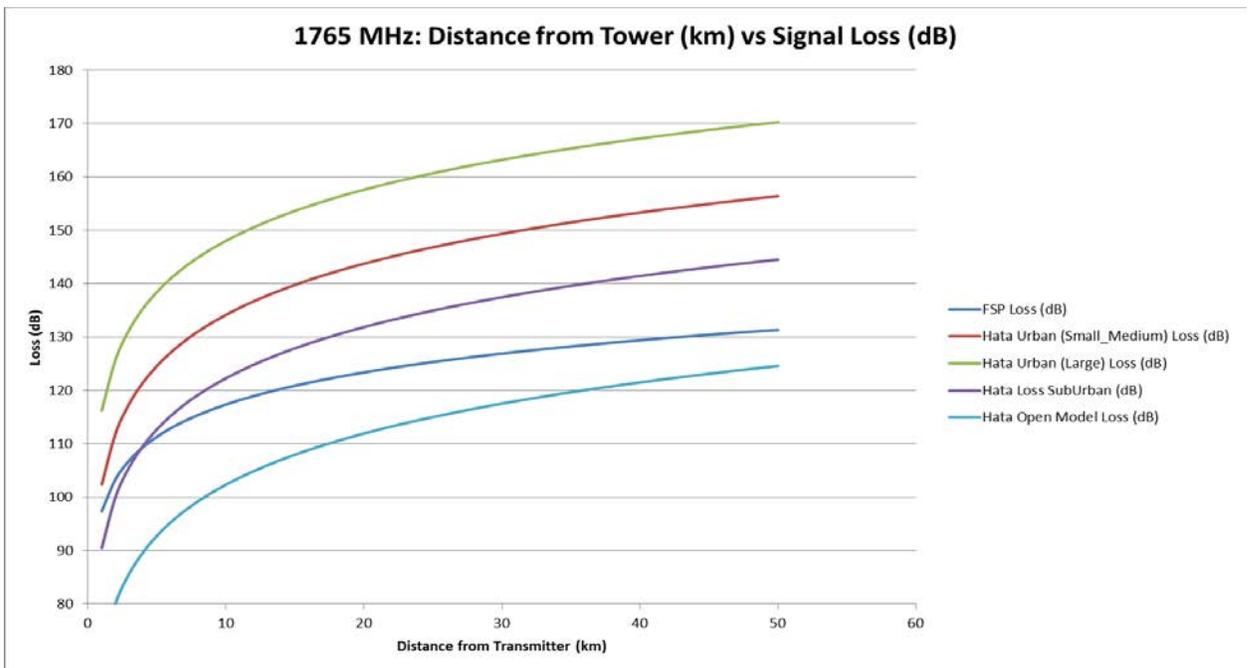


Figure 21. 700MHz Propagation Loss Model



**Figure 22. 900 MHz Propagation Loss Model**



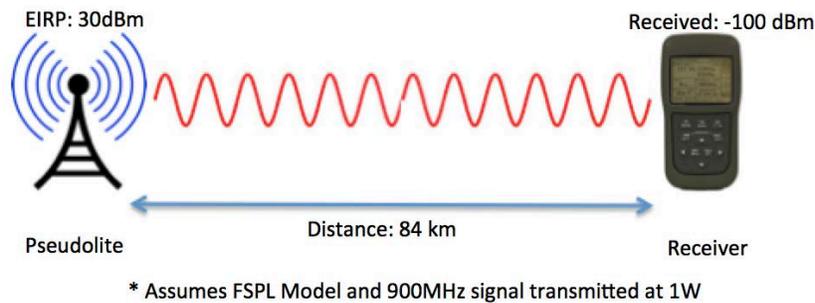
**Figure 23. 1765 MHz Propagation Loss Model**

While the general trends between the different frequencies are the same for signal path-loss, the actual values vary significantly. The various models take into account the differences between the frequencies to determine how the signal will propagate based of the pathloss curves above.

Other observations can be derived from the propagation loss figures above. First is that the Hata Large Urban model predicts a path-loss almost 40 dB greater than the Hata Open model. This is expected due to the fact that in large urban environments buildings and other structures will attenuate signals much more significantly then in open space. The propagation models above are implemented in the simulations in this chapter through the empirical equations in Chapter II.

### **Transmit and Received Power**

To develop the aggregate model the Effective Isotropic Radiated Power (EIRP) of the transmit location and the minimum received power of the receivers needs to be determined. Figure 24 below shows a simplified diagram of transmit and received power.



**Figure 24. Transmit and Received Power**

The FCC states that most transmitters in urban areas broadcast at 10 watts per channel EIRP [16]; therefore, the inputs to the model in urban locations are 10 watts or less. For rural areas it is projected that EIRP is higher due to the greater spacing between towers and therefore less concern of towers interfering with one another. Rural area inputs therefore were modeled at 10 watts.

Once a signal is transmitted, it must also be received by an antenna and processed by the receiver. For GPS the minimum guaranteed receive power for L1 C/A code is -128.5 dBm at 5 degrees elevation. This means that a receiver at sea-level will receive a signal greater than or equal to -128.5 dBm when a GPS satellite is at 5 degrees elevation or higher. One of the benefits discussed with pseudolites is the fact they are able to produce relatively higher received signal powers, due to the fact they are terrestrial based transmitters (versus space based). The Locata transmitter recommends a received signal power of -100 dBm to ensure “robust” quality of the signal. This additional 28.5 dBm provides a significant increase (~140 times greater) in power, thereby providing additional anti-jamming protection for a pseudolite.

### **Model Verification**

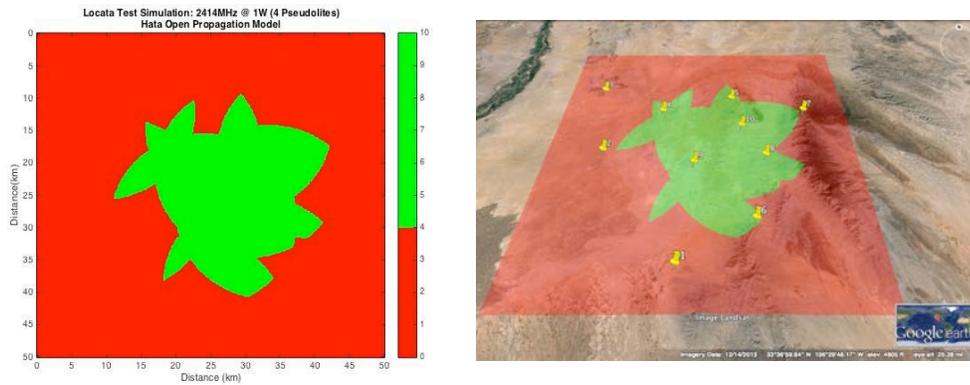
This thesis relies heavily on models generated to determine pseudolite coverage based on tower locations and propagation models. To ensure the integrity of the MatLab pseudolite model it was checked against separate calculations. To do this Microsoft Excel was used to calculate specific instances of each model. These results were then compared to the numerical results of the model. Frequency, antenna height, transmitter

power and receiver height variables were altered to provide a number of test cases. The results showed that the model outputs matches the various test cases conducted in Excel.

### **Locata Test (White Sands Missile Range)**

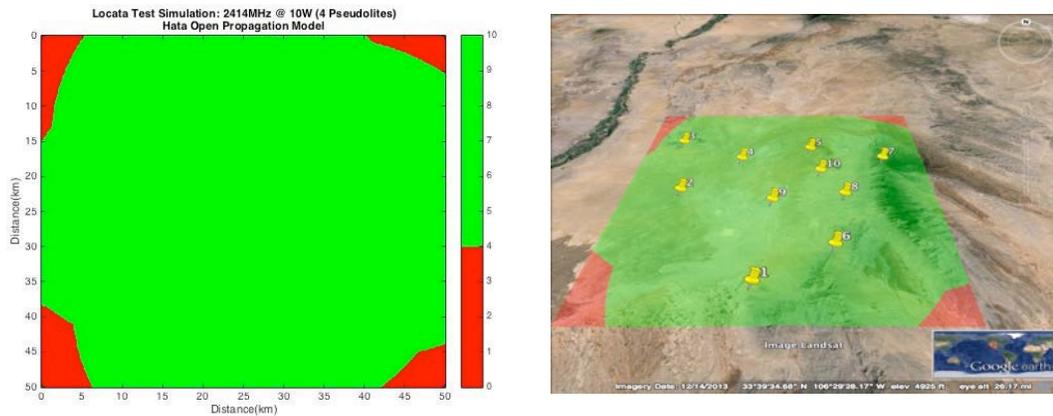
The first pseudolite network modeled is based off a test at White Sands Missile Range (WSMR) performed by the Locata Corporation and 746<sup>th</sup> Test Squadron, United States Air Force in 2011. This test was performed using 10 Locata pseudolites located across the WSMR test range. (Location data for the 10 pseudolites is located in Appendix B.) The test utilized an aircraft flying various patterns over the range, and calculating position based off of the pseudolites. This data was stored and then compared with GPS data to determine the accuracy of the pseudolites.

Figure 25 is the first implementation of the pseudolite network model. The image on the left depicts the raw data output of a receivers ability to track four pseudolites based on a 2414MHz signal being broadcast at 1W. This model utilizes the hata-open propagation model due to the fact WSMR has minimal obstructions from buildings, trees or other terrain. From the published test report, the initial tests utilized 1W pseudolite transmitters. Figure 25 shows that the pseudolites near the center of the simulation are able to track four or more pseudolite towers within the simulation boundary. Receivers outside of approximately 30km for the simulation center are unable to track enough transmitters to calculate an accurate position.



**Figure 25. Locata Test Simulation: 2414MHz @ 1W (4 Pseudolites)**

The report noted, “10 watts of transmitted power enables acquisition and tracking out to 50 km or better.[17]” This increased power was required to provide more adequate positioning data to the test receiver, which was determining position from an aircraft flying in the test range. To prove this the test team increased power from 1W to 10W. Figure 26 uses the model to simulate the increased powers impact on the ability of the receiver to track four or more transmitters. Shown in Figure 26, the increase from 1W to 10W allows tracking for nearly all of the 50 km x 50 km simulation area. This result relates directly with the test data information from the Locata Test Report at WSMR [17].

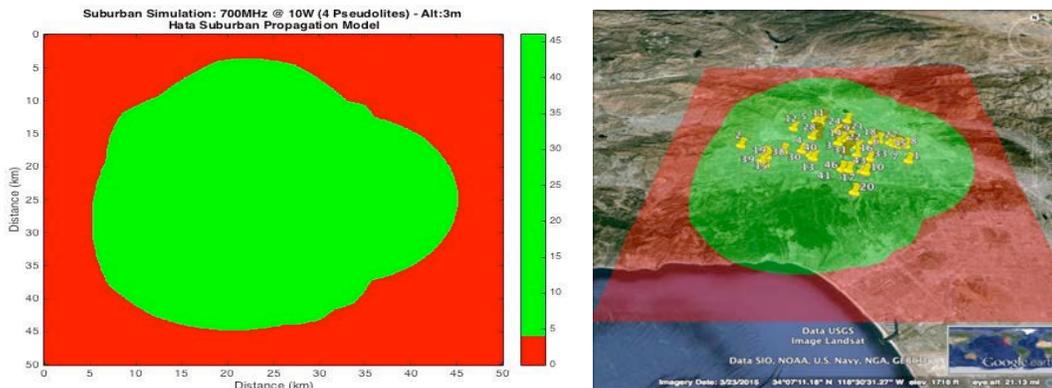


**Figure 26. Locata Test Simulation: 2414MHz @ 10W (4 Pseudolites)**

This application of the model shows the value of being able to model a test case for positioning coverage prior to an actual test. While this was not the primary goal of the research, it does prove the versatility of the model to be utilized in real world test planning and execution for future pseudolite tests.

### Suburban Pseudolite Network

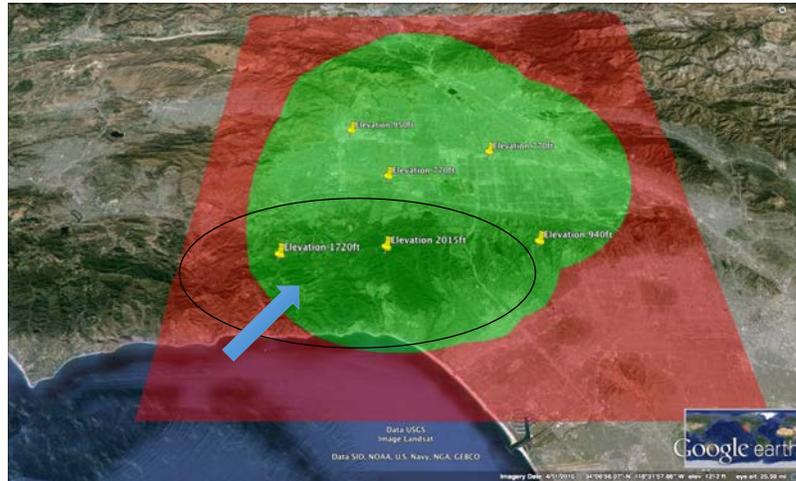
The first population center that the model is applied to is a suburban model of San Fernando Valley near Los Angeles California. Forty six tower locations were found in the area that are utilized in the modeling of a suburban region. Similar to the WSMR model, Figure 27 shows the MatLab output on the left, where the green color correlates to a receiver in that region being able to track four or more pseudolites at minimum received power of -100 dBm. The model in Figure 27 uses a 10W transmitter at 700 MHz and assumes the receiver is at three meters elevation.



**Figure 27. Suburban Simulation: 700MHz @10W (4 Pseudolites), Receiver Height: 3m**

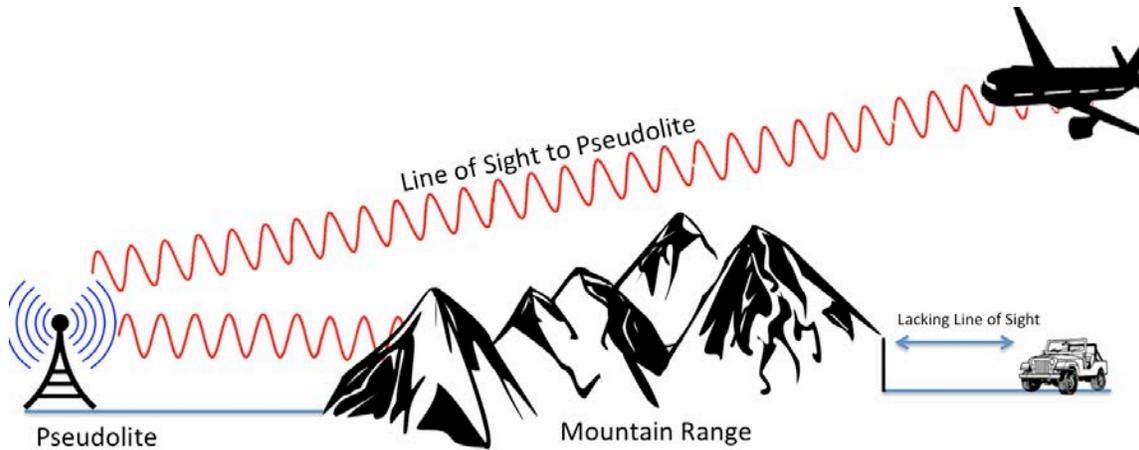
Figure 27 shows that for the scenario modeled the number of towers provides extremely good coverage of four pseudolites in view. Although this seems promising further review of the data shows a flaw in the model with respect to mountainous terrain.

Figure 28 is an elevation map for this region. As is revealed by the figure, the valley is between 750-950 feet, but the mountains that surround the valley are between 1700-2100 feet.



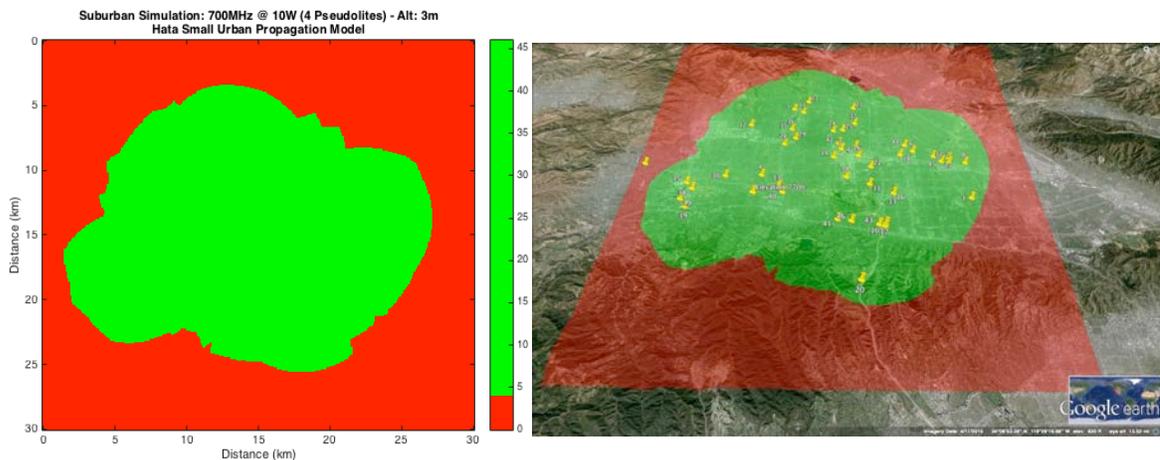
**Figure 28. Suburban Location Elevation Map – Hata Suburban Propagation Model**

It is unreasonable to assume that a signal would propagate over a mountain range and be able to be received on the other side at a lower elevation. This is due to the fact RF waves over 30 MHz require line of site between a transmitter and receiver. Figure 29 is a basic representation of the issue discovered with the model as originally implemented in Figure 27.



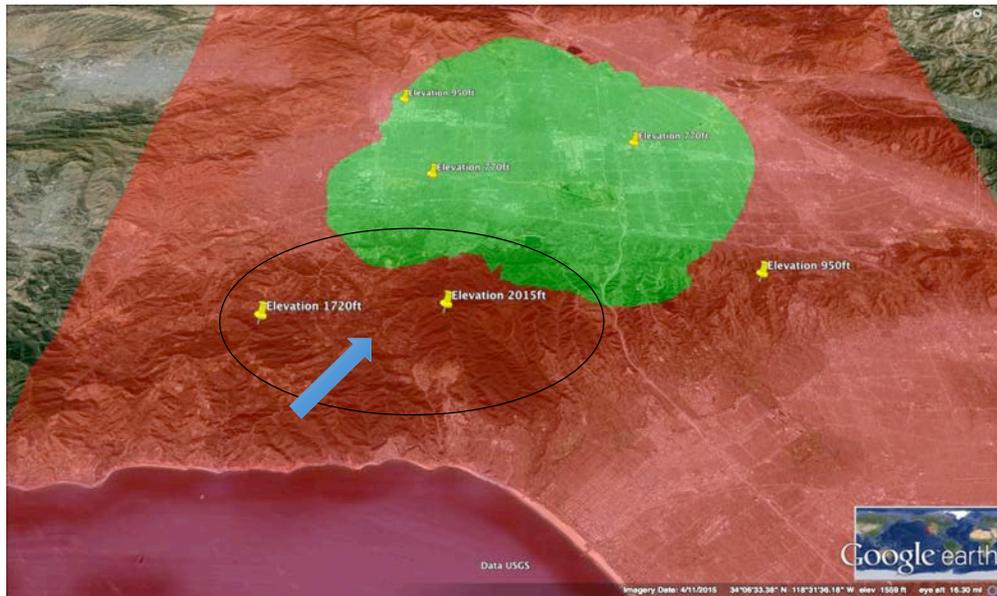
**Figure 29. Line of Site Propagation**

To accommodate the terrain elevation concerns the model was altered to assume that the surrounding mountains represented urban buildings. This was accomplished by altering the equations utilized to generate the figure. Figure 30, utilizes the same input data as Figure 27, but utilizes the Hata Small Urban propagation technique as discussed in Chapter 2, equations 6-8. This method treats the mountain obstruction similar to a large building without transmitters on the peak or near the base.



**Figure 30. Suburban Simulation: 700MHz @ 10W (4 Pseudolites), Receiver Height: 3m (Hata Small Urban Propagation)**

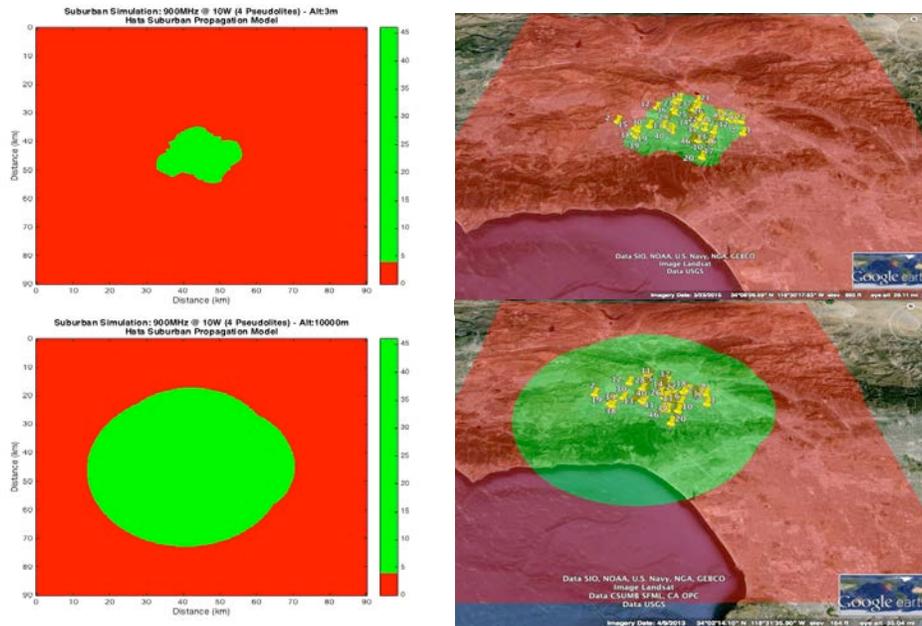
As can be seen from Figure 30 and Figure 31 utilizing the Hata Urban model corrects the line of sight error on the opposite side of the mountain. Chapter VI discusses a recommendation for fixing this modeling error in a more formal manner.



**Figure 31. Suburban Location Elevation Map – Hata Small Urban Propagation Model**

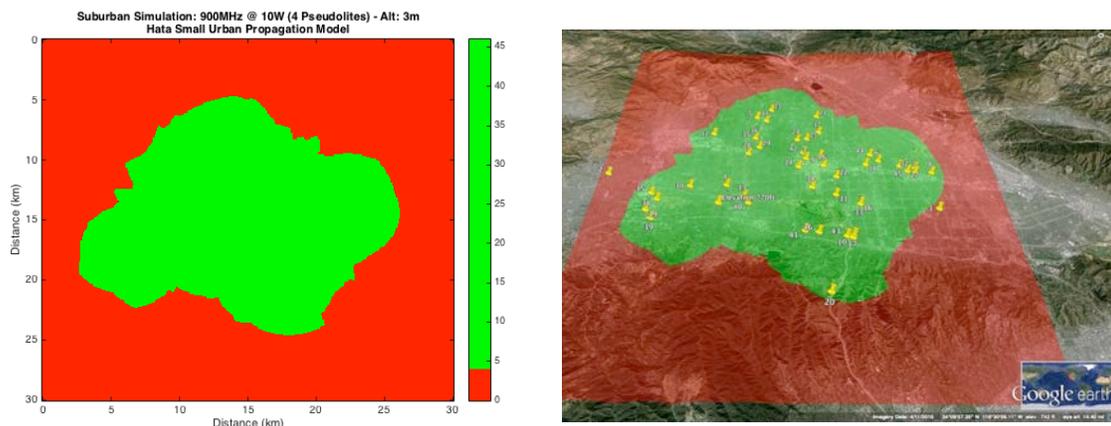
As depicted in Figure 29 receivers with line of sight to a pseudolite transmitter have a better chance of receiving and processing the signal. Satellites have the ability to avoid many line of sight concerns and it is one reason space based positioning systems are preferred to ground based systems. Current GNSS systems have nearly a continuous line of sight with most points on earth due to the fact they are located in medium earth orbit around the earth. Pseudolites coverage increases as a function of receiver altitude due to the fact line of sight with the receiver increases. Figure 32 is an example of how coverage increases as a function of altitude. The top portion of the figure shows coverage of a receiver at an altitude at 3 meters above the ground. The bottom section of Figure 32 shows the coverage of a receiver at an altitude of 10,000 meters above the ground. The

model shows that coverage increases from an approximate radius of 30km<sup>2</sup> to nearly 60km<sup>2</sup> when the altitude is increased by ~10,000 meters.



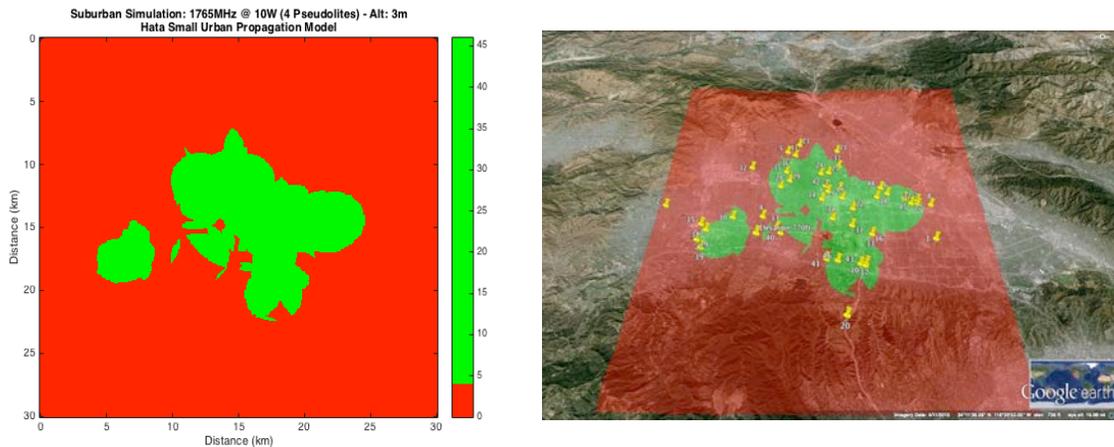
**Figure 32. Suburban Simulation: 900MHz @ 10W (4 Pseudolites), Receiver Height: 3m and 10000m**

The frequency at which pseudolite transmits greatly impacts the model. Figure 33 and Figure 34 utilize the same input variables as the 700MHz simulations above, but alter the frequency to 900MHz and 1765MHz respectively.



**Figure 33. Suburban Simulation: 900MHz @ 10W (4 Pseudolites), Receiver Height: 3m**

Although it is a basic premise that coverage decreases as frequency increases, it is interesting to note that at 1765MHz the model provides significantly less coverage (versus 700 and 900MHz simulations) based on the 46 tower suburban simulation. This could easily be rectified in an operational scenario by deploying additional towers near regions where a receiver would not be able to track four or more pseudolites.



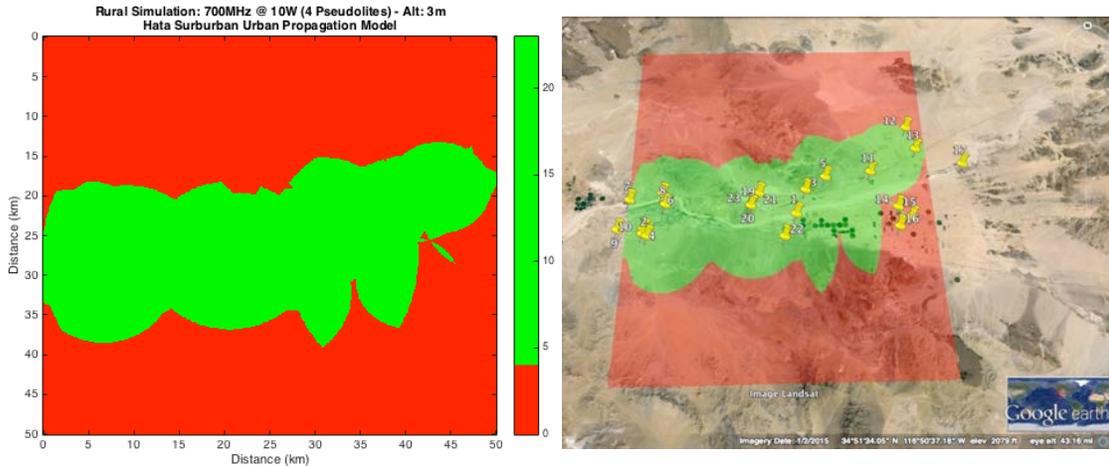
**Figure 34. Suburban Simulation: 1765MHz @10W (4 Pseudolites), Receiver Height: 3m**

### **Rural Pseudolite Network**

Next the model was applied to a rural population area along a major freeway. This model centers on Barstow, CA and the I-15 freeway that connects Los Angeles, CA and Las Vegas, NV. Utilizing currently available tower data, it was determined that 20 towers currently exist along 50 km of the route. Attachment B, Table 6 contains the tower location and elevation data used for the rural model.

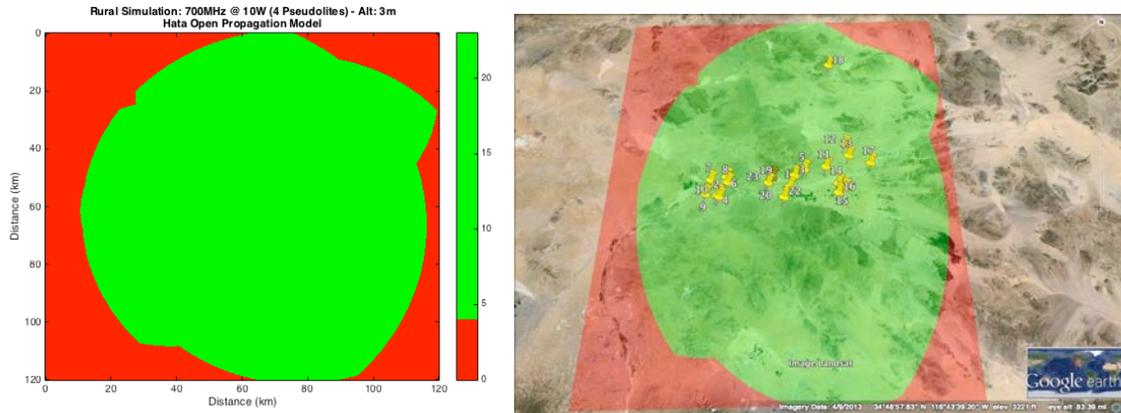
The first rural simulation uses pseudolites transmitting 10 watts of power at 700 MHz, and assumes the receivers are at 3 meters altitude. Similar to the suburban pseudolite network, for the rural network the receiver must receive a signal power of -100

dBm or greater to consider the pseudolite as providing a positioning solution. Using the more conservative Hata Suburban Model, Figure 35 shows that 4 pseudolites provide a positioning solution to a receiver along the highway.



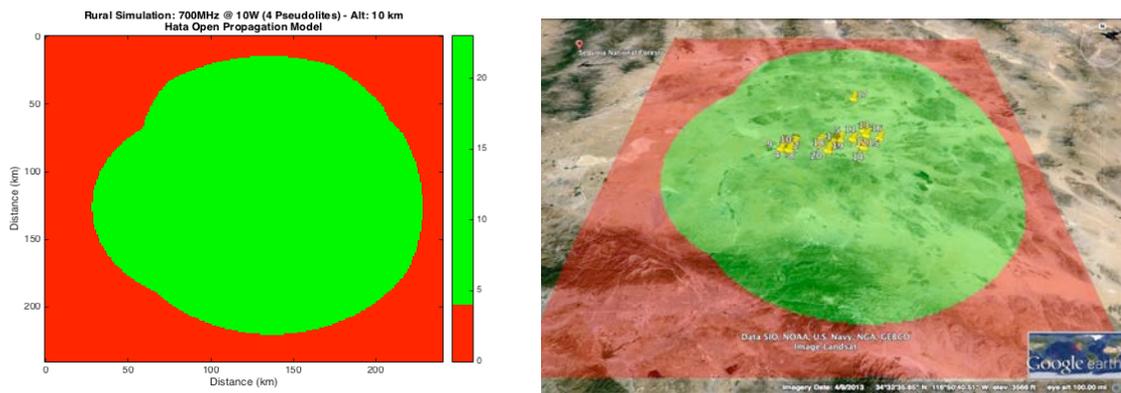
**Figure 35. Rural Simulation: 700MHz @10W (4 Pseudolites), Receiver Height: 3m – Hata Suburban Model**

Using the same inputs as above and the less conservative hata-open model, Figure 36 shows that the area of coverage increases significantly. Along the freeway the coverage increases from 50km to over 100km using the hata-open model. In addition Figure 36 shows that coverage can be anticipated to the north and south, where as Figure 35 predicts coverage limited to the general vicinity of the transmitters.



**Figure 36. Rural Simulation: 700MHz @ 10W (4 Pseudolites), Receiver Height: 3m – Hata Open Model**

Similar to the suburban model, as altitude increases the coverage area increases as well. Figure 37 uses an altitude of 10km to simulate a plane flying at cruising altitude. Coverage increases from by nearly double when comparing a receiver at 3 meters to a receiver at 10km. This increase in coverage is similar to what is seen in the suburban model (Figure 32).



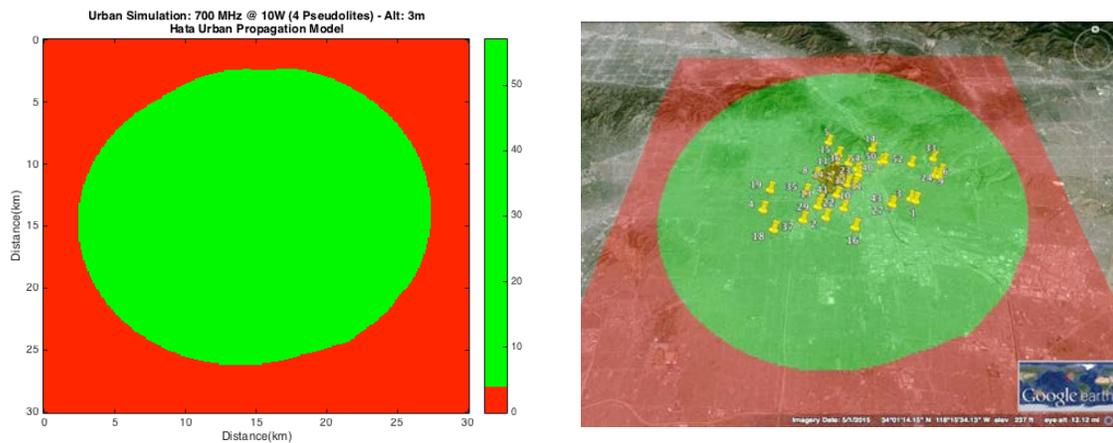
**Figure 37. SRural Simulation: 700MHz @ 10W (4 Pseudolites), Receiver Height: 10km – Hata Open Model**

### Dense Urban Network

Finally, the model was applied to an urban population area. This model centers on Los Angeles, CA. Utilizing currently available antenna data, it was determined that

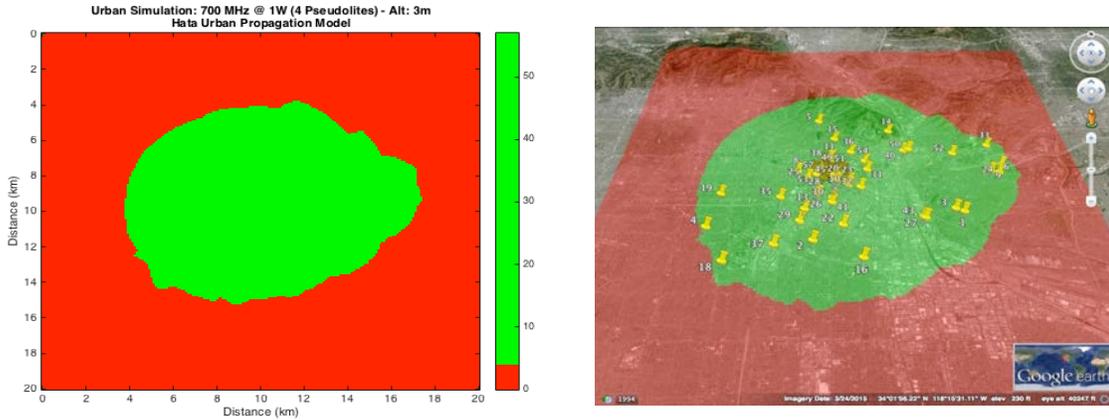
57 towers currently exist in the 15 km x 15 km city area. Attachment B, Table 7 contains the tower location and elevation data used for the urban model.

The simulation results in Figure 38 uses pseudolites transmitting at 10 watts of power at 700 MHz, and assumes the receivers are at 3 meters altitude. As with all the models in this chapter the urban model assumes the receiver must receive a signal power of -100 dBm or greater. Using the Hata Urban propagation calculations Figure 38 shows that the receivers in and around the simulation area would be able to track 4 or more pseudolites and therefore be able to determine position.



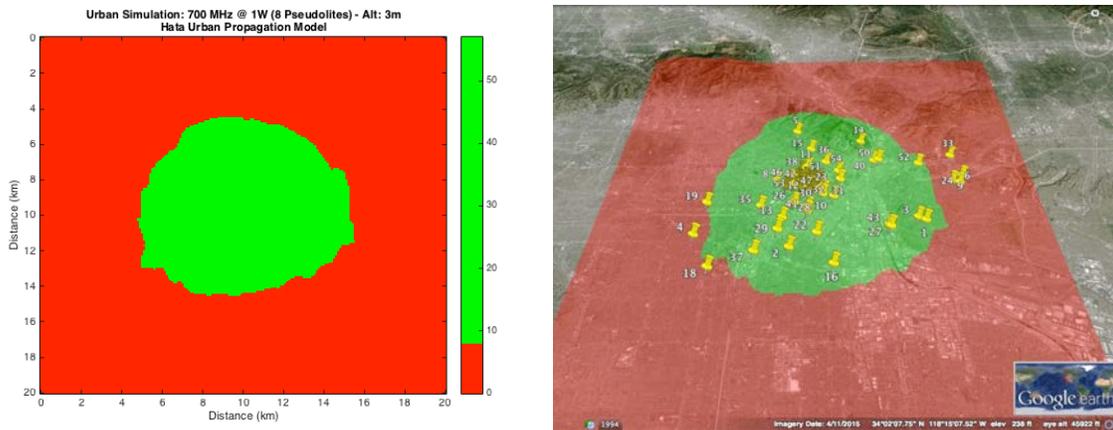
**Figure 38. Urban Simulation: 700MHz @10W (4 Pseudolites), Receiver Height: 3m**

One concern with the simulation generated in Figure 38 is that in a city center 10 watts of power may cause self-interference due to the close proximity of the transmitters. To account for this, the simulation in Figure 39 reduces the power from 10W to 1W to simulate a decrease in transmitter power. As can be seen from Figure 39 the reduction in power still allows a receiver to track 4 or more pseudolites within the simulation area.



**Figure 39. Urban Simulation: 700MHz @1W (4 Pseudolites), Receiver Height: 3m**

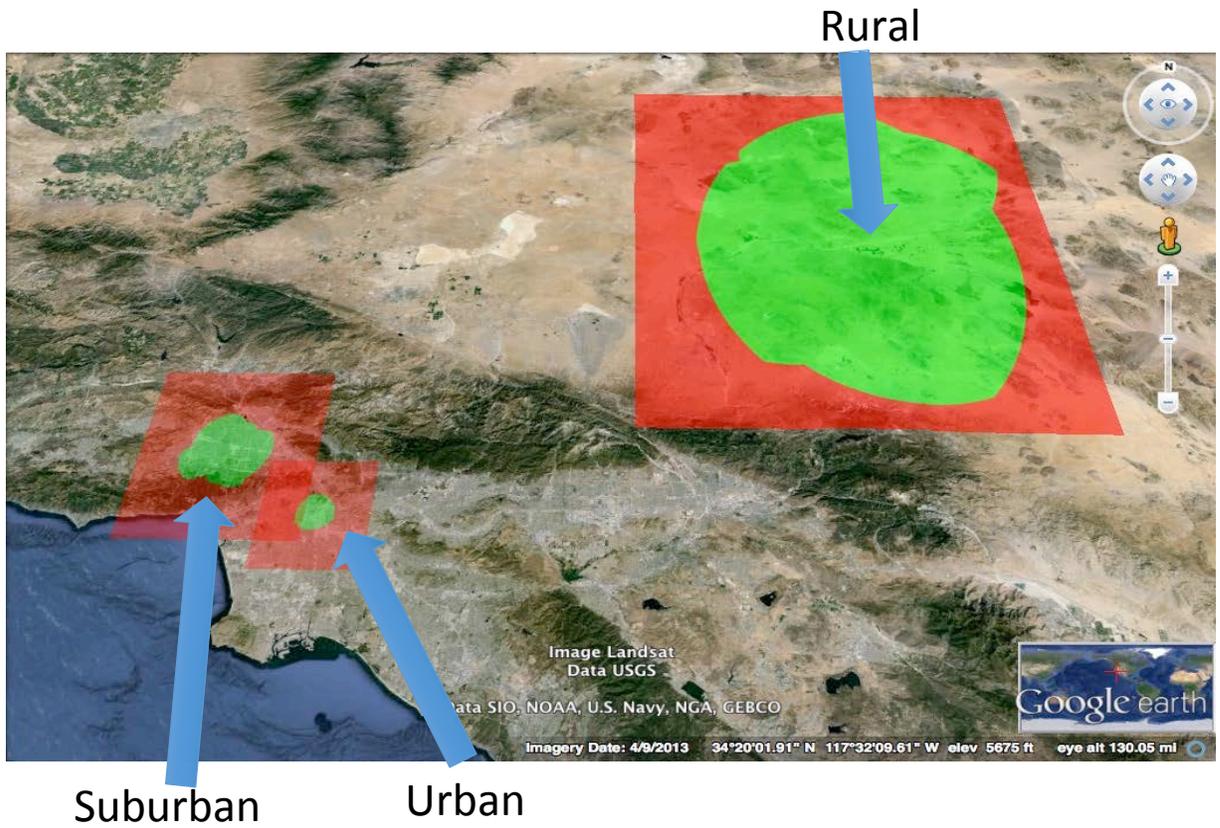
As discussed in Chapter II having geometrically separated pseudolites helps to increase the positioning precision of the receiver. Within the urban environment having additional pseudolites may help improve accuracy since transmitters are extremely close. To simulate this case Figure 40 increases the number of pseudolites a receiver is required to track from four to eight. This increase allows for better position accuracy in the densely populated region. Figure 40 shows that doubling the number of pseudolites required to track only slightly decreases the coverage area for the urban setting.



**Figure 40. Urban Simulation: 700MHz @10W (8 Pseudolites), Receiver Height: 3m**

## **Aggregate Network**

Due to limitations in available tower location data a full aggregate model of a region could not be generated based on the current United States infrastructure. Despite this limitation enough data was gathered to model three representative areas in Southern California. Figure 41 shows the three simulated areas on a map. The figure shows that the rural simulation, which contained the least amount of towers, had the greatest coverage area. Conversely the urban simulation, which had the greatest amount of towers, had the least coverage area. The main factor contributing to this effect is the propagation models that were applied to the various models. In an urban environment attenuation due to large buildings creates a situation where a wave will not be able to propagate as easily. In a rural environment RF waves more closely mimic that of free space propagation, decreasing in power following a simple inverse squared relationship.



**Figure 41. Aggregate Pseudolite Model (Southern California)**

## VI. Conclusions and Recommendations

### Conclusions of Research

This research provides a concept for deploying a nationwide pseudolite alternative to GPS. Using currently available infrastructure data on cellular towers it was determined that utilizing this infrastructure could be a feasible method of deploying this network. In addition, the MatLab models generated and available in Appendix A provide a way to develop, test and predict coverage of a pseudolite network.

### Investigative Questions Answered

The following section answers the investigative questions presented in Chapter I of this this.

- **What is a proposed architecture for a pseudolite solution that would provide CONUS PNT coverage?**

The proposed architecture for a pseudolite solution is discussed in-depth in Chapter IV. One characteristic proposed that differs vastly from other proposed pseudolite systems is to utilize a Geosynchronous Orbiting (GEO) satellite to provide continuous time synchronization.

- **What are the ideal frequency or frequencies for deployment of a pseudolite network, based on spectrum that could realistically be allocated in the future?**

Three candidate frequencies were identified for deployment of the pseudolite network in Chapter II. Based on the simulations frequencies in the 700-900MHz range perform well for a ground based solution to PNT. As the frequencies increase coverage decreases. Due to the fact no spectrum is currently allocated for this

specific solution set, it is recommended further studies be conducted with respect to a viable frequency.

- **What are ranges for transmit and received power to make a pseudolite network viable?**

The simulations all show that EIRP levels between 1W and 10W provide adequate coverage. This assumes that a receiver needs to receive a -100 dBm signal and have four or more pseudolites in view to provide a positioning solution.

Depending on the final receiver designs it is likely a receiver could receive much lower signal powers. Currently GPS specifications guarantee only -158.5 dBm of power. If pseudolite receivers could track a signal 3 to 6 dB less than -100 dBm (-103 to -106 dBm respectively) it would further reduce the number of pseudolite towers required.

- **How will a pseudolite deployment differ based on different geographical environments (e.g. mountainous, canyon, rural, urban, suburban, etc.)?**

Chapter V discusses how a pseudolite deployment differs based on geographical environments. In general urban areas will require more pseudolites to ensure sufficient coverage and precision. Rural Areas will require less pseudolites, but may run into issues with currently available infrastructure to support a pseudolite deployment. In rural situations the likelihood of GPS jamming is likely reduced, therefore decreasing the need and reliance on pseudolites.

- **Do certain propagation models apply more locally to specific locations? If so which models should be applied?**

Overall the freespace propagation model was determined not to be appropriate for modeling the coverage provided by the pseudolites. The freespace model assumes

waves radiate outward without attenuation or interference. Due to this fact the model returned “all-green” for every simulation that was run. “All green” refers to the fact the freespace model always showed that four or more pseudolites were in-view for a given simulation. The Hata Models on the other hand provided reasonable results based on the population areas being modeled

- **What is the deployment for different geographical development environments?**

Figure 41 presents the models capability to aggregate pseudolite networks coverage. The model created for simulating pseudolite coverage can easily be applied to thousands of towers at various power levels to predict coverage.

- **What are options for time synchronization between pseudolites?**

As discussed in Section II, there are multiple options to provide time synchronization between pseudolites. The chip-scale clock option will be the best option in the long term but may be a few years away before being fully implemented because the technology is rather new and more research is needed. Therefore, the immediate option of using the common-view technique can be used early on and then a transition to the smaller chip technology later is preferred.

## **Recommendations for Future Research**

### *Model Improvements*

One key area for future research would be to refine the model created in this research. Below is a list of improvements that are recommended:

- 1) Add in elevation data for all locations in the “location matrix”

- 2) Determine if a tower has line of site to a receiver based on receiver height, tower height and location elevation
- 3) Automatically provide recommend towers to remove based on “over coverage” (where “over coverage” is determined by providing greater than the number of pseudolites required for a receiver to track in a given region)
- 4) Provide a predicted position accuracy based on geographic separation and signal power received

### *Physical Testing of Model*

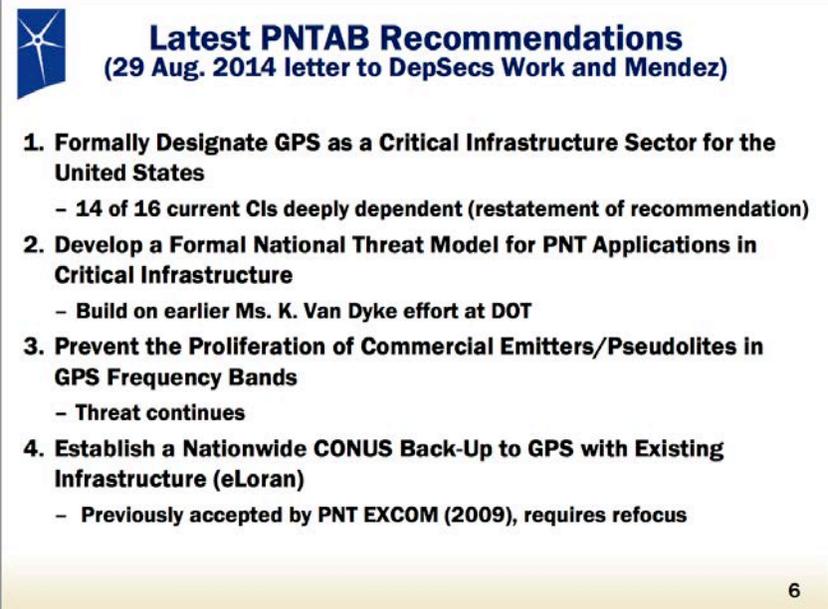
One limitation of this research was the inability to actually test the model against fully representative test data. Fortunately the model was compared to data provided during a 2011 pseudolite test. It is recommend that this model be tested against an actual set of pseudolites and further refined based on the test results.

### **Summary**

As more and more critical infrastructure in the U.S. moves to rely and depend on GPS there is an important need to develop a suitable back-up system to GPS. During a presentation on 11 Jun 2015 to the National Executive Committee for Positioning, Navigation and Timing this requirement was highlighted. The committee sought to formally designate GPS as a critical infrastructure sector for the United States; develop formal threat models for PNT applications; and to prevent the proliferation of commercial emitters/pseudolites in GPS frequency bands.

The National Executive Committee for PNT proposed to “Establish a Nationwide CONUS Back-Up to GPS with Existing Infrastructure. (See Figure 42).” While the solution discussed at the committee was to utilize eLoran, this thesis proposes a more robust approach based on pseudolites in separate frequency bands from GPS. A properly

implemented nationwide pseudolite infrastructure could one day allow assured freedom of navigation for autonomous vehicles, unmanned aircraft and provide a backup to GPS for critical national infrastructure.



**Latest PNTAB Recommendations**  
(29 Aug. 2014 letter to DepSecs Work and Mendez)

- 1. Formally Designate GPS as a Critical Infrastructure Sector for the United States**
  - 14 of 16 current CIs deeply dependent (restatement of recommendation)
- 2. Develop a Formal National Threat Model for PNT Applications in Critical Infrastructure**
  - Build on earlier Ms. K. Van Dyke effort at DOT
- 3. Prevent the Proliferation of Commercial Emitters/Pseudolites in GPS Frequency Bands**
  - Threat continues
- 4. Establish a Nationwide CONUS Back-Up to GPS with Existing Infrastructure (eLoran)**
  - Previously accepted by PNT EXCOM (2009), requires refocus

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Figure 42. National PNT Chart

## Appendix A: Matlab Modeling Script

```
clear all;

%Imports Tower Locations (Reference#, Latitude, Longitude, Antenna
Height)
%Update this based on the Tower Matrix .mat file name
load('SuburbanEncinoFinal.mat');
TowerMatrix=SuburbanEncinoFinal;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Radius of Earth(km)
R=6371;

%Sets up box for simulation (xx (km) X xx (km)
simsizeprompt = 'Input Simulation Size(km): ';
sim_size = input(simsizeprompt); % grid interval in km

%Set up simulation resolution in (km)
resolutionprompt = 'Input Simulation Resolution (km): ';
resolution=input(resolutionprompt);

%Set Number of transmitters in view required
transmitter_inview_prompt = 'Input Towers Required Inview of
Location(#): ';
tower_inview_min=input(transmitter_inview_prompt);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Generate Lat/Longs
%Lat Matrix
Lat_Mat_deg=(TowerMatrix(:,2));
Lat_Mat=deg2rad(TowerMatrix(:,2));
%Long Matrix
Long_Mat_deg=(TowerMatrix(:,3));
Long_Mat=deg2rad(TowerMatrix(:,3));
%Antenna Matrix
Antenna_Mat=(TowerMatrix(:,4));

%Determine simulation center
latcenter = mean(Lat_Mat_deg);
longcenter = mean(Long_Mat_deg);
latcenter_rad=deg2rad(latcenter);
longcenter_rad=deg2rad(longcenter);
simCenter = [latcenter longcenter]; % [lat lon]

%Determine delta Lat/Longs
delta_lat_mat=latcenter_rad-Lat_Mat;
delta_long_mat=longcenter_rad-Long_Mat;

%Set Receiver Height
receiverheightprompt= 'Input Receiver Altitude (km):';
```

```

receiver_height=input(receiverheightprompt);

%Sets box for Simulation
N=radtodeg(latcenter_rad+km2rad(sim_size/2)); %North
S=radtodeg(latcenter_rad-km2rad(sim_size/2)); %South
E=radtodeg(longcenter_rad+km2rad(sim_size/2)); %East
W=radtodeg(longcenter_rad-km2rad(sim_size/2)); %West

%Set Transmitter Power (dBm)
EIRP_prompt = 'Transmitter Power (W): ';
EIRP = input(EIRP_prompt);
EIRP_dBm = 10*(log10(1000*EIRP));

%Set Frequency for simulation
freqprompt = 'Simulation Frequency (MHz): ';
frequency = input(freqprompt);

%Set Minimum Recieved power for receiver (dBm)
minrecpower = 'Minimum Receiver Power (dBm): ';
min_rec_power = input(minrecpower);

%%%%%%%%Set Simulation Zeros Matrix%%%%%%%%
sim_size_resolution=sim_size*(1/resolution); %sets x and y matrix
dimension
zero_matrix=zeros(sim_size_resolution+1,sim_size_resolution+1); %sets
up matrix of zeros at the simulation size +1
center_sim=[(sim_size_resolution/2)+1, ((sim_size_resolution/2)+1)];

%%%%%%%%Determine Number of Towers%%%%%%%%
Tower_RefMatrix=TowerMatrix(:,1);
iteration_count=Tower_RefMatrix(end); %Picks out the last number in
matrix

%%%%%%%%Determine Distance from Center for Tower Locations%%%%%%%%
a=(sin(delta_lat_mat/2)).^2 +
[((cos(Lat_Mat)).*(cos(latcenter_rad))).*(sin(delta_long_mat/2).^2)];
c=2*atan2(sqrt(a),sqrt(1-a));
distance_vector=R*c;
theta=atan2(sin(delta_long_mat).*cos(Lat_Mat),(cos(latcenter_rad)*sin(L
at_Mat)-(sin(latcenter_rad)*(cos(Lat_Mat).*cos(delta_long_mat))));
theta_degrees=radtodeg(theta);

%%%%%%%%Generate the X and Y distances from center of
simulation%%%%%%%%
x=(distance_vector.*(cos(theta-3.14)))/resolution;
y=(distance_vector.*(sin(theta-3.14)))/resolution;

x_position_mat=(center_sim(1,1)+x);
y_position_mat=(center_sim(1,2)+y);

position_mat=[x_position_mat,y_position_mat];
position_mat_int=abs(round(position_mat));

%%%%%%%%Generates Custom Colormap%%%%%%%%

```

```

total_towers=iteration_count;
k=1;
colormatrix = zeros(total_towers,3);
while k<=tower_inview_min
    colormatrix(k,1)=1;
    k=k+1;
end
k=tower_inview_min+1;
while k<=total_towers
    colormatrix(k,2)=1;
    k=k+1;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
k=iteration_count;
i=1;
while i<=k
    x=position_mat_int(i,1);
    y=position_mat_int(i,2);
    zero_matrix=zeros(sim_size_resolution+1,sim_size_resolution+1);
    zero_matrix(x,y)=1;
    zero=bwdist(zero_matrix);
    zero_1=zero*resolution;
    M{i}=zero_1;
    i=i+1;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Freespace Propagation
k=iteration_count;
i=1;
while i<=k
    FSP_Matrix{i}=EIRP_dBm-
    (20*log10(M{1,i})+20*log10(frequency)+32.45);
    i=i+1;
end
FSP_Matrix_Power{:,:}=FSP_Matrix{:,:};

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Set C_H value based on Frequency
if frequency < 200
    C_H = 8.29*((log10(1.54*receiver_height)).^2)-1.1;
elseif( frequency > 200 ) && (frequency <=2500)
    C_H = 3.2*((log10(11.75*receiver_height)).^2)-4.97;
else
    % if frequency is greater then 2500MHz
    fprintf('frequency out of range');
end

k=iteration_count;
i=1;
while i<=k

```

```

        L_Urban{i}=EIRP_dBm-[(69.55)+(26.16*(log10(frequency)))-
(13.82*log10(Antenna_Mat(i,1)))-(C_H)+[[44.9-
(6.55*log10(Antenna_Mat(i,1)))]*log10(M{1,i})]];
        i=i+1;
    end
    L_Urban_Power{:,:}=L_Urban{:,:};

    %%%%%%%%%Hata Model Propagation Small/Medium Urban%%%%%%%%

    C_H_sm=0.8+((1.1*log10(frequency)-0.7)*receiver_height)-
(1.56*log10(frequency));

    k=iteration_count;
    i=1;
    while i<=k
        L_Urbansmall{i}=EIRP_dBm-[(69.55)+(26.16*(log10(frequency)))-
(13.82*log10(Antenna_Mat(i,1)))-(C_H)+[[44.9-
(6.55*log10(Antenna_Mat(i,1)))]*log10(M{1,i})]];
        i=i+1;
    end
    L_Urban_small_Power{:,:}=L_Urbansmall{:,:};

    %%%%%%%%%Hata Model Propagation SubUrban%%%%%%%%

    k=iteration_count;
    i=1;
    while i<=k

    L_SubUrban{i}=L_Urbansmall{i}+[(5.4)+(2*((log10(frequency/28)^2)))]};
        i=i+1;
    end
    L_SubUrban_Power{:,:}=L_SubUrban{:,:};

    %%%%%%%%%Hata Model Propagation Open Model%%%%%%%%

    k=iteration_count;
    i=1;
    while i<=k
        L_Open{i}=L_Urbansmall{i}+[(4.78*(log10(frequency)^2))-
(18.33*(log10(frequency)))+40.94];
        i=i+1;
    end
    L_Open_Power{:,:}=L_Open{:,:};

    %%%%%%%%% Create Single Transmitter Propagation Plot For Open%%%%%%%%
    L_Open_Power{1,1}(L_Open{1,9} >= min_rec_power) = 1;
    L_Open_Power{1,1}(L_Open{1,9} < min_rec_power) = 0;
    L_Open_Power=L_Open_Power{1,1};

    %%%%%%%%%Generate Binary Power Matrices based on minimum receive
power%%%%%%%%

    k=iteration_count;
    i=1;
    while i<=k

```

```

FSP_Matrix{1,i}(FSP_Matrix{1,i} >= min_rec_power) = 1;
FSP_Matrix{1,i}(FSP_Matrix{1,i} < min_rec_power) = 0;
L_Urban{1,i}(L_Urban{1,i} >= min_rec_power) = 1;
L_Urban{1,i}(L_Urban{1,i} < min_rec_power) = 0;
L_SubUrban{1,i}(L_SubUrban{1,i} >= min_rec_power) = 1;
L_SubUrban{1,i}(L_SubUrban{1,i} < min_rec_power) = 0;
L_Urbansmall{1,i}(L_Urbansmall{1,i} >= min_rec_power) = 1;
L_Urbansmall{1,i}(L_Urbansmall{1,i} < min_rec_power) = 0;
L_Open{1,i}(L_Open{1,i} >= min_rec_power) = 1;
L_Open{1,i}(L_Open{1,i} < min_rec_power) = 0;
i=i+1;
end

%%%%%%%%%Compare Power Matrices to Generate Aggregate Matrix%%%%%%%%%

k=iteration_count;
Total_Count_FSP=zero_matrix;
Total_Count_HataUrban=zero_matrix;
Total_Count_HataUrbansmall=zero_matrix;
Total_Count_HataSuburban=zero_matrix;
Total_Count_HataOpen=zero_matrix;
i=1;
while i<=k
    Total_Count_FSP=FSP_Matrix{1,i}+Total_Count_FSP;
    Total_Count_HataUrban=L_Urban{1,i}+Total_Count_HataUrban;

Total_Count_HataUrbansmall=L_Urbansmall{1,i}+Total_Count_HataUrbansmall
;
    Total_Count_HataSuburban=L_SubUrban{1,i}+Total_Count_HataSuburban;
    Total_Count_HataOpen=L_Open{1,i}+Total_Count_HataOpen;
    i=i+1;

    Total_Count_FSP(1,1)=iteration_count;
    Total_Count_HataUrban(1,1)=iteration_count;
    Total_Count_HataUrbansmall(1,1)=iteration_count;
    Total_Count_HataOpen(1,1)=iteration_count;
    Total_Count_HataSuburban(1,1)=iteration_count;
end

%%%%%%%%%Make Images out of Figures%%%%%%%%%

%%%%%%%%%FSP IMAGE%%%%%%%%%

data = Total_Count_FSP;

x = linspace(0,50,size(data,2));
y = linspace(0,50,size(data,1));
cLimLow = 0; %min(min(data));
cLimHigh = iteration_count; %max(max(data));
altitude = 0;
alphaMatrix = ones(size(data))*0.75;

kmlFileName = 'FSP_Model.kml';

```

```

% make the custom colormap
%cmap = [0,0,1;0,1,0;1,0,0];
cmap = (colormatrix); %// apply colormap
%cmap = 'winter';
caxis([0 iteration_count]);
figure
imagesc(x,y,data,[cLimLow,cLimHigh]);
colormap(cmap)
colorbar

output = ge_imagesc(x,y,data,...
    'imgURL','FSP_Tower.png',...
    'cLimLow',cLimLow,...
    'cLimHigh',cLimHigh,...
    'altitude',altitude,...
    'altitudeMode','absolute',...
    'colorMap',cmap,...
    'alphaMatrix',alphaMatrix);

output2 = ge_colorbar(x(end),y(1),data,...
    'numClasses',20,...
    'cLimLow',cLimLow,...
    'cLimHigh',cLimHigh,...
    'cBarFormatStr','%+07.4f',...
    'colorMap',cmap);

ge_output(kmlFileName,[output2 output],'name',kmlFileName);

%%%%%% Put Simulation onto Google Earth%%%%%%%%

url = ['FSP_Tower.png'];

kmlStr = ge_groundoverlay(N,E,S,W,...
    'imgURL',url,...
    'viewBoundScale',1e3,...
    'polyAlpha','7C');

ge_output('FSP_Tower_Model.kml',kmlStr)

%%%%%HATA URBAN MODEL IMAGE%%%%%%%%%

data = Total_Count_HataUrban;

x = linspace(0,sim_size,size(data,2));
y = linspace(0,sim_size,size(data,1));
cLimLow = 0; %min(min(data));
cLimHigh = iteration_count; %max(max(data));
altitude = 0;
alphaMatrix = ones(size(data))*0.75;

kmlFileName = 'Hata_Model.kml';

% make the custom colormap

```

```

%cmap = [0,0,1;0,1,0;1,0,0];
cmap = (colormap); %// apply colormap
%cmap = 'winter';
caxis([0 iteration_count]);
figure
imagesc(x,y,data,[cLimLow,cLimHigh]);
colormap(cmap)
colorbar

output = ge_imagesc(x,y,data,...
    'imgURL','Hata_Tower.png',...
    'cLimLow',cLimLow,...
    'cLimHigh',cLimHigh,...
    'altitude',altitude,...
    'altitudeMode','absolute',...
    'colorMap',cmap,...
    'alphaMatrix',alphaMatrix);

output2 = ge_colorbar(x(end),y(1),data,...
    'numClasses',20,...
    'cLimLow',cLimLow,...
    'cLimHigh',cLimHigh,...
    'cBarFormatStr','%+07.4f',...
    'colorMap',cmap);

ge_output(kmlFileName,[output2 output],'name',kmlFileName);

%%%%%% Put Simulation onto Google Earth%%%%%%%%

url = ['Hata_Tower.png'];

kmlStr = ge_groundoverlay(N,E,S,W,...
    'imgURL',url,...
    'viewBoundScale',1e3,...
    'polyAlpha','7C');

ge_output('Hata_Tower_Model.kml',kmlStr)

%%%%%HATA URBAN SMALL MODEL IMAGE%%%%%%%%

data = Total_Count_HataUrbansmall;

x = linspace(0,sim_size,size(data,2));
y = linspace(0,sim_size,size(data,1));
cLimLow = 0; %min(min(data));
cLimHigh = iteration_count; %max(max(data));
altitude = 0;
alphaMatrix = ones(size(data))*0.75;

kmlFileName = 'Hata_Model_small_urban.kml';

% make the custom colormap
%cmap = [0,0,1;0,1,0;1,0,0];

```

```

cmap = (colormatrix); %// apply colormap
%cmap = 'winter';
caxis([0 iteration_count]);
figure
imagesc(x,y,data,[cLimLow,cLimHigh]);
colormap(cmap)
colorbar

output = ge_imagesc(x,y,data,...
    'imgURL','Hata_Tower_small_urban.png',...
    'cLimLow',cLimLow,...
    'cLimHigh',cLimHigh,...
    'altitude',altitude,...
    'altitudeMode','absolute',...
    'colorMap',cmap,...
    'alphaMatrix',alphaMatrix);

output2 = ge_colorbar(x(end),y(1),data,...
    'numClasses',20,...
    'cLimLow',cLimLow,...
    'cLimHigh',cLimHigh,...
    'cBarFormatStr','%+07.4f',...
    'colorMap',cmap);

ge_output(kmlFileName,[output2 output],'name',kmlFileName);

%%%%%% Put Simulation onto Google Earth%%%%%%%%

url = ['Hata_small_urban_Tower.png'];

kmlStr = ge_groundoverlay(N,E,S,W,...
    'imgURL',url,...
    'viewBoundScale',1e3,...
    'polyAlpha','7C');

ge_output('Hata_small_urban_Tower_Model.kml',kmlStr)

%%%%%HATA SUBURBAN MODEL IMAGE%%%%%%%%

data = Total_Count_HataSuburban;

x = linspace(0,sim_size,size(data,2));
y = linspace(0,sim_size,size(data,1));
cLimLow = 0; %min(min(data));
cLimHigh = iteration_count; %max(max(data));
altitude = 0;
alphaMatrix = ones(size(data))*0.75;

kmlFileName = 'Hata_Model_suburban.kml';

% make the custom colormap
%cmap = [0,0,1;0,1,0;1,0,0];
cmap = (colormatrix); %// apply colormap

```

```

%cmap = 'winter';
caxis([0 iteration_count]);
figure
imagesc(x,y,data,[cLimLow,cLimHigh]);
colormap(cmap)
colorbar

output = ge_imagesc(x,y,data,...
    'imgURL','Hata_Tower_suburban.png',...
    'cLimLow',cLimLow,...
    'cLimHigh',cLimHigh,...
    'altitude',altitude,...
    'altitudeMode','absolute',...
    'colorMap',cmap,...
    'alphaMatrix',alphaMatrix);

output2 = ge_colorbar(x(end),y(1),data,...
    'numClasses',20,...
    'cLimLow',cLimLow,...
    'cLimHigh',cLimHigh,...
    'cBarFormatStr','%+07.4f',...
    'colorMap',cmap);

ge_output(kmlFileName,[output2 output],'name',kmlFileName);

%%%%%%%% Put Simulation onto Google Earth%%%%%%%%

url = ['Hata_Tower_suburban.png'];

kmlStr = ge_groundoverlay(N,E,S,W,...
    'imgURL',url,...
    'viewBoundScale',1e3,...
    'polyAlpha','7C');

ge_output('Hata_suburban_Tower_Model.kml',kmlStr)

%%%%%%%%HATA OPEN MODEL IMAGE%%%%%%%%

data = Total_Count_HataOpen;

x = linspace(0,sim_size,size(data,2));
y = linspace(0,sim_size,size(data,1));
cLimLow = 0; %min(min(data));
cLimHigh = iteration_count; %max(max(data));
altitude = 0;
alphaMatrix = ones(size(data))*0.75;

%kmlFileName = 'Hata_OPEN_suburban.kml';

% make the custom colormap
%cmap = [0,0,1;0,1,0;1,0,0];
cmap = (colormatrix); %// apply colormap
%cmap = 'winter';
caxis([0 iteration_count]);

```

```

figure
imagesc(x,y,data,[cLimLow,cLimHigh]);
colormap(cmap)
colorbar

output = ge_imagesc(x,y,data,...
    'imgURL','Hata_Tower_open.png',...
    'cLimLow',cLimLow,...
    'cLimHigh',cLimHigh,...
    'altitude',altitude,...
    'altitudeMode','absolute',...
    'colorMap',cmap,...
    'alphaMatrix',alphaMatrix);

output2 = ge_colorbar(x(end),y(1),data,...
    'numClasses',20,...
    'cLimLow',cLimLow,...
    'cLimHigh',cLimHigh,...
    'cBarFormatStr','%+07.4f',...
    'colorMap',cmap);

ge_output(kmlFileName,[output2 output],'name',kmlFileName);

%%%%%%%% Put Simulation onto Google Earth%%%%%%%%

url = ['Hata_Tower_open.png'];

kmlStr = ge_groundoverlay(N,E,S,W,...
    'imgURL',url,...
    'viewBoundScale',1e3,...
    'polyAlpha','7C');

ge_output('Hata_open_Tower_Model.kml',kmlStr)

```

## Appendix B: Tower Location Data

ID Number	Latitude	Longitude	Tower Height
1	34.1747222	-118.41028	305.133
2	34.2032222	-118.62903	263.6
3	34.2166667	-118.49444	243.8
4	34.1933333	-118.54778	180.455
5	34.2572222	-118.53083	137.802
6	34.2144167	-118.44431	120.0846
7	34.2041667	-118.42022	105.9763
8	34.2039444	-118.40925	100.0705
9	34.2191389	-118.4845	95.149
10	34.1536111	-118.467	92.4
11	34.2536944	-118.52367	89.8994
12	34.2404444	-118.56167	81.0407
13	34.1841667	-118.53564	78.9
14	34.2091667	-118.49972	76.1192
15	34.1866667	-118.59647	75.6
16	34.1785278	-118.46033	74.8068
17	34.1555556	-118.46644	73.8
18	34.2111111	-118.45342	69.8853
19	34.1731944	-118.59719	67.1
20	34.1186111	-118.48228	65.9481
21	34.2585556	-118.48575	64.9638
22	34.2005556	-118.47417	62.339
23	34.26525	-118.52039	62.0109
24	34.2344444	-118.50056	61.3547
25	34.23525	-118.49369	61.0266
26	34.2103611	-118.48242	61
27	34.2052778	-118.42533	60.7
28	34.2213611	-118.53508	60.6985
29	34.2271667	-118.52758	60.0423
30	34.1925556	-118.57189	59.7142
31	34.1856667	-118.47542	59.058
32	34.20825	-118.42008	58.7299
33	34.1783333	-118.46008	58.4018
34	34.1916944	-118.49092	58.0737
35	34.2361111	-118.53092	57.9
36	34.2361111	-118.53092	57.9
37	34.2418056	-118.48486	57.0894
38	34.1817778	-118.59167	56.7613
39	34.1669444	-118.59258	56.4
40	34.1790556	-118.53236	55.777
41	34.1583333	-118.49617	54.9
42	34.2218889	-118.4965	54.7927
43	34.1547222	-118.47061	53.6
44	34.22	-118.4495	53.3
45	34.2098611	-118.43025	51.8398
46	34.15725	-118.48758	51.8

**Table 5. Suburban Tower Simulation Locations (Encino, CA)**

ID Number	Latitude	Longitude	Tower Height
1	34.8731944	-116.83019	25.9
2	34.8468611	-117.04528	30.5
3	34.9055	-116.81531	32
4	34.8558056	-117.05058	46
5	34.92275	-116.78475	50.9
6	34.9035833	-117.02725	52.1
7	34.8955278	-117.07531	52.7
8	34.8885278	-117.02217	55.1208
9	34.8558056	-117.08861	89.8994
10	34.8497222	-117.05194	180.1269
11	34.9294167	-116.71642	23.2
12	34.9938611	-116.65419	19.8
13	34.9614167	-116.64344	27.4
14	34.8801667	-116.67989	150.926
15	34.86675	-116.66197	129.9276
16	34.9380278	-116.57558	51.8398
17	35.2583333	-116.69778	100.0705
18	34.9019167	-116.88475	30.5
19	34.8434722	-116.84764	59.7
20	34.8858333	-116.89667	63.7

**Table 6. Rural Tower Simulation Locations (Barstow, CA)**

Reference Number	latitude	longitude	Height (m)
1	34.0310833	-118.20969	44.9497
2	34.0196667	-118.26303	46.9183
3	34.0323611	-118.21247	48.2
4	34.0250556	-118.29983	48.2307
5	34.0777778	-118.26144	49.7
6	34.0489722	-118.1925	49.8712
7	34.0453611	-118.25439	50
8	34.05	-118.26925	50.6
9	34.0499167	-118.19533	50.8555
10	34.0433333	-118.25006	50.9
11	34.0572222	-118.25644	51.5
12	34.0472222	-118.25617	53.3
13	34.0322222	-118.26617	53.6
14	34.0716667	-118.23256	54.9
15	34.0669444	-118.255	55.1208
16	34.0131389	-118.24642	56.1051
17	34.0505556	-118.25339	56.7
18	34.0118889	-118.29228	56.7613
19	34.0391944	-118.29694	57.0894
20	34.0458333	-118.25506	57.9
21	34.05	-118.25228	58.8
22	34.0258333	-118.25258	59.7142
23	34.0452778	-118.24978	60
24	34.0525833	-118.19081	60.0423
25	34.0469444	-118.26533	61.3
26	34.0391667	-118.26144	63.4
27	34.0286111	-118.22367	64
28	34.0394444	-118.262	65.8
29	34.0271944	-118.26772	67.9167
30	34.0373056	-118.25619	68
31	34.05075	-118.24261	70.1
32	34.04225	-118.24558	73.2
33	34.0634444	-118.19369	73.8225
34	34.0465833	-118.25922	75
35	34.0375	-118.27506	76.2
36	34.0597222	-118.24861	76.8
37	34.0180833	-118.27608	79.3
38	34.0563889	-118.257	84.7
39	34.0547222	-118.2595	85.3
40	34.0608333	-118.22756	91.4
41	34.0352778	-118.25636	94.8
42	34.0500278	-118.25747	109.7
43	34.0288889	-118.22444	110.2416
44	34.05	-118.25922	133.2
45	34.0480556	-118.25533	137.8
46	34.0508333	-118.26339	146.6
47	34.0465278	-118.25064	152.8946
48	34.0491944	-118.25503	190.8
49	34.0513889	-118.25728	223.4
50	34.0616667	-118.22544	229.9981
51	34.0507778	-118.2525	232.951
52	34.0591667	-118.20833	246.075
53	34.0483333	-118.262	250.5
54	34.055	-118.24333	259.199
55	34.0494444	-118.257	271
56	34.0482222	-118.25689	275.2
57	34.0502778	-118.26	332.2

**Table 7. Urban Tower Simulation (Los Angeles, CA)**

## Appendix C: Bibliography

- [1] C. Hagerty, "Evolution of the Global Navigation Satellite System (GNSS)," *Proceedings of the IEEE*, vol. 96, no. 12, pp. 1902 - 1917, 2008.
- [2] Global Positioning Program Office, "Global Positioning System Precise Positioning Service Performance Standard," Air Force, 2007.
- [3] C. Matyszczyk, "CNet," 11 August 2013. [Online]. Available: <http://www.cnet.com/news/truck-driver-has-gps-jammer-accidentally-jams-newark-airport/>.
- [4] L. Thomson, "The Register," 29 July 2013. [Online]. Available: [http://www.theregister.co.uk/2013/07/29/texas\\_students\\_hijack\\_superyacht\\_with\\_gpsspoofing\\_luggage/](http://www.theregister.co.uk/2013/07/29/texas_students_hijack_superyacht_with_gpsspoofing_luggage/).
- [5] J. A. Czabaranek, *PSEUDOLITE ARCHITECTURE AND PERFORMANCE ANALYSIS*, Wright-Patterson Air Force Base, Ohio, 2013.
- [6] Locata Corporation, "Locata Signal Interface Control Document," Griffith Australia, 2014.
- [7] J. Strada and D. Henderson, "Navstar Field Test Results," *Institute of Navigation*, vol. 26, pp. 12-24, 1979.
- [8] J. W. T. T. C. R. Liwen Dai, "Pseudolite Applications in Position and Navigation: Modelling and Geometric Analysis".
- [9] Y. Yang and J. A. Farrell, "Magnetometer and Differential Carrier Phase GPS-Aided INS for Advanced Vehicle Control," *IEEE Transactions on Robotics and Automation*, vol. 19, no. 2, pp. 269-282, 2003.
- [10] Y. Okamura, "Field Strength and its Variability in VHF and UHF Land-Radio Service," *Electrical Communications Lab.*, vol. 16, no. 9, pp. 825-73, 1968.
- [11] T. K. Sarkar, M. C. Wicks, M. Salazar-Palma and R. J. Bonneau, *Smart Antennas*, John Wiley & Sons, Inc., 2003.

- [12] M. Hata, "Empirical Formula for Propagation Loss in Land Mobile Radio Services," *IEEE Trans. Vehicular Technology*, Vols. VT-29, pp. 317-25, 1980.
- [13] V. Abhayawardhana, I. Wassell, D. Crosby, M. Sellars and M. Brown, "Comparison of Empirical Propagation Path Loss Models for Fixed Wireless Access Systems," *IEEE Vehicular Technology Conference*, vol. 1, pp. 73-77, Jun 2005.
- [14] M. A. Lombardi, "Microsecond Accuracy at Multiple Sites: Is It Possible Without GPS?," *IEEE Instrumentation & Measurement Magazine*, vol. 15, no. 5, pp. 14-21, 2012.
- [15] D. D. C. I. Officer, "The DoDAF Architecture Framework Version 2.0," 10 December 2009. [Online]. Available: [http://www.prim.osd.mil/Documents/DoDAF\\_2-0\\_web.pdf](http://www.prim.osd.mil/Documents/DoDAF_2-0_web.pdf). [Accessed June 2015].
- [16] Federal Communications Commission (FCC), "Human Exposure to Radio Frequency Fields," Washington, DC, 2014.
- [17] L. Corporation, "Final Test Report and Demonstration of UHARS System at White Sands Missile Range," Locata Corporation, Australia.
- [18] M. Atamanesh and F. Farzaneh, "Precision enhancement in ETSI-Hata propagation model tuning using experimental data in a dense urban area," *International Journal of Communication Systems*, pp. 101-108, 2009.
- [19] Z. Nadir and M. I. Ahmad, "Characterization of Pathloss Using Okumura-Hata Model and Missing Data Prediction for Oman," *American Institute of Physics*, vol. 5, p. 11, 2010.
- [20] J. Milanovic, S. Rimac-Drlje and I. Majerski, "Radio Wave Propagation Mechanisms and Empirical Models for Fixed Wireless Access Systems," *Technical Gazette*, vol. 17, pp. 43-52, 2010.
- [21] The National Association of Amateur Radio, "The National Association of Amateur Radio," [Online]. Available: <http://www.arrl.org/what-is-ham-radio>. [Accessed 24 February 2015].

- [22] E. D. Kaplan and C. J. Hegarty, *Understanding GPS: Principles and Applications*, Norwood: Artech House, Inc., 2006.

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