IS IT SUITABLE TO APPLY TRADITIONAL PROPAGATION MODELS AND INTERFERENCE MODELING METHODS FOR SPECTRUM POLICY-MAKING ACTIVITIES REGARDING SMALL CELL NETWORK ARCHTIECTURES?

by

GREG QUIJANO LEON

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written by Greg Quijano Leon
has been approved for the Interdisciplinary Telecommunications Program

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Douglas Sicker

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Dale Hatfield

____

Ken Baker

Date_____________

The final copy of this thesis has been examined by the signatories, and we Find that both the content and the form meet acceptable presentation standards Of scholarly work in the above mentioned discipline.

Leon, Greg Quijano (M.S. Telecommunications, Interdisciplinary Telecommunications Program)

Is it suitable to apply traditional propagation models and interference modeling methods for spectrum policy-making activities regarding small cell network architectures?

Thesis directed by Professor Douglas Sicker

The increase in mobile broadband data services has created significant demand for spectrum. Based on a low supply spectrum market, there is major interest in sharing spectrum between incumbent users and mobile broadband services. Radars are a large user of spectrum worldwide, therefore are a potential sharing partner. Mobile broadband service operators are trending toward small cell architectures. Therefore, it is imperative to develop appropriate spectrum sharing policy that supports both incumbent radar protection and spectrum utilization by small cell systems. One vital aspect of developing appropriate sharing policy is accurately modeling the interference potential between services. The thesis examines if it is suitable to apply traditional propagation models and interference modeling methods for spectrum policy-making activities regarding small cell network architectures. The advances in technology that support spectrum sharing should not be bottlenecked by legacy interference modeling techniques when more granular methods are currently available. A specific scenario was selected for detailed analysis which is ship-borne naval radars interacting with small cell systems in the 3550-3650 MHz band. NTIA recommended ship-borne radar exclusion zones were analyzed using modern propagation modeling methods and compared to traditional modeling work completed by the NTIA. Modeling of aggregate interference impacts from small cell systems to ship-borne radars was completed. The new methods showed that ship-borne radar exclusion zones can be significantly reduced in ship-borne radar operation areas. In addition, it was found that there was insufficient information provided by the NTIA in regards to radar equipment specifications to accurately model interference potential. We conclude that the ITM propagation model was insufficient for accurate modeling of small cell systems. Correspondingly, to accurately model small cell systems in a site-specific manner, the use of higher resolution geographic data and a propagation model that can utilize this data is necessary. It was also found that small cell device loading for aggregate interference impact analysis can be accomplished through use of census and city data and can be done in site-specific manner.

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INTRODUCTION AND LITERATURE REVIEW

Chapter 1 provides a framing for the traditional modeling and revised modeling methods. Radar and small cell systems are defined. Interference modeling methods of interference over noise, frequency dependent rejection, required minimum path loss for interference protection and aggregate impact analysis are defined and analyzed. The revised propagation model and interference methods are defined. A review of measurement campaigns at 3.5 GHz is analyzed.

1.1 Introduction

The increase in mobile broadband data services has created significant demand for spectrum. The short supply of spectrum relative to demand is a current policy topic that is of great importance to the United States government and the wireless industry. The discussion is framed by the lack of available spectrum for use by commercial wireless carriers to provide the necessary network capacity to meet the growing data traffic generated by pervasive mobile data devices such as smart phones and tablets. In order to reduce the ill effects of this lack of spectrum such as economic impairment, it is necessary to provide access to additional spectrum to both commercial and unlicensed users [1]. Based on the recommendations defined in the National Broadband Plan, the Obama Administration directed the National Telecommunications and Information Administration (NTIA) to find available Federal spectrum that could be cleared for reallocation or shared with non-Federal users [1]. The NTIA produced a report in 2010 that identified spectrum bands that are available for reallocation or sharing. One of the major bands identified for sharing was the 3550-3650 MHz [2]. The major incumbent user of this band is radar systems of the armed services. Radar is a vital use of spectrum for our country considering its application in homeland defense. However, radar systems are a natural spectrum sharing partner because they tend to operate in very specific areas on a normal basis and when necessary expand their footprint of usage as security threats and emergencies occur.

Based on a low supply spectrum market, there is major interest in sharing spectrum between incumbent radar users and mobile broadband services. Also, in a low spectrum supply market, wireless operators are motivated to use technologies that are more spectrally efficient. One method for improving spectral efficiency is to leverage cell-splitting methods also known as increasing frequency reuse. Mobile broadband service operators are trending toward small cell architectures in order to increase spectral efficiency. Small cells are low powered cellular base stations that are placed outdoors or indoors to provide improved coverage or capacity within a short coverage range of typically one kilometer or less. Small cells are becoming more important to the wireless industry and are projected to gain significant use in the coming years [3]. Therefore, it is imperative to develop appropriate spectrum sharing policy that supports both incumbent radar protection and spectrum utilization by small cell systems. An ideal spectrum policy will support clear and protected spectrum to radar operators within their normal operating areas as well as the ability to have clear and protected spectrum anywhere within the United States when the need arises. Although the purpose of this thesis is not to define such a policy, the research developed herein is aimed at providing a useful approach to shaping portions of this policy definition process.

One vital aspect of developing appropriate spectrum sharing policy is accurately modeling the interference potential between services. The question posed for this thesis is:

Is it suitable to apply traditional propagation models and interference modeling methods for spectrum policy-making activities regarding small cell network architectures?

This encompasses analyzing propagation modeling methods for interference analysis of high powered and interference sensitive radar systems and low powered and interference limited small cell systems. A specific scenario was selected for detailed analysis which is ship-borne naval radars interacting with small cell systems in the 3550-3650 MHz band as defined by the NTIA Fast Track report [2]. NTIA recommended ship-borne radar exclusion zones were analyzed using the revised propagation modeling methods and compared to the traditional modeling work completed by the NTIA [2]. Also, modeling of aggregate interference impacts from small cell systems to ship-borne radars was completed and analyzed. The intent of this research is to demonstrate that modern propagation modeling techniques support an increase in modeling granularity and accuracy therefore supporting more granular and informed policy making.

The thesis is organized as follows:

- Section 1.2 – 1.5 provides a literature review of available research of the topic
- Chapter 2 defines the revised propagation modeling methods and aggregate impact analysis methodology
- Chapter 3 presents the results and comparison of the modeling approaches
- Chapter 4 provides a discussion on the results and presents major findings
- Chapter 5 presents the overall conclusions

1.2 Radar Systems

Radar systems provide a vital function to our armed services and to the country generally. These radiolocation and radionavigation systems assist our military in defending the homeland by monitoring air traffic, tracking targets such as missiles and enabling targeting of their weapon systems on enemy targets [2]. Radar systems consist of high powered transmitters on the scale of megawatts and high gain antennas [2]. The simple description of their operating mode is to transmit a high powered pulse of energy into the environment and then listen for the echo from the target. The received echo signal is typically very low and hence the radar receivers are highly sensitive to noise and interference [4]. There are many types of radar systems implemented today from air traffic control radars that have revolving antennas to tracking radars that have large adaptive antenna arrays [2]. In order to constrain the analysis completed in this research, the radar types selected for modeling are those that are used in or near the 3550-3650 MHz band as defined by the NTIA. Within their Fast Track report, the NTIA identified different types of ship-borne radars, land-based radars and air-borne radars [2].

Specifically, this research focuses on the five classes of ship-borne radars used in the 3550-3650 MHz band. The NTIA did not define the actual radar system name designation but an index system of ship-borne radar types 1-5. Table 1.1 provides the radio description of each radar type.

Radar Type	Transmit Peak Power(dBm)	Average Power(dBm)	Antenna Gain(dBi)	Antenna Height(m)	System Losses(dB)
Ship1	90	60	32	50	2
Ship2	83	75	47	30	2
Ship3	98	80	41.8	30	3.4
Ship4	84	84	38.9	30	2
Ship5	93.3	93.3	43.3	30	2

Table 1.1 Ship-borne Radar RF Definitions [2]

Some of the radars defined by index number were mapped to actual radar models via literature research. Ship-borne 1 is a SPN-43 which is a type of air traffic control radar that operates from 3500-3700 MHz and is quite common on navy ships [5]. Ship-borne 5 is a SPY-1 radar which is a phased-array radar operating from 3100-3500 MHz that is a tracking type radar [6]. Ship-borne 2-4 were not identifiable. The NTIA also provided other information regarding the radars of interest specific to their operating criteria such as minimum received signal level, noise levels and rejection abilities. Table 1.2 provides a summary of this available information.

Radar Type	Receiver Noise Level (dBm)	I/N Criteria(dB)	Interference Threshold (dB)	Frequency Dependent Rejection at 3550 MHz (dB)
Ship1	-108	-6	-114	49
Ship2	-95	-6	-101	53
Ship3	-94	-6	-100	40
Ship4	N/A	-6	N/A	46
Ship5	N/A	-6	N/A	N/A

Table 1.2 Ship-borne Radar Interference Attributes [2]

Table 1.1 and 1.2 define attributes that are of interest for interference modeling of ship-borne radars 1-5. It is noted here that Ship 4 and Ship 5 have missing information in regards to their description. This missing information is a significant problem with being able to accurately model interference potential between radar systems and small cell systems and will be discussed further in the section 4.2. Also, I/N criteria and Off Frequency Rejection are defined in following subsections in this chapter.

In addition to the missing information above, another glaring problem with interference modeling of radar systems is the lack of antenna pattern data that describes how the radar radiates energy into physical space as well how the antenna receives energy from the environment. This lack of antenna radiation pattern information requires the use of generic antenna pattern descriptions that may not be appropriate for the scenario of interest. In order to match the same modeling approaches used by the NTIA, the radar antenna pattern used in this modeling work was based on the ITU-R M.1851 recommendations [2]. ITU-R M.1851 defines the Cosine equation defined in Table 1.3, which was recommended for use by the NTIA.

Pattern type	**Mask equation beyond pattern break point where mask departs from theoretical pattern (dB)**	**Peak pattern break point where mask departs from theoretical pattern (dB)**	**Average pattern break point where mask departs from theoretical pattern (dB)**	**Constant added to the peak pattern to convert it to average mask (dB)**
Cosine	$-17.51 \cdot \ln\left(2.33 \cdot \frac{\lvert\theta\rvert}{\theta_3}\right)$	−14.4	−20.6	−4.32
The function ln() is the natural log function.				

Table 1.3 ITU-R M.1851 Equation [7]

ITU-R M.1851 also defines two separate pattern descriptions, one for single entry interference analysis which is based on the peak pattern, and one for aggregate impact analysis which is based on the average pattern.

1.3 Small Cell Systems

As defined in section 1.1, small cell systems are typically defined as low powered base stations or access points that provide improved coverage or increased capacity. Small cells can be characterized by names such as femto-cells, pico-cells, metro-cells or micro-cells. Each of these device types will have different radio characteristics in terms of transmitter, receiver and antenna specifications. The umbrella nature of the term “small cell” gives rise to confusion of what exactly is a small cell in terms of modeling them for interference purposes. In order to provide clarity for modeling purposes, this thesis will use the parameters set forth in the Federal Communications Commission (FCC) GN Docket No. 12-354. This docket is a Notice of Proposed Rulemaking for enabling secondary use of the 3550-3650 MHz band by small cell systems. According to this docket, a small cell device consists of a transmitter with 23 dBm of output power and an omni-directional antenna with 7 dBi of gain resulting in an effective radiated power of 30 dBm or 1 Watt [8]. The receiver specifications were not defined by the docket. However, if you examine the potential technologies being implemented in small cell architectures, then it is clear that it will resemble a LTE, UMTS or WiFi receiver. Hence, the receiver specifications of a small cell can be assumed to fall within the industry standards for these devices. To be clear, the purpose of this work is not to determine the effective ability of the small cell to deal with interference impacts but to simply propose a methodology for better predicting the potential interference levels between small cells and radars.

Small cells can be placed indoors or outdoors depending on the needs of the user. The general view is that the majority of small cells will be deployed indoors as this is where there is both poor coverage and low capacity. However, it is assumed that outdoor small cells will be pervasively deployed as well. In terms of propagation modeling and interference analysis, the worst case deployment scenario is the outdoor small cell device that would be line of sight to a radar system. Therefore, the modeling work will be done on the worst case scenario of an outdoor small cell placement. Although in theory small cells can be placed on top of tall buildings and large towers, the likelihood of that deployment case is rare. Most likely, any spectrum sharing policy efforts regarding small cells will set a mounting height limit based on height above average terrain. However in practice, outdoor small cells will be deployed on utility poles, street lights, and sides of buildings. Due to this mounting constraint, the average height of 8 meters above ground level was be used for small cell mounting height. The antenna of the small cell was defined as a generic omni-directional antenna with a 14 degree vertical beam-width. This antenna was selected because it resembles a general small cell device's antenna.

In addition to small cells, it is important to define and model the mobile devices that would be communicating to the small cells. These devices have both the potential to be impacted by radars and to impact radar systems. Although mobile devices can have a wide variety of radio profiles, the assumption in this modeling work is that the mobile unit has a maximum transmit power of 18 dBm and no antenna gain. Like small cells, the assumption is made that mobile devices fall under industry standards for transmission emission masks and receiver filters.

1.4 NTIA Modeling Methods

The NTIA performed significant modeling work on the 3500-3650 MHz band during 2010 in order to determine the viability of sharing the band with commercial users [2]. The report defined the incumbent Federal users of the band and then proceeded to model interference potential of these users with commercial WiMax systems. This report found significant interference potential between ship-borne radars and WiMax systems [2]. The report defined geographic exclusion zones along the West, East and Gulf coasts of the United States where WiMax systems would both be impacted by radars and would have impact on radars. Figure 1.1 shows the NTIA produced geographic exclusion zones for ship-borne radars and WiMax systems.

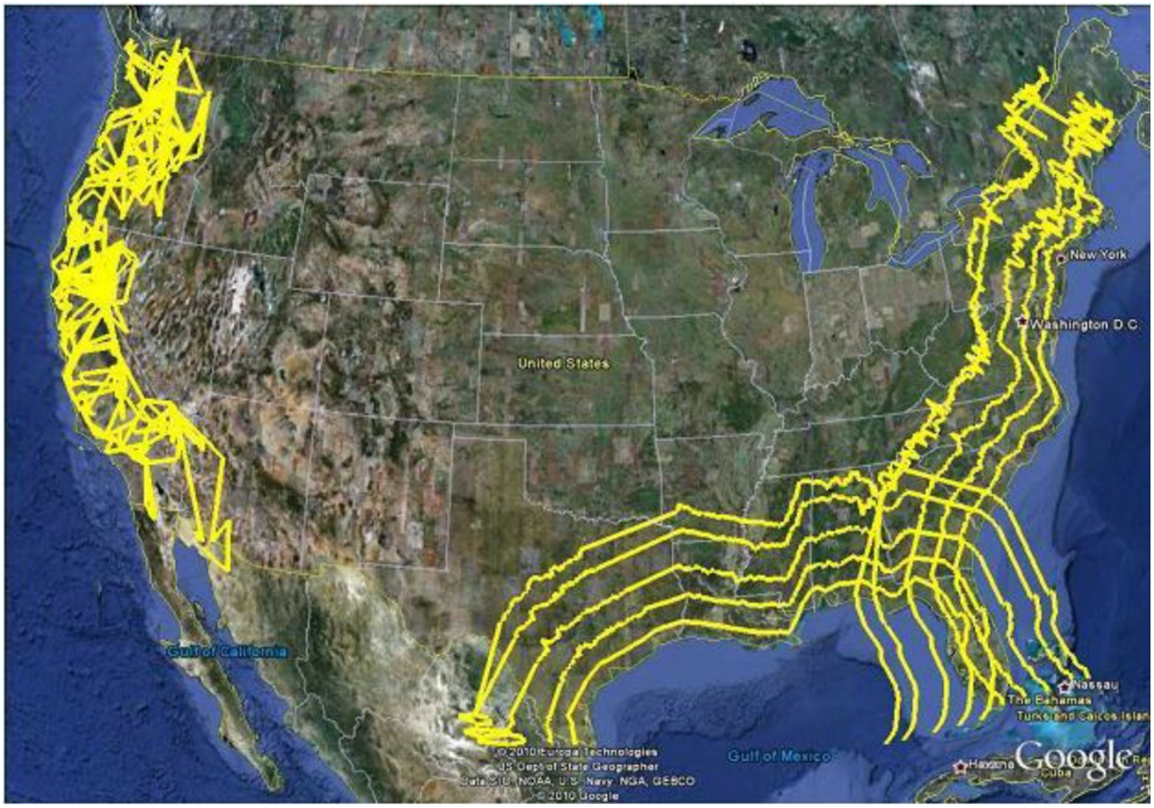

Figure 1.1 Composite Exclusion Zones of Ship-Borne Radars and WiMax Systems [2]

The areas from the ocean up to the yellow boundary lines correspond to the areas where WiMax systems would be excluded from operating. The multiple yellow lines correlate to five classes of ship-borne radars. The NTIA also provided numerical distances as shown in Table 1.4.

Radar Identifier	Radar to Wireless Broadband System Interaction			
	Radar-to-Base (Single Entry)		Radar-to-Mobile (Single Entry)	Base/Mobile-to-Radar (Aggregate)
	Geographic Area	Exclusion Zone Distance (km)[a]	Exclusion Zone Distance (km)	Exclusion Zone Distance (km)
Shipborne Radar – 1	East Coast West Coast Gulf Coast	361 343 339	68	310
Shipborne Radar – 2	East Coast West Coast Gulf Coast	154 235 106	32	45
Shipborne Radar – 3	East Coast West Coast Gulf Coast	224 286 200	47	53
Shipborne Radar – 4	East Coast West Coast Gulf Coast	448 404 458	143	305
Shipborne Radar – 5	East Coast West Coast Gulf Coast	455 415 557	309	Not Available
Note a: The exclusion zone distance is based on the maximum value. The detailed terrain dependent exclusion zone distances are provided in Appendix E.				

Table 1.4 NTIA Exclusion Zone Distances [2]

Table 1.4 shows the exclusion zone distances for Radar-to-WiMax Base Station and Radar-to-Mobile Unit which was based on single entry interference analysis. Also, the WiMax Base/Mobile aggregate impact on radars is defined in the table. Based on these exclusion distances, 190 million people or 60% of the US population would be unable to use the band because they would fall within the exclusion zones [8]. The results of the NTIA analysis are informative because it defines the modeling approaches that NTIA believes is appropriate for radar and WiMax system interaction studies and it provides a baseline to compare against. However, the fact that the exclusion zone modeling was done for high powered WiMax base stations with high gain directional antennas 60 meters above ground level does not provide enough guidance for implementing sharing policy between radars and small cells.

The NTIA defined a number of modeling approaches that are of interest to this research effort. They are defined and analyzed in the following subsections.

1.4.1 Interference/Noise (I/N)

The NTIA defined I/N per ITU-R M.1461-1 as the preferred method for determining interference thresholds for radar systems and commercial WiMax systems. Figure 1.2 presents the equations for calculating the interference threshold of a system based on I/N.

$$I_T = {}^{I}/_{N} + N$$

where:

I/N: Maximum permissible interference-to-noise ratio at the receiver intermediate frequency (IF) output (detector input) necessary to maintain acceptable performance criteria (dB)

N: Receiver inherent noise level at the receiver IF output referred to the receiver input (dBm)

Figure 1.2 Interference Threshold Equations [2]

The I/N value selected by NTIA for radar and WiMax systems was -6 dB which corresponds to a 1 dB increase in the receiver noise [2]. The reasoning behind this selection was that radar receivers already operate near their receiver's noise floor so they can tolerate very little interference from wireless broadband systems [2]. The modeling work produced in this research used the NTIA defined -6 dB I/N value for radar systems.

Within the Fast Track report, the NTIA defines the I/N method as the preferred method for determining impacts on wireless broadband systems such as WiMax or other OFDM based technologies like LTE. However, these OFDM based systems are interference limited [2]. A more appropriate method for determining interference thresholds for these types of systems is based on a carrier to interference plus noise (C/(I+N)) [2]. According to a different technical report done by NTIA, it is more appropriate to use C/(I+N) instead of I/N for commercial non-Federal systems like small cells [9]. The purpose of using this method is that it respects the interference limited nature of small cell systems and supports the use of a carrier signal as a variable in determining impact on the small cell system. However, using C/I+N values in the interference modeling of small cell as victim in this ship-borne exclusion zone case is not a direct process. The main reasons it is not direct are the following. First, predicting a reliable carrier signal is impossible if you do not know where small devices are physically located. Also, within a small cell system there will be internal sources of interference that contribute to the I value in the C/(I+N). In order to deal with these issues, the following assumptions were made:

1. Small cells are LTE systems that can operate with -6 dB C/(I+N)
2. Reasonable service is determined to be above 0 dB C/(I+N)
3. This corresponds to a 0 dB I/N level
    a. Results in a 6 dB decrease in the minimum required path loss of the NTIA modeling definitions

1.4.2 Irregular Terrain Model Propagation Model

The NTIA used the Irregular Terrain Model (ITM) for its propagation modeling exercises within the Fast Track report [2]. This model is a revision of the standard Longley-Rice model that was originally coded in 1982. The ITM model is considered a standard propagation model by the NTIA and FCC although it is typically used outside of its intended coverage [10]. The implementation that NTIA used for the ship-borne to wireless broadband system modeling was the point-to-point mode of the ITM model. The point-to-point mode uses a terrain database to determine impacts of terrain on a given path. The aggregate impact analysis of wireless broadband devices upon radars used the ITM model in area prediction mode [2]. The area mode uses the concept of terrain roughness for a given area instead of actual terrain data. Neither of these modes supports the use of additional environmental data such as three dimensional structure data or land use/land cover (LULC) data that would allow for a more complete description of the propagation environment [11].

The original development of the ITM model was focused upon analog television broadcast modeling [10]. However, the ITM model coverage supports a frequency range from 20 MHz to 20 GHz and uses a mix of deterministic propagation modeling approaches and empirical/statistical adjustments developed from an extensive set of measurements [11]. The benefit of the model to the radar exclusion zone modeling application is that it supports empirical adjustments for trans-horizon propagation effects like scattering [12]. Also, as mentioned previously, the model is widely accepted which sometimes can be more important than actual accuracy and applicability of the model [13]. The model is quite complex in terms of what the model is doing in each particular path condition [10]. This makes the ITM model difficult to dissect in regards to how a particular empirical adjustment may be impacting the prediction. Also, there is a known accuracy issue in the model in regards to antenna height determination. ITM uses a concept of effective antenna height which is different than structural antenna height and this creates uncertainty in the appropriate implementation of the model for each site condition [11]. Another known issue with the ITM model is the transition zone between the transmitter to horizon and the diffraction zone. A receiver location in the transmitter to horizon zone contains a weighted portion of the diffraction zone loss [12, 14]. Also, the ITM model was not developed for short paths of two kilometers or less which are the dominant path condition for small cell systems [10].

However, the main concern with the ITM model in regards to this modeling work is that the model does not support the use of structure data or LULC which is of importance for site-specific modeling [11]. Small cell systems will be typically be at antenna heights that are below the building heights and overall clutter height, hence have a significant likelihood of propagation paths being impacted by these objects. Also, at the frequency range of interest for these systems, research shows that tree cover and building cause significant blockages to transmitted signals. To prove this point, the following example examines San Francisco with the ship-borne radar transmitting at 30 meters above sea level offset 10 kilometers from the coast and the small cell device placed at 8 meters above ground level. The Anderson-2D model supports the use of buildings and LULC data along any path. Figure 1.3 shows line-of-sight (LOS) conditions with terrain data only using the point-to-point mode of ITM where green is LOS and red is a non-LOS condition (NLOS). Figure 1.4 also shows the results of the Anderson-2D model with terrain only. Figure 1.5 shows the results of the Anderson-2D model with terrain, buildings and tree LULC data.

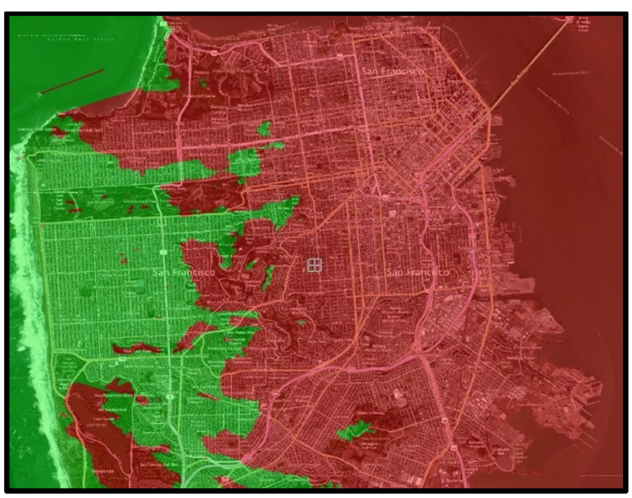

Figure 1.3 ITM

Figure 1.4 Anderson-2D

Figure 1.5 Anderson-2D with Bldgs/Trees

Figure 1.3 and 1.4 are exactly the same as both models are predicting LOS based on terrain only. Figure 1.5 shows a decrease in LOS areas or those areas not impacted by buildings and tree LULC data. The square area of impact was tabulated in Table 1.5 below.

Propagation Model	Buildings and Trees Used	LOS Area (sq km)	NLOS Area (sq km)
ITM	N	38.280	100.757
Anderson-2D	N	38.280	100.757
Anderson-2D	Y	22.008	117.030
Percent Decrease in LOS Areas		**42.50%**	

Table 1.5 LOS/NLOS Square Area Impact

Table 1.5 shows a 42.50% decrease in areas that are considered LOS by using buildings and LULC data. Granted that San Francisco is a dense urban environment, there will be less reduction in open and rural areas where there is less buildings and LULC issues. However, small cells have greatest applicability in urban and suburban environments where this impact will be evident.

1.4.3 Frequency Dependent Rejection

The concept of Frequency Dependent Rejection (FDR) is one that is specific to interference modeling between services that are operating in either a co-frequency or adjacent frequency condition. This definition was pulled from the Fast Track report.

> "FDR is a calculation of the amount of undesired transmitter energy that is rejected by a victim receiver. This FDR attenuation is a composed of two parts: on-tune rejection (OTR) and off-frequency rejection (OFR). The OTR is the rejection provided by a receiver selectivity characteristic to a co-tuned transmitter as a result of an emission spectrum exceeding the receiver bandwidth, in dB. The OFR is the additional rejection, caused by specified detuning of the receiver with respect to the transmitter, in dB. The FDR values used in this analysis were computed using an automated program." [2]

The NTIA used an automated program to determine the FDR values for this analysis which is available for download from the NTIA website. NTIA did not provide actual measured transmission emission masks of the radar systems and also did not provide receiver selectivity curves of the radar receivers. It is not known if NTIA used generic inputs into the automated software program to determine FDR values for the radar devices or used actual measured curves. This lack of transparency makes it difficult to determine how much confidence can be provided by the modeling work. The reasoning behind this lack of transparency could be either that NTIA sees releasing this information as a security threat, the information is proprietary to the vendors of the radar equipment or that the information is just not available. However, it is clear that the NTIA does believe that FDR calculations based on assumptions is a non-ideal method for determining actual FDR. In NTIA Report 07-447, NTIA finds that the FDR calculation method for Land/Mobile systems "overestimates the transmitted power outside of the band and underestimates the receiver filter attenuation" [9]. This overestimation of interference energy and underestimation of receiver filter selectivity efficiency results in an overestimation of received interference power levels between the systems [9]. Within this same report, NTIA recommends that actual transmitter power spectral density curves and receiver filter selectivity curves to be used in interference analysis [9]. In addition to the FDR issues defined above, ship-borne 5 did not have a FDR defined at all. This makes accurately modeling interference potential between this radar type and small cells impossible. However, it was defined earlier that ship-borne 5 is most likely the SPY-1 type of radar. This radar was also found to be defined in a separate NTIA report, NTIA TR-99-361, regarding technical characteristics of radiolocation systems in the 3.1-3.7 GHz band. This radar is defined as radar type B in this report [15]. The report defines that FDR used for radar type B was based on measured emission spectra [15]. Figure 1.6 shows the FDR curve for ship type B.

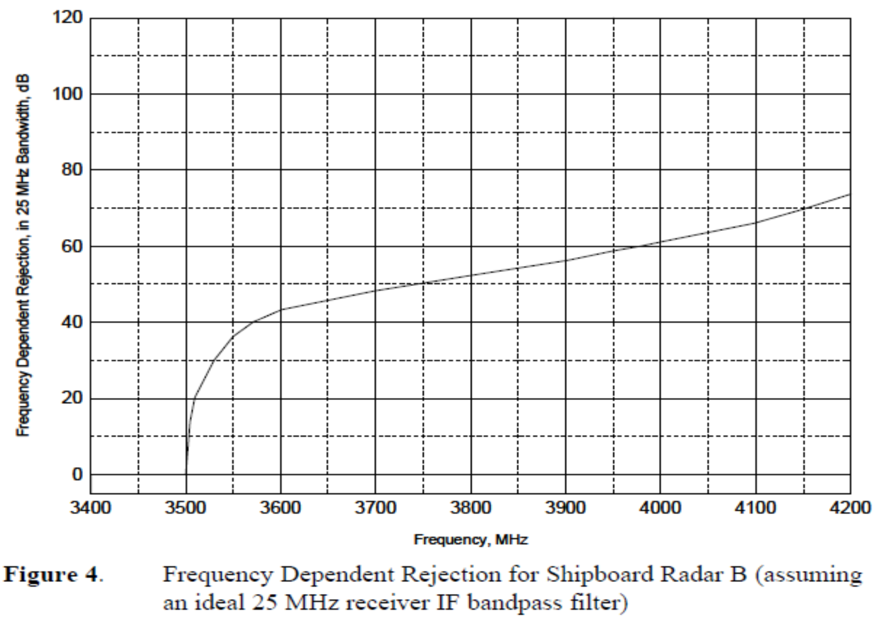

Figure 1.6 FDR Curve of Radar Type B (Ship-borne 5) [15]

From this curve, it can be estimated that a reasonable baseline FDR for ship-borne 5 is approximately 35 dB at 3550 MHz. This assumption is applied to the modeling of ship-borne 5 systems.

1.4.4 Required Minimum Path loss for Interference Protection

In order to determine the required exclusion distance for any given coastal location, the NTIA proposed the following equation in Figure 1.7 for determining the required minimum path loss to achieve the I/N value for interference protection of wireless broadband receivers [2]. This is actually the recommended approach as defined by the ITU-R M.1461 document [16].

$$L_{Required} = P_T + G_T + G_R - L_T - L_T - I_T - FDR$$

where:

$L_{Required}$:	Minimum required propagation loss necessary to preclude potential interference (dB)
I_T:	Receiver interference threshold (dBm)
P_T:	Power of the transmitter (dBm)
G_T:	Antenna gain of the transmitter in the direction (azimuth and elevation) of the receiver (dBi)
G_R:	Antenna gain of the receiver in the direction (azimuth and elevation) of the transmitter (dBi)
L_T:	Transmitter insertion loss (dB)
L_R:	Receiver insertion loss (dB)
L_P:	Propagation loss (dB)
FDR:	Frequency dependent rejection (dB)

Figure 1.7 Required Minimum Path Loss Equation [2]

Based on this recommended approach, and making adjustments for small cell link budget differences from WiMax devices, the following required minimum path loss values in Table 1.6 were determined for ship-borne exclusion zones in regards to small cell as victim.

	Original Path loss at -6 I/N (dB)	Antenna Gain Change (dB)	Revised Path loss at -6 I/N (dB)	Revised Path loss at 0 I/N (dB)
50 MHz Offset				
ship1	159.2	6	153.2	147.2
ship2	185.2	6	179.2	173.2
ship3	196.6	6	190.6	184.6
ship4	193.1	6	187.1	181.1
ship5 - with FDR	252.8	6	211.8	205.8
100 MHz Offset				
ship1	151.2	6	145.2	139.2
ship2	178.2	6	172.2	166.2
ship3	184.6	6	178.6	172.6
ship4	180.1	6	174.1	168.1
ship5 - with FDR	252.8	6	203.8	197.8

Table 1.6 Revised Minimum Path loss Values for Small Cells

The table provides minimum path loss values in dB for both I/N of -6 dB and I/N of 0 dB. The reason both are listed here is based on the discussion in section 1.4.1 where 0 I/N was determined to a more reasonable metric for a LTE system such as a small cell.

1.4.5 Aggregate Impact Analysis

The NTIA used a non-site-specific approach to modeling aggregate impact on radars form wireless broadband devices. This approach used the concept of concentric zones of deployment areas (urban, suburban, rural) and weighted distribution of wireless broadband base stations through each zone based on rough cell radii values. It then distributed a certain number of mobile devices to each base station based on a generic loading scheme [2]. This methodology seems to be a simplified version of the method defined in NTIA Technical Memorandum 09-461 which was originally developed for aggregate impact analysis of 5 GHz WLAN devices impacting radars [17].

Although the aggregate impact analysis of small cell devices impacting radar receivers seems to be a similar problem to the small cell as victim analysis in regards to propagation modeling, the NTIA used different methods. First, NTIA selected the area-mode of ITM which does not account for site-specific terrain propagation impacts [2]. Also, they applied an extra loss factor in the interference equation which was to account for building and non-specific terrain losses. The values selected for this loss factor was variable based on whether the interfering device was set to an urban, suburban or rural assignment [2].

Once the devices are placed and propagation results tabulated for each device's power level at the radar receiver, then the equation in Figure 1.8 is used to determine aggregate interference levels from all loaded devices.

$$I_{AGG} = 10\log\left[\sum_{j=1}^{N} I_j\right] + 30$$

where:

I_{AGG}: Aggregate interference to the Federal system receiver from the wireless base and mobile/portable transmitters (dBm)

N: Number of wireless base and mobile/portable transmitters

I: Interference power level at the input of the Federal system receiver from an individual wireless base and mobile/portable transmitter (Watts)

Figure 1.8 Aggregate Interference Equation [2]

Although the NTIA provides results for ship-borne radars 1-4, they only provide the necessary data, specifically the interference threshold requirement for ship-borne radar 1-3 [2].

There are issues with the NTIA prescribed method for aggregate impact analysis and the applicability of this method to small cell systems is of special concern. Recently, the

Commercial Spectrum Management Advisory Committee (CSMAC) released a report for the 1695-1710 MHz band that recommends the use of a site-specific approach for aggregate impact analysis and recommends the use of ITM in the point-to-point mode [18]. Also, the device loading methodology should be accomplished in a manner that is appropriate for small cell systems so that device densities and locations more closely match the expected commercial deployment scenarios.

1.5 Propagation Model and Measurement Review

This section reviews potential propagation model alternatives to the default ITM choice and also examines any available measurement data of the 3.5 GHz frequency range.

Propagation models are an important tool for the design of physical wireless networks but also in the design of spectrum policy. There are many propagation models that are available for use. Some of these models are proprietary and others are open models. Proprietary models tend to be black box models that are only available for use within a vendor's propagation software tool. Also, the black box nature of the models makes it impossible to determine the underlying methodology and hence they are impossible to duplicate. Open models are those models that have been published in research and/or have been clearly defined so they can be easily duplicated by third parties. Since the purpose of this research is to define viable propagation modeling methods for small cells and radar interference analysis which can be used for public policy making, the models should be of the open type. This allows anyone who wants to duplicate the results the ability to do so.

Measurements are of great importance to better understand the statistically varying nature of radiofrequency systems. RF engineers understand that field measurements are vital to properly understanding the behavior of an RF system. Also, since propagation models are a prediction tool, the use of field measurements is necessary to improve the prediction accuracy of the models. When appropriate, the collection of even a small amount of measurements can greatly increase the ability to tune the propagation model of choice [19].

1.5.1 Propagation Model Alternatives

This research aims to test an alternative to the ITM model due to the inadequacies of the model defined in section 1.4.2. The proper selection of an alternative first requires a short review of available models. There are three classes of propagation models that were investigated for use in this work. The first class of model is an empirical type model.

1.5.1.1 Empirical Models

Empirical models are based off measurement data and are usually only applicable to a given deployment scenario and frequency range which would be matched to the measurement dataset scope. An example of a standard empirical model is the COST-231(Hata) model which is an extension of the popular Okumura-Hata model [14]. Also, the 802.16 SUI models are empirical models that are defined to be applicable in the 2-4 GHz range [14]. Empirical models do not typically use environmental databases such as terrain and LULC data. Also, empirical models are typically tuned extensively with significant measurement campaigns [14]. Finally, the majority of empirical models are found at frequency ranges below 3.5 GHz. For these reasons, empirical models are not appropriate for site-specific modeling exercises of radar and small cell interaction studies.

1.5.1.2 Physical Models

Physical models are models that are based on the basic free space path loss equation. These models typically support the use of terrain, LULC data and building data and use physics based methods for predicting the interaction of the signal with the obstacles found in the databases. These models are appropriate for site-specific modeling exercises because they directly interact with the environmental data describing the physical environment thus giving a site-specific view of path loss. The models vary in how they calculate interactions of the environmental data such as diffraction over terrain or buildings or reflection. In regards to small cells, they support the modeling of a small cell at street pole height level because they can support the modeling of impacts of such obstacles as trees, buildings and terrain. These free space based models typically incorporate a two-ray analysis method for LOS paths and some type of diffraction method for NLOS paths. There are many variants of physical models available for use.

The model selected for use in this modeling work was the Anderson-2D model[1]. This model was selected for a number of reasons. First, the model is a physical model that supports the use of terrain, LULC and building data. Second, the model was selected by the Telecommunications Industry Association (TIA) as the definitive model for TSB-88A/B for predicting coverage and interference for mobile radio systems in the United States [9, 14]. Third, the model was found to outperform, in regards to average standard deviation of the prediction errors, the Longley Rice (ITM), TIREM and other physical and empirical models when compared against a wide range of measurements [14, 20]. Additionally, the model supports the lookup of LULC and the height of each LULC bin so that an accurate model of

1. I am an employee of EDX Wireless which developed the Anderson-2D Model. This model is an open model that is defined publicly and available for use by any interested party. Adjustments and extensions of the model can be implemented by EDX Wireless or within a public working group setting

clutter heights can be accounted for in the path loss calculation. The Anderson-2D model can support the use of LULC data in three. The first a is a clutter loss at point method which determines the LULC type at the study point of interest and applies an appropriate loss factor based on that LULC type and system frequency. The second is a pass-through mode that uses the height of the LULC and determines where the path is infringing into the clutter and then applies a dB/km loss factor which is based on LULC code and system frequency as it passes through that portion of clutter. The final method treats all LULC as diffracting objects based on the height of each LULC grid point. The method used in this analysis was the clutter loss at point since is a generally accepted method of applying LULC losses as defined by the TSB-88-B [9].

Finally, the model is a basic physical model that is not dependent on measurement data or empirical adjustments hence it is suitable in a wide range of propagation circumstances. Hence the model has the ability to be extended to support new approaches to interacting with LULC, building, and terrain data as these databases becoming increasing accurate and complete.

Although the Anderson-2D model has many benefits, there are weaknesses that need to be defined and understood. First the model does not have a forward scatter mode or adjustments for anomalous propagation effects like ducting [21], which are important for trans-horizon propagation modeling of radar system's path loss at low altitudes [22]. Also, the model behaves poorly in long range over the horizon smooth earth path conditions like what is found in the Gulf coast. The model over-predicts path loss in these cases due to not supporting a smooth Earth mode.

1.5.1.3 Hybrid Models

A hybrid model is one that uses both empirical methods and physical methods to construct the path loss result. An example of this is the ITM model or Hata Extended/Epstein-Peterson. The ITM model uses the basic two-ray mode just like a physical model but also provides a collection of empirical adjustments based on the particular path condition. Hata Extended/Epstein-Peterson uses the Hata empirical approach but also applies corrections based on the terrain diffractions found along the path. As discussed previously in section 1.4.2, hybrid models like ITM make it difficult to discern what particular empirical adjustment is being made for any given path.

1.5.1.4 Ray Tracing Models

Ray tracing type models are a class of models that support the high resolution modeling of reflections, diffraction, and scattering of electromagnetic energy [14]. These models use concepts from geometric optics, uniform theory of diffraction and a variety of scattering approaches. The application of these models is typically relegated to dense urban environments or indoor environments because they require very accurate descriptions of the environment to be useful. This high resolution data is typically not available over large geographic areas so their application in radar and small cell interaction studies is difficult. Also, the computation requirements for these models are very significant for even very small propagation problems [14].

However, these models are appropriate for modeling in the small cell deployment environment because they support the calculation of reflections off building surfaces which is not possible with the two-ray based physical models. The results from these models can assist in better path loss predictions, understanding of indoor penetration, understanding of delay spread of arriving signals as well as the angular dispersion of arriving signals [14].

1.5.2 Measurements found at 3.5 GHz

Although no measurements were taken in this research, there have been documented measurement campaigns in the 3.5 GHz band that are of use for review. The measurements are informative to understand what researchers have found for reasonable path loss ranges for varying environments like rural or urban.

There have been many fixed WiMax deployments in the 3.5 GHz band [23]. One particular network in rural Italy provides some basic insight into measured path loss values over ranges up to 10 kilometers. It found path loss values from 120-150 dB for 10 kilometer paths from a 30 meter AGL base station antenna linking to either a two meter AGL mobile or a 10 meter AGL customer premise equipment. It also found proof that empirical models are not appropriate for the 3.5 GHz band in rural environments. The following graph in Figure 1.9 shows that the 802.16 SUI models and COST-231 do not perform well against the collected measurements which are represented by the best-fit (BF) curves.

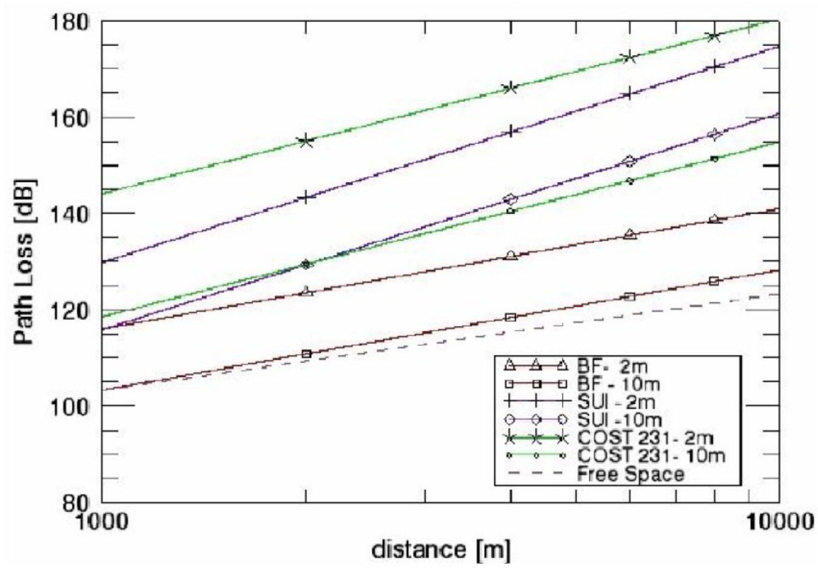

Figure 1.9 Comparison of Measurements to Model [23]

Another measurement campaign examined an urban deployment case at 3.5 GHz. This case was performed for a base station at roof level (~25 meters) with measurements taken at 2.5 meters AGL. The results for this case were only graphed out to 1 kilometer. Figure 1.10 shows the results of this campaign. The best-fit curve in this measurement campaign shows around a 130 dB average path loss at 1 kilometer from the base station [24].

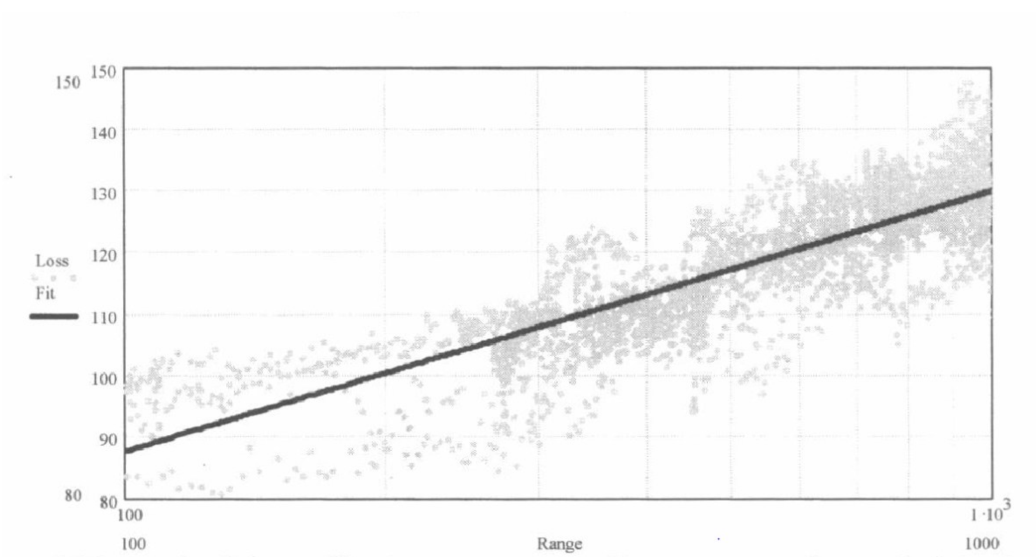

Figure 1.10 Urban 3.5 GHz Measurement Results [24]

Overall these measurements show that in a rural environment, empirical propagation models are not appropriate. Also, they show there is an expectation of 120-150 dB for path loss for 10 kilometer paths in rural areas and approximately 130 dB of path loss at 1 kilometer in a dense urban environment. What this also shows is that the propagation model selected for modeling systems that operate in both rural long distance scenarios as well as dense urban environments needs to be able to model the varying path conditions.

CHAPTER 2

METHODS

Chapter 2 defines the experimental methodology for implementing the revised modeling approach. An analysis of small cell as victim via the single entry method as well as radar as victim via the aggregate impact method is defined. A small cell device loading scheme used for the radar as victim analysis is defined.

2.1 Small Cell as Victim

This section covers the propagation modeling methods applied for the case of a ship-borne radar transmitter impacting a small cell receiver. The inputs defined for the various ship-borne radars were used based on the definitions by NTIA as described in section 1.2. The NTIA recommended placing ship-borne radar transmitters at 10 kilometer intervals offset 10 kilometers from the coast which was the method used in this modeling effort. The inputs for the small cell device were used based on the definitions described in section 1.3.

2.1.1 Environmental Databases

The propagation modeling exercises used digital elevation data also known as terrain data. This data was produced by the USGS National Elevation Dataset and is a 1 arc second resolution. This corresponds to approximately a 30 meter database resolution. Figure 2.1 shows a view of a portion of the West coast's terrain data.

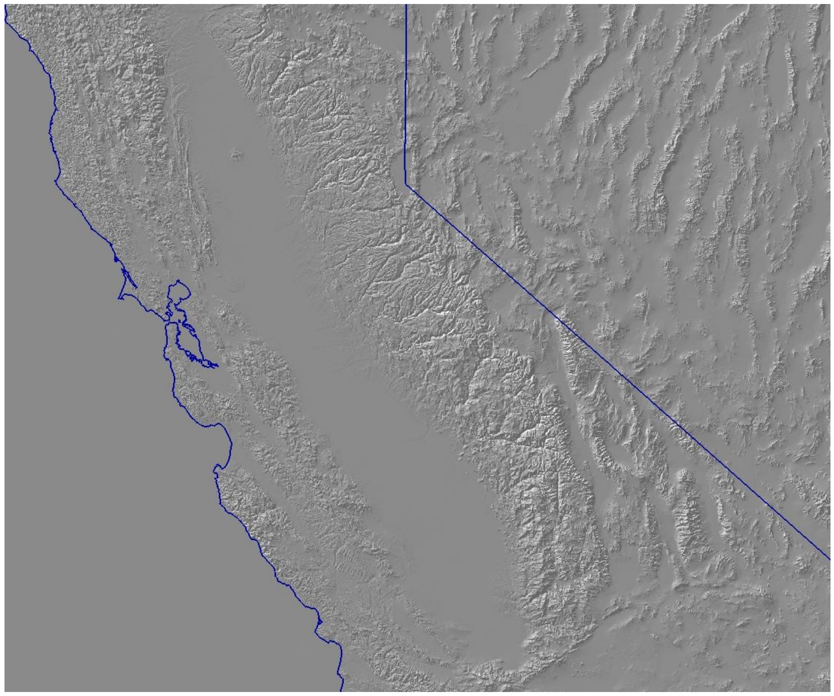

Figure 2.1 USGS 1 arc second Terrain Data

Also, the USGS National Land Use/Land Cover data from 2006 was used for the LULC database. This data is also a 30 meter resolution database. The USGS 2006 LULC data does not natively use the TSB-88 LULC category assignments; therefore, they were mapped to the appropriate TSB-88 category assignments. Figure 2.2 shows a view of the USGS 2006 LULC data covering a portion of the West coast.

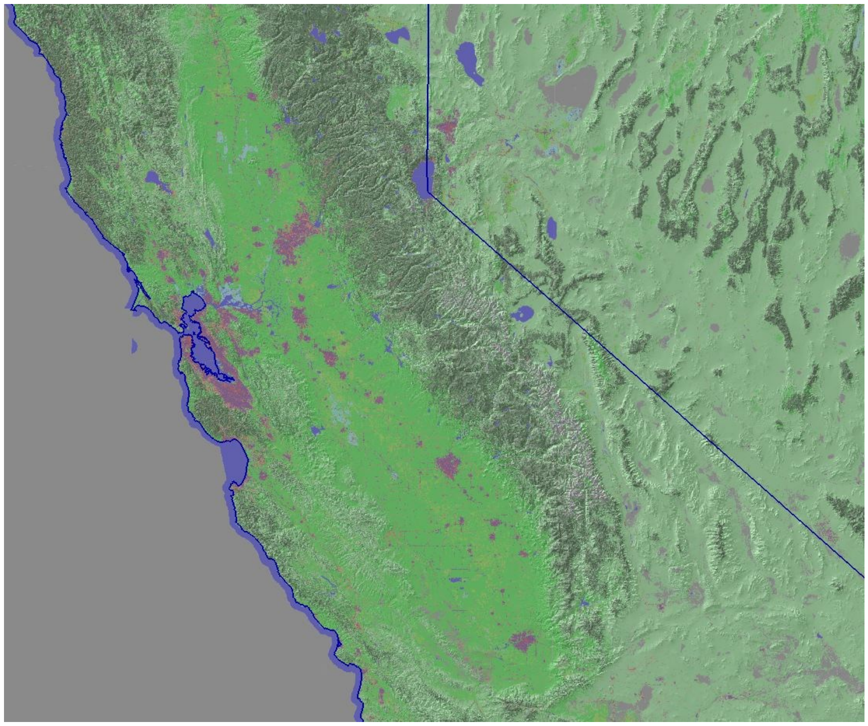

Figure 2.2 USGS 2006 LULC Data

2.1.2 Propagation Model

As defined in section 1.5.1, the Anderson-2D model was selected for experimentation. The model was set to use both terrain and clutter data. The LULC method selected was the clutter loss at point method as defined in section 1.5.1. Also, the ITM model with the LULC data was used for comparison purposes. It was set with the same inputs as defined in the NTIA Fast Track report [2]. Both models were run at 100 meter sampling resolution in 1 degree increments using a radial line calculation method. For each ship location, the necessary number of radials was used to provide complete analysis of potential interaction with land based small cells.

2.1.3 Single-Entry Analysis

An area-wide/ coverage study was run for the downlink path loss return value for each study point. This resulted in a coverage map showing path loss values for each grid point. For each coast area, there were multiple passes of the study generated. These included running the path loss analysis with radars at 30 meters above ground level (AGL) and 50 meters AGL and also varying the propagation model selection and options. Each pass was then analyzed to determine maximum distance from the coast that reached the minimum path loss requirement to achieve the appropriate I/N value. This provided a relevant comparison point to the NTIA exclusion zone results as well as pass to pass comparison. Also, a demographic analysis based on US Census 2010 data was completed to determine how large of a population was found to be in areas that were below the minimum path loss threshold. This method used a grid-based query method to determine bins that were below the path loss threshold and the population centroids within that path loss bin were determined to be impacted. This output provided additional information regarding how radars may be impacting the population and thus potential use of the spectrum.

2.2 Radar as Victim

The aggregate impact of small cell devices upon radar receivers was modeled using a novel loading device loading method as well as using the recommended propagation model. Also, based on the loading scheme completed, the same impact analysis was completed with the ITM model and compared to the Anderson-2D model results. The assumption of a FDR of 40 dB was used since this information was not provided by NTIA. Hence the results are more informative in regards to presenting the method and showing a trend between the two propagation methods.

2.2.1 Environmental Databases

The same environmental databases that were used in the small cell as victim analysis were used in the aggregate impact analysis. The difference between the two experiments was that in the aggregate impact analysis, a building database was also used. The building database defined each building structure in terms of its footprint and height. The LULC was only used to determine where areas of forest were located. Figure 2.3 shows the view of buildings over the city of San Francisco. Figure 2.4 shows a close up view of individual building polygons.

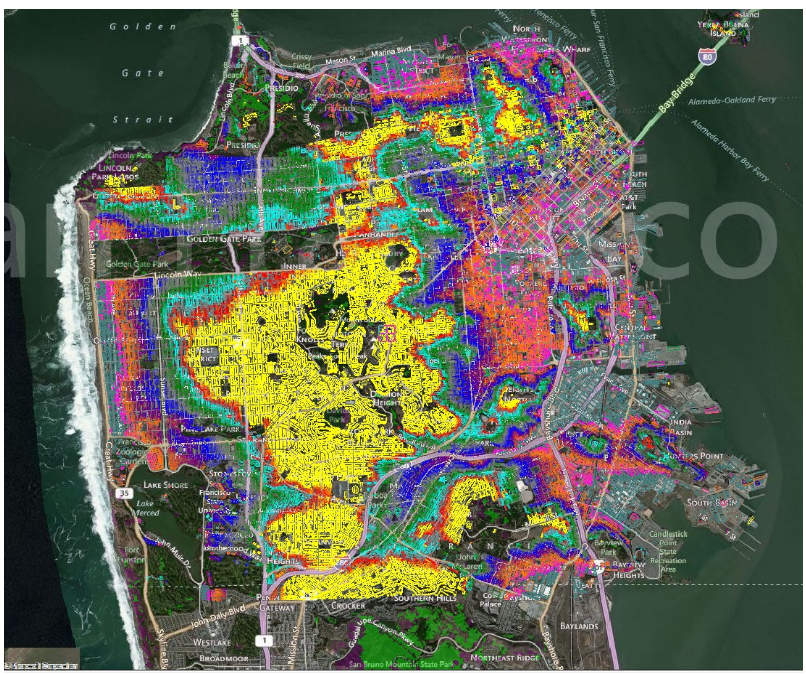

Figure 2.3 3D Buildings San Francisco

Figure 2.4 3D Buildings San Francisco Zoomed View

2.2.2 Propagation Model

As defined in section 1.5.1, the Anderson-2D model was selected for experimentation. The model was set to use terrain, buildings and LULC tree/vegetation clutter types only. The LULC method selected was the clutter pass through loss method as defined in section 1.5.1. Also, the ITM model was used for comparison purposes. It was set with the same inputs as defined in the NTIA Fast Track report [2]. Both models were run at 5 meter sampling resolution in half degree increments using a radial line calculation method.

2.2.3 Small Cell Device Loading Methods

The initial small cell device loading was done with specific market data as provided by the city of San Francisco. Although this method is specific to San Francisco, a modified method can be developed that can support automated loading across large areas of the US.

2.2.3.1 San Francisco Loading Methodology

The approach defined in this section is based on a site-specific approach to loading small cell devices into the environment. Small cells will be used by private businesses, government institutions, and consumers in both indoor and outdoor settings. Therefore any device loading scheme must be able to account for both indoor and outdoor devices as well as the varying link budgets that may exist based on location or user type. Table 2.1 represents the classification scheme used for device types used.

Device Type	Power (dBm)	Height (AGL m)	Antenna Gain (dBi)	Local Losses (dB)	% Distribution
mobile residential	18	1.5	0	10	9
small cell residential	23	8	7	10	2
mobile business	18	12	0	15	67
small cell business	23	12	7	15	18
outdoor small cell	23	8	7	0	1
outdoor mobile	18	1.5	0	1.5	2

Table 2.1 Small Cell Device Classifications

The varying types of small cell devices have a unique link budget and also have a unique local loss value based on whether the device is indoors or outdoors. The local loss value is a factor that is added to support the addition of extra losses that cannot be calculated by the proposed propagation model such as indoor penetration loss. The final column in Table 2.1 corresponds to distribution percentage used when loading the devices into the San Francisco environment. These values were developed by using population data from the Census 2010 dataset and city data on number of business located in the city limits of San Francisco.

Table 2.2 maps the number of households in San Francisco and defines how many small cells and mobiles communicating to that small cell would exist for an average household. Then a market penetration factor is applied to determine how many consumer small cells and mobiles should be loaded into the city.

Residential	**#**	**# Small Cells**	**# Mobiles**	**Market Penetration %**	**# Small Cells**	**# Mobiles**
San Francisco Households	391581	1	3	5	19579	58737

Table 2.2 Residential Small Cells and Mobiles

Table 2.3 maps the number of business in San Francisco and defines how many small cells and mobiles per small and large businesses should be loaded based on a 5% market penetration factor.

San Francisco Business	**#**	**Small Business %**	**Large Business %**	**Small Biz Small Cell**	**Small Biz Mobile**	**Large Biz Small Cell**	**Large Biz Mobile**	**Market Penetration %**	**# Small Cell**	**# Mobile**
San Francisco Business	227247	97.7	2.3	4	12	100	400	5	70537	237746

Table 2.3 Business Small Cells and Mobiles

The last devices to be defined are outdoor small cells and mobiles. Again, this is an area of additional research because this can be variable based on the spectrum band rules. However, it was determined that 10,000 outdoor small cells could be found in a city the size of San Francisco if a service provider or city was trying to provide blanket coverage across the entire city. An arbitrary two mobiles were assigned to each outdoor small cell which gives 20,000 outdoor mobiles.

After the raw number of small cells and mobiles are generated then a second factor needs to be applied that determines how many actively transmitting devices exist for any given moment in time. This is a factor that has significant impact on aggregate impact because it provides a clearer view of how many devices are actually transmitting. The method defined by NTIA for TDD systems is applied here which was that 62.5% of small cells would be transmitting and 37.5% of mobiles would be transmitting at any given time [2]. These values may be overly high or low depending on how you look at the problem. This is a suggested area of additional research and it may be appropriate to run Monte Carlo based simulations with a variable being duty cycle. Table 2.4 shows the final total loading of small cells that will be loaded.

Total	**5% MP**
Small Cells	100117
Mobiles	316483
Devices	416599
Duty Cycle Adjustment	
Actively transmitting	**5% MP**
Small Cell	62573
Mobile	118681
Total Number	181254

Table 2.4 Small Cells and Mobiles Loaded

The devices were then loaded into the city of San Francisco based on above numbers and the loading distribution defined in Table 2.1. A practical method of distributing the devices across San Francisco is to use the streets database and a bounding polygon. The devices can be laid out along the streets with a street centerline offset value based on the assumption that small cells will typically be placed in a structure which is nearby a street or along a street on street infrastructure. That is what was completed for this loading method.

However, instead of the streets method, it is also possible to distribute the devices based on LULC weightings and this should result in a more appropriate distribution of business devices where business actually exist and residential devices where homes are located.

2.2.4 Aggregate Interference Analysis – San Francisco

Once the devices were distributed across the city, then the radar receiver device was placed at a 10 kilometer offset from the coast. The radar receiver was modeled at both 30 meters AGL and 50 meters AGL. An uplink power coverage study from the small cell devices to radar was calculated. This provided a coverage map that defined if a generic small cell device was transmitting from any given grid point, what power would be received at the radar receiver from that device. This grid was then queried with the small cell device locations and a raw signal level was then found for each small cell location. Since each small cell device location had one of the small cell device classifications assigned to it, the proper loss factor was added to the raw signal level value. This resulted in a spreadsheet that defined the uplink power received from each small cell device at the radar receiver. These resultant values were then converted from dBm to Watts and run through the aggregate interference equation as defined by the NTIA to find a total interference level at the radar receiver.

CHAPTER 3

RESULTS

Chapter 3 presents the results and data analysis for small as victim and radar as victim modeling cases. The results show that significant reductions in exclusion distances were predicted with the revised approach in the small cell as victim case. The comparison of revised vs. traditional showed that the revised method impacted 38% of the original amount that the traditional method predicted. LULC impacts were found to be significant in the East coast. A linear correlation was found between population impacted and path loss. Aggregate impact analysis in the radar as victim case showed a ~25 dB less impact for revised method vs. traditional method.

3.1 Small Cell as Victim

The following results detail the outcome of modeling radar systems impacting small cells. The three propagation model configurations used for the analysis were Anderson-2D with terrain only, Anderson-2D with terrain and clutter (LULC) and finally ITM with clutter. A maximum distance value was determined that achieved the minimum path loss requirement for each radar type for each coastal region. Figure 3.1-3.3 shows the distance values determined for each region (raw data is found in Appendix I).

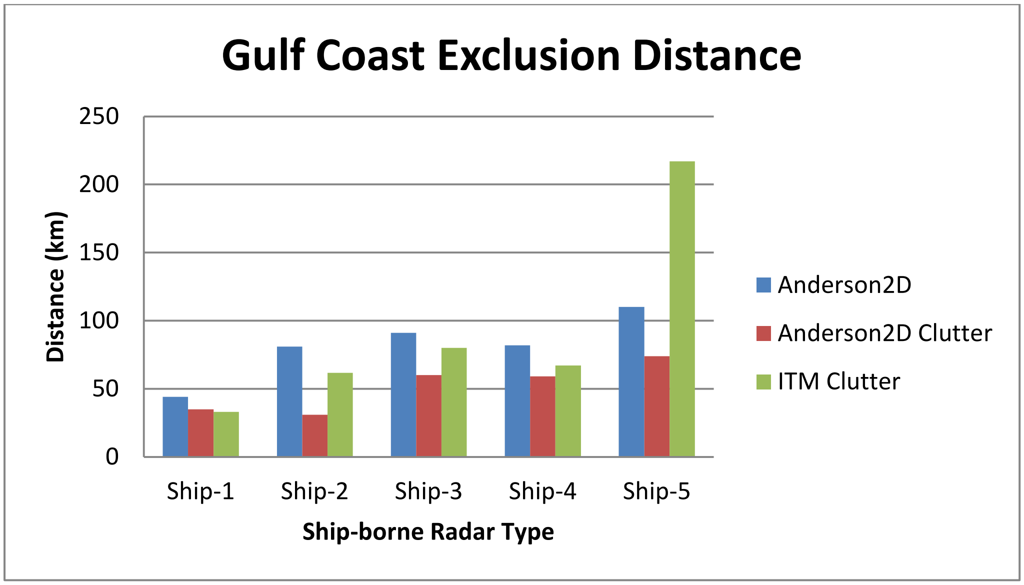

Figure 3.1 Gulf Coast Exclusion Distance

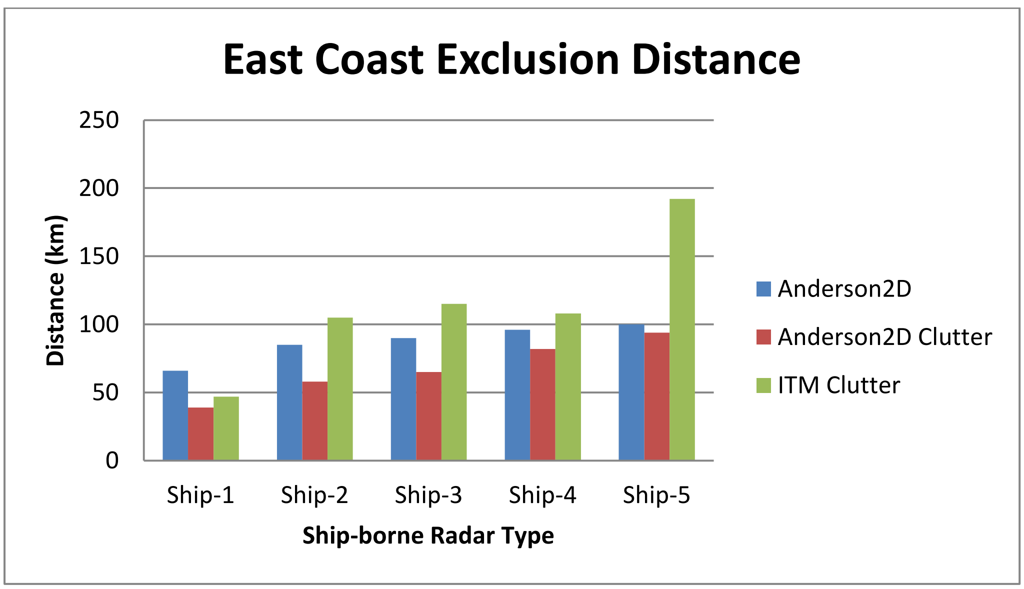

Figure 3.2 East Coast Exclusion Distance

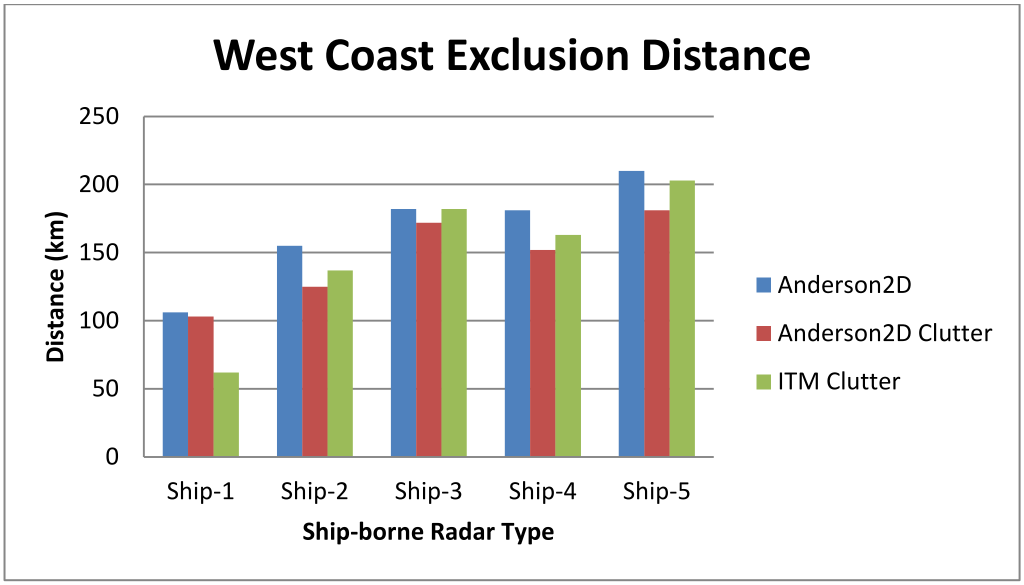

Figure 3.3 West Coast Exclusion Distance

The exclusion distance results show that the Anderson-2D with clutter model configuration consistently predicts the smallest exclusion zone distances. The only non-conforming runs are for Ship-1 on the West coast and Ship-1 on the Gulf coast. The West coast is most likely explained due to the Anderson-2D model predicting an improved range due to diffraction where the ITM does not calculate the same diffraction impacts. The behavior of Ship-1 on the Gulf coast is not understood.

Also, the ITM clutter configuration has vastly higher distances for Ship-5 in both the Gulf and East coast. The Gulf coast can be explained due to the ITM modeling the smooth Earth path case in the Gulf coast with a smooth Earth mode whereas the Anderson-2D model does not have a smooth Earth mode so it tends to over-calculate losses over flat areas for large distances. Also impacts from forward scatter or other empirical adjustments could be the source of the larger distance in ITM clutter. The East coast was found to have distant terrain peaks in the Maine region illuminated with path loss values below threshold whereas the Anderson-2D clutter model did not show these same peaks illuminated.

The population impact of each propagation model configuration for each coast area was also determined and the results are shown in Figure 3.4.

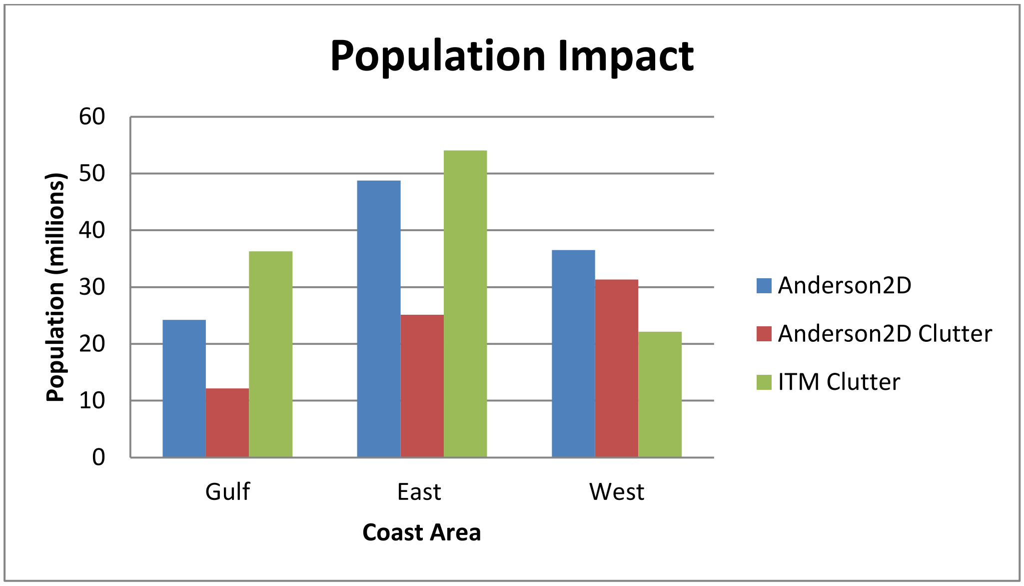

Figure 3.4 Maximum Population Impact

Also, the total population impact was determined for each run and is presented in Table 3.1.

Population Impact	**Anderson-2D**	**Anderson-2D Clutter**	**ITM Clutter**
Gulf	24,245,895	12,151,178	36,299,266
East	48,730,814	25,148,727	54,082,886
West	36,523,189	31,328,223	22,113,008
Total	**109,499,898**	**68,628,128**	**112,495,160**

Table 3.1 Total Population Impact

The Anderson-2D clutter model configuration had the smallest impact in terms of population with ITM clutter have the largest impact on population. This result was the expected outcome. However, what was unexpected was the larger population impact on the West coast for the Anderson-2D clutter configuration. The initial assumption was that across all coast areas, that Anderson-2D clutter would have the lowest maximum distance as well as the lowest population impact. However, ITM clutter is actually showing a lower outcome on the West coast. The total population impact when compared against the original 190 million impact value determined in the Fast Track report is a significant decrease for all propagation configurations [2]. The Anderson-2D clutter configuration is around 38.1% of the original total.

Another component of the exclusion zone modeling was to determine if there is any relationship between path loss levels and population impact. The idea being if there is value of improving the accuracy in FDR factors by improving equipment descriptions of radars. This relationship can approximate the population value of a dB. Figure 3.5-37 show the relationship between path loss and population impact for each propagation model configuration in each coast area.

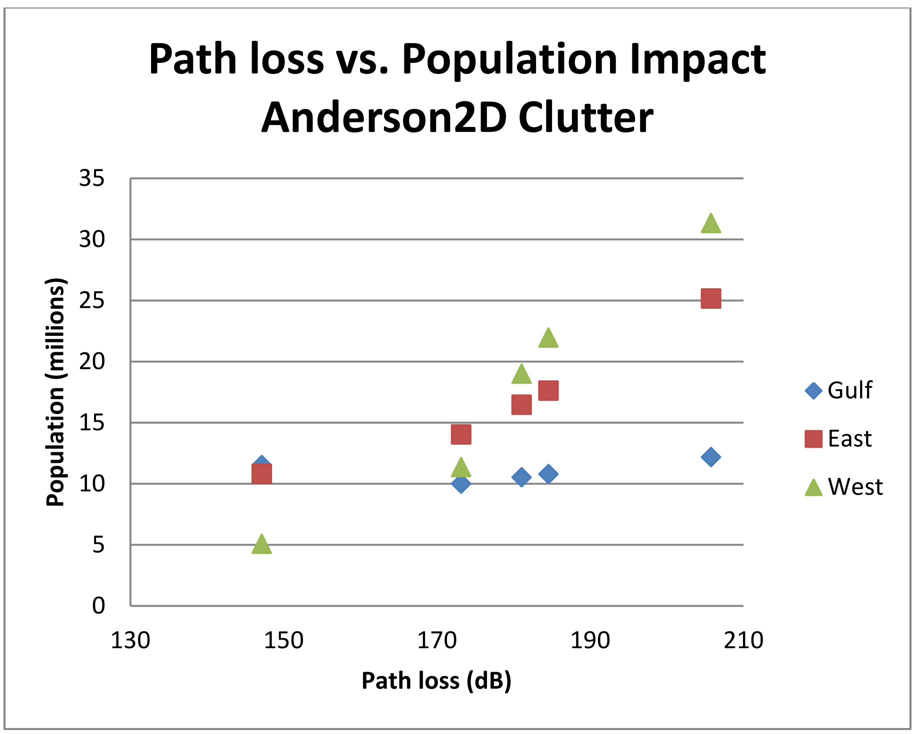

Figure 3.5 Population per dB – Anderson-2D Clutter

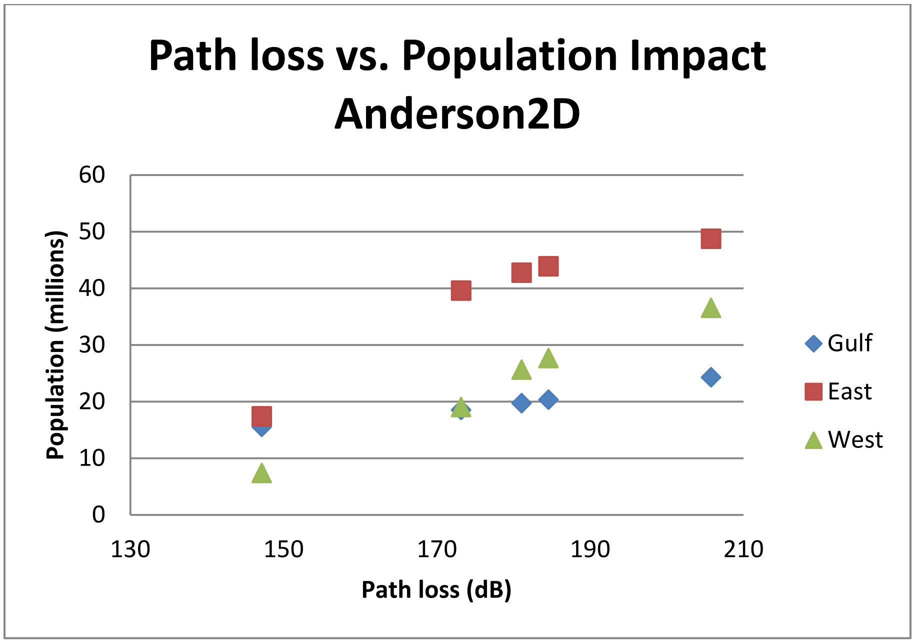

Figure 3.6 Population per dB – Anderson-2D

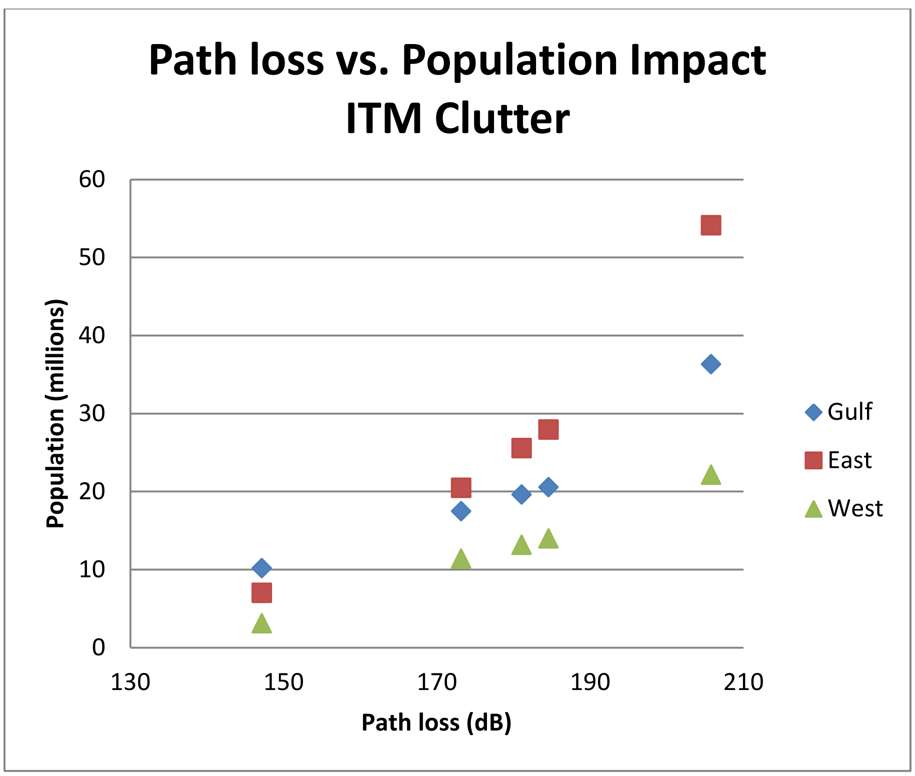

Figure 3.7 Population per dB – ITM Clutter

The relationship was found to match closest to a linear regression based on R^2 values of various regression techniques. Table 3.2 shows the slope values, average and standard deviation of the slopes per propagation configuration.

	Anderson-2D	**Anderson-2D Clutter**	**ITM Clutter**
Gulf	148213	10518	428115
East	544982	242036	780128
West	509414	462440	319010
Average	**400869.7**	**238331.33**	**509084.3**
Std Dev	219528.6	225983.78	240986.5

Table 3.2 Average Slopes of Population vs. Path loss

The interpretation of this table is that for each dB increase of pathloss on the West coast using the Anderson-2D clutter method will result in 462,440 people being impacted. The overall results from this analysis are not clear though. First, there are not enough sample points to provide a reasonable level of standard deviation. Second, the Anderson-2D clutter method has the outlier value for the Gulf coast which is due to the smooth earth propagation problem discussed previously. What this also shows is that the population per dB path loss depends completely on the propagation model that is being used and the coast region being analyzed.

In addition, one of the other significant differences between this modeling work and NTIA's work in the Fast Track report is the inclusion of clutter data into the prediction model. An analysis was done to determine how the use of clutter impacted the population within the exclusion zone. Figure 3.8 shows the impact of using clutter in the Anderson-2D model.

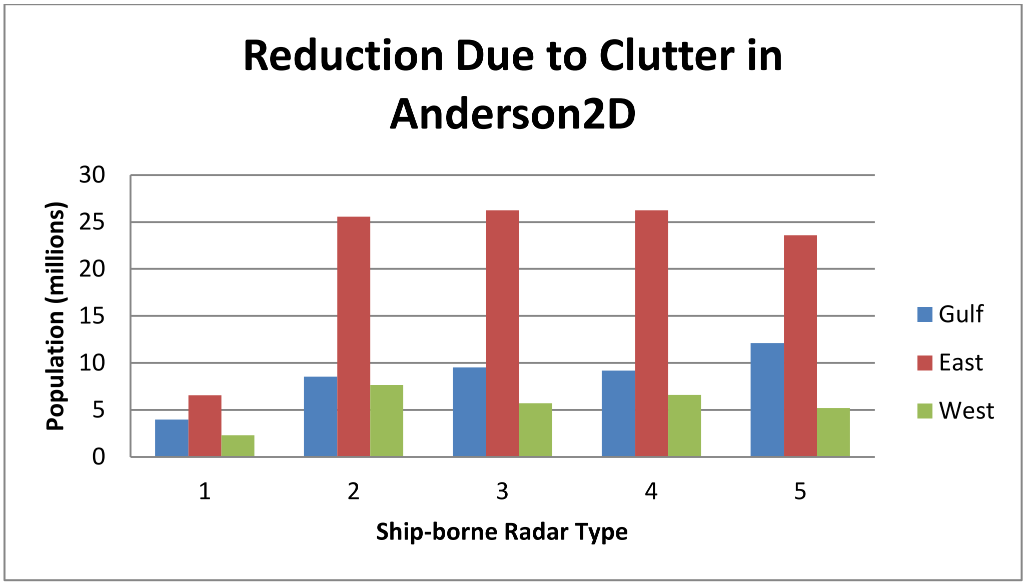

Figure 3.8 Clutter Impact in Anderson-2D

The East coast was found to have the most impact due to the addition of clutter in the Anderson-2D model. The reason for this is that the East coast is heavily forested and built up so there is significantly more clutter here than the Gulf coast. Also, the West coast is more terrain dependent so clutter would have less impact in terms of propagation impacts. Figure 3.9 shows

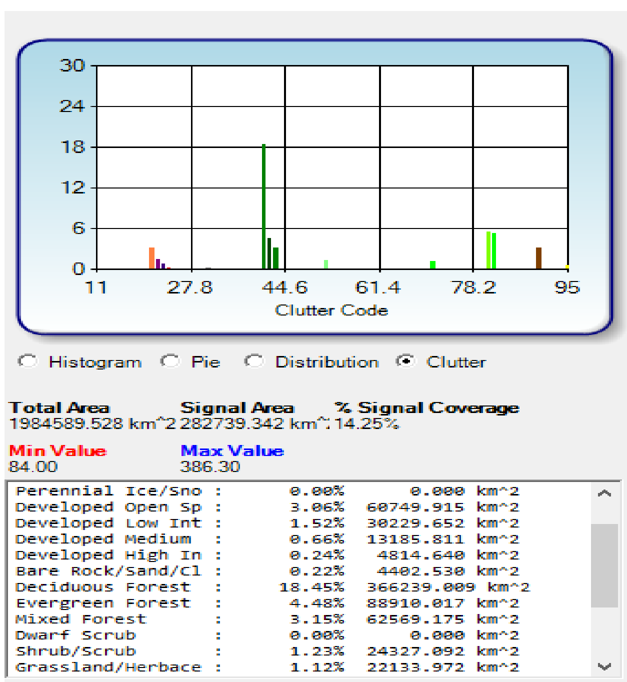

Figure 3.9 Clutter Distribution East Coast

the distribution of clutter on the East coast. In the area of interest on the East coast, tree cover makes up 26% of the land area. Tree cover has a significant attenuation impact, hence is a driver for the increased level of population reduction on the East coast.

In addition to the prior comparison, another comparison was made between the Anderson-2D clutter configuration and the ITM clutter configuration. Figure 3.10 shows the differences between the two models. Positive population values correspond to an increase in population for the ITM clutter model.

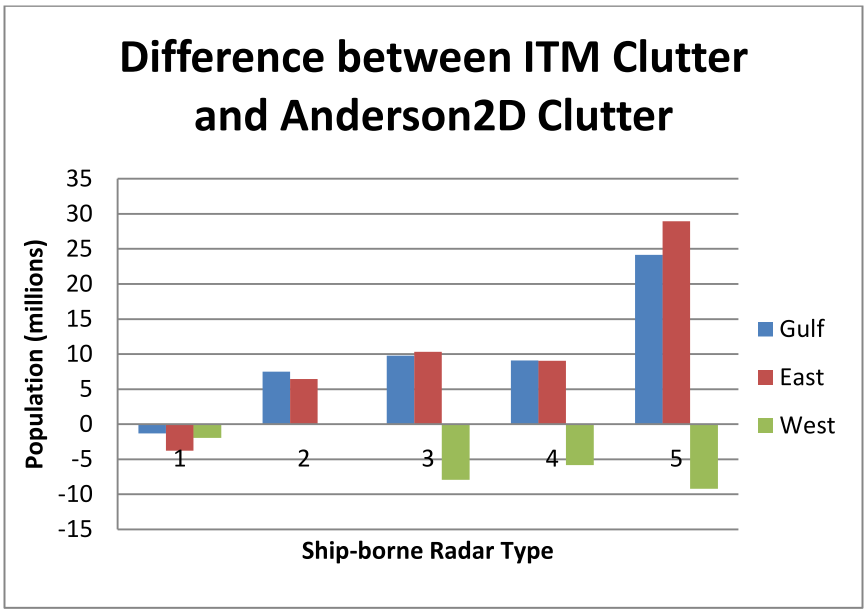

Figure 3.10 ITM Clutter Compared to Anderson-2D Clutter

The graph shows that ITM tends to impact more population for the Gulf and East coasts, however it tends to impact less population for the West coast. It also was shown to predict less impact for Ship-1 which was at a higher antenna height than Ships 2-5. Also, Ship-1 has a significantly less minimum path loss value than Ships 2-5.

The final comparison was determining what differences exists between the original NTIA analysis and the studies generated in this work. The comparison is difficult to make because they are different modeling scenarios including 2 variable factors. The first is the different model configurations but also the fact that instead of a 60 meter AGL WiMax antenna that NTIA used, this work is based on a 8m AGL small cell antenna. However, the comparison is instructive because it shows that improving propagation modeling methods and dropping antenna height provide for a major decrease in exclusion zone distances. Table 3.3 shows the percentage of the NTIA defined exclusion distance that each study resulted in, with 100% corresponding to the full NTIA exclusion distance.

Exclusion Distance - KM	**Anderson-2D**	**Anderson-2D Clutter**	**ITM Clutter**
Gulf			
Ship-1	13.0%	10.3%	9.7%
Ship-2	76.4%	29.2%	58.3%
Ship-3	45.5%	30.0%	40.0%
Ship-4	17.9%	12.9%	14.7%
Ship-5	19.7%	13.3%	39.0%
East			
Ship-1	18.3%	10.8%	13.0%
Ship-2	55.2%	37.7%	68.2%
Ship-3	40.2%	29.0%	51.3%
Ship-4	21.4%	18.3%	24.1%
Ship-5	22.0%	20.7%	42.2%
West			
Ship-1	30.9%	30.0%	18.1%
Ship-2	66.0%	53.2%	58.3%
Ship-3	63.6%	60.1%	63.6%
Ship-4	44.8%	37.6%	40.3%
Ship-5	50.6%	43.6%	48.9%

Table 3.3 Percentage of NTIA Exclusion Distances

The results in Table 3.3 show that a reduction was found in all cases and that Anderson-2D with clutter showed the greatest reduction overall.

3.2 Radar as Victim

The results of the aggregate interference analysis are detailed in this section. Figure 3.11 shows the loading distribution of small cell devices. It is also showing an example of a study result of the devices that are producing signal levels at the radar receiver that are above the interference threshold level.

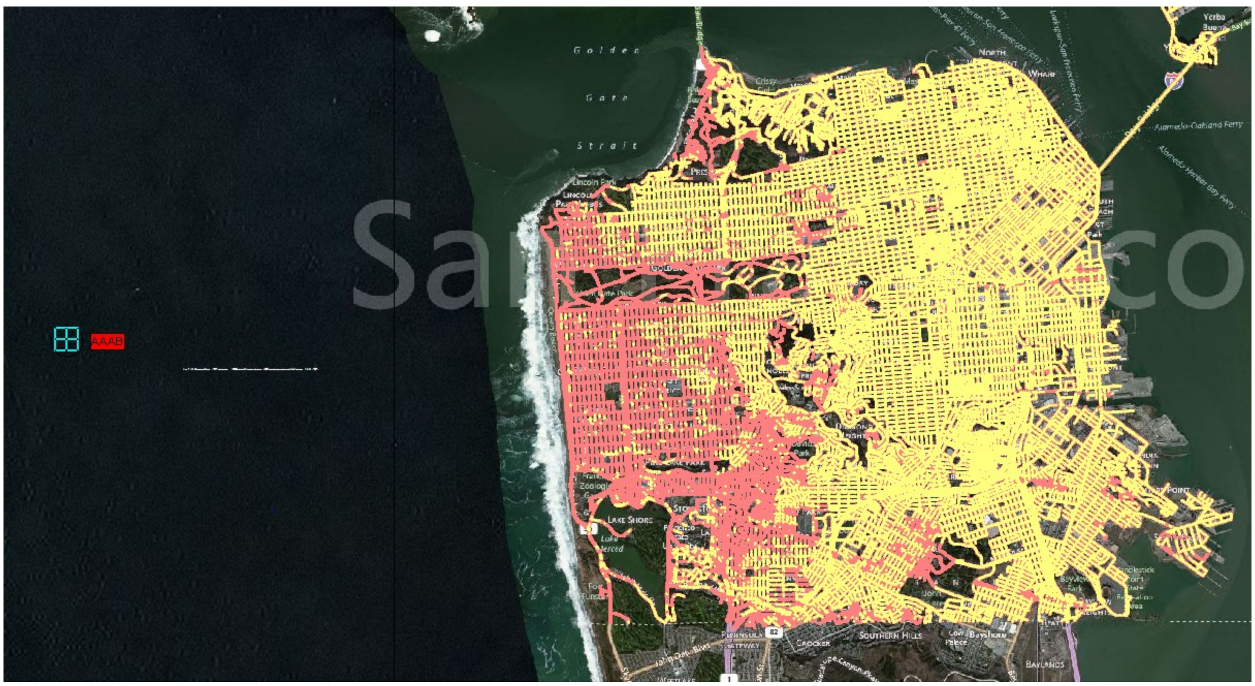

Figure 3.11 Small Cell Device Distribution

Table 3.4 shows the calculated aggregate impact of both model configurations for Ship 1-3.

Ship Type	Aggregate Power at Radar Receiver (dBm) Anderson-2D w/Bldgs and Trees	Aggregate Power at Radar Receiver (dBm) ITM Terrain Only	Anderson-2D and ITM Difference (dB)
Ship 1	-92.6	-68.0	24.6
Ship 2	-77.9	-53.0	24.9
Ship 3	-83.2	-58.2	25

Table 3.4 Aggregate Impact Results

The results show a fairly consistent difference of ~25 dB in aggregate interference levels at the radar receiver between Anderson-2D and ITM. Generally speaking, ITM most likely is over-predicting interference impacts as it is only using terrain data and not accounting for the dense built-up environment of San Francisco. This over-prediction will translate to an increase in exclusion zone distance definition. To make matters worse, the traditional method that NTIA used for this aggregate impact study was ITM in area mode which does not even account for specific terrain losses, although their method does provide for a non-specific terrain loss variable factor. This would have resulted in significantly more devices contributing to aggregate impact. This also shows that location matters. The site-specific nature of exclusion zones should be based on site-specific modeling of aggregate interference impacts.

CHAPTER 4

DISCUSSION

Chapter 4 provides a discussion of the results chapter and presents major findings in regards to propagation models, environmental data, equipment information, exclusion zones and aggregate impact analysis. The Anderson-2D model provides a solid framework for small cell and radar modeling but needs extension regarding smooth earth and over the horizon path conditions. The ITM model is insufficient for modeling of small cells due to it is lack of support for LULC and structure data. Higher resolution environmental data is necessary for modeling of small cell propagation cases. NTIA provides limited information regarding radar equipment which hinders granular interference modeling. Exclusion zones can be decreased via the revised modeling method. Aggregate impact analysis can be accomplished in a site-specific mode and provides more granular data to spectrum policy making.

4.1 Propagation Models

The propagation models used in this research included Anderson-2D and ITM. The models were both used to predict exclusion zone ranges over a vast swath of the US. However, it was found that ITM does not support the use of high resolution environmental data such as building data and high resolution LULC data. The model does not have a mode to support the look-up of building data or LULC along a path. Also, technically the model is not supposed to be used with LULC data at all. These limitations of the model and the various other issues described previously result in a model that is not applicable in modeling of small cell systems.

The Anderson-2D model was tested and found to support the use of building data and LULC data. The model is a basic physical model that can adapt to the introduction of higher resolution datasets and use these in a deterministic way. The adaptability of the model to various propagation scenarios and the ability to respect the defined physical environment makes it a better method of modeling small cell systems. The model does have shortcomings in regards to over the horizon propagation effects especially in regards to a smooth Earth path condition. The recommendation based on the research completed is that the Anderson-2D model or other similar basic physical model can be extended via an open technical working group to provide adjustments for over-the-horizon and smooth earth path conditions.

In addition, it is recommended that more investigation is completed on LULC methods and their applicability to small cell modeling.

Also, it was found that there has not been significant measurement work done on 3.5 GHz radars operating over land areas especially of long range path conditions. It is recommended that a measurement campaign be developed to support modeling of these propagation scenarios so that the modeling approach can be validated.

4.2 Environmental Data

The industry trend towards small cell architectures requires modeling techniques that provide an adequate description of the propagation environment. This requires the use of higher resolution environmental databases that are becoming increasingly available. The ITM model was developed in an era when there were not digital elevation models (terrain) available, although it has been updated to support 3 arc second (100 m) terrain data. There are now 1/3 arc second (10 meter) terrain databases freely available over the entire US from the USGS. Also, there are commercial LULC datasets that have been developed for RF propagation modeling that provide full coverage of the US at 15 meter resolution with the ability to produce even higher resolution datasets as needed. In addition to the available terrain and LULC data available there is also 5 meter and higher resolution digital surface model data of the entire US that can be used to derive the actual heights of each LULC grid point. Finally, there are available building databases that can either be found freely or purchased from a commercial data vendor. As data becomes more readily available, then spectrum policy crafters should be able to take advantage of this improved information.

If you examine current regulatory propagation models like ITM, it has been shown to only operate with the lower resolution databases. Hence all of regulatory bodies that have built spectrum policy methods upon ITM are basing that on data that was developed in the 1980's. The recommendation of this researcher is to transition to a method that takes advantage of the newer and more accurate environmental databases. An ideal dataset would be the 30 meter terrain data (10 meter for terrain sensitive areas) coupled with 15 meter LULC data with clutter heights. This data currently exists for the entire US. It is recommended that future research examine this database platform and compare this against current modeling techniques and measurements.

4.2 Equipment Information

One of the most interesting findings of this work was that acquiring accurate equipment profiles for radar systems was very difficult if not impossible. The analysis of FDR and the impact of not having an FDR based on measured emission masks and receive filters is informative of the need for access to this information from the Federal government. It was also found that although one NTIA report stated that it could not provide a FDR for a radar model, it was available in another NTIA report. This leads to a potential solution of a third party or neutral clearinghouse where this information can be found and shared within the realm of developing spectrum policy. One research group out of MITRE has recommended a system called Model Based Spectrum Management that would aid in this sharing process [25].

4.3 Exclusion Zones

The small cell as victim exclusion zone modeling work found that all exclusion zones can be reduced when using Anderson-2D or ITM with LULC. This result supports the premise that as the modeling approach granularity increases, the ability to produce more granular spectrum policy increases. This can lead to greater potential spectrum utilization and benefit for the country. This also leads to the result that using a more granular propagation modeling approach is necessary when examining small cell systems in regards to spectrum policy crafting.

Also, after analyzing all of the exclusion zone data and coverage maps that were used to derive the exclusion zone distances, it was apparent that hard and fast exclusion zones can be seen as an inefficient mode of dealing with this radar and small cell sharing scenario. There are extreme cases of mountain tops being illuminated far beyond most impacted areas; this can result in a skewed max exclusion zone. Especially if you consider that a small cell would have a very low probability of being placed on a rugged mountain-top peak such as Mount Rainer outside Seattle. This would result in an inefficient allocation of available spectrum for the sharing service. This effect happens on many levels throughout a large geographic area such as what was examined in this research which results in many missed opportunities for spectrum utilization. A more granular approach would allow operations within these clear zones even though beyond that distance spectrum usage may be not available due to interference potential.

The database technology that was developed for television white-spaces can support this more granular approach and this should be investigated further.

4.4 Aggregate Interference

The aggregate interference modeling completed provided a novel method for loading small cell devices into a site-specific environment. It also demonstrated the use of high resolution environmental data and a propagation model that supports the data. This modeling showed a significant decrease in aggregate interference impact for the same device loading when compared to the ITM approach. There are cases where the opposite result could arise, where the ITM model under predicts aggregate interference. This provides motivation to use a site-specific approach coupled with an appropriate propagation model to developing reasonable exclusion zones. Further work needs to be developed to generalize the approach so that it can be automated and executed over the entire coast regions of the US.

CHAPTER 5

CONCLUSION

The research found that ship-borne radar exclusion zones can be significantly reduced in ship-borne radar operation areas to 38% of the original levels defined by NTIA [2]. In addition, it was found that there was insufficient information provided by the US government in regards to radar equipment specifications to accurately model interference potential, therefore reducing the ability of the policy-maker to achieve appropriate sharing policy. Also, it was found that the ITM propagation model does not use land use data or building data along radio propagation paths, which is necessary for accurate modeling of small cell network deployment cases. Therefore, ITM is insufficient for modeling of radar and small cell system interaction studies. Correspondingly, to accurately model small cell systems in a site-specific manner, the use of higher resolution geographic data and a propagation model that can utilize this data is necessary. It was also found that small cell device loading for aggregate interference impact analysis can be accomplished through use of census and city data and can be done in site-specific manner. This site-specific methodology can support more granular interference potential modeling data that can better shape spectrum policy work.

Generally, the wireless industry and spectrum regulators as a whole have been creating opportunities for increased spectrum access over the last 50 years. They have been accomplishing increased spectrum opportunities by improving technology to the point that Shannon's limit is being approached, denser network topologies such as cellular and now small cells, and novel spectrum policy to support increased utilization of unused spectrum. Typically spectrum regulators are behind the technology advancements and adhere to legacy methods in order to maintain a sense of stability and certainty for incumbents and new entrants. The use of antiquated propagation modeling methods is a result of this dynamic. However, advances in technology that support this capacity expansion should not be bottlenecked by legacy propagation and interference modeling techniques when more granular methods are currently available and proven.

BIBLIOGRAPHY

[1] B. Obama, "Presidential Memorandum: Unleashing the Wireless Broadband Revolution," The White House, Washington DC, June 28, 2010.

[2] "An Assessment of the Near-Term Viability of Accommodating Wireless Broadband Systems in the 1675-1710 Mhz, 1755-1780 MHz, 3500-3650 MHz, and 4200-4220 MHz, 4380-4400 MHz Bands," U.S. Department of Commerce, Washington DC, Oct. 2010.

[3] "An Assessment of the Value of Small Cell Services to Operators," Realwireless Ltd., West Sussex, UK, Tech. Rep. Oct. 2012.

[4] M. Skolnik, *Introduction to Radar Systems*. 3rd ed. New York: Mcgraw-Hill, 2001, ch. 1, pp. 1-5.

[5] *United States Radar Equipment*, MIL-HDBK-162B, Washington DC, 1973, pp. 835-948.

[6] N. Friedman, *World Naval Weapons Systems*. 1st ed. Annapolis, MD: US Naval Institute, 1989, pp 150-230.

[7] *Recommendation ITU-R M.1851, Mathematical Models for Radiodetermination Radar Systems Antenna Patterns for use in Interference Analysis*, Int'l Telecommunication Union, 2009.

[8] *FCC GN-Docket No. 12-354, Amendment of the Commission's Rules with Regards to Commercial Operations in the 3550-3650 MHz Band*, FCC, 2012.

[9] B. Joiner *et al*., "Assessment of Federal and Non-Federal Land Mobile Radio Frequency Assignment Methodologies," NTIA, Tech. Rep. NTIA Report 07-447, May, 2007.

[10] Caleb Phillips, Douglas Sicker, and Dirk Grunwald, "The Stability of the Longley-Rice Irregular Terrain Model for Typical Problems," University of Colorado at Boulder, Tech. Report. CU-CS-1086-11, 2011.

[11] A. Paul *et al*., "Evaluation of Two Site-Specific Radio Propagation Models," NTIA.

[12] G. Hufford, "The ITS Irregular Terrain Model, version 1.2.2 the Algorithm," NTIA, Boulder, CO.

[13] "Propagation Models – What are they for?." Available: www.iucaf.org/sschool/darrel/propagat.ppt

[14] H. R. Anderson, *Fixed Broadband Wireless System Design*. 1st ed. West Sussex, UK: Wiley, 2003, pp 1-300.

[15] S. Jones *et al*., “Technical Characteristics of Radiolocation Systems Operating in the 3.1-3.7 GHz Band and Procedures for Assessing EMC with Fixed Earth Station Receivers,” NTIA, Tech. Rep. NTIA Report TR-99-361, Dec. 1999.

[16] *Recommendation ITU-R M.1461-1, Procedures for Determining the Potential for Interference between Radars Operating in the Radiodetermination Service and Systems in Other Services*, Int’l Telecommunications Union, 2003.

[17] E. Drocella *et al*., “Description of a Model to Compute the Aggregate Interference from Radio Local Area Networks Employing Dynamic Frequency Selection to Radars Operating in the 5 GHz Frequency Range,” NTIA, Tech. Memo 09-461, May, 2009.

[18] “Working Group 1- 1695-1710 MHz Meteorological-Satellite,” Commerce Spectrum Management Advisory Committee, Rep. Jan. 2013.

[19] Phillips, C.; Sicker, D.; Grunwald, D., "Bounding the error of path loss models," *New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011 IEEE Symposium on* , vol., no., pp.71,82, 3-6 May 2011

[20] H.R. Anderson, “New Physical 2D EM Model Selected,” *IEEE Vehicular Technology Society News*, Aug. 1997, pp. 15-22.

[21] *Anderson 2D Model*, EDX Wireless, Inc., Eugene, OR.

[22] M.L. Meeks, *Radar Propagation at Low Altitudes*. 1st ed. Dedham, MA: Artech House, 1982.

[23] Imperatore, P.; Salvadori, E.; Chlamtac, I., "Path Loss Measurements at 3.5 GHz: A Trial Test WiMAX Based in Rural Environment," *Testbeds and Research Infrastructure for the Development of Networks and Communities, 2007. TridentCom 2007. 3rd International Conference on* , vol., no., pp.1,8, 21-23 May 2007.

[24] Walden, M.C.; Rowsell, F.J., "Urban propagation measurements and statistical path loss model at 3.5 GHz," *Antennas and Propagation Society International Symposium, 2005 IEEE* , vol.1A, no., pp.363,366 Vol. 1A, 3-8 July 2005.

[25] J. A. Stine, S. Schmitz, “Model-Based Spectrum Management,” MITRE, Tech. Rep. 110131, Apr. 2011.

APPENDIX I

I.1 Small Cell as Victim Raw Data

Exclusion Distance - KM	**Anderson-2D**	**Anderson-2D Clutter**	**ITM Clutter**
Gulf			
Ship-1	44	35	33
Ship-2	81	31	61.8
Ship-3	91	60	80
Ship-4	82	59	67.2
Ship-5	110	74	217
East			
Ship-1	66	39	47
Ship-2	85	58	105
Ship-3	90	65	115
Ship-4	96	82	108
Ship-5	100	94	192
West			
Ship-1	106	103	62
Ship-2	155	125	137
Ship-3	182	172	182
Ship-4	181	152	163
Ship-5	210	181	203

Exclusion Zone Max - KM	**Anderson-2D**	**Anderson-2D Clutter**	**ITM Clutter**
Gulf	110	74	217
East	100	94	192
West	210	181	203

Population Impact	**Anderson-2D**	**Anderson-2D Clutter**	**ITM Clutter**
Gulf			
Ship-1	15,469,426	11,486,826	10148211
Ship-2	18,512,514	9,973,656	17473497
Ship-3	20,290,500	10,764,165	20515058
Ship-4	19,682,648	10,509,240	19600793
Ship-5	24,245,895	12,151,178	36299266
East			
Ship-1	17,344,312	10,784,014	6999033
Ship-2	39,579,185	14,024,504	20450262
Ship-3	43,853,984	17,601,992	27920276
Ship-4	42,706,078	16,456,039	25518690
Ship-5	48,730,814	25,148,727	54082886
West			
Ship-1	7,354,801	5,049,595	3106392
Ship-2	18,981,642	11,339,912	11392682
Ship-3	27,653,044	21,942,656	13984789
Ship-4	25,580,742	18,997,467	13160934
Ship-5	36,523,189	31,328,223	22113008

Population Impact Total	**Anderson-2D**	**Anderson-2D Clutter**	**ITM Clutter**
Gulf	24,245,895	12,151,178	36,299,266
East	48,730,814	25,148,727	54,082,886
West	36,523,189	31,328,223	22,113,008
Total	**109,499,898**	**68,628,128**	**112,495,160**

I.2 Anderson-2D Clutter Coverage Maps

I.2.1 West Coast

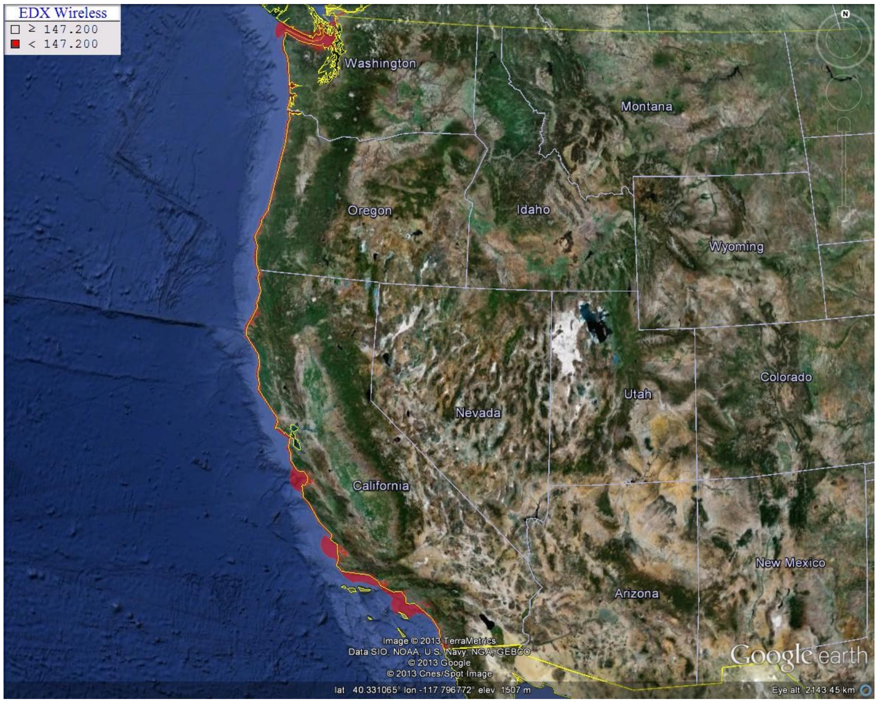

Figure I.1 Ship-1 West Coast I/N =0

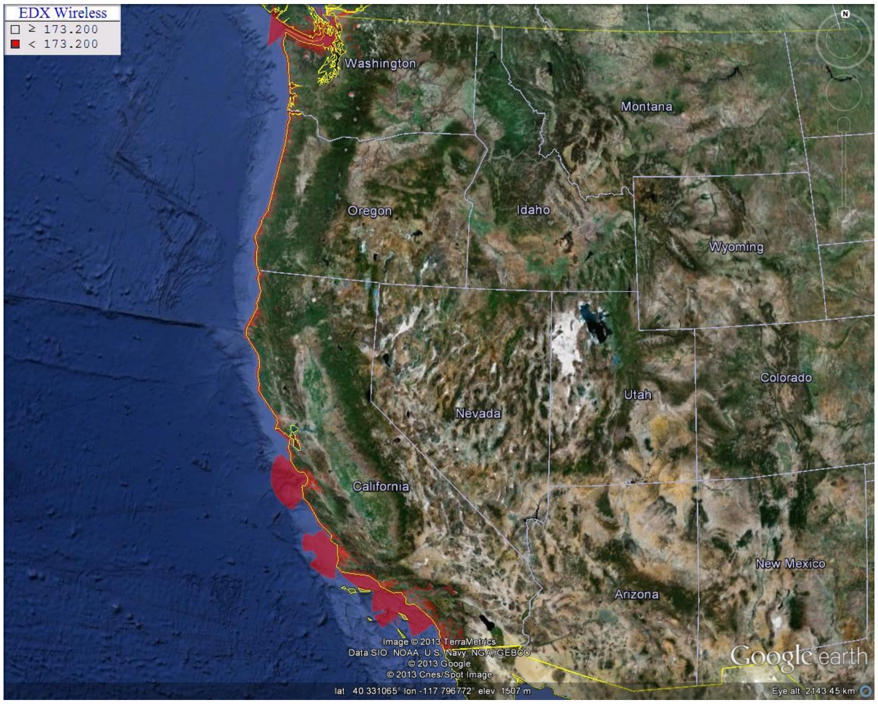

Figure I.2 Ship-2 West Coast I/N = 0

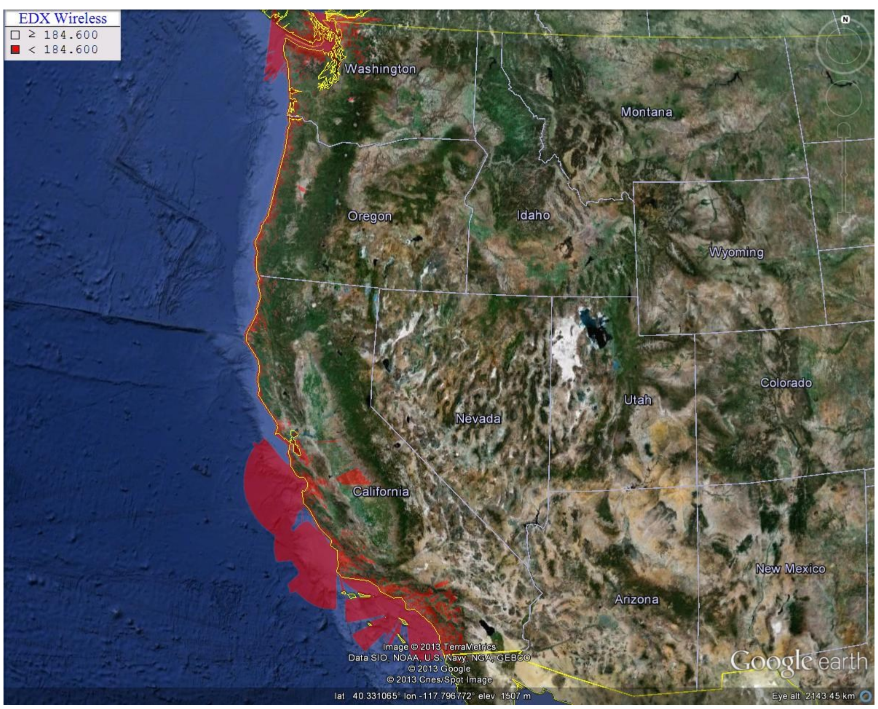

Figure I.3 Ship-3 West Coast I/N = 0

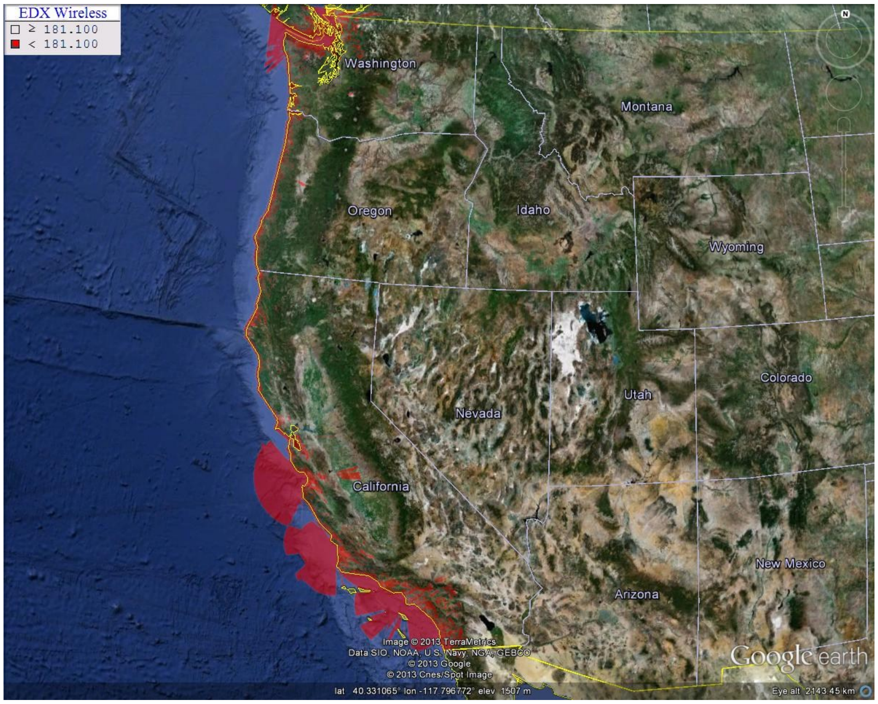

Figure I.4 Ship-4 West Coast I/N = 0

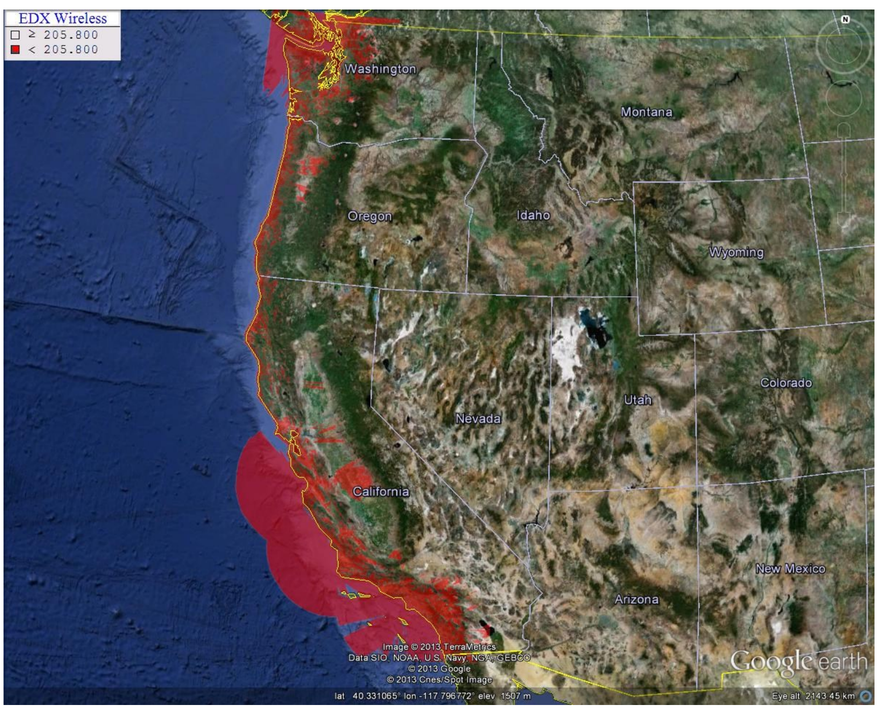

Figure I.5 Ship-5 West Coast I/N = 0

1.2.2 East Coast

Figure I.6 Ship-1 East Coast I/N=0

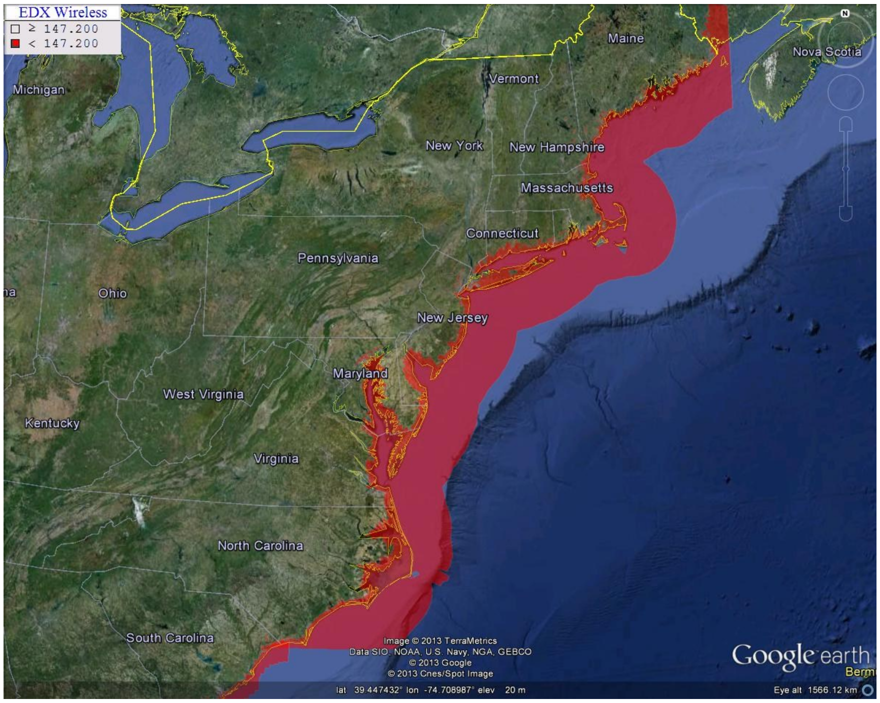

Figure I.7 Ship-2 East Coast I/N=0

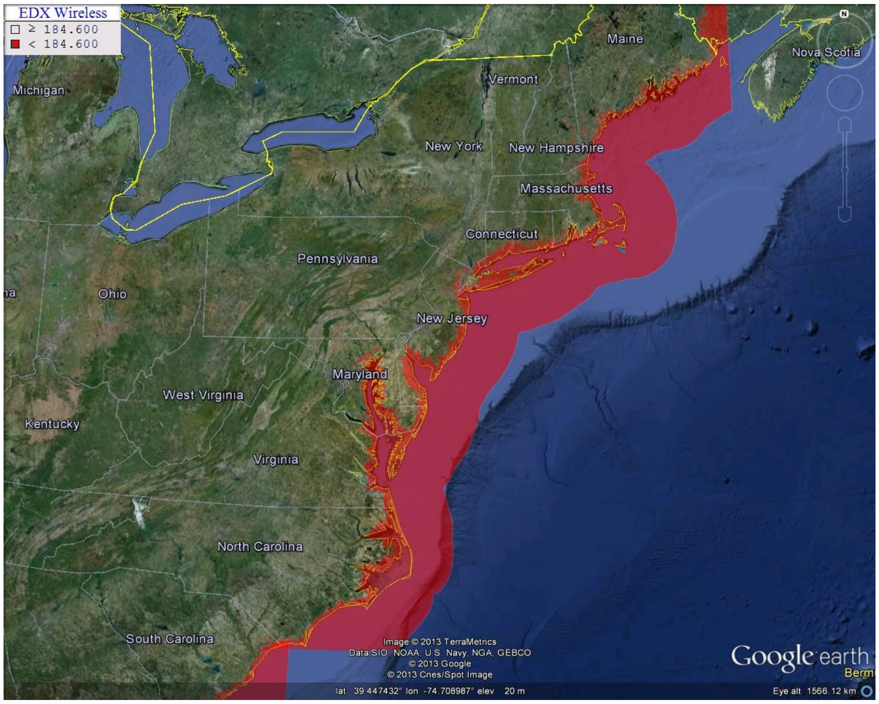

Figure I.8 Ship-3 East Coast I/N=0

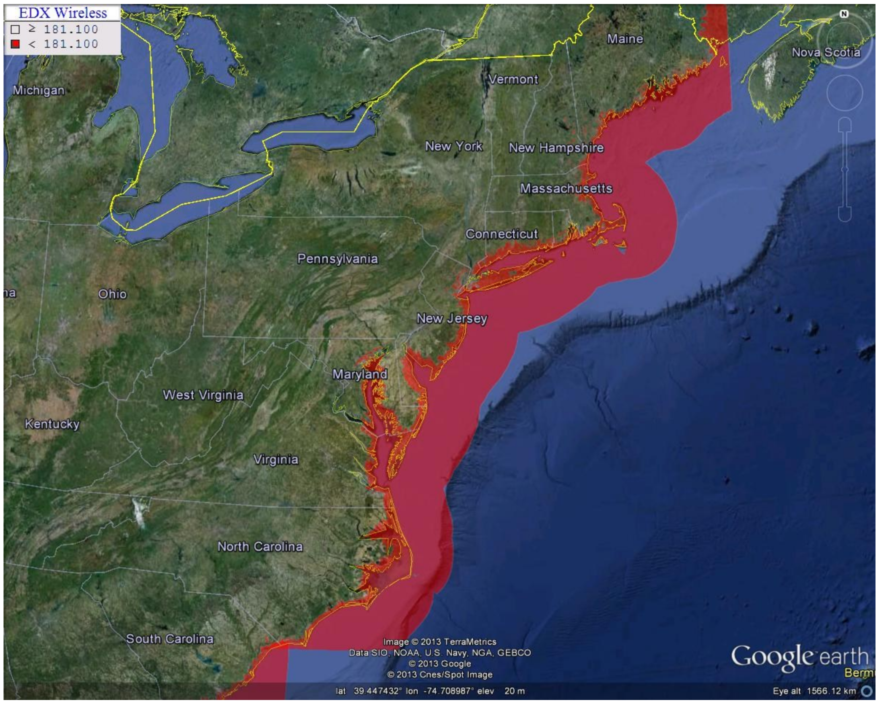

Figure I.9 Ship-4 East Coast I/N=0

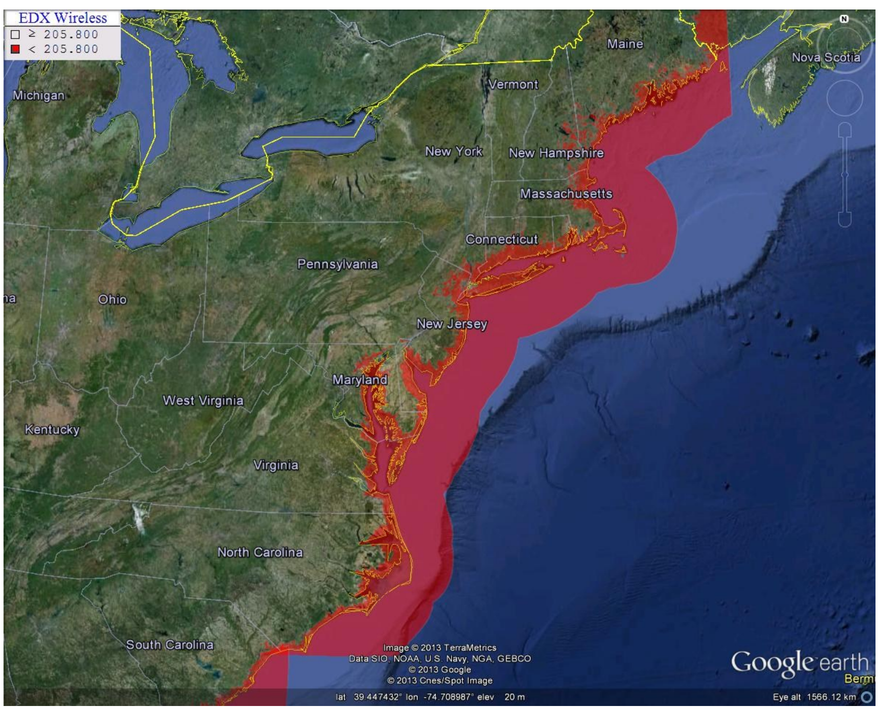

Figure I.10 Ship-5 East Coast I/N=0

1.2.3 Gulf Coast

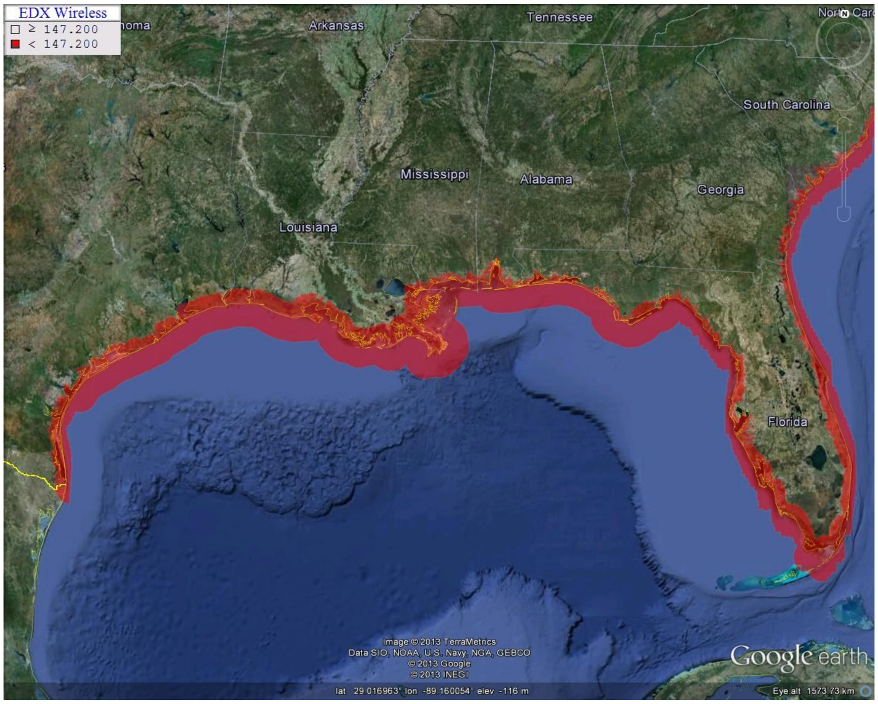

Figure I.11 Ship-1 Gulf Coast I/N=0

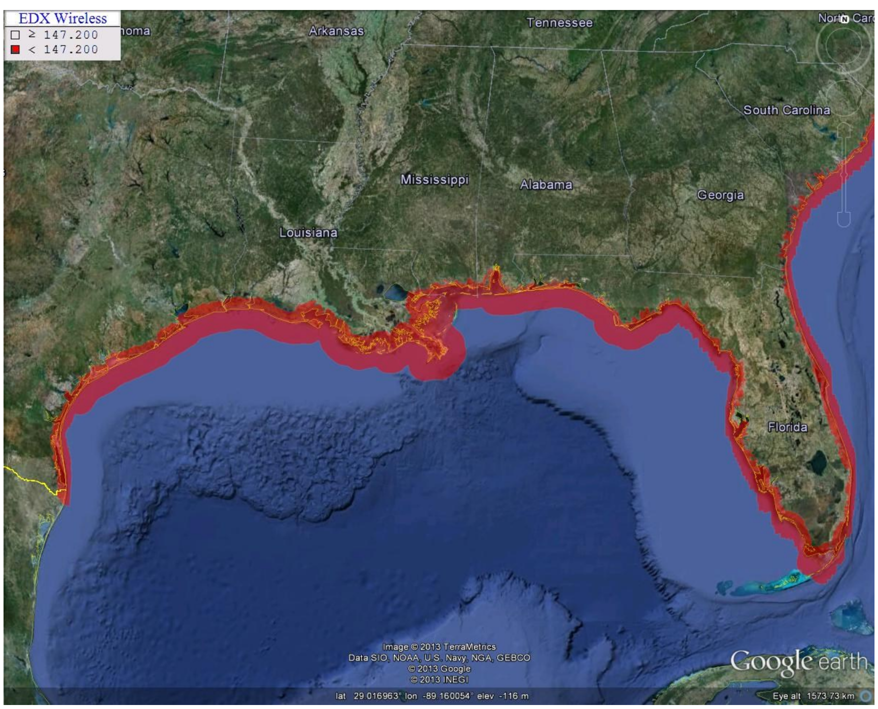

Figure I.12 Ship-2 Gulf Coast I/N=0

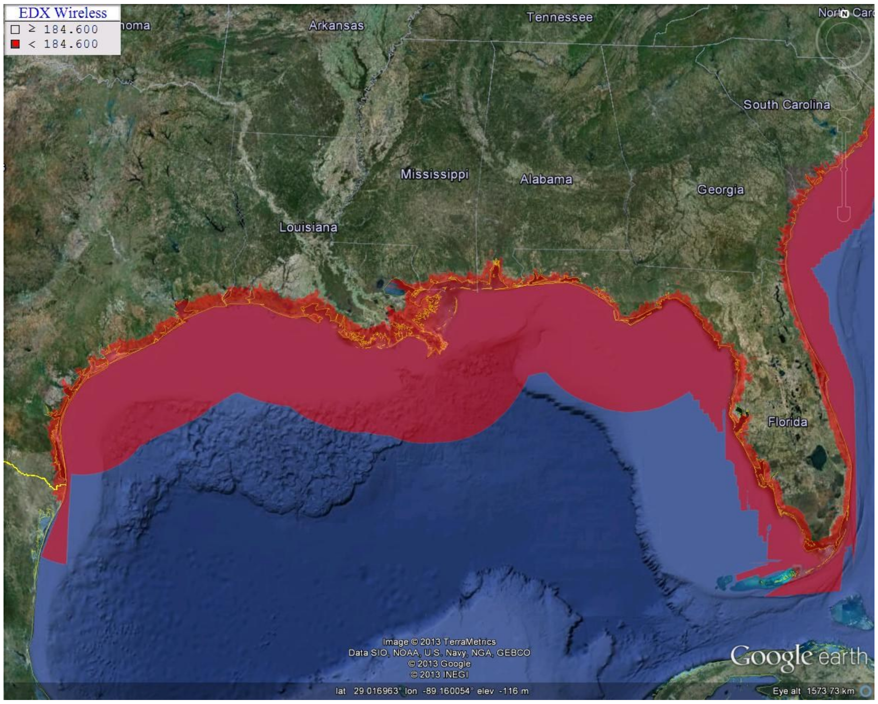

Figure I.13 Ship-3 Gulf Coast I/N=0

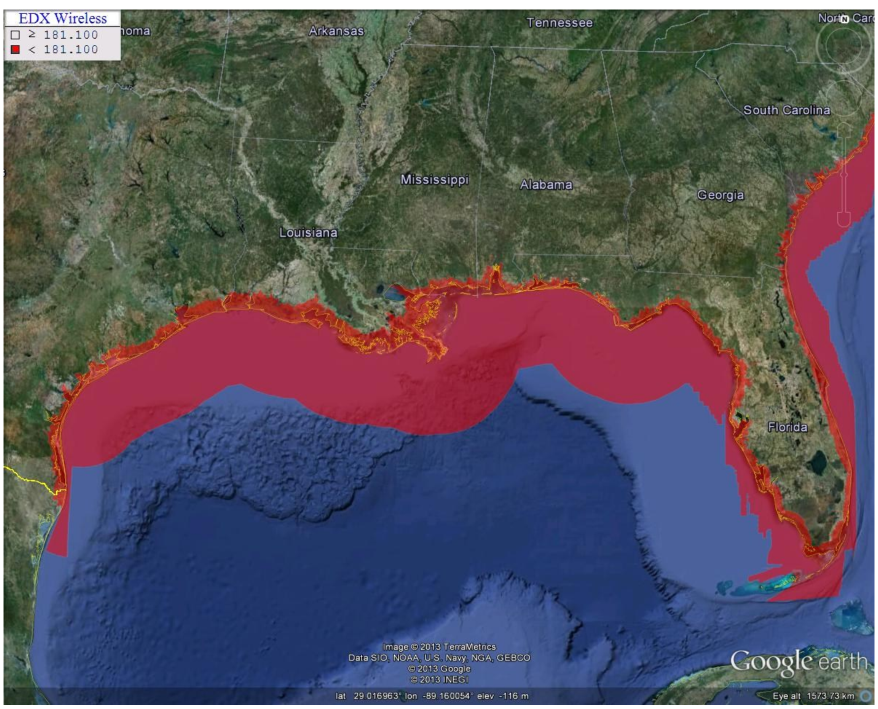

Figure I.14 Ship-4 Gulf Coast I/N=0

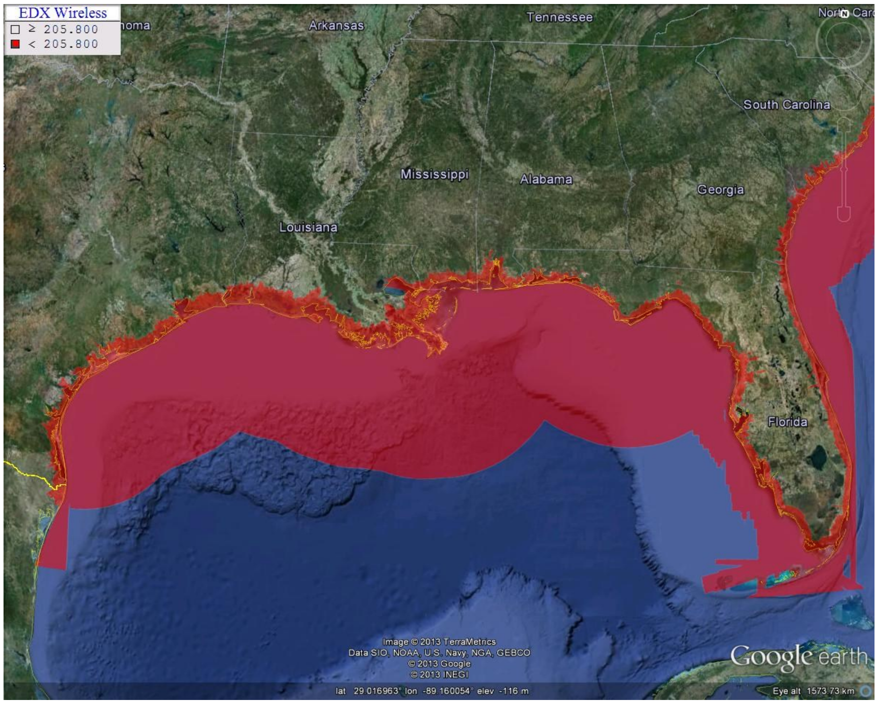

Figure I.15 Ship-5 Gulf Coast I/N=0

I.3 ITM Clutter Coverage Maps

1.3.1 West Coast

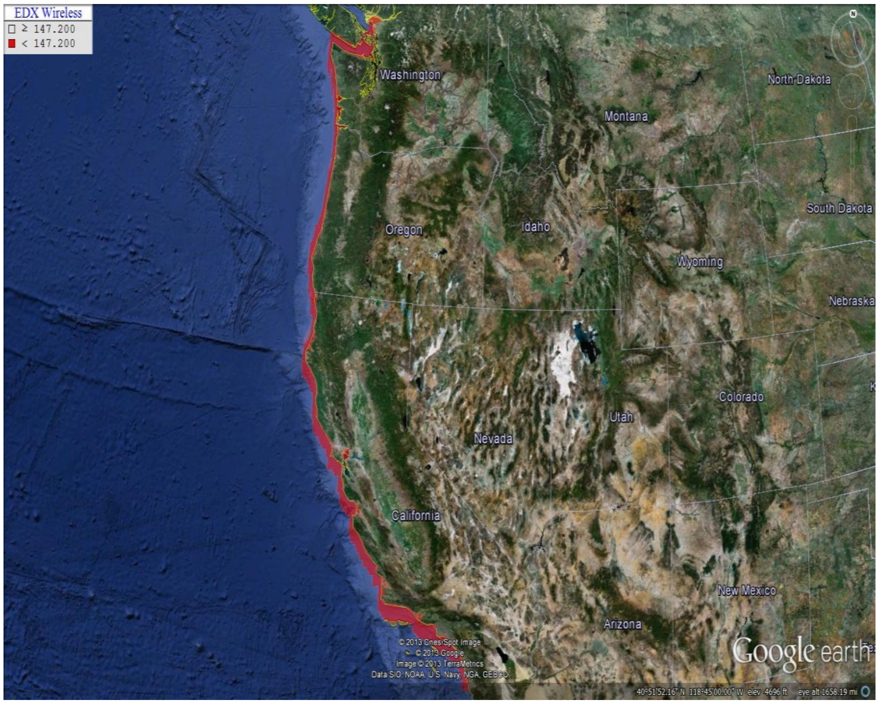

Figure I.15 Ship-1 West Coast I/N=0

Figure I.15 Ship-2 West Coast I/N=0

Figure I.15 Ship-3 West Coast I/N=0

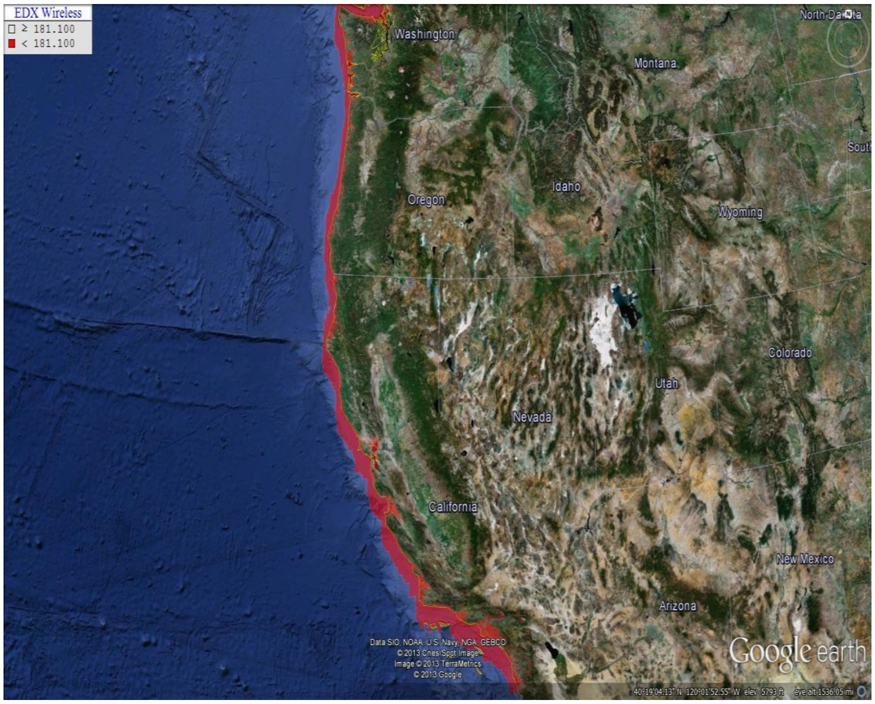

Figure I.15 Ship-4 West Coast I/N=0

Figure I.15 Ship-5 West Coast I/N=0

1.3.2 East Coast

Figure I.15 Ship-1 East Coast I/N=0

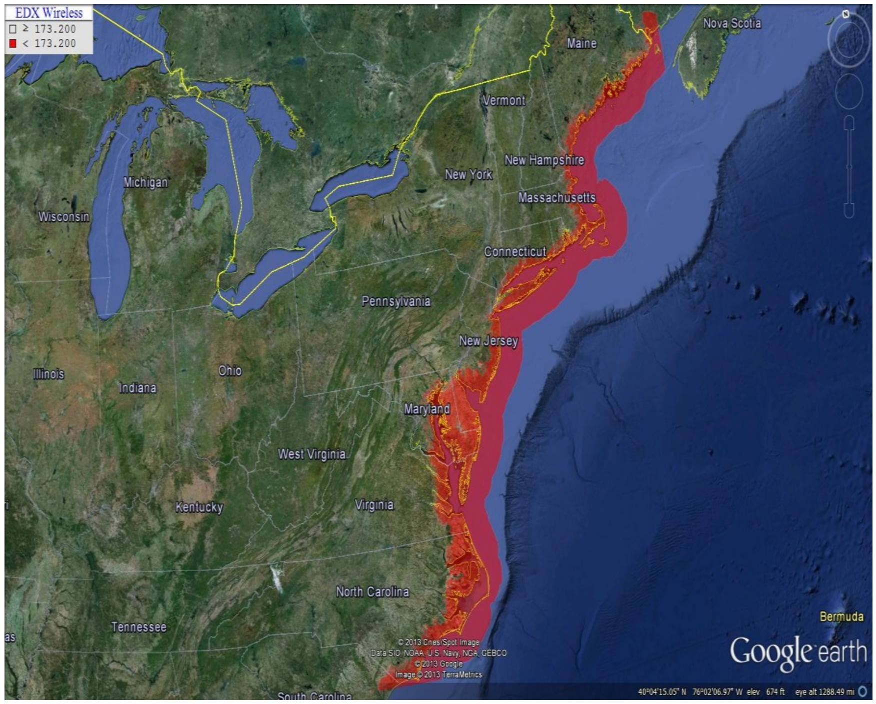

Figure I.15 Ship-2 East Coast I/N=0

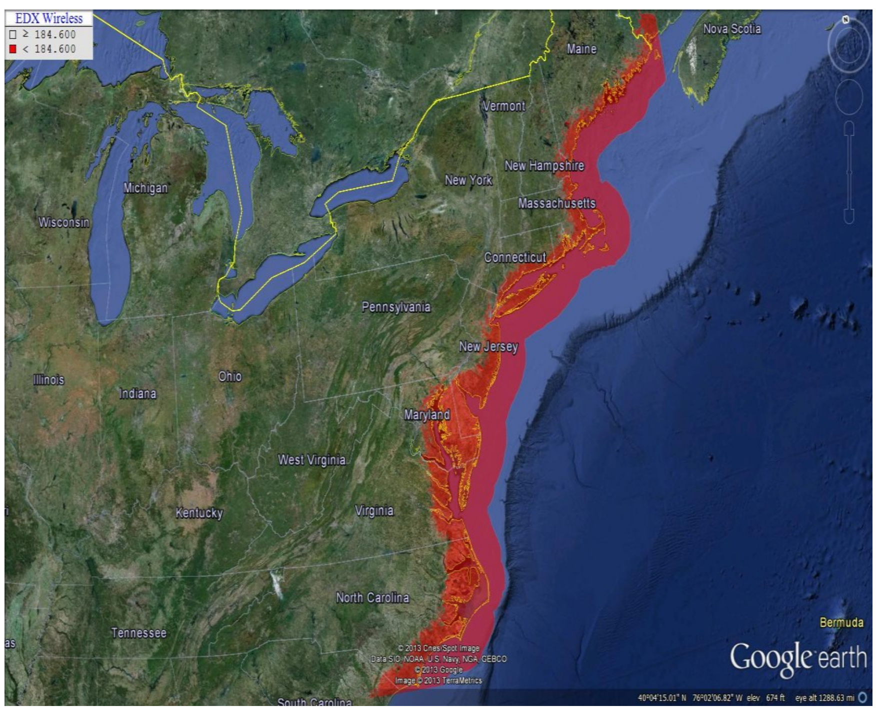

Figure I.15 Ship-3 East Coast I/N=0

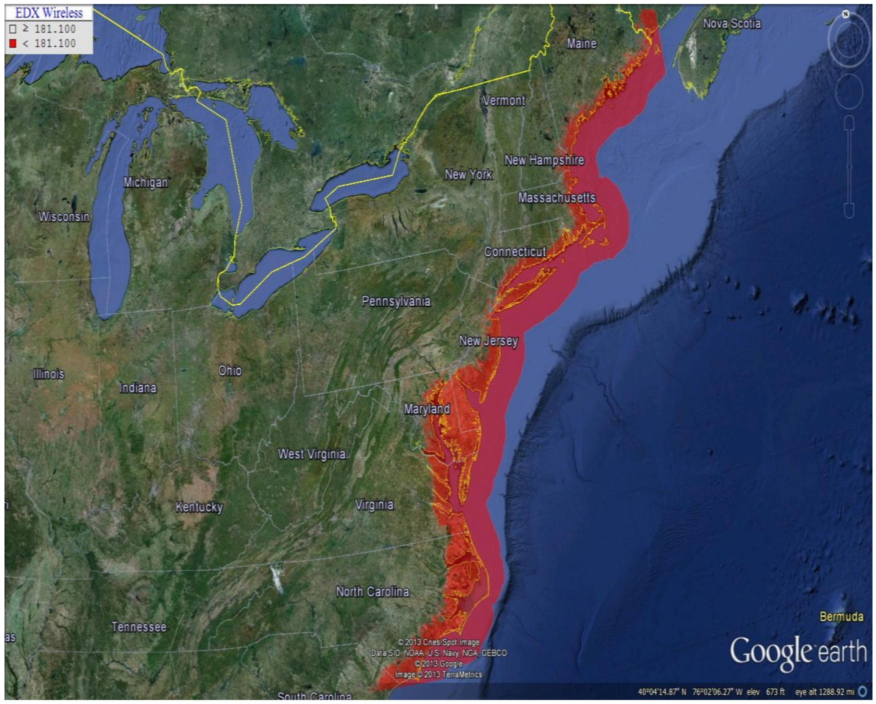

Figure I.15 Ship-4 East Coast I/N=0

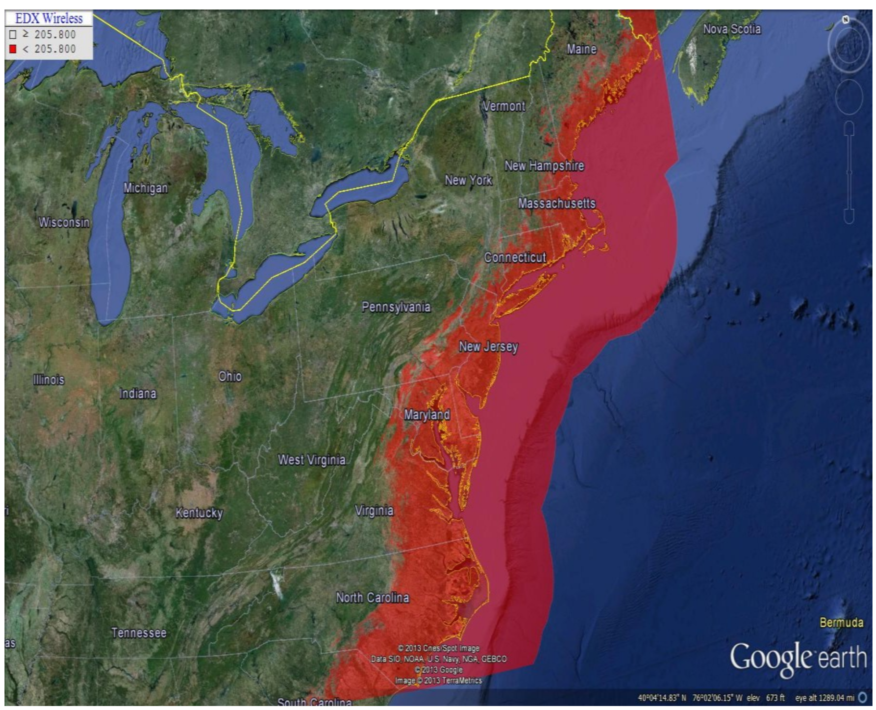

Figure I.15 Ship-5 East Coast I/N=0

1.3.3 Gulf Coast

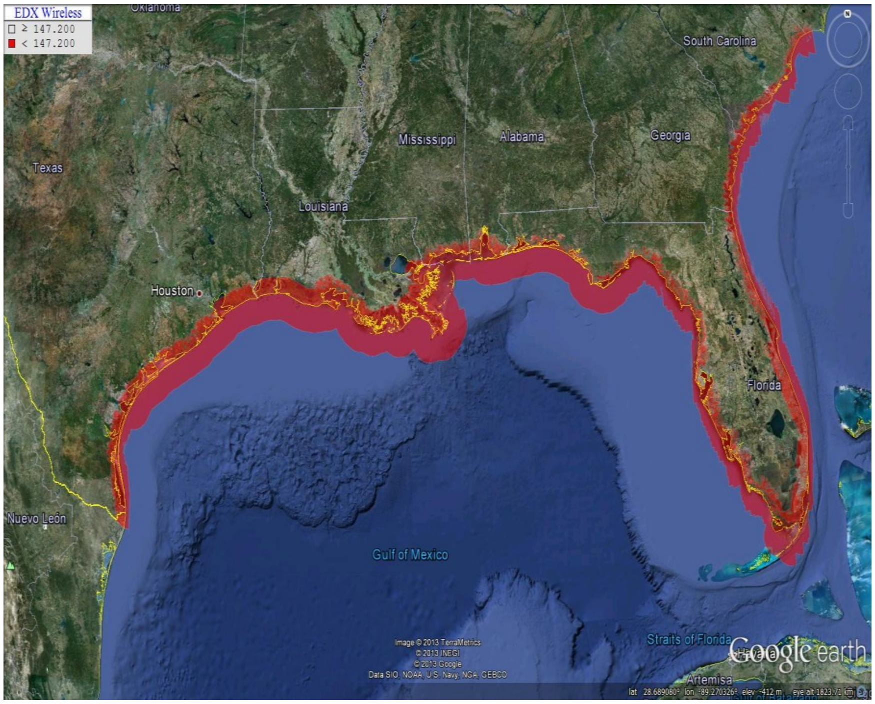

Figure I.15 Ship-1 Gulf Coast I/N=0

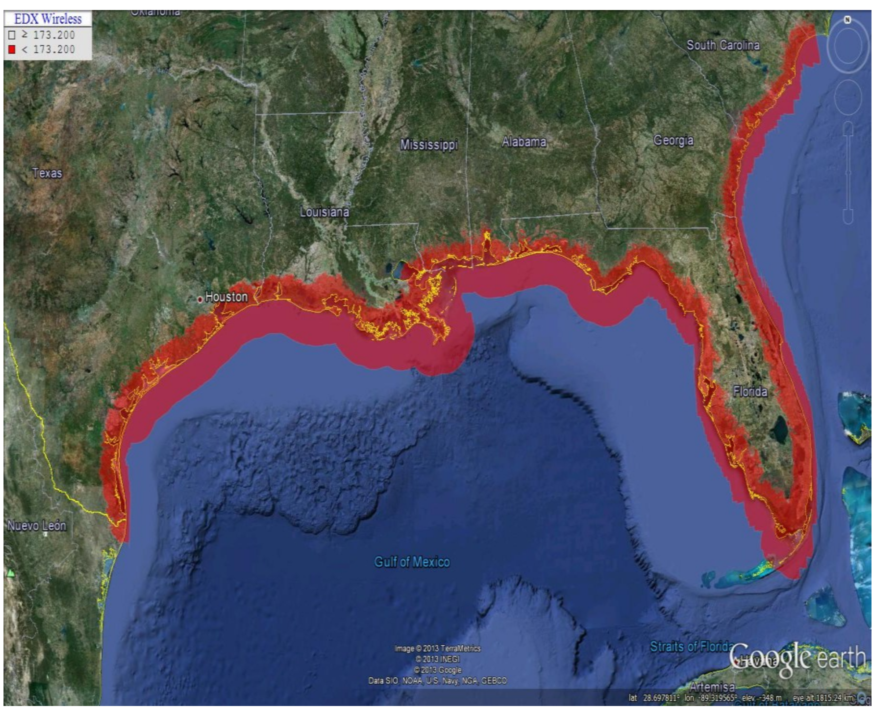

Figure I.15 Ship-2 Gulf Coast I/N=0

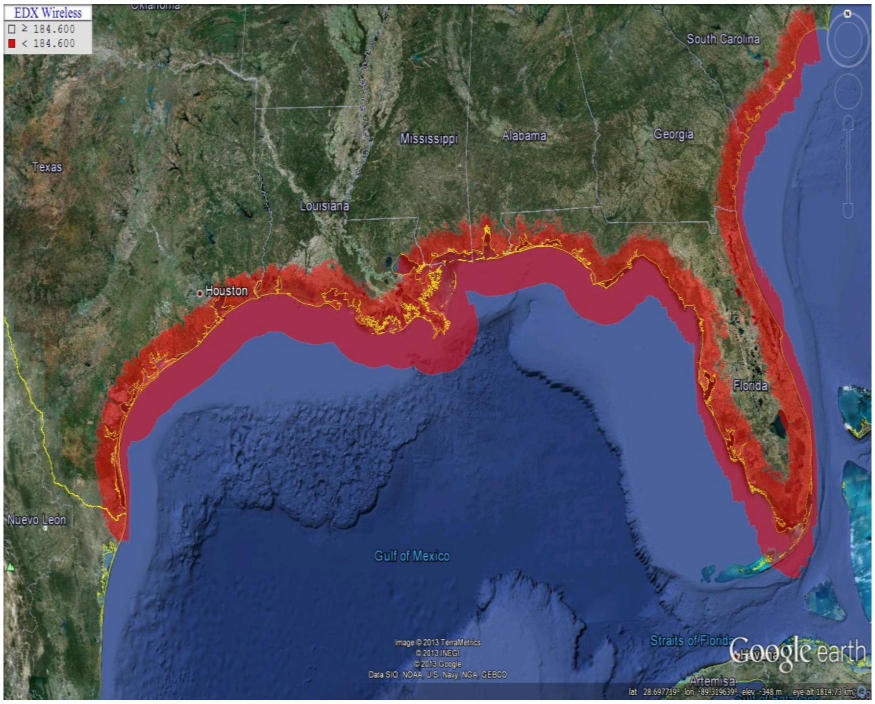

Figure I.15 Ship-3 Gulf Coast I/N=0

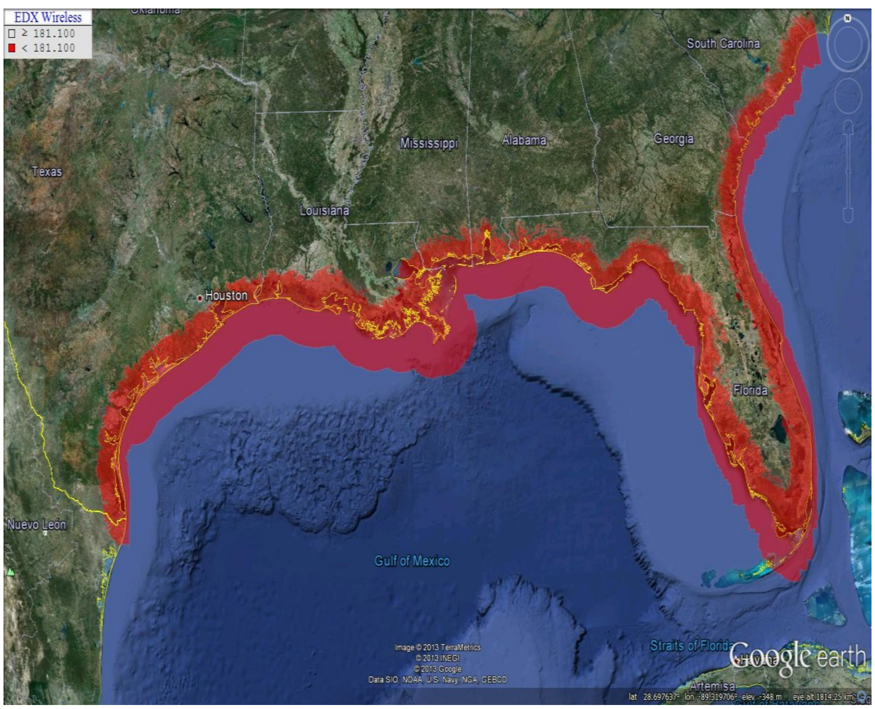

Figure I.15 Ship-4 Gulf Coast I/N=0

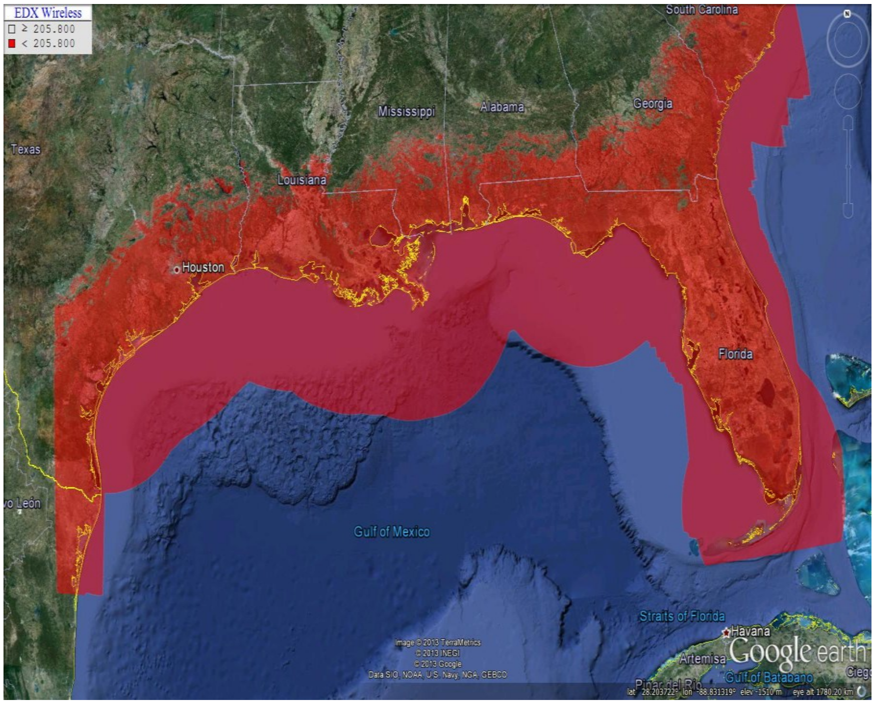

Figure I.15 Ship-5 Gulf Coast I/N=0

I.4 Aggregate Interference Plots

I.4.1 Anderson-2D

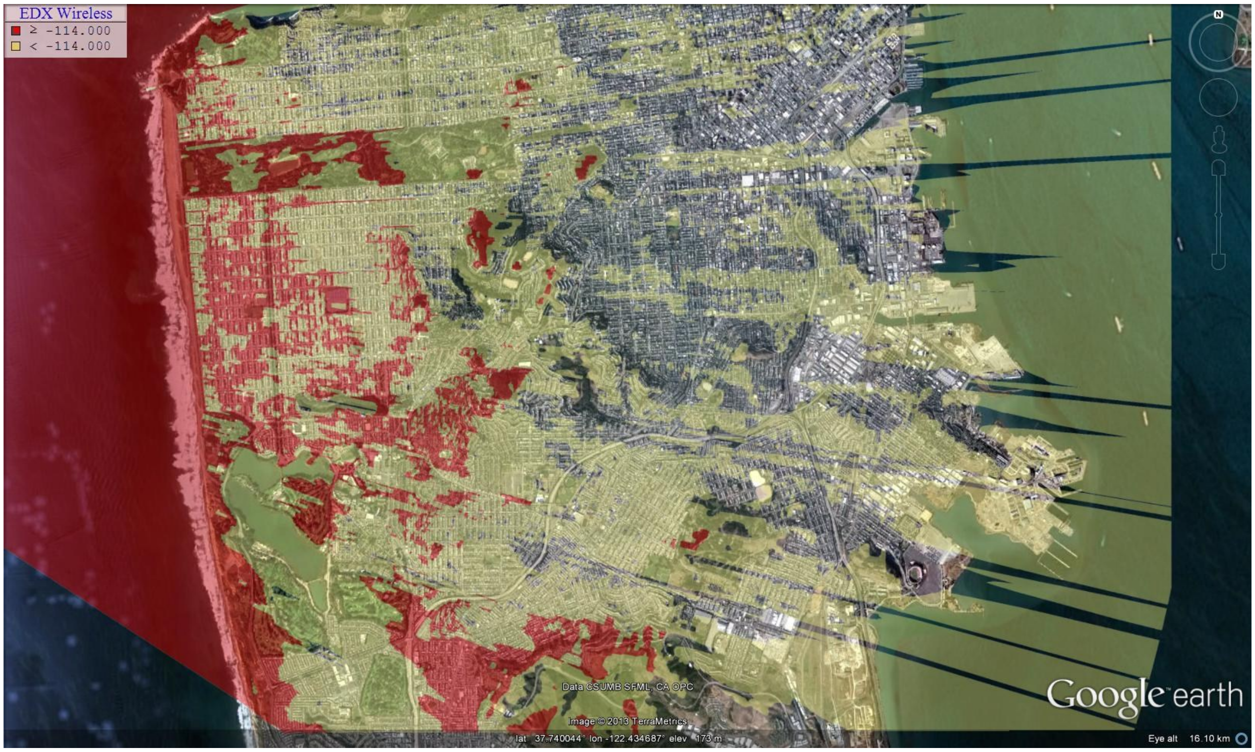

Figure I.16 Ship-1

Figure I.17 Ship-2

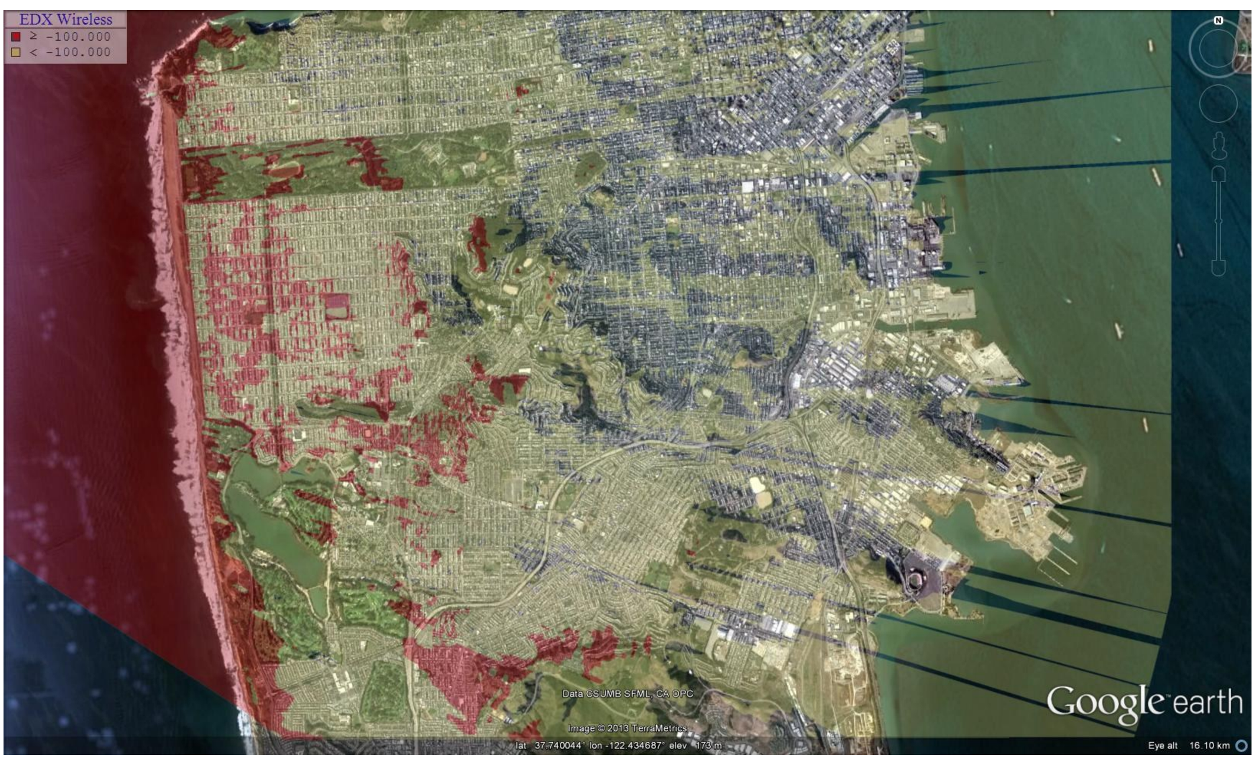

Figure I.18 Ship-3

I.4.2 ITM

Figure I.19 Ship-1

Figure I.20 Ship-2

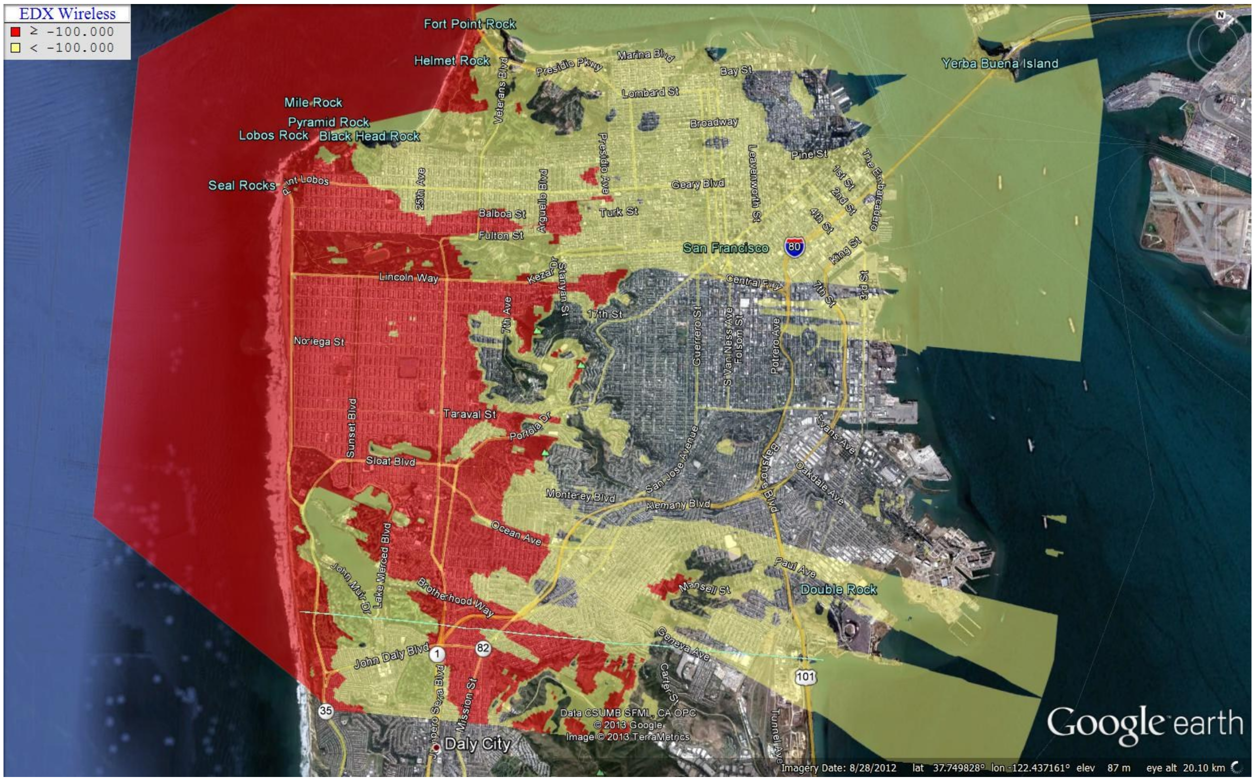

Figure I.21 Ship-3