ON THE ITU-R RECOMMENDATION P.1812-7: A PROPOSAL OF CLUTTER MAPPING

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DISSERTAÇÃO DE MESTRADO
EM ENGENHARIA ELÉTRICA

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DISSERTAÇÃO DE MESTRADO SUBMETIDA AO PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA ELÉTRICA DA UNIVERSIDADE DE BRASÍLIA COMO PARTE DOS REQUISITOS NECESSÁRIOS PARA A OBTENÇÃO DO GRAU DE MESTRE.

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To my parents for being my best teachers in life.
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ABSTRACT

The enhancement telecommunications is crucial for both economic and social progress in contemporary society, as it fosters connectivity among individuals, stimulates innovation, and enables service delivery. Within Brazil, characterized by its extensive and diverse land cover that ranges from urbanized areas to dense forests, the effectiveness of telecommunications planning relies on precise models for predicting signal propagation. Within this context, the ITU-R P.1812-7 model is a very useful tool, however its efficiency might be limited in environments presenting high variability of clutter including features such as vegetation and buildings. In order to refine the losses provoked by such obstructions, this work aims at developing a system using the MCD12Q1 dataset from National Aeronautics and Space Administration (NASA) for clutter mapping, which provides detailed information on terrain to feed the ITU-R P.1812-7 model. For that reason, the proposed system was designed to optimize ITU-R P.1812-7 predictions. To validate its effectiveness, data from the National Telecommunications Agency (ANATEL) and the Brazilian Institute of Geography and Statistics (IBGE) were used, comparing the propagation loss predictions obtained through the optimized system in relation to simpler clutter mapping approaches. The results showed a significant increase in precision, with differences between methods peaking at up to 45 dB in some cases and Mean Absolute Error (MAE) surpassing 10 dB in certain states of the federation. This testifies that the system is able to master the subtleties of Brazil and increase the accuracy even in complex terrains. So, the results show that mapping clutter using high-resolution data should help to improve the propagation signal prediction models, assisting in telecommunications planning for diverse areas and have a positive impact on Brazilian society by facilitating better connectivity, digital inclusion, and greater efficiency in the use of technology.

Keywords: Telecommunications Planning, Signal Propagation, Clutter Mapping, ITU-R P.1812-7

RESUMO

TÍTULO: RECOMENDAÇÃO ITU-R P.1812-7: UMA PROPOSTA DE MAPEAMENTO DE OBSTRUÇÕES

O aprimoramento das telecomunicações é essencial para o desenvolvimento econômico e social na sociedade moderna, conectando pessoas, impulsionando inovações e facilitando serviços. No Brasil, com suas vastas áreas de terrenos complexos e variados, de regiões urbanizadas a densas florestas, a eficiência do planejamento das telecomunicações depende de modelos de predição de propagação de sinal precisos. Neste contexto, o modelo ITU-R P.1812-7 é uma ferramenta de extremo valor, mas sua eficácia pode ser limitada em ambientes com grande variação de clutter (obstruções como vegetação e edificações). Para aprimorar a acurácia das perdas causadas por essas obstruções, este trabalho propõe um sistema que utiliza o dataset MCD12Q1 da *National Aeronautics and Space Administration* (NASA) para realizar o mapeamento de clutter, fornecendo informações detalhadas sobre o terreno para alimentar o modelo ITU-R P.1812-7. Sendo assim, o sistema proposto foi projetado para otimizar as predições do ITU-R P.1812-7. Para validar sua eficácia, dados da Agência Nacional de Telecomunicações (ANATEL) e do Instituto Brasileiro de Geografia e Estatística (IBGE) foram utilizados, comparando as predições de perdas de propagação obtidas com o sistema otimizado em relação a abordagens mais simples de mapeamento de clutter. Os resultados mostraram uma melhoria significativa na precisão, com a presença de erros máximos entre as abordagens em até 45 dB em alguns cenários e *Mean Absolute Error* (MAE) superior a 10 dB em certos estados da federação. Isso destaca a capacidade do sistema em lidar com a complexidade do terreno brasileiro e melhorar a acurácia em regiões desafiadoras. Esses achados sugerem que o uso de dados de alta resolução para mapear clutter pode otimizar modelos de predição de propagação, beneficiando o planejamento das telecomunicações em áreas de difícil acesso e, também, a sociedade brasileira, ao poder proporcionar maior conectividade, inclusão digital e eficiência no uso de tecnologias, essenciais para o desenvolvimento do país.

Palavras-chave: Planejamento de Telecomunicações, Propagação de Sinais, Mapeamento de Clutter, ITU-R P.1812-7

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E_p	Field Strength
L_b	Basic Transmission Loss
μ	Mean
σ	Standard Deviation

GLOSSARY

ANATEL	National Telecommunications Agency
AppEEARS	Application for Extracting and Exploring Analysis Ready Samples
BGC	Biome-Biogeochemical Cycles
CDF	Cumulative Distribution Function
CNN	Convolutional Neural Network
DEM	Digital Elevation Model
DTT	Digital Terrestrial Television
FR	Functional Requirements
HDF4	Hierarchical Data Format, Version 4
HDF5	Hierarchical Data Format, Version 5
IBGE	Institute of Geography and Statistics
ID	Identifier
IDE	Integrated Development Environment
IGBP	International Geosphere-Biosphere Programme
IoT	Internet of Things
ITU	International Telecommunication Union
LAI	Leaf Area Index
LiDAR	Light Detection and Ranging
LoS	Line-of-Sight
MAE	Mean Absolute Error

MCom	Ministry of Communications
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NFR	Non-Functional Requirements
PFT	Plant Functional Types
QoS	Quality of Service
RET	Radiative Energy Transfer
RX	Receiver
SAR	Synthetic Aperture Radar
SRTM	Shuttle Radar Topography Mission
TV	Television
TX	Transmitter
UMD	University of Maryland
VS Code	Visual Studio Code
WGS84	World Geodetic System

CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

In the 21st century, people require constant and broad access to data. This is due to the fact that the world today is characterized by interconnectivity, where there is a need for faster information on different aspects of daily life. For example, in emergencies like natural disasters or health problems, accessing information promptly is vital to save lives. Also, learners and educators rely on uninterrupted Internet connection so as to access online learning platforms, virtual classrooms, and digital resources. Some business requirements call for sound communication systems that aid telecommuting, supply chain management and infiltration into international markets among others. Furthermore and according to [1], the researches and development of smart cities, that intend integrate information and communication technologies to improve the quality of urban services, highlights the importance of reliable transmission.

In this context, wireless communication and its effective use of spectrum, on the one hand, are major problems that need resolution by both industry and the academic community [2]. These issues are critical for technological development, promoting national growth, and global interconnection. This is especially true for various uses, including Wi-Fi, cellular networks, Television (TV) transmission, and national defense. In countries like Brazil, where vast land covers and great diversity in topography places additional demands upon wireless system deployment, these problems become more of a concern. Additionally, due to their wide geographical area, these nations find it much harder to deploy as well as manage communication systems that depend on radio waves. The scale of this challenge can be better appreciated by looking at data indicating that 96% of all homes in Brazil rely on radio waves for TV broadcast purposes [3].

A vital function has been performed by the Digitaliza Brasil Program initiative in Brazil's transition into Digital Terrestrial Television (DTT) especially for broadcasting. This program targeted at having standard measures to change analog transmissions to digital signals by December 2023 [4]. The aim of this government program to improve signal transmission quality as well as provide high definition services. Thus, there is a clear and current need for improvements and processes that make possible national telecommunication planning and policy choices more effective so that people can get maximum benefits from this services. In Brazil this huge burden has been assigned to National Telecommunication Agency (ANATEL) as well as Ministry of Communications (MCom). Among their main tasks, there are the controlling the transition from conventional transmission ways to digitized broadcasting, optimizing spectrum utilization together with ensuring deployment of telecommunication system networks all over country [5].

An instrument for addressing these issues is the ITU-R P.1812-7 recommendation [6], which is suggested by the International Telecommunication Union (ITU) for predicting the propagation signals over different terrains and conditions. This guideline has a systematic approach that is useful when predicting signal coverage in wireless networks and Quality of Service (QoS). However, this model should be optimized to take account of diversity in topography in such large countries like Brazil which have diverse geographical features. This study aims to enhance efficiency of the ITU-R P.1812-7 by adopting modern techniques of clutter mapping through remote sensing. This optimize the calculation of losses caused by obstacles along the link, bringing it closer to real-world conditions.

To achieve this, the clutter mapping focuses on using community datasets such as data generated by National Aeronautics and Space Administration (NASA) and other publicly available data. The inclusion of these datasets enhance transparency in research work as well as cooperation among researchers hence making it possible to continually re-evaluate and refine how things are done in real life. This not only boost model accuracy, which directly impacts the calculation of clutter losses, but also makes it possible for other participants in telecommunications planning to get involved and benefit from every change made. As far as is known, Brazil does not have any open systems that leverage this kind of technology or database specifically for telecommunication planning and development up to this point. While proprietary systems exist and offer similar functionalities, they are often costly, have limited customization options, and may lack transparency in their underlying models and data processing methods. The proposed approach addresses these limitations by offering an open, flexible, and customizable framework, enabling better adaptation to the country's specific geographic and environmental characteristics. Additionally, the integration of open datasets and the possibility of extending the system through community-driven improvements further enhance its potential for long-term development and accessibility. The aim of this study is to fill that gap by providing a national asset for planning purposes and an international scientific one for researchers all over the world.

1.2 OBJECTIVES

The aim of this research is to provide a practical system/methodology that integrates precise clutter mapping for large and diverse area of environments like Brazil, thus enhancing usability of ITU-R P.1812-7 model for broadcast communication and optimizing losses arising from these obstacles along the link. This methodology is made to deal with the distinctive geographical and topographical obstacles in Brazil, therefore providing more precise and reliable predictions for wireless communication systems. This work aims at improving national telecommunications planning efficiency by taking into account the vast and diverse landscape. Ultimately, this effort results in better service provision and connectivity across the country. Specifically, the study intends to fulfill the following specific objectives:

- **Analyze the ITU-R P.1812-7 recommendation**: conduct a analysis and evaluation of the ITU-R P.1812-7 propagation model to assess the impact of clutter on basic transmission loss and identify its limitations and potential areas for improvement in applications to the Brazilian environment;

- **Identify and evaluate auxiliary products for clutter mapping**: get additional materials that strengthen the clutter mapping technique, and concurrently assess their suitability and potential for integration with respect to the accuracy and reliability of clutter losses;

- **Develop clutter mapping techniques**: create methods for accurately mapping clutter in environments like Brazil considering the different types of land cover and topographic configurations present, leading precise classification of land cover;

- **Implement a clutter mapping system**: develop a clutter mapping system that integrates precise geographical and topographical information to precisely illustrate the various forms of clutter found in Brazil;

- **Evaluate the performance of the clutter mapping system**: assess the ITU-R P.1812-7 model's performance in predicting losses due to clutter, comparing results with and without the proposed methodology/system. Simulations have been carried out using databases from Brazilian governmental agencies such as ANATEL and MCom;

- **Publish and disseminate results**: publish research techniques and findings in academic publications as well as presenting results in conferences to disseminating the results to the Brazilian government and scientific community.

1.3 CONTRIBUTIONS

The objective of this research, regarding losses due to clutter, is to enhance the usability of a signal prediction model in order to make contributions in several aspects. Consequently, increased predictability models can allow more simplified as well as precise installation of wireless communication systems and this is essential for national advancement.

Furthermore, this research tends to enhance openness and accountability by offering scientifically verified approaches that policymakers and telecommunications agencies might implement. By leveraging data from Brazilian governmental agencies, such as ANATEL and MCom, the research findings can be immediately pertinent and applicable to the national context, guaranteeing that the results are pragmatic and influential.

This study intends to contribute to the development of better telecommunication planning methodologies in Brazil. By suggesting affordable techniques and producing relevant results, this study will serve to support decision-making processes of concerned stakeholders from different sectors-in such fields as academia, government, and industry-in developing a more data-oriented approach to telecommunications planning.

1.4 WORK STRUCTURE

This work is structured into six chapters, as follow:

- The first chapter presents an extended overview of the research topic, stating the key objectives, justifying the research, and the research questions guiding the investigation;
- The second chapter describes the basic principles that need to be known for an understanding of the research. First, it considers the basics of wireless communications, with special focus on the ITU-R P.1812-7 propagation model. The last section addresses the basics of remote sensing, then describes its various types and approaches, finally describing in detail the MCD12Q1 product, relevant to the study;
- The third chapter undertakes a review of the relevant literature and related works regarding the research topic. The studies investigates the research of the pathloss due to clutter and the methods used for their representation, with specific interest in the modeling of signal propagation. In the end, the chapter identifies areas where is not adequately covered in academic researches;
- The fourth chapter describes the clutter mapping system that is designed to enhance loss predictions in the ITU-R P.1812-7 model. The design of the system deals with the functional and non-functional requirements of the system. The next section discusses the implementation of the system, which includes processing and data collection, followed by key components, tools, and methodologies used during the implementation process. The chapter concludes by presenting the methodologies used to evaluate the system's clutter classification performance and its impact on pathloss prediction results.
- The fifth chapter elucidates the results obtained from the conducted experiments. The primary aims of this step are to assess the effectiveness of the suggested system in the domain of clutter mapping and to determine its efficiency in improving error predictions when applied to the ITU-R P.1812-7 model;
- The sixth chapter of this work provides in-depth analysis of results obtained from the system and methodology proposed, emphasizing significant contributions of the research.

1.5 PUBLICATIONS

The following paper was published during the research:

D. R. C. Aguiar, H. P. T. Silva, H. S. Silva, and U. S. Dias, "Enhancing Signal Prediction Across Brazil: A Clutter Mapping Module for the ITU-R P.1812," in *Anais do XLII Simpósio Brasileiro de Telecomunicações e Processamento de Sinais*, 2024. DOI: 10.14209/sbrt.2024.1571036517.

CHAPTER 2

THEORETICAL BACKGROUND

In this chapter, a brief theoretical basis of this work is presented. In the first section, wireless communications are explored, including their basic principles, signal prediction models, and an extensive review of the ITU-R P.1812-7 recommendation. The second section focuses on some of the fundamental ideas underlying remote sensing techniques and discusses different methods and their practical applications. Additionally, it ends with a comprehensive analysis of MCD12Q1, a land cover classification product.

2.1 WIRELESS COMMUNICATION

Wireless communication has really changed much since its beginning back in late 19th century. By demonstrating electromagnetic waves Heinrich Hertz's innovative research in the year 1880s [7] was historic fact while Guglielmo Marconi's feat of transmitting radio signals across of Atlantic Ocean could pass for the first breakout on wireless communication field during 1900s decade [8]. Therefore, it is not surprising that in early 20th century radio broadcasting invaded life and changed how news music and entertainment reached every home across the globe. A major development of this period was TV transmission during mid-century XX which significantly altered the way people consumed media and obtained information.

Subsequently, the invention of transistors [9] and also emergence of cellular networks [10], for instance, have significantly improved the capabilities and applications of wireless systems. Communication without wires has become an integral part of present-day civilization, ensuring a variety of mobile phone functions, internet connectivity, satellite navigator systems as well as Internet-of-Things (IoT) projects. These technologies have grown so deeply integrated into our daily lives that it is difficult to envision a world without the effortless connectivity they offer.

Nonetheless, because of their intrinsic characteristics, as shown in Fig. 2.1, wireless communications are hard to make successful. Unlike guided communication in the form of cables, electromagnetic waves traveling through air are open to several undesired incidents depending on their operating frequency and other factors. Additionally, the existence various physical environments like walls, houses, trees, and other obstacles have a significant effect on signal propagation [11]. These variables, including diffraction, reflection, scattering, and refractions, make wireless communications more complex and less reliable [12]. Thus, to drive forward and improve on them, it is necessary to know these things first so as to reduce their effects.

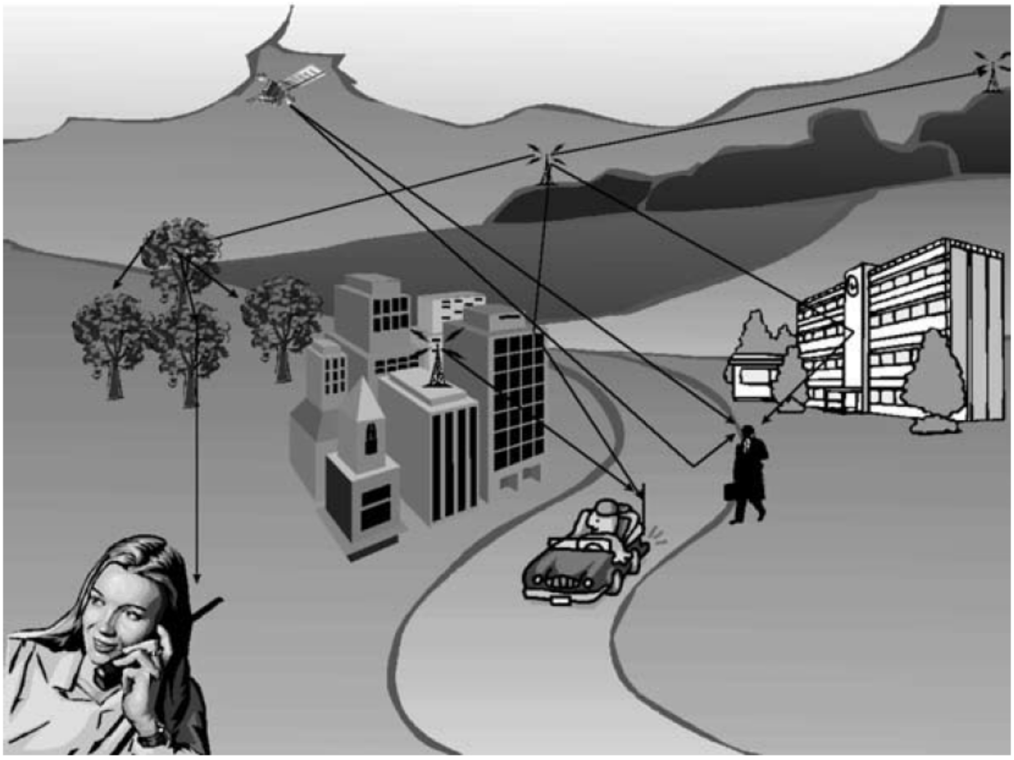


Figure 2.1. Wireless propagation landscape [13].

In wireless communications, often electromagnetic waves bounce off objects such as buildings or bodies of water in a phenomena as know as reflection. This happens because such obstacles have dimensions that are far greater than the wavelength of the waves and its effects both good and bad may result. There may be constructive interference as a result of this phenomenon while there is also multipath interference which means signals can take various paths before they reach the receiver.

Also, diffraction is an action in which electromagnetic waves get distorted around obstacles. As far as radio waves are concerned, diffraction allows signals to get around buildings, mountains or any other obstructions and thus be received even when the sender and receiver are not within Line-of-Sight (LoS) [11]. This phenomena supports keeping urban places and hills covered by signals. However, diffraction also brings about shadow regions or areas with weak signal strength.

Refraction which is governed by the Snell's law refers to bending of electromagnetic wave when they transport between two media having several densities leading to variations in speed as well as direction. This have serious consequences on signal path and coverage areas with regards to telecommunication systems. A classic representation of refraction is that of the evident bending of a straw when it is positioned in a glass filled with water. As light rays cross from air (which is less packed) into water (which is more packed), their velocity decreases and hence they curve whereby making the straw appear broken or shifted right at the surface area of the water. Similarly, radio waves passing through various layers of atmosphere or other obstacles may change course due to refraction making it difficult for telecommunications transmissions.

Finally, scattering is a phenomenon whereby electromagnetic waves encounter small objects or irregularities in the environment, causing the waves to spread out in different directions. The degree of scattering depends both on the angle of incidence and on the relative roughness of the surface with respect to the wavelength [13]. Such phenomena are very common in areas with dense vegetation or rugged terrain. Scattering may result in signal attenuation and oscillations of the received signal intensity; thus, it will break on the reliability and accuracy of wireless communications.

Due to the challenges, it is crucial to participate in thorough planning in order to precisely predict the spread of signals in various environments. Efficient strategic planning is essential to ensure that wireless communication systems maintain optimal levels of performance and reliability, even in challenging and diverse physical environments. This highlights the importance of creating and improving propagation models that can consider the various factors that affect signal behavior.

2.1.1 Propagation Models

Radio wave propagation models are utilized to predict signal coverage and ensure that broadcasts reach the widest possible audience without interference. These models are thus vital during the designing and optimization of a wireless communication system as they help in understanding and mitigating the various factors that may affect signal strength and quality. According to [14], propagation models can be categorized into three categories:

- **Empirical**: extensive measurements and observations serve as the basis for these models. They enable a general insight into how signals propagate in different environments without extensive knowledge on specific sites. System-level concepts and rough estimations of the number of required sites in large areas are usually their main uses. Prominent examples include Okumura-Hata, Lee's model, ITU-R P.1546-6 and ITU-R P.1812-7;
- **Semi-empirical**: models that combine both empirical data and deterministic approaches. These models utilize site-specific information like terrain and buildings to enhance accuracy of prediction. They are applied for more refined planning and are appropriate in predicting coverage in broad zones such as urban areas. Semi-empirical models include Walfisch-Ikegami model and Walfisch-Bertoni model [15];
- **Deterministic**: in order for those models to make predictions that are as accurate as possible, they absolutely need extremely thorough information about their surroundings—including details such as floor plans, elevation levels, types of obstructions present in the area etc. They make use of mathematical and physical principles while simulating radio waves behavior giving rise to extraordinarily precise predictions. A typical example of a deterministic model is represented by Ray-Tracing models [16].

For this study, the ITU-R P.1812-7 model was chosen because of its comprehensive adaptation and approach to different environments. This model is a recommendation by International Telecommunication Union (ITU) for predicting point-to-area terrestrial propagation, making it suitable for a wide range of applications from rural to urban settings. Unlike the ITU-R P.1546-6 recommendation, which is more general and does not require detailed environmental data, the ITU-R P.1812-7 necessitates detailed clutter mapping, thereby offering greater accuracy [17]. Furthermore, another reason is that its documents are supported by research work from different organizations in telecommunication and universities, thus credibility and relevancy of this research paper's findings are verified. Other than that, DTT applications, which is part of this study's main focus, have been widely tested with this model [18]. The potentiality of this recommendation on collecting precise data about surroundings further makes it most suitable when dealing with challenges in terms of wave traveling through Brazil's various landcovers or topologies.

2.1.1.1 ITU-R P.1812-7

Specifically designed for frequencies from 30 MHz to 6 GHz, the ITU-R P.1812-7 recommendation proposes a method for predicting signal propagation in terrestrial point-to-area services. This recommendation developed by ITU aims at providing precise guidance on planning telecommunications services regarding signal prediction. The eighth revision of the recommendation [6] is notable because it can predict pathloss and field strength; hence it helps in identifying coverage areas and ensuring QoS. Due to its wide frequency band coverage and ability to predict point-to area, ITU-R P.1812-7 is fit for broadcasting services like DTT and FM radio. By predicting accurate signal levels across various terrain profiles and atmospheric conditions, it enables efficient and reliable establishment of broadcasting services.

The following benefits, among other factors, can be highlighted in the utilization of this recommendation:

- **Efficient spectrum utilization**: guarantees the optimal and cost-effective utilization of the radio frequency spectrum, which is a limited and valuable asset.

- **Interference minimization**: guarantees the reducing interference between stations operating on neighboring frequency channels, thus ensuring clear and stable communication.

- **Effective planning**: enhances the ability to plan telecommunications networks by allowing for accurate prediction of transmission losses and optimization of signal strength in different locations. This capability is crucial for determining the geographical range and accessibility of desired signal levels (coverage).

- **Support for broadcasting services**: provides a comprehensive examination of terrain profiles to assist in the advancement and improvement of broadcasting services. The capability to forecast pathloss and signal strength is crucial in the development and implementation of efficient and dependable broadcasting networks, thereby enhancing the overall QoS.

As well as covering a broad spectrum of frequencies, the ITU-R P.1812-7 model also includes supplementary features and input variables that are crucial for forecasting. These specifics are effectively depicted in Table 2.1.

Table 2.1. Characteristics and basic input parameters of the ITU-R P.1812-7 recommendation.

Characteristic	**Description**
Frequency Range	30 MHz to 6 GHz
Distance Range	250 m to 3000 km
Path Profile Resolution	30 m to 1 km
Terminal Height	Up to 3 km above ground
Percentage of Time	1 % to 50 %
Percentage of Locations	1 % to 99 %
Terrain Altitude	Above sea level
Clutter Heights	As specified in Table 2.2
Radio-climatic Zones	Coastal, Inland or Sea
Signal Polarization	Vertical or Horizontal
Transmitter and Receiver Latitude	$-80°$ to $80°$
Transmitter and Receiver Longitude	$-180°$ to $180°$

The content provided implies that ITU-R P.1812-7 is an important source of information for all telecommunications experts like engineers and network planners. This recommendation is further essential in that it intends to greatly improve efficiency and effectiveness in spectrum utilization and service delivery, hence an essential tool in the field.

There are several critical elements that the model documentation outlines as being key for the accurate prediction of signal propagation. These include: LoS propagation, diffraction, tropospheric scatter, anomalous propagation, location variability, and building entry loss [6, p. 8]. Clutter can potentially affect all these components, but it firstly impacts diffraction. According to [6, Section 3.2.1], clutter like buildings and vegetative cover alter the terrain profile by introducing clutter heights representative enough to affect the signal propagation. As a result, incorporating this into computations greatly influences diffraction calculations since there are possible moments when diffraction losses are increased due to other environments which may be obstructed by obstacles (clutters). Therefore producing accurate clutter maps is very important because they help in reflecting real-world situations hence improving the credibility of signal propagation predictions.

From an analytical perspective, including clutter in the model involves altering the terrain profile used in the calculations. The formula for the surface height g_i at each profile point i is modified to incorporate the representative clutter height, as expressed in [6, Equation 1d], in the following manner

$$g_i = \begin{cases} h_i + \text{representative clutter height} & \text{for } i = 2, \ldots, n-1, \\ h_1 & \text{for } i = 1, \\ h_n & \text{for } i = n, \end{cases} \tag{2.1}$$

in which h_i represents the terrain height at the i-th profile point above sea level.

The clutter height is a important parameter in the model, as this comprises all kinds of obstacles, from buildings to foliage, which have an effect on how signals are transmitted. These heights shall, therefore, be categorized in correspondence with the different contexts of clutter. Table 2.2 presents the representative heights of clutter for diverse environments.

Table 2.2. Representative clutter heights [6].

Clutter Environment	**Representative Height (m)**
Water/Sea	0
Open/Rural	0
Suburban	10
Urban/Trees/Forest	15
Dense Urban	20

Then, the variable g_i is used in the Bullington method as a combination with spherical-Earth diffraction loss in order to calculate the diffraction loss [6, Section 4.3]. In Bullington‘s method, g_i denotes the degree of vertical distance between the surface of i-th profile point and sea level [6, Section 4.3.1]. This includes the introduction of representative clutter heights for better estimation of obstructions created by natural or artificial objects. This means that when g_i is combined with spherical-Earth diffraction loss technique, a technique called delta-Bullington becomes available through which an accurate prediction regarding the possible signal loss can be obtained when there is obstruction on LoS [6, Section 4.3.4].

Also, the model incorporates within its specifications the standard deviation of location variability denoted by σ_L [6, Equation 64] in order to account for the loss in location variability. For different environments, necessary frequency and prediction resolution are determined using an empirical formula that enhances the precision of estimating location variability. The mathematical equation representing this correlation is expressed as

$$\sigma_\mathrm{L} = 0.024f + 0.52w_a^{0.28}, \tag{2.2}$$

in which f represents the desired frequency in GHz, and w_a denotes the resolution for prediction in meters. Currently, in outdoor environments, the clutter height serves as a modifier for σ_L using the function $u(h)$ [6, Equation 65], which represents the variation in location variability height and multiplies σ_L. The function $u(h)$ is explicitly defined as

$$u(h) = \begin{cases} 1 & \text{for } 0 \leq h < R, \\ 1 - \frac{(h-R)}{10} & \text{for } R \leq h < R+10, \\ 0 & \text{for } h \geq R+10, \end{cases} \tag{2.3}$$

in which h denotes the elevation of the receiver from the ground, and R represents the height of the representative obstacles at that location, according to Table 2.2. Ultimately, the outcome of this modification for the standard deviation, referred to as σ_Loc, is employed to compute the basic transmission loss and, consequently, the electric field strength [6, Section 4.9]. The functions are explicitly defined as

$$\sigma_\mathrm{Loc} = u(h)\sigma_L, \tag{2.4}$$

and

$$L_b = \max\left[L_{b0p}, L_{bc} + L_{be} - \left(\frac{p_L}{100}\right)\sigma_\mathrm{Loc}\right], \tag{2.5}$$

in which L_b is the basic transmission loss in dB. The purpose of these adjustments to the model is to precisely represent the impact of clutters on signal propagation. As a result, ITU-R P.1812-7 is strongly recommended for use in complex environments, such as those encountered in Brazil. Nonetheless, it is essential to undertake a novel and vital measure in utilizing the model, particularly the precise and consistent delineation of clutter, as inaccurate data can lead to substantial inaccuracies in signal forecasting.

These adjustments to the model aim a single purpose: to accurately depict clutter effects on signal transmission. Thus, in complex situations, such as those found in Brazil, ITU-R P.1812-7 is highly recommended for use. Nevertheless, it is necessary to apply one more critical and new step in using the model, namely accurate and consistent mapping of clutter, because wrong data can result in a large error in signal prediction.

2.2 REMOTE SENSING

Remote sensing is the act of collecting information about things or places without any physical contact [19]. This method commonly relies on sensors that are located on aircraft or satellites, employ electromagnetic radiation to collect data on the target item, which can either reflect or emit energy. The concept of remote sensing can be dated back to the mid-19th century, when aerial photographs were initially used for mapping and reconnaissance-related purposes. Remote sensing has experienced tremendous development in the 20th century due to fabulous innovations in aviation and space exploration technologies. Many other disciplines, such as agriculture, environmental monitoring, or disaster management, have also come to depend upon remote sensing. This became all the more true with the advent of digital images, hyperspectral sensors, and light detection and ranging (LiDAR) techniques that allow a more accurate and complete extraction of data for multiple applications.

Considering the events captured above, remote sensing is posed to present a very promising way to enhance the accuracy of ITU-R P.1812-7 recommendation. This would mean enhanced clutter mapping, considering that technology has the potential to improve the effectiveness of network planning and service quality integrated with other technologies.

2.2.1 Remote Sensing Sensor Types and Systems

Remote sensing systems can be classified depending on the kind of energy source employed in them (active or passive) and the exact range of the electromagnetic spectrum that is used for data collection (optical or microwave) [20].

Optical sensors are those sensors based on the visible light and nearby parts of the electromagnetic spectrum to capture images of the object that is desired. The classes into which these optical sensors could generally be classified fall under the following:

- Passive sensors utilize sunlight that is reflected by the Earth's surface [21]. Examples of passive sensors are satellite cameras and multispectral scanners [22], which function within specific wavelength ranges: visible (0.4 µm to 0.7 µm), near-infrared (0.7 µm to 1.1 µm), and shortwave infrared (1.1 µm to 3 µm);
- Active sensors emit their own light or radiation and measure the reflection of this radiation from the target. One example is LiDAR systems, which use laser pulses to accurately map detailed topography [23].

Conversely, microwave sensors have a frequency range of between 300 MHz and 40 GHz and are widely used due to their ability to penetrate clouds, fog, and even the surface layer of ground. Just like optical sensors, microwave sensors can also be categorized as:

- Passive sensors detect microwave radiation emitted by the Earth's surface and are mostly employed for monitoring soil humidity and sea surface temperature [24].
- Active sensors encompass Synthetic Aperture Radar (SAR) that are capable of capturing high-resolution images regardless of weather conditions [22]. Some examples of SAR sensors are TerraSAR-X and RADARSAT-1.

The choice between optical and microwave sensors depends on specific requirements of the application. Optical sensors are appropriate for land use and vegetation cover mapping because of high spatial resolution detail and large spectral range. However, its performance is limited by current weather and illumination conditions. On the other hand, microwave sensors can acquire their information regardless of the weather and illumination conditions. Therefore, microwave sensors are favored over others in monitoring catastrophes and observing oceans.

2.2.2 Overview of the MCD12Q1

The MCD12Q1 product [25], derived from the Moderate Resolution Imaging Spectroradiometer (MODIS), is highly regarded in the academic community as a prominent example of passive optical remote sensing products. This product is employed for several applications, such as environmental monitoring, climate modeling, and other geographic usage. The MCD12Q1 product obtains its land cover classification data by measuring the solar radiation reflected by the Earth's surface using NASA satellites named Terra and Aqua.

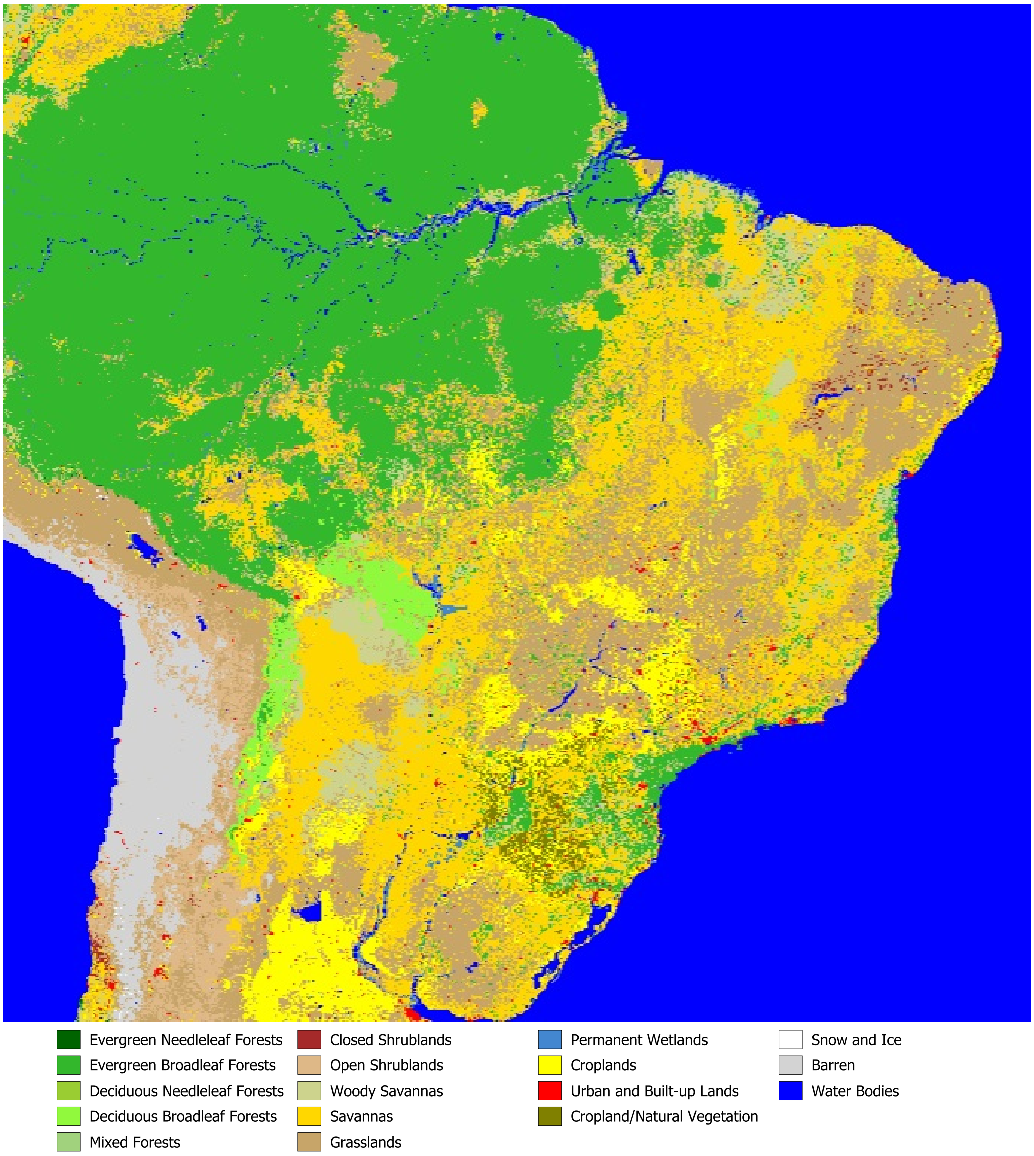


Figure 2.2. Remote sensing land cover classification of part South America using MCD12Q1 dataset with the IGBP classification scheme.

The purpose of MCD12Q1 is to produce data on land cover classification. This is to be done through supervised classification methods with spectral properties of the surface of the Earth, which enable a detailed classification of cover categories of the land using systems as recognized and accepted, some of which include:

- **International Geosphere-Biosphere Programme (IGBP)**: managed by an international consortium of scientists specializing in the examination of the interplay among biological, chemical, and physical mechanisms that govern the Earth system, this is a method of classification that organizes land cover according to vegetation types and land utilization in 17 categories;

- **University of Maryland (UMD)**: developed and maintained by the University of Maryland, this classification scheme divides the Earth's surface into 16 types of cover, such as evergreen and deciduous forests, agricultural areas, urban areas, among others;

- **Leaf Area Index (LAI)**: similar to the IBGP, it is similarly maintained by an association of scientists, including substantial contributions from NASA. There are a total of 11 different categories that describe the types of land cover;

- **Biome-Biogeochemical Cycles (BGC)**: the BGC system, created by experts specializing in global biogeochemical cycles, categorizes the Earth according to the biogeochemical cycles of different biomes. The total number of categories is 9;

- **Plant Functional Types (PFT)**: Additionally, this system is created and upheld by a group of scientists and researchers. It is utilized in the field of climate modeling, investigations of how ecosystems react to climate change, and research on the diversity of species and the functions of ecosystems. There are 12 separate categories for classifying land cover.

The MCD12Q1 product raster file comprises separate bands for every classification scheme [26]. This design allows an individual to investigate different classifications at once for any chosen geographic coordinates, so as to gain more understanding of different land cover characteristics. For instance, when assessing landcover classification of an extensive area, all the existing classifications can be compared through their congruence with every individual characteristic. Table 2.3 shows categorizations according to IGBP and UMD schemes.

Table 2.3. Land cover classification for the IGBP and UMD schemes [26].

Code	IGBP	UMD
0	-	Water Bodies
1	Evergreen Needleleaf Forest	Evergreen Needleleaf Forest
2	Evergreen Broadleaf Forest	Evergreen Broadleaf Forest
3	Deciduous Needleleaf Forest	Deciduous Needleleaf Forest
4	Deciduous Broadleaf Forest	Deciduous Broadleaf Forest
5	Mixed Forest	Mixed Forest
6	Closed Shrublands	Closed Shrublands
7	Open Shrublands	Open Shrublands
8	Woody Savannas	Woody Savannas
9	Savannas	Savannas
10	Grasslands	Grasslands
11	Permanent Wetlands	-
12	Croplands	Croplands
13	Urban and Built-up Lands	Urban and Built-up Lands
14	Cropland/Natural Vegetation Mosaics	-
15	Permanent Snow and Ice	Barren
16	Barren	-
17	Water Bodies	-
255	Unclassified	Unclassified

Also, the MCD12Q1 provides annual land cover maps for the entire planet at a spatial resolution of 500 metres. The data is kept in Hierarchical Data Format, version 4 (HDF4) files and is packed in tiles that approximately measure 10 × 10 degrees at the Equator. The tiles are ordered using a sinusoidal projection. This product is accessible to researchers through various platforms, including [27], [28], and [29]. Table 2.4 summarizes the characterizing features of MCD12Q1.

Table 2.4. Characteristics of the MCD12Q1.

Parameter	Description
Pixel Size (m)	463 m
Number of Pixels per Tile	2400 × 2400
Projection	Sinusoidal
Data Format	HDF4
Temporal Coverage	Annual (2001-present)
Spatial Resolution	500 m
Classification Legends	IGBP, UMD, LAI, BGC, PFT, LCCS
QA Layers	Included

Numerous land cover products exist apart from MCD12Q1 among them CCI-LC by European Space Agency [30], GLCNMO by National Mapping Organisations [31] and Copernicus

Global Land Cover [32]. Each of these products has its own characteristics and advantages. For example: CCI-LC provides high resolution maps with a spatial resolution of 300 m and updates at specific intervals; whereas GLCNMO offers the largest resolution which is 500 m making it appropriate for global scale analysis; while Copernicus Global Land Cover's dataset emphasizes precise and comprehensive map data for Europe and other regions at 100 m resolution.

There are some crucial factors that drive the choice of MCD12Q1 as a basis for developing a clutter mapping system intended to improve ITU-R P.1812-7 optimization. This dataset has a spatial resolution of 500 m which makes it very suitable for carrying out detailed clutter analysis without generating too much data. Furthermore, it provides yearly updates and a variety of classification schemes such as IGBP and UMD which give us a much better understanding of the different land cover types. The reliability and authenticity of data obtained from MCD12Q1 is beneficial given Brazil's diverse landscapes ranging from the Amazon rainforest to urban areas like São Paulo. The precise representation of various land cover types is essential for telecommunications design in varying terrains across Brazil. Therefore, MCD12Q1 appears to be the appropriate dataset for the task of supporting a clutter mapping system to optimize the accuracy of ITU-R P.1812-7 considering the complex Brazilian terrain and land cover.

CHAPTER 3

RELATED WORKS

This chapter reviews related work to frame the background of the research done in this study. The first section examines previous studies which discuss losses caused by clutter in general. Second section, clutter mapping methods are considered, applied in the different experiments carried out with special emphasis on forecasting signal propagation. Finally, the last section underlines important elements which can orient future research and academic studies.

3.1 CLUTTER LOSSES

Clutter mapping is one of the factors that taken into consideration for natural and man-made impediments, including buildings, trees, and topographical differences. This represents a significant component in the improvement of signal propagation predictions. Clutter losses should be taken into account with a huge deal of accuracy to avoid wrong projections in results in the future [13], especially when using widely-used models like ITU-R P.1812-7, which are used to predict signal attenuation in different situations. Clearly, the accuracy of such predictions is strongly dependent upon the accurate representation of the clutter. This urgent matter has been addressed by the ITU through a recommendation made in 2021, entitled ITU-R P.2108-1 [33]. Such a recommendation suggests that statistical models should be used when the knowledge of the environment is such that it would not be possible to map the clutter accurately.

An interesting investigation explores the impact of cluttered terrain on specific prediction models [34] within the realm of Very High Frequency (VHF) and Ultra High Frequency (UHF) frequencies. This study offers insights into how topography and obstruction affect pathloss models, which are crucial for enhancing the efficiency of wireless communication. Thus, in [34] 15 channels of VHF/UHF are measured using a spectrum analyzer, while the measured received signal strength at different distances from the transmitter is compared with that predicted by models to come up with prediction errors. The results underline the need to enhance predictive models of signals by factoring in more environmental factors and increasing their accuracy to enable optimal planning of wireless communication in different geographical areas.

In addition, the authors in [35] has conducted a research to determine effectiveness of ITU-R recommendations P.526-13, P.1546-5 and P.1812-4 for uneven terrain and dense forest cover in Rio de Janeiro, Brazil. The study compared real measurements with predictions made by the proposed models. Findings indicate that prediction methods used in ITU-R P.526-13 and ITU-R P.1812-4 recommendations are more effective due to forest cover considerations and use of correct information on clutter height.

In general, the studies validates the effectiveness of clutter mapping in the creation of signal predication models. Characterizing terrain and obstacles at a higher level of detail allows models, including ITU-R P.1812-7, to widely enhance the accuracy of predictions associated with signal attenuation. This enhanced accuracy is crucial for further optimization of planning for wireless communication and for greater assurance in the expectation of the signal coverage in the diversified geographical areas. Therefore, accurate mapping of clutter still remains significant in the development of the signal propagation models and, hence, efficiently implementing wireless communication systems.

In summary, the evidence of these results supports the importance of inculcating the aspect of clutter mapping into the signal prediction models. For example, with the incorporation of model-specific data, which links the environmental data, such as terrain and obstacles, models like the ITU-R P.1812-7 derive particular benefit towards fine-tuning and boosting actuality in the prediction of signal loss. Further improvement in accuracy is needed to practically support wireless communication planning optimization and to ensure that the signal coverage is dependable in various geographical regions. Furthermore, the process of developing detailed models for the propagation of signals and practical deployment of successful wireless communication systems requires precise mapping of clutter.

3.2 TECHNIQUES FOR CLUTTER MAPPING

Clutter mapping techniques are generally acknowledged to be categorized into two main groups: traditional methods and modern ones. Traditional approaches generally depend on on-site measurements, local sensors, paper maps, whereas modern techniques utilize the state-of-the-art features of remote sensing and machine learning technologies [36].

The authors in [37] employs conventional field measurements in Caracas, Venezuela to comprehend the influence of terrain and other forms of obstruction on signal transmission. The study, which specifically examines DTT services, suggests that the ITU-R P.1812-4 recommendation, when enhanced with these field measurements, provides a significant enhancement in accuracy. The proposed method is interesting and, in fact, has a tendency to be extremely precise. However, when it comes to more comprehensive studies, such as devising a solution that can be implemented throughout the entire Brazilian area, this approach is not realistic. In addition, the authors in [38] adopt a similar methodology by conducting extensive empirical measurements in the cities of Aalborg, Gothenburg, and Tokyo to examine the influence of clutter on signal propagation in urban environments. As a result, they create a statistical model to predict the reduction in signal quality caused by interference in these situations. Nevertheless, the suggested model lacks consideration of the reduction in signal caused by vegetation-related clutter.

Still adopting a traditional approach, in [39] the authors introduces a MATLAB tool that predicts radio coverage. This tool is specifically built for tactical communication systems operating in the VHF and UHF frequency bands. This study assesses the effectiveness of the ITU-R P.1812-4 and ITU-R P.1546 models in comparison to the Okumura-Hata. The study provides an intuitive simulation operator perspective that employs standard values as input for clutter heights. Nevertheless, this approach has the potential to result in either an overestimation or underestimating of prediction. This issue can be further intensified by the intricate nature of the region being examined. Utilizing standard values for clutter mapping simplifies the simulation process, although it also adds the possibility of mistakes. Therefore, by including more intricate and adjustable information about clutter in the simulation inputs, the precision of signal predictions could be improved, especially in complex geographical environments. Precise representation of clutter is crucial for enhancing the accuracy of signal propagation models and guaranteeing dependable communication coverage.

In additon, the study in [40] provides a methodology for determining clutter losses, highlighting the significance of clutter mapping in signal predictions. The estimating approach relies on the mean heights of buildings and the roughness of the terrain in the area under investigation. Its accuracy was confirmed by comparing it with maps of Tokyo city. Although the proposed strategy has been shown useful, particularly in urban environments, this approach may face challenges in the Brazilian context due to geographical complexity, as well as the ongoing transformation of environments caused by urbanization and agricultural activities.

In work [41], the authors examines how modern methods of predicting clutter loss, especially in satellite communications, can be enhanced using machine learning techniques. The results reveal a signal prediction advancement that is significant through these advanced methods, thereby enhancing the precision of wireless communication. Also in a recent study, [42] conducted a work where Convolutional Neural Networks (CNN) were used to enhance the accuracy of clutter categorization in satellite images. This is research growth that has great potential for improvement to any number of wireless communication propagation models. The main aim of the work [42] was to generate high-resolution annotated clutter maps by classifying satellite pictures into distinct categories. To do this, satellite images obtained from [43], data from [44], and locally sourced data in Canada was made use of. In terms of addressing clutter-induced attenuation dependence on progressive signal transmission models, this study underscores increasing adoption of high technology.

The study conducted by [45] introduces a novel approach to improving the accuracy of pathloss predictions using a network architecture based on CNN. The methodology employs satellite imagery datasets and environmental characteristics from [44]. Though not specific for ITU-R P.1812-7 application or its performance in complex environments like Brazilian land covers, results indicate considerable reduction in prediction errors through integration of advanced technologies with signal prediction models. The use of modern technologies for better signal predictions was also investigated by [46]. A new PL prediction method using CNN has been proposed in this research work. It employs features such as terrain obstacles and building distribution obtained from 3D maps. The study revealed how able the CNNs are to carry out different predictions tasks, with both high precision and effectiveness ratings. Compared to traditional methods, it took shorter time before arriving at accurate results when using CNN. These findings suggest that wireless communication planners could find great value in the use of a CNN.

In another relevant study, the work [47] present an open-source tool based on their research to improve pathloss predictions in a foliage-dominated environment—rural areas—by using the ITU-R P.1812-6 recommendation. In doing so, high-resolution images of the terrain elevation and Canadian DEM databases are used. For the loss occasioned by foliage, the authors apply a physical model called the Radiative Energy Transfer (RET) model to calculate the amount of such loss. The proposed approach combines these technologies and strategies in an effort to make ITU-R P.1812-6 more efficient in rural environments. Moreover, the contribution by the authors is immense because it is not only within the scientific community that the tool will be put into use but even by people from the general public.

Although in signal predictions it is quite useful to account for clutter losses, most of such studies do not specify the methods used in determining clutter heights. Studies by [48] and [49] are cases in point. The authors in [48] focus on the enhancement of efficiency related to DVB-T2 Single Frequency Networks using the ITU-R P.1546 and ITU-R P.1812 models, without citing the revisions used. They explain how the introduction of a clutter loss model together with topographical data enables one to achieve a much better prediction of the coverage. They consider field strength curves for a number of different frequencies in relation to factors such as distance, antenna height, and temporal and spatial variability. The approaches taken to map the clutter heights, a critical factor in their models, are not detailed.

On the other hand, in [49] the authors conduct a comparative analysis between ITU-R P.1546 and ITU-R P.1812 models, without citing the revisions used, with empirical data from real terrain. Their interest is how accurate these models are in predicting signal coverage by comparing software predictions and actual terrain measurements. Although they provide a detailed comparison between the two models, they again do not mention the techniques used for determination of clutter heights. Their findings show that the ITU-R P.1546 model, including terrain information, tended to be more accurate in urban areas. This, again, identifies the need for detailed clutter mapping techniques to be included in enhancing the accuracy of predictions, but both studies fail to include the explicit methodologies used in determining these clutter heights.

3.3 FUTURE DIRECTIONS

The literature review brings out the need to take into consideration clutter effects in the designing of wireless communications, with emphasis on propagation model improvement and optimization. A strong trend is also observed toward making these processes aided by state-of-the-art technologies like machine learning and remote sensing to increase the accuracy of predictions made using propagation models.

On the contrary, despite the high interest in this area, nearly no effort was explicitly done to demonstrate the signal propagation in the complex geographic geography of Brazil for any kind of broadcasting services, together with various techniques and fields, as well as an integration of remote sensing data extracted from renowned and freely available sources. Such integration of telecommunications services would make it easier to monitor and regulate them by the relevant control authorities in Brazil and by society as a whole. In that sense, this research is well-timed and relevant.

CHAPTER 4

THE SYSTEM OF CLUTTER MAPPING

This chapter presents the design of the proposed system with regard to clutter mapping and its practical use in supporting ITU-R P.1812-7 for pathloss prediction. The first section describes the system design, which places special emphasis on its functional and non-functional prerequisites. The second section details the system's implementation, which contains a close description of how data collection and preparation were done, the integration of vital datasets, the main components that would enable the system to meet its needs, and optimization strategies used during the development. The final section evaluates the system's capability to detect and classify clutter effectively and examines how accurate clutter classification influences pathloss prediction results based on the ITU-R P.1812-7 model.

4.1 DESIGN

Designing any technological solution is a very important stage of its development since it gives a framework and elements that compose the end product [50]. In this research, focused on creating a methodology/system for mapping clutter, a very proper planning of the system design is necessary to increase the prediction pathloss accuracy from the ITU-R P.1812-7 recommendation. An optimally engineered system for this proposed should be able to deliver resilience, scalability, and the capability of delivering real time data with precision needed for planning and operation in telecommunication.

The adoption of the MCD12Q1 dataset, which is a derivative of MODIS data and provides extensive information on land cover, was a crucial decision that has been described in Subsection 2.2.2 - Overview of the MCD12Q1. However, it is also important to conduct a thorough investigation into the needs and purposes which must be achieved by the proposed system. This includes identifying every aspect needed to guide its progressive function thus ensuring that all planned goals are met. Ensuring that it not only accomplishes its duties but also remains appropriate in its conduct while delivering good results is imperative.

In addition, the architecture designed for the clutter mapping system should allow the collection of extensive data, its processing, and storage seamlessly and efficiently. Considering the needs of the system, modular approaches have to be adopted wherein every component has its specified role but is integrated within the system to ensure its cohesiveness and efficacy. This system shall be able to process a huge amount of geographic coordinates, handling all the complexity of the different kinds of terrains and land covers that exist in Brazil. This includes dealing with heterogeneous data from towns, forests, mountains, and coastal areas—the clutter mapping done accurately and comprehensively for different landscapes.

Also, the architecture should not only meet the current need, but also allow easy maintenance and extendibility, which definitely require scalable and flexible technologies that can support any increase in the flux of data. Besides, it should provide an opportunity for continuous integration of new technologies within the architecture in order to gain upgradeability and adoptability of new tools and methodologies. This shall include integration with future versions of the ITU-R P.1812-7 model to ensure that the system remains relevant and efficient as the recommendation evolves.

In other words, clutter mapping system design must be robust, flexible, and ready to accommodate future expansion and technological evolution. This approach makes sure that the systems are durable and significant, but also operationally effective to provide assurance that the system will always be able to satisfy all the demands placed on it by users and the specifications of the radio propagation models in this case, ITU-R P.1812-7.

4.1.1 Functional Requirements

In software design, Functional Requirements (FR) are directly related to specific behaviors or functions of a system [51]. Requirements of this nature detail what the system is supposed to do by giving a description of the tasks, services, and functions that the software should perform. Clearly defined functional specifications are critical in this regard for a proposed software aimed at enhancing prediction pathloss capabilities in a signal propagation model.

These include, among others, data collection, processing, storage, and integration to existing models. An outline of these specifications makes sure that the system caters to user needs and fulfills the intended purpose noted below:

FR.1 - **Requirement:** Integration with the ITU-R P.1812-7.

Description: The ITU-R P.1812-7 recommendation should be integrated into the system in a seamless way, using clutter data to further improve predictions pathloss produced by this model.

FR.2 - **Requirement:** Generation of land cover maps.

Description: It shall be able to generate detailed land cover maps, with the geographic coordinates analyzed in a manner that ensures output of high accuracy and specific terrain features.

FR.3 - **Requirement:** Data processing and storage.

Description: Mass data processing, including large sets of geographic coordinates, must be efficiently handled. Additionally, classified geographic coordinate data must be stored in a manner that allows for easy retrieval and consultation at a later time.

FR.4 - **Requirement:** Classification of geographic coordinates individually or in bulk.

Description: It should be able to classify a single geographic coordinate or a group of geographic coordinates all at once. The system should be able to classify geographic coordinates either singularly or in groups, and this would bring along flexibility and efficiency in the analysis. This improves the performance and flexibility of the system to be used under different scenarios by the ability to classify geographic coordinates either singularly or in groups.

FR.5 - **Requirement:** IGBP land cover classification compliance.

Description: Ensure at least land cover classification according to the IGBP scheme, according to Table 2.3, as provided by the MCD12Q1 dataset, enabling correct and uniform terrain type categorization.

4.1.2 Non-Functional Requirements

According to [52], non-functional requirements (NFR) in software design are related to features not normally considered that refer to reliability, performance, accuracy, and security. In a case involving the proposed software, which intend improves predictions in a signal propagation model, it becomes essential to clearly outline specifications required in this case, as noted bellow:

NFR.1 - **Requirement:** Use of open-source solutions.

Description: The system should ideally use open-source solutions and technology to enhance transparency, reduce expenses, to easily make modifications and upgrades, and to permit unrestricted utilization by the entities of the government of Brazil and the wider community.

NFR.2 - **Requirement:** Offline operation capability.

Description: The system should be designed to work offline, with no requirement of constant internet connectivity for activities relating to data processing and categorization. Offline operation shall enhance the system's efficiency and dependability by working uninterruptedly, even in places where restricted or no internet connectivity is available.

NFR.3 - **Requirement:** Response time.

Description: The system should provide an low response time enough to complete the classification, more so where there is substantial data to be processed. That means that it would be a required aspect of the system to handle data fast and return results in the shortest time, especially at times of heavy load.

NFR.4 - Requirement: ITU-R P.1812-7 compliance.

Description: Any classifications developed by the system shall be in accordance with the requirements of ITU-R P.1812-7, at least, for the best possible application of this recommendation.

4.2 IMPLEMENTATION

The implementation of the proposed clutter mapping system is essentially the translation of the design and requirements materialized in Section 4.1 into a practical and operational solution. To do so, there is a need to understand the interrelationship of the system components. The overall structure and workflow of the system are elaborated with the help of a flowchart presented if Fig. 4.1, that illustrates the main components of the system are and how they interact with each other.

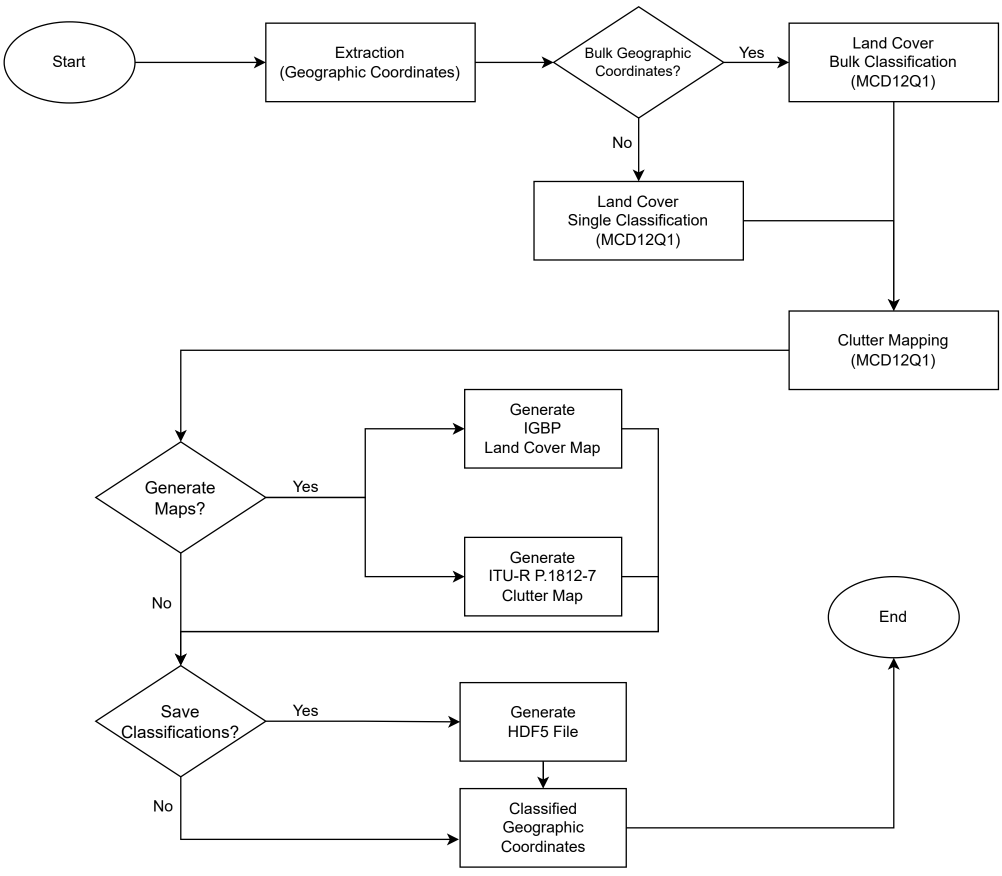


Figure 4.1. Flowchart of the clutter mapping system.

The flowchart outlines the steps in the system workflow as follows:

1. **Start**: the process begins with the initiation of the system's workflow;

2. **Extraction (Geographic Coordinates)**: first, the geographic coordinates to be analyzed are captured. For example, this is obtained from a GeoTIFF map (requirement **NFR.2**);

3. **Bulk Geographic Coordinates**: to target requirement **FR.4**, a decision point occurs when the system checks whether the input contains bulk geographic coordinates, which stands for a big number of geographic coordinates;

   - **Yes**: if there are bulk geographic coordinates in the input, the workflow proceed to "Land Cover Bulk Classification";
   - **No**: otherwise, it proceed to "Land Cover Single Classification" if not in bulk geographic coordinates.

4. **Land Cover Single Classification (MCD12Q1)**: for single geographic coordinate inputs, this step involves classifying the land cover. This classification assigns a specific land cover category to the single geographic coordinate;

5. **Land Cover Bulk Classification (MCD12Q1)**: for massive geographic coordinate inputs, this step does dynamic classification of land covers at many locations in one go. Clearly, hundreds or thousands of operations need to be executed in parallel so as to avoid the overhead of reading data from disk multiple times, which impacts performance (requirement **NFR.3**);

6. **Clutter Mapping (MCD12Q1)**: this stage maps the acquired land cover classes to the clutter categories according to the classes specified in the ITU-R P.1812-7 recommendation. The method is important for performing simulations based on the suggested model. With this step, the focus is objectively zeroed in on requirements **FR.1**, **FR.5** and **NFR.4**.

7. **Generate Maps**: another decision point where the system checks if it needs to generate maps based on the processed data;

- **Yes**: if maps need to be generated, it produces an "IGBP Land Cover Map" and an "ITU-R P.1812-7 Clutter Map";
- **No**: otherwise, the workflow would go straight to "Save Classifications?".

8. **Generate IGBP Land Cover Map**: this step generates a land cover map according to the IGBP classifications, provided directly by MCD12Q1. With this step, the focus is objectively zeroed in on requirement **FR.2**;

9. **Generate ITU-R P.1812-7 Clutter Map**: this step generates a map according to ITU-R P.1812-7 clutter categories, which is used for predicting signal propagation. Also, this step objectively targets requirement **FR.2**;

10. **Save Classifications**: the last decision point where the system checks if the classifications should be saved for future analysis;
    - **Yes**: if the classifications need to be saved, the workflow proceeds to the "Generate HDF5 File" step;
    - **No**: otherwise, the workflow proceeds to the "Classified Geographic Coordinates" step.

11. **Generate HDF5 File**: this step involve creating an Hierarchical Data Format, Version 5 (HDF5) file where the classified geographic coordinates are stored. HDF5 is a general system which provides both a data model, library and file format. It was designed to store and manage huge amounts of data. The idea is to target requirement **FR.3**;

12. **Classified Geographic Coordinates**: only confirms that the geographic coordinates have been classified and the process complete;

13. **End**: the workflow is completed. The classified geographic coordinates can now be fed into a signal prediction model.

4.2.1 Data Collection and Preprocessing

There are many public and scientific sources from where MCD12Q1 files can be acquired for analysis purposes. As seen in the Table 2.4, this dataset is originally presented in a sinusoidal projection, a cartographic projection designed to preserve areas, making it particularly suitable for global-scale studies. ITU-R P.1812-7 is a recomendation that establishes a standard for studies using the World Geodetic System (WGS84) geographic projection. Therefore, it would be necessary to perform some transformations of projections during this research. In this case, however, did not have to go through that step since NASA's Application for Extracting and Exploring Analysis Ready Samples (AppEEARS) tool [53] already provides for data converted into WGS 84 projection which ensures conformity with essential criteria for analyses.

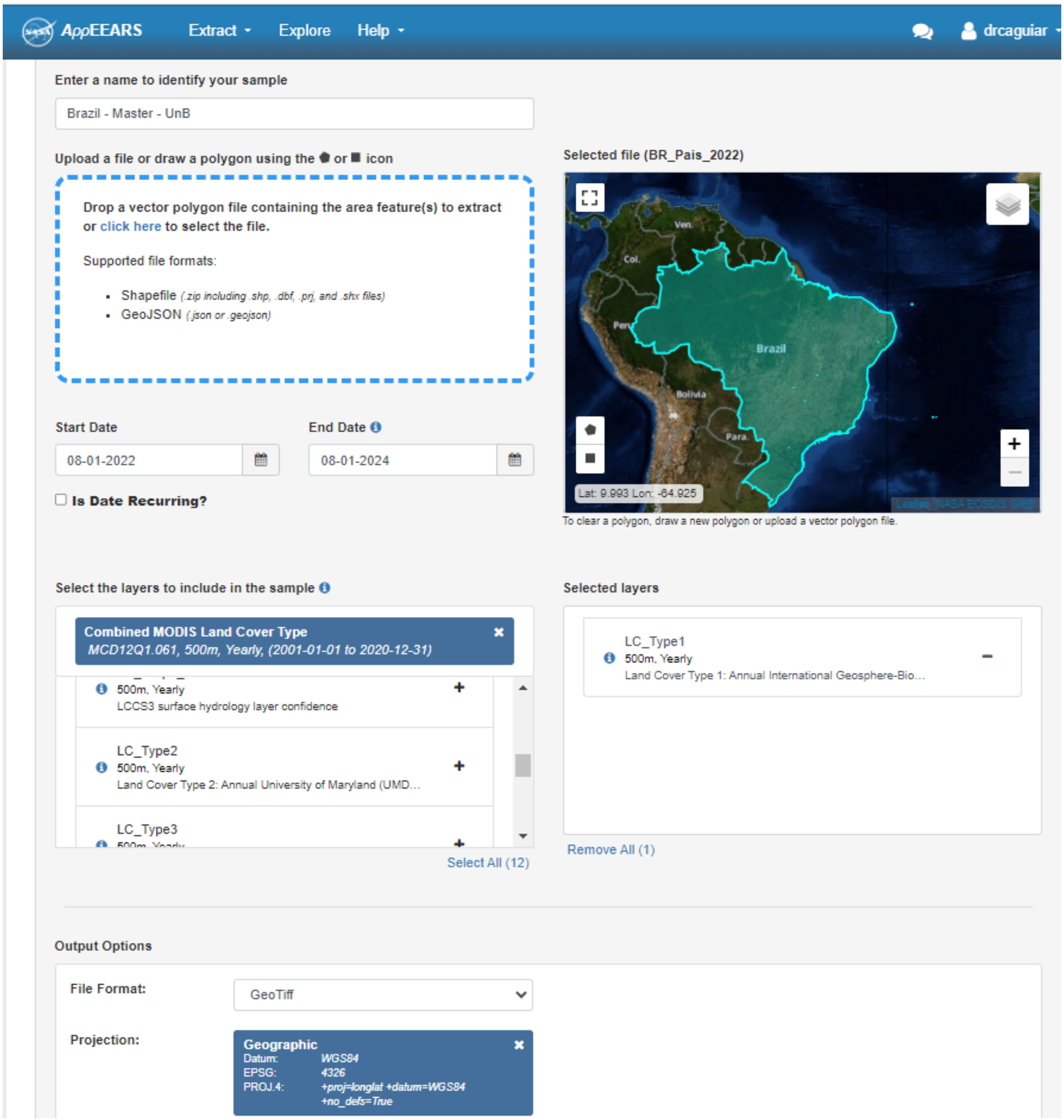


Figure 4.2. Interface of NASA AppEEARS [53].

Thus, the MCD12Q1 data were obtained using NASA's AppEEARS tool, which allows users to customize their data requests by uploading a shapefile that defines the area of interest. With a shapefile from Brazilian Institute of Geography and Statistics (IBGE) [54], the exact geographic borders for Brazil could be delineated. By passing this shapefile into NASA's AppEEARS, in addition to the specified product and its respective layer corresponding to the IGBP classification, it extracted data that exactly corresponded to the regions of interest, projected in advance into the WGS 84 projection, and adjusted to fit the specific spatial extent required by the research. This proved to be an effective way to assure a perfect match between data and geographic traits for the study area. Fig. 4.2 shows the extraction process with all the steps taken through the AppEEARS interface.

The output from this extraction process is a single-band GeoTIFF file of land cover classifications based on the IGBP land cover scheme, which has 17 different classes of land cover. Table 4.1 shows the metadata attributes of the resulting GeoTIFF.

Table 4.1. Characteristics and metadata of the GeoTIFF file.

Characteristic	**Description**
File Name	MCD12Q1.061_LC_Type1_doy2022001_aid0001.tif
File Format	GeoTIFF
Projection	WGS 84 (EPSG:4326)
Image Size	11 037 x 9923 pixels
Pixel Size	0.004 166° (463 m)
Upper Left Corner	75°1′30.00″ W, 6°19′15.00″ N
Lower Left Corner	75°1′30.00″ W, 35°1′30.00″ S
Upper Right Corner	29°2′15.00″ W, 6°19′15.00″ N
Lower Right Corner	29°2′15.00″ W, 35°1′30.00″ S
Center	52°1′52.50″ W, 14°21′7.50″ S
Value Range (Band 1)	1 to 17

Although the present work is not focused on this, the ITU-R P.1812-7 requires elevation data of the terrain to generate accurate predictions. To satisfy this demand, the system uses NASA's Shuttle Radar Topography Mission (SRTM) dataset. The SRTM is a worldwide Digital Elevation Model (DEM) that provides elevation data acquired via radar from a space shuttle flight in extraordinary detail. In the year 2000, a project was conducted that precisely mapped the elevation of the Earth's surface from 60°N to 56°S latitude. The spatial resolution from this mapping effort is approximately 30 m. The presence of SRTM data is crucial to the prediction model, as it ensures accurate ground elevation, thereby improving the reliability and accuracy of the propagation predictions to meet ITU-R P.1812-7 recommendation. Fig. 4.3 presents a hypsometric map derived from this SRTM dataset. The map represents a gradient of colors indicating different elevation ranges. The colors vary from blue, which depicts low elevations, through to red, which represents higher elevations. This type of visualization helps determine differences in terrain elevation based on the DEM provided by the SRTM.

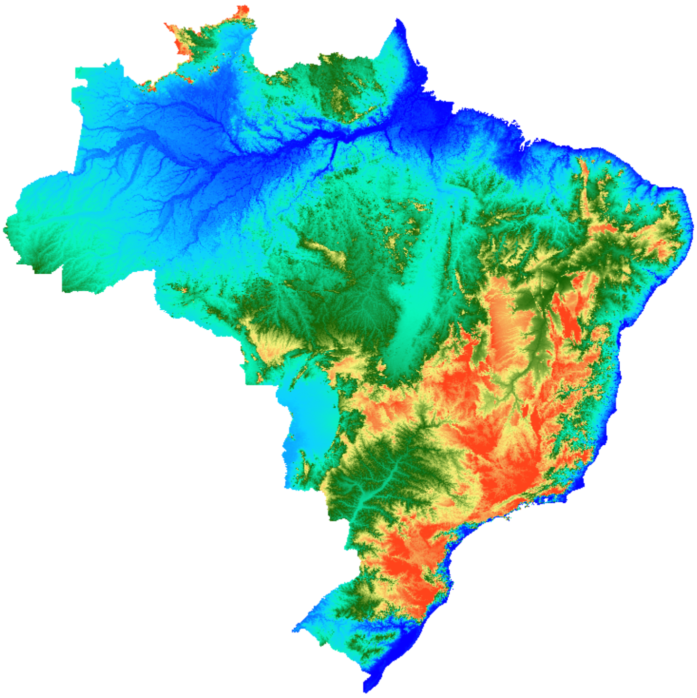


Figure 4.3. Hypsometric map of Brazil derived from SRTM dataset.

Another dataset used, not in the implementation of the system itself but for its validation and testing, is the IBGE shapefile containing the municipalities in the coastal zone [55]. The usage of this shapefile is focused on determining the radio-climatic zone types according to the ITU-R P.1812-7 documentation. As can be seen in the Table 2.1, such documentation defines the following three kinds of radio-climatic zones: Sea, Coastal, and Inland. Fig. 4.4 shows the projection of these municipalities on the map of Brazil.

4.2.2 Implementation of the System's Core Components

A key consideration in the successful application of this proposed work is the correlation of the IGBP land cover classes with the ITU-R P.1812-7 clutter categories, according to requirement **NFR.4**. Although advanced machine learning techniques could accomplish this task, developing or verifying such approaches is surely not the purpose of this work. In contrast, a

Figure 4.4. Map of Brazil showing the municipalities from the coastal zone.

direct and transparent methodology has been used whereby each IGBP class has been considered and matched to the most appropriate ITU-R P.1812-7 clutter category. This ensure the mapping is easy to understand and can be interpreted to provide an exact understanding of how various land cover types are represented under signal propagation modeling. In a conservative approach, "Unclassified" areas are particularly looked at and allocated to the category "Open/Rural" with a clutter height 0 m. This approach minimizes the possibilities of overestimation of the effects which may arise from these areas on signal attenuation, hence giving a robust and reliable model. By keeping a simple alignment, complexities and potential confusion that might be introduced by other approaches are avoided, ensuring transparency and easy reproducibility of the mapping process. Mapping results are presented in Table 4.2, outlining correspondence of the IGBP land cover classes with their corresponding ITU-R P.1812-7 clutter categories with their respective clutter heights.

Another important benefit for this direct mapping approach is speed in processing. It quickly assigns a clutter category to a land cover type, reducing the complexity and processing overhead of other advanced techniques, which is very useful in fulfilling the requirements of **FR.4** and **NFR.3** where speed in processing becomes an important factor. The efficient mapping process ensures that the system can handle large data and produce results in less time without any loss of accuracy or speed.

Table 4.2. Mapping of IGBP land cover classes to ITU-R P.1812-7 classes with associated clutter heights.

IGBP	**ITU-R P. 1812-7 Clutters**		
	Description	**Code**	**Height (m)**
Urban and Built-up Lands	Dense Urban	5	20
Evergreen Needleleaf Forests	Urban/Trees/Forest	4	15
Evergreen Broadleaf Forests	Urban/Trees/Forest	4	15
Deciduous Needleleaf Forests	Urban/Trees/Forest	4	15
Deciduous Broadleaf Forests	Urban/Trees/Forest	4	15
Mixed Forests	Urban/Trees/Forest	4	15
Closed Shrublands	Suburban	3	10
Open Shrublands	Suburban	3	10
Woody Savannas	Open/Rural	2	0
Savannas	Open/Rural	2	0
Grasslands	Open/Rural	2	0
Croplands	Open/Rural	2	0
Unclassified	Open/Rural	2	0
Permanent Wetlands	Water/Sea	1	0
Permanent Snow and Ice	Water/Sea	1	0
Barren	Water/Sea	1	0
Water Bodies	Water/Sea	1	0

4.2.3 Development Environment and Tools

Based on requirement **NFR.1**, the system under investigation is entirely developed in Python [56]. Python is widely accepted in the communities of science and engineering because it offers flexibility, ease of use, and comprehensive library support for data analyses, numerical computations, and automation of tasks. In this case, Python was chosen as the language due to its comprehensive library ecosystem that covers efficiently manipulation of geospatial data, API integration, and process automation. Along these lines, Python allows very fast prototyping and flexibility in development—features that would be very central to the development cycle of the system being proposed. Key libraries such as pandas [57] and NumPy [58] are used for data manipulation and processing, while GDAL [59] and rasterio [60] handle, respectively, vector and raster data.

The Integrated Development Environment (IDE) used is Visual Studio Code (VS Code).

This IDE is lightweight, extensible, and supports a large number of languages and development tools. VS Code integrates version control systems smoothly and has an integrated terminal with a host of extensions that accelerate the process of coding and debugging. Moreover, it is easy to set up the environment with code linting, automatic formatting, and version handling in order to ensure high quality of code and its consistency throughout the project.

Further to this, the simulation for the propagation of the signal is based on an implementation called Py1812, which is available on [61]. The proposed system gives inputs to this tool instantaneously, hence ensuring extraneous data and other variables are structured and formatted as per the model requirements. Because of direct integration, it is possible to run the simulation in an effective way by exploiting the compatibility between the generated data and the requirements of the simulation tool in terms of structure and format. According to its documentation, this implementation uses its own coding for the clutter categories, which can be seen in Table 4.2.

In the context of this work, ITU-R P.1812-7 has been adopted as the reference propagation model. However, the implementation Py1812 follows ITU-R P.1812-6 specifications. Despite this apparent version discrepancy, the implementation remains valid for calculating the L_b due to troposcatter. This is because ITU-R P.1812-7 explicitly recommends using the same troposcatter model described in ITU-R P.1812-6 when computing L_b. Specifically, ITU-R P.1812-7 identified limitations in the updated troposcatter model introduced from ITU-R P.617-5, recommending a return to the equations defined in ITU-R P.1812-6 for more accurate results under certain conditions [62]. As the Py1812 implementation uses the correct equations for L_b as defined in ITU-R P.1812-6, this ensures consistency with the most recent recommendations in ITU-R P.1812-7. Therefore, the use of this implementation does not compromise the accuracy or relevance of the simulation results presented in this work.

The simulations are conducted on dedicated equipment. Although this system is not classified as a high-performance computing machine, its specifications are sufficient to support the geospatial data processing and signal propagation simulations required by this work. Tab. 4.3 summarizes its key hardware and system characteristics.

Finally, the project is stored in a repository hosted by GitHub, a very respectable version control platform, with a reputation for reliability and strength. Using GitHub ensures smooth

Table 4.3. Hardware and system specifications of the simulation equipment.

Specification	Description
Model	Dell Vostro 3450
Processor (CPU)	Intel Core i3-2330M (2.2GHz, 3Mb Cache, 4 Threads)
Graphics Processing Unit (GPU)	Integrated Intel HD Graphics
Memory (RAM)	8 GB DDR3 @ 1333 MHz
Storage	256 GB SSD (SATA III)
Operating System	Ubuntu 22.04 LTS (64-bit)
Network Connectivity	1000 Mbps Ethernet / Wi-Fi 802.11n
Power Supply	90W AC Adapter

source code management, allowing for effective version control, collaboration, and change monitoring during development. Beyond this, there is a GitHub documentation platform where one is able to view source code, submit issues, and take part in projects by sending pull requests. After installing, it integrates with VS Code, which provides a smooth workflow for modifying, testing, and version controlling changes uninterrupted.

There are very important benefits for this research when using open source tools and platforms. Open source solutions provide for transparency, cooperation, and accessibility, thus allowing users to customize and adjust the system according to their individual requirements. The strategy adopted not only ensures flexibility and the ability of the system to adapt to any future technical developments but also fosters a community-driven environment in which continuous improvement and shared knowledge are some of the drivers behind the progress of the profession. This offer an integrated environment that help industry professionals and academic researchers take advantage of these open source technologies, promoting an inclusive and innovative setting for the project.

4.2.4 Optimization Techniques

This system also incorporates optimization techniques that enhance its performance and efficiency. Libraries in Python based on multiprocessing are utilized, which facilitates the parallelization of operations, thereby increasing processing speed. All rapid retrieval and manipulation of data should be executed using Python dictionaries. Furthermore, GeoTIFF files are loaded into the RAM to eliminate multiple unnecessary disk reads; consequently, most input/output bottlenecks are significantly reduced. Memory structures, such as lists and dictionaries, are systematically deallocated when they have fulfilled their purposes in order to prevent memory leaks and efficiently manage resources.

All these strategies are executed so as to meet up with the requirement of **NFR.3**, ensuring the best efficiency and performance of the system. Tests have revealed quite effective optimizations, resulting in major speedups and resource management based on the large amount of geographic coordinates that get processed. On treating geographic coordinates, more emphasis is given to scenarios involving large-scale processing. During such scenarios, efficient handling of data becomes very important for optimum system performance.

4.3 EVALUATION OF CLUTTER CLASSIFICATIONS AND IMPACT ON PREDICTIONS

The evaluation carried out focuses on two critical aspects: the system's capability to correctly detect and classify clutter across the challenging and diverse landscape of Brazil, and the impact of accurate clutter classification on the pathloss prediction results using the ITU-R P.1812-7 model.

The MOSAICO, a web-based spectrum management software developed by ANATEL [63], is used for the overall evaluation and validation of the proposed system through. This platform provides detailed and complex data concerning radio frequency spectrum usage all across Brazil, thereby becoming an important tool in testing and evaluation efforts. The evaluation process focuses on the spectrum bands allocated by ANATEL for TV and FM broadcast bands, which is the focus of this research. The MOSAICO software provides not only the geographic coordinates of the site but also important data required in making ITU-R P.1812-7 predictions, like operating frequency and antenna height. This research tends to complement MOSAICO by addressing its limitations in signal prediction accuracy and environmental adaptability. While Mosaico focuses on regulatory and broad-scale planning, the present work integrates the ITU-R P.1812-7 model with high-resolution datasets like MCD12Q1, offering refined modeling tailored to Brazil's diverse landscapes.

The TV and FM plan in MOSAICO software currently contemplates 37,150 sites, which cover the whole of Brazil. As this study aims to analyze the effects of clutter on signal propagation, it does not consider those sites that present the same geographical coordinates. The total number of unique locations in basic TV and FM plan drops to 23,366 if the duplicate geographic coordinates are removed.

The next step is a stratified sampling with respect to the Brazilian states, considering the territorial area of each state in proportion to the total area of Brazil. Territorial data is extracted from [64]. The size of the sample to be drawn from each state is computed using Cochran's formula [65], which has been one of the most popular techniques in survey sampling for determining an acceptable sample size in large populations. Cochran's formula is a way of finding the smallest sample size required to achieve a certain level of accuracy based on how much variation there is in the population. In this case, the formula is adapted for the finite population of the whole land area of Brazil. The adjustment ensure that the sample size to be needed is exact and representative, even when considering a very large yet limited area. Table 4.4 presents this information with the respective sample size by Brazilian state.

Table 4.4. Distribution of TV and FM sites sample size by Brazilian states.

State	**Sample Size**	**State**	**Sample Size**	**State**	**Sample Size**
AC	29	MA	57	RJ	8
AL	5	MT	146	RN	9
AP	25	MS	62	RS	49
AM	230	MG	99	RO	42
BA	95	PA	192	RR	39
CE	26	PB	10	SC	17
DF	1	PR	35	SP	44
ES	8	PE	18	SE	4
GO	59	PI	44	TO	48

The final sample has 1,401 sites over the Brazilian territory. Thus, the sample sites are optimally distributed across all states by the use of Halton's sequence for allocation. The Halton sequence [66] is one of the low-discrepancy sequences applied in techniques of quasi-random sampling. Unlike utterly random sequences, Halton's sequence is actually an antithetic variable designed to spread points out evenly over a given space, avoiding clustering and assuring that the area under study is better covered. This sequence proves particularly useful in this case, as the strategy enhances the general representativeness of the sample by ensuring that the selected sites disperse over the huge variety of Brazil's terrain and land cover and not be concentrated in a few areas. Fig. 4.5 shows the final distribution of the 1,401 sample sites projected in Google Earth, which enables visualization of how the sampling is undertaken in this study according to the defined methodology.

A high-resolution GeoTIFF image is generated for each of the 1,401 samples, and every image portrays an area of 2×2 degrees, with the site in question located at the center. The images are generated within a precise 7200×7200 pixel grid; therefore, giving a very fine spatial resolution that allows study areas surrounding the site. A 2×2 degree coverage area is chosen to provide an adequately broad but detailed view of the landscape and land cover around each site. This will be important in making an accurate assessment regarding the impacts of clutter on the signal propagation.

Before any clutter classification analysis can be performed in the proposed system, a re-sampling phase is executed on the GeoTIFF pictures. This step resizes the pixels to a size of approximately 463 m to have a resolution like MCD12Q1 dataset. The resampled map of each site contains approximately 160,000 geographic coordinates, hence being a rich and huge source, very suitable for accurate clutter categorization and further signal propagation modeling.

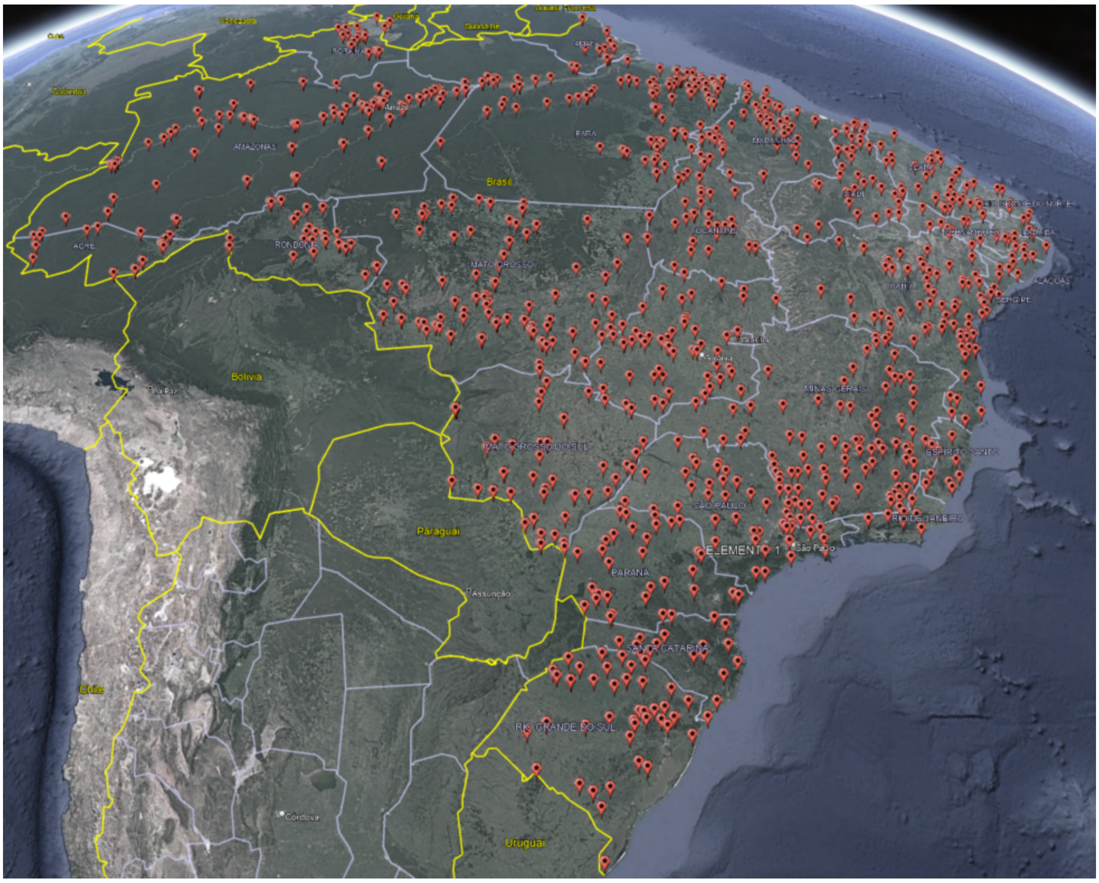


Figure 4.5. Geographical distribution of the 1,401 sample sites across Brazil.

CHAPTER 5

RESULTS AND DISCUSSION

This chapter presents the results obtained with the evaluation tests performed for the clutter mapping system and discusses its implications. The first section focuses on the process of clutter mapping, providing an in-depth investigation of Brazil's diverse regions and varied landscapes. The next section discusses the impact brought by the proposed system when implemented into the ITU-R P.1812-7 model by comparing its results to those obtained using traditional and more simplistic approaches to the estimation of the clutter parameter.

5.1 OVERVIEW OF RESULTS

From the analysis of the 1,401 sample sites, there are no geographic coordinates classified as "Unclassified" based on the MCD12Q1 dataset. That in such a great variety of geographical regions, no unclassified geographic coordinates existed proves the power and reliability of the MCD12Q1 dataset. The ability of the dataset to produce unique and accurate land cover classification, particularly in a complex region like Brazil, makes it very suitable for signal propagation modeling applications.

This consistency is all the more remarkable given the huge range of environmental conditions and land cover types across Brazil. Considering the heterogeneity of the places—huge metropolitan cities and vast rural areas—the MCD12Q1 dataset represents all places by its detailed classification. High information content is needed to enhance the accuracy of the predictions of the ITU-R P.1812-7 model. It is this level of detail that allows a better prediction. In this case, the successful use of the MCD12Q1 dataset confirms its reliability as a source of land cover information and further increases confidence in the proposed approach in real-life telecommunications design. Its ability to map clutter accurately over such a large range of landscapes increases its potential to improve the accuracy of ITU-R P.1812-7 predictions, particularly within a country like Brazil that is very geographically diverse. It thus shows the requirement for detailed and broad datasets, such as MCD12Q1, in such complex modeling situations where accuracy is maximum.

Analyzing the classifications of a sample, Fig. 5.1(a) illustrates the land cover classes according to the IGBP scheme, and Fig. 5.1(b) illustrates clutter categories according to the ITU-R P.1812-7. These classifications were generated by the proposed system, and, as defined in Section 4.3, consider an area of 2×2 degrees of size about the site identifier (ID)[1] 57dbab805f780, which is located in Brasília, in a place known as Digital TV Tower. Highlighted on the maps are the concerned sites, showing it to be the transmitter (TX). The idea is that in posterior tests and evaluation, all other geographic coordinates are potential receivers (RX) in the context of evaluation of pathloss predictions.

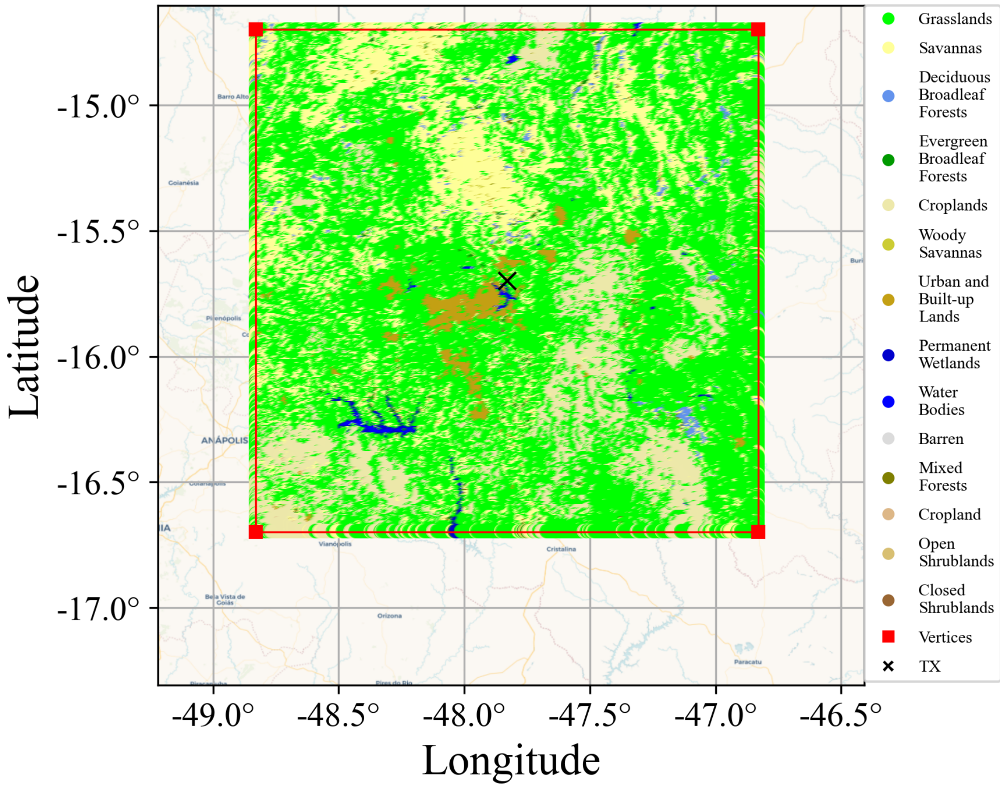
Continuing the analysis, Fig. 5.1(a) details land cover more clearly, such as "Savannas", "Grasslands", and "Urban and Built-up Lands". However, Fig. 5.1(b) primarily labels the clutter as "Open/Rural", indicating that this environment is mostly savanna like. Notably, the presence of areas labeled as "Dense Urban" might add some complexity to signal transmission in a rather heterogeneous cluttered setting, even if only in a limited scale. The propagation model takes as input this last land cover classifications according to the ITU-R P.1812-7 recommendation.

Also, Table 5.1 shows a full evaluation of land cover classes according to the ITU-R P.1812-7 standard for all 1,401 samples. This distribution reflects the high degree of diversity of geographical and environmental features that characterize Brazil, a country with huge variations across different land uses and coverage.

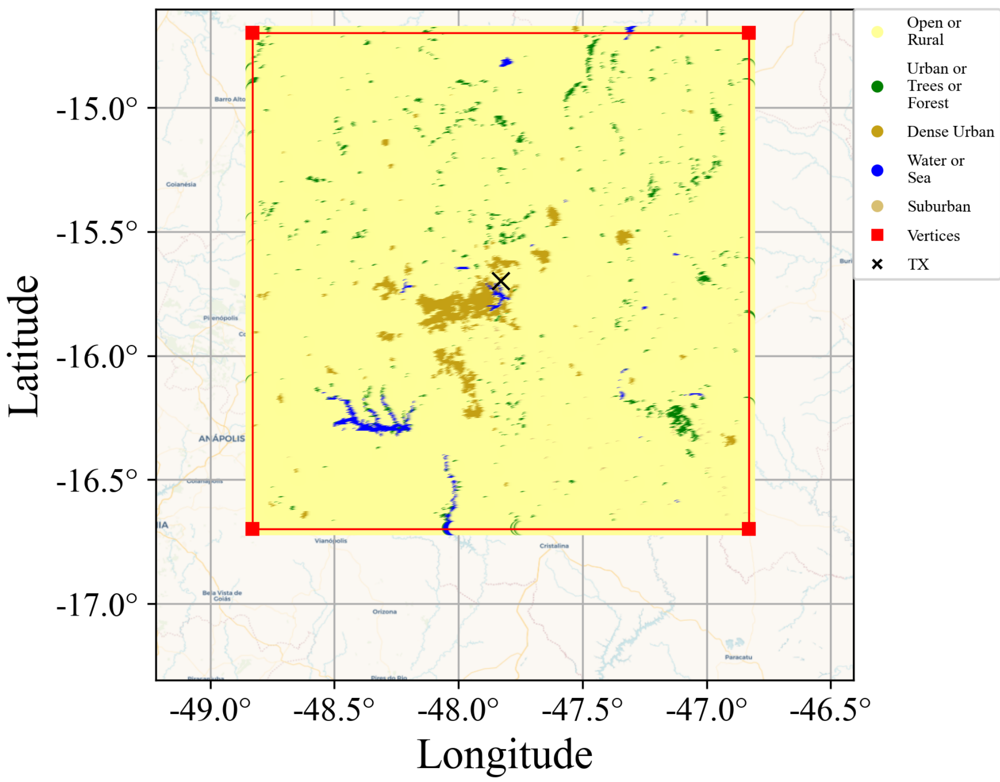
Table 5.1. Distribution of land cover across Brazilian regions, mapped according to ITU-R P.1812-7 classes, for 1401 samples.

Region	**Clutter Category**				
	Water/Sea	**Open/Rural**	**Suburban**	**Urban/Trees/Forest**	**Dense Urban**
North	8.035 %	34.172 %	0.006 %	57.615 %	0.172 %
Northeast	5.069 %	88.096 %	0.922 %	5.687 %	0.225 %
Central-West	0.688 %	84.329 %	0.044 %	14.616 %	0.323 %
Southeast	5.071 %	83.335 %	0.115 %	9.492 %	1.987 %
South	4.666 %	79.153 %	0.001 %	15.100 %	1.079 %

[1] Channel identifier used in ANATEL's MOSAICO software.



(a) IGBP.



(b) ITU-R P.1812-7.

Figure 5.1. Land cover map for site ID 57dbab805f780 using the IGBP and ITU-R P.1812-7 classification.

In the North, the 'Urban/Trees/Forest' category tops the list with more than 57 %, corresponding to the large area of forest with a comparably small population. The dominance of this category reflects its biological value for the Amazonian forest, where thick vegetation makes a huge contribution to the environment. In the North, one would more easily find a larger share of the "Water/Sea" category, with approximately 8 %, which could be predicted by the enormous network of rivers—the most famous and largest being the Amazon River—and large freshwater bodies that are integral to the topography and ecosystem of the region.

Conversely, the fraction of the area covered by "Open/Rural" class is very large in most of the Northeast. In this region, there is a great variety of ecosystems, with the Caatinga and large coastal areas. This preeminence of the "Open/Rural" class can be attributed to the large rural settings in this region, which are affected by agriculture and the semiarid climate affecting land cover in this region.

The Central-West region is very well known to cover a large area with agricultural grounds and pasture, which also has a high percentage, more than 84 %, of "Open/Rural" landscapes. This simply reflects the fact that it is one of the major agricultural centers in Brazil, with large-sized farms and vast open landscapes dominating the entire area. Significantly, this region also has the lowest expression of the "Water/Sea" category, which can be explained by its geography as the only region in Brazil without direct access to the coast. In addition to its peculiar topographical profile, the Central-West region is further distinguished by the nonexistence of large bodies of water.

As can be seen, the land cover distribution in Southeast and South varies a great deal due to the large extents of urbanization and industrial development of these regions. Such land cover in both regions is composed of a mix between "Dense Urban" and "Open/Rural" areas representing the urban-rural gradient common for these regions in the country. The Southeast, where major cities like São Paulo and Rio de Janeiro are located, forms a well-balanced area with the urban nuclei and their surroundings. The South is geographically a much smaller region, but also has a fairly large percentage of densely populated areas within urban settlements, mainly due to the presence of more significant agglomerations of population, such as Porto Alegre and Curitiba.

Basically, the land covers in different regions described in Table 5.1 not only showcases the vast range of geography in Brazil but also, more importantly, serves to underline the need to find unique methods for classifying clutter and simulating radio wave propagation in each region. Understanding these geographic differences is important in telecommunications planning, in that it enables the conceptualization of services tailored to the peculiar characteristics of each region.

Another very important fact to have been considered is this research deals with sample which had been created for TV and FM services whose placement legitimately accounted some population in their vicinity. This is due to their purpose: to serve the public with necessary broadcasting services; and this is why they most probably are located around or within peoples' reach. Beyond the minimization of clustering effects that can be caused by coaxing the Halton's sequences and applying Cochran's formula for sample size determination (Section 4.3 - Evaluation of Clutter Classifications and Impact on Predictions), this unavoidable bias remains, unfortunately, towards populated areas, as can see in Fig. 4.5.

Thus, this bias does also create another problem when trying to validate the land cover classification data using sources like MapBiomas [67]. Indeed, the MapBiomas holds a very good picture of the land cover across Brazil, but sometimes its generalized classification does not fit the localized characteristics of the areas around the sampling sites. Hence, validation of the clutter classification should be nuanced by these limitations. As such, the very distinctive geographic and anthropogenic contexts that surround the sample sites underscore the fact that site-specific data and methods should be considered in a way that bias is treated.

5.2 IMPACT ON ITU-R P.1812-7 PREDICTIONS

For the proposed methodology, the effect of clutter mapping on ITU-R P.1812-7 route loss estimations needs to be quantified. To do this, as described in Fig. 5.2, a simulation software [61] that uses model-specific key input parameters is used. The simulation incorporates both fixed and dynamic parameters specific to the model, as illustrated in the Fig. 5.2. In this work, the fixed parameters—antenna heights, signal polarization, location percentage, and time percentage—are used consistently for all simulations.

This research mainly focuses on one of the important output: Basic Transmission Loss (L_b). The other equally important constituent calculated by the ITU-R P.1812-7 model is the Field

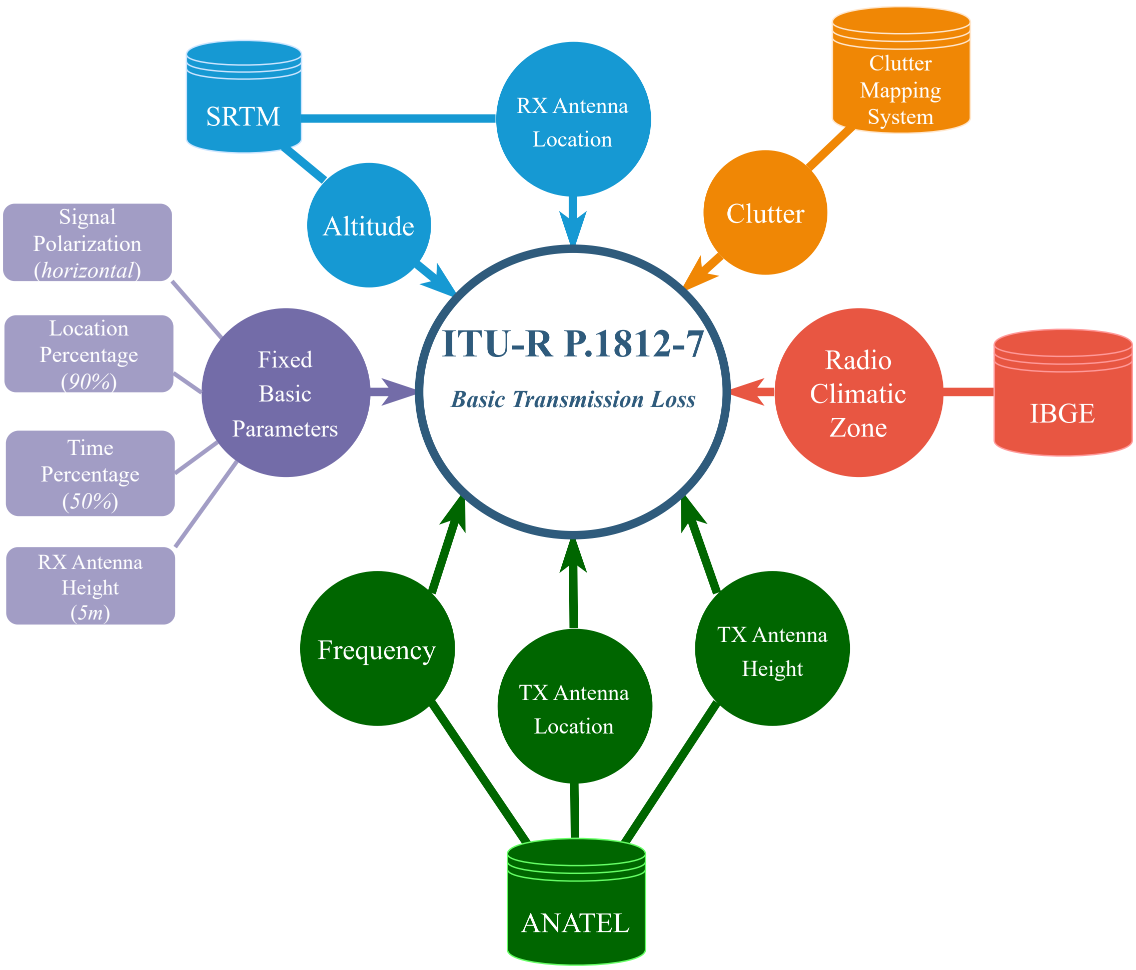


Figure 5.2. Key parameters and datasets integrated into the ITU-R P.1812-7 model for calculation of Basic Transmission Loss.

Strength (E_p). Placing emphasis on L_b is justified, as it constitutes one of the primary factors that directly affect E_p. The focus of this research is to understand and predict the signal propagation. Precise clutter mapping tends to directly influence L_b. Elements contributing to the electric field strength, such as the antenna radiation pattern and transmission power, are not considered in this study. This is because the focus is strictly on L_b, which is expressed in dB and represents the signal attenuation due to various environmental factors during propagation. Understanding L_b allows for a more detailed analysis of signal loss, which indirectly impacts E_p but remains independent of transmission system characteristics.

Although this research is going to concentrate on clutter mapping, it needs to be mentioned that simulation conditions relating to the frequency, the height of the antennas, geographical coordinates, and other are also very important when simulating the predictions. These are parameters that make a comprehensive model work in such a way that it can reflect all the environmental and technical variables properly. However, since they are not of primary concern in this research, they will not be discussed at any length in the present work. The methods used to obtain these auxiliary variables are referred to Section 4.3 (Evaluation of Clutter Classifications and Impact on Predictions), which provides a full description along with the appropriate references.

Similarly, to further assess the proposed approach, we again make use of dataset from MOISAICO to conduct a pathloss prediction analysis. To that end, we randomly select a total of 27 samples, each corresponding to one of the capital cities in Brazil. These samples are chosen to be significantly different with respect to geographical and environmental features all over the country. To increase the resolution of the study and concentrate on areas with higher densities of information, the map boundaries shrank to 1×1 degree squares, with each center based on a selected site, i.e., the TX. The smaller size of the map reduces the area under survey, allowing for a more concentrated examination of local signal attenuation—an essential factor in establishing the accuracy and reliability of the clutter mapping model, mainly in densely populated and urbanized areas. This has been driven by the fact that capital cities mostly exhibit complex clutter characteristics occasioned by their diverse urban infrastructure and varied land cover patterns. For even higher accuracy in the analysis, [68] is implemented to traverse from the TX through all pixels on the map. This result will then be a link profile showing the sequence of crossed terrain and clutter types by this path. Such a profile holds the key to accurate ITU-R P.1812-7 predictions.

The maps are also carefully resampled to the MCD12Q1 pixel size, about 463 m per pixel. It ensures that the resampling technique applied coheres well with the clutter data and the land cover classifications from MCD12Q1. There are now more than 260,000 geographic coordinates in these maps, hence providing a large dataset that allow a proper analysis of how clutter affects the transmission of signals. A high degree of detail is therefore extremely critical in capturing the fine details of land cover variations, which have a strong impact on signal attenuation and hence general accuracy in predictions. The incorporation of smaller map dimensions, careful resampling, and the use of the ITU-R P.1812-7 simulation tool set a robust framework for assessing this proposed clutter mapping approach.

One basic result of this simulation can be seen in Fig. 5.3. It is a heatmap showing the forecast L_b for several areas in Brasília with view of area located by channel ID 57dbab805f780. A color gradient in the heatmap represent different degrees of loss transmission, which undergo geographical features and built surroundings of the area. The propagation model underlines the main locations, showing their relative position and the interaction of their environments with signal strength. The TX is deliberately situated near Sobradinho, serving as the central point for the surveying of signal spread. It shows very clearly the sensitive interplay between Brasília's varied topography and its urban structure and how it affects the propagation of radio waves. Cities that hold more dense urban growth—characterized by larger and more developed buildings and infrastructure—tend to show greater transmission loss, represented by the cold regions in the heatmap.

The center of Brasília is within less than 20 km from the TX, yet the provided heatmap still shows an appreciable increase in L_b; this may be due to the huge process of urbanization in the area. This increase in fundamental transmission loss even for such a short distance provides evidence of the extremely high impact brought about by dense urban on the weakening of signals. Also, it can be observed that there are landforms of higher elevation around Brasília to the north and west. These might have produced barriers naturally, increasing L_b. From the map, one can identify areas with hills and valleys as a sudden change in the degree of signal attenuation. This situation gives an indication that these elevations basically cause barriers and shadowing effects, hence decreasing the intensity of the signals at areas close by.

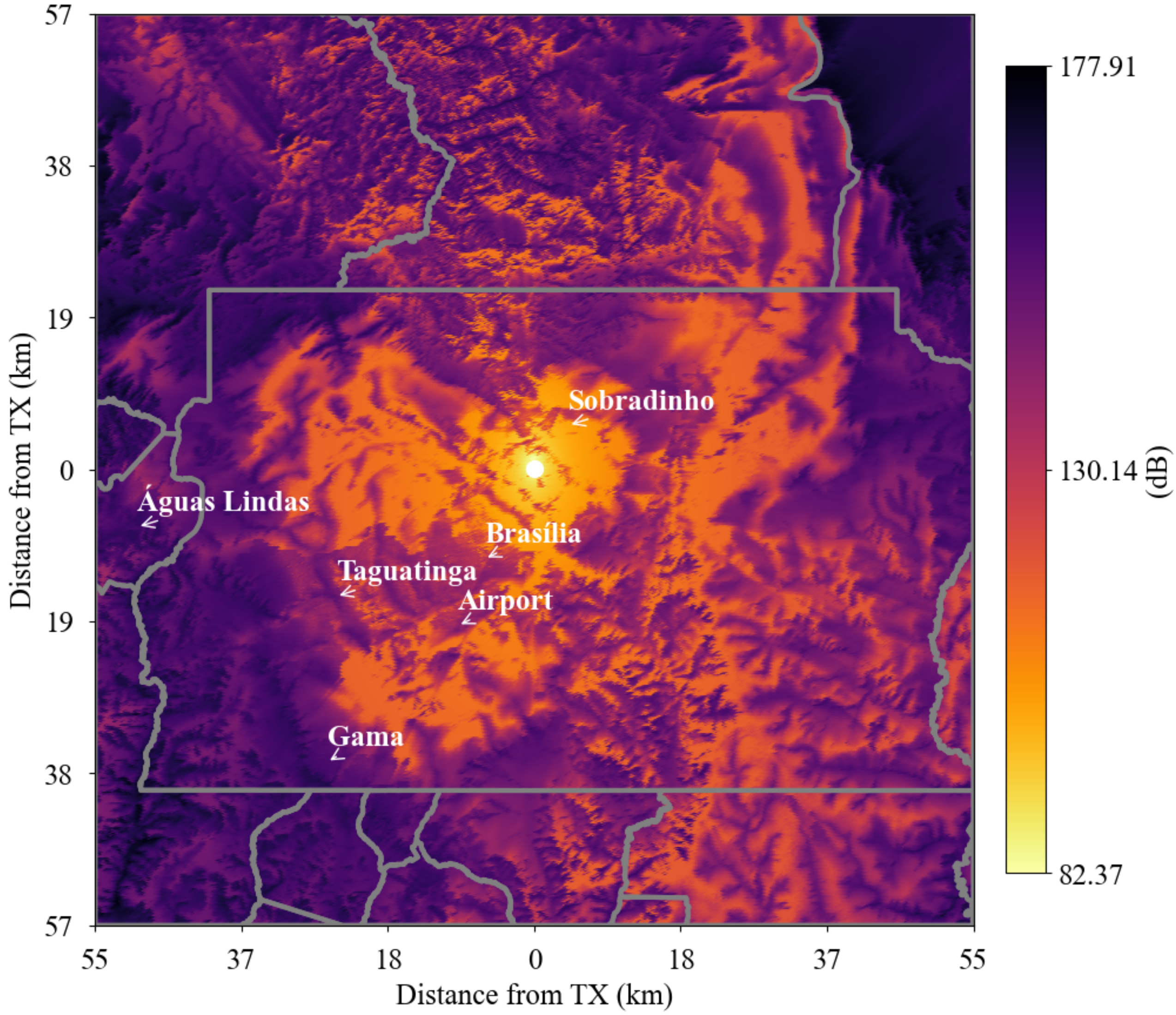


Figure 5.3. Basic transmission loss at site with channel ID 57dbab805f780, located in Brasília, with a frequency of 515 MHz and an antenna height of 178 m.

Another good example is that of Belém. The heatmap shown in Fig. 5.4 gives a very good overview of the city of Belém and allows one to assimilate valuable information regarding the effect of urbanization on the transmission of radio waves. Being sited ideally in the center of Belém, the TX with ID 65255123b3904 allows one to examine effectively how its thick urban environment causes high signal loss over relatively short lengths. The heatmap greatly underscores the complexity involved in signal integrity preservation within metropolitan environments. Buildings, infrastructures, and other man-made barriers abound in such scenarios, significantly altering the pathloss characteristics.

Moreover, additional complications in the signal dynamics in Belém are added by its physical features, very close to large bodies of water like the Bay of Marajó. These large bodies of water may introduce extra propagation phenomena, such as reflection and diffraction (2.1 - Wireless Communication), which have to be introduced into the propagation prediction. The high degree of urbanization and the peculiar topographic composition of Belém converge into a highly complex scenario for signal transmission, demanding advanced modeling and design to provide reliable communication services.

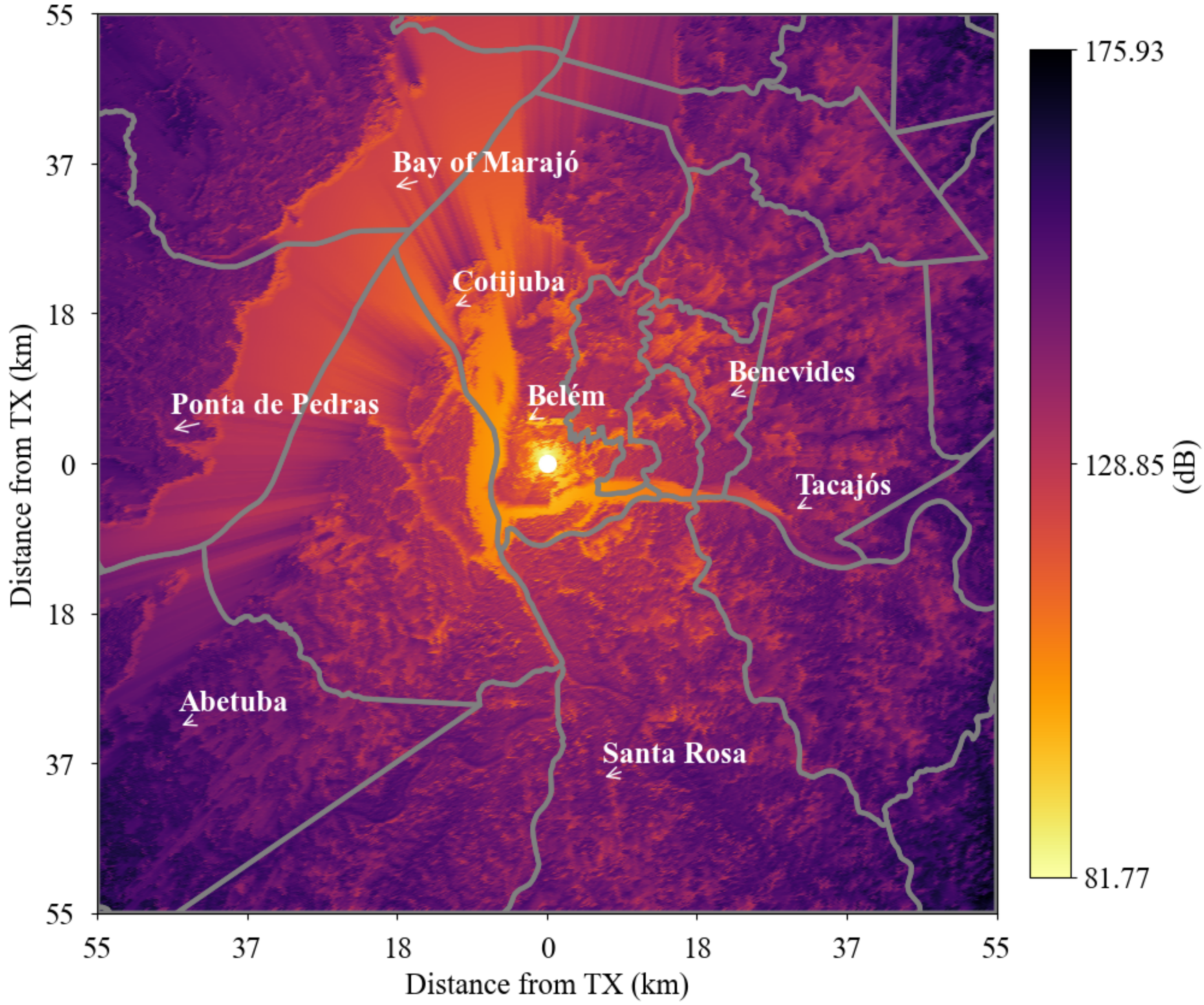


Figure 5.4. Basic transmission loss at site with channel ID 65255123b3904, located in Belém, with a frequency of 497 MHz and an antenna height of 150 m.

In addition, Fig. 5.5 also shows the expected L_b for a location in Porto Velho (site ID 65c0d1d7ae9d5), a city covered by large amounts of forest and a complex natural landscape. Also, what the graph does bring out quite clearly is that the attenuation of signals will be more significant where the landscape is heavily forested, underlining the basic role of natural landscapes in deteriorating signals. This impact is most clear on the wide rivers, like the Madeira River, and in heavily forested areas around the city, whereby transmission of signals is severely decelerated by the heavy foliage and rugged terrain.

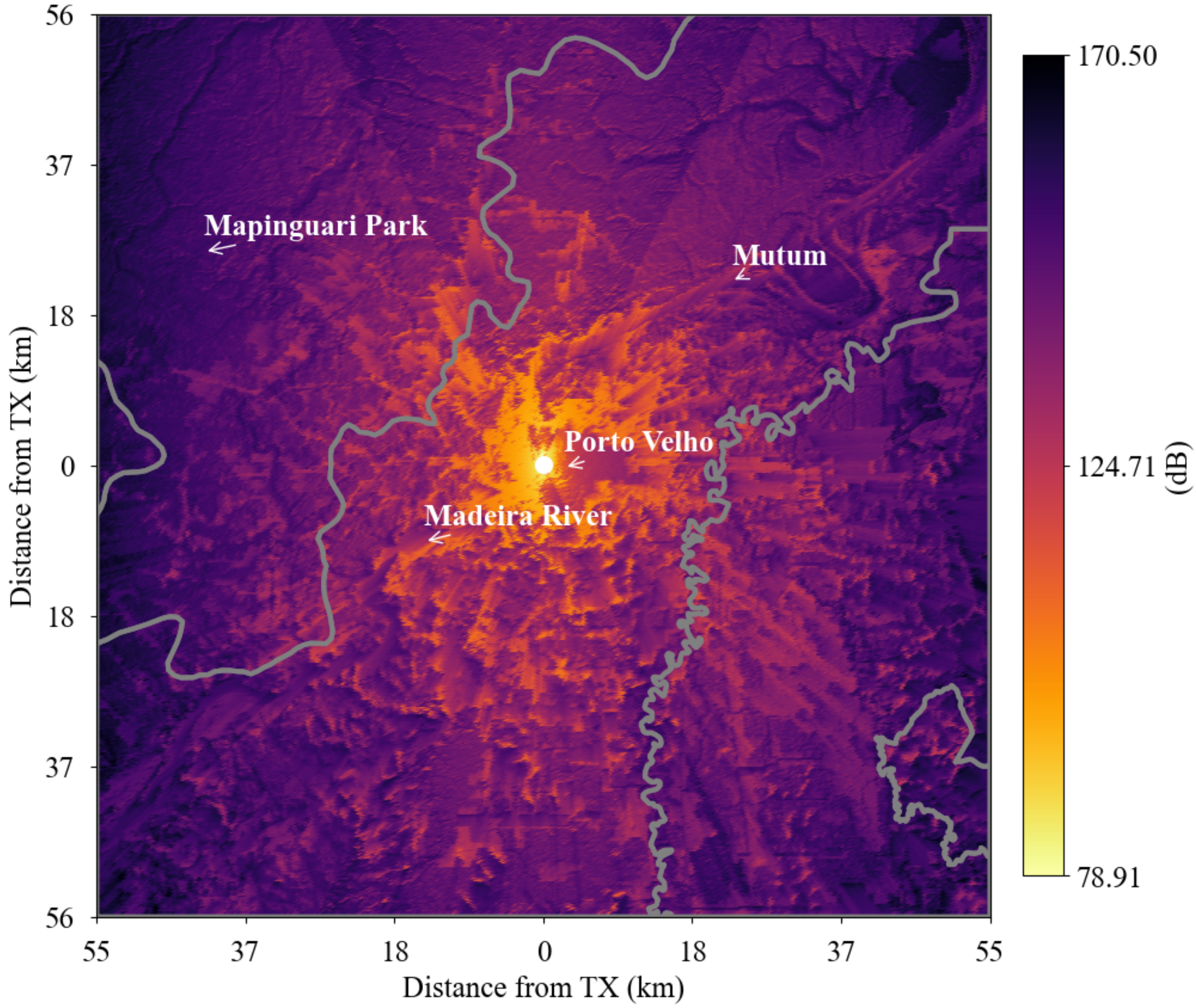


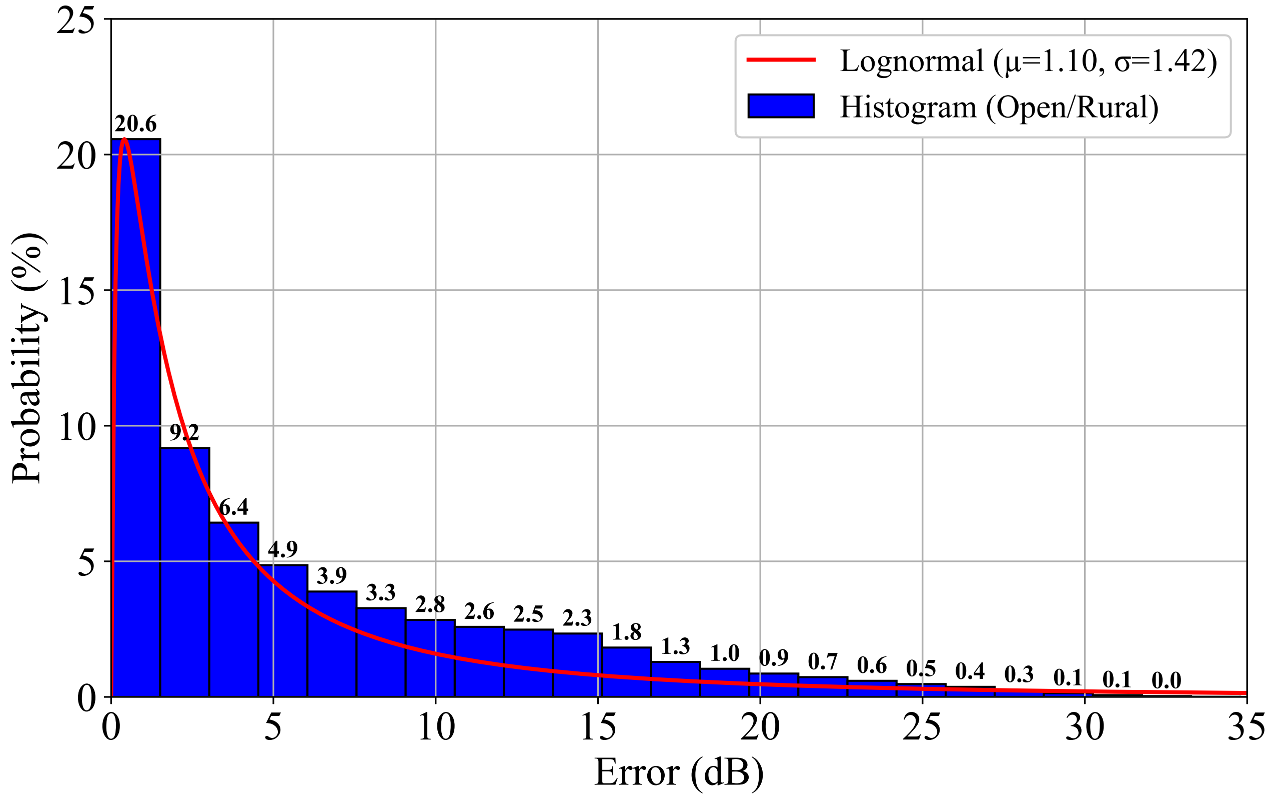
Figure 5.5. Basic transmission loss at site with channel ID 65c0d1d7ae9d5, located in Porto Velho, with a frequency of 521 MHz and an antenna height of 150 m.

The existence of Mapinguari Park and other forest reserves in the surroundings of Porto Velho enhance this attenuation signal because these protected areas have heavy trees that act as major barriers to radio wave transmission. This map perfect illustrates how natural conditions, like undulating landscapes and dense forest cover, set complex conditions for the establishment of reliable communication connections. These environmental issues call for special attention, because it is important in understanding challenges encountered in establishing resilient telecommunication networks within areas characterized by thick vegetation and complex geographical structures. The heatmap also points to the need to use individualized communication strategies in such environments, as traditional urban approaches may not be effective. Even in certain areas, the attenuation levels can already be judged to be significant, and other strategies may be required to overcome inherent barriers and ensure adequate signal coverage in those areas.

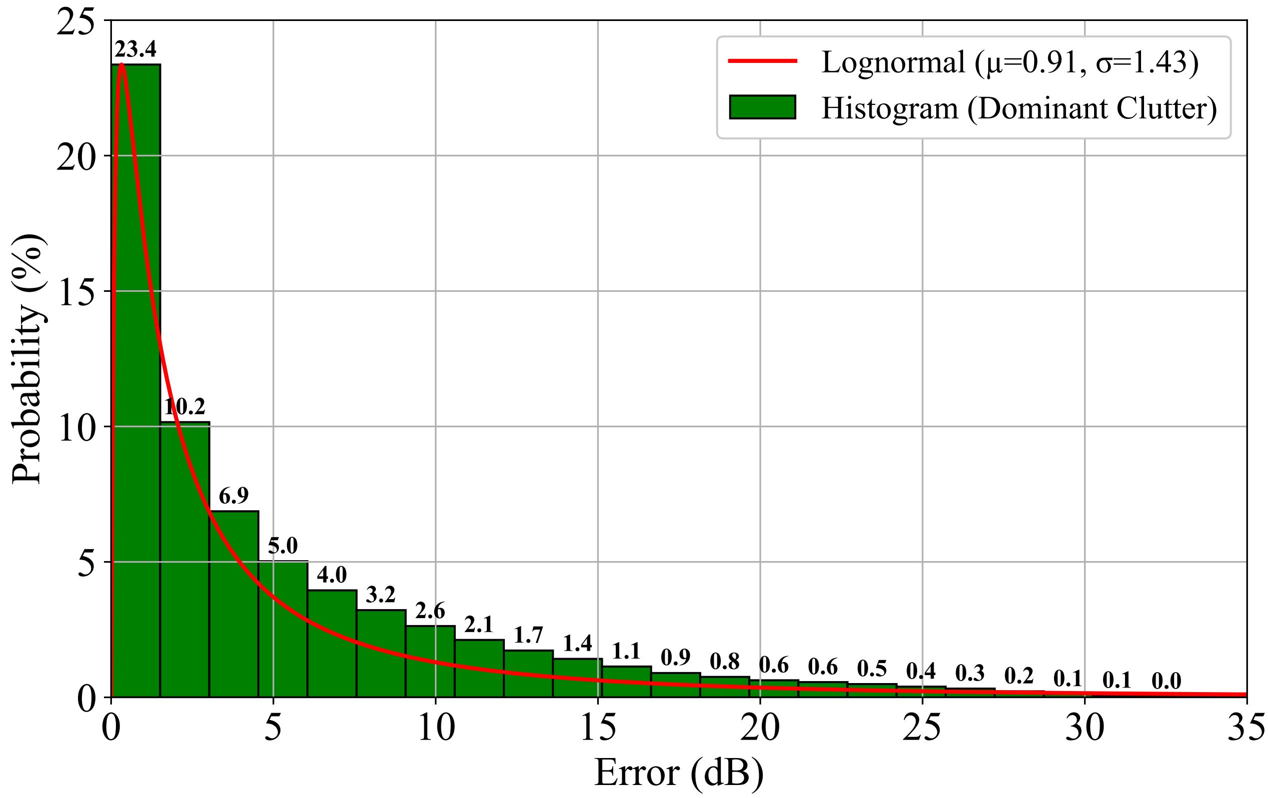
Checking these three different sites (Brasília, Belém, and Porto Velho) taken from the 27 samples submitted for analysis, puts forward that all the problems regarding the transmission of radio waves are completely different in these locations, reflecting geography and urbanism in Brazil. The complex urbanism together with the broad topography in Brasília has brought about large signal attenuation mostly at the center. The situation in Belém is quite different: here, the combination of vast urban infrastructure with proximity to large bodies of water, like the Bay of Marajó, brings additional complications to signal transmission. This shows the need for applying specially designed planning strategies in coastal and urban environments. Furthermore, Porto Velho presents a very pronounced contribution from natural environments in signal attenuation, considering the vast forests and intricate topography, which presents considerable obstacles to reliable links. From these examples, one major inference that can be derived is related to the importance of adopting region-specific approaches in any telecommunication planning process. Therefore, local geographical, urban, and environmental factors must be critically assessed to ensure maximum possible network performance and uniformity of signal coverage over Brazil's diversified terrains.

Another interesting assessment is to compare the predictions of ITU-R P.1812-7 considering the use of the clutter classification system with more simplistic approaches. To this aim, two approaches have been taken into account: the first takes, for all the classifications present on the analyzed map, the "Open/Rural" standard, representative of the total absence of obstruction; the second considers the "Dominant Clutter", that is, the most frequent one, representative of the operator's empirical intuition about the analyzed region. It is important to emphasize that the reference comparison is made against simulations considering the proposed clutter mapping system, not against other other systems or field measurements. The results are shown in Fig. 5.6.

This assessment excludes null errors and the "Water/Sea" category, focusing specifically on



(a) Open/Rural dominant approach.



(b) Clutter dominant approach.

Figure 5.6. Probability distribution of error between the two classification approaches and the proposed clutter mapping system.

cases where the clutter categorization system impacts predictions on land. The histograms reveal that the frequency of detected errors aligns well with a lognormal statistical distribution, reinforcing its suitability for modeling prediction errors in this domain.

A key conclusion drawn from this analysis is that, for the overall terrain, the "Dominant Clutter" approach outperforms the "Open/Rural" pattern, which lacks explicit clutter control. This is evident from the statistical parameters derived from Fig. 5.6(a) and Fig. 5.6(b). For the "Open/Rural" approach, the lognormal distribution has a mean (μ) of 1.10 and a standard deviation (σ) of 1.42. In contrast, the "Dominant Clutter" approach yields a lower μ of 0.91 with a similar standard deviation of σ of 1.43.

The lower μ in the "Dominant Clutter" approach indicates a systematic reduction in the overall prediction error, while the σ being nearly identical between the two methods demonstrates a similar level of variability in error values. This highlights that the "Dominant Clutter" approach not only shifts the error distribution towards smaller values but also maintains consistent dispersion, making it more effective for handling diverse and complex terrains.

Indeed, it is possible to check this statement using Fig. 5.7, which reports the comparison between the Cumulative Distribution Function (CDF) corresponding to the "Dominant Clutter" approach with the red curve and the "Open/Rural" method with the blue curve. The red curve shows a higher accumulation rate, indicating that the "Dominant Clutter" mechanism generally returns a smaller error in most cases. At an error level of 10 dB, nearly 90 % of the samples have accumulated using the "Dominant Clutter" technique, while only about 85 % have using the "Open/Rural" design. It means that the "Dominant Clutter" method works faster, hence managing to reduce errors and, as a result, representing more accurately the features of the examined area.

In any event, the clutter mapping system proposed herein offers considerable potential for improvement in the accuracy of pathloss ITU-R P.1812-7 predictions under both approaches. Although cases of major deviations are rare, this assess proves the ability of the proposed approach to significantly improve the accuracy of link prediction and reduce the potential for gross underestimation or overestimation of broadcasting connection conditions. Thus, this point out the necessity of correct mapping of clutter, influencing these disparities and ensuring more reliable propagation predictions.

Fig. 5.8 also strengthens this thought. The maximum error found ranges from 25.3 dB to 45.3 dB, which indicates a high increase in the improvement on the link pathloss prediction. The one which presents the most considerable inaccuracy is the sample taken from the state of São Paulo; it obtains 45.3 dB. Most likely is that this is the most urbanized area under test, where the effect of attenuation due to barriers is more evident, alongside the disparity in clutter height among the approaches. In any case, there are a high maximum error found in the analyzed samples that can significantly affect the loss prediction at certain points on the map.

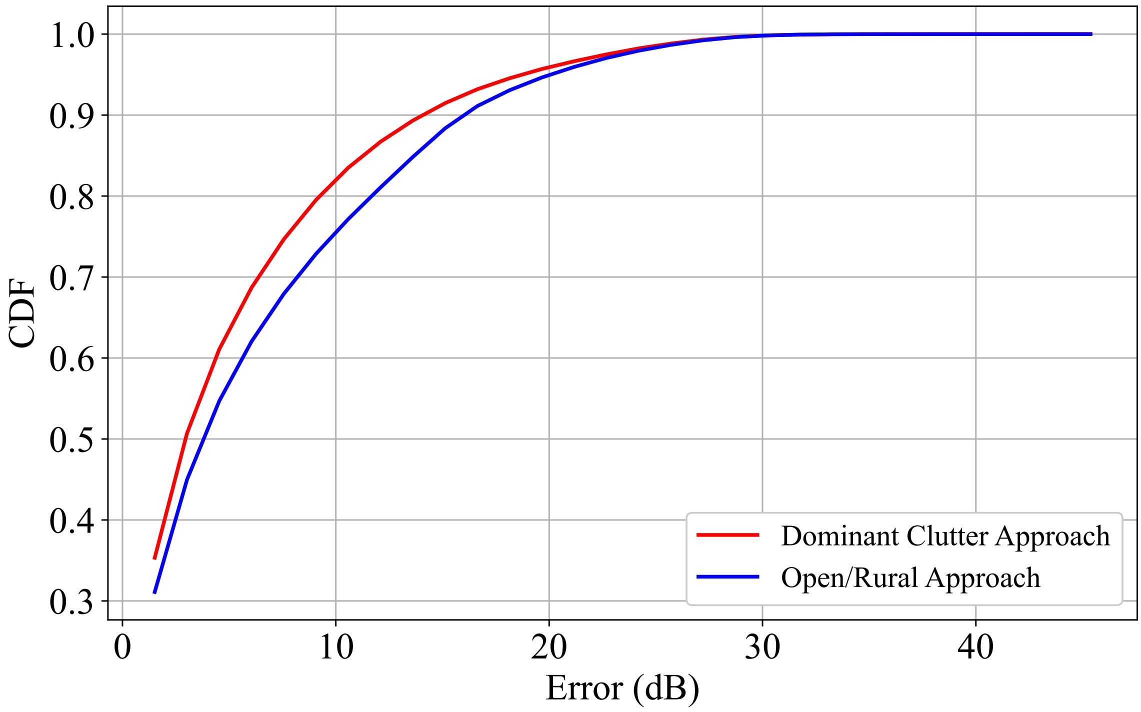


Figure 5.7. Cumulative Distribution Function comparison of error for the Open/Rural and the Dominant Clutter approaches.

A meaningful comparison involve evaluating the Mean Absolute Error (MAE) of both the "Open/Rural" and "Dominant Clutter" approaches against the proposed clutter mapping system using the 27 samples. Details on this are shown in Table 5.2. One key characteristic of the proposed clutter mapping system is that it actually substantially enhances the predictions produced by the ITU-R P.1812-7 model independently of the means used for comparison. For all states, the MAE computed with the proposed system always trends away from zero, indicating that the system is not only adapting itself to different regions but also significantly improving

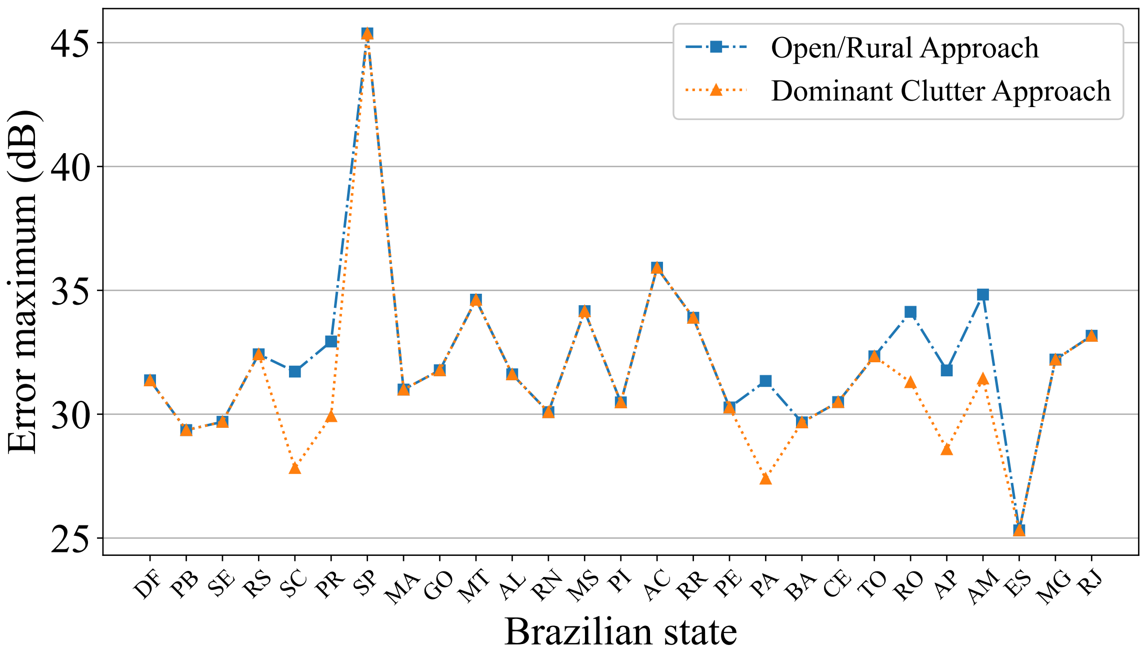


Figure 5.8. Maximum prediction errors for the Open/Rural and the Dominant Clutter approaches across Brazilian states.

the accuracy of predictions. This then implies that there is a strong capability for accurate capturing of regional differences in clutter with more precision. For instance, there is a huge gap in the MAE associated with the traditional methods and that of the newly proposed system in regions like Amapá and Roraima, which shows evident superiority of the technique. The results show that the proposed clutter mapping system improves performance while providing a solution more specifically adapted to each location's unique conditions and increasing the precision of predictions across various scenarios.

Also, an observation of Table 5.2 and Fig. 5.8 shows that in a few cases, the "Open/Rural" and the "Dominant Clutter" approaches have exactly the same MAE levels. This happens simply because both methods are picking on some environmental factors from the common environment in those states that eventually lead to a similar prediction. The states located in the north region differ nonetheless, due to the prevalence of large forest areas that create special conditions in modeling clutter. These cases show a much greater range of MAE results for the different approaches, highlighting additional complexity that these regions introduce to signal prediction models. This kind of variability stresses the relevance of devoting focused attention to these factors at the stage of formulation and execution of signal propagation models, including ITU-R P.1812-7, to enable them to yield accurate predictions tailored to the unique

Table 5.2. Comparison of MAE between the Open/Rural, Dominant Clutter, and the proposed clutter mapping system across Brazilian states.

State	MAE Open/Rural	MAE Dominant Clutter
DF	1.227	1.227
PB	1.351	1.351
SE	0.792	0.792
RS	3.115	3.115
SC	2.348	0.959
PR	2.834	2.840
SP	6.205	6.205
MA	3.275	3.275
GO	1.524	1.524

State	MAE Open/Rural	MAE Dominant Clutter
MT	1.607	1.607
AL	1.131	1.131
RN	1.222	1.222
MS	1.254	1.254
PI	1.690	1.690
AC	5.718	5.718
RR	2.729	2.729
PE	2.443	2.443
PA	9.062	3.334

State	MAE Open/Rural	MAE Dominant Clutter
BA	3.780	3.780
CE	2.291	2.291
TO	1.809	1.809
RO	10.347	3.014
AP	7.732	5.293
AM	9.789	1.734
ES	1.796	1.796
MG	1.169	1.169
RJ	2.356	2.356

features of the terrain. Indeed, it calls for a clutter mapping system complex enough to reflect the intricacies in these states located in the north region and improve forecasting under very unfavorable circumstances.

Additionally, large urban centers such as São Paulo have occasionally been classified under the "Open/Rural" category due to the analyzed square size of 1×1 degree, which covers approximately $12\,321\,\mathrm{km}^2$. This large grid size causes the analyzed area to extend far beyond the urban core, including surrounding rural and less developed regions. Consequently, the averaged clutter type becomes less representative of strictly urban environments, resulting in a classification that, while seemingly counterintuitive, reflects the inherent limitations of using a broad spatial resolution for data aggregation.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 CONCLUSIONS

The present work described the development of a clutter mapping system that expect to enhance the accuracy of loss signal predictions arising from clutter interference. This system was integrated with the ITU-R P.1812-7 recommendation and incorporated modifications aimed at addressing Brazil's complex and varied geographical and topographical characteristics. Extensive evaluation of the system was conducted using datasets from ANATEL and high-quality data provided by NASA satellites in various scenarios. The system improved in its prediction performance, thus indicating that it could potentially be useful in manifold complex situations.

These results revealed the need to incorporate advanced, site-specific adjustments in signal propagation models, especially in topographically varied areas like Brazil. The accuracy attained in loss prediction tend to play a very important role in the development and refinement processes concerning telecommunications infrastructure. The experimental findings revealed a enhancement in precision, with maximum prediction errors between the proposed system and the comparative approaches reaching as high as 45 dB in certain instances. Additionally, MAE surpassed 10 dB across various states within the federation. These results highlight the system's capacity to effectively address the complexities of Brazil's diverse landscape, thereby improving accuracy even in topographically challenging regions. It integrated local obstruction and geographical variability into propagation models, providing more reliable tools to telecommunications engineers and planners, who, through these models, could reduce the likelihood of coverage deficiencies and improve the QoS.

As a complementary finding, the holistic approach, referred to in this work as the dominant clutter approach, demonstrated better results compared to the approach that disregards obstacles in prediction. Numerically, more than 80% of the errors in the holistic approach are below 10 dB, whereas in the approach that disregards obstacles, this value is approximately 75%. These results reinforce the potential of the holistic approach for more accurate signal predictions, particularly in the absence of an effective clutter height prediction mechanism, such as the one proposed in this work.

Besides that, the study was designed to serve as an open-access resource for Brazilian society, adding social value by creating transparency and accountability within the infrastructure development arena. The applied methodology tend enhance not only the management of telecommunications but also tend provid communities and their stakeholders with the necessary information for good decision-making. With this intrinsic clarity, the venture can act as a foundation for further innovations, likely contributing to the advancement of telecommunications technology and infrastructure development in Brazil.

In conclusion, the proposed clutter mapping system is a basic instrument for the precise and reliable evaluation of signal transmission. The integration of this methodology into the ITU-R P.1812-7 recommendation provided greater capability for more effective and responsible management of telecommunications infrastructure. It is expected that this research will provide a basis for further investigation and application in the real environment, considering the potential benefits accruable, which could be extended to other regions with similar geographical and topographic features.

6.2 FUTURE WORK

Future works may focus on improving the system proposed and testing its performance with other propagation models. Enhancements can be brought about in a way that combines additional sensor data in conjunction with machine learning techniques and other remote sensing datasets. This will help provide a better precision of the clutter height and subsequently improve signal loss prediction estimates. Last but not the least, an important step would be to integrate the system to an IoT sensor network, which can collect data in and test signal forecasts.

Additionally, conducting field measurements could be a valuable approach to validate the proposed results. Real-world data collected from specific environments would allow for direct comparison with predicted values, enhancing the model's reliability and applicability.

Also, another direction of research could involve trying to adapt and evaluate the proposed methodology for the 5G and 6G networks, as well as for other propagation models beyond the ITU-R P.1812-7, which is limited to frequencies up to 6 GHz. With the rising adoption of millimeter waves, for example, it is important to delve into the effects of environmental factors on signal transmission.

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