LUNAR LTE: A Mathematical Path Loss Prediction Model for Shoemaker on Lunar South Pole

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Abstract— **This study presents the mathematical model development for the Shoemaker location on the lunar south pole. A 3D ray-tracing technique, executed through Wireless Insite software, was utilized for the simulation at the 3.5 GHz frequency band. The developed model was compared with an empirical SUI model. The path loss model's accuracy was characterized by Root Mean Square Error (RMSE), Standard Deviation Error (SDE), and Mean Absolute Error (MAE).**

The developed lunar model demonstrated RMSE values of 5.939 dB, 5.622 dB, 1.552 dB, 0.829 dB, and 4.17 dB for various scenarios, outperforming the empirical SUI model, which showed significantly higher errors. This comparison highlights the lunar model's improved predictive capability, offering reliable insights for future LTE-based communication systems on the Moon.

Keywords—LTE, Lunar Surface, Path Loss, Path Loss Exponent, Radio Frequency, FSPL, Prediction Model

I. INTRODUCTION

The convenience and high-speed mobile Internet connections demonstrated by the Fourth (4G) and Fifth (5G) generation networks to millions of users through mobile phones on Earth cannot be over emphasized [1]. In the year 2020, the National Aeronautics and Space Administration (NASA) announced the decision to build the first ever cellular network on the Moon, providing accessibility to reliable high data rate lunar surface communications to form an integral part of NASA's Artemis program. Long Term Evolution (LTE) technology as part of the fourth generation (4G) 3GPP cellular technologies was proposed to be the first technology to be deployed. Nokia was selected by NASA as a partner to advance the development and deployment of the first LTE/4G communications systems on the Moon, contributing greatly to the bedrock for a lasting human presence on the lunar surface as they explore different data transmission applications, streaming of high-definition video, and real time navigation [2].

Lunar LTE systems will provide wireless services to endpoints in respective locations through transmitted signals. Signals transmitted wirelessly are affected by environmental conditions and various obstacles, which cause attenuation, interference, and changes in the signal quality during propagation as established during terrestrial communication. The implementation of 3GPP technology as part of the lunar surface networking architecture requires understanding the behavior of radio signals with the environment and properties of the lunar surface. It is expected that the transmitted signals by the 3GPP cellular technology would experience various conditions such as reflection, multipath, scattering from hills and mountains, regolith, despite the absence of atmosphere on the Moon.

The propagation characteristics of the allotted 3GPP frequency bands recommended by the Space Frequency Coordination Group (SFCG) 32-2R4 may exhibit distinct behaviors compared to the terrestrial frequency bands. The potential frequency of operation for 3GPP mobile communication technologies on the Moon as discussed in [3], informed my choice of frequency for the simulation. One effect that is common in the transmission of radio signals is the attenuation of signal strength known as Path Loss (PL). Therefore, for effective planning, design and implementation of a LunarLTE on the Moon, the availability of accurate modeling and path loss prediction techniques are invaluable to help network optimization engineers determine transmitting and receiving antenna selection, operating frequency, base stations, base stations setup location and interference feasibility studies. Consequently, optimal location and improved coverage of transmitter antennas in the Lunar LTE network are crucial for effective communication, thus, accurate path loss modeling is essential to ensure reliable performance in this challenging environment. Previous work reported the modification of Longley-Rice model for path loss prediction [4] by utilizing digital elevation data representative of an analog lunar site, with analyses conducted at 30 MHz, 401 MHz and 2.4GHz. In [5], signal propagation analysis was performed on NASA's wireless communication and sensor systems using frequencies of 401 MHz and the S-band at 2.1 GHz. The authors found that signal strength degraded more significantly than in free space, with factors such as antenna height, frequency, and surface material influencing the results. In [6], a theoretical approach was introduced to understand transmission loss over the lunar surface in the presence of obstacles. The analysis accounted for factors such as diffraction loss, antenna gain, ground proximity loss, and space transmission loss, resulting in outcomes that closely matched the measured data. Nonetheless, none of these studies have explored the application of 3GPP cellular communication technology frequency designated for lunar surface communication. Moreover, no paper reported the development of mathematical based propagation model for path loss prediction on lunar surface cellular communication. Thus, the aim of this study is to develop a mathematical based path loss prediction model within the lunar spectrum frequency range [3], allotted for 3GPP on lunar surface.

The objectives of this study are:

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(i) Examine the impact of propagation loss at the Shoemaker location at 3.5 GHz involving five different scenarios.
(ii) Create a propagation loss prediction model utilizing a 3D ray-tracing technique to develop a generic prediction model at 3.5 GHz to represent the Shoemaker region at the lunar south pole.
(iii) Determine the path loss exponent (PLE), shadow factor, Standard Deviation Error (SDE), Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) values to characterize the path losses.
(iv) Compare the developed lunar model with an empirical model.

II. OVERVIEW

Signal degradation during wireless channel propagation has consistently been a prominent area of research over the years. The reduction in signal strength when a signal is being transferred between the transmitter and the receiver is described as signal loss [7][8][9]. Signal loss is a function of the strength of the signal and the environment it is being transmitted through [10]. The signal that ultimately arrives at the receiver has been significantly altered due to the various forms of degradation and attenuation encountered.

Consequently, the received signal is a weakened and distorted version of the original signal transmitted, having suffered losses due to obstacles, interference, and other environmental factors throughout the transmission process. The degree of signal attenuation varies in different environments and locations. The level of attenuation in an urban environment differs due to its characteristics of numerous tall buildings while environments such as rural settings benefit from line of sight (LoS) where there are fewer obstructions [11].

A. Propagation Models for LTE

Models designed to predict signal loss in LTE networks are crucial tools in network planning, specifically during feasibility studies and the early stages of system development. Creating an efficient mobile network that accurately accounts for signal attenuation requires the use of sophisticated analytical models that incorporate various environmental factors. Numerous such models have been developed for terrestrial environment but not reported for lunar environments. Such models available for terrestrial environments are discussed in this article which one of the listed were compared with the lunar LTE developed mathematical model.

B. Stanford University Interim (SUI) PL Model

The SUI model, created by the IEEE 802.16 committee, is a widely used empirical model for estimating path loss in wireless communication systems. It is specifically designed to predict path loss across different macro-cellular settings. The model applies to frequencies above 1900 MHz and is suitable for cell radii between 0.1 and 8 kilometers. It also considers the range of antenna heights, with transmitter antennas positioned between 10 and 80 meters, and receiver antennas ranging from 1 to 10 meters in height.

The model classifies terrain into three categories: Terrain A, Terrain B, and Terrain C, allowing flexibility across different geographical environments [12]. Terrain A is optimized for areas with rolling hills and dense vegetation, while Terrain B is suitable for hilly regions with sparse foliage or flat areas with varying levels of tree coverage. Terrain C is designed for flat, rural areas with minimal vegetation. The SUI model is mathematically represented as shown in the following equation (1).

$$PL_{\text{SUI}}(d)[\text{dB}] = \text{A} + 10n\log_{10}\left(\frac{d}{d_o}\right) + X_{fc} + X_{\text{RX}} + X_{\sigma} \quad (1)$$

A, is the FSPL, d is the distance in meters, d_o represents the reference distance, n means the PLE, X_{fc} denotes the frequency correction parameters above 2 GHz, X_{RX} represents the receiver's antenna height correction factor for receiving antenna height in meters, and X_{σ} denotes the correction factor for the shadowing due to trees and other obstacles having between 8.2 to 10.6 dB. In determining the PLE n, the following equation can be utilized:

$$n = a - bh_b + \left(\frac{c}{h_b}\right) \quad (2)$$

The variable h_b denotes the height of the transmitting antenna, which generally falls within the range of 10 t0 80 meters. Table I shows the values of the parameters a, b, and c for different environment settings [13].

The equations below can be applied to determine the correction factors specific to the terrain under consideration.

$$X_{fc} = 6 \times \log\left(\frac{f}{2000}\right) \quad (3)$$

$$X_{\text{RX}} = -10.8\log\left(\frac{h_b}{2000}\right) \text{ in use, Terrains A and B} \quad (4)$$

$$X_{\text{RX}} = -20\log\left(\frac{h_b}{2000}\right) \text{ for Terrain C} \quad (5)$$

Table I. SUI MODEL PARAMETERS

Parameters	Terrain A (Urban Area)	Terrain B (Suburban Area)	Terrain C (Rural Area)
a	4.6	4.0	3.6
$b\ (m^{-1})$	0.0075	0.0065	0.005
$c\ (m)$	12.6	17.5	20

III. MODEL DEVELOPMENT APPROACH ON LUNAR SURFACE

This research involves the development of a mathematical based path loss prediction model for LTE at the Shoemaker area of the lunar south pole region on the Moon. The study uses the Wireless Insite software® [14] to perform a 3D simulation on the Lunar Digital Elevation Model (LDEM) map of the Shoemaker as labelled on the LOLA topography for lunar south pole sites. The simulation was conducted in the 3.5 GHz frequency band with the permittivity and conductivity values being set according to the established literature values. The data generated was mined and analyzed and then performed the mathematical model development with the log-normal shadowing model. The idea is to be able to develop a mathematical based model that reflects the environmental scenario of the lunar surface for path loss prediction. The validity of the log-normal equation for lunar conditions can be justified by noting that the lunar surface has open, free space like characteristics with minimal or no atmospheric interference, making the model appropriate for

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the environment. Also, the path loss exponent can be adjusted based on the empirical or simulated data to accurately reflect the unique propagation characteristics of the lunar terrain, such as scattering from craters, regolith and mountain hills.

Materials such as mountains, craters, regolith, and hills exist on the lunar surface. These materials also reflect, absorb, and scatter radio signals during transmission through space. Therefore, we need to incorporate the shadowing factor in the log-distance propagation model in equation (12). The log-distance equation is represented below:

$$PL\,(d) = PL(d_0) + 10 * n * \log\left(\frac{d}{d_0}\right) \qquad (6)$$

where $PL\,(d)$ means the PL (in dB) at point d, d_0 represents the reference distance, n is the PLE.

The log-normal shadowing model is expressed as:

$$PL\,(d) = PL(d_0) + 10 * n * \log\left(\frac{d}{d_0}\right) + X_\sigma \qquad (7)$$

where X_σ (dB) is the normal distributed random variable with SD in dB representing the shadowing factor in the environment [15].

From equations (11) and (12) we can derive the shadow factor as:

$$\mathrm{X}_\sigma = PL(dB) - \overline{PL}(d_0) - 10 * n * \log\left(\frac{d}{d_0}\right) \qquad (8)$$

IV. METHODOLOGY

This section discusses an overview of the simulation software used, the selected location, and the parameters applied in this study.

A. Modeling Technique and Data Collection

In this study, we imported an LDEM map into the Wireless Insite (WI) software, which supports frequency ranges from 50 MHz to 100 GHz and utilizes high frequency electromagnetic methods for precise simulations [14]. The imported map includes features of the lunar surface, such as mountains, hills, craters, and regolith. In other to simulate the intended location at 3.5 GHz, a customized terrain material based on the dielectric half-space model of the ITU dry Earth, utilizing reported values for the permittivity and conductivity in the literature for lunar south pole region. The simulation procedure involves a single 55-meter transmitter height half-wave dipole antenna at the middle of the area and a 3.5-meter receiver height antenna set-up at different locations on a 2km grid map on the Shoemaker region on the lunar surface labelled as Shoemaker in Fig 1 [16].

The ray tracing X3D model was set up in Wireless Insite (WI) using the APG acceleration method that involves two diffractions and six reflections. The simulations were executed on a system equipped with an Intel Core ™ i7-10700 CPU at 2.90GHz, 8 cores and 16 Logical processors, as well as an Nvidia Quadro P2200 GPU, running on Windows 11 Pro. For this particular simulation, the setup consists of a single half wave dipole transmitter positioned at the height of 55 meters, and 6561 receivers positioned in an XY grid with a receiver of 3.5 meters. Data from five path loss scenarios were extracted from the simulation: for excess path loss (EPL) with and without antenna patterns, FSPL with and without antenna patterns, and the total path loss (PL). Data such as received power, received signal strength indicator (RSSI), throughput, transmission loss were also extracted. The Python programming language and MATLAB 2023 were also used as tools in this research. Table II outlines the simulation parameters used before extracting the five path loss scenarios. Also, the methodology of simulation is depicted in Fig 2.

B. Data Interpolation

The generated datasets comprise 6561 data points including distance and respective path loss data profiles. It was observed that about 3.81% of the total data for each of the five scenarios were filled with 250 as the path loss values which is identified as an outlier in the simulation results. While this may seem like a small percentage, the impact on the model was disproportionately large and this is a major concern considering the highly sensitive analysis of path loss prediction on lunar surface. The deviation caused by the outliers distorted the prediction of the path loss exponent and, consequently, impacting the overall model performance.

The idea of logarithm interpolation as a simple approach to this scenario is to mitigate the potential skew caused by these outliers (discussed above) and to capture the variability of the lunar environment. This approach adjusts for the exponential nature of the data, ensuring that the interpolated values better represent the underlying trend rather than being extremely influenced by anomalous data points. This method is critical for maintaining the accuracy and reliability of the developed model, allowing more precise conclusions about path loss behavior on the lunar surface.

C. Study Location

The Shoemaker region on the lunar south pole is the location for this study. It is evident that the lunar south pole is characterized by its extreme environment, with permanently shadowed craters, hills and mountains [17]. These craters may hold deposits of water ice, making them scientifically valuable and potentially useful for future exploration. Also, the rugged landscape of the south pole, with its mix of thick regolith and areas of alternating sunlight and shadow presents both challenges and opportunities for upcoming lunar missions [18].

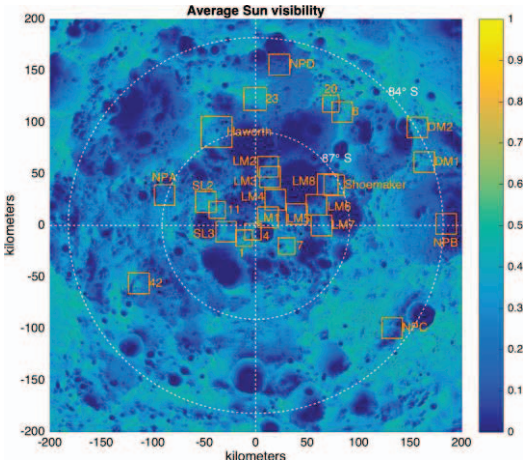


Fig. 1. Representation of LOLA Topography for Lunar South Poles Sites [16]

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Table II. MODEL CONFIGURATION VARIABLE

Variables	Values
Frequency (GHz)	3.5
Antenna Polarization	Vertical
Propagation model	X3D ray tracing model
Bandwidth (MHz)	20
Transmit Power (dBm)	30
Transmitter Height (m)	55
Receiver height (m)	3.5
Permittivity	$\mu r = 3$
Conductivity	$\sigma = 1\times10{-}4$ S/m
Antenna Gain (dBi)	2.15
Antenna type	Half-wave dipole
User spacing (m)	25

D. Model Accuracy Evaluation

Evaluating the reliability of the developed mathematical model, statistical error analysis for each scenario was calculated utilizing Standard Deviation Error (SDE), Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) as reported in the following equations:

$$MAE = \frac{1}{n}\sum_{k=1}^{n}\left(S_{pl_k} - P_{pl_k}\right) \quad (9)$$

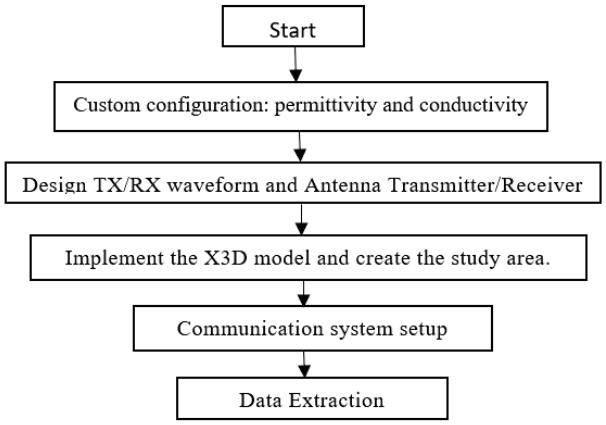


Fig 2: Block diagram for Simulation procedure

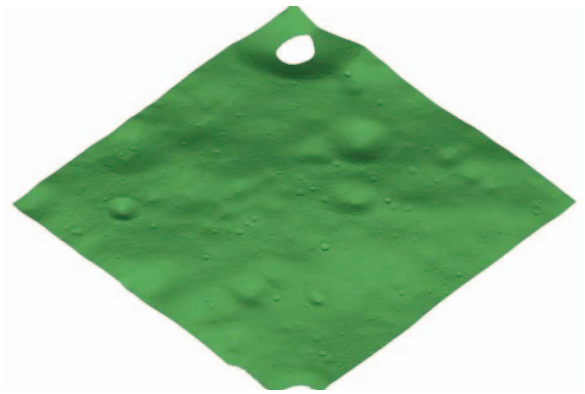


Fig. 3. Shoemaker LDEM Map on the Lunar South Pole

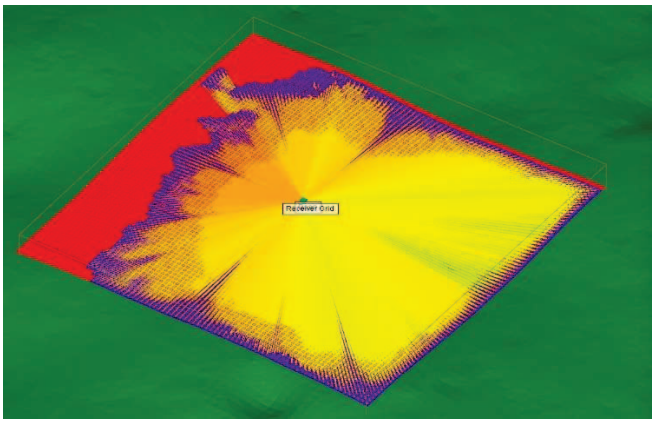


Fig. 4. Showing the propagation paths and areas with no signals

$$RMSE = \sqrt{\frac{1}{n}\sum_{k=1}^{n}(S_{pl_k} - P_{pl_k})^2} \quad (10)$$

$$SDE = \sigma = \sqrt{\frac{1}{n}\sum_{k=1}^{n}(S_{pl_k} - \overline{P_{pl_k}})^2} \quad (11)$$

Where S_{pl_k} represents the simulated path loss measurement, while P_{pl_k} denote the predicted path loss results and $\overline{P_{pl_k}}$ represent the mean of the predicted data.

V. RESULTS AND DISCUSSION

This sections described the efficiency of the developed model and a comparison with Stanford University Interim (SUI) path loss model.

Fig. 5 represents a path loss model showing the relationship between the transmitter and the receivers across the receiver grid as a function of distance. For this particular simulation, all scenarios TX-RX distance is 51.67 m to 1476.27 m. The experiment measures path loss values of the 6561 receivers within the grid either from single path or multiple paths. The figure also explains all the five scenario path loss data point.

Fig. 6 depicts the developed path loss model for all scenarios achieved by modification of the log normal shadowing concept which necessitates the calculation of path loss exponent and the shadowing factor to develop an identical path loss model for Shoemaker region on the lunar surface at the frequency of 3.5 GHz. The path loss exponent for EPL with antenna pattern, EPL without antenna pattern, FSPL with antenna pattern, FSPL without antenna pattern and path loss were -1.503, -1.493, -1.981, 1.972 and 1.976 along with the associated shadowing factors 4.212, 3.943, 0.918, 0.063 and 2.911 respectively. The path loss exponent of 1.976 depicts a closely related condition to free space, as such, the environment signal propagation path has favorable reflective surfaces that slightly enhances the signal strength. The path loss values saturating around -15 dB are excess path loss with and without antenna pattern. The saturation suggests that after a certain point, the additional environmental losses reach a stable state such that the additional effects from reflections, diffractions and multipath propagation appear to no longer significantly increase the excess path losses. There is increased path loss at close distances as depicted in Fig 5. At very close distances, the receivers might be within the

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near-field region of the transmitter, where the typical assumptions of the far-field do not hold. In this near-field region, there is a possibility of receivers experiencing additional losses or fluctuations due to reactive components from the transmitter. In addition, multipath effects such as reflections and scattering from crater surfaces or regolith can constructively or destructively affect the direct signal. Finally, the possibility of increased path loss values at the shorter distance to area been covered by the half-wave dipole antenna due to its minimal radiation along its axis. When receivers are positioned very close and directly aligned with the dipole axis, the received signal strength significantly reduced.

Fig. 7 shows the result of the SUI empirical model prediction for the experimental data collected from the Shoemaker location on the lunar surface. Terrain C of the SUI model parameters were used in this development, comparing it to an area with less building obstructions as there are none on the lunar surface. SUI model was applied on all the five scenarios to predict the values for the path losses.

A. Mathematical Path Loss Equation Development

The model is obtained by performing the least square regression of the simulated path loss in all five scenarios. The parameters associated with the development are the path loss exponent (n) and the shadow factor (X_σ) for all scenarios, which involves a normal distribution random variable with SD in dB representing (X_σ) [16]. The average values for the parameters were used to calculate a regression fitting model to develop the equation (12).

$$(PL)^{Lm}\ dB = PL(d)\ (dB) + 10.n.\log_{10} d + X_\sigma{}^m \quad (12)$$

$(PL)^{Lm}$ is the modified path loss model for lunar surface in dB, the $PL(d)\ (dB)$ is the mean path loss at each transmitter, while n is the average PLE, d is the average distance of the transmitter and the receivers and X_σ is the transmitter shadow factor. Utilizing the parameters and substituting them in equation (12) resulted in a new LTE path loss model for Shoemaker location on the lunar surface at 3.5 GHz.

$$PL^{Lm}\ (dB) = 63.306 + 5.864 \log_{10}(d) \quad (13)$$

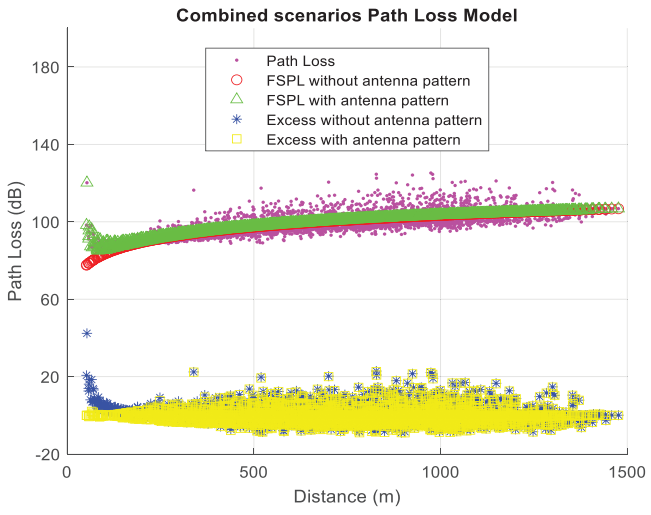


Fig. 5: Simulated Path Loss Model

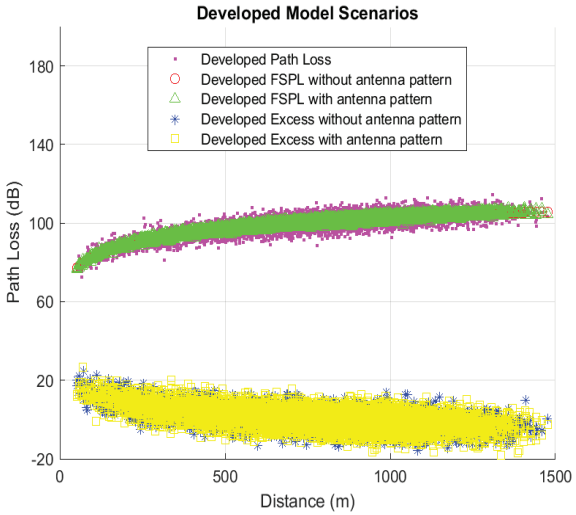


Fig. 6: Developed Path Loss Model

B. Performance Comparison between the Developed and SUI Model

Path loss model prediction accuracy is assessed using the RMSE (Root Mean Square Error) and other statistical means. It has been established that the best performance models exhibits RMSE values close to 0 dB. Nevertheless, the permissible RMSE values for urban terrain typically range between 6-7 dB, and up to 10-15 dB in suburban and rural areas [16][20]. The *Lm* RMSE values calculated for EPL with and without antenna patterns, FSPL with and without antenna patterns, and overall path loss resulted in 5.939 dB, 5.622 dB, 1.552 dB, 0.829 dB and 4.17 dB respectively while the SUI model was revealed to be 265.571 dB, 265.307 dB, 164.686 dB, 164.954 dB and 164.873 dB respectively. Similarly, the *Lm* MAE results for EPL with and without antenna patterns, FSPL with and without antenna patterns, and overall path loss revealed 4.628 dB, 4.387 dB, 1.069 dB, 0.824 dB and 3.112 dB respectively. In contrast, the SUI model demonstrated values of 265.439 dB, 265.158 dB, 164.634 dB, 164.914 dB and 164.797 dB correspondingly.

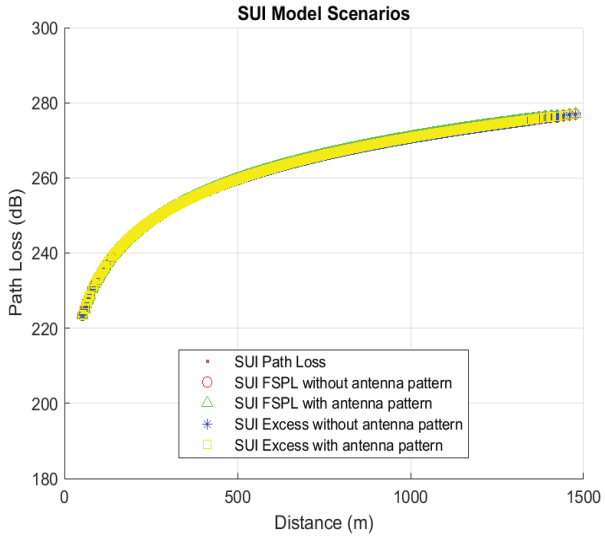


Fig. 7: Developed SUI Path Loss Model

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For the third statistical metric, the Lm SDE value for the aforementioned scenarios in that order showed 5.9 dB, 5.586 dB, 1.306 dB, 0.089 dB and 4.095 dB respectively. The SUI model SDE for the five scenarios was calculated to be 8.390 dB, 8.864 dB, 4.152 dB, 3.608 dB and 5.014 dB respectively. Comparing the developed lunar model (Lm) with the SUI model, it is evident that the RMSE values and both the MAE and SDE values resulted in lower values compared to the empirical SUI model.

VI. CONCLUSION

The comparison between the developed lunar model Lm and the empirical SUI model demonstrates a clear advantage in the Lm performance across key statistical metrics. With lower RMSE, MAE, and SDE values, the Lm consistently outperforms the SUI model, indicating a more accurate prediction of path loss at the Shoemaker region on the lunar surface. The Lm model's RMSE values, particularly in the range of 0.829 dB to 5.939 dB, are well within the acceptable thresholds for urban and suburban and rural areas [19], far below the values recorded by the SUI model, which ranged from 164 dB to over 265 dB. This highlights the suitability of the Lm model for predictions in the shoemaker location of the lunar south pole, as it adheres more closely to industry-accepted performance benchmarks for path loss prediction [15].

In addition, the reduced MAE and SDE values further reinforce the Lm model's accuracy and reliability. These lower error rates suggest that the Lm model can better account for variations in antenna patterns and free space path loss, offering a more refined prediction capability. In contrast, the SUI model, with significantly higher error values, struggles to provide an accurate representation, making the Lm model the preferable choice for lunar path loss predictions. The Lm model was compared with the SUI empirical model to determine how effectively the terrestrial developed empirical model performs in contrast to the Shoemaker (Lm) model. The key insight is the need for environment-specific modeling on the lunar surface, demonstrating that adapting terrestrial models is inadequate.

Consequently, the Lm model sets a new standard for modeling path loss in extraterrestrial environments, contributing to the ongoing development of reliable communication systems for lunar exploration.

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