

A MODELING OF RF PROPAGATION FOR LOW FREQUENCY IN NATURAL CAVES WITH 3D MODEL SIMULATION

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Abstract

The study of the RF propagation model within natural caves remains challenging. In the past, the propagation model in the tunnel was compared using waveguide theory because of the electrical conductivity of tunnel walls. However, waveguide models have limitations because a cut-off frequency from the tunnel dimension does not allow frequencies lower than the cut-off frequency to propagate. Although the frequency wave lower than the cut-off frequency cannot theoretically propagate, in practice, it can propagate through the cave. Therefore, this paper presents the modelling of RF propagation at low frequencies in natural caves using empirical methods by measuring the waves propagated within cave passages at the Chiang Dao Cave (limestone) and the Patihan Cave (sandstone). The measurement will focus on analyzing and comparing factors, propagation mechanisms, and behavior, which cover the frequencies at 300, 1000, 1650, 2325, and 3000 kHz, to develop the low-frequency attenuation model within the cave proposed in this paper. The 3D cave models obtained from a LiDAR scanner were used to calculate the physical factors of the cave walls, and then the path losses were calculated using our proposed model and compared to the experimental results. In addition, the path losses calculated using 1) CST simulation software and 2) the waveguide model were also compared with the results from the proposed model. The results obtained from the proposed model provide attenuation values similar to those of the experimental results. Finally, the concept of the low-frequency attenuation model can be used for the prediction and analysis of the propagation performance of low-frequency waves in caves, tunnels, or underground mines and lead to the development of cave communication technology and electromagnetic knowledge in the future.

Keywords: Cave; Cave Communication; Modeling; Simulation; Wave Propagation

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Introduction

Nowadays, cave technology is still challenging. Mainly due to the physical of the cave being non-uniform and complicated passage compared to tunnel and mine. Then, more than the concept of free-space propagation alone is needed to explain the propagation within the cave, tunnel, or mine. Over the years, many researchers have extensively studied radio propagation in tunnels. The concept of the mine propagation model was initiated by Emslie (1973) and Emslie (1975), who drew inspiration from comparing the coal mine tunnel with the waveguide theory. This approach helps to explain the attenuation caused by various factors in the tunnel. Emslie's research becomes a guideline for several subsequent studies on wave propagation models in the mine and cave. In 1976, Emslie (1976) also studied the propagation in the coal mine at the LF and MF frequency, which analyzed the effect of the conductivity in rock and coal seams. After a year, Deryck (1978) studied the propagation mechanism within the underground chambers to explore the relationship between propagation characteristics and transverse dimensions. Furthermore, numerous studies are dedicated to investigating RF propagation and developing the propagation model in the tunnel and mine (Kjeldsen and Hopkins, 2006; Rak and Pechac, 2007; Bedford and Kennedy, 2014; Hrovat *et al.*, 2014; Bedford *et al.*, 2017; Soo *et al.*, 2018; Javaid *et al.*, 2021; Jantaupalee *et al.*, 2023; Julthochai *et al.*, 2023).

Also, past research has primarily focused on studying the propagation of VHF to SHF bands that are widely used in wireless communication. However, there have been limited studies on wave propagation in caves, especially natural caves, mainly due to the complex environment within the cave passages. In recent years, Wongsan *et al.* (2022) investigated the propagation of LF to UHF bands in a natural limestone cave. This research shows that the non-uniform and implicated cave environment directly affects high-frequency attenuation, particularly non-line-of-sight (NLOS). In addition, the study found that low-frequency waves can propagate along the straight passage of the cave, which differs from the waveguide theory model, where frequencies below the cut-off frequency cannot propagate along the cave passage. However, when the low frequency propagates along the arc against the cave wall, it can penetrate through the cave wall. Based on this mechanism, Jantaupalee *et al.* (2023) proposed the concept of low-frequency propagation in the cave, using the hypothesis of the ground wave property in low

frequency to describe the relationship between cave dimensions, skin depth, and attenuation.

Therefore, this paper proposes the RF propagation modelling for low frequency in natural caves using empirical experiment methods by measuring the waves propagated within cave passages at the Chiang Dao Cave (limestone) and the Patihan Cave (sandstone) that are two rock types of caves found in Thailand, which have different physical characteristics, cave formations, and electromagnetic properties. The measurement will focus on analyzing and comparing factors, propagation mechanisms, and propagation behavior of the low-frequency wave at 300, 1000, 1650, 2325, and 3000 kHz. The experimental results will be used to develop the low-frequency model from the skin depth concept. After that, the 3D cave models obtained from the LiDAR scanner were used to calculate the physical factors of the cave walls, such as dimension, roughness, and tilt. These factors will be used to calculate the path losses with the proposed low-frequency model. In parallel, the results from 3D cave models will also be simulated with the CST simulation software. Finally, the results of the proposed model will be compared to the obtained results from the experiment, the waveguide model, and the CST software. In conclusion, the study and development of the proposed model in the natural cave will help to understand the mechanisms of low-frequency propagation in the cave and determine the appropriate way to communicate within this complex environment.

Propagation Experiment

Indeed, the study of sub-surface propagation is a subject that has been introduced previously. Researchers have been conducting research and experiments in this area for several decades. Those studies established a theoretical foundation for analyzing propagation in the tunnel by comparing it to a lossy waveguide. The propagation study required an empirical experiment by testing transmissions within the tunnel or the cave along the line-of-sight (LOS) at a unit distance from the transmitter. The results obtained from the measurement, which are the power attenuation per unit distance, will be analyzed for further model development.

Experimental Setup

To understand the wave propagation in the cave, we have to measure the propagation path loss

that will present the attenuation behavior of waves travelling within the cave. The measurement procedure in this research has the same method as (Kjeldsen and Hopkins, 2006; Rak and Pechac, 2007; Bedford and Kennedy, 2014; Soo *et al.*, 2018; Jantaupalee *et al.*, 2023; Julthochai *et al.*, 2023), which aims to find the slope of the signal level (path loss slope). The measurement will investigate the wave that propagates along the straight cave passage, which shows the effect of the electrical properties of the cave wall, cave dimension, and other physical environment.

However, this paper proposed to investigate low-frequency propagation, although we will choose the LF and MF bands from the beginning, the middle, and the end of the band. The experimental frequencies consist of 300 kHz, 1000 kHz, 1650 kHz, 2325 kHz, and 3000 kHz. Nevertheless, the frequencies below 300 kHz can't be measured to avoid impacting the bat population in the caves. Jones and Holderied (2007) and Moss

(2018) show many bat species that use ultrasonic waves to resonate with obstacles in front of them to measure distances with frequencies ranging from 20 kHz to 200 kHz.

The experiment uses a Rohde & Schwarz SMB100B signal generator by transmitting the continuous wave (CW) signal to the antenna via a low-loss cable LMR-240 with 16 dBm of the transmitting power, then amplified to 38 dBm with an RF power amplifier. The transmitting antenna consists of a passive shielded loop antenna (20 Hz-1 MHz AH Systems SAS-565L) at 300 kHz and an Isotron 200B antenna at 1,000 - 3,000 kHz. Both antennas provide an omnidirectional pattern, which transmits vertically linear polarization. For the receiver equipment, we use a Rohde & Schwarz FPH spectrum analyzer and a Rohde & Schwarz HE400HF antenna module (8.3 kHz - 30 MHz). The transmitter equipment was installed at the beginning point. The receiver will measure signal levels between the transmitting and receiving antenna at a progress distance of every 2 meters until reaching the destination of 20 meters, as shown in Figure 1. The received power will be normalized for all frequency bands.

The experiment locations consist of two caves that are the Chiang Dao Cave and the Patihan Cave. First, the Chiang Dao Cave is a limestone cave that is the cave type most found generally in Thailand. In the Chiang Dao Cave, we choose the Tham Nam section, which has a straight passage of about 20 - 30 meters, as shown in Figure 2. Another one is the Patihan Cave, as shown in Figure 3. Significantly, these two caves differ in their formation, chemical composition, and physical characteristics, all of which affect the travel of electromagnetic waves that will be analyzed in the later section.

Experimental Result

Figure 4 shows the results of the propagation measurement at the Chiang Dao Cave. The results illustrate that path loss slopes are 3.90 dB/m, 2.83 dB/m, 1.52 dB/m, 1.76 dB/m, and 2.06 dB/m at 300 kHz, 1000 kHz, 1650 kHz, 2325 kHz, and 3000 kHz respectively. Figure 5 shows the results of the propagation measurement at the Patihan Cave. The results have 1.57 dB/m, 1.51 dB/m, 1.25 dB/m, 1.40 dB/m, and 1.38 dB/m at 300 kHz, 1000 kHz, 1650 kHz, 2325 kHz, and 3000 kHz, respectively.

From the results, the frequency at 300 and 1000 kHz has a relatively high path loss. Following the wave propagation theory, the frequency in the LF and MF bands indicates the surface wave property. This property occurred by the conductivity in the medium (cave wall), which has slight conductivity. If the frequency of the waves is low enough, the cave walls act like dielectric walls.

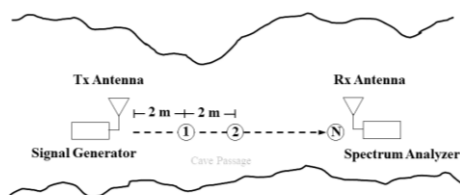


Figure 1. The diagram of the experimental setup



Figure 2. Chiang Dao Cave (Tham Nam)

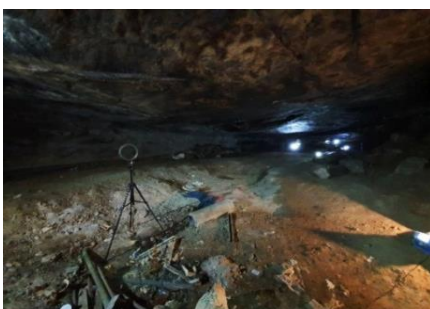


Figure 3. Patihan Cave

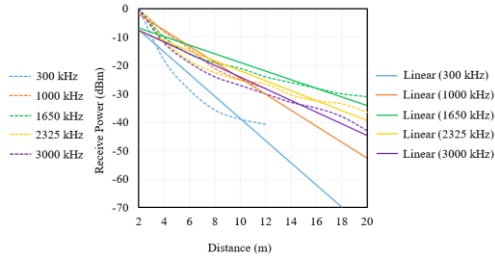


Figure 4. The experimental results compare the received power level and distance at the Chiang Dao Cave

When the low-frequency wave travels through the cave passage, some part of the waves penetrate through the cave wall due to the skin effect, while others will reflect and diffract to the receiver. The waves penetrating the cave wall will attenuate due to the dielectric layers within it. The higher frequencies at 1650 kHz, 2325 kHz, and 3000 kHz have lower path loss since they propagate along the cave cavity well rather than being affected by the cave wall. In conclusion, the experimental results led to the study of wave propagation models in the cave, especially at low frequencies, with the addition of the skin effect discussed in the next section.

Materials and Methods

Electromagnetic Properties

The mechanical and electrical properties of rocks significantly affect the propagation of waves within the cave. The Chiang Dao Cave is a limestone cave that originates from the gradual accumulation of sediment on the ocean floor over millions of years. Over time, geological shifts and erosion, driven by this slightly acidic water, contribute to cave formation. The Patihan Cave is a sandstone cave that exists in northeastern Thailand. Unlike the Chiang Dao Cave formations, Patihan Cave exhibits minimal dissolution but more than undergoes mechanical weathering processes. These formation processes cause to differ the homogeneity of the medium. In the case of the Patihan Cave formation, there will be gaps in the rock layers from the porosity and mechanical weathering process. As a result, the differences in the dielectric layers have occurred (i.e., air, sand, and soil) when the waves traveling through the dielectric layers will attenuate and reflect between the layers. In contrast, the Chiang Dao Cave has higher homogeneity because the medium is almost one layer throughout (Daniels, 2004; Gunn, 2003; Dunkley *et al.*, 2017; Sriporipibul, 2021; Putthapiban, 2021).

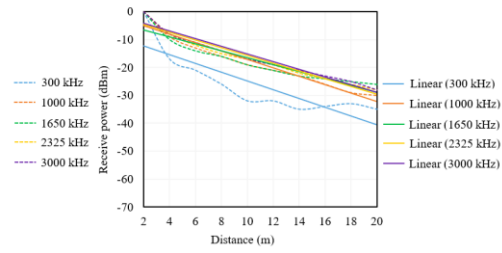


Figure 5. The experimental results compare the received power level and distance at the Patihan Cave

Additionally, the mineral composition and sedimentary grains of limestone and sandstone determine the electrical properties of rocks, which affect wave attenuation and electrical conductivity. Minerals that can conduct electricity are composite within the rock according to the porosity factor of the rock. Wannakomol and Chonglakmani (2018) researched the porosity of the Permian limestone, which is the same as the limestone at Chiang Dao cave. The Permian limestone had an average porosity of only 1.06%, compared to Gaewmood and Trisarn (2018) found the average porosity of the Phra Wihan sandstone was 12.6%. Also, Glover (2015) shows that porosity affects conductivity properties. When porosity increases within the same medium, it leads to higher electrical conductivity due to the replacement of various minerals. The conductivity of rocks will affect the skin effect of the medium discussed in the next topic. Limestone typically exhibits lower electrical conductivity than sandstone due to its lower porosity. The rock samples in each study by Milsom and Eriksen (1989), Murray (2000), Daniels (2004), and Glover (2015) found that limestone had less electrical conductivity than sandstone slightly. The relationship between electrical conductivity and resistivity is explained in Equation (1).

$$\sigma = \frac{1}{\rho} \quad (1)$$

Where the σ is the electrical conductivity ($S \cdot m^{-1}$), and ρ is the electrical resistivity ($\Omega \cdot m$).

Propagation Mechanism

According to Collin (1985) and Siwiak and Bahreini (2007), the frequencies ranging from a few kilohertz to several megahertz have the predominant propagation mode as a surface wave. The ELF to VLF frequency range utilized in underwater navigation, sonar, and long-range navigation has long wavelengths and large skin depths, allowing

them to propagate over the earth or sea surface. When electromagnetic waves travel through a conductive medium, the energy will oscillate the free electric charges in the conductor. This oscillation causes electromagnetic energy to convert into heat, which increases when the electric charge increases (high conductivity). As a result, the wave energy almost wholly attenuates at the medium's surface when traveling into the high-conductivity medium. The distance when the waves propagate through the conductive medium and energy is reduced to e^{-1} (36.8%), called skin depth (δ) (Balanis, 2012). In addition, Gibson (2014) and Bedford (2001) study the communication systems in caves with low-frequency waves, which can penetrate through rock layers caused by the high skin depth. The relationship between skin depth, conductivity, and frequency can be seen in Equation (2).

$$\delta = \sqrt{\frac{2}{\omega \sigma \mu}} \quad (2)$$

Where the δ is skin depth (m), ω is the angular frequency ($rad \cdot m^{-1}$), μ is permeability ($H \cdot m^{-1}$).

Moreover, when the waves travel inside the cave cavity, some part of the waves travel along the cave cavity while others penetrate the cave wall, which has dielectric layers that cause them to reflect and attenuate, as shown in Figure 6. In the lower frequency, it has more skin depth, resulting in an electrical dimension more than the physical dimension. But even so, the low-frequency antenna has a size limit and a narrow bandwidth, which is unsuitable for communications within caves. However, the electrical conductivity of the cave walls is lower than seawater, which makes the higher frequencies have a more usable skin depth but retain the ground wave property (Collin, 1985). This concept will lead to the model development of the low-frequency propagation inside the cave, explained in the next topic.

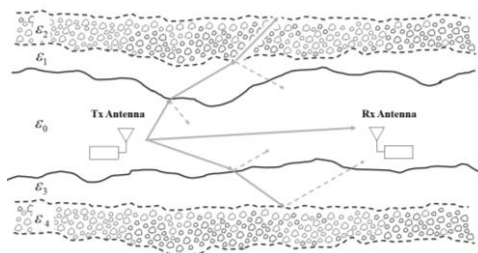


Figure 6. The experimental results compare the received power level and distance at the Chiang Dao Cave

Methodology

Waveguide Model

Wave propagation within tunnels and mines has been studied for a long time. Emslie *et al.* (1973), Emslie *et al.* (1975), and Deryck (1978) investigated electromagnetic propagation in underground tunnels with uniform shapes as a waveguide. The waveguide typically has a hollow structure with a wall capable of conducting transverse electric (TE) and transverse magnetic (TM) waves, generating electric and magnetic fields perpendicular to their direction. Additionally, the dimensions of the waveguide determine the lowest frequency that can be transmitted with minimal loss. The cut-off frequency value is dictated by the specific mode, also known as the dominant mode, which is determined by the size and shape of the waveguide. According to waveguide theory, the cut-off frequency is the lowest frequency that can pass through with minimal attenuation, obtained from the wavelength by comparing the dimensions of a natural cave resembling a rectangular waveguide. The cut-off wavelength equation is shown in Equation (3).

$$\lambda_{mn} = \frac{2\sqrt{ab}}{\sqrt{\left(m^2 \frac{b}{a} + n^2 \frac{a}{b}\right)}} \quad (3)$$

Where a is the width of the waveguide, b is the height of the waveguide, and mn is the mode of the waveguide.

However, it has previously only been studied in the high-frequency range, from UHF to SHF, where the waveguide model can still be used because the wavelength of the high-frequency band is typically smaller than the cave's dimension. Waveguide theory is used for attenuation modeling the wave propagation within the cave, as shown in Equations (4) to (8).

The shape and dimensions of the tunnel are non-uniform, and the dielectric mediums of the wall impact the propagation behavior. Non-uniformity in the tunnel medium that refraction by the floor and wall is termed refraction loss because when transmitted signals penetrate any medium, a portion of the signal is absorbed, resulting in considerable refraction loss. Refraction loss is calculated by considering both horizontal and vertical medium characteristics, depending on the width and height of a mine. Equations (4) and (5) provide the defined expression of refraction loss (Emslie *et al.*, 1975; Bedford and Kenedy, 2014; Bedford *et al.*, 2017; Javaid *et al.*, 2021).

$$a_h = 4.343\lambda^2 \left(\frac{\varepsilon_v}{a^3 \sqrt{(\varepsilon_v - 1)}} + \frac{1}{b^3 \sqrt{(\varepsilon_h - 1)}} \right) \quad (4)$$

$$a_v = 4.343\lambda^2 \left(\frac{1}{a^3 \sqrt{(\varepsilon_v - 1)}} + \frac{\varepsilon_h}{b^3 \sqrt{(\varepsilon_h - 1)}} \right) \quad (5)$$

where ε_h is the relative permittivity of the cave ceiling and floor, and ε_v is the relative permittivity of the side wall.

The non-uniform of the tunnel surface generates roughness that has a significant impact on the propagated electromagnetic wave. The roughness of the side walls serves signal scattering, resulting in attenuation. The roughness loss for the roughness wall is expressed as Equation (6).

$$a_{\text{roughness}} = 4.343\pi^2 \Delta h^2 \lambda^2 \left(\frac{1}{a^4} + \frac{1}{b^4} \right) \quad (6)$$

Where Δh is the RMS roughness height of the wall (m).

Attenuation from the inclination of the cave wall, which is shown in Equation (7) (Emslie *et al.*, 1975; Bedford and Kenedy, 2014; Bedford *et al.*, 2017).

$$a_{\text{tilt}} = \frac{4.343\pi^2 \theta^2}{\lambda} \quad (7)$$

where θ is the inclination angle of the cave wall (radian).

The tilt of the tunnel wall relative to the mean planes, which is determined by tunnel dimensions a and b , deflects power in the mode away from the directions given by the mode's phase condition. Equations (6) and (7) demonstrate that roughness is significant at low frequencies, whereas tilt is most significant at high frequencies.

The attenuation summary according to the propagation model in decibels per meter can be obtained from Equation (8).

$$a_{\text{total}} = a_{\text{refraction}} + a_{\text{roughness}} + a_{\text{tilt}} \quad (8)$$

Low-Frequency Model

The waveguide model indicates that waves at low frequencies cannot propagate within the waveguide with a dimension similar to the experimented caves because the attenuation approaches infinity. However, the measurements demonstrate that waves can propagate within cave

passages. The abovementioned mechanism for low-frequency propagation has led to the development of a model specific to low-frequency propagation within natural caves. In this study, we present a model utilizing the simplest form of the homogeneous medium models to simplify the mathematical of attenuation. We initiate the model by defining the walls and ceiling of the cave as a medium with uniform properties with the skin effect occurring by the low-frequency wave, represented by the relationship in Equation (3). This phenomenon causes the electrical dimension of the cave to be larger than its physical dimension, as illustrated in Figure 7.

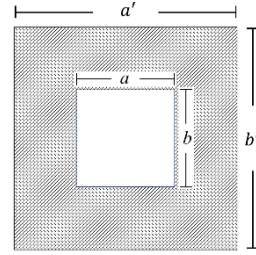


Figure 7. The skin effect on physical cave dimension

The electrical dimensions of the cave caused by skin effect changes can be described as Equations (9) and (10).

$$a' = a + \delta \quad (9)$$

$$b' = b + \delta \quad (10)$$

Substituting Equations (9) and (10) into the reduction Equations in (4) and (5) can be expressed as Equation (11) and (12). Only the predominant polarization is considered.

$$a_h = 4.343\lambda^2 \left(\frac{\varepsilon_v}{a'^3 \sqrt{(\varepsilon_v - 1)}} + \frac{1}{b'^3 \sqrt{(\varepsilon_h - 1)}} \right) \quad (11)$$

$$a_v = 4.343\lambda^2 \left(\frac{1}{a'^3 \sqrt{(\varepsilon_v - 1)}} + \frac{\varepsilon_h}{b'^3 \sqrt{(\varepsilon_h - 1)}} \right) \quad (12)$$

Then, substituting Equations (9) and (10) into the roughness attenuation equation, the result can be shown in Equation (13).

$$a_{\text{roughness}} = 4.343\pi^2 \Delta h^2 \lambda^2 \left(\frac{1}{a'^4} + \frac{1}{b'^4} \right) \quad (13)$$

Equations (11) to (13) explain why low-frequency waves can propagate through the cave with a size much smaller than the wavelength

despite the waveguide model approaching infinity. The results of the low-frequency model calculation will be presented in the later section.

CST Simulation

This section will explain the use of 3D models of the caves, both Chiang Dao Cave and Patihan Cave, to simulate wave propagation using the CST simulation software. The 3D models of the caves were obtained from the LiDAR 3D scanner (Leica BLK 360) in a 1:1 scale with high resolution, allowing for a comprehensive collection of the details of the caves. The 3D model of the experimental section of Chiang Dao Cave is shown in Figure 8, and Patihan Cave in Figure 9. These 3D cave models are used to simulate by transmitting the low-frequency wave from the same starting point with a waveguide port and using a similar waveguide port to receive at every 2 meters along the cave passage, same as the experimental conditions. The path losses consideration over distance will be assessed with the transmission coefficient (S21) at different distances. The transmission coefficient of the simulation results with the Chiang Dao model is shown in Figure 10, and the Patihan model is shown in Figure 11.

The electrical properties of the limestone and sandstone medium used in the simulation, we use the resistivity, relative permittivity, and relative

permeability from the study of Daniels (2004), Mount and Comas (2014), and Glover (2015). In general, consideration of the electrical properties of a non-homogeneous medium will be considered a range due to the non-uniformity of the medium. Therefore, the electrical properties of the simulations were obtained by the average values of previous research. Previous studies indicate that limestone has electrical conductivity in the range $10^{-1} - 10^{-8}$, relative permittivity in the range 7-13, and relative permeability in the range 7-8. Sandstone has electrical conductivity in the range $10^{-2} - 10^{-6}$, relative permittivity in the range 2-10 range, and relative permeability in the range 2-10 range.

Moreover, Figures 12 and 13 show the simulation results using the CST studio suite program, showing the current density at 300, 1000, 1650, 2325, and 3000 kHz occurring in the medium of both the Chiang Dao Cave and Patihan Cave models. The current density illustrates the phenomenon of waves traveling from within the cave passage through the cave wall based on the wave propagation mechanism of low-frequency waves. As the frequency increases, the current density penetrating the cave walls decreases with frequency. Finally, these results are compared with the measurement data and model results in the results and discussions section.

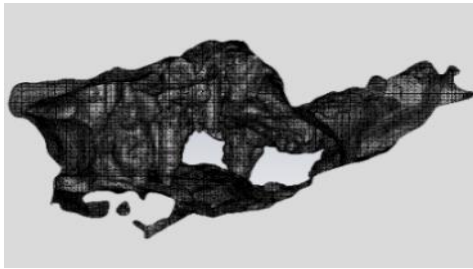


Figure 8. The 3D model of Chiang Dao Cave

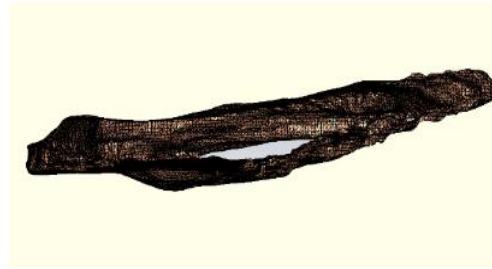


Figure 9. The 3D model of Patihan Cave

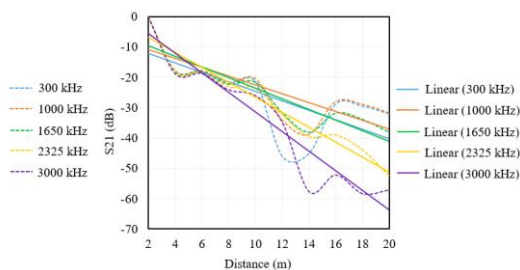


Figure 10. The simulation results of the transmission coefficient with the Chiang Dao Cave model

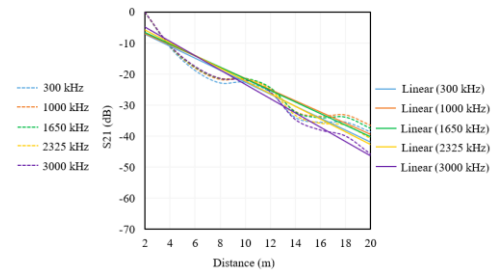


Figure 11. The simulation results of the transmission coefficient with the Patihan Cave model

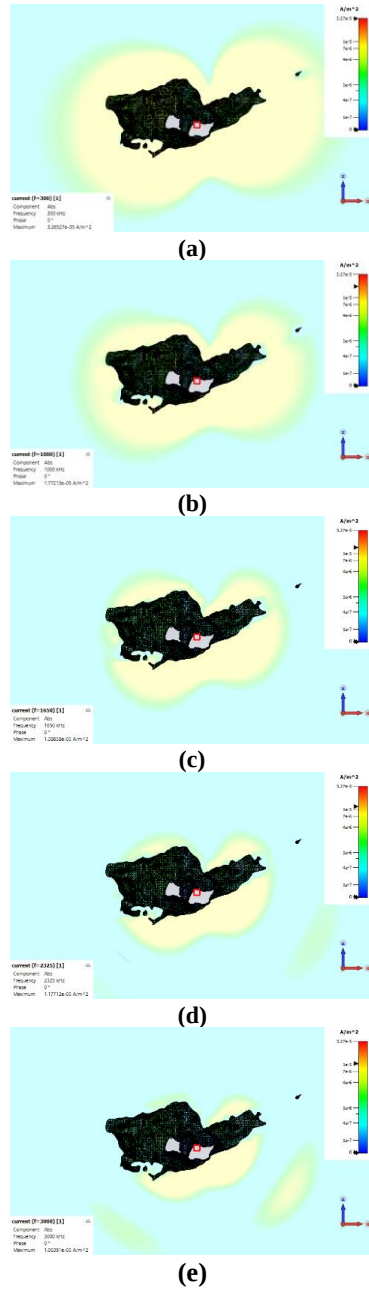


Figure 12. The CST simulation of current density with the Chiang Dao Cave model (a) 300 kHz (b) 1000 kHz (c) 1650 kHz (d) 2325 kHz (e) 3000 kHz

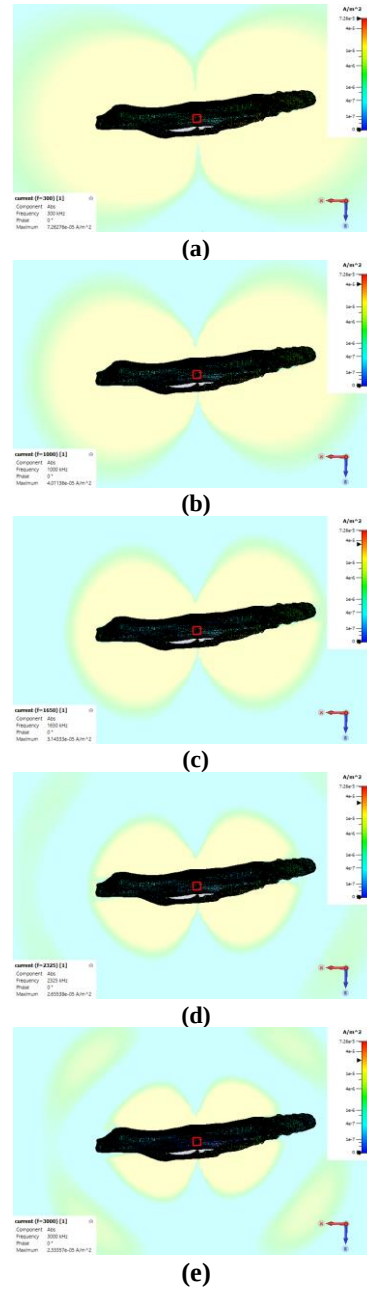


Figure 13. The CST simulation of current density with the Patihan Cave model (a) 300 kHz (b) 1000 kHz (c) 1650 kHz (d) 2325 kHz (e) 3000 kHz

Results and Discussions

This section compares the propagation path loss from the experimental results and the proposed model and also adds the CST and waveguide model results. Tables 1 and 2 show the comparison results for the Chiang Dao and Patihan Caves, respectively. The waveguide model uses Equations (4) to (8). Simultaneously, the proposed model uses Equations

(7) to (13). In addition, the 3D cave models shown in Figures 8 and 9 were used to calculate the physical factors of the cave walls, such as dimension, roughness, and tilt, along the cave passage. These factor calculations from the 3D cave models will provide accurate values. Then, all factors will be used to calculate the path losses using the proposed model. The calculated dimensions of the Chiang Dao Cave model are 6.3 meters high and

12 meters wide, the RMS roughness is 2 meters, and the wall inclination is 12.2 degrees. While the dimensions of the Patihan Cave model are 2.8 meters high and 17.1 meters wide, the RMS roughness is 0.8 meters, and the wall inclination is 9.2 degrees.

Table 1 shows the propagation path loss obtained from the experiment at Chiang Dao Cave and the proposed model, including the calculation results from the waveguide model and the CST simulated from the Chiang Dao Cave model at frequencies 300, 1000, 1650, 2325, and 3000 kHz. The results show that the low-frequency model gives most values similar to the experiment results, especially at low frequencies. Meanwhile, the waveguide model has an extremely high attenuation, especially at 300 kHz, and a lower attenuation at higher frequencies. In addition, the CST result has high attenuation following higher frequencies.

Table 2 shows the same pattern as Table 1 from the experiment at Patihan Cave and the calculation results. The results show that the experimental results give the propagation path loss at 1.3-1.6 dB/m, lower than Chiang Dao Cave and similar to the results from the proposed model. The results from the waveguide model gave a higher attenuation than those from Chiang Dao Cave, especially at 300 kHz, which has a high attenuation value of 495,880.55 dB/m.

All results demonstrate that the frequency waves are below the cut-off frequency defined by Equation (3), denoted as 27.5 MHz for the Chiang Dao Cave dimension and 62 MHz for the Patihan Cave dimension according to waveguide theory, but

can propagate within the cave. Furthermore, the electrical properties of the rocks, dimensions, and specifically their uniformity contributed to higher attenuation observed at Chiang Dao Cave compared to the more uniform characteristics at Patihan Cave.

The waveguide model reveals exceptionally high attenuation, particularly in the Patihan Cave. At low frequencies, the model attributes this heightened attenuation primarily to refraction loss related to the cave dimensions. Moreover, the dominant polarization considered is vertical, predominantly impacting the ceiling height and consequently affecting wave behaviour. The increased attenuation in the Patihan Cave is due to the lower ceiling height relative to the Chiang Dao Cave.

The calculation with CST using models from both caves yielded results similar to the experiment findings and those of the proposed model. The observed discrepancies are from the inherent homogeneity assumptions of the medium, such as the presence of dielectric layers with varying rock textures, decayed rock, sand, air, and other factors.

Specifically, the low-frequency model reveals that the impact of wall roughness and inclination on attenuation is the lowest because the low-frequency wave propagation mechanism can refract and deflect obstacles significantly smaller than wavelengths. Therefore, the observed attenuation due to refraction loss with skin depth is closely related to the experimental results. Finally, the proposed model gives results closest to the experimental results and has the same trend as the experimental results.

Table 1. The results of path loss at the Chiang Dao Cave

Frequency	Path loss (dB/m)			
	Experiment	Calculation by using		
		CST	Waveguide Model	Low-Frequency Model*
300 kHz	3.90	1.56	56,272.67	3.85
1,000 kHz	2.83	1.46	5,089.13	2.65
1,650 kHz	1.52	1.76	1,877.68	2.29
2,325 kHz	1.76	2.47	950.06	2.06
3,000 kHz	2.06	3.23	573.27	1.89

Remark: *The proposed low-frequency model.

Table 2. The results of path loss at the Patihan Cave

Frequency	Path loss (dB/m)			
	Experiment	Calculation by using		
		CST	Waveguide Model	Low-Frequency Model*
300 kHz	1.57	1.93	495,880.55	2.03
1,000 kHz	1.51	1.80	44,806.58	1.46
1,650 kHz	1.25	1.86	16,518.36	1.39
2,325 kHz	1.40	2.04	8,350.97	1.37
3,000 kHz	1.38	2.30	5,034.80	1.37

Remark: * The proposed low-frequency model.

Conclusions

This study investigated the modelling of RF propagation at low frequencies in natural caves, focusing on developing the model of low-frequency propagation by studying the wave propagation behavior in Chiang Dao Cave (limestone) and the Patihan Cave (sandstone). The investigation involved the transmission experiment at 300, 1000, 1650, 2325, and 3000 kHz in the cave passage. The study investigates the propagation mechanism of low-frequency waves to analyze the skin depth property that enables waves with frequencies lower than the cut-off frequency to propagate along the cave passage. The experimental results also show that frequency waves lower than the cut-off can propagate within the cave. This reason guided the development of the low-frequency model after the waveguide model by considering the skin depth that causes the electrical dimensions more than the physical. Afterwards, the 3D cave models obtained from the LiDAR scanner were used to calculate the physical factors of the cave walls, such as dimension, roughness, and tilt. These factors are utilized for calculating path losses using our proposed model. Also, the cave models were used for calculations using CST simulation software. The results were then compared between the experiment and the proposed model, including the calculation results from the CST and waveguide model. The comparison results show that the proposed model provides results very close to the experimental results, whereas the waveguide model gave high attenuation. In conclusion, the proposed model concept, which considers the skin effect, can be used to predict, analyze, and plan the application of low-frequency waves in natural caves, tunnels, and underground mines. Moreover, it has led to the development of communication technology, electromagnetic knowledge, and the application development of low-frequency waves in the future.

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