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A STUDY OF RADIO WAVE PROPAGATION IN THE CAVE FOR DEVELOPING THE THROUGH-THE-EARTH APPLICATION

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ABSTRACT: Radio waves are significant for operating in an underground tunnel or a cave, such as two-way radio systems or emergency communication during rescue operations. Most applications used in the tunnels require wired connections because of the high attenuation of the wireless propagation. In particular, the attenuation in caves is higher than in tunnels because of the non-uniform nature of the walls. Therefore, this paper presents a study of the radio wave propagation within a cave. The experiment covers the low-frequency (LF) to ultra-high frequency (UHF) bands that aim to analyze the attenuation and behavior of waves in caves. Study results show that the low frequency and medium frequency (MF) bands can penetrate cave walls due to the deeper skin depth. At the same time, higher frequencies perform well in line-of-sight (LOS) propagation over short distances, albeit encountering significant attenuation in non-uniform cave environments. The skin depth condition obtained in the propagation result led to the Through-the-Earth (TTE) experiment by making two hand-made transceivers in the beginning band of MF at 350 kHz for transmitting and receiving waves between the mountain surface and the cave passage directly through the rock layer. The results of the TTE experiment show that the transceivers can transmit to 571 meters with a received power of -85.0 dBm before encountering an obstacle that makes it impossible to continue. Finally, the results are significant for developing the application of radio frequency within caves or tunnels and improving the application of the TTE technique with more versatility and efficiency.

Keywords: Geophysics, Sub-surface, Cave technology, Wave propagation, Through-The-Earth (TTE)

1. INTRODUCTION

Radio waves have diverse applications in geology and sub-surface operations. Sub-surface sensing technologies encompass a range of methods for detecting, imaging, and characterizing sub-surface objects and phenomena, including Ground Penetrating Radar (GPR), electromagnetic induction (EMI), seismic methods, electrical resistivity tomography (ERT), and remote sensing [1,2]. Radio waves are essential in communication through two-way radio systems within underground mining. Yarkan, Guzelgoz, Arslan, and Murphy [3] have surveyed communication in an underground mine by discussing communication types, methods, and the significance of communication in the underground mine.

After that, Gibson [4,5] researched a new underground communication technique: the so-called Through-the-Earth communication (TTE), which transmits radio waves through the earth's surface into the underground. Such a method is still a wireless communication system, which is necessary for implementation in the cave due to the comfortable installing, relocating, and maintaining the equipment. Furthermore, much research has studied wave propagation in tunnels and caves to investigate the behavior of waves while propagating in caves or tunnels [6-9]. These applications highlight the wide-ranging utility of radio waves, offering significant improvements in safety, efficiency, and the exploration of the sub-surface environment in geology and underground mining operations.

Additionally, in 2018, twelve members of a junior football team with their assistant coach were trapped inside the Tham-Luang Nang-Non cave in northern Thailand due to heavy rainfall that flooded the cave and blocked their way out [10]. National and international rescue teams made extensive efforts to free them, resulting in their successful rescue after approximately seventeen days. This high-profile operation garnered significant worldwide attention and received cooperation from numerous organizations. The event highlighted the importance of studying radio waves and developing specific applications for cave and mine environments.

Therefore, this paper reported the experimental study of wave propagation in the cave to investigate their behaviors while traveling in the cave from LF to UHF bands both in line-of-sight (LOS), and non-line-of-sight (NLOS) as natural caves differ in cave geology, wall roughness, dimensions, bends, and the electromagnetic properties of rock. This study proceeded at Chiang Dao Cave, Chiang Mai, Thailand, a natural cave with the abovementioned properties.

Furthermore, the results of the experimental study will used to design a transceiver supporting the TTE application by using the hypothesis that the low frequency is a ground wave and has deeper skin depth that can be transmitted through the rock layer into the cave, effectively. In conclusion, we verified the experimental results by selecting the appropriate frequency for designing and constructing the devices for testing in Chiang Dao Cave. Finally, our experimental and testing results accorded together and effectively used in the long-distance cave passage with a TTE system.

2. RESEARCH SIGNIFICANCE

This research contributes considerably to understanding the propagation of radio waves within caves or similar structures such as mines and tunnels. This study covers frequencies from LF to UHF, both line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios. The study reveals the behavior and limitations of each frequency range while propagating in the cave. In particular, LF and MF bands exhibit ground wave properties suitable for TTE application, Underground radiolocation, or GPR application. These findings offer valuable insights for future geology and sub-surface applications such as the cave, mine, and tunnel, guiding the selection of appropriate frequency applications.

3. MATERIALS

3.1 Wave Propagation in Cave

The research reports of [11] and [12] mentioned that electromagnetic propagation in caves or underground tunnels with uniform structures is considered similar to a large spherical waveguide, which is typically a hollow structure with Transverse Electric (TE) and Transverse Magnetic (TM) conductive walls. These transverse waves create electric and magnetic fields perpendicular to the wave's direction. In addition, the waveguide cross-section determines the lowest frequencies that can pass through with minimal loss, and the cutoff-frequency values depend on the given mode that the waveguide's size and shape can define. In general, the cave passage is often considered a rectangular waveguide. However, neither a natural tunnel nor a natural cave can directly compare to a waveguide since the waveguide wall serves as a nearly perfect conductor. In contrast, when it responds to different frequencies, the cave wall provides a property more like a dielectric than the ideal conductor, such as an electrical insulator or a conductor. Furthermore, the boundary conditions of the electromagnetic field that occurred inside the cave passage also have an occurrence of the wave that is partly reflected back and forth within the cave passage and partially lost in the surrounding cave wall that is controlled by the refraction index between the different mediums (air and cave wall), which have different permittivities and magnetic permeabilities [1], as shown in Fig.1.

Although the cave dimension determines the cut-off frequency in the waveguide model, in practice, the lower frequency than the cut-off frequency can propagate through the cave moderately. Since the few waves are shifted from free-space propagation to surface waves traveling in the cave wall texture, that will be discussed in the topic of TTE communication afterward.

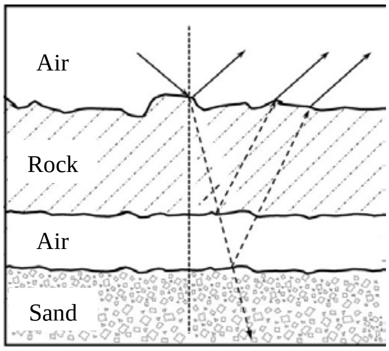


Fig.1 The wave travels between the multi-layered medium

3.2 Physical Properties

The geological study about the wave attenuations when traveling through the rock layer shows that it behaves differently between the radio wave transmitted through the cave and the transmission to free space. One of the significant factors is the rock's porosity, in which the sediment grains and mineral crystals affect the wave transmission into the medium. The energy transmitted will be absorbed and decrease the speed. The relationship between the velocity of a wave when traveling through a porous rock medium can be explained in Eq. (1) [13].

$$\frac{1}{V_M} = \frac{\phi}{V_F} + \frac{(1-\phi)}{V_R} \quad (1)$$

Where, ϕ is volumetric porosity fraction, V_M is measured velocity, V_F is the velocity in saturating liquid, V_R is the velocity in rock solid

Wannakomol and Chonglakmani [14] researched the porosity of the Permian limestone, which is the same-aged as the limestone at Chiang Dao cave with an average porosity of 1.06% less than the sandstone of the Phra Wihan rock category (Phra Wihan formation), which also exists in Thailand. Remark: Gaewmood [15] reported that the average porosity of the Phra Wihan sandstone is around 12.6%. It was found in the relationship in Eq. (1) that the porosity of Permian limestone is low, which causes the wave to travel faster, and less energy absorbed. According to [1], another factor contributing to the different attenuation in both rock types is the homogeneity of the medium. In the case of sedimentary rock formation, there will be gaps in the rock layers from deposition arrangement, the accumulation of sediments of that rock type, until it becomes cave formation. As a result, the differences in the dielectric layers have occurred (i.e., air, sand, and soil), and the waves will attenuate when traveling through each dielectric layer, as shown in Fig.1. On the other hand, the Permian limestone group of the Chiang Dao caves with higher homogeneity since the medium is only one layer throughout.

3.3 Electromagnetic Properties

The rocks with several chemical compositions result in different abilities for electrical conductivity. According to [16], porosity is a property that affects conductivity. In the same medium, as the porosity increases, which different minerals replaced, will increase the electrical conductivity too. The relationship between electrical conductivity and resistance can be explained in Eq. (2).

$$\sigma = \frac{1}{\rho} \tag{2}$$

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

The rock samples in each study by [1,16-18] show that limestone had less electrical conductivity than sandstone, which is related to porosity. Highly porous rocks are replaced by metallic minerals, resulting in higher electrical conductivity. In addition, when electromagnetic waves travel through a medium of high conductivity, 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 grows (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 that the wave energy reduced to $1/e$ ($\approx$36.8%) is called skin depth (δ), which occurs when electromagnetic waves propagate through a conductive medium. In addition, Gibson [5] and Bedford [19] study the communication systems in caves with low-frequency waves, which can penetrate through rock layers caused by the high skin depth property of such frequency bands verified by Eq. (3).

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu}} \tag{3}$$

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

4. METHODS

4.1 Frequency Bands

A previous study by [6-9] studied the propagation property in caves/tunnels at the specific high-frequency bands of UHF and super high frequency (SHF) bands. In comparison, this research studied the same issues. However, it covered the LF to UHF bands by choosing the experimental frequencies at each band's beginning, middle, and end, as illustrated in Table 1. However, to avoid the impact on the bat populations in caves, as followed the agreement between the research team (by the Suranaree University of Technology) and the Department of National Parks, Wildlife and Plant Conservation, therefore, the LF band at frequencies below 300 kHz cannot practice. Because the frequency range from 20 kHz to 290 kHz can interfere with ultrasonic use to resonate with obstacles in front of bats, as reported by [20,21].

Table 1 The frequency band for the experiment

Band	Freq 1	Freq 2	Freq 3	Freq 4	Freq 5
LF	No Tested	No Tested	No Tested	No Tested	300 kHz
MF	350 kHz	1000 kHz	1650 kHz	2325 kHz	3000 kHz
HF	3.5 MHz	10 MHz	16.5 MHz	23.5 MHz	30 MHz
VHF	35 MHz	100 MHz	165 MHz	232.5 MHz	300 MHz
UHF	350 MHz	1 GHz	1.65 GHz	2.325 GHz	3 GHz

4.2 Equipment Setup

The primary key of wave propagation study in the cave is to investigate the propagation path loss of the given frequencies, which can predict the attenuation behaviors of waves in each frequency while traveling in the cave. In our experiment, the propagation path loss was measured using a wideband RF signal generator, RF spectrum analyzer, and various types of antennas for each given frequency band.

A narrow-band continuous wave (CW) signal is supplied from the Rohde & Schwarz SMB100B signal generator to the transmitting antenna via a 50-Ohm low-loss cable LMR-240. At the same time, the receiving side consists of a Rohde & Schwarz FPH spectrum analyzer with a HE400HF antenna module (8.3 kHz – 30 MHz) and a HE400UWB antenna module (30 MHz – 6 GHz), as shown in Fig.2 and Fig.3.

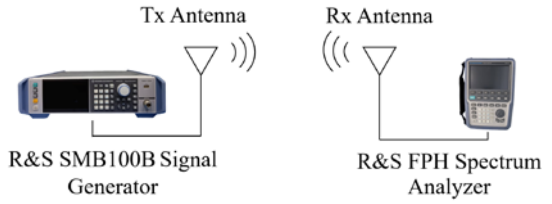


Fig.2 The equipment setup

The experiment location for the LOS testing in Chiang Dao cave is in a section called Tham Nam, which is the most linear cave passage and has several direct distances of approximately 30 - 50 meters, as shown in Fig.4a. However, the vital purpose of this experiment is to measure the propagation path loss. Therefore, the radiated power from the antenna propagating along the cave passage every two meters can be considered such loss directly. The slope of received power, as shown in the graph at each distance, can predict the behavior of waves traveling in the natural cave environment. If the sloping trend is steep, it indicates a high loss-per-distance value, whereas a smaller slope indicates a lower loss. Nonetheless, the received power in the cave environment at each distance may be caused by multipath fading resulting from the reflection of obstacles in the cave and causing the in-phase or out-of-phase wave. For the NLOS experiment, the location of the cave passage where the wall has a curved line can obscure the LOS signal to study the diffraction and reflection behavior of waves. At the same time, for the NLOS experiment location, we chose a section of Chiang Dao cave called Tham Phra Non, with the curve of the cave wall, and the distance along the curve is at least 20 meters, as shown in Fig.4b. It is hypothesized that the different frequencies could be deflected or reflected on the cave wall with winding routes. If these results can be verified, we can choose and optimize a proper frequency in a natural cave for effective communication with the obtained results.

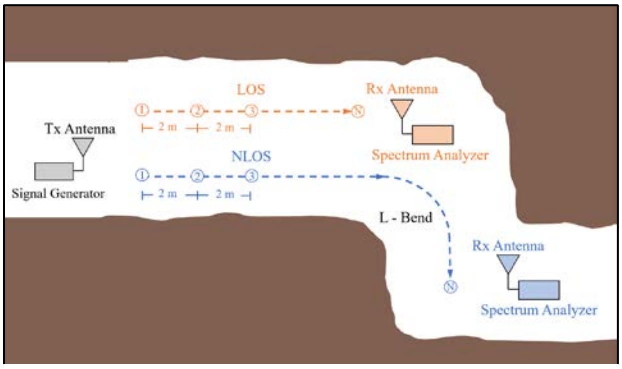


Fig.3 The experiment setup diagram

(a) (b)

Fig.4 The measurement locations (a) Tham Nam (b) Tham Phra Non

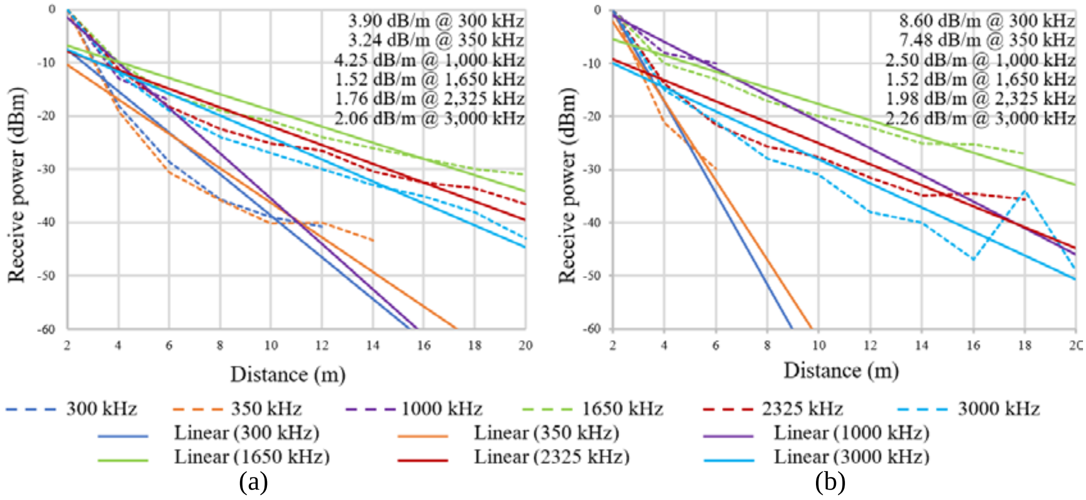


Fig.5 The experimental results of the LOS in the LF and MF band (a) V-V (b) V-H

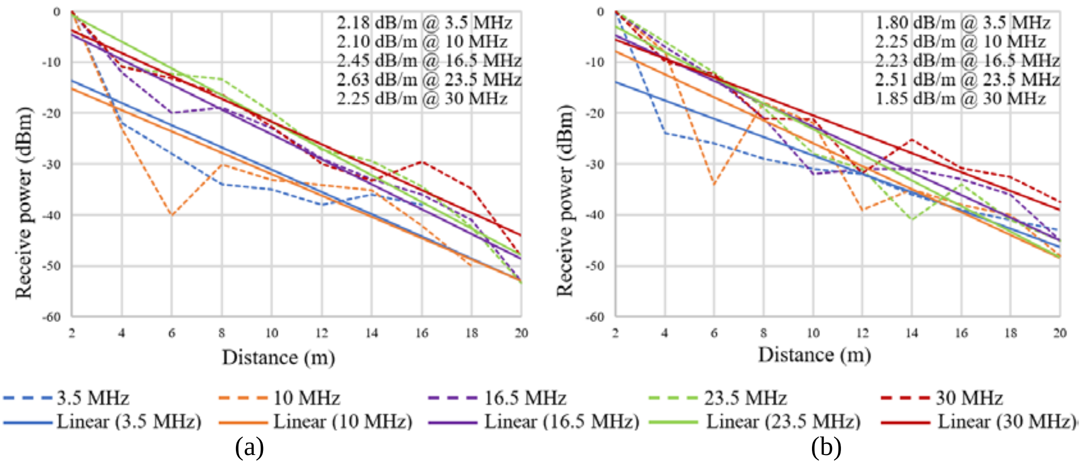


Fig.6 The experimental results of the LOS in the HF band (a) V-V (b) V-H

5. RESULTS AND DISCUSSION

This section presents a graph comparing the propagation loss per meter of the LOS experiment, as shown in Fig.5 to Fig.8, and the results of the NLOS experiment, shown in Fig.9 to Fig.12, with the vertical-vertical linear polarization (V-V) and the vertical-horizontal linear polarization (V-H).

5.1 LOS Experiment

From the results, we adjusted the range to reduce data duplication or normalized the received power in all frequency bands to focus on the propagation path loss per meter. In Fig.5, we found that the LF (300 kHz) and the MF bands (350 kHz and 1000 kHz) frequencies in both V-V and V-H polarization have relatively high path loss. Furthermore, the general propagation theory indicates that this frequency band yields the propagating property as a ground wave or a surface wave that can well penetrate the earth (below 2000 kHz). When the wave propagates to a medium such as soil or rock, which has electrical conductivity, some will induce into that medium rather than propagate along the line of sight in free space. The property of the MF band (1650 kHz - 3000 kHz) is still the surface wave. At frequencies higher than 1000 kHz, it can propagate on the surface of the cave wall and floor more than induces to the limestone medium. As a result, the wave power can be measured preferably while the receiving antenna is close to the cave wall. However, when the frequency is up to 3000 kHz, the late MF and early high frequency (HF) bands property will be the direct wave rather than the surface wave. For the V-H polarization case, the propagation path loss is higher than the measured value in the V-V polarization. In particular, at 1000 kHz to 2325 kHz, the propagation path losses are reduced due to a change in wave polarization, causing the horizontal receiving antenna to receive more power.

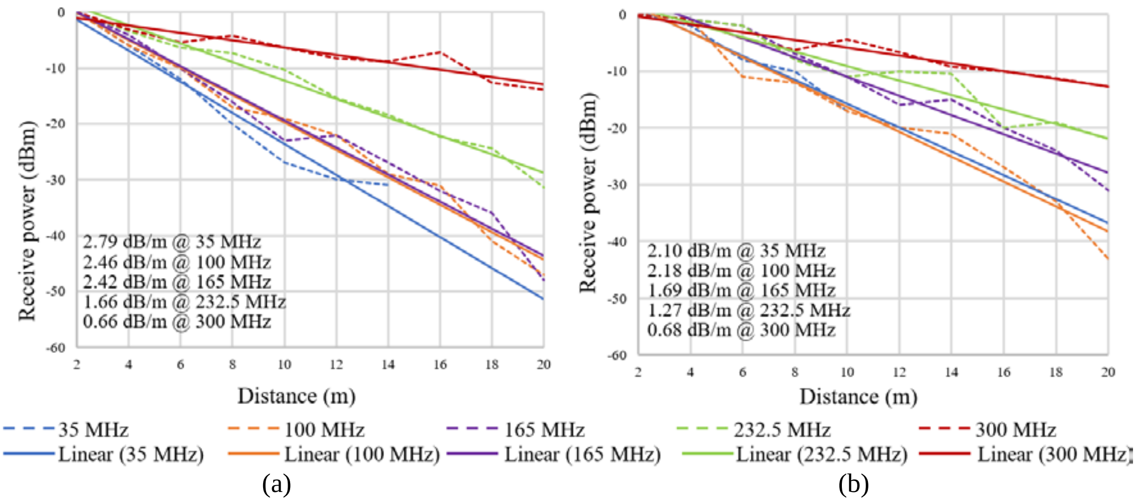


Fig.7 The experimental results of the LOS in the VHF band (a) V-V (b) V-H

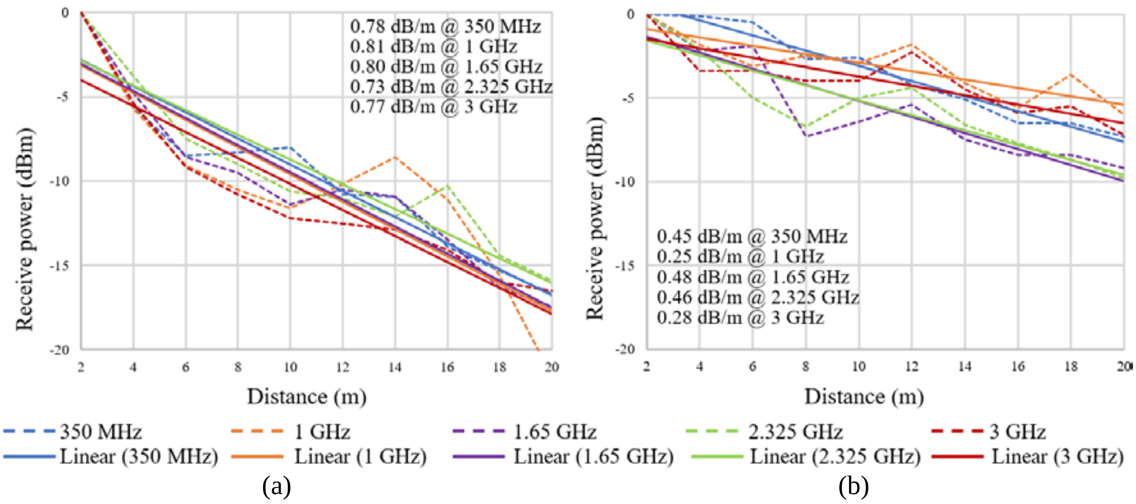


Fig.8 The experimental results of the LOS in the UHF band (a) V-V (b) V-H

In Fig.6, the propagation property of the HF band is the sky wave that can reflect or diffract in the atmosphere or the Earth's surface arc. However, when tested in a cave with a cross-section dimension smaller than the optimum wavelength in the waveguide theory and a different environment from free space, it caused relatively high attenuation. Overall, the propagation path loss in the HF band is not as high as in the LF and MF bands in both the V-H and V-V polarization.

From the results in Fig.7, the property of the very high frequency or VHF band (35 MHz - 300 MHz) is also a direct wave or free-space wave, and the wave propagation must be the line of sight only. Testing the LOS propagation, we found that the V-V polarization case at a frequency of 300 MHz provides the lowest path loss. Moreover, it is noted that the higher the VHF band, the lower the propagation path loss due to the shorter wavelength causing the wave to pass through the large cave well. In addition, when testing in V-H mode, it is found that a tendency of propagation path loss is similar to or slightly lower compared to the V-V polarization, but that does not mean it can transmit and receive the signals further than V-V polarization.

The measurement results in Fig.8 of the UHF band (350 MHz - 3 GHz), which this band retains the direct wave property same as the VHF bands, in which the path loss was similar and relatively low when measured in both V-V and V-H polarization. However, this band provided a path loss lower than in the VHF band, which contradicts the free-space loss theory. Since the waves in the UHF band perform a skin depth lower than frequencies in the VHF band, they can reflect well like wave propagation in a waveguide when these waves incident to the conductive cave walls. In addition, the cave dimension can sufficiently support the wavelength of the UHF band.

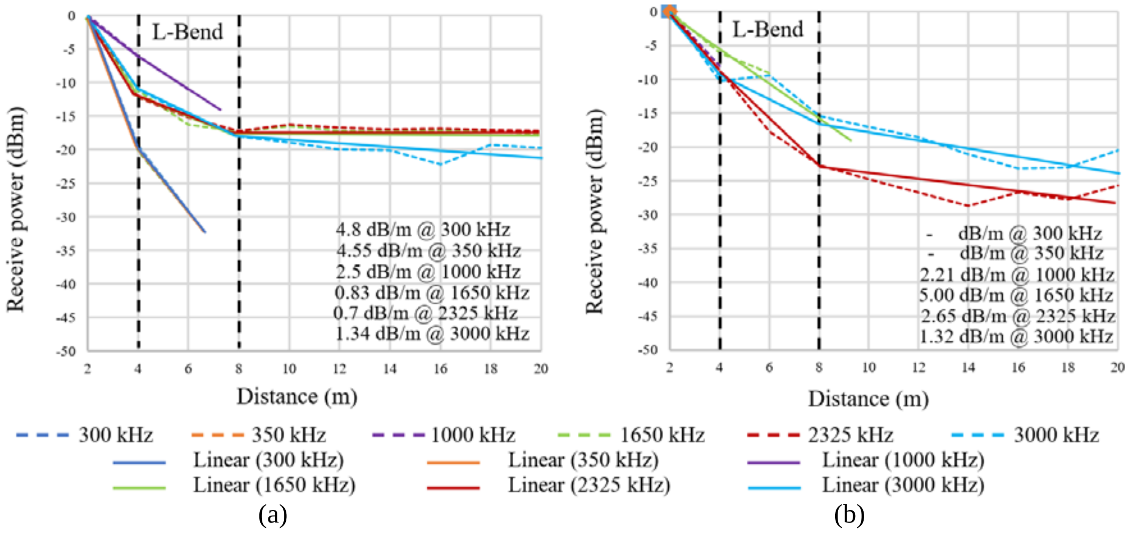


Fig.9 The experimental results of the NLOS in the LF and MF band (a) V-V (b) V-H

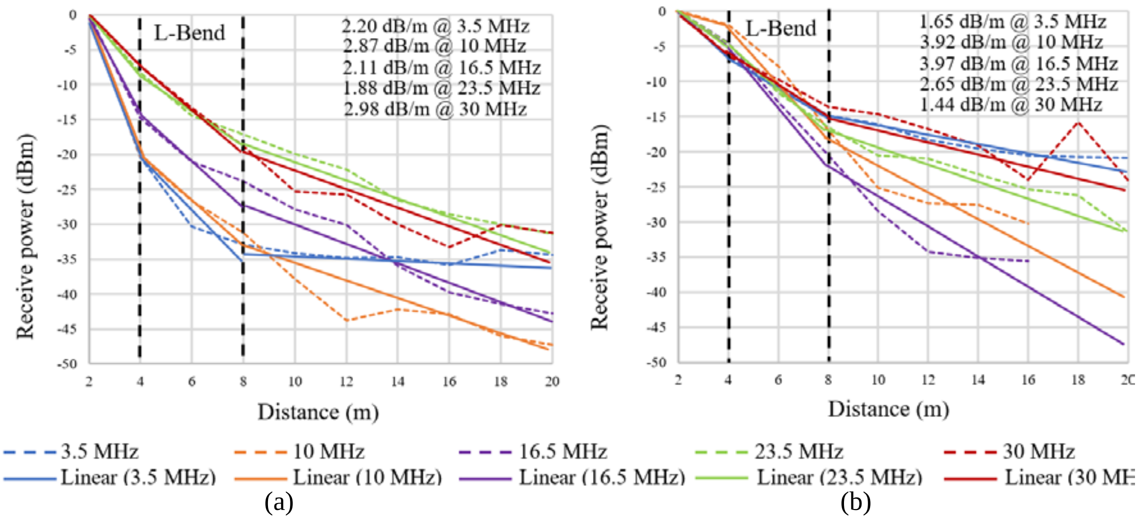
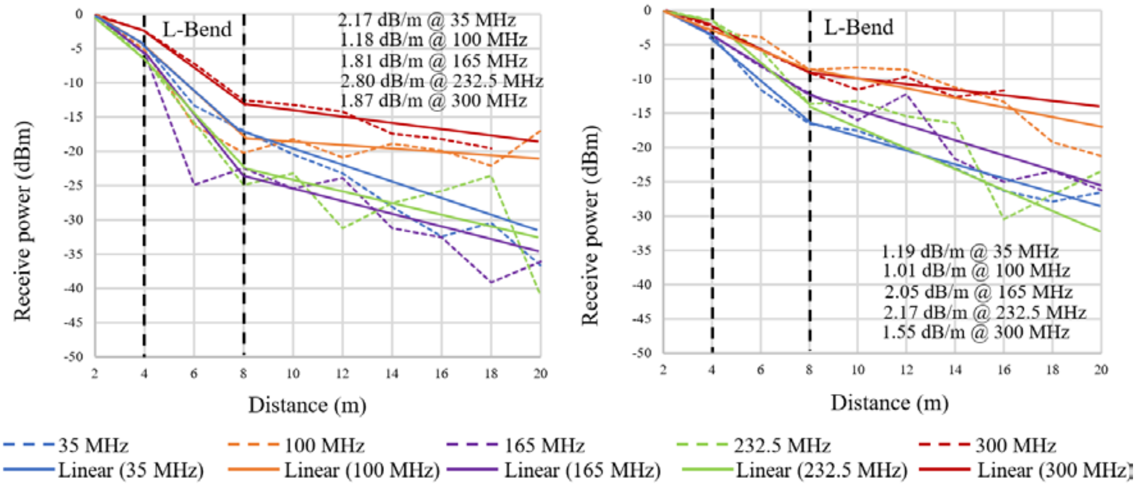


Fig.10 The experimental results of the NLOS in the HF band (a) V-V (b) V-H

5.2 NLOS Experiment

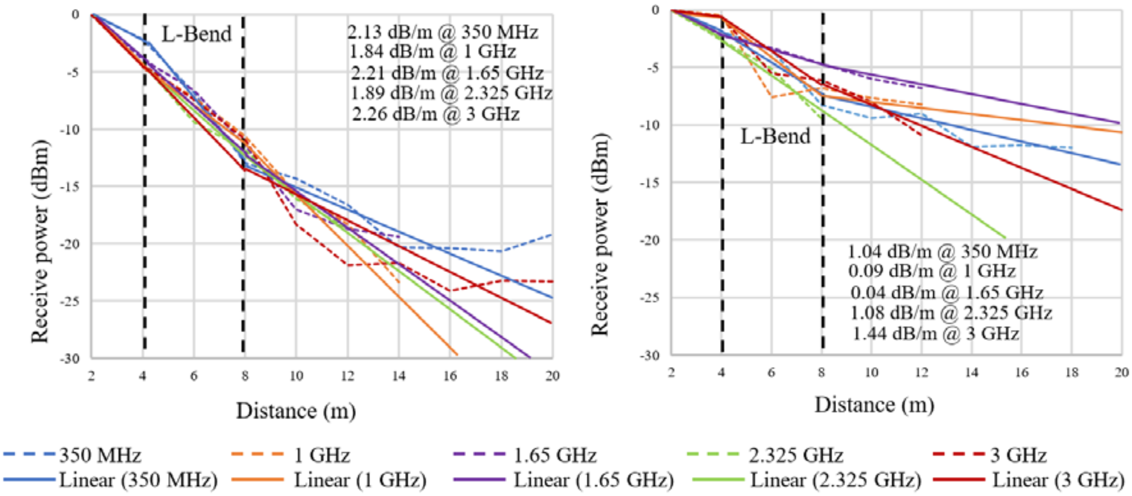
The NLOS measurement results can describe wave behaviors when encountering obstacles in the cave. The propagation loss is initially measured at a position two meters from the transmitting antenna and then progressively measured at 2 meters per step along the curve of the obstructed cave wall onto the straightway (L-Bend) in both the V-V and V-H polarization. Therefore, the NLOS test consists of a LOS part and an NLOS part, which is an L-shaped curve that obscures the traveling waves in line of sight. The L-Bend test location for observing the ability to reflect or diffract waves at each frequency is at a point of 4 still 8 meters.

In Fig.9, we found that in the LF band (300 kHz) and the MF band (350 kHz and 1000 kHz) with the V-V polarization, the path loss was specifically high at the frequencies of 300 kHz and 350 kHz, while the frequency rises to 1000 kHz its path loss will decrease. Since the propagation property of wave at 1000 MHz begins to change from penetration through the wall to propagation on the wall surface. Consequently, the receiving antenna that is parallel and close to the cave wall surface better receives the power. The V-H test at the LF band (300 kHz) shows that the path loss is slightly different from the V-V polarization. However, the total attenuation of the V-H test over the L-Bend is higher than the V-V case, which indicates that the wave at 300 kHz induced into the limestone will not change polarization. In comparison, the MF band (350 kHz)



(a) (b)

Fig.11 The experimental results of the NLOS in the VHF band (a) V-V (b) V-H



(a) (b)

Fig.12 The experimental results of the NLOS in the UHF band (a) V-V (b) V-H

with V-H polarization yielded the highest propagation path loss caused by the ground wave property of this frequency and polarization changing following the cave wall shape.

At the same time, Fig.9 also shows the measurement results for the MF band (1650 kHz - 3000 kHz), which retained the ground wave property in both the V-V and V-H polarization testing. However, we found that frequencies above 1000 kHz can propagate on the surface of the cave walls and floors rather than induce into the rock layer. Furthermore, the frequency that rises to 3000 kHz, which is both the end and beginning of the MF and HF band, respectively, will change a property to be sky wave rather than ground wave propagation, causing the path loss of this case to increase.

Fig.10 shows the graphs of propagation path loss in a cave for the HF band (3.5 MHz - 30 MHz), whose properties are sky waves. When these frequencies are transmitted in a cave with a given NLOS environment, a non-directional reflection and scatter will significantly appear after they incident to the cave wall and provide other path loss values when different environments of caves. Therefore, the obtained propagation path loss from measurement at only one NLOS location could not apply to the other positions in the same cave since intricate to implement the long-distance transmission covering all the cave passages.

Fig.11 shows the propagation path loss in a cave of the VHF band (35 MHz - 300 MHz), which has direct wave properties. The NLOS results in the case of the polarized V-H test provide the path loss lower than the polarized V-V test at almost all frequencies in this band unless 165 MHz, which is 0.24 dB higher than the path loss value of the V-V test, slightly. It shows that the wave polarization in the VHF band can be changed when reflecting from the cave walls because the receiving antenna can receive higher power from horizontal waves than the vertical one.

The propagation path loss of the UHF band (350 MHz - 3 GHz) is illustrated in Fig.12. This frequency band provides direct wave properties like the VHF bands, and its propagation in a LOS environment is better than NLOS. The experiment shows that the propagation path losses in the L-Bend distance were higher than in the LOS experiment for all frequencies. Since such frequencies in both the VHF and UHF bands have shorter wavelengths than the other frequencies in the lower bands, causing less diffraction through the L-bend. In summary, the NLOS experiment at the UHF band provides a relatively high attenuation, which is one of the limitations of the frequencies in VHF and UHF bands when traveling through the bend paths in the cave.

6. TTE COMMUNICATION EXPERIMENT

As aforementioned, regarding the wave propagation behavior inside the cave, we found that some frequencies in LF and MF bands yield relatively high skin depth when propagating through the rock or earth, a medium with moderate electrical electricity. From the results of NLOS experiments, it is also explicit that the cave wall's rock (limestone) medium exhibits different propagation behavior for each frequency band at the L-Bend section. When the low-frequency waves propagate through the cave cavity, the cave walls exhibit behaviors as a dielectric since the skin depth at low frequencies is very high, causing it to seem like a wave that travels through the cave walls. Whereas the high-frequency waves propagate through the cave cavity, it exhibits behavior like a waveguide because the skin depth at high frequencies is few. As a result, the waves will reflect back and forth in the cave cavity as they travel in the waveguide.

The skin depth condition obtained in the above result leads to the experiment of transmitting waves through the earth by selecting low-frequency waves from the LF or MF bands, which have the property of ground waves, are suitable for TTE communications, and are better than transmitting with the antenna through cave cavity directly that caused the high attenuation while traveling in.

The technique of TTE communications has been researched and developed by many researchers for a long time. In the past, it used the radio signal below the VLF band transmitted by a large antenna on the earth's surface through the earth layer to the underground mine. This technique will discharge an electric current into the earth's surface via two electrodes connected to soil or rock at both the transmitter and receiver, as shown in Fig.13. However, the electrical field generated from current intensity will exponentially attenuate from the earth's surface, and the attenuation also increases proportionally to the frequency. Therefore, low frequencies suit TTE applications [4,5,22-24].

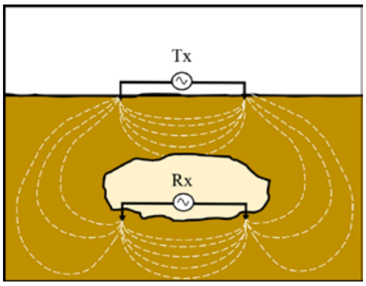


Fig.13 TTE communication concept

However, the limitations of low frequency are the large size of the antenna structure and the narrow bandwidth. Furthermore, the experiment in the cave at frequencies near 20 - 290 kHz will interfere with the bat's subsistence, which fatally affects the cave environment [20,21]. Thus, it was avoided by opting for the possible lowest frequency at 350 kHz, which is the beginning of the MF band and still has ground wave property that can transmit the waves through the earth. Therefore, this paper adds an experimental study of a 350 kHz TTE technique in Chiang Dao Cave as an alternative to developing the transceiver for TTE applications with shorter wavelengths, which makes it possible to build a smaller antenna and higher bandwidth that can also apply to more technologies.

6.1 TTE Measurement Procedure

In the measurement setup, the transmitter installed above the cave passage consists of a signal generator and a prototype of a radio transceiver with a transmitting carrier operated at 350 kHz. The prototype of the radio transceivers is specially developed and fabricated with an SSB modulation technique for communication between stations inside and outside the cave. For the testing procedure: 1) on the mountain, one radio transceiver and signal generator are connected to the earth-ground antenna by using a coaxial switch for selecting between a signal generator and transceiver. 2) on the cave passage, the receiver inside the cave consists of an earth-ground antenna placed on the cave floor, connected to the signal generator and another radio transceiver via a coaxial switch. The block diagram of the TTE experiment is shown in Fig.14. The transmitted power from the signal generator is amplified again by an RF power amplifier and then transmitted to the earth-ground antenna equals 38 dBm, where the end of the antenna is embedded in the ground by electrode rods on both sides. In the experiment, the transmitter on the mountain was located at 19.395822ºN, 98.926826ºE, and 516 meters above mean sea level.

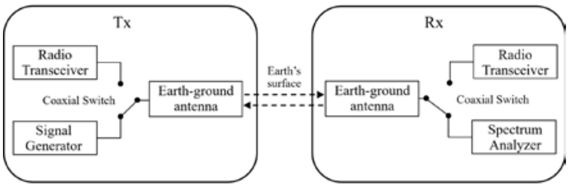


Fig.14 Block diagram of the TTE experiment

The limitation of the installing location comes from the conditions inside the cave, in which the cave floor is rugged rock terrain, causing some points cannot installed and causing the distance of each receiver to be non-linear. The location coordinates for the transmitter and receiver in this cave are studied by [25], as illustrated in Fig.15, which shows the top view of Chiang Dao Cave consists of several passages. First, the entrance to the cave (blue) is a path from the cave entrance to the junction between the Tham Nam (orange) and the Tham Ma (green). Next, the Tham Nam route (orange color) is a long straight path, which from [25] can measure the distance from the entrance to the endpoint as 576 meters. The endpoint is the last point that can be surveyed before encountering a sump, which makes it impossible to continue. Then, the Tham Ma route (green), which is a route that is placed higher than the Tham Nam route, with a total distance from the entrance of the cave 406 meters. Finally, Tham Kaeo (purple) is a path lower than Tham Nam and Tham Ma. In addition, Fig.16 shows a side view of the TTE experiment diagram, which explains how to transmit waves from above the cave passage down to the receiver inside the cave.

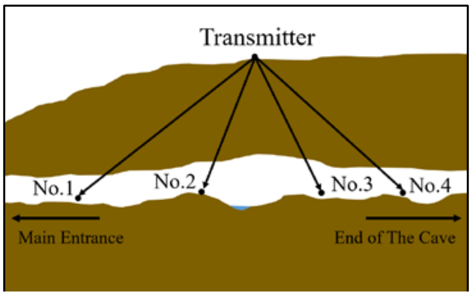


Fig.16 Side view of the TTE experiment diagram

6.2 TTE Measurement Result

Table 2 shows the received power between the transmitter above the mountain and the receiver inside the Chiang Dao Cave, which can be compared with Fig.15. From the experiment, the last points are No.4 and No.8, which can be tested before encountering an obstacle that makes it impossible to continue. No. 4 has a distance of 571 meters and can receive a power of -85.0 dBm. Then, No.8 has a distance of 396 meters and can receive a power of -92.0 dBm, which has a displacement distance from the transmitter farther than No.4, cause to receive the lower power. Therefore, the transmitter's location will be selected suitably to communicate, covering all the cave passages.

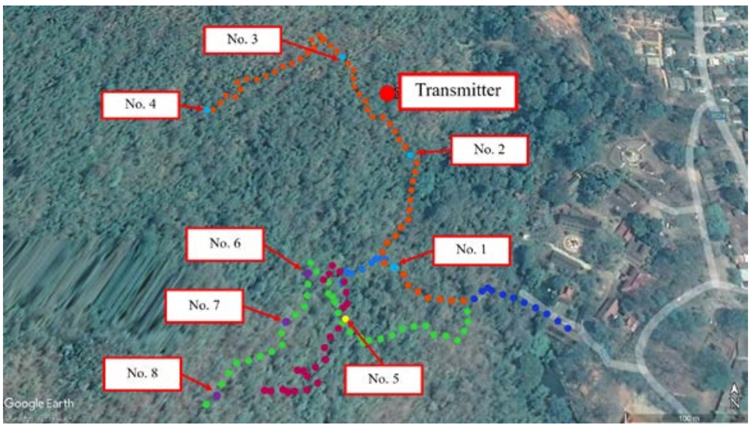


Fig.15 Top view of the TTE experiment

Table 2 Experimental results of received power for 350 kHz TTE

No.	Latitude (degree)	Longitude (degree)	Passage distance (m)	Rx Power (dBm)
1	19.394252	98.926909	101	-55.3
2	19.395267	98.927058	231	-50.2
3	19.396222	98.926473	361	-48.5
4	19.395715	98.925231	571	-85.0
5	19.393838	98.926511	202	-73.0
6	19.394191	98.926193	256	-58.9
7	19.393807	98.926044	306	-56.8
8	19.393262	98.925547	396	-92.0

Although theoretically, the lower frequency can penetrate with higher depth than the higher frequency but has a limitation on the size of the antenna. When the wavelength of a signal increases (frequency decreases), longer antennas are required to receive and transmit these longer wavelengths. However, with the limitation of the space and weight of the antenna, if using a small antenna of the same size, the high frequency will give better gain. In addition, some applications require wide bandwidth, making low-frequency antennas with narrow bands that are inefficient for various purposes. For example, GPR applications require high resolution, such as locating underground utilities (pipes, cables, and conduits) [1].

Compared to past research, it studied communication through rock layers, including the applications, technical issues of the TTE communication system, and a model of the TTE communication system [24]. Furthermore, Barkand, Damiano, and Shumaker [26] studied and discussed the testing of a prototype TTE communication in an underground mine. One of the TTE communication systems developed and used by the British Cave Research Association (BCRA) is HeyPhone. It is a radio transceiver connected to a loop or earth-ground antenna operating at 87 kHz. It has a communication range of almost 500 meters with a transmit power of 10 W or 40 dBm [19,27].

In summary, Table 2 exhibits a TTE system at 350 kHz that can transmit voice signals up to 571 meters away with a received power of -85.0 dBm. The results show a communication distance significantly and ways to enhance the performance of antennas due to the shorter wavelength. The SSB TTE 350 kHz cave radio transceiver in Fig.17 was developed from the study results mentioned above, including the design concept from a HeyPhone. Besides, the radio waves at 350 kHz can communicate throughout the Chiang Dao Cave, and the beginning of the MF band can travel in rock layers suitably more than propagating through free space in the cave cavity. Finally, the frequency at 350 kHz can improve and increase the communication range and also develop to transmit data and images between inside and outside the cave, which makes an alternative to the development of the application for underground mine communication and geological technology in the future.

Fig.17 Prototype of TTE 350 kHz cave transceiver

7. CONCLUSIONS

This paper outlines the study conducted on RF propagation within the natural limestone cave at Chiang Dao Cave, a cave similar to the Tham-Luang that was rescue operations in 2018. The primary focus of this study was to investigate wave behavior during propagation through the cave using an RF wave transmission experiment. The experiment encompassed a spectrum ranging from LF to UHF bands, considering both line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios, including the V-V and V-H polarization. The LOS experiment investigated the wave propagation behavior when propagating through the dielectric cave wall in the straight cave passage. At the same time, the NLOS studies the reflection, diffraction, and ability of waves while traveling through the winding cave passage. The experimental results show that the behavior of each frequency has advantages and disadvantages, including suitability for utilizing different characteristics.

The frequencies in the LF and MF bands provide ground wave properties due to the skin depth property from lower frequency and slight electrical conductivity of the medium. These frequency bands are suitable for applying to Through-the-Earth (TTE) or Ground Penetrating Radar (GPR) applications since these applications require high skin depth properties.

The HF band is the sky wave property that can reflect or diffract in the atmosphere or the Earth's surface more than penetrate the medium, but tested in a cave with dimensions smaller than the optimum wavelength in the waveguide theory, causing still relatively high attenuation.

The VHF and UHF bands exhibit direct wave properties, making them appropriate for free-space transmission. The theoretical free-space attenuation is directly proportional to the frequency, but these frequencies propagate to the winding path in the cave, causing very high attenuation from the obstacles. These frequencies are inappropriate for long-distance use in caverns or tunnels.

In addition, the results obtained from the wave transmission experiments have led to the study of TTE application from the properties of ground waves found in the LF and MF frequency bands. The TTE experiment in this paper uses the measurement of the RF transmission at 350 kHz, which is the end of LF and the beginning of MF. This TTE experiment made two hand-made transceivers at 350 kHz for transmitting and receiving waves between the mountain surface and the cave passage directly through the rock layer. The TTE experimental result, which has a transmitted power of +38 dBm, can transmit up to 571 meters away with a received power of -85.0 dBm.

In summary, the research findings demonstrate that radio frequency waves exhibit different propagation behaviors within different cave environments across various frequency bands. Lower frequency waves display ground wave properties that contribute to developing Through-the-Earth (TTE) applications. Conversely, higher frequency waves propagate more within the cave than penetrating the medium. By considering the appropriate frequency, such as at 350 kHz, it is possible to extend signal transmission ranges, enhance data and image transmission both within and outside the cave, and provide increased bandwidth for diverse applications. This understanding will pave the way for future studies on the principles of wave propagation through soil or rock. Ultimately, these studies offer avenues for furthering geology and subsurface applications such as resource survey and mining, including valuable insights for considering appropriate frequencies to improve cave and underground mine communications.

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