UHF Propagation in Caves and Subterranean Galleries

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***Abstract*—An experimental study is described on the natural propagation of UHF band radio waves in straight subterranean galleries. An extensive measurement project took place in five underground localities and, based on the experimental data, an empirical model of radio wave transmission was derived. The model was calibrated according to the measurement data and compared with the theoretical waveguide approach to propagation prediction. The presented results can be used for the practical planning of wireless communications in speleology applications and as an experimental basis for further theoretical works.**

***Index Terms*—UHF measurements, UHF radio propagation, underground electromagnetic propagation.**

I. Introduction

As IN OTHER fields, there are certain situations in speleology where it is necessary to use radio transmissions to communicate over relatively long distances [1]. Many references can be found to radiowave propagation issues in mining and confined media [2]–[6], but the subterranean spaces of caves and old mines explored by speleologists vary considerably in their characteristics. Caves tend to have uneven wall faces and dimensional irregularities on a number of planes. Typically they consist of either narrow and twisted galleries or large open spaces (such as chambers). The dimensions of galleries generally vary from 0.5×1 m to over 4×3 m, making them relatively small compared to, for example, road tunnels [7].

It can be expected that, in addition to the geometry of the intervening space, the dielectric parameters of the environment will also have a major influence on the propagation of electromagnetic waves in caves. The relative permeability of all rock types is unitary, only certain ores provide non-unitary values, however, this can be ignored for the moment. In nature all rock contains a certain amount of water. This is a fundamental unknown as water strongly affects the parameters of the rock, which do not then reflect its composition alone. Moisture content in standard bedrock is in single digit units of percent. The measured conductivity of this ground water, including its dependence on frequency, is discussed in [8].

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It is clear that it is almost impossible to come up with a precise description of the conditions affecting the propagation of radio waves in caves. The conditions are very variable both in terms of geometric configuration and dielectric conditions. This fact significantly limits our ability to apply models for the propagation of waves in standard tunnels that can be found in the literature [9]–[11]. Sophisticated models are available for mining tunnels [2], [5]. The most effective way to predict the propagation of waves in subterranean spaces for speleology applications seems to be an empirical approach based on experiments for standard scenarios. Such measurements do not appear often in publications [12]–[14]. The classical semi-deterministic waveguide approach [15], [16] was utilized as a reference model, but in the case of caves it is difficult to classify parameters for the gallery walls.

This paper covers an experimental study of the propagation of UHF band radio waves in straight subterranean galleries. More complicated scenarios were not addressed since it would be impossible to get reproducibility of results for diverse geometry of caves. Section II describes the arrangement of the experiment and the measurement method used. Section III introduces the measurements in five typical subterranean localities. On the basis of the experimental data, Section IV presents an empirical propagation model which is compared with the waveguide approach to propagation prediction. Section V then briefly summarizes the results. The presented outcomes can be used both for practical purposes when planning wireless communication underground and also as an experimental basis for further theoretical works.

II. Propagation Measurement Setup

The readings were taken at two frequencies – 446 and 860 MHz. The 446 MHz frequency is commonly used by Professional Mobile Radio (PMR) equipment. The 860 MHz frequency was selected because the theory predicts the best propagation at frequencies in the vicinity of 1 GHz and 860 MHz is the limit of the receiver used. Portable transmitters were used to generate continuous 446 and 860 MHz waves with a rated transmitting power of 0.5 and 1 W, respectively. Horizontally omnidirectional monopole antennas were polarized vertically. The transmitting antennas were placed on an anchored wooden rod 1.2 m high.

Vertically polarized simple half-wave dipoles were used to receive both frequencies. To limit the influence of the measuring person the dipoles were placed on a wooden rod. A Promax 8+ TV analyzer was used as a receiver. To increase the dynamic range a wide-band UHF antenna amplifier was utilized. The sensitivity of the receiver was approximately -110 dBm then. The received power level given in the graphs is before amplification.

Fig. 1. Location A.

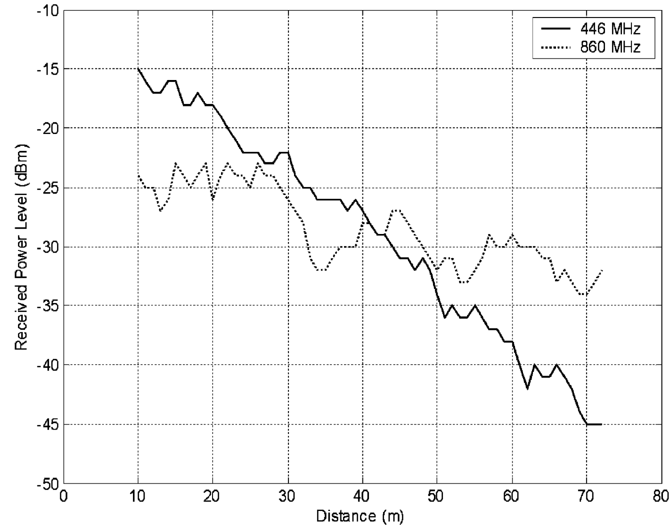

Fig. 2. Location A—received power level as a function of distance.

The receiving antenna was moved across the gallery profile in the given location to search for the maximum signal level. In this way the local minima caused by multipath propagation were eliminated. The aim was to find the slope of the signal level available for communications in a cave rather than to study multipath propagation.

Individual localities were selected with regard to the dimensions and profile of galleries and their accessibility for the equipment. The objective was to select typical scenarios with regard to conditions for radio wave propagation.

III. Measurement Results

A. Location A (“Prague—Sarka”)

This is a system of semicircular galleries 2.3-m wide and 2.2-m high (Fig. 1). The galleries travel through sandstone that displays no significant water content and can therefore be considered to be dry. In comparison with the other locations the walls are relatively smooth. Fig. 2 shows the absolute recorded signal strength as a function of distance between transmitting and receiving antennas in the gallery.

B. Locations B and C (“Morina—Amerika”)

The profile of the galleries at these two locations is rectangular, 2.3×2.1 m (Fig. 3) and 3.0×2.2 m, respectively. The galleries have rougher walls and pass through limestone. The floor is formed of clay and is rougher than for locality A. Although location B can be considered dry, location C showed slightly increased dampness with small pools of water in places. Fig. 4 presents received power level as a function of distance in location B.

C. Location D (“Svarov—Vojtech”)

The galleries in this location are significantly narrower than in the previous examples. A section with a straight gallery of

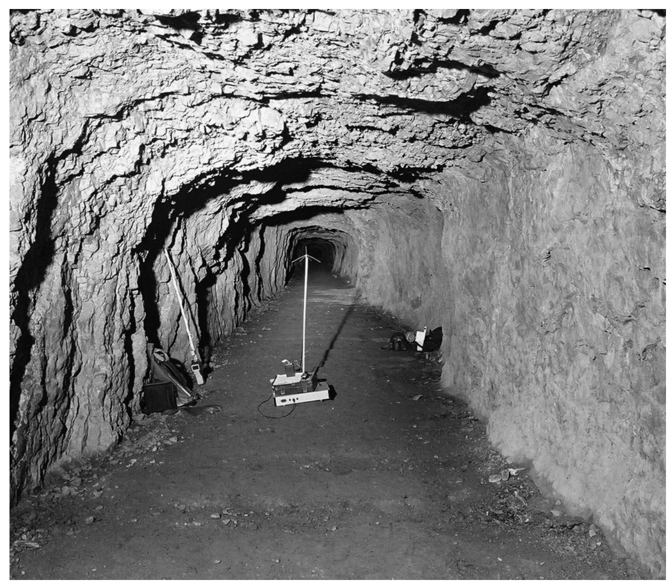

Fig. 3. Location B.

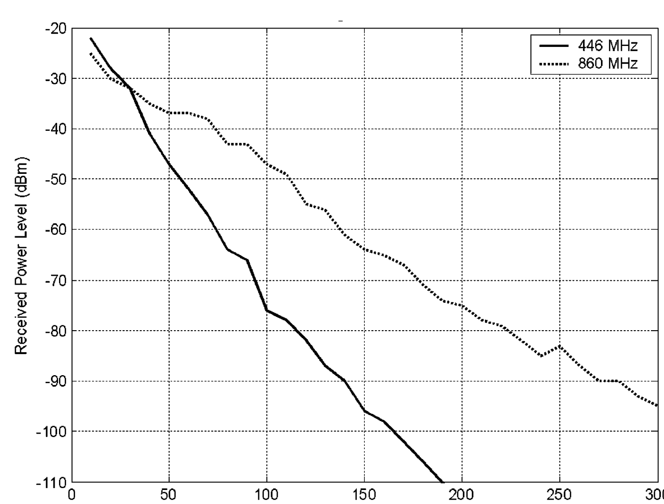

Fig. 4. Location B—received power level as a function of distance.

Fig. 5. Location D.

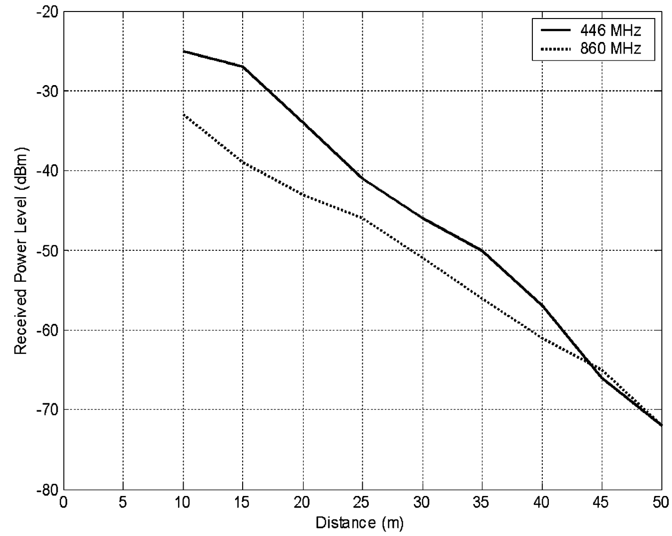

Fig. 6. Location D—received power level as a function of distance.

length 50 m was selected and measurements taken at 5 m intervals. The floor is covered in a continuous layer of water and the walls are damp and can be considered relatively good reflectors, limited only by the fact that they are rough and the profile fluctuates with an average width of 1.2 m and height of 1.9 m (measured to the water surface). The gallery profile from the 35th meter is shown in Fig. 5. The measurement results are given in Fig. 6.

D. Location E ("Jilove U Prahy—Radlik")

This location was selected because of the significant unevenness of the walls and the small and changing profile, which is typical for certain parts of caves and old mines. The average width is around 0.6 m and the height 1.8 m. Fig. 7 illustrates the gallery profile at the 25th meter. The floor was again covered with water and the walls were wet. Measurements were taken on a 50-m long section (Fig. 8); the measurement dynamics did not allow recordings over a longer distance.

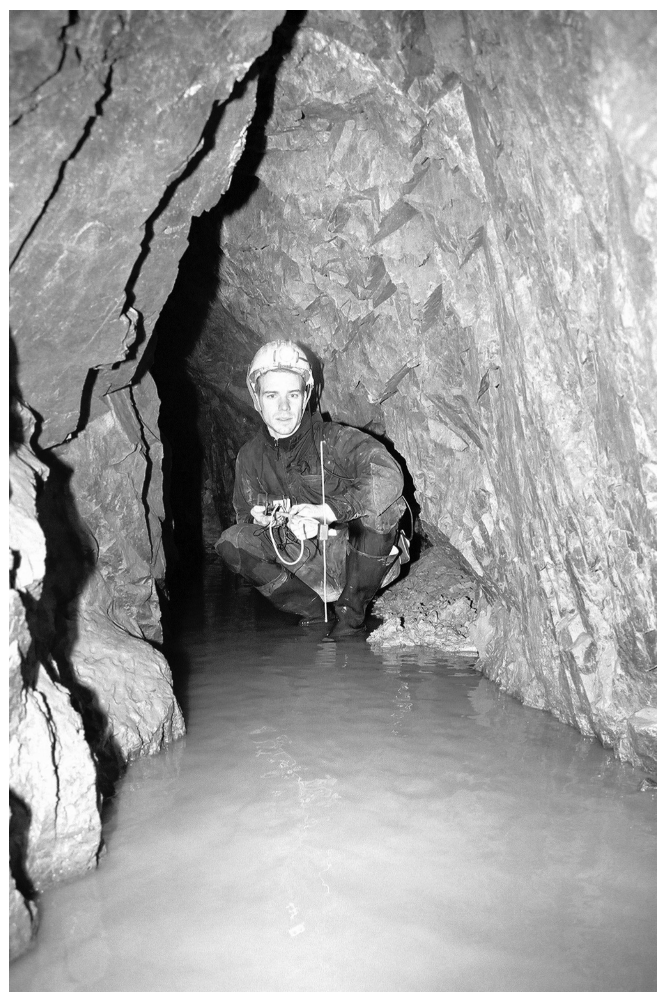

Fig. 7. Location E.

IV. Propagation Modeling

From the recorded measurements it is evident that the best approximation of path loss in straight subterranean galleries is given by a simple model of linear growth in decibels over distance

$$L(d) = L_{FB} + \alpha(d - d_{FB}) \tag{1}$$

TABLE I
SPECIFIC ATTENUATION α ACCORDING TO THE THEORETICAL MODEL (5) AND DERIVED EMPIRICALLY FROM MEASUREMENTS; THE MAXIMUM RANGE FOR A REFERENCE LINK BUDGET USING (1) AND THE SPECIFIC ATTENUATION OBTAINED FROM MEASUREMENTS

w×h (m)	roughness dampness	446 MHz			860 MHz		
		theory α (dB/m)	exp. data α (dB/m)	max. range (m)	theory α (dB/m)	exp. data α (dB/m)	max. range (m)
2.3×2.2	low low	0.62	0.49	177	0.20	0.15	494
2.3×2.1	medium low	0.64	0.41	212	0.21	0.21	359
3.0×2.2	medium medium	0.34	0.33	260	0.13	0.25	302
1.2×1.9	medium high	1.51	1.20	77	0.48	0.65	125
0.6×1.8	high high	13.17	2.70	37	5.82	2.00	47

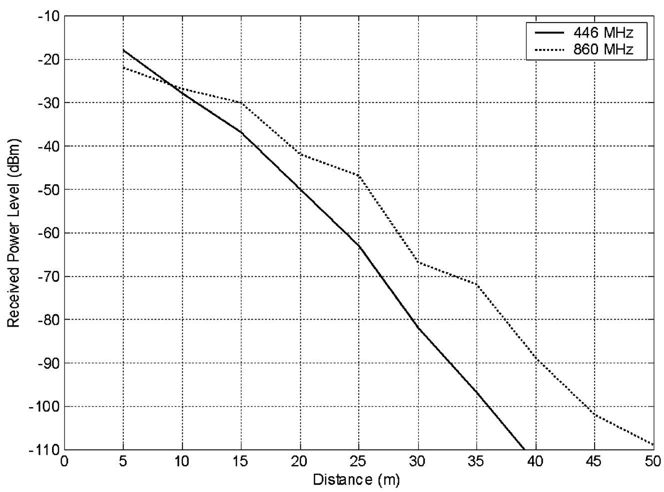

Fig. 8. Location E—received power level as a function of distance.

where $L(d)$ are propagation losses (dB), d the distance (m), L_{FB} the reference loss (dB) for a reference distance $d_{FB}(m)$ and α the specific attenuation rate (dB/m). Measurements have demonstrated that up to the reference distance d_{FB}, well known as the Fresnel break point, the propagation loss is approximately the same as in free space. Of primary interest is the value for specific attenuation, which was optimized for all the measured sections using the least square method. Values for the individual locations and frequencies are given in Table I. It must be noted that the agreement between the model and the experimental data was assisted by the method of taking measurements whereby at every point the maximum signal strength was searched out across the gallery profile. In practice signal strength varied across the profile at the individual measurement points due to multipath propagation. Nevertheless, the maximum was normally to be found in the center of the gallery.

In the next step the results were tested against a theoretical propagation model for galleries of regular profiles. As has already been mentioned above, the model [15] for specific attenuation α calculations based on the waveguide theory was applied. The calculation assumes a dominant mode EH_{11} in a lossy rectangular waveguide with the specific attenuation in dB/m expressed for vertical polarization

$$\alpha_{\mathrm{TUNNEL}} = 4.343\lambda^2 \left(\frac{1}{a^3} \frac{1}{\sqrt{\varepsilon_R - 1}} + \frac{1}{b^3} \frac{\varepsilon_R}{\sqrt{\varepsilon_R - 1}} \right) \quad (2)$$

where λ is the wavelength (m), a the width and b the height of the gallery (m) and ϵ_R the relative permittivity of the walls. The value of ϵ_R was chosen as 5 for dry and 10 for damp galleries. The relationship does not take conductivity into account as the permittivity dominates. It must be noted that the model, among others, assumes that the wavelength is small compared to gallery dimensions. This assumption is not met in all measured locations. The experimental results also indicate that its validity is limited to medium-sized galleries. Small galleries (e.g., location E) do not actually have as high values for path loss as predicted whilst, on the other hand, (2) is too optimistic for galleries with large profiles (road tunnels or metro) [17]. It is also necessary to observe that many other modes in addition to EH_{11} exist in a gallery and the resulting field is largely uniform and does not correspond to any of them. This calculation is therefore only approximate. A deterministic model would have to be used for precise predictions.

For rough walls in the case of galleries with a rectangular profile [15] provides the following correction in dB/m

$$\alpha_{\mathrm{ROUGHNESS}} = 4.343 \cdot \pi^2 h^2 \lambda \left(\frac{1}{a^4} + \frac{1}{b^4} \right) \quad (3)$$

where h is the effective height of irregularities of the walls (m). The following values were used to describe the surface roughness of walls: 0.05 m (low), 0.1 m (medium) and 0.2 m (high). A further correction factor in dB/m concerns the incline of the walls

$$\alpha_{\mathrm{TILT}} = \frac{4.343 \cdot \pi^2 \theta^2}{\lambda} \quad (4)$$

where θ is the effective angle of wall incline (radians). Since it is not feasible to precisely define the parameter for the given galleries a correction factor using the incline angle of 1° was considered for all localities regardless of their actual profile (in accordance with [15]). The resulting specific attenuation is therefore

$$\alpha = \alpha_{\mathrm{TUNNEL}} + \alpha_{\mathrm{ROUGHNESS}} + \alpha_{\mathrm{TILT}}. \quad (5)$$

Equation (5) allows the calculation of the specific attenuation of a gallery on the basis of the geometric and electrical parameters of the environment without the need for measurements. [15] also gives antenna losses caused by impedance unmatched conditions with the tunnel waveguide. A comparison of these calculated losses and the measurement results lead to the conclusion that they cannot be fully present. The reference distance of the Fresnel break point in (1) is calculated by

$$d_{FB} = \min\left(\frac{a^2}{\lambda}, \frac{b^2}{\lambda}\right) \tag{6}$$

and the corresponding reference loss can be approximated as free space loss

$$L_{FB} = 20\log\frac{4\pi d_{FB}}{\lambda}. \tag{7}$$

The applicability of the model for the measured galleries, which in many ways differ from regular galleries, is shown in Table I. This gives an estimation of the environmental parameters for all the measurement locations and a comparison of the specific attenuation calculated using (5) and the specific attenuation derived from measurements. As a practical guideline for communications in galleries the maximum range is given for a reference link budget (1 W transmitter output power, two 3 dB gain antennas, $-90\ \mathrm{dBm}$ receiver sensitivity) using (1) and the specific attenuation obtained from measurements.

From Table I it can be seen that in the first four locations, the value of specific attenuation calculated from the waveguide theory is more or less in accordance with the experimental results. Only in locality E do the figures differ significantly, as was mentioned above. In addition, a significant disagreement between the theory and measurements were observed in locality C for 860 MHz, probably due to an improper estimate of the environmental parameters. In other cases the estimate of the environmental parameters proved to be acceptable although the different influence of the floor and surrounding walls (dielectric and roughness) was not included. From the individual series of measurements it can be seen that at no location was a strict propagation mode created and that a combination of many modes arose as the frequency was well above the cutoff frequency of the hypothetical waveguide. A significantly scattered field arose with increased distance from the transmitter due to the irregularity of the walls. The scattering causes wave depolarization and very similar path losses for both orthogonal polarizations. The scattered field significantly contributes to signal propagation into bends.

V. Conclusion

Based on the experimental data, a simple propagation model in the UHF band along straight subterranean galleries of various profiles and types of wall was presented. It was demonstrated that for the typical situations in the experiment an empirical linear model of path loss could be used. The parameters of individual types of galleries were also verified for the application of the theoretical waveguide model for signal propagation in tunnels. This model is only suitable for regular galleries such as occur, for example, in mines and not for irregular profiles that often occur in caves. Basic guidelines for estimating the specific attenuation in underground galleries of various profiles and wall properties were given for the UHF band, which can be considered as advantageous for wireless communications in speleology applications.

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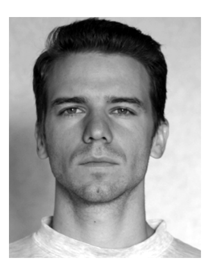

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