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Wireless Propagation in a Metallic Pipe for the Transmission of Sensory Oil and Gas Well Data

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***Abstract*—The feasibility of a wireless system is examined for propagation inside an oil and gas well pipeline. The well bore environment is modelled as a circular aluminium pipe and treated as a metallic microwave waveguide. The experimentation test bed was based on the nominal diameters of commercially available oil and gas well pipelines. At the transceivers, half-wave dipole antennas operating at 2.5 GHz were employed. Due to the excitation frequency and the enclosed pipe environment, parameters such as the propagating mode, the directivity and the realized effective gain of the antennas also needed to be investigated for this scenario. Additionally, a numerical transmission path loss (TPL) model was developed and verified using full-wave simulations and measurements. The communications link facilitated the continuous monitoring of sensory data with real time temperature and pressure levels transmitted using N210 universal software radio peripheral (USRP) modems by National Instruments and symbol coding using orthogonal frequency division multiplexing (OFDM). This study and experimental work can be a basis for the implementation of a high-speed wireless communications method for deployment inside oil and gas well pipelines for real-time data transmission at microwave frequencies.**

***Index Terms*—circular waveguide, directivity, half-wave dipole, pipeline, sensory data, oil and gas well, transmission path loss**

I. INTRODUCTION

IN the oil and gas industry, significant efforts have been made to obtain reliable real-time monitoring of the downhole drilling parameters and the integrity of wells to maintain safe production and operations. Unique electromagnetic challenges arise when attempting to overcome the severe environmental and geological conditions to allow critical high-speed data communications within oil and gas wells. For example, the transmission of real-time data pertaining to well condition monitoring, productivity, and seismic evaluation are important to ensure the safety of operational activities. An available medium for said data communications, which has not been exploited previously, is the inside region of the pipeline structure itself which acts as an enclosed metallic waveguide. The constraints imposed by the well environment are in stark contrast to other modern wireless-based systems such as 4G, 5G and Wi-Fi where data communications are based on radiating antennas and free-space propagation [1].

A limited number of studies have reported possible technologies for monitoring sensory data for sub-surface oil and gas applications and these were found to be in the low (sub-kHz) frequency ranges [1], [2]. This is mainly because the propagation environment for transmitting at higher frequencies inside the well can be extremely lossy due to the borehole fluids contained inside the pipelines which typically may be a liquid and gas composition causing major attenuation at higher frequencies (i.e. MHz, GHz). In [1], for example, it was also expressed that maintaining communication links for monitoring real time drilling operations is very challenging and demands technically novel innovations. Following this key motivation, two major telecommunication technologies for drilling measurements at low frequencies ($<$ 30 Hz) were tested: the mud-pulse telemetry (MPT) and electromagnetic telemetry (EMT) techniques [1] and [2]. In addition, enhanced signal processing methods (such as noise cancellation and equalization) were studied and applied to MPT using phase-shift-keying (PSK) in an effort to improve system performance [1] - [2]. More specifically, spatial diversity and dynamic models for signal processing and algorithms for noise cancellation were used to improve the data transfer quality.

In this letter we introduce a novel method using microwave frequencies for wireless propagation to achieve high speed real-time data communications inside a circular pipeline over a distance d, defining a maximum experimental range of a few hundred meters. The modeled pipeline radius selected is based on commercially available tubular dimensions for oil and gas wells. An important differentiator is that, the proposed pipeline-based communications system, can be used simultaneously during the production process when the composition is mainly dry gas; i.e. methane [3], to obtain the transmission of essential sensory information, such as, temperature and pressure data within the interior of the pipe.

A brief comparison of the proposed system with EMT and MPT is also outlined in Table I. It is important to identify that the specific application and the borehole gaseous medium is different for the proposed microwave wireless system when compared to EMT and MPT. Also, the specific fluid composition within the pipeline can help to more accurately define the carrier frequency for data exchange. Based on the successful results reported in [4], the more developed transmission system with supporting electromagnetic modeling, in this letter, offers higher data transmission rates when compared to those employing lower frequency methods. Also, the successfully demonstrated system at 2.5 GHz (see Fig. 1) offers an alternative modulation scheme in contrast to [1] and [2], providing a potential advancement for communications within oil and gas wells.

Two half-wave dipoles are placed at the edge of the circular aluminum pipe defining the transceivers for the developed system (Fig. 1). In particular, the dipoles are connected in series with an N210 universal software radio peripheral (USRP) modem by National Instruments for the data modula-

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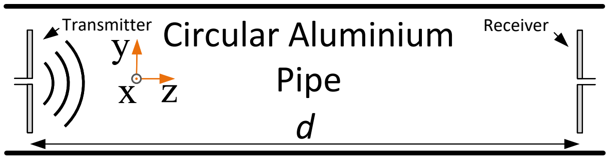

Fig. 1. Setup for the wireless system showing the cross-section of the circular aluminum pipe which is representative of an oil and gas well pipeline. The transceiver half-wave dipoles are illustrated, separated by a distance d, and placed vertically in the middle of the pipe enforcing signal propagation in the $+z$-direction when the transmitter dipole is driven as shown.

tion/demodulation. Orthogonal frequency division multiplexing (OFDM) was adopted as the modulation scheme for the communications system since this method can assist in reducing multipath effects inside the pipe when transmitting over long distances [5]. Some preliminary findings, which focussed on the data communication protocols when employing the USRPs, can be found in [4]. However, new results are reported in this letter focusing on the wireless propagation inside the pipeline and the behaviour of the antenna dipoles when placed in this enclosed environment.

The reported findings and analyses herein sets the foundational method for a new communication systems at microwave frequencies for deployment inside oil and gas well pipelines. The intended application of the proposed system is for dry gas (e.g. methane), shallow, sub-surface well environments (of approximately 150 meters for the pipeline length) where data can be transmitted from underground sensors to the surface such that the integrity and efficiency of the oil and gas pipeline can be remotely monitored by an operator.

To the knowledge of the authors, no similar wireless system has been studied and experimentally tested by applying microwave electromagnetic principles and propagation analysis for the transmission of real-time data packets at the 2.5 GHz industrial, scientific and medical (ISM) frequency band. Findings from this paper are closely applicable to other communication scenarios within enclosed environments, which include, metallic air-ducts, airplanes [6], tunnels [7], [8], and mines [9]. In principle, any other challenging and internal electromagnetic environment requiring wireless signal propagation, which demands new solutions for data exchange.

II. HALF-WAVE DIPOLE WITHIN THE CIRCULAR PIPE

This study is based on classic waveguide theory, as the circular metallic pipe is treated like a waveguide. However, it differs on the excitation method as it uses a half-wave dipole which is placed inside the waveguide (Fig. 1). The reason which an antenna is used instead of vertical probe or loop feed is related to the challenging environment of the oil and gas pipe. For instance, antennas are employed in the proposed system because they can offer transceiver gains which route more power to the desired direction even in the enclosed pipeline environment. This excitation causes some complexity and therefore, parameters such as the dipole effective gain and the transmission path loss (TPL), need to be carefully considered. A housing for the antenna (similar to a radome) can also be designed and built for its protection, from the gas within the pipe, ensuring good system operation [3]. However, we will not refer further to such an antenna housing, as it is beyond the scope of this letter. Also, as further described herein, an antenna is more able to keep the waveguide/pipeline characteristics stable by enforcing excitation of the dominant mode (only) for propagation within the pipe.

TABLE I
OIL & GAS WELL COMMUNICATION SYSTEM COMPARISONS

System	Operational Frequencies	Propagation Environment	Max Signal Attenuation	Data Modulation Scheme
EMT [1], [2]	< 100 Hz	Borehole Fluid	High^1	Analog
MPT [1], [2]	< 30 Hz	Borehole Fluid	High^1	PSK
Proposed	2.5 GHz ISM	Dry Gas (Methane)	^{2}0.005 dB/m	OFDM

[1] Exact loss values were not reported but were stated as *High*.
[2] Considering the conductor loss per meter of pipe.

It should be mentioned at this stage that the conditions in conventional well pipelines contain several multi-phase mixtures such as combinations of oil, gas, and water. Also, for example, there are oil-only or gas-only well types. In addition, these gas-only pipelines can be saturated with moisture defining a wet well. More often the well-stream can consist of a full range of hydrocarbons from gas (methane, butane, propane, etc. with methane being the most common), to condensates (medium density hydrocarbons), and to crude oil [10]. Actually, the different hyrdocarbon compositions are many and can change based on well operations, and thus for brevity, it is not practical to consider all possible production situations [10] in this letter. The authors also wish to acknowledge that any water content (defining a wet well) may absorb or partially reflect a propagating microwave signal, therefore, we mainly assess signal propagation under typical dry gas scenarios for commonly found well types, rather than considering the detrimental effects of other crude mixtures [3]. For these reasons, the product which flows within the representative oil/gas well pipeline is assumed to be a common methane mixture (in its dry gaseous phase) which has the electrical properties of air [3].

Following these considerations, a half-wave dipole antenna was placed into the selected pipeline to conduct a first proof-of-concept experiment. The directivity of the half-wave dipole in free space is 2.15 dB [11], however, when placed in a circular metallic environment, the radiating near fields are apparent altering the classic definition of transceiver gain. This is important when determining a link budget. Following this, the directivity of the half-wave dipole when placed inside a circular aluminum pipe was simulated and results are presented in Fig. 2. Starting with a radius for the pipe of 50 mm, and gradually increasing this radial parameter (until it reached the far field region), the directivity was recorded. It can be observed that as the radius of the pipe becomes larger, the directivity approaches the free-space value of 2.15 dB.

More simulations were completed comparing the directivity of the half-wave dipole with respect to the length of the waveguide (L) and for various radii of the waveguide (Fig. 3). The half-wave dipole was placed at the edge of the waveguide as the length of the pipe was varied from 0 to 1 m. The directivity of the dipole was recorded for each of those lengths. Results suggest that the directivity is related

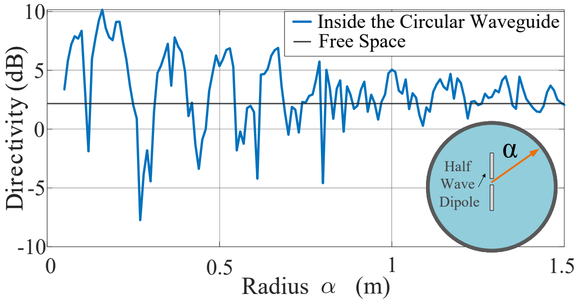

Fig. 2. Simulated directivity of the half-wave dipole in the $+z$-direction, operating at 2.5 GHz with respect to the radius (α) of the circular aluminum waveguide, where it is operating within. A pipe length of a few wavelengths was employed whilst ensuring this length was representative of the conventional far-field range for the dipole. A comparison is also shown with the free-space directivity value (maximum); i.e. the 2.15 dB horizontal line.

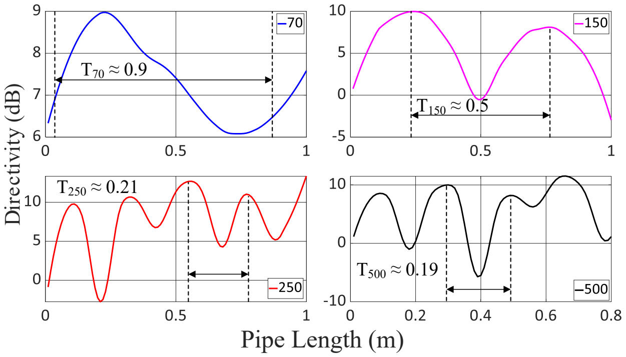

Fig. 3. Simulated directivity of the half-wave dipole, operating at 2.5 GHz versus length, for various circular waveguides with radius 70, 150, 250, 500 mm. The observed period T is identified for each case.

to a periodic function which is linked to the omnidirectional-like radiation pattern of the dipole. According to the results in Fig. 3 the value for the period T, which defines this periodic function, decreases as the radius of the waveguide increases. For example, as observed in Fig. 3 the period is about 900 mm and 190 mm for pipe diameters of 70 mm and 500 mm, respectively. On the other hand, the amplitude range of this function, defined as A, increases as the radius of the waveguide increases. The amplitudes are about 1.9, 5.5, 8.2, 10.6 dB when the radius is 70, 150, 250, 500 mm, respectively.

Considering all these investigations, it can be observed that the effective directivity, and therefore the effective gain of the half-wave dipole (when placed into a circular waveguide) is a function of the pipe radius and its length, i.e. $G_{eff}(\alpha, L)$. This function cannot be easily defined in an exact form, as simulations have shown it is related to the pipe length and radius, L and α, respectively. For this reason a simulation and measurement study follows using the typical pipe dimensions as employed for commercial oil and gas wells.

An aluminum pipe of radius $\alpha \approx 0.6\lambda_0$ and wall thickness $0.06\lambda_0$, at 2.5 GHz was selected for further simulations and experimental testing while transmitter and the receiver dipoles where placed in the middle of the pipe (Fig. 1). For better understanding of this scenario, it is important to define the modes and the TPL between the half-wave dipoles. Based on waveguide theory, the dominant mode in a circular waveguide is the TE_{11} mode whilst the TM_{01}, TE_{21} modes can be excited for propagation at 2.5 GHz [11] for the employed pipeline dimensions (all results not reported). This defines a mutli-moded waveguide which is unwanted. Simulating the system, by stimulating the dipole transmitter (see Fig. 1) with the pipe air-filled at lab conditions, the extracted electric field is that of the TE_{11} mode (see also Fig. 2 from [4]) with field propagation as well as the power flow in the $+z$-direction.

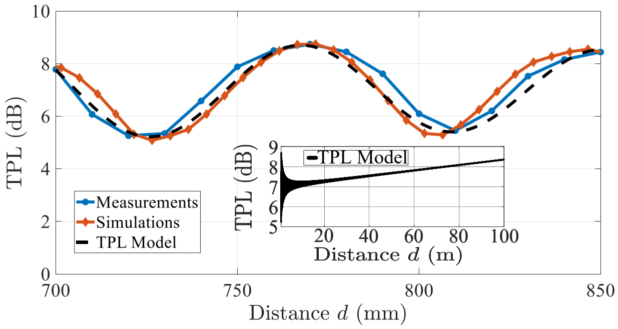

Fig. 4. Simulated, measured and calculated transmission path loss (TPL) for the two dipole transceiver system when they are placed inside the waveguide. The inset also provides a projection of the TPL model up to 100 m.

The TPL is defined in this work by studying the simulation and measurements of the system and this path loss will be described in detail next. Specifically, maintaining a steady position for the transmitter dipole, the receiver dipole was gradually moved along the pipe and the transmission loss was sampled at each position. The range of the distance moved was from 700 mm to 860 mm. At each edge of the waveguide pipe, absorbing boundary conditions were imposed in the simulator so that no power was radiated outside of the model. Similarly during the measurements, practical microwave absorber was positioned at the pipe edges being well in the far-field zone of the antennas whilst following standard definitions.

As observed in Fig. 4 there is a very good agreement between the full-wave simulations and the measurements. A numerical model was then developed and plotted (see Fig. 4) as described by (1) and is a function of the system losses (SL) and the realized effective gain of the transmitter and receiver antennas (G_{eff_t}, G_{eff_r}). The SL includes the power directed in the backward direction, power lost at the antenna receiver, and the loss due to conductivity of the pipeline walls. Given these conditions, the TPL can be defined in dB:

$$\mathrm{TPL} = \mathrm{SL}(\alpha, L) + G_{eff_t}(\alpha, L) + G_{eff_r}(\alpha, L). \qquad (1)$$

From the measurements and the simulations it can also be extracted that the sum of the SL and the effective dipole gains and therefore of the TPL is given by

$$\mathrm{TPL}{=}P + \propto \times d + \left(A/d\right)\ \sin\left(2\pi d/T\right)\ \mathrm{dB}. \qquad (2)$$

The radius in this case is steady and the constant values P and $\propto$ are depended on the radius. Moreover, by inspection of the simulations and measurements in Fig. 4 the values of the constants P and $\propto$ are 7 and 0.013505, respectively. The amplitude A is 1.8 dB while the period is about 80 mm for this specific pipe diameter. Also, it can be observed that the periodic function declines as long as the distance increases, thus the TPL model has a more linear form, as it is demonstrated in the inset of the Fig. 4. The inset also shows the projection of the TPL for distances up to 100 m.

After some further investigations in the simulator, it was found that the aforementioned periodic function, $\frac{A}{d}\sin\left(\frac{2\pi}{T}d\right)$, is related to the omnidirectional-like radiation pattern of the half-wave dipole. This was realized because in other simulation and measurement studies, with a more directive end-fire

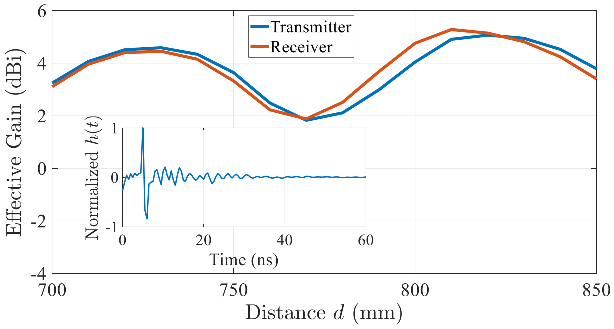

Fig. 5. Effective gain of the transceivers based on the measured impulse response of the dipoles which were placed inside the aluminium pipe. The inset also shows the measured impulse response.

antenna placed at the pipe edges, the power was more simply injected into the waveguide, and moreover that, this periodic function did not appear (see [4]).

This investigation helps to further understand the behavior of the effective gains of the half-wave dipoles when placed inside the pipe. Also, an analytical expression to characterize the realized effective gain can be provided through the impulse response $h(t)$. Connecting the transceiver antennas to a vector network analyzer (VNA), the complex transmission coefficients S_{21} and S_{12} can be measured. The Fourier transform of the normalised impulse response $(H_N(\omega))$ using transmission coefficients [12] is

$$H_N(\omega) = \left(\frac{d\upsilon_g}{j\omega} \mathrm{S}_{21}(\omega) e^{j\omega \frac{d}{\upsilon_g}} \right)^{1/2}, \tag{3}$$

where υ_g is the group velocity of the propagated mode. Also, the relation between the gain of the transmitter and the impulse response of the antenna is given by [13]:

$$G_t(\omega) = 4\pi \mid H_N(\omega) \mid^2 / {\lambda_g}^2, \tag{4}$$

where λ_g is the wavelength of the propagated mode. Respectively, the gain of the receiver is given by the use of $\mathrm{S}_{12}(\omega)$ instead of $\mathrm{S}_{21}(\omega)$. It should also be mentioned that (3) and (4) have been recast from [12] and [13] considering the group velocity υ_g and the guided wavelength λ_g, respectively, instead of the speed of light c and the free-space wavelength λ_0.

When further reviewing our measurements with the aluminum pipe (having a 70 mm radius), and placing the two half-wave dipoles at both ends of the pipe, the S-parameters were measured. Therefore, based on (4), the gains of the transmitter and the receiver dipoles inside the circular waveguide were calculated as reproted in Fig. 5 with respect to the distance at 2.5 GHz. Also, the impulse response of the system when the distance was 700 mm, is shown in the inset of Fig. 5. It can be observed that the values of those gains (determined using the impulse response) follow a periodic function. This means that when the gains increase the losses decrease. These findings also provide some justification that the noted periodicity as well as the dipole directivity and effective gain are related to fields generated for a certain pipe radius and length; i.e. $G_{eff}(\alpha, L)$ as previously discussed.

III. SENSORY DATA TRANSMISSION THROUGH THE PIPE

A proof-of-concept experimental setup was built and tested within an anechoic chamber (Fig. 6). A half-wave dipole was placed at the edge of the circular aluminium pipe and connected in series with the USRP modem. See [4] for additional information on this experimental channel as well as the full capabilities of the transceiver USRPs and setup.

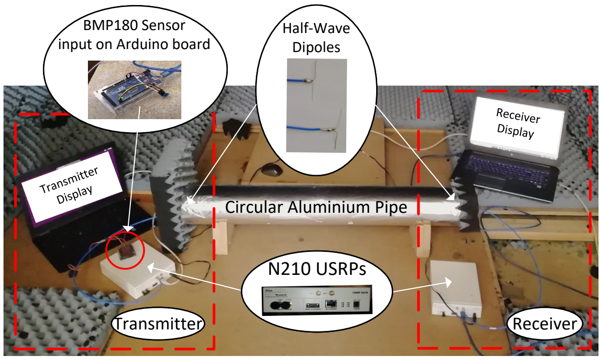

Fig. 6. Channel experimental setup. The dipoles were placed at the ends of the circular aluminum pipe and connected to the USPRs. At the transmitter side the BMP180 sensor was connected to Arduino capturing the environmental data. The receiver accurately decoded the sensor data in real-time.

A barometric pressure/temperature (BMP180) sensor by Bosch was connected to the input of an Arduino (ATmega328P) microcontroller at the transmitter, to allow the measurement and recording of the ambient temperature and pressure inside the pipe. The aforementioned setup describes the arrangement of the transmitter side, which was positioned at a distance, $d = 850$ mm from the receiver. At the receiver side the half-wave dipole was connected to the USRP. The communications system was programmed by OFDM modulation to send sensor data continuously, or as a single transmission test for monitoring the real-time sensor data.

In a simple experiment, the USRP transmission power was set at -25 dBm, and based on Fig. 4, the measured transmission loss was $\approx$ 8 dB, and the received power was calculated to be -33 dBm. The testing of the communications link was successful, as the sensory data was received and monitored accurately in real-time. The temperature data that was transmitted was 28.06 °C and the pressure was 102.2 kPa. In a subsequent test, a hot air blower was set next to the sensor and the rise in temperature was monitored at the receiver. A measurement increase in temperature from 28.06 °C to 31.79 °C was observed and verified with a digital thermometer. The air pressure was also monitored at the receiver to be 101.9 kPa, being in accordance with the transmitted data.

IV. CONCLUSION

A wireless communication system for propagation inside an oil and gas well pipeline was presented. By following classic metallic waveguide analysis and antenna theory, parameters such as the dominant TE_{11} mode and the TPL were studied to estimate the propagating signal strength between the dipole transceivers. Sensory data such as temperature and pressure were successfully transmitted and monitored, in real-time, using OFDM and software defined radios; i.e. USRPs at the transmitter and the receiver for a 2.5 GHz ISM band carrier frequency. Further experimental testing by considering carbon steel pipelines, and significantly increasing the transmission ranges, are planned as future work as well as sending more elaborate sensory data forming real-time transmission of images and video. Also, depending on the possible transmit powers and system implementation as well as any observed conductor and transmission losses within practical pipelines, repeaters may be required when transmitting over long ranges.

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REFERENCES

[1] A. Jarrot, A. Gelman, and J. Kusuma, “Wireless digital communication technologies for drilling: Communication in the bitss regime,” *IEEE Signal Processing Magazine*, vol. 35, no. 2, pp. 112–120, 2018.

[2] N. Franconi, A. Bunger, E. Sejdic, and M. Mickle, “Wireless communication in oil and gas wells,” *Energy Technology*, vol. 2, 10 2014.

[3] D. Joinson, Senior Production Technologist for Shell Amsterdam, Private communication, August 2020.

[4] K. Kossenas, S. K. Podilchak, and M. Beveridge, “RF system development for sensor and wireless communication applications inside a circular pipe,” in *2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting*, 2020, pp. 1143–1144.

[5] G. Forbes, S. Massie, and S. Craw, “Wifi-based human activity recognition using raspberry pi.” M. Alamaniotis and S. Pan, Eds. Institute of Electrical and Electronics Engineers, 2020, pp. 722–730.

[6] V. Gómez-Guillamón Buendía, S. K. Podilchak, G. Goussetis, D. Masotti, A. Costanzo, and P. Nicole, “A smart cable offering selective and distributed antenna radiation using RF switches and non-conventional hybrid couplers,” *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 11, pp. 6346–6351, 2018.

[7] A. Malone and C. D. Sarris, ““Electromagnetic Vision”: Machine intelligence models of radiowave propagation in tunnels,” in *2018 IEEE International Symposium on Antennas and Propagation USNC/URSI National Radio Science Meeting*, 2018, pp. 557–558.

[8] S. Bickerstaff and C. Langmaid, “Design of wireless communication sensing networks for tunnels, trains and buildings,” vol. 2, 01 2009.

[9] Q. P. Soo, S. Y. Lim, and D. W. Gin Lim, “Investigation of rough surfaces for propagation modeling in caves,” in *2018 IEEE International Symposium on Antennas and Propagation USNC/URSI National Radio Science Meeting*, July 2018, pp. 555–556.

[10] J. G. Speight, *Chapter 4 - Reservoir Fluids, in Introduction to Enhanced Recovery Methods for Heavy Oil and Tar Sands*. Laramie, Wyoming, USA: Gulf Professional Publishing, 2016.

[11] C. A. Balanis, *Antenna Theory: Analysis and Design*. New Jersey, NJ: John Wiley & Sons, Ltd, 2016, ch. 2.

[12] B. Scheers, A. Marc, and A. Vander Vorst, “Time-domain simulation and characterisation of tem horns using a normalised impulse response,” *Microwaves, Antennas and Propagation, IEEE Proceedings*, vol. 147, pp. 463 – 468, 01 2001.

[13] L. Bowen, E. Farr, and W. Prather, “Fabrication and testing of two collapsible impulse radiating antennas,” *Sensor and Simulation Notes*, p. note 440, 01 1999.