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A Novel Wireless Measurement While drilling System for Geotechnical and Geophysical Applications *

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***Abstract*— This paper presents the development of a wireless measurement system based on 2.4GHz wireless technology and waveguide theory. The prototype system is installed on a rotary geotechnical drilling rig with the purpose of providing a wireless communication link between down-hole sensor(s) contained inside the drilling string and a logging computer/ receiver on the surface. In hazardous environment, this setup can be attached to an autonomous vehicle or robot while data can be remotely collected. The results are promising, the developed system significantly reduce the time and cost of a wide range of geophysical borehole investigation methods. This includes detection and clearance of deeply-buried Unexploded Bombs (UXBs). In this paper, the structure of the system and results from practical test will be introduced and discussed.**

I. INTRODUCTION

Borehole geophysics is a branch of geophysical methods usually conducted at a depth to measure different physical properties; it involves manually lowering sensors into a borehole to record continuous data. Common borehole geophysical methods include down-hole seismic, borehole magnetometry, borehole resistivity and borehole gamma ray logging. Basic applications of borehole geophysics include mapping and characterising of subsurface infrastructure, groundwater and bedrock depth and supporting civil and geotechnical engineering investigations.

Borehole geophysical methods require a borehole to be drilled and cased before the start of the survey. The borehole is usually drilled using a suitable rotary drilling method. Once the required depth is reached, the drill string is withdrawn from the borehole and a suitable casing is installed to prevent the borehole from collapsing. After that, an appropriate probe is lowered down manually and the data are collected. In some cases the drilling of the borehole is carried out in stages (typically 1m) at each stage, for example, the clearance of unexploded bomb using borehole magnetometry.

It is obvious that traditional borehole geophysical methods are very time-consuming and costly. Cone penetration Test (CPT) is a more efficient method that provides real time borehole data [1]. It works by pushing an instrumented cone into the ground under hydraulic pressure using a CPT rig. The collected data are transmitted over a cable that runs through the string to the logging device/computer located inside the CPT truck. Limitations of this method are ground conditions which prevent penetration of the cone to the required survey depths. As a result, the CPT method cannot be employed in more than 40% of greater London [2].

In this paper we present a novel wireless telemetry system that helps to conduct several borehole geophysical surveys in a more efficient way by providing real time down-hole measurements during the drilling process. The system is to be fitted on a rotary drilling rig which can penetrate most ground conditions and this overcomes the limitation of the CPT method. In particular, this system will greatly improve the efficiency and the safety of detecting deeply-buried UXBs.

The proposed solution can be attached to autonomous or tele-operated robotics systems for use in hazard and risky environments. Mobile robots fitted with rotary drilling systems are used for ground, underwater and space application [3-4]. In addition, robotics systems are widely employed for de-mining activities [5]. The suggested system can be combined with these robotics technologies to offer an efficient and safe survey method for deeply UXBs.

II. THE DRILLING METHOD OF CHOICE

Various drilling methods may be found in oil and gas, construction and geotechnical industries. The proposed telemetry system would suit a dry rotary drilling method such as Auger drilling [6]. Where the drilling operation is carried out without water or fluid, instead, it is removed by a mechanical mean. Thus, the electronics for the proposed system can be placed inside the drill string without disturbing the cutting removal mechanism. In addition, having a hollow drill string with no drilling fluid would ease the communication with the surface as we will see in the following section.

III. THE DRILL STRING AS A WAVEGUIDE

The main challenge associated with the development of the proposed system is the transmission of the down-hole data from the bottom of the borehole to the surface while drilling in real time. This telemetry system needs to be wireless due to the nature of the drilling procedure and the rotation of the drill pipe, however, direct radio frequency (RF) link through the ground to the surface is not feasible as the electromagnetic (EM) signal will get highly attenuated by the ground layers.

In the oil and gas industry, measurement while drilling (MWD) systems do exist, they provide operators with real time information such as formation properties and borehole geometry while the borehole is being drilled. The main MWD method used in the oil and gas industry is the mud pulse telemetry; other less frequently used methods include EM telemetry and acoustic telemetry. Current MWD

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methods used in oil and gas industry are generally complex and expensive as they have been designed to operate at very deep depths and extreme conditions. In addition, these methods provide very limited bandwidth [7].

Due to the facts that the wall of the drill string is made out of a conductive metal and that the drill string is hollow, a novel approach can be applied here that utilise the drill string itself as a communication channel. The idea is to consider the stem of the drill string as a circular waveguide and by carefully choosing the carrier frequency; electromagnetic waves can be guided along the metal pipe up to a receiver at the top of the drill string.

Waveguides are usually carefully designed to meet particular frequency requirement. The waveguide will be excited by a basic antenna that radiates inside the hollow drill string. Inside the waveguide, there are different possible field configurations or patterns, each pattern is called mode. Each mode has a specific cutoff frequency. In order for a wave to propagate through the waveguide, it has to be greater than the lowest waveguide cut-off frequency. The first mode to propagate is the mode with lowest cutoff frequency and it is called dominant mode. The cutoff frequency depends mainly on the dimensions of the waveguide, mode of propagation and the characteristic of the fill material, the cut-off frequency for circular waveguide is [8]:

$$f_{c-TM} = \frac{p_{nm}c}{2\pi a\sqrt{\epsilon}} \quad (1)$$

$$f_{c-TE} = \frac{p'_{nm}c}{2\pi a\sqrt{\epsilon}} \quad (2)$$

Where p_{nm} and p'_{nm} are the m^{th} root of the n^{th} order Bessel function of the first kind and its derivative respectively. Values of p_{nm} and p'_{nm} are given in mathematical tables.

The dimensions of hollow stem drill pipes are not standardised between various drill pipes manufacturers. A typical range of hollow stem pipe diameters is shown in table 1. The table also list the cutoff frequency for the TE_{11} mode which is the dominant mode for a circular waveguide.

TABLE 1. TYPICAL DRILL PIPE SIZES WITH CORRESPONDING TE11 CUTOFF FREQUENCY

Auger Internal Diameter (mm)	Outside (Flights) Diameter (mm)	Weight (kg)	TE_{11} cutoff frequency
57.2	136.5	20.9	3.07 GHz
82.6	187.3	37.2	2.13 GHz
100	200	40	1.76 GHz
111	215.9	50	1.58 GHz
168.3	273.1	57.2	1.04 GHz
209.5	314.3	67.1	839.2 MHz
260.3	368.3	114.8	675.4 MHz
311.2	419.1	134.7	564.9 MHz

By evaluating the lowest cutoff frequencies for typical drill pipe diameters listed in table 1, it can be noticed that the popular 2.4 GHz ISM band can propagate through most of commercially available drill pipe sizes. This fact will greatly simplify the design challenge since the 2.4GHz band requires no special license and 2.4GHz-based radio frequency modules are widely available off the shelf at low prices.

IV. SIGNAL ATTENUATION

A standard drill pipe with 100mm diameter was considered. At 2.4 GHz, two modes can propagate, TE_{11} and TM_{01} with cutoff frequencies of 1.76GHz and 2.29GHz respectively. If more than one mode is propagating, the waveguide is said to be overmoded. In waveguide applications, multimode propagation is not desirable and usually avoided as it may increase transmission loss.

The power inside a waveguide drops exponentially with the distance. Fig. 1 depicts the theoretical attenuation constant expected inside the drill pipe for TE_{11} and TM_{01} modes over the frequency range of interest. The total power will be distributed between the excited modes. The overall attenuation constant depends on power radiated in each mode, which in turn depends on the antenna radiation characteristics, antenna orientation and position inside the drill pipe, waveguide cross sectional area and operating frequency [9].

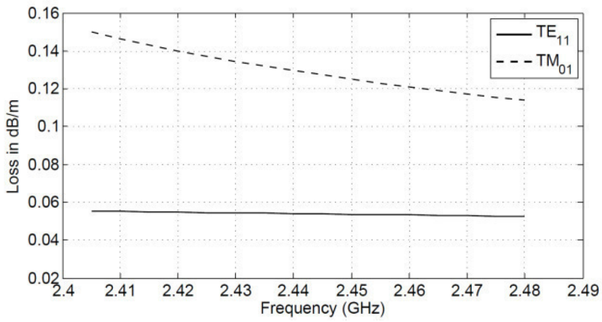

Figure 1. Attenuation constant in dB/m for TE_{11} and TM_{01} modes

It is fairly complex to accurately calculate overall signal attenuation inside a drill pipe. This is mainly due to the fact that the drill pipe is not an ideal waveguide. There are some other factors that affect signal propagation. In addition to the dielectric and metallic loss which are experienced in any waveguide, the drill pipe suffers from the following:

- Drill pipe sections are made from steel which is vulnerable to rust and corrosion, as a result, the conductivity of the material reduces and the metallic loss increases.
- The excitation of the drill pipe is not optimal. The requirement of simple integration into different drill pipe sizes and drilling rigs dictates that the radiating element (antenna) is randomly placed inside the drill pipe, thus, maximum power transfer may not be achieved and antenna coupling loss may increase.
- At both ends, the drill pipe is terminated with metallic objects, acting as reflectors. As a result, each antenna will receive multiple reflections from both ends, leading to an extra loss.
- The EM signal will get attenuated by the dust, water and mud which may penetrate into a badly-sealed drill string during drilling activities.

- Extra losses may arise by the joints between drill pipe sections and the roughness of the internal wall of the drill pipe.

Even with all the loss factors mentioned above, total channel loss is expected to be relatively low when compared to free space and indoor communications.

A general exact solution for the path loss inside the drill pipe is fairly complex. In addition, there are several random factors associated with the channel such as conductivity of the drill pipes used, modes excitation conditions and other signals disturbances mentioned above. Analysis of similar propagation conditions do exist in the literature, waveguide effect and propagation in tunnels and mine like environment has been studied in the past (10). The most relevant study was done by a group of researchers where indoor radio wave propagation using heating, ventilation and air conditioning duct (HVAC ducts) was proposed and studied in details [11-13]. Pavel Niktin and others proposed [12] a simple analytical propagation model for straight duct, the model accounts for mode excitation, reflections from terminated ends but it requires knowledge of mode-dependant antenna impendence. T. Ozan and others [14] presented an empirical model to predict path loss inside an HVAC duct operating in the 2.4 – 2.5 GHz, experimental measurements were used to determine attenuation loss and antenna coupling loss for HVAC duct of 0.3m diameter, the attenuation loss was found to be 0.16 dB/m, while the antenna coupling loss was 14.8 dB.

V. CONCEPT DEMONSTRATION

A simple test was conducted to validate the concept of using the drill pipe as a communication channel. The test was performed with a drill string of 3.2 m length (two drill pipe sections). Two IEEE 802.1.5.4 2.4GHz wireless transceivers modules have been used. Each module consists of a programmable PIC® microcontroller and MRF24J40A transceiver [15]. The used transceiver has a sensitivity of -94dBm and maximum output RF power of 0dBm.

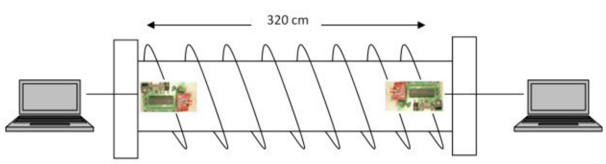

Figure 2. Test setup for measuring the frequency response of the auger/drill pipe

The transceiver has the option of adjusting the output power from a minimum of -38.75 dBm up to a maximum of 0 dBm in steps of 1.25 dB. It also provides a measure for the received signal strength with an accuracy of +/- 5dBm. Accordingly we were able to vary the output power and to measure the received signal strength in different conditions. For a reliable communications, the received signal strength needs to be higher than -80dBm.

The MRF24J40A supports the IEEE 802.1.5.4 standard, which divide the 2.4 GHz ISM band into 16 channels. Fig. 3 plot the frequency response obtained by varying the operating frequency and measure the average of the received signal strength. The centre frequencies of the 16 supported channels were tested. Fig. 3 shows two curves, the first curve represents the measurements obtained with both ends of the drill pipe are open, this condition simulate a matched load as there is no reflection from the ends. The second curve is for the measurements obtained while the ends of the drill pipe are terminated by a conductive metal sheet, this simulate a short circuit condition in which reflections from both ends are expected. It can be noticed that the loss due to reflections from the terminated ends is quite small. This agrees with the results achieved by other researchers [12, 14].

Among the frequency range of interest, the average of overall loss is 12dB. The attenuation constant of the waveguide is expected to be very low (see Fig. 1), for the HVAC duct, 0.12 dB/m was reported by stencil [13] and 0.16 dB/m reported by Ozan [14]. It is believed that, the majority of the loss mainly comes from antenna coupling. An antenna coupling loss of 14.8 dB was reported by Ozan [14] for a monopole antenna radiating inside a HVAC duct. Stencil [13] also estimated an antenna coupling loss of 20 dB. If we ignore losses due to joints and conservatively assume a 25 dB coupling loss, 0.2 dB/m waveguide loss and 10dB error margin, then, for a receiver with -80 dBm sensitivity, the communication range would be 225 meters.

In order to assess the reliability and the quality of the communication through the drill pipe, 1000 messages were transmitted from the first modem to the second modem at the other side of the drill pipe, and the number of the received messages was counted. This experiment was repeated for the 16 tested channels and there was no message loss at all.

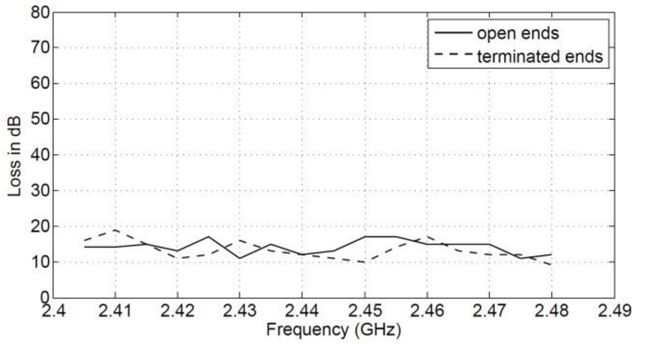

Figure 3. Frequency response measured inside a drill pipe of 3.2 meter length and 100mm diameter.

VI. PROTOTYPE AND FIELD TEST

In order to test the proposed measurement system, a prototype has been built and fitted on a rotary drill rig. Fig. 4 shows the block diagram of the implemented system. The system consists of four main units, namely: down-hole unit, relay unit, logging unit and the logging computer. The down-hole unit is located at the bottom of the drill pipe; it comprises down-hole sensors, processor, wireless transceiver and a rechargeable battery. The down-hole unit sample and process the outputs of the sensors in order to transmit them; In general, it will control the operations of the down-hole system and act as a slave unit which responds to the enquiries of the logging computer (the master unit). The relay unit is fitted at the top of the drill pipe. This unit will receive the data transmitted from the down-hole unit and retransmit them over a long-range external communication link. The external wireless link operates at 868 MHz. an extended antenna is connected to the unit to allow data to be transmitted to the free space. The logging computer runs the application software and acts as a master that controls the complete measurement system. The logging computer collects down-hole data from the sensors wirelessly through the logging unit, which provides a wireless interface for the system. In addition, the logging computer record instantaneous borehole depth which is provided by the drill rig instrumentation through a serial cable. The collected data are processed by the logging computer and then displayed against the depth in real time.

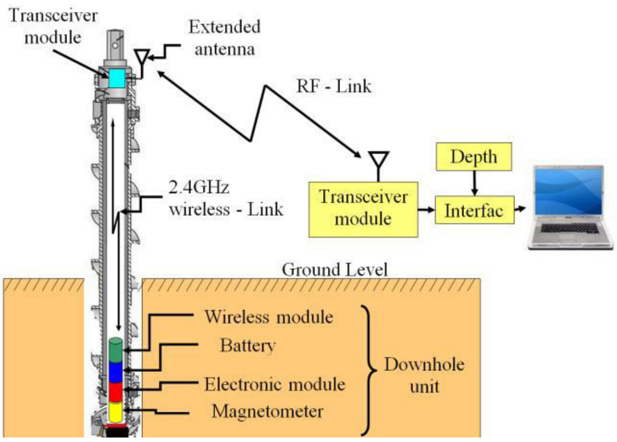

Figure 4. System block diagram

The reliability of the system was tested by drilling several boreholes under various drilling conditions. For each borehole, the signal strength inside the drill pipe was monitored and recorded. The results are shown in Fig. 5, the received signal strength was very high as expected. The received signal strength for borehole 4 has dropped to -50dBm at one stage because we have encountered water during the drilling and some water/mud has penetrated into the drill string.

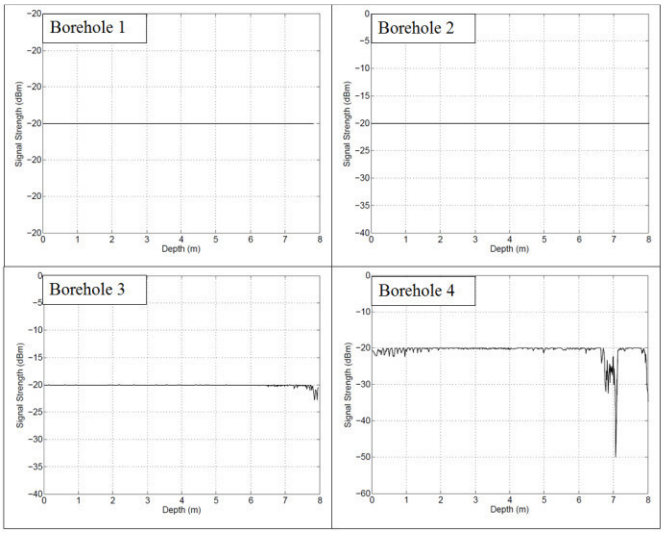

Figure 5. Signal strength measured inside drill pipe in different drilling tests.

VII. Conclusion

This paper introduces a novel down-hole telemetry method. The method is based on guiding the electromagnetic waves inside the drill string. The possibility of communication through a hollow drill pipe has been validated experimentally through a simple test. The proposed method has been implemented and successfully tested in the field. Results show that the loss is relatively low and long communication range can be achieved. The low cost and the reliability of the telemetry system alongside with the long communication range allow the system be utilised in several geotechnical drilling applications or in other areas of research applications. For example, down-hole vibration, sound, temperature and gamma rays can be monitored in real time and provide sensitive information about the underground layers and formation. In addition, robotics systems with drilling capabilities can utilise the presented telemetry system for the detection of deeply buried UXBs and metal objects.

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References

[1] J.J.M. Brouwer. In-situ Soil Testing. IHS BRE Press, 2007.
[2] Map for the geology of greater London , Zetica Ltd, www.zetica.com.
[3] Beji, L. ; Benchikh, L. (2017), 'A Method of Drilling a Ground Using a Robotic Arm', World Academy of Science, Engineering and Technology, International Science Index 131, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering, 11(11), 1821 - 1826.
[4] Glass, Brian & Thompson, Sarah & Paulsen, Gale. (2010). Robotic planetary drill tests. Proc. 13th Int. Symp. on Artificial Intelligence, Robotics and Automation in Space. 464-470.
[5] Y. Baudoin, M.K. Habib, I. Doroftei, Mobile robotics systems for humanitarian de-mining and risky interventions, Using Robots in Hazardous Environments,Woodhead Publishing,2011, Pages 3-31.
[6] Morris R. England B. and Wakeling R. Drilling Technology. British Drilling Association, 1992.
[7] Baker Hughes INTEQ, Houston,USA. Baker Hughes INTEQ Guide to Measurement While Drilling, September 1996.
[8] D.M. Pozar. Microwave engineering. Wiley, 3rd edition; 1997.
[9] P.V. Nikitin, D.D. Stancil, A.G. Cepni, A.E. Xhafa, O.K. Tonguz, K. Areklett, and D. Brodtkorb. Antennas in a waveguide propagation environment. In Antennas and Propagation Society International Symposium, IEEE, pages 1181 – 1184 vol.2, June 2003.
[10] C.L. Holloway, D.A. Hill, R.A. Dalke, and G.A. Hufford. Radio wave propagation characteristics in lossy circular waveguides such as tunnels, mine shafts, and boreholes. Antennas and Propagation, IEEE Transactions on, 48(9):1354 –1366, Sep 2000.
[11] H. Andersson, P. Larsson, and P. Wikstrom. The use of HVAC ducts for WCDMA indoor solutions. In Vehicular Technology Conference. VTC 2004-Spring. 2004 IEEE 59th, pages 229 – 233 Vol.1, May 2004.
[12] P.V. Nikitin, D.D. Stancil, A.G. Cepni, O.K. Tonguz, A.E. Xhafa, and D. Brodtkorb. Propagation model for the HVAC duct as a communication channel. Antennas and Propagation, IEEE Transactions on, 51(5):945 – 951, May 2003.
[13] D.D. Stancil, O.K. Tonguz, A. Xhafa, A. Cepni, P. Nikitin, and D. Brodtkorb. High-speed internet access via HVAC ducts: a new approach. In Global Telecommunications Conference, 2001. GLOBECOM '01. IEEE, volume 6, pages 3604 –3607 vol.6, 2001.
[14] O.K. Tonguz, A.E. Xhafa, D.D. Stancil, A.G. Cepni, P.V. Nikitin, and D. Brodtkorb. A simple path-loss prediction model for HVAC systems. Vehicular Technology, IEEE Transactions on, 53(4):1203 – 1214, July 2004.
[15] MRF24J40MA 2.4 GHz IEEE Std. 802.15.4 RF Transceiver Module. Data sheet, Microchip Technology Inc, 2008.