Gigahertz Ground Penetrating Radar (GPR) for Sediment Exploration

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***Abstract*—In order to detect measurement objects (e.g. cables and ammunition) in the Wadden Sea, a procedure via ground penetrating radar from a drone is to be determined. For this purpose, a feasibility study with different dispersion media will be carried out in an aquarium. First, a series of measurements in water with a high degree of absorption will be implemented, followed by air as reference medium, followed by sediment with different degrees of saturation with seawater. The measured data are then evaluated in order to calculate the attenuation and the propagation velocity for each medium. The aim is to determine the attenuation in order to define the required signal power for GPR with GHz in the Wadden Sea with penetration depth up to two meters lateron.**

***Index Terms*—Ground penetrating radar, GPR, attenuation, seawater saturated sediment, GHz, ultra-wideband, UWB**

I. INTRODUCTION

Ground penetrating radars have been state of the art since the 1970s and became commercial in the 1980s [1]. Fields of application are e.g. searching for groundwater in dry areas or measure the depth of icefields [2]. The most common and originally intended application is the search for landmines or unexploded ordnances (UXO) [3]. Most of the applications have in common that irregularities in the ground close to the surface are to be detected. The depth of penetration into the ground ranges from a few centimeters to several meters. The transmission frequency is chosen in such a way that it represents a compromise between the desired penetration depth and the desired resolution.

This paper deals with the detection of irregularities in the seabed from a drone, so without direct contact to the ground. When the signal passes into the seabed, a large part of the signal is already reflected. In addition, salt water has a very high attenuation and further significantly weakens the transmitted signal when the sediment is saturated with it. Nevertheless, the signal strength must be sufficiently high to be able to get an impression of the seabed.

In detail it is to be explored whether there are big stones or a change of sediment in the first meters of the seabed. Therefore, the feasibility of the ground penetrating radar in the salt water saturated seafloor has to be verified first. In order to testify the feasibility, the attenuation of the seabed is determined. Since the salt water content has a major influence on the attenuation and the amount of salt water varies greatly in the seabed, different saturation levels are investigated.

The measurement setup is characterized by the following properties:

- We use an ultra-wideband (UWB) pulse with 3 GHz center frequency as transmitted signal. The high transmission frequency allows a compact measurement setup with a small antenna size. The focus of this setup is to reach the highest possible depth into the seabed for this small antenna size.
- The measurements are performed in an attenuating environment to avoid interfering reflections and multipath propagation.
- The target quantities are the relative attenuation of the dispersion medium as well as the propagation velocity of the radar signal in this medium.

II. RELATED WORK

A majority of the work on ground penetrating radar refers to the publication *Ground Penetrating Radar for High Resolution Mapping of Soil and Rock Stratigraphy* (Davis, J.L. and Annan, A.P., 1989)[4]. This opus provides information on physical relationships in ground penetrating radar as well as physical properties of various dispersion media. This includes values for propagation velocity and attenuation in dry sand, saturated sand, and seawater in MHz range. These values serve as comparison values and help to qualify the measurements. However, there are only literature values for dry and saturated sand.

The present work deepens the focus on the ground in the Wadden Sea. This includes sand with different grain sizes and varying saturation levels of salt water. Both the grain size and the saturation level have a major impact on the attenuation. Therefore it is important to know the salinity and the exact composition of the sediment and to measure different conditions in order to get a general overview of the attenuation behavior. The sand used in this work has a grain size of $0 - 2\ \mathrm{mm}$, the gravel has a grain size of $2 - 4\ \mathrm{mm}$ and the salt water has a conductivity of $3,44\ \mathrm{S/m}$.

The compact system design causes the antenna size to be kept small. That is why the penetration depth will decrease in comparison to lower transmission frequencies. The exact composition of the sediment as well as the small antenna size require that the material properties are determined as accurately as possible at different saturation levels.

III. APPROACH

This section explains the specifics of the setup as well as the mathematical approaches used to determine the parameters sought.

A special challenge in the measurement of radar systems are reflections. In order to eliminate them, a high computational effort is required and in order to prevent them, a very large measurement environment is needed. Therefore, the measurements explained here are not performed in air, but in an aquarium filled with salted water. The salt water causes that no signals reflected by wall or floor reach the receiver. Consequently, the radar signals reach the receiving antenna only via the line of sight (LOS) through the dispersion medium. Further details on the measurement setup are explained in the following sections.

The aim of this work is to determine material properties of different sediments. From this setup, the attenuation as well as the propagation velocity are determined. For both values the approach is followed that air is considered as reference medium and the respective sediment is relatively related to this medium. This approach has the advantage that characteristics of the measurement setup are not of any importance, since no absolute values are measured.

The attenuation α in dB is generally calculated according to the following formula:

$$\alpha = 10 * log(P_e/P_a) \tag{1}$$

In this case, the power is not measured directly, but results from the ratio of the squared received voltage and the impedance of the antenna. Since the impedance does not change due to another dispersion medium, it is considered constant and is reduced in the fraction. The voltage level of air is to be considered as input power for each medium.

The velocity of propagation is also calculated by the relative ratio of the sediment to air. The theory states that the wave propagates in air almost at the velocity of light. The higher the attenuation, the lower the propagation velocity is expected to be. Consequently, for a known distance, the velocity is determined by the time delay of the received signal compared to the velocity of light. This time delay is calculated using the correlation of the received data.

For both material properties, the calculations are described more precisely in Section V. But first, the setup and the procedure of the measurements will be described in detail.

IV. IMPLEMENTATION

In this chapter, the general conditions of the measurement are explained in more detail. This includes the physical measurement setup as well as the description of the transmitted signal.

A. Measurement Setup

As already mentioned in Section III, the measurements are performed in an aquarium filled with salted water with $\sigma = 3,44\ \mathrm{S/m}$, so there are no multipath components. This procedure has the advantage that the whole system is built up by a multiple smaller than a free field measurement. This is due to the fact that the waves propagate almost unhindered in the free field and are reflected by obstacles such as walls or the ground. These reflections are prevented by the high attenuation in the aquarium. The exact physical setup is shown in Figure 1.

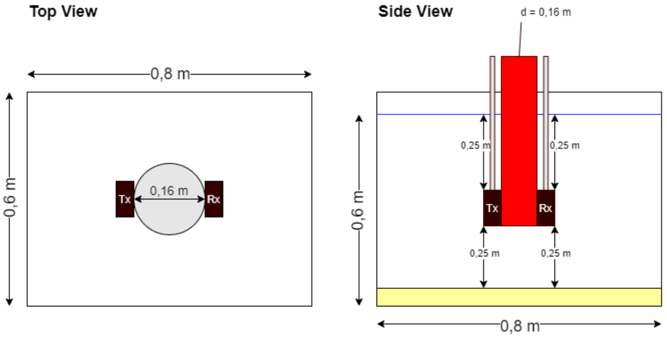

Fig. 1. Measurement setup

The figure shows that the transmission link is composed of a closed system of transmitting antenna, transmission medium and receiving antenna. This system is completely surrounded by salt water so that the signal reaches the receiving antenna only via the LOS.

The disadvantage of this design is the high sealing effort. Both the antennas and the container with the sediment are to be protected against salt water ingress. The antennas require sealing to prevent corrosion and damage to the measuring equipment, and the sediment must be sealed to control the saltwater content in the sediment. In addition, the transition of the antennas to the sediment must be as free of salt water as possible, as this would unnecessarily weaken the signal strength.

Despite all this, the advantages outweigh the disadvantages, since on the one hand there are no unwanted interfering reflections and on the other hand the system is considered in itself. This means that the approach of the calculation is robust against disturbing influences of the measurement setup, since measurements are always made in relation to a reference medium.

The signal flow through the measurement system is shown in Figure 2.

B. Description of the Components

Since the GPR operates in the GHz range, the antennas are of a small dimension. In detail it is about PCB antennas of the size $5\ \mathrm{cm} * 3\ \mathrm{cm}$. The further measurement equipment is listed in Table I.

TABLE I
MEASUREMENT EQUIPMENT

Device	Type designation
Signal generator	Tektronix AWG70002A
Oscilloscope	Tektronix DPO72304DX
Amplifier	Mini-Circuits ZVA-183-S+
Antenna	Decawave WB002 PCB Antenna

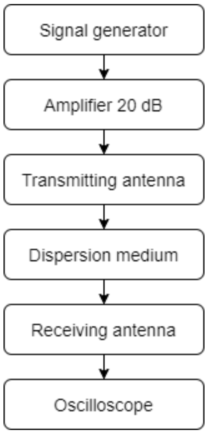

Fig. 2. Block diagram: Signal flow

C. Transmission Signal

The transmission signal is an UWB pulse with a center frequency of 3 GHz and a bandwidth of 800 MHz. The center frequency was adjusted to the antennas and enables a very compact design of the same.

The UWB is used because, in addition to signal characteristics in the time domain, special features in the frequency domain become visible. This includes, for example, spectral shifts due to grain size or salt water content.

D. Measuring Procedure

This section describes the procedure during the measurement. It is valid for all transmission media that the transmitted signal is repeated continuously and an average of 100 periods of the received signal is recorded. This is stored as a text file with the index of the measured value and its amplitude.

In the first step, the measurement was carried out for the reference medium air. That means that the pipe between transmitting and receiving antenna is filled with air. This was followed by the measurement with salt water, which represents the worst case. In the third step, the measurement was made for dry sand. This was then topped up with salt water in steps of 200 ml until complete saturation was reached at 1400 ml. The same procedure was followed for gravel. Here, complete saturation was reached at 2000 ml.

V. SIGNAL PROCESSING

This part of the work describes the exact procedure for processing the measurement data in order to obtain the desired material properties. The individual processing steps are described with the mathematical background and the advantages and disadvantages of these steps are explained.

A. Attenuation in Time Domain

The first variable to be determined is the attenuation of the transmission medium. This is at first determined on the basis of the analog voltage signal over the measurement period. In order to minimize the impact of the noise on the signal, the signal is windowed and cut to the main transmission peak. As already described in Section III, the formula of the power attenuation $\alpha = 10 * log(P_e/P_a)$ is used for this. Since the power is not measured absolutely, it is replaced in the formula of attenuation by $P = U^2/R$. For simplification, the assumption is made that the impedance remains constant regardless of the transmission medium. Thus it will be shortened in the formula of the attenuation and the following relation results:

$$\alpha[dB] = 10 * log(U_e^2/U_a^2) \qquad (2)$$

The input voltage U_e^2 is defined by the voltage accumulated over time for the transmission medium air. This voltage represents the reference value for all other media. For example, the attenuation for dry sand is expressed by $\alpha\ [\mathrm{dB}] = 10 * log(U_{air}^2/U_{drysand}^2)$.

The attenuation calculated so far applies to the distance $d = 16\ \mathrm{cm}$, i.e. the path through the transmission medium. This value is scaled up to a distance of $1\ \mathrm{m}$, resulting in the attenuation in $\mathrm{dB/m}$.

B. Signal to Noise Ratio

The determination of the attenuation is not available to any extent, instead it is limited upwards as well as downwards.

Downwards, the resolution is limited by the accuracy of the measurement setup. Since most interferences are excluded by the system, this limitation is of little importance. In addition, the difference in attenuation between air and dry sand is already so large that the lower limit of the resolution does not come into play.

The situation is different for the upper limit. Physical influences such as the low amplitude of the transmit signal of $+/-200\ \mathrm{mV}$, an additional amplifier on the transmitter side of $20\ \mathrm{dB}$ as well as the line length of the antennas ensure that the receiver signal is not evaluated with arbitrary accuracy. To be able to estimate the information content of the calculated data, the signal-to-noise ratio (SNR) is calculated. For this purpose, the noise voltage of the receiver signal is recorded before the UWB pulse arrives. This part of the signal only consists of noise at that time. The noise voltages of all media are averaged to determine a value that is as accurate as possible. For this value, the attenuation, i.e. the SNR, is calculated in the same way as the attenuations in Section V-A.

C. Attenuation in Frequency Domain

An UWB signal was selected for the transmitted signal in order to obtain additional information from the spectral view. Thus, the attenuation will be calculated not only over time but also over the complete frequency band.

The procedure is based on the calculation of the attenuation in the time domain, i.e. Equation 2 is also the basis for this. First, the voltage signal is transferred into the frequency domain via Fast Fourier Transformation (FFT). The voltage signal in the frequency domain is shown in Figure 3.

Comparable to the time domain, the voltage of each signal received by the different transmission media are then plotted over the frequency band of the UWB transmission signal. Unlike in the time domain, all frequencies are considered here,

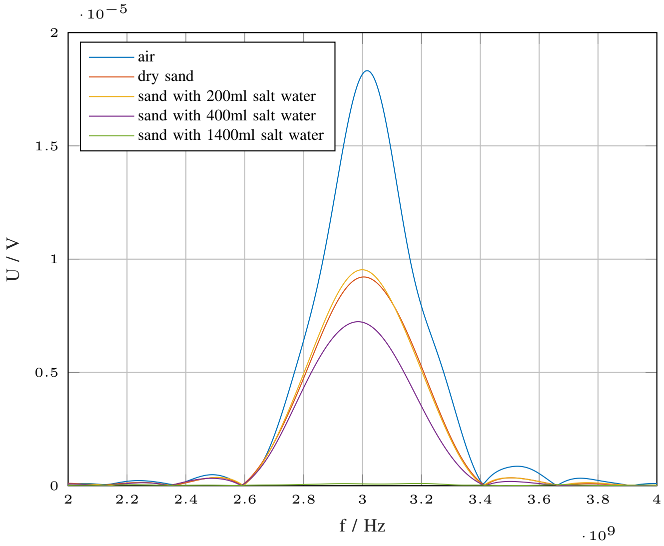

Fig. 3. Received signals in frequency domain

not only those of the main pulse. The ratio of the squared and summed voltages also results in the attenuation in the frequency domain.

D. Propagation Velocity

The second important material property is the propagation velocity. This results from the signals arriving at the receiver antenna with a delay as the salt water content increases. This time offset is calculated from the measurement data by determining the maximum of the cross- correlation of the received signal for the medium air and each dispersion medium. This leads to the temporal difference to the reference medium air, i.e. the δt.

The following values are also known:

- The propagation velocity in air c_0 with $\approx 3 * 10^8$ m/s
- The distance $d = 16$ cm between the transmitting and receiving antenna
- Resulting from the first two values the transmission time t_0 for air as propagation medium

With the use of these values, the dispersion velocity for the sediment with different degrees of saturation is determined according to the following formula:

$$v_{prop}\ [\mathrm{m/s}] = d/(t_0 + \delta t) \tag{3}$$

If the ground penetrating radar is used in unknown sediment or to find objects in the sediment, the velocity of propagation indicates the material the sediment consists of.

VI. EVALUATION

Within this chapter the results of the previous chapter are summarized. Each calculation is discussed and the results and special characteristics are explained and interpreted. According to the structure of Section V this part also starts with the attenuation in the time domain.

A. Attenuation in Time Domain

As explained in Section V-A, the attenuation in $\mathrm{dB/m}$ is calculated by considering as input power the receiver power in air and as output power the receiver power in the medium. This attenuation is calculated for the following transmission media:

- Air
- Salted Water
- Sand
- Gravel

For air, calculating the attenuation by $\alpha_{Air} = 10 * log(P_e/P_a) = 10 * log(P_{Air}/P_{Air})$ logically results in the value $0\ \mathrm{dB/m}$.

Salt water was selected as the worst case transmission medium, as this is known to have a high attenuation. Nevertheless, the attenuation as well as the other parameters are also determined for salt water to see whether the signal penetrates this medium at all. Water with a conductivity σ of $\sigma = 3.44\ \mathrm{S/m}$ was used for the measurements. According to the calculation, the attenuation of salt water is $231\ \mathrm{dB/m}$. However, the significance of this value should be viewed with caution, which will be explained in more detail in the evaluation of the SNR.

Sand and gravel were measured with different degrees of saturation of salt water. The amount of salt water has a decisive influence on the attenuation of the sediment, which is why both sediment types were measured stepwise from dry condition to complete saturation. The measured values are plotted in Figure 4. Saturation for sand occurres at a lower water volume, so the curve of gravel contains more data.

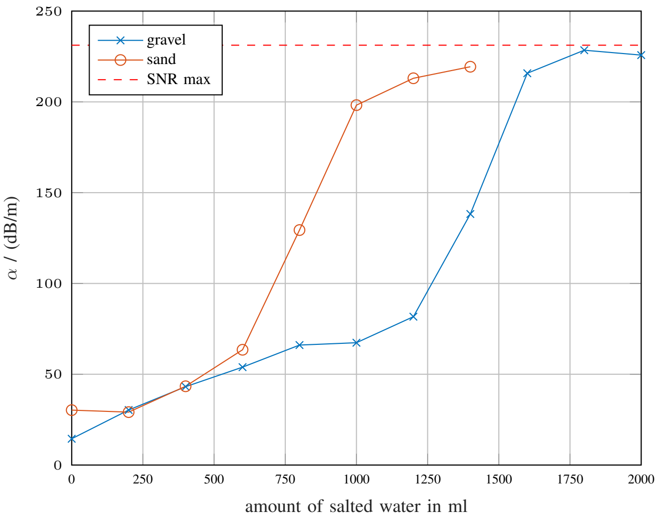

Fig. 4. Attenuation in time domain

The diagram shows similar curves for sand and gravel. Both sediments show an almost linear curve at low saturation until the attenuation increases sharply above a certain salt water content. At full saturation, the attenuation remains constant. At the upper limit, however, it should be noted that the value here almost reaches the SNR of $231\ \mathrm{dB/m}$.

B. Signal to Noise Ratio

The SNR indicates how much the effective signal differs from the noise signal. The higher the salt water content in the medium, the lower the signal strength. From a certain degree of saturation, the useful signal is hardly or not at all distinguishable from noise, i.e. the signal is no longer measurable at the receiver. The calculation of the SNR resulted in a value of $231\ \mathrm{dB/m}$. The attenuation of the sediments with complete saturation thus hardly differs from the SNR, which means that the useful signal is hardly detectable in saturated sediment. For this reason, the attenuation values for saturated sediment and salt water represent not exact values, but an indicator that the signal has been almost completely attenuated by these media.

C. Attenuation in Frequency Domain

As a pendant to the calculation in the time domain, the calculation of the attenuation of both sediments was also carried out in the frequency domain. For this purpose, the voltage was squared and summed over the complete frequency band and the attenuation was also calculated according to Equation 1: $\alpha[dB] = 10 * log(P_e/P_a)$ with respect to air. The results from Section VI-A could be confirmed, the differences of the attenuation are marginal. For the purpose of completeness, the values are listed in Table IV.

D. Propagation Velocity

As already described, the propagation velocity results from the time-delayed arrival of the signal at the receiving antenna. In general the propagation velocity decreases the more the salt water content in the medium increases. Some calculated values follow in Section VI-F.

Figure 5 shows the arrival time of the received signals for the media air and sand. By calculating the maximum of the cross- correlation of air and the current medium, the time shift δt is determined. This value is required to determine the propagation velocity.

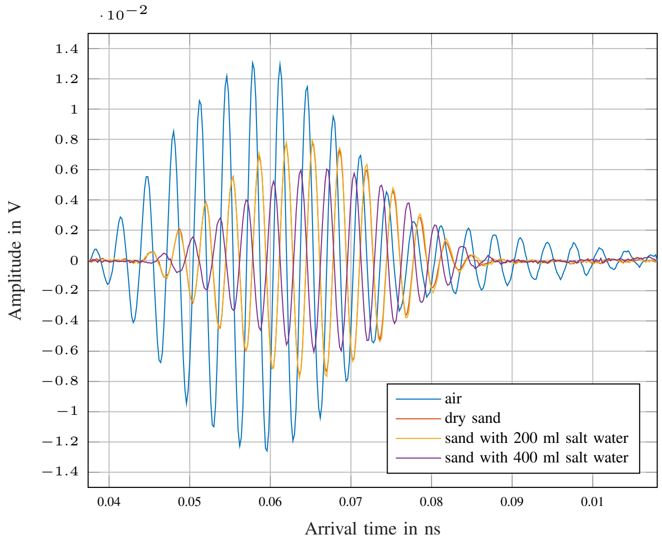

Fig. 5. Measured voltage signals of air and sand

The position of the maximum correlation, the resulting time difference δt and the finally calculated propagation velocity are listed for the medium sand in Table II.

TABLE II
PROPAGATION VELOCITY OF SAND

Medium	Max. correlation pt.	δt / ns	V_{prop} / (m/ns)
Air	0	0	0.300
Dry sand	37	0.74	0.126
Sand 200 ml	37	0.74	0.126
Sand 400 ml	46	0.92	0.110

E. Comparison to Literature

Due to the different frequencies of the GPR, a direct comparison of the results obtained in this work for the attenuation to the literature is not possible. However, in *Davis, Annan, Figure 4* [4], the relationship between the frequency and the attenuation is shown. In this diagram, the same order of magnitude of about $10^2\ \mathrm{dB/m}$ is reached in the low GHz-range.

The transmission rate, on the other hand, does not depend on the transmission frequency and is therefore comparable. The measurement results are compared with the literature values in Table III.

TABLE III
COMPARISON OF PROPAGATION VELOCITY

Medium	$V_{measured}$ / (m/ns)	$V_{literature}$ / (m/ns)
Air	0.30	0.30
Dry sand	0.126	0.15
Saturated sand	0.09	0.06

The same order of magnitude is achieved here as well. The differences are due to the fact that the terms *dry* and *saturated* are not clearly defined. The sand itself as well as the salt water content are not identical, which results in small deviations.

F. Summary of the Material Properties

TABLE IV
MATERIAL PROPERTIES

Dispersion medium	α_{TD} / (dB/m)	α_{FD} / (dB/m)	V_{prop} / (m/ns)
Air	0	0	0.30
Dry sand	30.30	30.31	0.126
Sand 200 ml	29.14	29.15	0.126
Sand 400 ml	43.38	43.39	0.110
Sand 600 ml	63.49	63.52	0.099
Saturated sand	[219.35]	[232.27]	0.090
Dry gravel	14.47	14.48	0.192
Gravel 200 ml	30.30	30.31	0.179
Gravel 400 ml	43.14	43.16	0.161
Gravel 600 ml	53.91	53.93	0.158
Saturated gravel	[231.39]	[248.73]	0.116

Finally, all calculated material properties are summarized and listed in Table IV. The attenuations for salt water as well as saturated sand and gravel are excluded, since these values are no longer clearly distinguishable from noise. For this reason, no propagation velocity is listed for salt water either, since the transmitted signal is no longer detectable in the received signal for this medium.

VII. CONCLUSION AND FUTURE WORK

First of all, the measurement setup is evaluated on the basis of the results. For each material property, plausible values were calculated which have the same order of magnitude as the literature values related to the same transmission frequency. The resolution is sufficient to draw a qualitative conclusion about the properties. The signal characteristics do not show any irregularities or disturbances.

Therefore, it is concluded that the measurement setup in the aquarium fulfils the expectations and that no reflections arrive at the receiver despite the small dimensions.

Going back to the original problem, all constellations of sand and gravel require a very high signal power already in dry condition to be reflected at a penetration depth of $1\ \mathrm{m}$. For sediment of any type with higher saltwater content, GPR in the GHz range is not feasible for these depths from a drone.

An extension of this project with a graduating transmission frequency is conceivable to increase the depth of penetration. According to the equation $\lambda = c/f$, the propagation velocity $c_0 = 3 * 10^8\ \mathrm{m/s}$ and the center frequency of the UWB pulse $f = 3\ \mathrm{GHz}$ result in a wavelength λ of $\lambda = 0{,}1\ \mathrm{m}$. If the path through the dispersion medium is set as the maximum wavelength λ_{max}, this corresponds to a minimum transmission frequency f_{min} of $f_{min} = 1.875$ GHz.

The constraint remains that the antennas remain small and lightweight enough to be attached to a drone.

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