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Underwater Electromagnetic Test Range Calibration

Abstract

Methods of communicating with electromagnetic systems have been of interest since electromagnetic technologies. Since then many systems have been researched, however only ELF electromagnetic systems have been successful. However there is a developing niche for very short, range very large bandwidth underwater electromagnetic communications. Underwater antennas need to be developed for these systems to be successful but, for this to occur, a means of finding the characteristics and effectiveness of these antennas must first be devised. The focus of this project is the characterisation of an underwater test range. It is intended that this test range will be used to develop antennas for an underwater electromagnetic system for the School of Engineering and Information Technology.

0.1 Introduction

Underwater communications is the transmission and reception of data in a underwater environment. While underwater communications can be achieved in both fresh and sea water, the scope of this thesis focuses only the sea water environment, which is an electrically conducting medium. Many applications require transmission of data to and from object or platform that is submerged in the ocean, such as communication with unmanned underwater vehicles or submarines. At the present time transfer or data is frequently carried out with acoustic systems, cables or by moving the platform to the surface to enable data transfer.

The aim of this project is to conduct investigation into the development of electromagnetic antennas that are intended for use in an underwater environment. No preceding work on underwater electromagnetic wave antennas has been conducted by a student of the School Of Engineering and Information Technology at the University of New South Wales at the Australian Defence Force Academy. This area was chosen because the Underwater communications research group is interested in developing a short-range underwater communications network for a swarm of sensors to be placed on the sea bed. However, the university had no specific facilities where it could conduct experiments when developing these antennas. As such, the calibration of an underwater test range was the focus of this project.

This report will begin with an outline of past developments in the field of underwater electromagnetic communications and the major theories used. It will then outline experimentation with antennas in air and the reasons for such experiments, as well as outlining the underwater test range and the investigations performed. Finally the report will list conclusions drawn from the project and provide recommendations for future work in this area.

Underwater electromagnetic communications have been investigated since the advent of electromagnetic technology in the 19th century[1]. There was a large scale development during WWII by the Kriegsmarine, Nazi Germany’s Navy, long range communications with submarines. This system was called Goliath. Installed in the River Elbe, it was a VLF system capable of a maximum output around 2 MW, which was able to signal submarines in the Indian Ocean[2]. There was a resurgence in development of underwater electromagnetic communication systems in the late 1960s and 1970s[3]. ELF communication systems were developed by both the Russian and the United States governments for communication with submerged submarines. The US system
operated at 76 Hz while the Russian system operated at 82 Hz[1]. The systems had data rates of a few bits a minute, much less than the rate required for real-time voice communications. Instead the systems were used to send a signal to the submarine to let the crew know they should surface. Further communication was then conducted using traditional electromagnetic systems. To date these are the only successful underwater electromagnetic communications systems developed[4][5][6].

Acoustic systems are favoured over electromagnetic systems for underwater communication because of the huge attenuation of an electromagnetic signal as it propagates through a lossy medium. However, acoustic systems suffer from noise much more than electromagnetic waves, especially in shallow waters. Acoustic noise has a large number of sources, such as ships, underwater drilling, waves and sea life. Acoustics also suffers from multipath effects, signal bending and movement due to currents. It is in areas of high acoustic noise and distortion where electromagnetic technologies would be useful. Electromagnetic systems are also useful when a high data rate is needed, as it can support a greater bandwidth than acoustics. This greater bandwidth come from the ability to design and build ultra-wideband electromagnetic systems, whereas most acoustic systems are narrowband[7], although this advantage is only present at very short ranges.

There are many possible applications for short range, high bandwidth electromagnetic antennas in the underwater environment. There are a wide range of applications where electromagnetic antennas could be very useful. The main organisations that are interested in developing these technologies are the defence industry, medical industry and the oil industry. When only used for short range applications electromagnetic antennas have many advantages over acoustics systems. One possible application that electromagnetic would be far superior to an acoustic system is underwater data collection by a UUV. If sensors are placed on the sea bed to collect oceanographic data, the data could be collected by a UUV, stored and brought back to a home station to be analysed. The UUV data collection could utilise electromagnetic antennas to quickly transfer collected data from the sensor to the UUV without the need for the UUV to dock with the underwater sensor. This same transfer method could be used to transfer to the home station without removing the UUV from the water.

Another possible application could be data transfer from a submerged UUV to a fibre optic cable lowered to the sea floor in an acoustically noisy environment. A large cable with a fibre optic transmission line could be dropped to a work area with a weight and UUV attached. When the cable reached the work area the UUV could be released from the cable and could conduct its mission without the hindrance of the cable, reducing the power requirements of the UUV. The UUV could then collect data, such as video and send it to the cable using electromagnetic antennas. This would be especially useful if the water environment was one of high acoustic noise, such as during drilling operations.

A third possible application for this technology is in the field of medicine. The body is mainly composed of lossy liquids and antennas that are developed for another lossy medium could easily be modified for use in the body. The antennas could be used to send information from inside the body, lessening the need for procedures such as exploratory surgery. An interesting application of electromagnetic antennas in the human body is the destruction of tumours without the need for chemotherapy or major surgery. If an RF field is released inside the body adjacent to a tumour, it will heat up malignant cells, causing thermal cytotoxicity[8].

0.2 Technical Background

0.2.1 Loop Antenna Theory

Loop antennas are generally classified into two categories: electrically small and electrically large. Electrically small loop antennas are defined as having a circumference, C, of less that one-tenth of the wavelength, \( C = \frac{\lambda}{10} \), and electrically large are defined as having a circumference of approximately one wavelength, \( C \approx \lambda [9] \).

Equations for a Loop Antenna

The equations for a loop antenna were found in Ulaby [11]. The easiest way to geometrically arrange a loop antenna is to place it at the origin of the \( xy \) plane. It is assumed that the wire used in the antenna has a very...
small cross section and the current is uniform over the entire loop. The current distribution is:

\[ I_{\phi} = I_0 \]  

where \( I_0 \) is a constant. This uniform current distribution is true only for small loop antennas; for a non-uniform current distribution the equations are much more complex. The electromagnetic fields radiated from the loop are found using[11]:

\[ H_A = \frac{1}{\mu} \nabla \times A \]  
\[ E_A = -\nabla \phi_e - j\omega A \]

These equations state that the magnetic field, \( H \), is proportional to the curl of the magnetic vector potential multiplied by the inverse of the permeability of the medium. The vector potential function, \( A \), is used as an interim step to make the equations less complex. For electric fields there is a scalar vector potential, \( V \) which is related to the electric field, \( E \), such that[10]:

\[ E = -\nabla V \]

A comparable term for the magnetic field is the magnetic vector potential. From Gauss’s Law[10] for magnetic fields it is known that the divergence of any magnetic field is equal to zero:

\[ \nabla \cdot B = 0 \]

From vector identities it is known that the divergence of the curl of any vector must be zero[10]:

\[ \nabla (\nabla \times A) = 0 \]

Therefore, the \( B \) in terms of \( A \) can be defined as:

\[ B = \nabla \times A \]

The equation for the potential function \( A \)[11], is:

\[ A(x', y', z') = \frac{\mu}{4\pi} \int I_e(x', y', z') \frac{e^{-jkr}}{R} dl' \]

where \((x', y', z')\) are the coordinates of the loop and \((x, y, z)\) are the coordinates of the observation point, \( P \). \( R \) is the distance from the loop to the observation point. The current in the loop can be expressed as:

\[ I_e(x', y', z') = a_x I_x(x', y', z') + a_y I_y(x', y', z') + a_z I_z(x', y', z') \]

These equations are in rectangular coordinates. However, because the current travels around a loop is is more convenient to express these equations in cylindrical coordinates. This gives [11]:

\[
\begin{bmatrix}
I_x \\
I_y \\
I_z
\end{bmatrix} =
\begin{bmatrix}
cos \phi' & -sin \phi' & 0 \\
sin \phi' & cos \phi' & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
I_\rho \\
I_\phi \\
I_z
\end{bmatrix}
\]

When this is expanded this gives:

\[ I_x = I_\rho \cos \phi' - I_\phi \sin \phi' \]  
\[ I_y = I_\rho \sin \phi' + I_\phi \cos \phi' \]  
\[ I_z = I_z \]

Radiated fields are usually determined using spherical coordinates. Converting the equation for \( a_x, a_y \) and \( a_z \) into spherical coordinates gives:

\[ a_x = \hat{a}_e \sin(\theta) \cos(\phi) + \hat{a}_\phi \cos(\theta) \cos(\phi) - \hat{a}_\theta \sin(\phi) \]  
\[ a_y = \hat{a}_e \sin(\theta) \sin(\phi) + \hat{a}_\phi \cos(\theta) \sin(\phi) + \hat{a}_\theta \cos(\phi) \]  
\[ a_y = \hat{a}_e \cos(\theta) - \hat{a}_\theta \sin(\theta) \]
When these values are substituted into the equation for $I_e$, it simplifies to:

$$I_e = \hat{a}_r \sin(\theta) \sin(\phi - \phi') + \hat{a}_\theta I_\phi \cos(\theta) \sin(\phi - \phi') + \hat{a}_\phi I_\phi \cos(\phi - \phi')$$  \hspace{1cm} (17)

These equations are then used to find the equations of each field component. The equation for $A$, having had $I_e$ substituted into it, is substituted into (2) and (3), which gives:

$$H_r = \frac{I_e dA}{2 \pi r^3} [1 + \gamma r] e^{-\gamma r \cos \theta}$$  \hspace{1cm} (18)

$$H_\theta = \frac{I_e dA}{4 \pi r^3} [1 + \gamma r + \gamma^2 r^2] e^{-\gamma r \sin \theta}$$  \hspace{1cm} (19)

$$E_\phi = -i \mu \omega I_e dA \frac{1}{4 \pi r^2} [1 + \gamma r] e^{-\gamma r \sin \theta}$$  \hspace{1cm} (20)

where $I_e$ is the current in the loop, $dA$ is the area of the loop, $r$ is the distance from the loop to the observation point $(x, y, z)$ and $\gamma$ is the propagation coefficient of the medium (explained in the next section). $\theta$ is the angle from the normal of the loop and $\phi$ is the angle around the $xy$ plane.

Figure 1: Polar Radiation of a loop antenna orientated in the $z$ axis to a point $P$

### 0.2.2 Biot-Savat Law

The equations for the Biot-Savat Law were taken from Ulaby [11]. The Biot-savat Law states that a differential magnetic field $dH$ produced by a steady current, $I$, flowing through a differential length $dl$ is given by the formula:

$$dH = \frac{1}{4\pi} \frac{dl \times \hat{R}}{R^2}$$  \hspace{1cm} (21)

where the distance vector between $dl$ and the observation point is $R = \hat{R}R$. The differential magnetic field is orthogonal to the distance vector. To determine the total magnetic field, $H$, produced by a length of wire, made up of many $dl$’s, the effect of every $dl$ needs to be added together. Therefore the Biot-Savat Law becomes:

$$H = \frac{I}{4\pi} \int \frac{dl \times \hat{R}}{R^2}$$  \hspace{1cm} (22)
0.2.3 Properties of Electromagnetic Wave in a Medium

The propagation coefficient, $\gamma$, of an EM wave is

$$\gamma = \alpha + j\beta \quad (23)$$

$$\gamma = j\omega \sqrt{\mu \varepsilon} \sqrt{1 - j \frac{\sigma}{\omega \varepsilon}} \quad (24)$$

$$\gamma = j\omega \sqrt{\mu_0 \mu_r \varepsilon_0 \varepsilon_r} \sqrt{1 - j \frac{\sigma}{\omega \varepsilon_0 \varepsilon_r}} \quad (25)$$

where $\omega$ is the frequency in radians per second, $\mu_0$ is the permeability of free space, $\mu_r$ is the relative permeability of the medium, $\varepsilon_0$ is the permittivity of free space, $\varepsilon_r$ is the relative permittivity of the medium and $\sigma$ is the conductivity of the medium. $\alpha$ is the attenuation of the EM wave per unit distance from the source, known as the Attenuation Constant and $\beta$ is the amount of phase change of the wave per meter of propagation, known as the Phase Constant.

Using $\alpha$ and $\beta$, other propagation parameters can be found. The wavelength, $\lambda$, of the wave in the medium is found using:

$$\lambda = \frac{2\pi}{\beta} \quad (26)$$

The skin depth is found using:

$$\delta = \frac{1}{\alpha} \quad (27)$$

The velocity of the wave in the medium is:

$$\nu = \omega \lambda \quad (28)$$

The intrinsic impedance, $\eta$, of the medium is found using:

$$\eta = \sqrt{\frac{j\omega \mu}{\sigma + j\omega \varepsilon}} \quad (29)$$

0.2.4 Antennas In Matter

The book Antennas in Matter by King and Smith [11] provides theoretical expressions for an insulated wire placed in a conducting medium. King represents the wire as a piece of transmission line.

The Transmission Line

The transmission line of length $l$ is represented by King as having an inner conductor (region 1) of radius $a$, a dielectric coating (region 2) of radius around the inner conductor, inside a thin glass tube (region 3) of radius $c$, which is then surrounded by an outer conductor (region 4) of radius $d$. When there is no glass tubing region 3 is neglected. However the outer conductor still remains region 4. At one end of the inner conductor there is a signal generator, while the other may have an open circuit, a short circuit or a load. Figure 2 below shows a graphical representation, marking out the 4 regions and showing the three load types.

The emf source, $V_0^e$, is placed a $z = -l$ and the load, $Z_S$ is placed at $z = 0$. When the load is an open circuit $Z_S = \infty$, the inner and outer conductor are not connected. When the load is a short circuit $Z_S = 0$ and the inner conductor and outer conductor are connected directly. The wave numbers for the four regions are represented with the time dependence $e^{jut}$. For region 1, which is a good conductor and region 2, which is a $k_1$ is:

$$k_1 = \alpha_1 + j\beta_1 = \sqrt{j\omega \mu \sigma_1} = (1 + j) \sqrt{\frac{\omega \mu \sigma_1}{2}} \quad (30)$$

$$k_2 = \alpha_2 + j\beta_2 = \omega \sqrt{\mu_0 \mu_r \varepsilon_0 \varepsilon_r} \sqrt{1 + j \sigma / \omega \varepsilon_0 \varepsilon_r} \quad (31)$$
$k_3$ and $k_4$ can be found using the same equations but by substituting in the values for $\sigma$ and $\epsilon$. $k$ is related to $\gamma$, as $k = j\gamma$. For modelling an insulated line in a salt water tank, region 3 can be ignored as there is not glass tubing. Also the insulation are kept small such that:

$$|k_2| < 1$$

however no such restriction is placed on region 4. The current in the line can be expressed by the differential equation:

$$(\frac{d^2}{dz^2} + k_L^2)I(z) = 0$$

where $k_L$ is the complex wave number defined as $k_L = j\gamma = \sqrt{(-z_Ly_L)}$, where $y_L$ is the shunt admittance per unit length and $z_L$ is the series impedance per unit length. $z_L$ has 3 parts, the internal impedance per unit length of the inner and outer conductors and the external impedance $z^e$. Inner refers to the impedance associated the magnetic field inside the conductors and the external refers to the impedance associated with the magnetic field produced inside the insulator. The equation for $z_L$ is:

$$z_L = z_1^i + z_4^i + z^e$$

Where $z_1^i$ is the internal impedance of the wire and $z_4^i$ is the internal impedance of the outer conductor. The equation for the internal impedance of a metal conductor and the outer conductor are given by:

$$z_1^i = \frac{1}{\pi a^2 \sigma e_\epsilon} k_1 a J_0(k_1 a)\frac{1}{2} J_1(k_1 a)$$

$$z_4^i = \frac{1}{\pi c^2 \sigma e_\epsilon} k_4 c J_0(k_4 c)H_1^{(1)}(k_4 d) - H_0^{(1)}(k_4 c) J_1(k_4 d)\frac{1}{2} J_1(k_4 d)H_1^{(1)}(k_4 c) - H_1^{(1)}(k_4 d) J_1(k_4 c)$$

The solutions for (2.33) can be found for an open circuit, short circuit and terminated load. The equation for an open circuit load is shown in (37), short circuit in (38) and terminated load (39).

$$I(Z) = -\frac{iV_0^e}{2Z_c} \frac{\sin k_L(h - |z|)}{\cos k_L h}$$

$$I(Z) = \frac{iV_0^e}{2Z_c} \frac{\cos k_L(h - |z|)}{\sin k_L h}$$

$$I(Z) = -\frac{iV_0^e}{2Z_c} \frac{\sin[k_L(h - |z|) + i\theta_s]}{\cos(k_L h + i\theta_s)}$$
where $\theta_s$ is the angle characterized by the normalised terminal impedance\[13\]: $\theta_s = \coth^{-1}\left(\frac{Z_s}{Z_c}\right)$. The characteristic impedance of the line can be defined as\[13\]:

$$Z_c = \sqrt{\frac{\omega \mu k_L}{y_L}} = \frac{\omega \mu k_L}{2\pi k_2} \ln\left(\frac{b}{a}\right) + n_2^2 \ln\left(\frac{c}{b}\right)$$ (40)

Which can be reduced, if there is no region 3, to\[13\]:

$$Z_c = \left(\frac{\omega \mu k_L}{2\pi k_2}\right) \ln\left(\frac{b}{a}\right)$$ (41)

### Validity of the Transmission Line Model

While the transmission line model outlined in King and Smith\[13\] was developed using both theoretical expressions and measured data, the range over which this theory is valid was not established. This work was undertaken in 2000 Hertel and Smith\[18\] (the same Smith who wrote King and Smith). This work used a finite-difference time-domain method was used to analyse the insulated linear antennas. The validity of the FDTD method was established by comparing the FDTD method results with the measured data. The use of a network analyser, provided a much greater accuracy for Hertel than King was able to produce. The variables that were examined were the geometry and the electrical properties of the antenna.

The FDTD method results were compared with results for the transmission line theory described in King. Hertel’s results show that for an insulated linear antenna placed in air the error in the resistance at resonance was higher than 5%. However when the antenna was placed inside a lossy medium the accuracy was much higher, with errors for the resistance at resonance is less than 5%.

### 0.2.5 TEM Cells

Transverse ElectroMagnetic cells (TEM cells) were introduced in the 1970s. TEM cells “are devices used to establish standard electromagnetic (EM) fields in a shielded environment”\[22\]. The TEM cell used in this experiment was a wave guide, with closed ends. Both ends taper to a point were devices can be connected. For the purpose of this project a signal generator attached at one end and a power meter was attached at the other. The TEM cell used also had a wave guide at the side. This allowed objects to be placed inside the TEM cell, but prevented the fields produced inside the TEM cell from not propagated into the environment. This is an important safety measure to ensure te user is not radiated. At the signal generator end a wave is created which propagates along the TEM cell and is received at the other end. Due to the construction of the TEM cell, there is no reflection of the wave. This means that the fields produced are constant. The power received the field strength in the TEM cell can be calculated from the power received. In this configuration, the TEM cell can be used to calibrate.
0.3 Air Experiments

0.3.1 Aim

The aim of conducting experiments in air with a pair of loop antennas was to develop an experimental procedure that can be transferred into the water environment at a later stage. During the conduct of these experiments, solutions were developed for common problems, and the experimental process was refined. This ensured that the underwater experiments could be conducted with maximum efficiency.
0.3.2 Functional Block Diagram

![Functional Block Diagram](image)

The Agilent 33220A Function Generator was used to supply signals to the transmit (Tx) antenna. The signal supplied to the Tx antenna allowed the creation of the field that was received by the receive (Rx) antenna. Both the transmit and receive antenna were potted loop antennas, made from copper wire wound around a small section of PVC pipe. Both antennas had 200 turns and an internal diameter of 12 cm. The ends of the copper wire were soldered to a piece of coaxial line. The coaxial line had a 3 pin connection which had to be wired to a BNC connector to allow the antennas to be connected to the signal generator and pre-amplifier. The pre-amplifier had been built by the Electronics Workshop at SEIT at ADFA (then ITEE at ADFA). It was powered by two 9 V batteries and was set to +50 dB during the experiment. The pre-amp was connected to a Rhode and Schwartz FSV-B9 Signal Analyser, which was used to measure the amplitude of the received signal. This set-up is illustrated in the Figure above.

0.3.3 Practical Method

The experiment was conducted in the Microwave laboratory located in Building 16 in at ADFA. A rig was set up to allow the antennas to be raised above the floor. The suspension of the antennas was necessary to reduce the effect of signal scattering created by the re-enforcing in the floor. It was important that the rig use non-metallic objects in order to reduce the scattering. The rig used was a 2.4 m plank of wood placed on a box and a chair, see Figure 3.1. The Transmit antenna was connected to the Function Generator. The output voltage was set to maximum (13.33 V\text{pk−pk}) and the frequency set to 20 kHz. This antenna was placed at the far edge of the box. The receive antenna was connected to the amplifier, which was then connected to the Rhode and Schwartz FSV-B9 Network Analyser. The gain of the amplifier was set to 50 dB and amplifier is shown in the Figure below. This antenna was placed on the plank of wood. Care was taken throughout the experiment to ensure the antennas were in the same horizontal plane. Starting with the centre of the antennas 20 cm apart the received signal was recorded. The distance between the antennas was increased by 10 cm and the received signal again recorded. This process was repeated until the antennas were 2.7 m apart (the maximum distance achievable with the rig). The full experimental procedure was repeated for 30 kHz and 40 kHz. The obtained results were then compared to theoretical results.

0.3.4 Development of theoretical curves

Theory curves were developed using equation (18). Two curves were developed. The first curve is the field expected at each measured distance from the transmit antenna minus the radius of the receive antenna. The second curve is field expected at each measured distance from the transmit antenna plus the radius of the receive antenna. This was done to account for the variation of the field across the antenna, as the size of the antenna was significant compared to the distances that the measurements were taken over.
When the theory curves were developed effect of a number of inputs on the received signal were unknown. To compensate for this, the theory curves were scaled until they lined up with the measured data. The scaling of the curves means that the comparison of the magnitudes is not possible, however the attenuation with respect to range can be compared.

![Experimental set up with antennas and the amplifier used in experiment](image)

**Figure 5:** Experimental set up with antennas and the amplifier used in experiment

### 0.3.5 Results

The results for the three test frequencies used are shown in the three Figures below. Each graph shows the measured data (in green), and the two theoretically calculated curves, the curve for the closest side of the receiving antenna is represented by a blue curve, while the curve for the further side of the antenna is represented by a cyan curve.
Figure 6: Received fields vs theory for 20 kHz

Figure 7: Received fields vs theory for 30 kHz
Figure 8: Received fields vs theory for 40 kHz

**0.3.6 Discussion**

When the results obtained were compared with the theoretically obtained curves it can be seen that the measured value has a similar shape to that of the two theory curves. However the experimentally received signal does attenuate slightly faster than the two theory curves. This could be due to the scattering of the transmitted signal by the environment surrounding the test rig. Care was taken to try to reduce the amount environmental scattering of the signal. While there were many objects that could absorb or reflect the transmitted signal in the laboratory, including the roof, floor and the rig used to suspend the antennas. The floor of the lab was re-enforced concrete - the metal re-enforcing would have scattered the signal. The effect of absorption is more clearly seen the as the range is increased - the greater the distance the further the signal has to travel, the greater the number of objects that the signal has to pass through.

Another explanation for the attenuation is close to the antenna there could be near field affects that are not accounted for in the by the theoretical curves. The theory produces the value for a field at a point, whereas the antennas are measuring the field over an area. Close to the transmit antenna the variation of the field across the receive antenna, both axially and horizontally is much greater than at a range of 2 m. As the theoretical curves and measured curves have a closer correlation the further apart the two antennas were, this is the more likely explanation.

The two theory curves that were produced start over 10 dB apart but converge as the distance increases until they are less than 1 dB apart. This highlights the need for the two theory curves, as close to the transmitting antenna there is a large variation in the field across the receiving antenna. To reduce this problem a smaller receiving antenna should be used, especially in an underwater environment as the attenuation over such distances will be much greater. Ideally the antenna should be much much smaller than the ranges the measurements are being taken over. However this could be impractical if measurements must be taken very close to the transmitter.
0.4 Underwater Test Range

0.4.1 Introduction

The experiments carried out on the test tank were performed to determine the operation of the tank, so it could be used as an underwater test range. By knowing how the tank operates, fields can be set up inside the tank and the field strength can be known at every point in the tank. This would allow the tank to be used in a similar fashion to a TEM cell, to characterise an antennas operation in the underwater environment. The tank attempts to simulate the ocean environment; however it is much much smaller than the ocean. To compensate for this experiments can be frequency scaled, where the antenna is operated at a higher frequency than would be used for ocean experiments. This larger frequency results in a smaller skin depth, making the tank look electrically larger. Therefore, a physically smaller tank could be use to represent a significantly larger tank if made to look the same size electrically.

The investigations performed using the underwater test range were intended to find the current in the line, the attenuation with respect to distance from the wire with the antenna orientated perpendicular to the signal, the attenuation with respect to distance from the wire with the antenna orientated parallel to the signal and the surface wave, which travels along the air/water boundary.

0.4.2 Underwater Test Range Tank

The test tank was constructed to be used as an experimental tank for the Underwater Communications subject taught at UNSW@ADFA. It is constructed from 15 mm plywood and is 2.4 m long, 60 cm wide and 30 cm high. There is an insulated wire running down the middle of the tank along the z axis, see the 3D rendered image and pictures below. At each end it has an aluminium plate on the inside, which forms a connection with the water. The insulated line passes through the metal plate at each end of the tank and is connected to a BNC connector attached to a die-cast box. The die-cast box is screwed into the tank and the metal plate forming an electrical connection with the metal plate. The tank was filled with approximately 360 L of water and 9 kg of salt. The conductivity was found to be around 5.5 Sm$^{-1}$.

The test tank has a load end and a signal generator end. The load end of the tank, where the wire passes through the aluminium plate is considered the origin. The wire runs down the z axis in the negative z direction, such that the point where the wire passes through the aluminium plate at the signal generator end of the tank is considered $z = -235$ cm. The z axis will be referred to as the axial direction in the tank. The x-axis is horizontally across the tank, with the positive direction being towards the working side of the tank (the other side was against the wall). The x axis will be referred to as the horizontal direction. The y axis is the vertical axis, the positive direction being upwards towards the surface of the wire.

0.4.3 Antennas

The antennas used to collect the data in this experimental investigation were small loop antennas created specifically for this purpose. They consisted of a piece of semi-rigid cable, with an SMA connector on one end and a circular piece of conductor soldered on the other end. The piece of conductor (which would act as the antenna) had one end soldered to the centre conductor of the semi-rigid cable and the other end soldered to the cables shield.

The properties of the antenna, such as radiation resistance, were unknown. However, all that was required was for the antennas to measure the field strength in the tank. To find out what power would be received by the spectrum analyser due to a certain field a TEM cell was used. The antennas were being used as RF probes. Fields of varying strength were set up in the TEM cell for three different frequencies and the power received by the spectrum analyser for each field strength and frequency was recorded. Using the ratio of the fields in the TEM cell to the power received the scaling factor was calculated. This scaling factor was then used to convert the data recorded from the tank into field strength in $Am^{-1}$.
Waterproofing

It was decided that the prototype antennas should be waterproofed after considering the evidence presented in Wait[14] and Hertel[18]. They state that, if the antenna is not insulated from the conducting medium, currents present will be conducted into the antenna and contribute to the power received. While this investigation was only concerned with the fields in the medium, it can be assumed that the reverse is true. Therefore any transmitting antenna that is not insulated from the medium will leak current into the surrounding medium rather than converting the current into electromagnetic fields.

Many options considered for the waterproofing process and some tested. A requirement for the waterproofing was that it could be removed if necessary, in case repairs or other work needed to be performed on the antenna. Initially, a small plastic bag was placed over the end of the antenna and held to the antenna with heat shrink. This was difficult to do, as the heat shrink was often too small to fit over the loop but too big to provide waterproofing. The idea was then modified, replacing the small bag with a condom, and using a much smaller piece of heat shrink. However the condoms were prone to melting when the heat shrink was being applied and it was also found that latex will lose its ability to remain waterproof if immersed for long periods of time. Another problem with this method is that it created a small pocket of air around the antenna, similar to a ray dome, which adds another layer of complexity to the antenna and any theoretical calculations required.

To overcome this the antennas were painted in a coating that would be waterproof and could be removed. The substance chosen was shellac, as it had been used in electronic applications before and it could be removed by immersion in methylated spirits. Once an adequate amount of shellac was applied the antennas were waterproof. However, during the conduct of the investigation there was never the need for the antennas to be worked on, so a commercial sealant would have been adequate and would have saved time.

0.4.4 Investigations

Outline below are the methods used to obtain the data in the four investigations performed. During these experiments the antenna was held between two pieces of wood which were clamped together. This was then
clamped to a plank of wood which spanned the width of the tank. The plank could be moved along z axis of the tank, the antenna moved along the plank of wood, the tanks x axis, and the antenna could be moved up and down between the pieces of wood, the tanks y axis. This gave the ability to place the antenna anywhere within the tank.

**Axial Sweep**

The aim of this investigation was to find the current in the line. It was assumed that the current in the line was directly proportional to the fields produced directly outside the line. This means the change of the field is directly proportional to the change in current as the current moves down the line.

The antenna was placed in the tank beside the wire, perpendicular to the fields produced with the centre of the antenna 5 mm from the wire at the signal generator end of the tank (z = -235 cm). The antenna was moved in increments of 2.5 cm and a reading was taken for each position. The sweep was then repeated with the antenna 15 mm and 35 mm from the wire. All three sweeps were conducted at 40 MHz, 70 MHz and 300 MHz.

This experiment is similar to one performed by Dunbar in 1986. However this was performed with a small inductor and capacitor acting as the antenna, which were attached to the end of a piece of coax line. The capacitor was used as a tuning capacitor, to that the antenna was resonate at 40 MHz. Dunbar’s investigation was also conducted only at 40 MHz. In order to prove the validity of my method, Dunbar’s experiment was repeated in the test tank with a very similar antenna. This antenna was not waterproofed in the same way as
the other antennas. This antenna was placed in a perspex tube with a silicon plug in one end.

Figure 11: 40 MHz z sweep at y = 0

Figure 12: 70 MHz z sweep at y = 0
The data recorded for both 40 MHz and 70 MHz displays characteristics of a signal propagating down a transmission line, which is what is expected. There is a reflection of the signal at the load end and the transmitted and reflected waves form a standing wave pattern. The standing wave has more peaks and troughs for the 70 MHz signal than for the 40 MHz signal, which is expected. The propagation coefficient can be found from the standing wave pattern. As the antenna was moved away from the wire the signal strength dropped but the pattern remained the same. The wavelength in the wire for 40 MHz was found to be 1.75 m, which gives $\beta = 3.5904$. The wavelength for 70 MHz was found to be 1.1 m, which gives $\beta = 5.7120$.

While the 300 MHz signal does not show the same standing wave pattern as the 40 MHz and 70 MHz signals, this does not mean it is not acting like a transmission line. It means the attenuation in the line is much greater at 300 MHz when compared to 40 and 70 MHz. The interference pattern cannot be seen until after $z = -140$.
cm for the $x = 5\, \text{mm}$ sweep. However for the other sweeps it is present much earlier than $z = -175$. Also, the three sweeps seem to converge after $z = -30\, \text{cm}$. This is indicating that there is another source of signal other than the line in the tank and that the field produced is only proportional to the current in the line when the antenna is close to the line. The reason the effect is not seen for the 40 and 70 MHz could be because the antenna has not been moved as many skin depths away from the wire. The skin depth at 300 MHz is much smaller than at 40 or 70 MHz, so the distances are much bigger electrically for 300 MHz. The wavelength in the wire for 300 MHz was found to be approximately 47.5 cm, which gives $\beta = 13.2278$.

When the 40 MHz received signal for the alternate antenna was compared with the results in Dunbar it was found that there was a close correlation between the two. There was also a correlation between the small single loop antenna and the inductor antenna. The standing wave pattern is very similar however the spacing between the three sweeps is not the same. This difference can be accounted for by the size of the antennas. The inductor antenna used in the investigation has a very small effective area but many more turns. However when the single loop antenna is placed with the centre 5 mm away from the wire the edge of the antenna is touching the wire, whereas when the inductor antenna is 5 mm away from the line the edge of the antenna is still 2 mm away from the line. Due to the high rate of falloff of the signal in the first few millimetres immediately adjacent to the wire the amount of signal the single loop antenna can receive is much greater. However as the antenna is moved away the change in field across the single antenna is much less. The small inductor antenna cannot receive the much larger signal close to the wire, which is why there is a smaller gap between the 5 mm sweep and the 15 mm sweep for the inductor antenna.

The above results for 40 MHz can be compared to the results shown in Dunbar[16]. The results are shown below. These results have a close correlation to Dunbar’s results, with a similar standing wave pattern, the same number of peaks and troughs at the same locations in the wire.

![Figure 15: 40 MHz z sweep by Dunbar[16]](image)
Differing Loads

The aim of this experiment was to investigate the effect of changing the load on the tank. To vary the load the die-cast box was opened and the BNC connectors removed from the end of the line. To achieve a short circuit load a solder tag was screwed into the die-cast box, which formed an electrical connection with the die-cast box. There was already an electrical connection between the die-cast box and the water, as the die-cast box is screwed into the aluminium plate. The line was then soldered straight to the solder tag. To achieve an open circuit load the wire was left disconnected, with the line pulled tight, along the z axis. To achieve a variable load a potentiometer was wired between the end of the line and the solder tag. A capacitor was also wired in series in an attempt to cancel out the reactive component of the impedance of the line.

In order to achieve a matched line the load impedance needs to be exactly the same as the impedance of the line. If there is any difference between the load and line impedance there will be reflection of part of the signal. This will result in the standing wave pattern seen in the previous section. To get a matched load experimentally the potentiometer resistance was varied and an axial sweep was taken of the line from $z = -100 \text{ cm}$ until $z = 0 \text{ cm}$. This shorter distance, rather than the full tank length was used to reduce the time taken for each sweep and therefore to reduce the time required to see the effect of changing the potentiometer. The results were plotted and compared to previous sweeps. Initially the potentiometer was varied coarsely, by approximately $5 \Omega$. When the best results were found with this method the variation was reduced to $1 \Omega$. The best match was the resistance that gave the smallest standing wave pattern. This was found to be around $34 \Omega$.

This process was then repeated with a capacitor as the variable rather than a potentiometer. The potentiometer was left attached and different capacitors were wired in series with the potentiometer. This variation did not cause significant change the standing wave pattern, but the magnitude of the signal received was affected.

Once the best match was found a full axial sweep was conducted for an open circuit, short circuit and 'matched' load. The results are shown in the Figure below. The sweeps were all conducted at 70 MHz.

![Figure 16: Axial sweep for an open circuit load (blue), short circuit load (red), and matched load (green)](image)

The experimental results show that the short circuit has a similar pattern to the open circuit but they are out of phase. The two signals should be out of phase by $180^\circ$, but they are not. This is most likely because the load is not an exact short circuit or open circuit, though the open circuit is closer to ideal then the short circuit. For the short circuit to be ideal there would need to be a direct connection between the line and the aluminium
plate at z = 0. This could have been achieved, however the tank would need to have the water emptied from it and the short circuiting would be permanent. The closest feasible solution was wiring the line to the die-cast box. This means though that there is impedance due to the extra wire, the solder tag, the die-cast box and the screws. These impedances mean that there is a small load rather than a short circuit. For the open circuit, the real part of the load impedance is very large, close to infinite, but there will be a reactive part due to the extra length of wire. Both the impedance in the short circuit and the reactance of the open circuit contribute to the signals not being 180° out of phase.

The distance between the corresponding nulls between the open circuit and short circuit signals should be a quarter of a wavelength. As the two signals were not exactly 180° out of phase the wavelength will not be accurate. The wavelength was calculated to be 80 cm. This is smaller then the wavelength calculated from the axial sweeps from the previous section.

The short circuit results show that the load is not a matched load. The load has reduced the amount of signal being reflected from the load end but not eliminated it. More experimentation needs to be performed to achieve a perfect matched load. The data collected is not sufficient for an accurate estimation of the attenuation coefficient of the line to be approximated.

**Horizontal Sweep**

The aim of this investigation was to find the attenuation with respect to distance of the signal. To find the attenuation of the signal the centre of the antenna was initially placed 5 mm from the line at z = -175 cm and y = 0. The antenna was then moved away from the line, increasing the x distance by 5 mm and recording the signal at each point. The distance was increased until the centre of the antenna was 26 cm away from the line.

The sweeps were conducted at 40 MHz, 70 MHz and 300 MHz. These frequencies were chosen because of the high attenuation of the signals. To see to effect of the attenuation there needed to be a minimal reflections from the walls, bottom and the surface. The attenuation at 40 MHz is 216.54 dB/m, at 70 MHZ is 286.46 dB/m and at 300 MHz is 593.03 dB/m. There was an open circuit at the load end (z = 0). The plots of the received signal are shown below.

![Figure 17: 40 MHz x sweep at y = 0, z = -175 cm](image)
The results obtained show that there is a significant falloff for all frequencies as the antenna is moved away from the wire. The falloff is quite rapid initially and slows down as the distance between the antenna and wire is increased, as expected. For the 40 MHz curve the attenuation appears to level off after about x = 4.5 cm (other than a few rouge data points) and the falloff is constant. The rapid initial falloff and then levelling out of the signal is expected. However the 70 MHz results do not show this. The rapid falloff initially is present but then there is a random placement of points, followed by the received signal increases before levelling off similar to the 40 MHz signal, except there appears to be a slight increase in the signal the further away the antenna is moved. The obtained results for the 300 MHz signal are extremely strange. The initial rapid falloff is present but then the signal goes up and down slightly, similar to a triangle wave. There is then a huge spike, which is approximately 80% of the maximum received signal, around 13 cm from the wire. It was believed this was a
There are many strange behaviours for both the 70 MHz and 300 MHz obtained results. These behaviours could be explained by reflections off the boundaries of the tank. However this is unlikely because of the high attenuation inside the tank at these frequencies. Another source of this strange behaviour is experimental error. Incorrect placement of the antenna in the tank or having the antenna not perpendicular to the field could result in the strange behaviour, thought this is unlikely to explain the large peak in the 300 MHz signal. The presence of a surface wave leaking down into the water could also explain some of the behaviour but it is unlikely that the surface wave could penetrate to the depth the antenna was located at during the test. The effects may be because at these distances from the wire the field produced is not longer proportional to the current in the line and a standing wave pattern is being produced in the tank. However further investigation would be required to see if this is even possible.

**Surface Wave**

When difficulties were experienced with taking accurate measurements it was found there was significant unexpected field at the top of the tank. This was assumed to be a wave travelling along the air/water boundary. It was believed that the wave was propagating along and leaking into the water. To see how significant an effect this surface wave had, axial sweeps were performed just below the surface of the water. Three sweeps were taken, above the wire, halfway between the top of the wire and the side of the tank and close to the side of the tank. Sweeps were conducted at 40 MHz, 70 MHz and 300 MHz so that they could be directly compared with the results obtained for the current in the line and attenuation with distance.

The sweeps were very similar to the axial sweeps performed to find the current in the line. Measurements were taken every 2.5 cm from z = -235 cm to z = 0 cm. The antenna was placed just below the surface at y = 15 cm and swept at x = 5 mm, 15 cm and 25 cm. There was an open circuit at the load end (z = 0).

![40 MHz z sweep at y = 15 cm](image)
This investigation proves the existence of a surface wave on the tank which is present at all frequencies. For the 40 MHz signal the surface wave is two orders of magnitude lower than the signal near the wire. For the 70 MHz signal the surface wave is an order of magnitude lower than the signal near the wire. However for the 300 MHz signal the surface wave is of similar magnitude to the signal received at the wire. From this it can be concluded that for the lower frequencies (40 MHz and 70 MHz) the surface wave will have little effect, if any, on the signal being received at the wire. However at 300 MHz there will be a problem, especially halfway between the wire and the surface, as the magnitudes of the signals should be equal. To investigate the effect of the surface wave, a vertical profile from the wire to the surface needed to be taken (see Vertical Sweeps section below).
The surface waves do not seem to be proportional to the field being produced in the wire.

**Vertical Sweeps**

The aim of this investigation was to find the effect that the surface wave has on the tank. To see how far the surface wave penetrated the tank measurements were taken from just about the wire to the surface of the water.

The antenna was placed just above the wire at \( x = 0, z = 175 \) cm and moved towards the surface keeping the \( x \) and \( y \) positions constant. The antenna was oriented in the \( x\)-\( z \) plane, which, when placed above the wire would make the antenna parallel to the field produced by the wire but perpendicular to the surface wave as it penetrates the water. The antenna was chosen so that only the field from the surface wave could be seen. The distance from the wire was incremented by 1 cm and the received signal recorded at each point. There was an open circuit at the load end \((z = 0)\).

![Figure 23: y sweep at \( x = 0, z = -175 \) cm for 40, 70 and 300 MHz](image)

This data shows that close to the wire all three frequencies have a similar field strength. The field strength is expected to be low as the field and the effective area of the antenna are parallel. The field received is approximately 15 dB below the signal received very close to the wire when the fields were perpendicular, where maximum signal would be received. The 40 MHz signal falls off rapidly initially and then plateaus, except for two data points which may have been measurement errors. This plateau is real signal and not the noise floor, as the noise floor was approximately -158 dB \((\text{H/m})\). The 70 MHz signal also initially attenuates as a similar rate to the 40 MHz signal but then the 70 MHz signal increases and levels out about 10 dB lower then the signal detected at the wire. These two frequencies show similar behaviour, however the 300 MHz signal shows different results. The signal increases as the antennas is moved away from the wire. This suggests that there is another source of signal which is stronger at the surface then at the wire and it has a greater effect at higher frequency.

### 0.4.5 Vector Network Analyser

An investigation was conducted on the tank that is the focus of this project by Dr G. Milford[23]. A Vector Network Analyser, which was used to determine the transmission and reflection of the tank from 100 kHz to 500 MHz and to attempt to de-embed the effect of the die-cast boxes, tail wire and BNC connectors. The characteristic impedance of the line was also investigated. Both \( S_{11} \) and \( S_{22} \) measurements were taken. In order to de-embed the effects of the die-cast box assembly an inductance calibration box was built. A die-cast box of
the same dimensions as the two on the tank was acquired. This box was altered to be an exact representation of the boxes connected to the tank. A piece of PCB was used as the backing instead of aluminium plate and the wire was soldered onto the PCB. One port measurements were taken of this box, to determine the inductance over the frequency range. This was then removed from the measurements taken of the tank. All effects were then compared with theoretically predicted responses.

From the results shown in Milford[23] it can be seen that the measured data for the attenuation of the line and the propagation velocity agree with the predicted results up until approximately 300 MHz. The attenuation is linear up until this point. There is also agreement between the predicted and measured data for the characteristic impedance. Once again, this is only true close up to approximately 30 MHz.

0.4.6 Difficulties experienced when taking measurements

When experiments were first conducted in the tank, the signal generator for the TEM Cell was used to supply the signal. It was used because it provided a high power signal to the tank at a much higher frequency than was possible with the signal generator that had been used. The previous Agilent signal generator was only capable of a maximum 20 MHz. The TEM Cell signal generator is a crude piece of equipment, and is only capable of providing a 70 MHz signal. If experiments were to be conducted at other frequencies another signal generator would be necessary. However the main problem with the TEM Cell signal generator was the lack of isolation. The box radiated signal into the environment which was then absorbed by the coax cables used to connect the receiving antenna to the spectrum analyser. If the receiving antenna was removed signal could still be received as the coax was acting like an antenna. This was providing large inaccuracies in the data collected, as the relative position of the TEM Cell generator to the tank and position of people relative to the TEM Cell generator could change the amount of received signal.

To rectify the problems with the TEM Cell generator an Agilent 33250A signal generator was used instead. This gave the ability to perform experiments up to 80 MHz. The experiments were re-conducted at 70 MHz and performed at 40 MHz. However it was once again found that the signal generator was not properly isolated and current was leaking out from the generator and cable attached to it and being absorbed by the receiving antennas cables, affecting the signal. The Agilent generator was then replaced with a Rhode and Schwartz SMIQ 03B signal generator, which could produce signals from 100 kHz to 3.3 GHz. This was used to re-conduct the experiments at both 40 MHz and 70 MHz and to conduct a further set of experiments at 300 MHz.

Another difficulty experienced while taking measurements was achieving the correct placement of the antenna with respect to the wire. When the tank was constructed it had metal re-enforcing bands attached to the sides to stop the tank bowing out when filled with water. Unfortunately these were inadequate and the sides of the tank were not square when filled. This made it difficult to ensure the antenna position relative to the wire when conducting axial sweeps. To overcome the problem a straw, which was filled with water to minimise it effect, was attached to the antenna. The end if this straw was kept against the line throughout the whole sweep, however ongoing adjustments of the antenna position dramatically increased the time it took to collect the data.

0.5 Conclusions

0.5.1 Lessons Learned

There were many lessons to be taken out of this project. The first was the use of proper equipment that is fit for purpose. There were significant delays were caused by using faulty equipment, or equipment that caused errors in measured data. Proper analysis and checking of all experimental equipment should be conducted to avoid time and effort being wasted on work that will be later to be redone.

Another lesson learned is that a wire immersed in salt water will displays the characteristics of a transmission line. Signal will propagate along the wire and be reflected at the load end, which will cause a standing wave pattern.

A major lesson taken away from this project was the correct development of an engineering investigation.
It is now clear that the process must be thought out and planned correctly otherwise it will fail. An investigation cannot begin with attempting to take some measurements and expecting to be able to work it out from what has been collected. If the area is entirely unknown and there is no way of predicting what will happen, detailed, well thought out measurements need to be taken so that all the effects can be determined. Early on in this project it took too long to realise equipment was broken because this was not being looked for. However if theory does exist and results can be predicted they should be developed before the experiment is undertaken. This project development is aided when the theory was developed beforehand.

It was also learned that it is very easy to underestimate the work required for a project. However, it may not be possible to complete the work in the time it was expected to take. Delays are likely especially if the project is a new undertaking.

0.5.2 Suggested Future Work

The first future that should be to strengthen the sides of the tank, to ensure the sides no longer bow. This will allow an automated rig to be purchased/constructed that will be able to sit on the tank and be programmed to move the antenna around the tank. The rig would need to be able to move axially long the tank, horizontally across the tank and be able to move the antenna vertically up and down in the water. There would need to be some way out automatically storing the data as the antenna is moved to each point. This would greatly speed up the time it takes to take sets of data and remove the human error present in the current experimental procedure.

Once an automatic rig has been acquired the entire tank can be mapped. This would greatly expand the understanding of how the tank worked and how it can be effectively used as an underwater test range. If a script was developed then the rig could be set to take measurements of the entire tank for many frequencies from ELF to microwave frequencies, without a person needed to physically do the work.

Another area that need to be explored is developing a matched load for a few frequencies. This matched load should match both the real and imaginary parts of the impedance of the line, and cancels out any effect the die-cast boxes have. This would allow the attenuation co-efficient, $\alpha$, of the line to be found. As the value for $\beta$ can already be found, the propagation constant of the line at many frequencies can be found. This can then be compared to theory to find how close the correlation is, which if the correlation is close, will prove the validity of the experiment.

The test tank should eventually be used to conduct research into the operation of electromagnetic antennas and communication systems. The main area of research in underwater electromagnetic communications is the creation and reception of fields underwater and this should be used for furthering our understanding of this. It should also be used to test the change in performance of current antenna designs that are used in air, as that was the initial goal of the project.

0.5.3 Acknowledgements

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