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Multipath Acoustic Navigation
PDI Final Report

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Contents

Chapter 1

Introduction

This document is the final report of the course *Preparação da Dissertação* of the Master's in Electrical and Computer Engineering at FEUP. It presents the current state of the art for the two major topics of interest to this work: Ocean acoustics and mobile robot localisation and navigation. While the latter has been extensively researched for some time now, the former is a more recent subject of interest, and somewhat less accessible. For this reason, a bigger effort on presenting detail is made on ocean acoustics.

Following the state of the art the problem to be tackled is presented in, still, a rather exploratory form. The purpose is to present a first discussion on the ideas on how it might be possible to solve it and go through the issues that are expected to be found.

Finally, a plan of the work to be developed is shown. A brief description on each task is done and a Gantt chart is presented.

Chapter 2

State of the Art

In this chapter an overview of the current state of the art related to the subject of study is presented. In the first section, the basic acoustic properties of the ocean are discussed. The purpose is to show that, even at a glance, sound transmission in this medium is far from being a trivial matter. The first object of discussion is sound speed and how it changes with respect to, fundamentally, three quantities: temperature, salinity and pressure. While salinity can usually be considered constant in a given area, the same is not valid for temperature and pressure. An overview of how the first changes with depth is given. As for pressure, it can be related to depth using the Leroy-Parthiot equation, for example [1].

Transmission loss and doppler spread both play important roles in understanding this subject, so they are discussed separately.

With the basics gone through, some model is required to fully understand underwater acoustic wave propagation. Due to it's intuitive nature, it's simplicity and it's natural adequacy to localisation problems, ray tracing is the model focused. Other models are briefly mentioned but with no intent of providing much detail.

After going through ocean acoustics, it is important to discuss localisation and navigation, which is the main purpose of this work. Extensive research has been done on these matters, and while a complete discussion is by no means be presented, the fundamental ideas for a basic understanding of what follows are discussed.

2.1 Ocean Acoustics

The ocean can be thought of as a waveguide limited by the sea surface and the seafloor [2]. In a homogeneous medium, waves propagate in straight lines. However, as in the case of light in a medium where the refractive index is not the same in every point, sound rays are curved if the velocity of propagation is not constant. This suggests that an analogy can be established between sound propagation and geometrical optics, which is true for sound of very high frequency when certain phenomena like diffraction and absorption can be ignored [3]. When considering sound refraction in the sea, it is usually assumed that temperature varies only vertically, which is the same as considering the ocean as consisting of strata, in any one of which the temperature is constant along a large horizontal distance [3]. The speed of sound in any medium, at any given point, is determined by the pressure and density of the medium at that point. In the ocean, pressure increases with depth and density changes with both temperature and salinity. This relation can be expressed by the following simplified expression [2]

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1 - 34 - 0.01T)(S - 35) + 0.016z\,. \tag{2.1.1}$$

Usually, however, when deriving distances from time-of-flight measurements, more accurate formulas are used. Such an example is the equation by Chen and Millero [4], used in [5]. Looking at (2.1.1), it is easy to understand that seasonal and diurnal changes have an effect on sound speed in the upper part of the ocean. In non-polar regions, near-surface oceanographic properties result from wind and wave activity near the boundary between air and sea. In this layer, water temperature is constant and, thus, sound speed increases in it in an approximately linear fashion with depth. The more agitated the upper layer is, the deeper this region, known as the surface duct, is. Below the surface duct, temperature decreases with depth and, consequently, so does sound speed. This region is known as the thermocline. Below it, the temperature is constant and sound speed increases only due to increasing pressure [2]. In shallow waters (a few hundred meters deep), only the upper part of the described profile is relevant, which is affected mainly by season and time of day. Having discussed the basic principles of sound propagation in the ocean, it is necessary to develop a propagation model in order to have a good understanding of the medium in different scenarios so it is possible to successfully deploy a localisation system. The rest of this section is dedicated to discussing several issues related with ocean acoustics as well as different models for sound propagation in this medium, emphasising ray tracing.

2.1.1 Ray

Throughout the rest of this document, the definition of ray will be important. A ray is a normal to a wavefront. Rays can be used to trace the paths that waves travel through and separate computations can be made on individual rays. Furthermore, an eigenray is defined as a ray that travels precisely from a source to a destination of interest. These are the rays that define the acoustic wave that actually reaches the destination, and are thus the rays of interest.

2.1.2 Transmission Loss

As sound propagates through water, it suffers attenuation due to several different factors. The standard unit of measure of underwater acoustic propagation is acoustic intensity (I) [6], which is defined as

$$I = \frac{p}{\rho c}\,, \tag{2.1.2}$$

where p is the pressure amplitude of the plane wave, ρ is the water density and c the speed of sound in the water. Transmission loss is usually defined as

$$TL = 10\log_{10}\frac{I_{ref}}{I(r,z)}\,, \tag{2.1.3}$$

where I_{ref} is the intensity measured at 1 m from the source and $I(r, z)$ the intensity measured at an arbitrary point at range r and depth z.

There are three main factors contributing to transmission loss: geometrical spreading, absorption and rebounds both at the surface and the bottom [5], each one of which is now described.

Geometrical Spreading

Geometrical spreading is caused by the expansion of the acoustic wave through the medium [5]. In other words, it's a measure of the signal weakening as it propagates outward from the source [2]. Two types of spreading are considered: spherical spreading and cylindrical spreading. The first one occurs when we consider the field near a source point, while the second occurs when we consider larger ranges. Transmission loss for both of these cases can be computed as, respectively, $20\log r$ and $10\log r$ [2] where r is the distance travelled by the ray considered.

Absorption

Part of the acoustic energy of a travelling sound wave in water is transformed into heat continuously. This absorption effect is partly due to the viscosity of the liquid and by scattering of sound waves by different inhomogeneities [7]. The combined effect of absorption and scattering is called sound attenuation and is typically only possible to measure their combined effect. Absorption increases with frequency and is dependent on temperature, salinity, depth and the pH value of the water [8]. The transmission loss due to absorption is a function of the distance r travelled by the ray being analysed and is calculated as $\alpha\, r\, 10^{-3}$, where α is the absorption coefficient. As for the coefficient α, there are empirical formulas to compute it, for example the Francois-Garrisson equation [9] and the one by Marsh and Schulkin [10].

Rebounds

The analysis of sound propagation is greatly simplified if no rays are traced into the bottom [8]. If the ocean is deep in the region of interest, bottom interaction will have little effect, so this can be safely assumed. In shallow waters, however, this is not true, as we will see.

When a ray hits the surface, it is reflected and suffers a transmission loss that can be computed by the simple equation given by the Beckmann-Spizzichino formula [5, 11].

2.1.3 Doppler Effect

This section follows the works of [2], [12] and [13]. Other references will be made in the text where appropriate.

Basic physics tells us that a moving source or receiver causes a frequency Doppler shift in the received signal whose magnitude is proportional do the ratio of the relative velocity of the transmitter/receiver and the speed of sound $a = v/c$. In the ocean, every source/receiver moves even if not intentionally due to currents. Furthermore, because sound speed is much smaller than the speed of light, Doppler shifts in acoustic transmissions in the water are proportionally much bigger than electromagnetic transmissions in free space. To complicate matters further, while in free space frequency shifts are expressed by a simple relation that makes a received signal be distorted in time having duration $T/(1 + a)$ and a frequency offset $a\, f_c$ (where f_c is the frequency of the carrier), in a waveguide or stratified environment, such as the ocean, the Doppler structure found is much more complicated because of multipath phenomena. Each ray that arrives at the receiver has suffered a different Doppler shift, causing what's known as Doppler spread.

Another related and important effect, introduced as the dynamic effect of swell in [5] is caused by the random variability of the channel in time. Since the surface of the ocean is not perfectly flat, it's roughness introduces scattering and makes any assumption of specular reflections essentially wrong. What we have in the ocean surface are actually diffuse reflections. The vertical displacement of the surface can be modelled accurately as a zero-mean Gaussian random variable whose power spectrum is characterized by the windspeed [7]. This displacement that causes the scattering of reflected signal induces a very large Doppler spread that can easily dominate over the one caused by other phenomena. The following equation can be used to calculate this spread [7]:

$$B = 0.0175 \left(\frac{f}{c}\right) w^{3/2} \cos\theta\,, \tag{2.1.4}$$

where c is taken to be $1500\,\mathrm{m\,s^{-1}}$, w is the windspeed and θ is the angle of incidence of the ray on the surface.

2.1.4 Multipath Propagation

Every wireless communication channel suffers from multipath effects. However, while an electromagnetic wave propagating travelling in free space will have this unwanted effect only due to reflections on obstacles, underwater there are mainly two components that contribute to the overall multipath: reflections on the surface, bottom and any object on the water and ray bending due to refraction. The intersymbol interference caused by this multipath in a single carrier communication system in the horizontal underwater acoustic channels can be of several hundred symbol intervals for moderate to high data rates as opposed to the typical several symbols for a common radio channel [13]. Although in theory there are infinitely many signal echoes from sender to receiver, the amount of rays that haven't lost most of their energy at the moment they reach the receiver, having gone through the significant paths, are finite in number [12]. If we consider the ocean surface to be flat, reflections on it are specular, meaning that the angle of incidence is equal to the angle of reflection with respect to the normal to the surface. As we seen previously, though, scattering must be accounted for by introducing Doppler spread in the channel's transfer function. Bottom reflections are much more complicated, as they depend on the type of bottom and the grazing angle [12, 2].

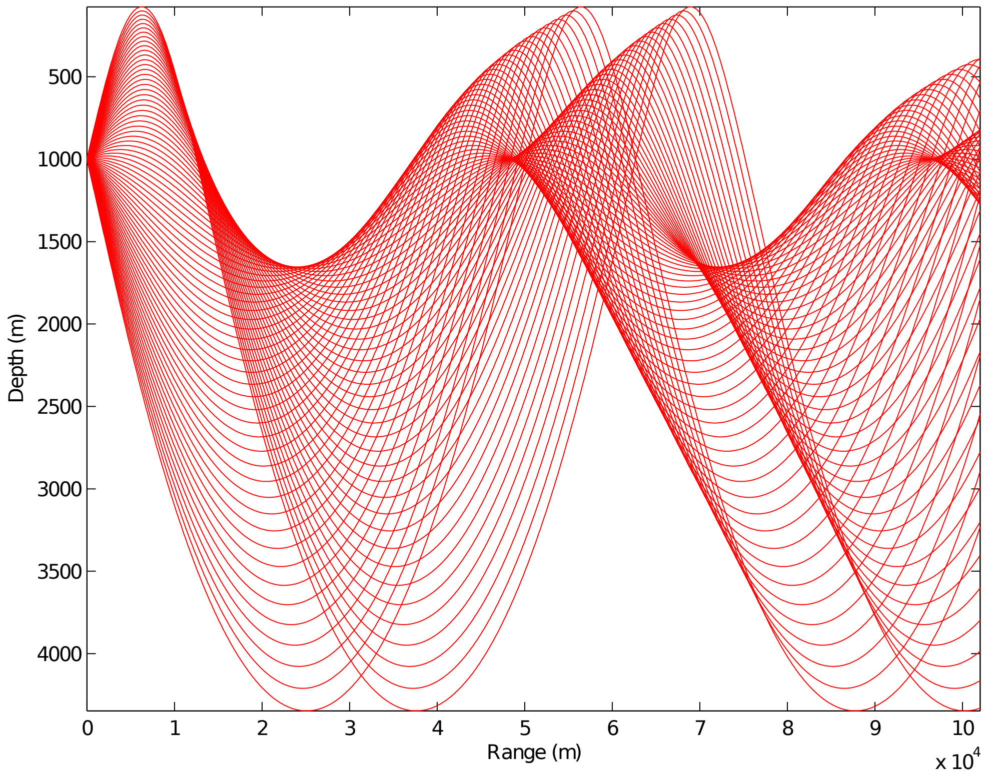


Figure 2.1: Rays calculated by **Bellhop** in a flat deep water waveguide. Taken from [14].

Fig 2.1 shows a typical ray trace diagram calculated by Bellhop showing several different paths. The result of multipath is that, in any given point any given point in the ocean receives multiple copies of the same signal that have travelled through different paths and carry different amounts of energy, having also different delays. All of this causes several negative effects such as distortion and de-correlation between the same signal received at different sources [15]. Distortion has important consequences, as transmitted pulses are stretched at the receiver due to the several delayed arrival. [15] shows an example where an explosive pulse with a duration of a few milliseconds is measured in seconds at the receiving end.

Sound propagates very differently in deep waters than it does in shallow waters. What accounts for these differences is mainly multipath differences, as we shall now see. The definition of shallow and deep is somewhat vague, but shallow usually refers to the region of continental shelves, with depth less than about 100 m and deep the region past continental shelves [13].

Deep Water

In deep water, longer range propagations are possible without bottom interaction. The significant rays are typically either bended only due to refraction or refracted and reflected at the surface [2]. The situation will depend on the depth at which we are transmitting. Since rays bend towards layers where sound speed is lowest, it is possible to have a situation where the sound rays are confined in the region where their speed is minimum (axis of the deep sound channel) [13]. This property is used to communicate at several thousands of miles because the sound energy is essentially trapped in this channel. This situation is depicted in Fig. 2.2. In many situations, however, we will be interested in transmitting relatively close to the surface,

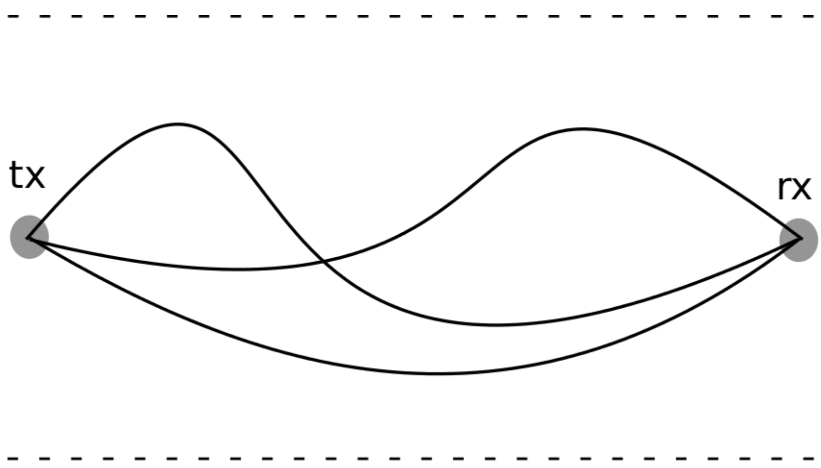


Figure 2.2: Multipath example in deep water.

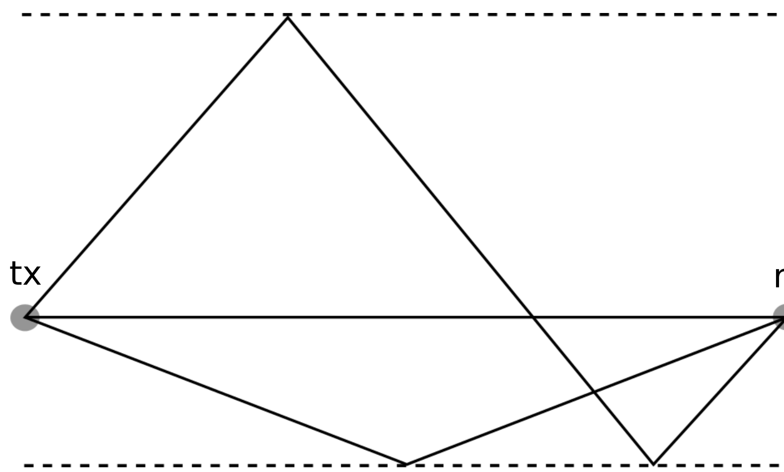


Figure 2.3: Multipath example in shallow water.

so sound rays will still be reflect on the surface, but bottom interactions may safely be ignored, leading to a much simpler problem than that that will be described next.

Shallow Water

The situation is quite different when considering shallow water. In such cases, sound speed may be taken as approximately constant [12]. In these conditions, sound rays travel in straight lines and bounce both on the surface and bottom for as long as they have energy. A typical scenario is shown in Fig. 2.3. It is generally much harder to preform accurate ray tracing in shallow water. Even though we're assuming there is no refraction, bottom interactions can be much harder to deal with than this effect. Without knowing the type and shape of the bottom, little can be done to predict how rays will reflect on it. The two dimensional model generally used cannot even be relied upon in circumstances where rays diverge from the vertical planes they were launched in. Nevertheless, even though communication in this scenario is very hard, localisation may be possible.

2.1.5 Ray Tracing

Ray tracing is about understanding how rays propagate in order to trace the propagation of wavefronts. The underlying assumption is that the energy of the wave is confined in different paths [5]. An acoustic source creates rays that propagate in every direction in free space, though the interest is in tracing the ones that make propagation from a particular source understandable [2]. Ray theory can be derived from the wave equation taking advantage of some simplifications. The method essentially involves a high-frequency approximation, so it is sufficiently accurate for applications involving communication systems for short and medium short distances. [8] shows, however, that ray theory can also be applied for low frequencies. One of the first descriptions of ray tracing in underwater acoustics is given by Lichte [16]. He presented an intuitive way of understanding how sound rays propagate in the ocean. The starting point is realising that the ocean is acoustically inhomogeneous in horizontal layers. As a result, sound rays are not straight lines, but rather curves. However, turning back to our layered ocean model in which sound travels at a constant speed horizontally, we can use Snell's law to trace the entire path of a ray. Fig.2.4 shows such a scenario. The refraction law tells us that

$$k_1 \cos\theta_1 = k_2 \cos\theta_2 \,. \tag{2.1.5}$$

Using this for k_2 and k_3 , k_3 and k_4 , and so on, and allowing k to vary continuously as a function of the depth z, the above can be rewritten as

$$k(z_1)\cos\theta(z_1) = k(z_2)\cos\theta(z_2)\,. \tag{2.1.6}$$

For an origin depth z_0 and corresponding declination angle θ_0 , the ray angle at a specified receiver depth z_r is given by

$$\theta(z_r) = \arccos\left[\frac{k(z_0)}{k(z_r)}\cos\theta(z_0)\right]\,. \tag{2.1.7}$$

Considering Fig.2.4 again and letting r be the horizontal axis and z the vertical one (depth), and considering the limit case where the number of layers is infinite, we can write the following differential equation

$$\frac{dr}{dz} = \cot\theta(z)\,, \tag{2.1.8}$$

which can be integrated to yield

$$r(z) = \int_{z_0}^{z_r} \cot\theta(z)\,dz\,. \tag{2.1.9}$$

When integrating the ray path, care should be taken so that when the ray becomes horizontal, the integration step dz becomes negative. While the geometrical approach just described has been used with some success [5], finding eigenrays by interpolating the properties of two adjacent rays that suffer the same number of rebounds such that the receiver is in the middle of them (see Fig. 2.5), the classical, more formal approach starts with the Helmholtz equation in Cartesian coordinates $\mathbf{x} = (x, y, z)$:

$$\nabla^2 p + \frac{\omega^2}{c^2(\mathbf{x})} = -\delta(\mathbf{x} - \mathbf{x_0})\,, \tag{2.1.10}$$

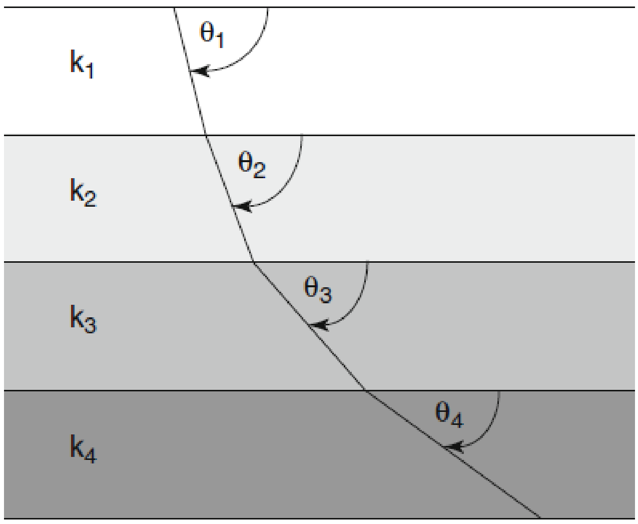


Figure 2.4: A ray refracting through a stack of layers. Taken from [2]

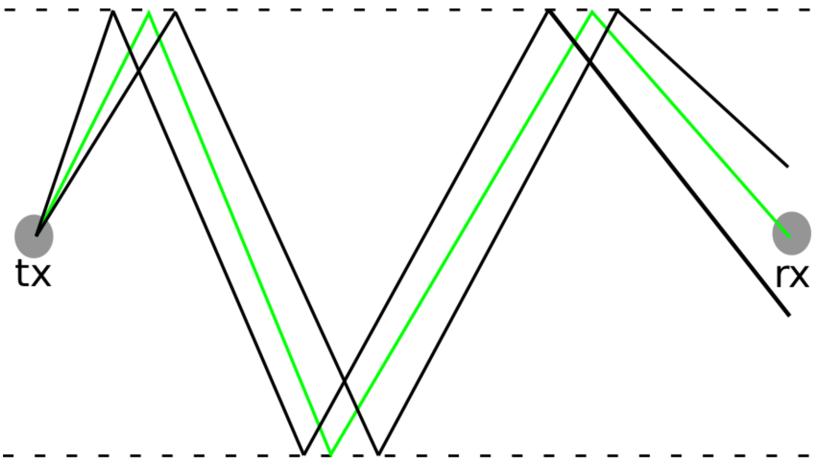


Figure 2.5: Geometrical approach to obtain an eigenray interpolating the properties of two adjacent rays.

where $c(\mathbf{x})$ is the speed of sound and ω is the angular frequency of the source located at $\mathbf{x_0}$. A full derivation of the ray equations from this starting point can be found in [2]. These are typically written in cylindrical coordinates

$$\frac{dr}{ds} = c\,\xi(s), \qquad \frac{d\xi}{ds} = -\frac{1}{c^2}\frac{\partial c}{\partial r}\,, \tag{2.1.11}$$

$$\frac{dz}{ds} = c\,\zeta(s), \qquad \frac{d\zeta}{ds} = -\frac{1}{c^2}\frac{\partial c}{\partial z}\,, \tag{2.1.12}$$

where $[r(s), z(s)]$ is the ray trajectory, s is the arclength along the ray and, since the tangent vector to such a curve is given by $[dr/ds, dz/ds]$, the pair $c[\xi(s), \zeta(s)]$ represents the tangent vector to the ray. The most common way of solving these equations is by using standard numerical integrators. One of the simplest of such methods is the Euler's method. Though it's a very simple first order method, it is very inefficient and yields an error per step proportional to the square of the step size. A second order Runge Kutta method might be more appropriate when accuracy is needed. In the case of the Bellhop program [14], a widely used ray tracing code, a two step polygon method is used.

Finally, it is worth noting that, although standard codes exist to solve the ray equations, the sound speed profile of a particular section of the ocean is not typically known. A further issue has to do with the reflections on the surface and the bottom of our waveguide. The integration must then be restarted. While this might be straightforward for surface reflections, it is far from being trivial when bottom reflections must be considered, since the bathymetry of a given area it not likely to be available. It is also worth noting that currently almost all methods for modelling the acoustic underwater channel are two dimensional, considering only range and depth. The assumption made is that a sound ray launched into a particular vertical plane remains in that plane over the entire transmission path [17]. This assumption is reasonable if we take into account the fact that horizontal sound speed variations are negligible. In shallow waters, however, this assumption may not be accurate due to bottom interactions, since the acoustic wavelength might be comparable to the ocean depth. Under these conditions, a reflection in the bottom of the ocean (which will not always be flat) will cause rays to reflect to different vertical planes.

Problems with Ray Theory

Although ray theory is widely used and provides good results under certain conditions, it suffers from some problems that make it diverge from experimental results. [3] provides a good summary on the efforts developed to understand this divergence, the first of which is *diffraction*. If we consider sound propagating from a point below which sound speed decreases, a shadow zone into which no rays penetrate appears [18]. The problem with this is that, such as light, shadow boundaries are not sharp. Light is diffracted around obstacles and so is sound. However, diffraction effects become bigger with increasing wavelengths (and consequently so does ray theory), and since for localisation applications we're mostly interested in high frequency signals, limiting this negative effect of diffraction.

Scattering effects are also not predicted by ray theory, but they may be responsible for the discrepancies shown with respect to experimental results. In the same fashion that sunlight scatters with raindrops to create rainbows, sound waves are known to suffer from scattering in the sea.

Finally, even though the horizontal temperature gradient in the ocean is much smaller than the vertical one, it is not zero. Although this is mentioned by [3], more recent works such as [2] assume a zero gradient. The results achieved in, for example, [5], show that this is a reasonable assumption to make in most conditions.

A more serious issue found in ray theory is the existence of singularities known as caustics [8]. According to ray theory, at these points ray intensity goes to infinity, which is obviously false. A workaround for this problem is presented in [2].

2.1.6 Other Models

Although ray tracing is a reasonable model that is still widely used, it is important to recognise that other models to describe sound waves underwater exist. Although different, they all have the same thing in common: their starting point. Every model naturally starts from the wave equation, and they differ essentially in the approach chosen to solve it. They furthermore assume harmonic solutions to this equation to obtain the Helmholtz equation, which is the one actually solved. There are fundamentally five methods to solve this equation [6, 2], which are: **ray methods**, **wavenumber integration** techniques, **normal modes**, **parabolic equations** and **finite differences and finite elements** approaches. [2] gives a very detailed analysis of each one of these methods.

As argued before, ray theory was the approach chosen for this work due to it's adequacy to localisation problems, where the frequencies used are typically high.

2.2 Localisation and Navigation

Localisation, in terms of mobile robots, is about the robot being able to determine where it is with respect to some reference. It is key for successful navigation and several challenges exist in this area When considering underwater localisation, knowing where the robot is is critical to ensure that correct and repeatable measurements are being taken for, for example, reef surveying [19]. Good information on localisation is also essential for safe operation and recovery of an Autonomous Underwater Vehicle (AUV) [20]. The three primary methods for AUV navigation are dead-reckoning and inertial navigation, acoustic navigation and geophysical navigation [20]. Our focus is on acoustic navigation. In the end a brief description of sensor fusion and the Kalman Filter is given. Before going into detail about these, though, techniques, some challenges of localisation in general are first discussed.

2.2.1 Sensor Noise and Aliasing

This section is mostly based on [21] who presents a very good discussion on this subject. The first thing to notice in our particular environment is that there is no access to a GPS system, since water is essentially opaque to electromagnetic waves. Even if we had access to GPS positioning, what we're interested in most of the times is actually the relative position with respect to some object (a dam, for example) rather than the absolute position with respect to the Earth's reference frame.

Sensors are how a robot perceives it's environment, so the correctness of their readings must be understood. Every sensor is affected by noise that limits the consistency of their readings, and the source of this noise cannot usually be compensated for. A typical case is the one of a sonar. When a sonar emits a sound towards a surface, it's reflection will not be perfect, and some of the energy will not return. The distortion that the echoed sound suffers depends on a number of things, such as the roughness of the material it reflected on, for example. Multipath can also interfere with sonar readings. Other factors, such as variations on the speed of sound, introduce noise that cannot be factored out. The consequence of this is that noise reduces the amount of useful information that we can obtain from sensors. The solution is generally always taking multiple readings and combine information from several sensors while statistically representing their noise.

Sensor aliasing is a different but also important phenomena that occurs frequently with sensor readings. Even without the presence of noise, aliasing can be a limiting factor when trying to localise a robot. The problem is that sensors will naturally give the same reading for different situations, so usually several readings from different sensors are required to uniquely determine a robot's position.

2.2.2 Inertial Navigation

One of the most common localisation and navigation techniques is based on integrating acceleration and velocity to obtain position. Common sensors merged to do this include accelerometers, gyroscopes and Doppler velocity logs [20, 22]. Integrating inertial information with information from different sensors using a Kalman filter is a very common approach which largely improves overall performance. The problems with relying on inertial navigation are:

- Initialization of the system;
- Position drif.

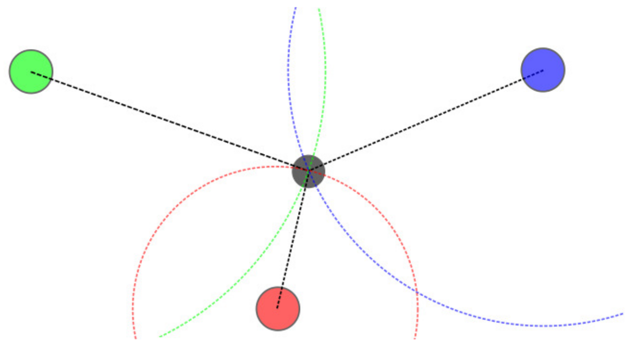


Figure 2.6: An example of 2D localisation using LBL.

The first problem has to do with the fact that, if we rely exclusively on an inertial navigation system (INS), we must be able to somehow determine where we're starting, otherwise integrating velocity doesn't help in determining the robots position. The second problem is related to the integration that has to be performed constantly. Since inertial sensors suffer from noise as any other sensor, when integrating their readings to obtain position we're actually integrating error as well, which accumulates and translates into a position drift that grows bigger with time and must somehow be bounded. A common way of bounding this error is to have to vehicle come near the surface to get a position fix from, for example, a GPS receiver [20].

2.2.3 Acoustic Navigation

There are typically two types of systems that have been used for acoustic positioning: long baseline (LBL) and ultra-short baseline (USBL) [20]. They provide low frequency measurements that can be used to update predictions obtained by an INS using, typically, a Kalman filter. [22] employs this strategy. In LBL systems, an array of transponders with known locations is deployed. Periodically, the AUV send a ping and the transponders respond to this ping. From this response, the AUV can calculate the time of flight to every transponder and either calculate it's position by intersecting spheres (or circumferences in a 2D scenario shown in Fig. 2.6) or use the raw time of flight measurements directly in a Kalman filter [20, 23]. USBL systems work in a different way: they have receiver arrays that can measure the angle and the range to an acoustic beacon [20].

A key issue in these systems is the problem of multipath interference. Rejection of outliers is usually a difficult problem

2.2.4 Geophysical Navigation

[20] provides a brief discussion on geophysical navigation. This type of navigation requires a known map of the environment including elements such as bathymetry and magnetic field. Matching sensor data with known data it is possible to develop navigation systems. However, no details will be given here about these techniques since they are out of the scope of our work.

2.2.5 Time of Flight calculation

An important issue when using acoustic systems like LBL and USBL is how to calculate times of flight of pings sent by an AUV. A first approach is to actually count the time from the moment the signal is sent to the moment the response from a transponder is received. This is a naive approach though and it is prone to large errors since it is highly dependent on a local clock precision. The typical approach is to, instead, keep a local copy of the signal that's received and correlate it with the one actually received. It is then an easy matter to get the time of flight from the correlation peak. Such an approach is taken in, for example, [5], and is the one typically used. If we have several beacons transmitting to our AUV, however, it isn't enough to correlate the received signal with a local copy of each of the signals transmitted by the beacons. The received signal will actually be a sum of all the transmitted signals, each of which delayed by a certain amount of time:

$$r(t) = b_0(t - t_0) + b_1(t - t_1) + ... + b_n(t - t_n)\,. \tag{2.2.1}$$

[5] uses what is known as Complementary Sets of Sequences, presented in [24], to code the signals used. These signals have very good cross-correlation properties, meaning that they are ideally orthogonal so that the correlation between any two of the signals in the set is zero.

2.2.6 Sensor Fusion and the Kalman Filter

Sensor fusion is the group of techniques that merge information from several different sensors in order to obtain a better estimate than that that would be obtained by considering only single independent measurements. [25] presented one of the most widely used algorithms ever for performing this task, famously known as the Kalman Filter. A very brief description of what it does is now given, without going into much detail. For a simple introduction that provides the material for implementation is given in [26].

First of all, we're trying to estimate a certain state $\mathbf{x} = [x_1, x_2, ..., x_n]$. A covariance matrix representing the error associated with this state vector is also maintained. The state vector may include the robot position but it may include any other state variable of interest, such as a map representation. It is important to be aware that the Kalman Filter assumes that all noise is Gaussian. In practice, however, it is used whether or not this is exactly true. A typical case where the noise is not Gaussian is the GPS. The algorithm is recursive and consists of essentially two steps: a prediction and a correction. It is particularly suited to the case where we have high frequency sensors such as accelerometers that can be integrated to **predict** a position and low frequency sensors like GPS or LBL to **correct** the prediction made. A simple proof that the resulting error of combining these two steps is better than using either one of them separately is given in [21]. One of the most interesting aspects of the algorithm is that it keeps track of the errors of our state estimations (by means of the covariance matrix). This can be very useful in decision making by an AUV: it can decide whether or not it is safe to perform a certain action based on how certain it is that its position is the one on the current state vector, for example.

Chapter 3

The Problem

The problem we're interested in is the one of performing the relative localisation of an underwater receiver (an AUV, for example) with respect to some transmitter. As we've seen, multipath makes underwater communication challenging. The goal of this work is, however, understanding how we can use these multiple paths sound takes to help us perform the target's localisation and ultimately develop a system that performs this task. This section is dedicated to explaining how this might be possible and discuss some issues that appear from trying to perform such a task.

The approach taken here is to consider a single transmitter and a single receiver and explore possible solutions to the problem considering first only a direct sound path, then a surface reflection and finally a surface and a bottom reflection. No single bottom reflection is considered because this would be a unrealistic scenario. We assume that there is a way to calculate the time of flight for each ray and for every segment of this ray. Considerations on how to do this are given in section 2.2. We also assume for now that accurate ray tracing has been performed so we have information on every eigenray, and that we can distinguish these eigenrays from each other at the receiver.

Direct Path

Considering only the direct path from sender to receiver is the simplest case, and it is shown in Fig. 3.1. In this case, the only information we have is the ray length and time of flight. It is possible to obtain the distance between the transmitter and the receiver but nothing else, as shown by the dashed line. In reality, the transmitter can be anywhere on the boundaries of a sphere centred in the source with radius equal to this distance measured. In the two dimensional problem considered, however, we consider that it lays somewhere on the circumference of the same radius. We're also assuming that the receiver will be in a straight line with the transmitter, which will not always be the case.

Surface Reflection

When we consider one surface reflection added to the direct path, and if we add the assumption that sound propagates in straight lines (which is approximately true for shallow water), we have the situation illustrated in Fig. 3.2. It is clear that new information is gained when we consider that the distance between the point of reflection and the receiver is known. By intercepting both circumferences we can already get the range and depth of the receiver relatively to the transmitter. It may happen, however, that these intercept at more than one viable point (in

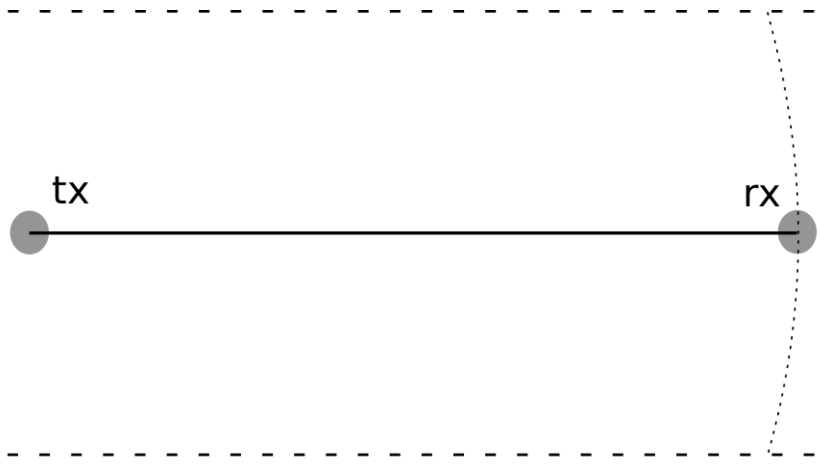


Figure 3.1: Direct path only.

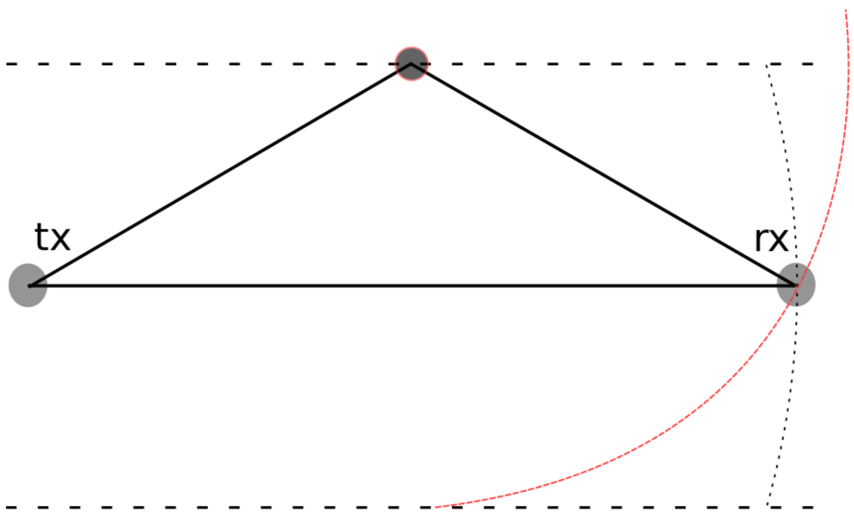


Figure 3.2: Direct path and surface reflection.

the case of Fig. 3.2 the second interception would be outside of the ocean), and so, as usual, more information to solve this ambiguity is needed.

Surface and Bottom Reflections

The final scenario considered is shown in Fig. 3.3. We again assume we know the distance between the reflection point on the bottom of the ocean and the transmitter. It is clear that no more ambiguity remains and it is possible to position the receiver with respect to the transmitter easily.

3.1 Expected Issues

Although the discussion just presented makes the problem seem relatively straightforward, there are several considerations needed to understand the validity of the assumptions made and to understand the viability of performing localisation in this fashion in real time.

First of all, we considered that the receiver is in a straight line with the transmitter. This will not generally be the case. If sound does actually approximately propagate in straight lines,

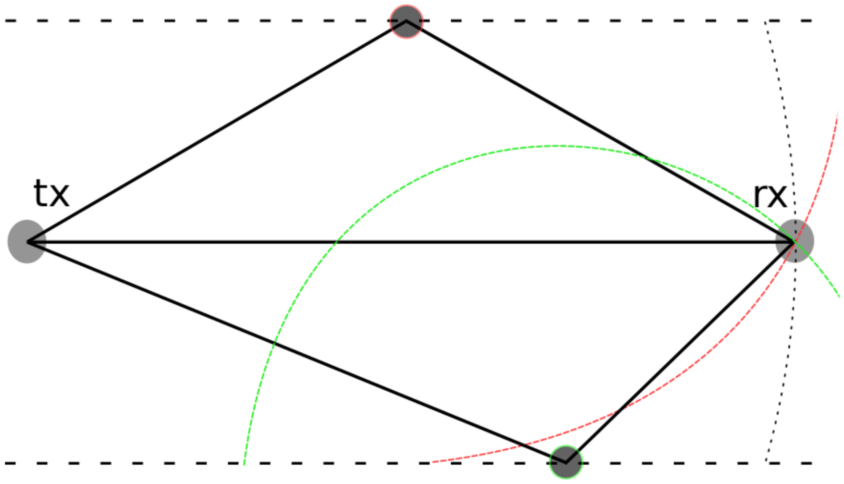


Figure 3.3: Direct path, surface reflection and bottom reflection.

this is not much of as issue though, since every conclusion previously drawn is directly valid. If rays are not straight, though, some extra work is required to get the straight lines between the receiver and the transmitter and between the reflection points and the transmitter. Although since ray tracing gives us the start and end coordinates of the eigenrays so we cay easily get these straight lines, this represents further computations that need to be performed.

The biggest question that comes to mind at this point is: is it possible to perform such a task in real time? Particularly, are we able to perform, online, ray tracing followed by these calculations and afterwards use the information acquired together with the rest of the vehicle sensors? The typical sequence of events for a receiver would be, after receiving a signal:

- Perform ray tracing;
- Distinguish every significant ray received;
- Calculate time of flight for every different significant ray;
- Compute the straight lines required;
- Compute the estimated relative location.

The final information obtained can be thought of as the information from a sensor like any other. The amount of computations required to do this can easily pose very big constraints in the applicability of such a method. Moreover, the longer it takes to perform these tasks, the less valid the result becomes, since both the receiver and the target are moving. As such, one of the big tasks presented at this stage is how to make this as efficient as possible.

The first steps in developing this system will be, however, collecting data to treat offline and work on develop algorithms to process it in, as much as possible, an online fashion.

Chapter 4

Work Plan

This section briefly describes the work plan for this thesis. An overview of each expected task is given followed by a Gantt chart. Due date is considered to be the 30th of June, so the total time available from the 16th of February (due date of the present report) is of 135 days, or approximately 19 weeks.

4.1 Task Description

Development of a platform (A)

This task will be mainly focused on selecting a platform for transmitting and receiving sound underwater so data acquisition may start. This task is expected to last 1 week.

Development of an acoustic transmitting system (B)

The purpose of this task is to develop a platform that transmits different kinds of acoustic signals at different transmission powers that is easily configurable in order to be able to determine the best signal conditions for different testing environments. The time expected to accomplish this task is of 2 weeks.

Development of multipath detection algorithm (C)

This part of the work consists of developing or using an existing ray tracing program in order to obtain the significant eigenrays at a receiver. Estimation of time required is 3 weeks.

Testing for data acquisition (D)

This will consist of acquiring as much relevant data as possible in different scenarios (deep water vs shallow water, different times of day...). It is expected to last 2 weeks.

Relative positioning algorithms development (E)

One of the cores of this work will be the development of algorithms that are able to determine the relative position of a receiver with respect to a transmitter, which is not an easy task in the media of interest. The time expected to complete this task is 3 weeks.

Sensor fusion algorithms development (F)

After having the relative positioning algorithm, an algorithm to merge this information with the information available from other sensors is required. 2 weeks are reserved for this task.

Testing the system in a real environment (G)

Finally, the system should be tested in a real environment in order to assess it's viability and perform any tuning required. The time reserved for this is 2 weeks.

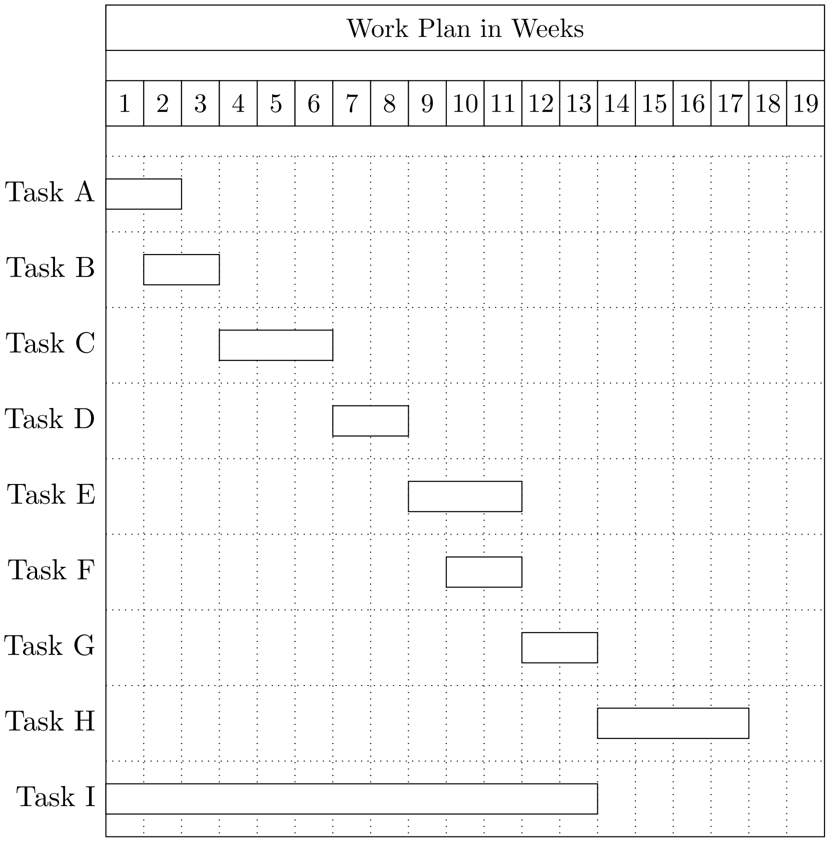
Writing the thesis (H)

The time reserved to write the final thesis is of 4 weeks.

Web page development (I)

Though the base development of the web page will be concentrated in a short amount of time, it's contents will be updated regularly throughout the project. To reflect this, a continuous task is introduced that overlaps the entire duration of the work, except the time reserved for writing.

4.2 Gantt Chart



Due to the existence of some overlap between tasks, 2 weeks of slack exist to compensate for any delays that might happen.

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