Salinity Sensor

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Acknowledgements

Abstract

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Abbreviations

‰ Parts Per Thousand

ADC Analogue to Digital Converter

CTD Conductivity, Temperature, Depth

DAC Digital to Analogue Converter

EMI Electromagnetic Interference

ENIG Electroless Nickel Immersion Gold

FPU Floating Point Unit

PCB Printed Circuit Board

PSU Practical Salinity Units

SST Sea Surface Temperature

Chapter 1

Introduction

Antarctica is the coldest continent on Earth covered in a vast sheet of ice that contains about 30 million cubic kilometres of ice [2] which is about 60% of the world's fresh water. This ice sheet is currently melting at an increasing rate due to global warming and other factors and scientists are trying to understand why. One of the methods being used to analyse sea ice is drilling ice cores and analysing the ice for various properties from the concentration of gases to the concentration of dust particles. One of the properties that is currently difficult to analyse is the salinity of the melted and solid sea ice. This project aims to develop a system that can measure the salinity of the melted sea ice at the bottom of the ice cores mentioned.

1.1 Background

m̃ore about the project sea ice and what this analysis will help with.

1.2 Objectives

The objectives of this project are to create a device that is able to measure the salinity of sea ice at the bottom of ice cores. The device should be able to measure the salinity of the ice in harsh conditions and cold environments that will be present in Antarctica. The device should also be able to measure the salinity of the ice in a non-destructive manner so that the ice core can be used for other analysis after the salinity has been measured.

1.3 System Requirements

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1.4 Scope & Limitations

The scope of this project includes the design and development of a device that can measure the salinity of sea ice at the bottom of ice cores. It includes the calibration of the devices, calculations for it, and establishing the accuracy of the device. The scope does not include the capture and analysis of the data from the device.

It is limited to performing in the conditions of Anartica and measureing melted sea ice. It is limited by a budget of R2000 for the full design and development of the device.

1.5 Report Outline

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Chapter 2

Literature Review

2.1 A Brief History of Salinity

The most common definition of salinity relates it to the total amount of dissolved *salts* in a solution, however, salinity's definition has had several more complex iterations over the years. The first definition of salinity was the total amount of dissolved *material* in grams in one kilogram of water [3]. This is a dimensionless quantity was expressed in Parts Per Thousand (‰) or $g.kg^{-1}$ where most ocean water's salinity falls between 34.60‰ and 34.80‰ as shown in Figure 2.1. The problem with this definition of
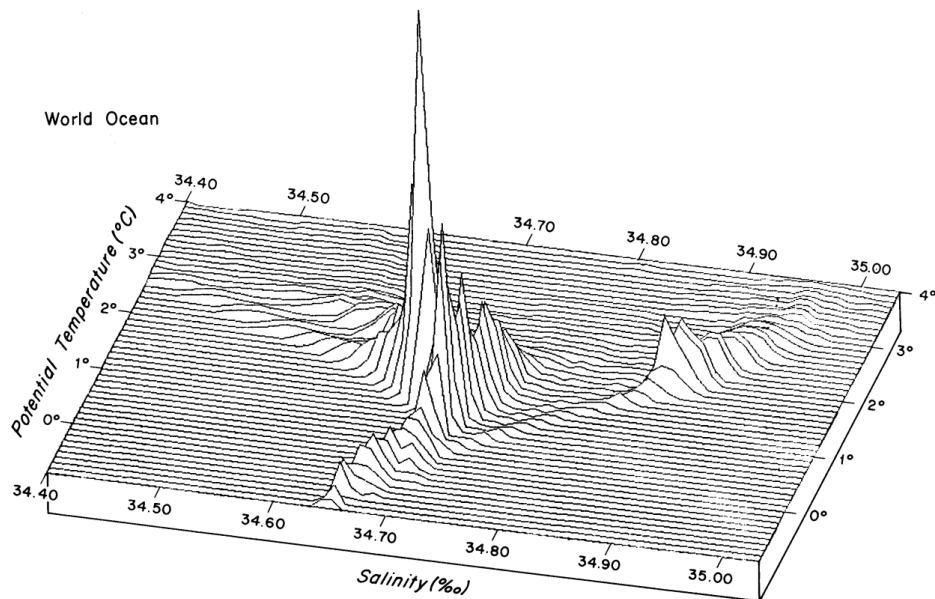
Figure 2.1: Histogram showing the volume of ocean water relative to temperature and salinity bins. The highest peak corresponds to a volume of 26 million cubic kilometres of ocean water [1].

salinity lay with its testability. Trying to obtain the mass of the dissolved material through evaporation removed certain compounds making this method almost impossible to achieve [4] and thus salinity needed to be redefined in a way that was easily and reliably testable. The next definition of salinity related it to the amount of chlorine present in the water, or the chlorinity of the water. Thus, in 1969, salinity was redefined to be directly proportional to the chlorinity of the water [3]. The calculation of salinity from chlorinity is further discussed in Section 2.2.1.

Around the same time as the salinity-chlorinity relationship was established, oceanographers had begun

experimenting with the use of conductivity to measure salinity. Conductivity was found to be more precise and significantly easier to measure than the titration required to measure chlorinity [5]. In 1978, the Practical Salinity Scale was established and salinity was updated to be related to conductivity which is the current definition of salinity[5]. This relation also included terms for temperature and depth as these affect the conductivity of an electrolyte solution [6].

The Practical Salinity Scale uses its own dimensionless units of salinity which are not interchangeable with ‰ in the current definition of salinity. Although the Practical Salinity Scale is sometimes given in Practical Salinity Units (PSU), it is more technically correct to refer to it as a certain Practical Salinity 'on the Practical Salinity Scale PSS-78' [5]. The calculation of salinity from conductivity is further discussed in Section 3.1.

2.2 Salinity Measurement Methods

Salinity has had a long history of being measured using a variety of methods with varying degrees of accuracy. Currently, the most common method of measuring salinity is through the use of a Conductivity, Temperature, Depth (CTD) which is a device that measures the conductivity, temperature, and depth of a sample of water. *table summary*

2.2.1 Salinity from Chlorinity

The chemical composition of ocean water with a salinity of 35‰ contains 19.35‰ of Chlorine and 10.77‰ of Sodium with the following ions only accounting for a total of just above 3‰ of the total dissolved solids in the water [7]. This allowed oceanographers to estimate that the salinity of ocean water was directly proportional to the amount of chlorine in the water. The chlorinity of a solution had an established definition which was 'the mass of silver required to precipitate completely the halogens in 0.328 523 4kg of the ocean-water sample' [8] which could be tested to a degree of accuracy using titration. In 1969, an accurate relationship between these was established by Reference [8] and thus salinity S was redefined using chlorinity Cl as shown in Equation 2.1.

$$S(‰) = 1.80655 \times\ Cl(‰) \tag{2.1}$$

accuracy achieved?, device?, limitations?

2.2.2 Salinity from Conductivity

The conductivity of a liquid is a measure of the ability of the water to conduct an electrical current which is related to the number of free electrons present in the liquid which is in turn related to the number of ions present in the liquid. In the case of salt water, the ions present are from the dissolved salts in the water which are how salinity is quantified. The relationship between salinity and conductivity takes into account all the ions present in the water and thus was a more apt measure of salinity than chlorinity which is why salinity was redefined in terms of salinity. Calculating salinity from conductivity was however not as straight forward requiring several equations which are discussed in Section 3.1. *accuracy achieved?, device?, limitations?*

2.2.3   Salinity from Density

The density of pure water varies with temperature and is considered to be approximately $1000 kg.m^{-3}$ at $4°C$ [9]. The concept of measuring salinity with density is based on the fact that the density of water increases with the amount of denser matter, for example, dissolved salts added to the water which in turn relates to salinity. The relationship between salinity and density can be estimated to be linear by Equation **??** where ρ is the density of the water, ρ_0 is the density of pure water, k is a proportionality constant, and S is the salinity of the water [10][11].

$$\rho = \rho_0(1 + kS) \tag{2.2}$$

This relationship was further refined by Reference [12] which included temperature variation in the relationship. Reference [12] also claimed that the relationship between salinity and density was a better measure of salinity than conductivity as the standard potassium chloride solution used to calibrate the conductivity meters did not account for the other ions commonly present in salt water while the density of the water did. *accuracy achieved?, device?, limitations?*

2.2.4   Salinity from Microwave Radiation

Microwave radiation interacts with salt water in unique ways. Different temperature molecules in the water scatter microwaves differently and the pressure of the water can also affect this, but the most significant effect on the microwave radiation is from the presence of dissolved salts in the water which absorb and scatter the microwaves in detectable ways [13]. The relationship between salinity and microwave radiation is complicated but since microwave radiation does not require direct contact with the water, it is possible to measure the salinity of a sample of water from a far distance including from space [14]

This has allowed for the development of satellites that can measure the salinity which have been used to develop global salinity maps as shown in Figure **??**. The data measured using this method is reported to be accurate to within 0.1PSU [15], but this method requires multiple different readings to be taken in order to account for the different factors that affect the microwave radiation including Sea Surface Temperature (SST), surface air pressure, surface air temperature, faraday rotation, and surface wind speed [15].

2.2.5   Salinity from Interferometry

2.2.6   Salinity from Electromagnetic Induction

2.2.7   Salinity from Refractive Index

2.3   Salinity Measurement Devices

Chapter 3

Theory Development

3.1 The Calculation of Salinity From Conductivity

Salinity meters that use electrical conductivity are commonly known as CTDs which stands for CTD. As depth is a measurement derived from pressure, CTp is the preferred designation when performing calculations. This allows for the conductivity of a sample of water to be denoted by $C(S, T, p)$ where conductivity is a function of salinity S, temperature T, and pressure p which is the convention in oceanography [5].

Pressure in the salinity equation is taken relative to sea level where $p = 0dbar$ is equivalent to an absolute pressure of $P = 101\,325Pa$. Using decibars (dbar) for pressure is a common practice in oceanography as it is a unit of pressure that is equal to roughly one meter of water depth [16].

The Practical Salinity Scale defines Practical salinity S_p in terms of a conductivity ratio K_{15} which is the conductivity of a sample of water at a temperature of 15°C and a pressure equal to one standard atmosphere divided by the conductivity of a standard potassium chloride solution at the same temperature and pressure. The standard potassium chloride solution is $32.4356g$ of KCl dissolved in $1.000kg$ of water and when the ratio between the conductivity of a sample of water and the standard solution, or K_{15}, equals 1 the Practical Salinity S_p is, by definition, 35.

When K_{15} is not equal to 1, the Practical Salinity S_p can be calculated using the PSS-78 equation shown in Equation 3.1.

$$S_p = \sum_{i=0}^{5} a_i (K_{15})^{i/2} \quad \text{where} \quad K_{15} = \frac{C(S_p, 15°C, 0)}{C(35, 15°C, 0)} \tag{3.1}$$

All the coefficients for the salinity-conductivity equations, including a_i, are given in Table 3.1.

To calculate the salinity of a sample of water that is not at 15°C and $0dbar$, the conductivity ratio of the sample can be expanded into the product of three ratios which are labelled R_p, R_t, and r_t respectively. The conductivity measurement taken in the field $C(S_p, t, p)$ is related to the conductivity of the standard solution $C(S_p, 15°C, 0)$ which the device is calibrated with and is represented by R in Equation 3.2. [17]

$$R = \frac{C(S_p, t, p)}{C(S_p, 15°C, 0)} = \frac{C(S_p, t, p)}{C(S_p, t, 0)} \cdot \frac{C(S_p, t, 0)}{C(35, t, 0)} \cdot \frac{C(35, t, 0)}{C(35, 15°C, 0)} = R_p R_t r_t \tag{3.2}$$

In order to calculate the salinity of the sample R_t must be found which takes a similar for to K_{15}. r_t is

first calculated using the temperature of the sample

$$r_t = \sum_{i=0}^{4} c_i(t)^i \tag{3.3}$$

following which R_p is calculated using the sample's pressure p, temperature t and conductivity ratio R,

$$R_p = 1 + \frac{\sum_{i=1}^{3} e_i p^i}{1 + d_1(t) + d_2(t)^2 + R[d_3 + d_4(t)]} \tag{3.4}$$

and finally R_t is calculated using r_t, R_p and R.

$$R_t = \frac{R}{R_p r_t} \tag{3.5}$$

Note that for a sample temperature of 15°C and pressure of $0 dbar$, r_t and R_t both equal 1 which leaves R_t equal to R and thus Equation 3.1 can be used to calculate the Practical Salinity S_p. For temperatures other than 15°C, the Practical Salinity S_p can be calculated using Equation 3.6 where $k = 0.0162$. [17]

$$S_p = \sum_{i=0}^{5} a_i (R_t)^{i/2} + \frac{t - 15}{1 + k(t - 15)} \sum_{i=0}^{5} b_i (R_t)^{i/2} \tag{3.6}$$

Table 3.1: Coefficients for the PSS-78 equations [17].

i	a_i	b_i	c_i	d_i	e_i
0	0.0080	0.0005	$6.766097 \cdot 10^{-1}$		
1	-0.1692	-0.0056	$2.00564 \cdot 10^{-2}$	$3.426 \cdot 10^{-2}$	$2.070 \cdot 10^{-5}$
2	25.3851	-0.0066	$1.104259 \cdot 10^{-4}$	$4.464 \cdot 10^{-4}$	$-6.370 \cdot 10^{-10}$
3	14.0941	-0.0375	$-6.9698 \cdot 10^{-7}$	$-4.215 \cdot 10^{-3}$	$3.989 \cdot 10^{-15}$
4	-7.0261	0.0636	$1.0031 \cdot 10^{-9}$	$-3.107 \cdot 10^{-3}$	
5	2.7081	-0.0144			

Note that the coefficients a_i precisely sum to 35 such that the Practical Salinity S_p is 35 when K_{15} or $R_t = 1$ as per Equation 3.1 and Equation 3.6. Additionally, the coefficients b_i precisely sum to 0 such that the Practical Salinity S_p does not depend on the temperature of the water when $R_t = 1$ as per Equation 3.6. [17]

Equation 3.1 to Equation 3.6 are valid for $2 < S_p < 42$ and $-2°C < t < 35°C$ and $0 dbar < p < 10\,000 dbar$ [17]. The range for salinity has been extended using estimations by Reference [18] for $0 < S_p < 2$ and Reference [19] for $42 < S_p < 50$.

The temperatures used in Equation 3.1 to Equation 3.6 are on the IPTS-68 scale [20] and have not been corrected to the currently used ITS-90 scale [21]. In order to correctly calculate the salinity, the

temperatures should be converted to the IPTS-68 scale using the equation $t_{68} = 1.00024t_{90}$ before calculating salinity [21].

3.2 Electrical Characteristics of Salt Water

PSU vs TSD vs conductivity vs resistivity, salinity equation, capacitance of salt water, non-constant conductivity vs voltage.

3.3 External Factors Affecting Electrical Characteristics of Salt Water

3.4 Electrical Fringing in Conductive Materials

3.5 Electromagnetic Interference of Salt Water

Chapter 4

Methodology

4.1 Device Design

4.1.1 Salinity Measurement Method

help Of the available methods for measuring salinity, the most common method used in oceanography is the conductivity method. This is because conductivity of salt water is the easiest to repeatably measure and provides the most consistent accuracy. Information on other methods can be found in the literature review.

One of the most common methods of measuring conductivity of a liquid is to measure the resistance between two electrodes or probes in the liquid and use that to determine its conductivity. The shape and material of the probes are an important factor which affect the measurement accuracy and drift as well as the ease of calculation from resistance to conductivity.

4.1.2 Conductivity Probe Material

Ideal probes for measuring conductivity in salt water need to have zero resistance, infinite corrosion resistance and be able to confine the electrical current in the water to a specific volume. The zero resistance will allow the resistance that it measured to be entirely due to the water, although most conductive materials have a conductivity in the order of $10^8 S/m$ which causes negligible resistance compared to water which has a conductivity range of $0 - 5S/m$. The infinite corrosion resistance will allow the probes to last indefinitely in the highly corrosive salt water. The confinement of the electrical current allows for an easier calculation of the conductivity ρ from resistance R if the cross-sectional area A and length l of the water between the probes is known as shown by Equation 4.1.

$$\rho = \frac{RA}{l} \tag{4.1}$$

There are several metals known for their corrosion resistance which are used in corrosive environments including marine environments. The most abundant of these are aluminium and stainless steel, followed by nickel and copper alloys, such as Monel or brass, and finally titanium. Additionally, the precious metals gold, silver and platinum are also known for their exceptional corrosion resistance which exceeds the aforementioned metals, although they are significantly more expensive.

The choice of material aimed at using materials with the highest corrosion resistance while still choosing materials that were attainable and within this project's budget. Titanium is the most corrosive resistant of the non-precious metals and has an acceptable resistivity of $4.5 \cdot 10^{-7} \Omega \cdot m$ which is about 25 times

that of copper. Titanium wire was available through off-cuts from a project being conducted by the Chemical Engineering Department of the University of Cape Town, and thus it was possible to use this material for the electrodes.

Of the precious metals, gold is one of the most accessible as it is a common material used in Printed Circuit Boards (PCBs) manufacturing primarily because of its high corrosion resistance while it maintains a low resistivity of $2.44 \cdot 10^{-8}\Omega \cdot m$ similar to copper. Electroless Nickel Immersion Gold (ENIG) PCB manufacturing is a process where nickel followed by gold are deposited onto the copper of the PCB using chemical reactions. While this process is expensive, it is affordable within this project's budget and made gold a possible material for the electrodes.

Gold and titanium were both used as electrodes for this project due to their high corrosion resistance, conductivity and availability.

4.1.3 Conductivity Probe Design

Gold electrodes made using the ENIG PCB manufacturing process were chosen to be the primary electrodes for the device. The high corrosion resistance and conductivity of gold were advantageous, and the PCB allowed the probes to be made with a known area and length of the water between the probes.

Some scientific papers that attempt to measure salinity have an uncertainty on whether salt water has a constant resistivity relative to the voltage applied to it or not. In order to verify this, the resistance of the water between the probes needed to be measured at different voltages while other factors were kept constant which necessitated close attention to the fringing effect of the electrical current between the probes. Thus, wide flat pads were used on the PCB probes, and they were placed them close together to reduce the amount of current fringing allowing for a more accurate calculation of the conductivity. To further reduce the fringing, a fringe guard was added to the probes which consisted of a pad that outlined the main conductivity pads that repeated the same voltage as the main pads using an op-amp which would allow for the fringing to be taken up by the fringe guard and not affect the resistance measurement.

The dimensions of the gold electrodes were chosen somewhat arbitrarily with the pads having a large area while being placed relatively close together to reduce the fringing but not too close to prevent water from flowing between the pads. Additionally, the aim was to keep the resistance between the pads low to lower the amount of voltage required to generate a current through the water thus further reducing the fringing. The gold electrodes were designed with a $20mm \times 20mm$ pad area with a $2mm$ wide fringe guard surrounding the majority of the pad and were spaced $10mm$ apart as shown in Figure 4.1. This gave a resistance of 3.75Ω to 6.25Ω between the gold electrodes for salinities of 40 to 25 on the practical salinity scale respectively.

The titanium electrodes are substantially simpler and cheaper than the gold electrodes and would be the preferred electrodes if the fringing effect could be accounted for. Provided the testing with the gold electrodes is able to prove a constant resistance-voltage relationship, the fringing effect between the titanium electrodes could be measured and accounted for allowing for them to be used as the primary electrodes in a future iteration of the device. The titanium wire that was available for this project
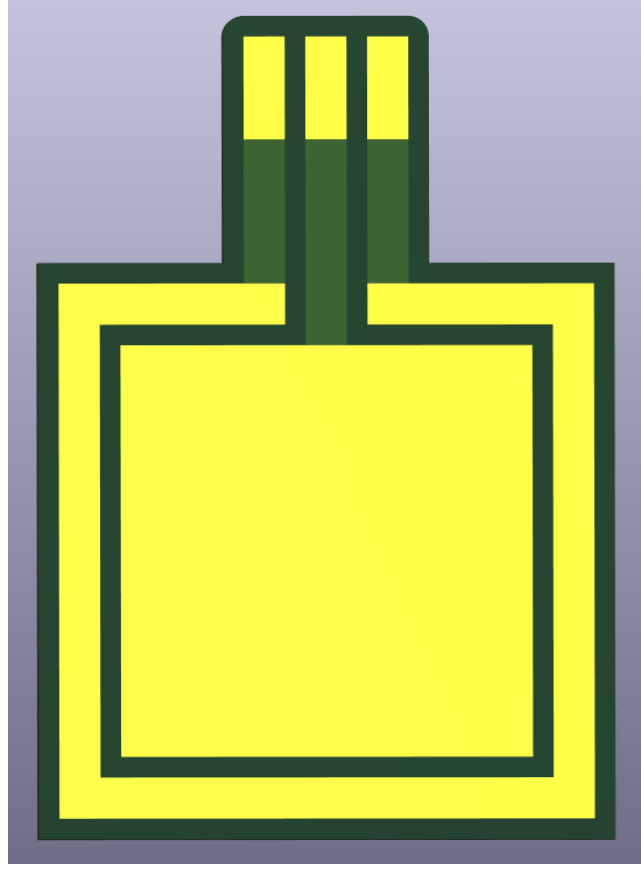
Figure 4.1: The gold electrode PCB design.

was $1mm$ in diameter and in order to account for the unknown resistance between the electrodes, the design allowed for an adjustable spacing between the electrodes and adjustable electrode length.

4.1.4 Resistance Measurement Method

The most common and practical method of measuring resistance is to use a resistor divider circuit. Current meters are also used to measure resistance, but most of them use the same principle of a resistor divider circuit to determine the current. This project chose to use a large R_1 in series with the electrodes such that the voltage between the probes would be lower which would further reduce the fringing effect. The measurement taken from the voltage divider was then amplified by a factor of 11 to increase the resolution of the measurement.

4.1.5 Circuit Overview

Figure 4.2 shows a simplified overview of the resistance measuring circuit that was used in this project. The voltage driving the resistor divider was provided by a Digital to Analogue Converter (DAC) such that the voltage could be varied and the resistance-voltage relationship could be determined for the titanium electrodes. The resistance across the titanium electrodes remained uncertain and thus, in addition to the varied spacing and electrode length, alternative resistor values for R_1 were provided which could be selected using solder jumpers on the device.

The R_1 values were chosen to be 100Ω, $1k\Omega$ and $10k\Omega$ which would be used when the resistance between the probes is $1\Omega - 10\Omega$, $10\Omega - 100\Omega$ and $100\Omega - 1k\Omega$ respectively. This would allow for a
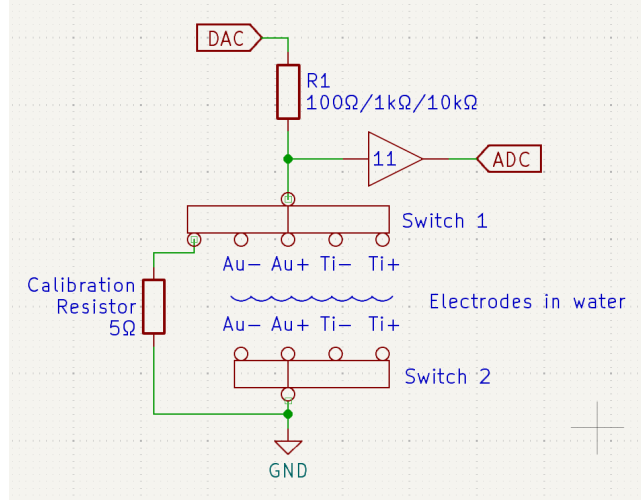
Figure 4.2: A simplified representation of the resistance measuring circuit.

minimum resolution of 11% of V_{CC} for the voltage measurement by the Analogue to Digital Converter (ADC) as shown by Equation 4.2.

$$\frac{1\Omega}{1\Omega + 100\Omega} * 11 = 11\% \quad \frac{10\Omega}{10\Omega + 100\Omega} * 11 = 100\% \tag{4.2}$$

Switch 1 allows R_1 to be connected to any of the four electrodes or a calibration resistor of 5Ω and switch 2 allows for the other electrode to be connected to ground. For example, switch 1 could be connected to Ti+ and switch 2 could be connected to Ti- to measure the resistance between the titanium electrodes. This configuration also allows current to flow in both directions between electrodes which can prevent excessive build of chlorine gas or sodium electroplating on the electrodes by taking a resistance measurement in both directions in rapid succession.

In order to increase the measurement accuracy of the resistance, multiple high accuracy resistors were placed in series to attain the values of R_1 and the calibration resistor as this decreases the uncertainty of their resistance. This decreases the total uncertainty $\delta_{R_{total}}$ by a factor of the number of parallel resistors n compared to the individual resistor uncertainty δ_R as shown by Equation 4.3 to Equation 4.5.

$$[!h] R_{total} = \left[\sum_{i=1}^{n} \frac{1}{R}\right]^{-1} = \left(\frac{n}{R}\right)^{-1} = \frac{1}{n} \cdot R \tag{4.3}$$

$$[!h] \text{for a function } f(x_1, x_2, \ldots, x_n), \text{its uncertainty } \delta_f = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i} \delta x_i\right)^2} \tag{4.4}$$

$$[!h] \therefore \delta_{R_{total}} = \sqrt{\left(\frac{\partial R_{total}}{\partial R} \delta_R\right)^2} = \sqrt{\left(\frac{1}{n} \delta_R\right)^2} = \frac{1}{n} \delta_R \tag{4.5}$$

The resistances for R_1 were made from 3 parallel resistors with tolerance $\pm 1\%$ giving a total uncertainty of $\pm 0.\bar{3}\%$ and the calibration resistor was made from 4 parallel resistors with tolerance $\pm 1\%$ giving a total uncertainty of $\pm 0.25\%$.

Figure 4.3 shows an example switch configuration where the gold electrodes are used. The buffer
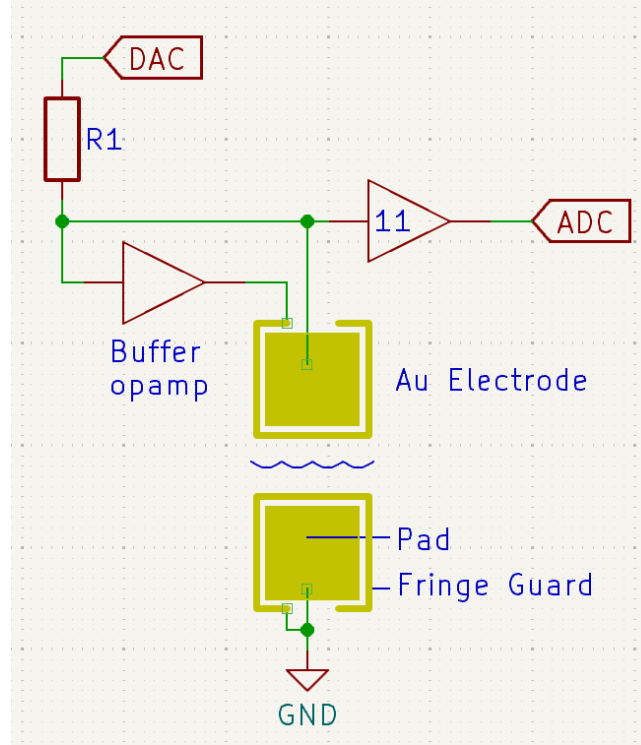
Figure 4.3: A simplified representation of the resistance measurement circuit using the gold electrodes with the fringe guard.

op-amp has unity gain and is used to repeat the voltage going to the pad of the top electrode to its fringe guard while the other pad and fringe guard are connected to ground. In theory, this should allow for the fringing to be absorbed by the fringe guard and not affect the resistance measurement, however switches were added electrically connect or disconnect the fringe guard should it interfere with the resistance measurement. The current flowing between the fringe guards was assumed to be less than that of the pads and thus there was no need to limit the current from the op-amp.

4.1.6 Salinity Calculation and Display

In order to measure the salinity of the sea ice, the probe needed to be lowered into the water and measure salinity at various depths. There are two methods for capturing the salinity data: either to constantly record the salinity data as the device it lowered through the water column or to have the device take a measurement when instructed by a controller. The former method creates logistical problems with waterproofing the device and retrieving data while the latter was a more user-friendly approach allowing researchers to control exactly which depths the salinity is measured at and was chosen for this project.

The controller consisted of a PCB with input buttons and two output 7-segment displays to control and relay salinity information, and a RS485 communication port and a simple microcontroller. The RS485 communication port was chosen as the communication protocol as RS485 has the longest range and a high noise resistance which is necessary for the device to be used in the ocean which has high Electromagnetic Interference (EMI). The microcontroller was arbitrarily chosen from the STM32F030 series as it was relatively cheap, and it did not need to perform any complex calculations.

With an external controller, a waterproofed probe could be lowered into the water and measure the water's salinity. The chosen method of making a waterproof probe was to create a PCB and coat it with a layer of epoxy resin to waterproof it as this was the most familiar and cost-efficient method available. The probe PCB was designed with the equipment necessary to measure the salinity including ports for the conductivity probes, the circuitry required to measure the resistance as shown in Figure 4.2, temperature and depth sensors which are discussed in Section 4.1.7, an RS485 communication port and a microcontroller. The microcontroller that was chosen was from the STM32F401 series as STM microcontrollers as it had a Floating Point Unit (FPU) which allowed for calculating salinity on the probe.

4.1.7 Temperature and Depth Measurement

Depth sensors that a waterproof are too expensive for this projects budget. However, there have been alternative approaches which use non-waterproof sensors that are isolated form the water using a flexible membrane that would allow the pressure to be transmitted to the sensor. This project included a depth sensor with the aim to use this method to measure the depth of the probe in the water, however it also included a method for the user to manually input the depth of the probe in the water using the controller should this method fail.

The temperature sensor used in this project was an arbitrarily chosen, surface mount temperature sensor that had high accuracy and a wide temperature range. The temperature sensor should be coated with a thin layer of epoxy resin to waterproof it as epoxy resin is a poor thermal conductor and thus a thinner layer would allow for a more accurate temperature measurement. Lastly, as a convenient backup, the STM32F401 series of microcontroller contain a temperature sensor which is significantly less accurate with an accuracy of about $1°C$

4.2 Device Coding

ur mom

Chapter 5

Conclusions

The purpose of this project was to...

This report began with...

The literature review was followed in Chapter...

The bulk of the work for this project followed next, in Chapter...

In Chapter...

Finally, Chapter... attempted to...

In summary, the project achieved the goals that were set out, by designing and demonstrating...

Chapter 6

Recommendations

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