

Salinity Sensor



Prepared by:

Cameron Clark Department of Electrical Engineering
University of Cape Town

Prepared for:

Justin Pead
Department of Electrical Engineering
University of Cape Town

September 22, 2024

Submitted to the Department of Electrical Engineering at the University of Cape Town in partial fulfilment of the academic requirements for a Bachelor of Science degree in Mechatronics

Keywords: Salinity, Sensor, Conductivity, Temperature, Water, Measurement, Electronics, PCB

Declaration

1. I know that plagiarism is wrong. Plagiarism is to use another's work and pretend that it is one's own.
2. I have used the IEEE convention for citation and referencing. Each contribution to, and quotation in, this report from the work(s) of other people has been attributed and has been cited and referenced. Any section taken from an internet source has been referenced to that source.
3. This report is my own work and is in my own words (except where I have attributed it to others).
4. I have not paid a third party to complete my work on my behalf. My use of artificial intelligence software has been limited to (specify precisely how you used AI to assist with this assignment, and then give examples of the prompts you used in your first appendix).
5. I have not allowed and will not allow anyone to copy my work with the intention of passing it off as his or her own work.
6. I acknowledge that copying someone else's assignment or essay, or part of it, is wrong, and declare that this is my own work



September 22, 2024

Cameron Clark

Date

Acknowledgements

Abstract

Contents

List of Figures	vii
Abbreviations	viii
1 Introduction	1
1.1 Background	1
1.2 Objectives	1
1.3 System Requirements	1
1.4 Scope & Limitations	2
1.5 Report Outline	2
2 Literature Review	3
2.1 A Brief History of Salinity	3
2.2 Salinity Measurement Methods and Devices	4
2.2.1 Salinity from Chlorinity	4
2.2.2 Salinity from Conductivity	5
2.2.3 Salinity from Density	5
2.2.4 Salinity from Microwaves	5
2.2.5 Salinity from Satellite Remote Sensing	5
2.2.6 Salinity from Interferometry	5
2.2.7 Salinity from Electromagnetic Induction	5
2.2.8 Salinity from Refractive Index	5
2.3 Salinity Measurement Devices	5
3 Theory Development	6
3.1 The Calculation of Salinity	6
3.1.1 The Salinity and Chlorinity Relationship	6
3.1.2 The Salinity and Conductivity Relationship	6
3.2 Electrical Characteristics of Salt Water	8
3.3 External Factors Affecting Electrical Characteristics of Salt Water	8
3.4 Electrical Fringing in Conductive Materials	8
3.5 Electromagnetic Interference of Salt Water	8
4 Methodology	9
4.1 Device Design	9
4.1.1 Salinity Measurement Method	9
4.1.2 Conductivity Probe Material	9
4.1.3 Conductivity Probe Design	10

4.1.4	Conductivity Measurement and Calibration	11
4.1.5	Accounting for Electrical Fringing	12
4.1.6	Accounting for Unkown Resistivity of Salt Water	12
4.1.7	Salinity Calculation and Display	12
4.1.8	Temperature and Depth Measurement	12
4.1.9	Controller and Data Logging	12
4.2	Device Coding	12
5	Conclusions	13
6	Recommendations	14
	Bibliography	15

List of Figures

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 kilometers of ocean water [1].	3
4.1	The gold electrode Printed Circuit Board (PCB) design.	11

Abbreviations

‰ Parts Per Thousand

CTD Conductivity, Temperature, Depth

ENIG Electroless Nickel Immersion Gold

PCB Printed Circuit Board

PSU Practical Salinity Units

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

more 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

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetur id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

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

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetur id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

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

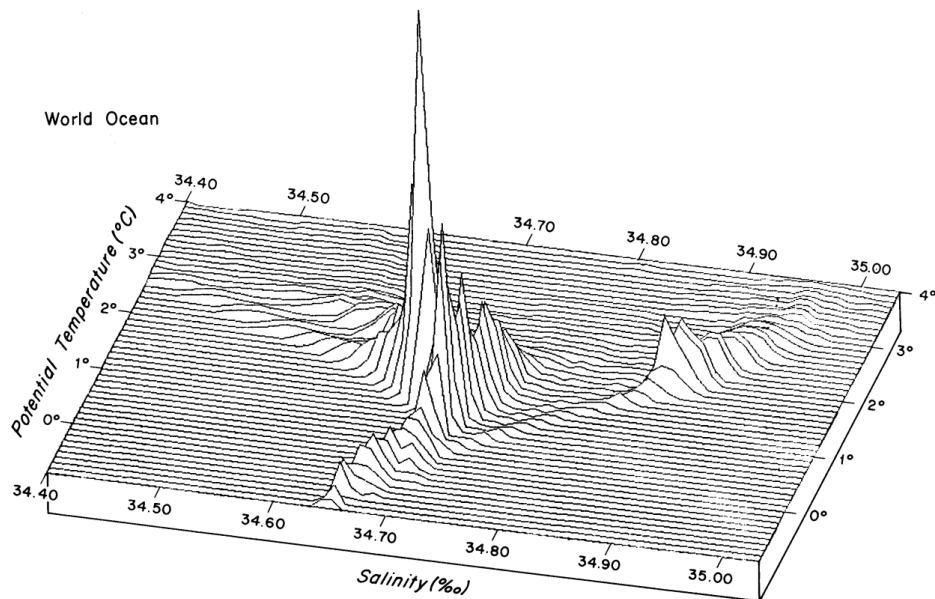


Figure 2.1: Histogram showing the volume of ocean water relative to temperature and salinity bins. The highest peak corresponds to a volume of 26 million cubic kilometers of ocean water [1].

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 3.1.1.

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.

2.2 Salinity Measurement Methods and Devices

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.

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

accuracy achieved?, device?, limitations?

2.2.2 Salinity from Conductivity

2.2.3 Salinity from Density

2.2.4 Salinity from Microwaves

2.2.5 Salinity from Satellite Remote Sensing

2.2.6 Salinity from Interferometry

2.2.7 Salinity from Electromagnetic Induction

2.2.8 Salinity from Refractive Index

2.3 Salinity Measurement Devices

CTDs, refractometers, conductivity meters, salinometers.

Chapter 3

Theory Development

3.1 The Calculation of Salinity

3.1.1 The Salinity and Chlorinity Relationship

3.1.2 The Salinity and Conductivity Relationship

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 $p = 0\text{dbar}$ is equivalent to an absolute pressure of $P = 101\,325\text{Pa}$. 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 [9].

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.

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

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 $C(S_p, 15^\circ\text{C}, 0)$ which the device is calibrated with and is represented by R in

Equation 3.2. [10]

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

In order to calculate the salinity of the sample R_t must be found which takes a similar form to K_{15} . r_t is first calculated using the temperature of the sample

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

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

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

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

$$R_t = \frac{R}{R_p r_t} \quad (3.5)$$

Note that for a sample temperature of $15^\circ C$ 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 $15^\circ C$, the Practical Salinity S_p can be calculated using Equation 3.6 where $k = 0.0162$. [10]

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

Table 3.1: Coefficients for the PSS-78 equations [10].

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. [10]

Equation 3.1 to Equation 3.6 are valid for $2 < S_p < 42$ and $-2^\circ C < t < 35^\circ C$ and $0 \text{ dbar} < p <$

10 000 $d\text{bar}$ [10]. The range for salinity has been extended using estimations by Reference [11] for $0 < S_p < 2$ and Reference [12] for $42 < S_p < 50$.

The temperatures used in Equation 3.1 to Equation 3.6 are on the IPTS-68 scale [13] and have not been corrected to the currently used ITS-90 scale [14]. 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 [14].

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

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 $0 - 5 S/m$. 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.

$$\rho = \frac{RA}{l} \quad (4.1)$$

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

The 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 calculate salinity have an uncertainty on whether salt water has a constant resistivity 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 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 op-amps 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 goal to have pads with a large area put relatively close together to reduce the fringing but 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 the gold electrodes a resistance of around 5Ω .

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 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.

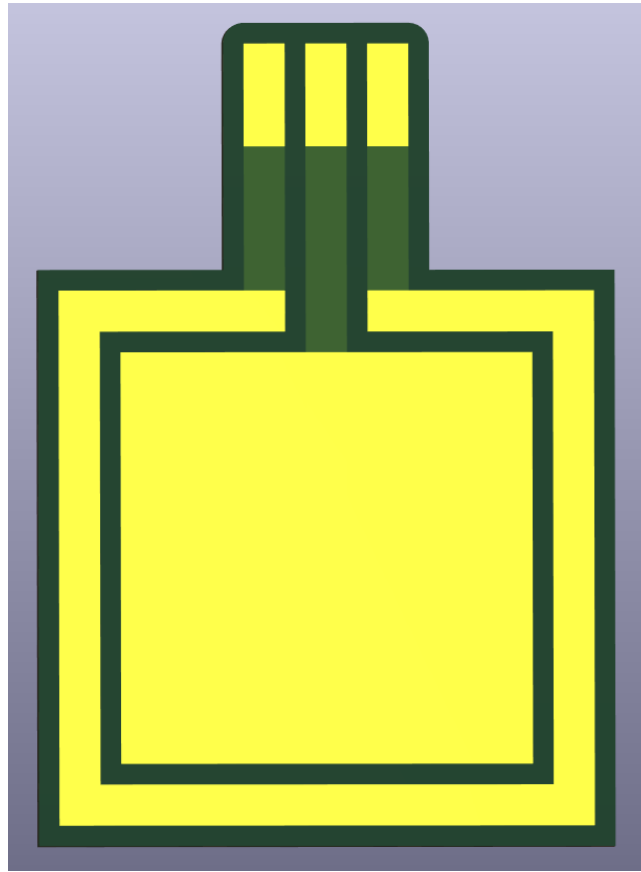


Figure 4.1: The gold electrode PCB design.

4.1.4 Conductivity Measurement and Calibration

The conductivity measurement is done by measuring the resistance of the water between the two electrodes and performing a calculation to convert this to a conductivity value. The most common and practical method of measuring resistance is to use a resistor divider circuit and measure the voltage across the water.

As electrical fringing is a problem in conductive materials such as salt water and increase exponentially with voltage, this device aimed to keep the voltage across the water low. This was achieved by aiming for a resistor divider with R_1 around 10 times greater than R_2 which would be the salt water. The voltage of the voltage divider was then amplified by a factor of 10 to increase the resolution of the measurement.

A distributed factor about salt water is whether its resistivity is constant or not. To determine this, the resistor divider was powered using a DAC which would allow for the voltage across the water to be varied and the resistance to voltage fit could be calculated.

To account for certain uncertainties of the design such as the resistance between the titanium electrodes, the resistor R_1 was given multiple options which could be selected using solder jumpers in the device.

Additionally to combat the effects of fringing a fringe guard was added to the gold electrodes that would ideally take up all the fringing allowing for the resistance measurement to be completely accurate.

fringe guard image and calcs here

4.1.5 Accounting for Electrical Fringing

fill from above

4.1.6 Accounting for Unkown Resistivity of Salt Water

fill from above

4.1.7 Salinity Calculation and Display

The salinity probe was required to be lowered into the water and the salinity to be measured. The two options for capturing the salinity were to either record the data and write it to an SD card which would create problems with waterproofing the device and making the SD card accessible. The alternative was to have a probe that communicates with a controller where the controller would instruct the probe to take a measurement and then the probe would send the data back to the controller. RS485 for coms.

4.1.8 Temperature and Depth Measurement

The depths sesnors that are waterproof are increadibly expensive which made them unfeasable for this project. 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.

The temperature sensor used in this project was a XXX which was chosen for its accuracy and low cost. The temperature sensor must be close to the water to prevent the low thermal conductivity of the epoxy resin from affecting the temperature measurement. Additionally the STM was powerful enough to include its own temperature sensor.

4.1.9 Controller and Data Logging

waterproofing device

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

Bibliography

- [1] *The Influence Of Formation Anisotropy Upon Resistivity - Porosity Relationships*, ser. SPWLA Annual Logging Symposium, vol. All Days, 06 1981.
- [2] N. Snow and I. D. C. (NSIDC), “Ice sheet quick facts,” 2024. [Online]. Available: <https://nsidc.org/learn/parts-cryosphere/ice-sheets/ice-sheet-quick-facts>
- [3] R. H. Stewart, *Introduction to Physical Oceanography*. Texas A&M University Press, 2004. [Online]. Available: <https://www.uv.es/hegigui/Kasper/por%20Robert%20H%20Stewart.pdf>
- [4] R. F. HU Sverdrup, MW Johnson, *The Oceans, Their Physics, Chemistry, and General Biology*. New York: Prentice-Hall, 1942. [Online]. Available: <http://ark.cdlib.org/ark:/13030/kt167nb66r/>
- [5] E. L. Lewis and R. G. Perkin, “Salinity: Its definition and calculation,” *Journal of Geophysical Research*, vol. 83, no. C1, pp. 466–478, 1978. [Online]. Available: <https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/JC083iC01p00466>
- [6] Y. Zheng, Y. Liu, J. Zhou, and Y. Wang, “Electrical conductivity of the global ocean,” *Earth, Planets and Space*, vol. 69, no. 1, pp. 1–10, 2017.
- [7] E. B. editors, “Seawater,” *Encyclopædia Britannica*, 2024. [Online]. Available: <https://www.britannica.com/science/seawater>
- [8] W. S. Wooster, A. J. Lee, and G. Dietrich, “Redefinition of salinity,” *Journal of Marine Research*, vol. 27, no. 3, 1969.
- [9] S.-B. Scientific, “Conversion of pressure to depth,” 2024. [Online]. Available: <https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwuj6ebU1sCIAxXPiv0HHXDELasQFnoECCMQAQ&url=https%3A%2F%2Fwww.seabird.com%2Fasset-get.download.jsa%3Fid%3D54627861710&usg=AOvVaw1fK2h9jmgpiBuyu8lkM1tl&opi=89978449>
- [10] I. O. Commission, “Teos-10: The international thermodynamic equation of seawater (teos-10) for temperature, salinity, density, sound speed, and other oceanographic variables,” *Manuals and Guides*, vol. 56, 2010. [Online]. Available: https://www.teos-10.org/pubs/TEOS-10_Manual.pdf
- [11] T. L. Hill, *An introduction to statistical thermodynamics*. Courier Corporation, 1986.
- [12] A. Poisson and M. H. Gadhoumi, “An extension of the practical salinity scale 1978 and the equation of state 1980 to high salinities,” *Deep Sea Research Part I: Oceanographic Research Papers*, vol. 40, no. 8, pp. 1689–1698, 1993. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/096706379390022U>

- [13] G. T. Furukawa, J. L. Riddle, and W. R. Bigge, “The international practical temperature scale of 1968 in the region 13.81 k to 90.188 k as maintained at the national bureau of standards,” *Journal of Research of the National Bureau of Standards-A. Physics and Chemistry*, vol. 77A, no. 3, pp. 309–322, 1973. [Online]. Available: https://nvlpubs.nist.gov/nistpubs/jres/77A/jresv77An3p309_A1b.pdf
- [14] H. Preston-Thomas, “The international temperature scale of 1990 (its-90),” *Metrologia*, vol. 27, no. 107, pp. 3–10, 1990. [Online]. Available: https://www.nist.gov/system/files/documents/pml/div685/grp01/ITS-90_metrologia.pdf