# Floating RF-based Salinity Measurement Station

30.102 Electromagnetics and Applications, 2D Project

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***Abstract*—In this paper, an alternative to conventional commercial salinity measurement techniques that exploit the conductivity of water is proposed and tested. The proposed alternative is a single antenna construction with a multi-layer substrate which utilises the water under test, salt-water, as a dielectric (20 mm thickness). The design is tested by changing the salinity of salt-water from 30 to 40 practical salinity units (PSU). A vector network analyser is then used to record and determine the changes in the various parameters of the antenna — reflection coefficient and frequency — as the salinity of the water is modified. Results gathered suggest that though there exists a linear change in the magnitude of the reflection coefficient as the salinity is increased, the minor change observed coupled with the device's sensitivity to minor external movements makes current fabricated design iteration unsuitable for commercial applications in aquaculture.**

***Index Terms*—Near-field sensing, Salinity measurements, S parameter measurements, Salt-water, Aquaculture**

## I. Introduction

Commerical salinity measurement probes as seen in [6] and [5] utilise the conductivity of water in order to measure its salinity. However these probes may not be optimal for always-active, wide-area measurements for use in large-scale aquaculture with autonomous operation. Other methods of salinity measurement also exist in literature with methods such as refractometry and inteferometry demonstrated to work.

Existing antenna-based solutions for salinity measurement has been explored in literature. Almost all of such antenna-based solutions rely upon measuring the changes of various S-parameters as the salinity is varied. This is only possible as dielectric properties of water vary with changes in salinity levels. Such changes in the dielectric properties of aqueous solutions has been quantified previously [1]. Some of the references utilised by the team are detailed below.

The paper by K. Lee [4] analysed the effect of changing salinity on resonance frequency using a micro-strip patch antenna with "water-under-test" as a substrate. The patch and the ground planes are fabricated on two separate silicon substrates which sandwich a chamber for the water as a substrate. This paper has proven the feasibility of employing electromagnetic in salinity sensing by measuring the shift in resonant frequency of the antenna. Our design is similar to this particular setup albeit with key differences in size, size, and the results gathered. In [3], the researchers used a single micro-strip loop antenna to study the different responses of the reflection coefficient propagating through water when subjecting it to a different salinity. A. Hales et. al. [2] has demonstrated the use of a two antenna setup, with one being the transmitter and the other being the receiver, to quantify the attenuation of electromagnetic waves through the brine. Their results showed that the attenuation changes non-linearly within a range of salinity.

After conducting a literature review, the team aimed to create a patch antenna design capable of measuring the salinity of water with its end-use in aquaculture.

## II. Solution

### A. Design

The sensing unit, the patch antenna, is designed with multiple substrate layers as seen from the side in Figure 8. The layer thickness in the diagram is not to scale. The dimensions of the thickness are detailed in table I. For a 3-dimensional view of the antenna, view figures 4 and 5. Full dimensions of the sensing unit assembly is provided in figure 3. Here, the PLA plastic housing is used as a mould for precision epoxy casting. Epoxy is used to prevent water ingress through the plastic housing and affect the sensitive components of the antenna directly.

| | Thickness in mm |
|---|---|
| Copper | 0.035 |
| Rogers RO4350B Substrate | 0.762 |
| Epoxy | 2 |
| PLA Plastic | 2 |
| Water | 15 |

TABLE I: Substrate thicknesses

The proposed overall solution is a device that consists of a Single Board Computer (SBC), a sensor unit, a battery, and solar panel charging unit all of which are connected as seen in figure 7. The battery and solar panel make up the charging unit, which will ensure the device is able to sustain itself with minimal human efforts for maintenance.

The SBC serves as the processor of the data, as well as the communication bridge between the device and the operator. It will allow the operator to remotely control this device to work and receive a clear visualisation of the data collected if necessary.

The sensor unit, made up of the antenna and a MiniVNA (a commercially available Vector Network Analyser with 500 points with a bandwidth of up to 3 GHz), is the major detection component. The MiniVNA will measure the reflection coefficient and resonance frequency of the wave propagating through the two plates. This data will have to be calibrated to make into useful interpretations indicating salinity level. A screen capture of the application, VNA/J, used by the SBC to gather the S-parameter data from the antenna is provided as an example in figure 14.

### B. Working principles

The underlying theory behind why the relative permittivity of a medium changes is mentioned in the paper by E. Cheng et. al. [3]. The polarisation of $H_2O$ molecules vary due to the amount of ions present in the water. This causes the dielectric property of the medium to change, resulting in the different responses of the wave propagating through the medium as the relative permittivity of medium changes.

$$C' = \frac{\epsilon \cdot \omega}{h}$$

$$Z_0 = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}}$$

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

$Z_L$ is the impedance of our antenna which could be simulated using a parallel plate model.In the third equation above, $Z_L$ is the impedance value while the $Z_O$ is calculated from the second equation. As the relative permittivity of the substrate increases due to the rise in salinity, $C'$ will increase, leading to an increase in $Z_L$. Hence, based on third equation, the reflection coefficient will increase. This relationship is in line with the result obtained from experiments.

### C. Validation through Simulation

The antenna is designed using CST Microwave Studio with the antenna simulations run prior to fabrication with a PCB milling machine. This enables us to perform an antenna parameter sweep to quantify and optimise its performance. For example, a matching circuit with capacitors is designed for better $S_{1,1}$ parameter gain (Figure **??**). The antenna is designed to avoid radio and WiFi working frequencies in the frequency spectrum and is designed with a high Q-factor (having a sharp trough in $S_{1,1}$) to increase the antenna's sensitivity at a specific resonant frequency (approximately 1 GHz). This is evident in the simulation result Figure 10 which shows the resonant frequency of the antenna at around 1 GHz. It should be noted that the experimental value of the antenna's resonant frequency is 966 MHz.

Once the matching circuit is finalised, a simulation is conducted with changing salinity by varying the relative permittivity $\epsilon_r$ of the water substrate from 74–80. A linear relationship between the gain and the relative permittivity can be observed as shown in Figure 9.

### D. Experimental Setup

Multiple experiments have been conducted with increasing salinity ranges from 30 psu to 40 psu with an increment of 1 psu. The antenna is submerged in the salt-water and the results were taken (See figures 12 and 13. Temperature is kept constant at room temperature of 30 $\deg C$ and the water in the container is made sure to be still. Solutions at individual salinity levels were well prepared using a blender to allow for homogeneity. Before each experiment, the antenna is cleaned with dry paper towel to ensure that no residuals from the previous solution interfere with the current salinity level.

## III. Analysis and Discussion

Based on the experiments, salinity of water body can be measured using our antenna prototype. There is a strong relationship between salinity and antenna gain, which is described as a 2nd order polynomial fit.

However, we found that the pattern is not highly consistent on each run. Figure 15 shows the randomness of the measurement which we suspect is due to the connection of the antenna and the interference of surrounding signals, while figure 16 shows the antenna when it worked properly.

The second pattern 17 introduced different behaviour whereas the data have 2 different operating frequencies. The first section of the data, 31-37 PSU operates at 962.857 MHz with a 2nd order polynomial fitting. The fitting of this section shows that there is a strong correlation between salinity and antenna gain with 0.966 of R2 (Figure 18. The second section of the data, 38-40 psu, shows a random value in terms of gain and different operating frequencies which can be disregarded. We took the first section of the data set, and it shows a nice trend with 0.9361 R2.

The last data set 19 represents the more accurate data collection with bench top VNA (Figure 13) for final testing purposes. As a result, the bench top VNA also gave a promising result. From the figure, we can conclude that there is indeed a relationship between salinity and antenna gain in terms of 2nd order polynomial.

Based on our experiment, there is potential for measuring salinity with electromagnetic waves which have the advantage of getting a higher resolution reading compared to the existing salinity meter in the market. However, even though there are some data sets that show good relations, the setup was still not ready to be deployed in the real fish farm situation. It needs further testing with more proper conditions to find and determine the exact mathematical model to describe the relationship between salinity and the antenna gain.

Future improvements may include fabrication of a more robust setup, preparation of a better saltwater solution, introduction of substrates that are present in fish farm water bodies, and lastly more intensive testing to find the best way to quantify salinity.

## IV. Areas for Improvement

Current experimental results do not investigate how the effect of temperature, the presence of ions and other minerals might affect the performance of the antenna and its readings. Additionally, the construction of the antenna can be more robust as in its current iteration, the readings gathered can be inconsistent when the assembly is touched or modified in some way. Another area for improvement is to ensure that the design of the antenna allows for large changes in the measured S1,1 parameter when the salinity level changes. Current variations in the S1,1 parameter when salinity is varied are small enough that the results may be easily mistaken from the noise floor present without doing time-consuming multiple-run averages.

## V. Conclusion

This project shows the potential of the use of near-field electromagnetic sensing for salinity detection. The experimental data collected showed promise though there are many areas to work on for this solution to be considered reliable and robust enough for use in the field. However, with further experimentation and improvement, this antenna can most likely be used as an alternative to existing salinity measurement devices.

## Acknowledgment

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## References

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[6] Vernier. "Salinity sensor." (2022), [Online]. Available: https://www.vernier.com/product/salinity-sensor/.

## Appendix


Fig. 1: Salinity probe as sold by Omega


Fig. 2: Salinity probe as sold by Vernier

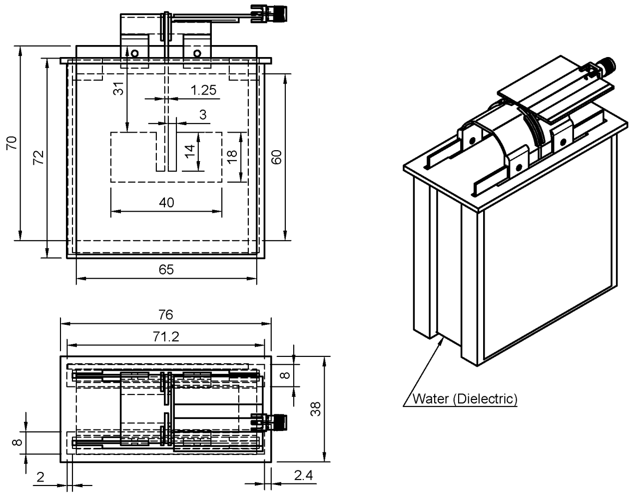


Fig. 3: Dimensions of the antenna assembly

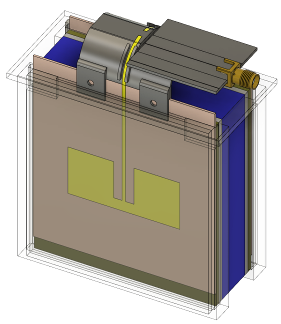

Fig. 4: View of the antenna design from the patch antenna side

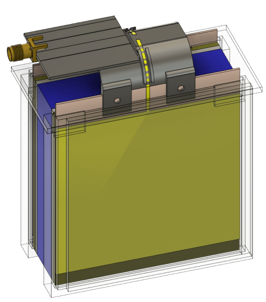

Fig. 5: View of the antenna design from the ground plane side

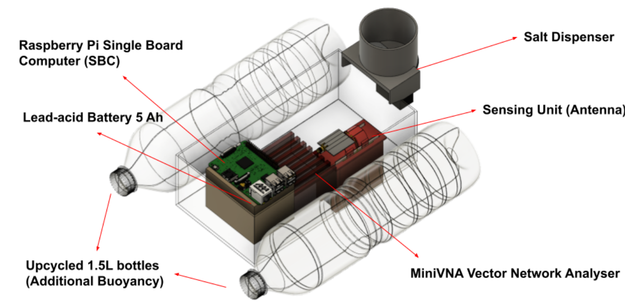


Fig. 6: Annotated render of the assembly with flotation bottles and salt dispenser

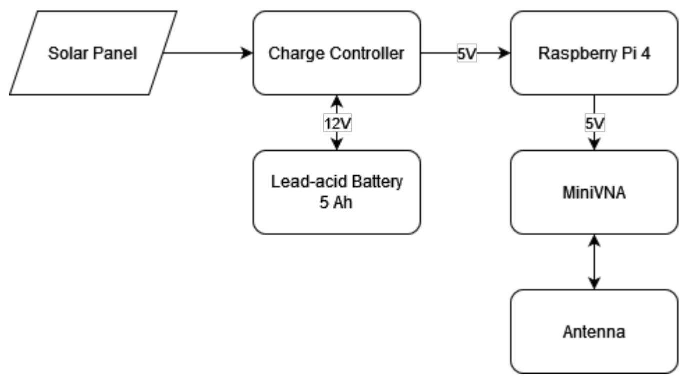


Fig. 7: Diagram of the power network

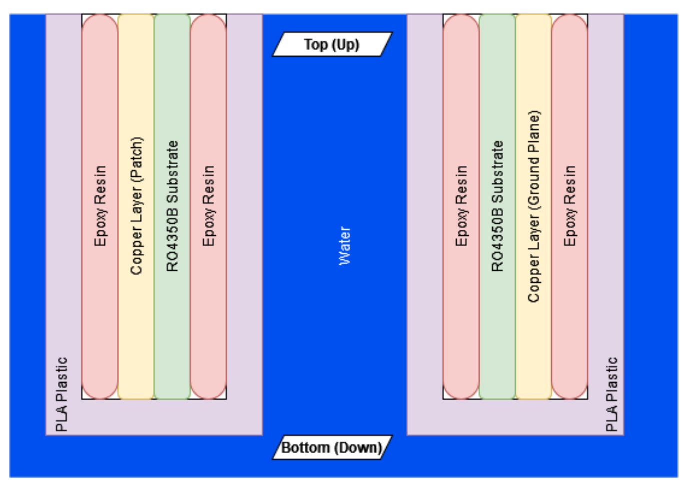


Fig. 8: Diagram of the antenna's multi-layered substrate

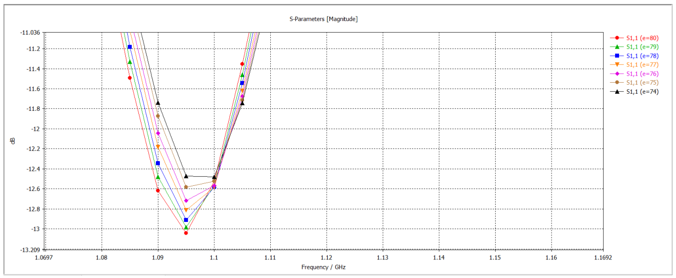


Fig. 9: Simulation S1,1 enlarged view at minimum point. Results with a matching circuit

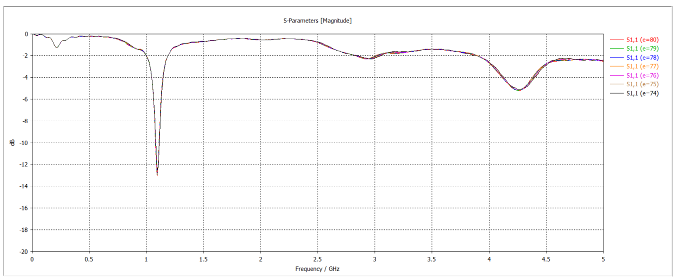


Fig. 10: Simulation S1,1 full spectrum view. Results without a matching circuit

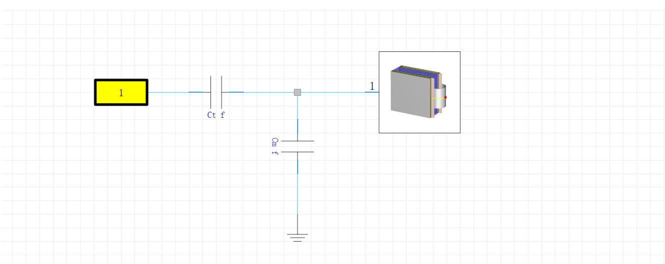

Fig. 11: Matching circuit

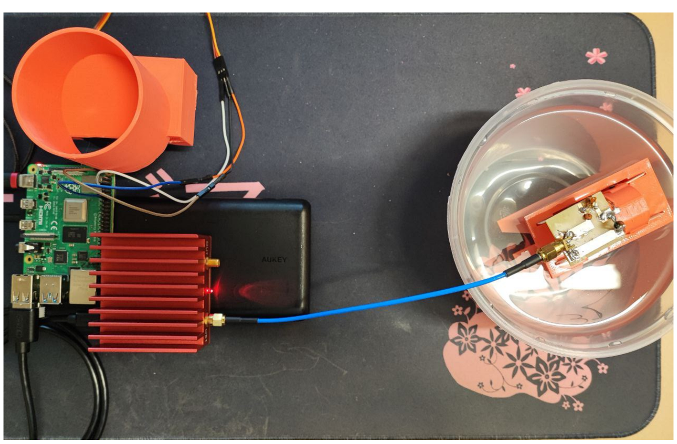

Fig. 12: Experimental setup with MiniVNA

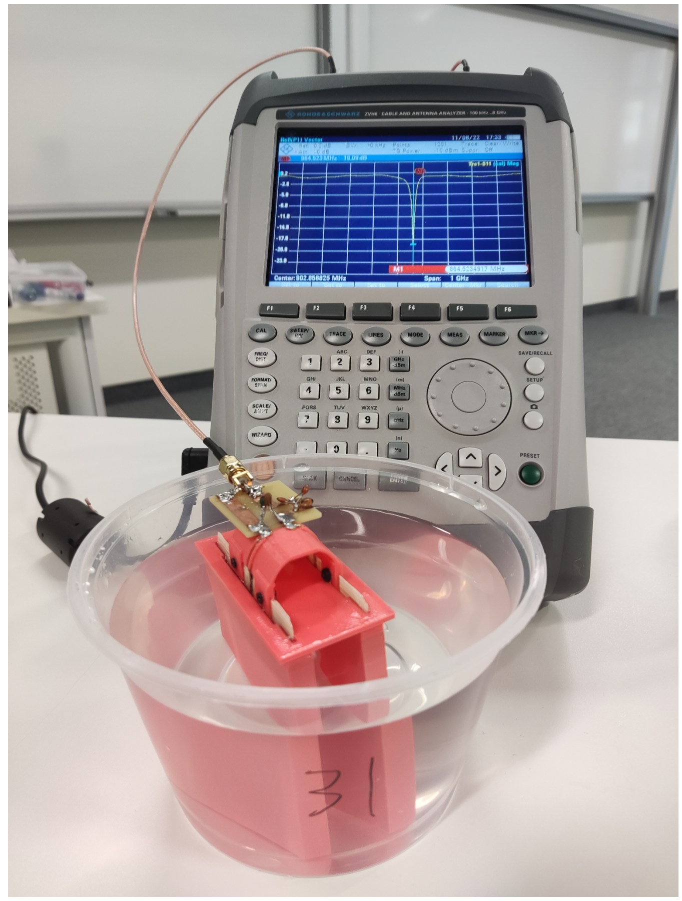


Fig. 13: Experimental setup with R&S Portable VNA

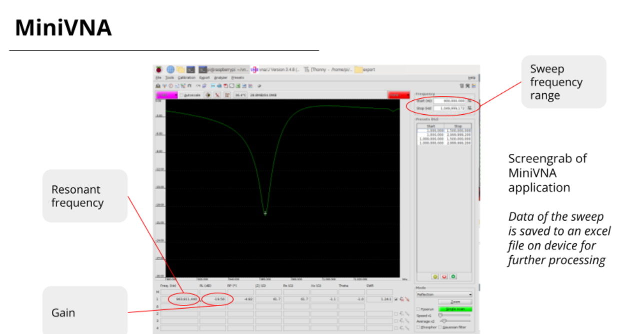


Fig. 14: A frequency sweep as done by the MiniVNA

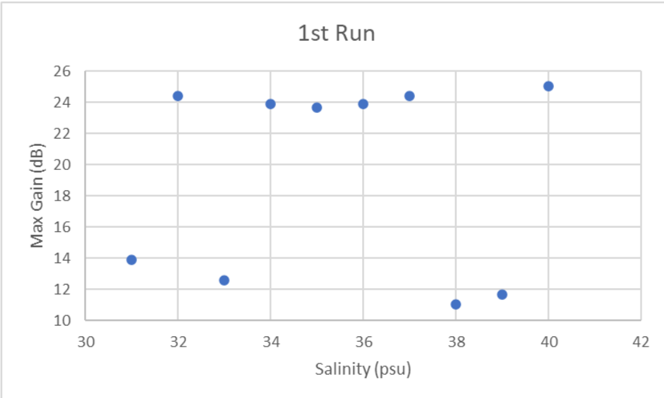


Fig. 15: Run 1a

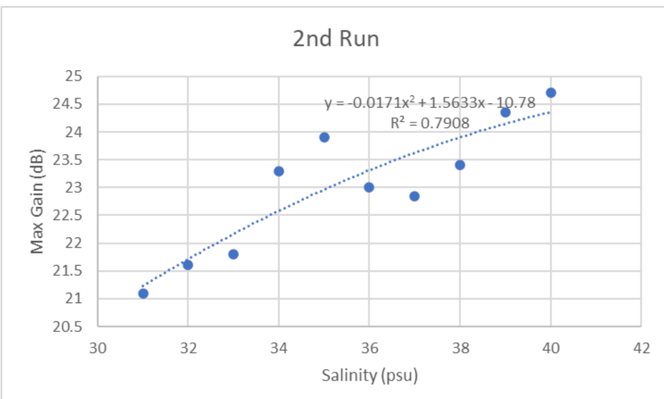


Fig. 16: Run 1b

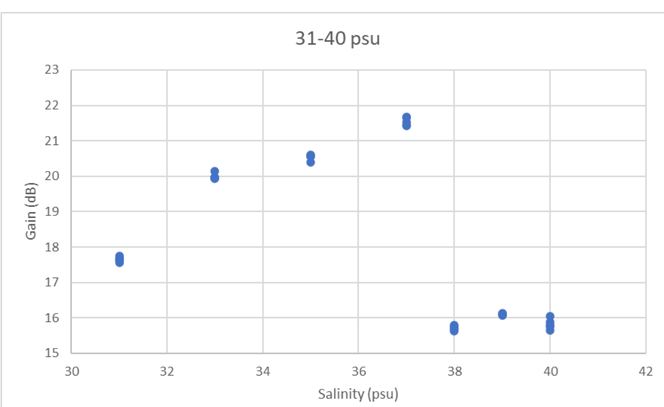


Fig. 17: Run 2a

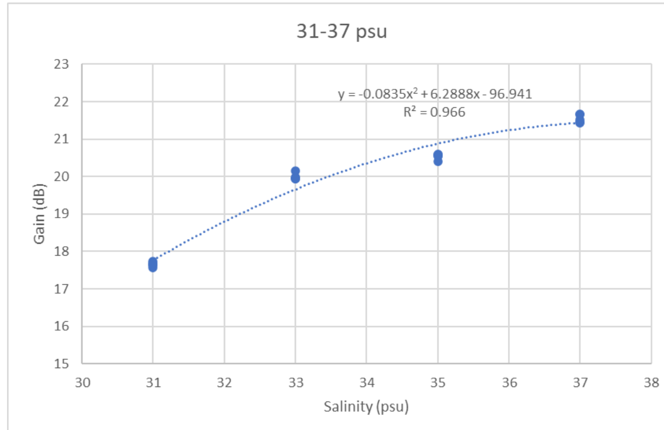


Fig. 18: Run 2b

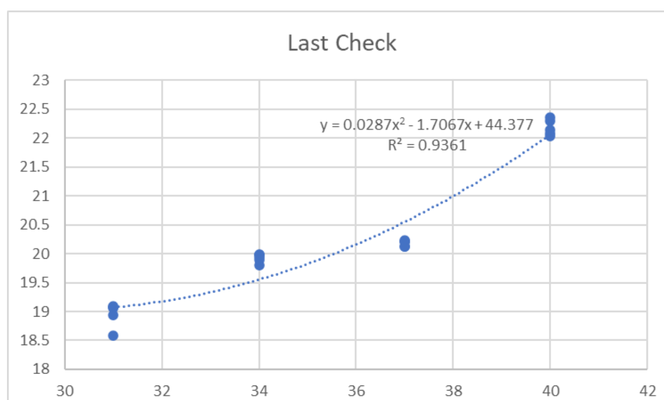


Fig. 19: Run 3