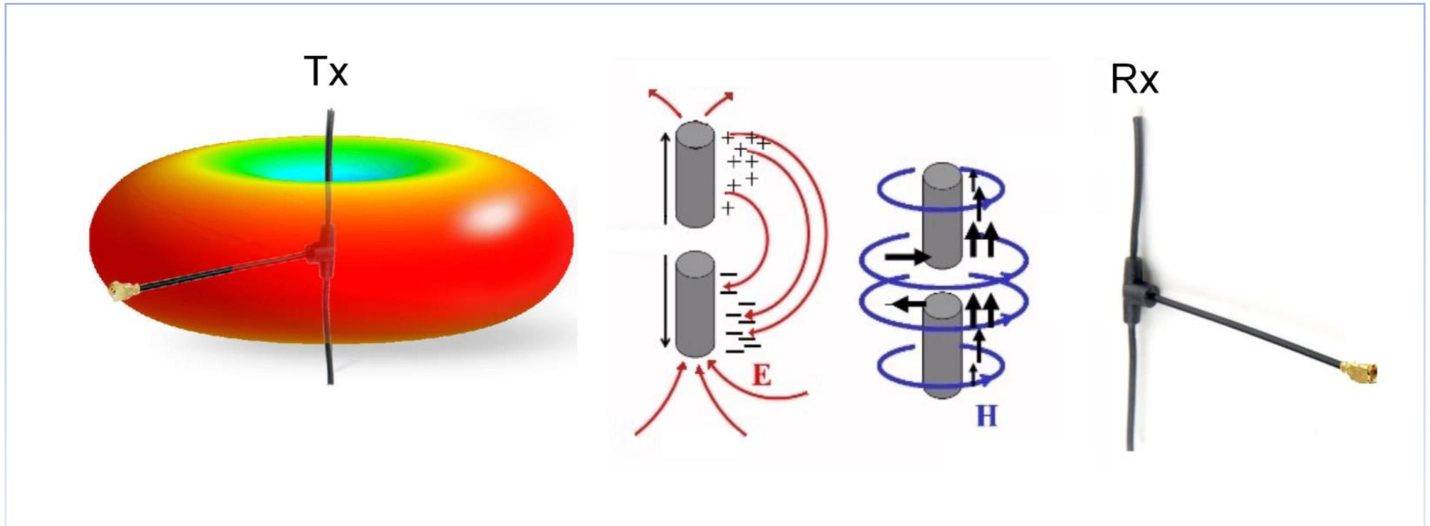


E = electric field, H = magnetic field

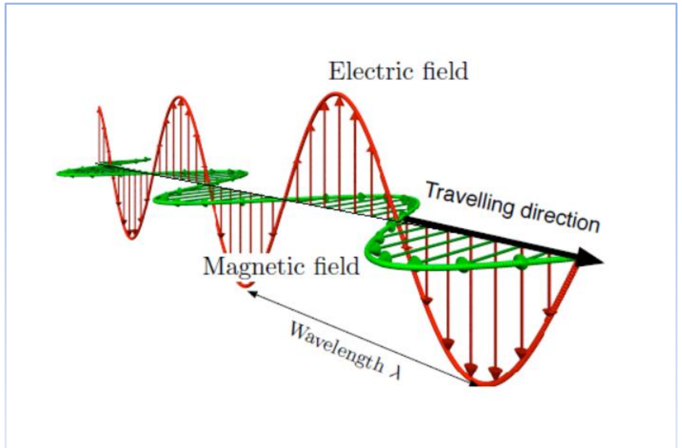


Table of content

1 Notes

- Pictures are added at the end of this document.
- Source files for the design of a matching PCB can be downloaded from my website. Amongst others this involves Gerber files for PCB production. The PCB design is made with Ki-Cad. The matching PCB for the antenna described in this document is referred to as: “wet_dip_ant_match_pcb”.
- The reader is assumed to have some basic understandings of electronics.
- The phrase “wet” is used to indicate a wet measurement (hull with antenna submersed in fresh water).

2 Abbreviations

DUT	Device Under Test
ID	Inner Diameter
IMP	Impedance
OD	Outer Diameter
RC	Radio Control
SWR	Standing Wave Ratio

3 Revision history

Revision	**Date**	**Comments**
001	20230715	Initial release
002	20230716	Second 6V battery found. Measurement in open water again. Now with 2x6V battery in series.
003	20230729	Added pictures matching PCB
004	20240120	Corrected picture chapter 7.1

4 Introduction

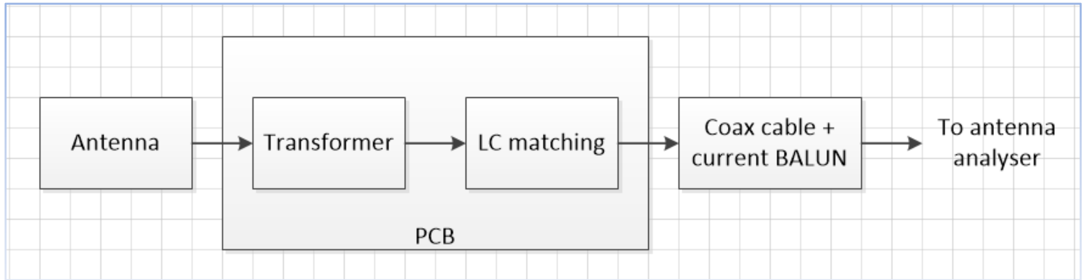
The purpose of this paper is to demonstrate that an isolated wire dipole antenna placed on the outside of the hull of a submersible vessel is an option to consider. The idea for such an antenna originated from the thesis of Oluyomi Aboderin about Antenna Design for Underwater Applications, chapter 4.5 page 111 (135 of 198), see: https://repositorio-aberto.up.pt/bitstream/10216/121833/2/345909.pdf.

For illustration purposes and easy construction a PVC tube is used. The antenna is glued on the outside of the PVC tube. Guidelines are provided for construction and antenna impedance matching. There are some constraints to the design and use, such as:

- The antenna is intended for use in fresh water (conductivity between 500 and 1000uS/cm). In general this includes lakes- ,rivers- , harbours- and tap water.
- Although practically hardly noticeable, theoretically one has to anticipate for somewhat of a lesser range when operating an RC model submarine in a swimming pool. This is because of the often higher conductivity figure due to chlorine or saltiness.
- The material from which the hull is made must be plastic (not metal).
- Preferable the relative permittivity (dielectric constant) of the hull material and that of the antenna wire insulation is in the range of approx. 2 to 4ξr. This includes materials like for instance: Polymethyl Methacrylate (Plexiglas), Polyester, PE and PVC. See also, https://www.kabusa.com/Dilectric-Constants.pdf
- Suitable for receiving and transmitting.
- For antenna wire feedthrough two holes need to be drilled through the hull. The downside of this method is the risk for water leakage. Depending on the dive system used, there might also be a risk for hull atmosphere leaking to water.
- In case of an RC model submarine the antenna is often mounted in the longitudinal direction of the vessel. As a result feedthrough of the antenna wires through the hull is approx. in the middle of the vessel. This can have consequences for metal ballast often position in the mid bottom of the hull.
- The proposed method is applicable to single- and double hull submersibles. In case of a double hull it is assumed that water is present between the outer- and watertight inner hull. If so, the antenna can also be attached to the outside of the watertight inner hull.
- When considering an antenna ashore and on the vessel (submersed) the maximum range can be achieved with the antenna ashore setup in air. This is because of the huge attenuation of electromagnetic waves in water. When simplifying matters one could state that in this case electromagnetic waves only have to bridge the distance of water column between the submersed vessel and the water surface.

4.1 Block diagram

Note, locate the current BALUN as close as possible to the PCB. Although the arrows in the drawing might suggest this antenna is suitable for reception only, it can also be used for transmitting purposes.



4.2 Why a dipole antenna?

Often inside an RC model submarine a 1/16 wave length end-fed wire antenna is used. End-fed wire antennas, however, are in need of a counter-poise. How the counter poise is realized in practice has much influence on the reception characteristics. With a dipole antenna, one of the elements acts as a counter-poise. In practice, this means that the electrical properties of the counter-poise are better controlled and therefor reception characteristics also.

From an electrical efficiency point of view a ½ wave length antenna is preferred over a 1/16 wave length antenna. To put it In other words, with a ½ wave length antenna, a larger distance can be bridged. Unfortunate a ½ wave length antenna does not fit inside an RC model submarine. However by moving the antenna from the inside (air) to the outside (water) it is possible to use a ½ wave length antenna. This is because the propagation of electromagnetic-waves in water is about 9 times slower than in air.

Although more difficult to construct a folded dipole antenna can most likely be used too. In general the electrical benefits of a folded dipole- over a dipole antenna are higher impedance (approx. 300 Ohm) and larger bandwidth. In case the bandwidth of a dipole antenna is considered too small one might try to the use a folded dipole antenna. Although no tests have been performed with a folded dipole antenna, it is expected that for impedance matching the same procedure can be used as described in this document.

4.3 Current BALUN

The current BALUN is a part that comes highly recommended. Applying it often helps to lower the SWR value. The current BALUN attenuates currents that might flow on the outside of the coax shield. While doing so the shield of the coax shield radiates less because it is better insulated from the antenna elements. As a result this measure help to improves antenna efficiency. Also a current BALUN helps to reduce the effect of changing receive conditions when for instance touching the coax cable.

Coax cable:

- 50 Ohm
- RG174
- 35cm needed for construction

2x 4½ winding
on ferrite toroid
FT-82-43 (Amidon)

Do not tighten cable ties too tightly.

Note, the left cable tie in the picture illustrates a cable tie that has been tighten too much.

5 Equipment and materials

5.1 Water conductivity meter

Makes sure the device used has temperature compensation built-in. Two different models are used and there measurement result averaged. Perform measurements in fresh water with a conductivity of 750uS/cm (700 to 800 uS/cm).

5.2 Antenna analyser

In this case the MR300 antenna analyser is used. When considering buying this equipment make sure the AD9851 is used inside (CMOS 180MHz DDS/DAC synthesizer). For measurements in the plastic container a 12VDC regulated switching power supply is used. For measurements in open water a 12V battery is used. In case of a 12V switching power supply, the use of a suitable common choke (ferrite folding clamp) attached to the DC power cable is mandatory.

5.3 DUT

For testing a PVC tube (OD=125mm) is used and some isolated multi-stranded copper wire with an ID of 0.5mm (AWG24). Note wire-isolation is often made of PE or PVC. Inside the PVC tube there are two metal tubes that simulate internal metal ballast which is often located at the bottom of the hull of an RC model submarine. In the bottom of the PVC tube two holes are drilled to fed the antenna wires through.

5.4 Coax cable

For construction of the current BALUN a coax-cable is required with a small OD, like for instance RG174.

5.5 Glue

For realizing water tight cable/wire feedthrough and antenna wire ends, Bison glue for soft plastic is used. This glue is tough, remains somewhat flexible, has a wide temperature range and is waterproof.

5.6 Antenna wire

Insulated, multi-stranded, copper, ID=0.5mm

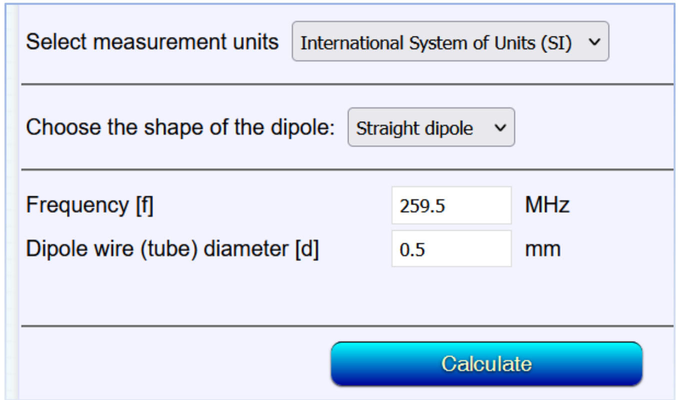
5.7 Plastic container

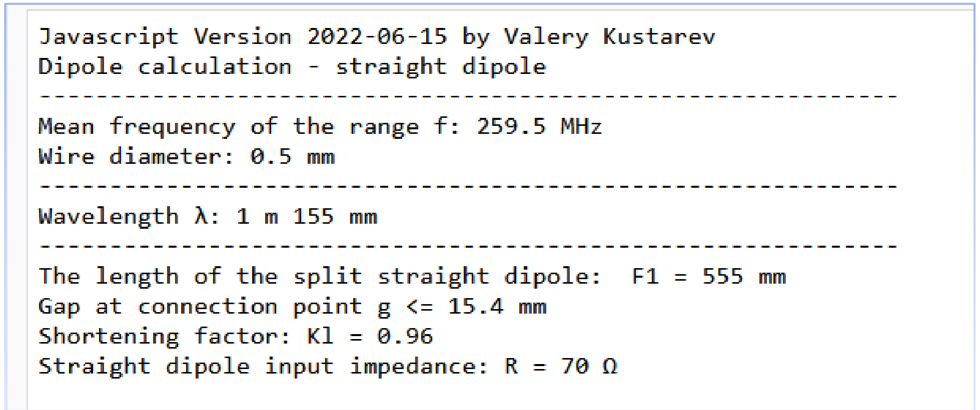
A plastic container (75x55x40cm) is filled for 3/4 with tap water. Then table salt was added until a conductivity of 750uS/cm was reached. To minimize the influence of solid ground on the measurement, the container is elevated on a wooden frame.

6 Antenna

6.1 Calculations

To calculate the length of the antenna elements the following antenna calculator is used: https://3g-aerial.biz/en/online-calculations/antenna-calculations/dipole-online-calculator. The frequency is calculated as follows: F = (27.2MHz x 9) + 6% = 259.5MHz. The ratio 9 represent the speed difference of electromagnetic waves in air and in water. The 6% is compensation for resonance frequency shift in water. This figure is an estimation derived from the graph on page 85 (109 of 198) of the thesis of Oluyomi Aboderin (figure 4.4). A more detailed graph in the range of 0-0.5 S/m couldn't be found. Note 27.2MHz is the mid of the 27MHz-band.





In this case the gap = 12mm. As a result the length of each element is 271.5mm.

6.2 Measurement (wet)

With the antenna analyser the complex impedance of the antenna is measured: 32-113j. Note keep all wires as short as possible.

6.3 Alternative construction

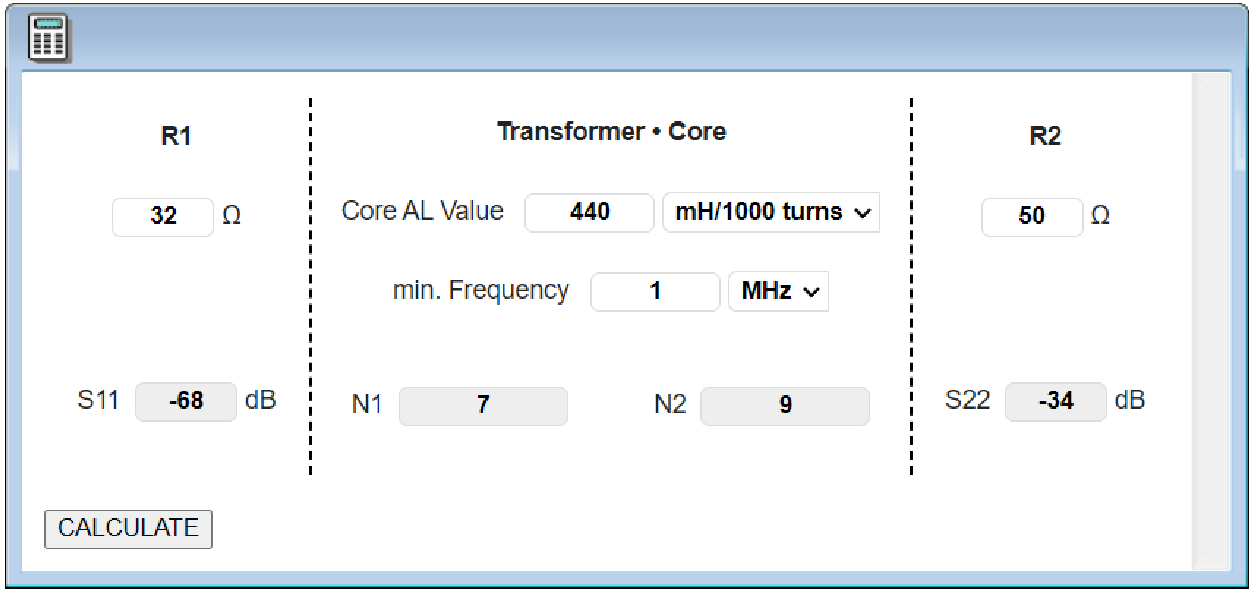
If the wall thickness of the hull allows for it, integrating the antenna in the hull material itself might also be an option to consider. It is thought of that this construction might reduce the risk for water leakage. A solid copper wire with a minimum diameter of 0.5mm can be used (un-insulated). If possible use an antenna wire with a larger diameter. Note this construction has not been tested.

7 Transformer

Besides impedance transformation the transformer also provides galvanic isolation. The latter helps to reduce noise and ground loop/common mode problems. Therefore, the use of a transformer is mandatory in this design.

7.1 Calculations

To calculate the winding of the transformer the next calculator is used: https://www.changpuak.ch/electronics/broadband_transformer_matching.php. As ferrite toroid for the transformer I used Amidon FT50-43. This is also where the figure 440 is coming from. Note this is a small ferrite toroid which cannot house many windings, approx. 15 is the max. Also note the reel part of the complex antenna impedance is used for R1 (antenna side).



For reasons yet unknown, but for good practical results, it has become a standard practice to reduce the number of N1 winding provided by this calculator by one (N1=6, N2=9).

This worked multiple times with different types of underwater antennas.

For the windings emulated copper wire with an OD of 0.5mm is used.

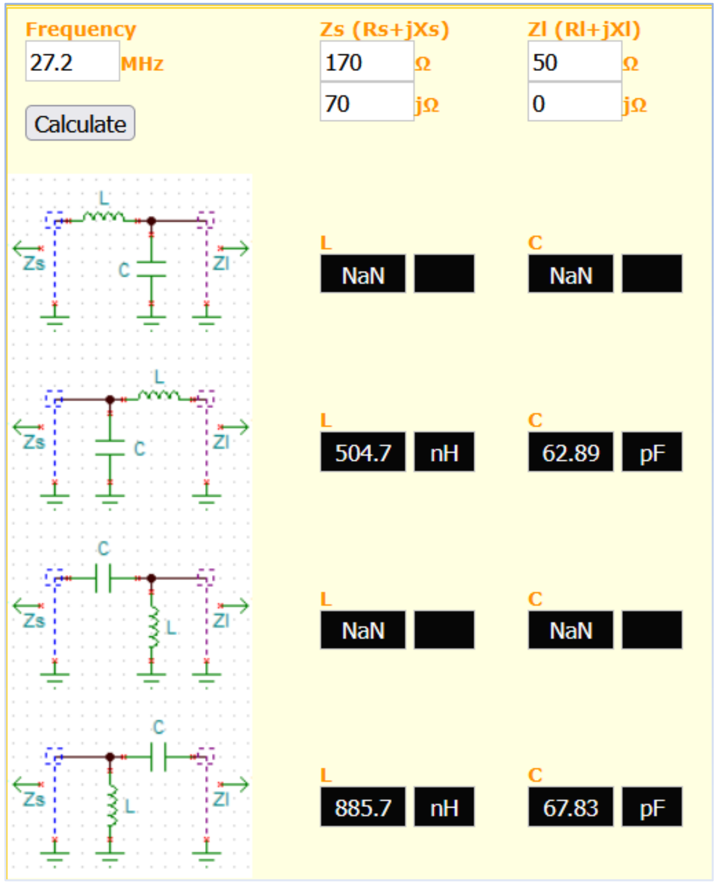
Be precise on the number of windings. Make sure the number of wires is an integer (not for instance 8½).

7.2 Measurement (wet)

With the primary side (N1) connected to the antenna the complex impedance is measured on the secondary side of the transformer (N2: 170+70j). Again keep all wires as short as possible.

8 LC impedance matching

Finally an LC matching circuit is coupled to secondary side of the transformer (N2). For this purpose the following LC matching calculator is used: https://leleivre.com/rf_lcmatch.html.



In this case option 4 is used. L consists of 820nH and 68nH in series. C is a 100pF trimmer capacitor.

Make sure that the self-resonance frequency of L is well above 27MHz (5-10x higher) and that L can handle currents of at least 200mA without saturating.

After trimming the capacitor, SWR=1.25 and IMP=53 Ohm (without current BALUN).

Note Zs connects to the secondary side of the transformer (N2). Zl connects to the antenna analyser.

To be able to adjust the matching PCB more precise, use a trimmer capacitor that meets “C” as close as possible and a fixed capacitor close to “C/2”.

Again, keep all wires/cables as short as possible.

9 Measurement results and recommendations

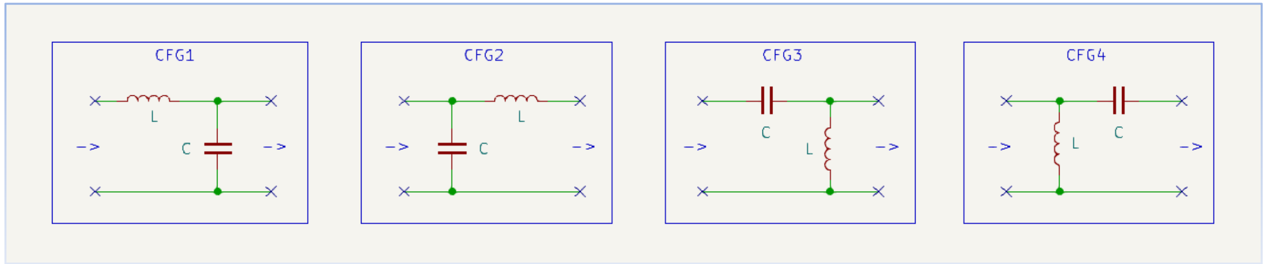
The measurements described in the document reveals that the proposed antenna performs well, SWR=1.0 and IMP=50 Ohm (with current BALUN). Sometimes antenna calculators do not allow calculations of antenna elements with a diameter smaller then 2.0mm. The reason for this that the bandwidth might become too small. With the antenna described here the antenna impedance varies approx. +/-2.5 Ohm in the 27MHZ band (27.0-27.4MHz). Under these conditions SWR varies +/-0.05. If possible it is advised to use an antenna wire with a larger ID.

Pushing the PVC tube deeper into the water in the plastic container did not lead to any significant changes in measurement values. The same goes for measurements in open water.

10 Matching PCB

10.1 Electrical configuration LC components

The next drawing illustrates the available LC configuration options of the matching PCB. For pictures of the matching PCB itself, please see the chapter "pictures".



The preferred configuration can be selected with jumpers.

10.2 Components size

The matching PCB supports the following components dimensions:

- SMD inductors: 0805 and 1008
- Fixed SMD capacitors: 0603
- THT trimmer capacitors: OD=6.2mm and pitch = 5mm
- SMD trimmer capacitors: Voltronics JZ

Note, fixed- and trimmer capacitors are electrically connected in parallel.

10.3 Configuration

	CFG1	CFG2	CFG3	CFG4
J5	1-2	1-2	2-3	1-2
J7	2-3	1-2	1-2	1-2
J8	1-2	1-2	2-3	2-3
J9	2-3	2-3	1-2	1-2

11 Pictures

11.1 Measurement setup

11.2 Power supplies MR300 antenna analyser

12V regulated switching AC/DC adapter with common mode choke and 2x6V battery in series.

11.3 Water conductivity meters

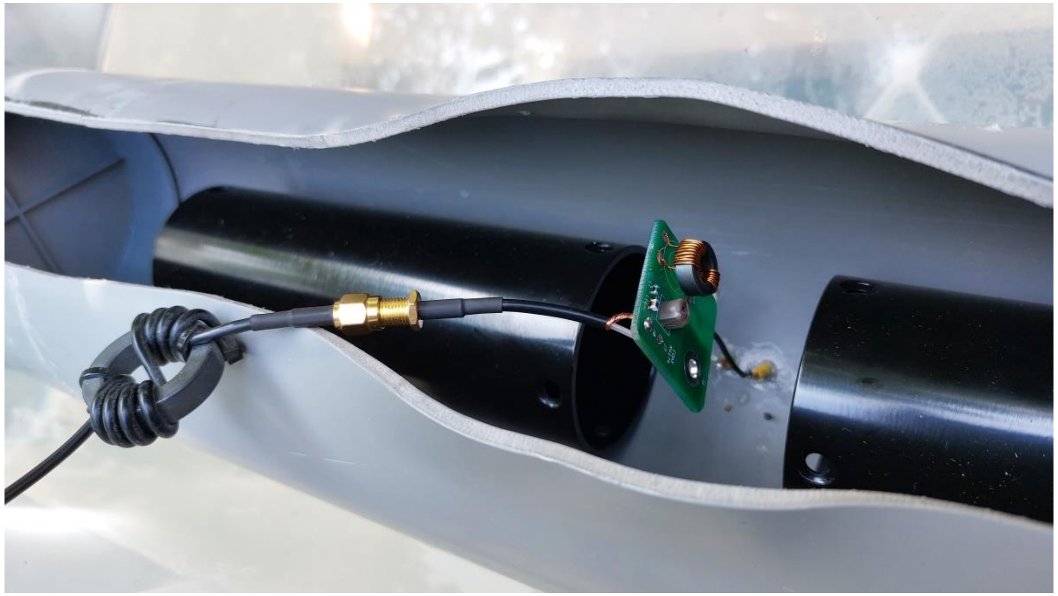
Both are temperature compensated.

11.4 Transformer

Primary 6 and secondary 9 windings.

Note the antenna is connected to the primary side of the transformer.

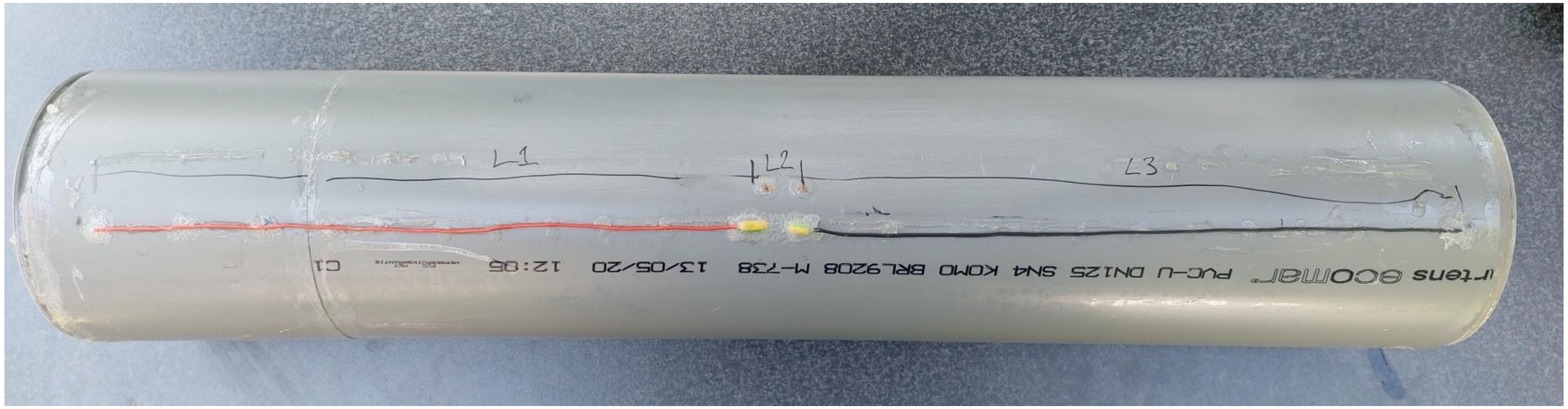
11.5 Experimental matching PCB and current BALUN



11.6 PVC tube

11.6.1 Top view

11.6.2 Bottom view with isolated wire dipole antenna



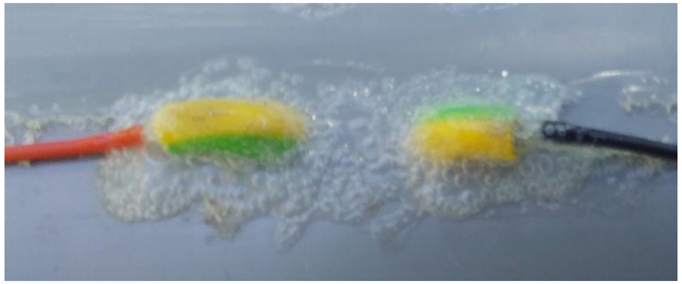
L1=L3=271.5mm

L2=12mm

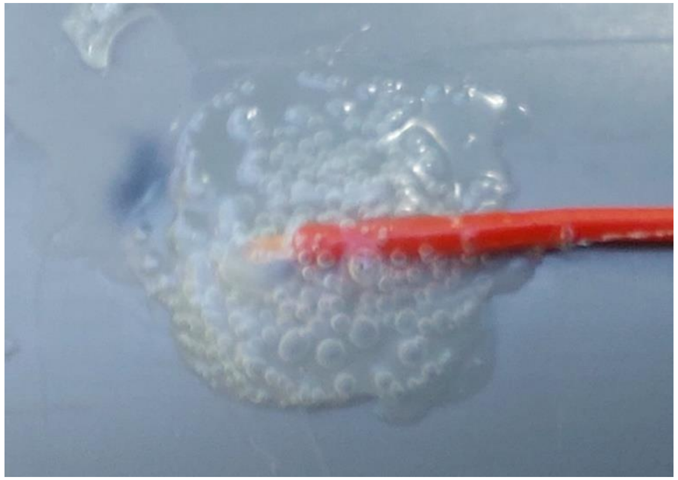
L1+L2+L3=555mm

11.7 Details watertight making

11.7.1 Antenna wire feedthrough



11.7.2 Antenna wire end



11.8 Measurement results

11.9 Matching PCB