Air-coupled Ultrasonic Transduction System as an Applied Method for the Robotic Utility Inspection Collar

| *Proposal* |

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Abstract

The task presented to our group was to evaluate the condition of wooden utility poles including the interior structure in a non-invasive, non-destructive manner. Florida Power & Light (FPL) Lineman can easily identify visual defects outside the pole simply by observing the structure on the surface. Further consideration to assess the internal structure of the pole is needed to identify defects that otherwise cannot be detected by traditional methods. Air-coupled ultrasound is a non-destructive, quantitative method that acoustically penetrates wood to detect rot, holes, cracks, and other defects without altering any element of the wood structure. High performance piezocomposite non-contact

ultrasonic transducers present a commending argument for this functional requirement. Studies in a laboratory environment (Vössing, 2018) have been conducted on wooden structures with their thickness measuring approximately 300 mm and densities of up to 500 kg/m^3. For Chromated Copper Arsenate (CCA) type "C" (oxide) treated Southern Yellow Pine (wood treatment and species of the utility poles), the average thickness and density across all poles is approximated to be within the range of the two measurements given above. These transducers produce accurate, irrefutable, and cost-effective readings. Thus, providing a compelling solution for the inspection requirements set forth by FPL.

Keywords: non-destructive, ultrasound, utility poles, wood structure.

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1. Introduction

FPL has approximately 1.1 million of wooden utility poles across South Florida (NextEra Energy, n.d.). To comply with safety guidelines and regulations, FPL Lineman are required to inspect these poles for defects and efficiency conditions. Currently, FPL Lineman use a testing method called the “Hammer Test”, it involves striking the pole with a hammer and listening to the sound produced from the impact. Defected pockets inside the pole will produce a less profound rebound and dull sound compared to that of a non-defective pole (Labor, n.d.). The hammer test is limited in that it does not provide a quantitative assessment on the internal structure of the pole in question. The resulting flaw of this test is that it is susceptible to error and can possibly miss or misinterpret a defect from inside the pole.

There are several alternatives to the traditional hammer test and ultrasonic through transmission remains the most efficient and cost-effect one. Ultrasonic through transmission involves a transmitting and receiving transducer that are placed at opposite ends of the given material. The pulse wave emitted from the transmitting transducer propagates through the material. When the propagated wave arrives from the transmitter, the receiving transducer collects pulse wave information such as time of flight, amplitude, phase width, and velocities of the various directional waves.

The difference in acoustic impedance in air compared to the impedance of wood structures is extremely large (Kommareddy, Air-coupled ultrasonic measurements in composites, 2003). Thus, the implementation of conventional piezoelectric transducers that propagate through air as the medium, is nearly impossible. Conventional ultrasonic transducers must rely on a coupling medium such as petrolatum to avoid the large impedance mismatch in order to be effective.

The proposed Robotic Utility Pole Inspection Collar (RUPIC) features the ability to move vertically along the utility pole. Hypothetically speaking, if conventional ultrasonic transducers were attached to the RUPIC, then the collar would have a mechanism to continuously emit the coupling medium along the pole as it moves up and down. The inference from this is that the whole concept of a coupling medium applied to the RUPIC is difficult and terribly inefficient.

Contrary to conventional ultrasonic transducers, air-coupled non-contact ultrasonic transducers provide a reliable means to efficiently transmit waves through wood material. An air-coupled ultrasound (ACU) system does not require physical contact and uses air as the coupling medium.

2. Air-Coupled Ultrasonic Transduction

The concept of air-coupled ultrasonics (ACU) was first implemented in 1973 in which a study was conducted by propagation of waves through metal plates (M. Luukkala, 1973). Since then, there has numerus studies leading to the significant advancement of ACU. There are many applications as well as testing methods for ACU leading the industry to conclude that air-coupled ultrasonic transduction (ACUT) is a viable, cost-effective, and non-destructive method used to evaluate defects in wood composites.

Conventional ultrasonic methods use a liquid or water immersed coupling agent. The direct contact, leading to the inevitable damage, as well as the need for a coupling agent to continually be dispersed along the surface of the pole would conclude that conventional ultrasonics would not work for our application.

Because of the high impedance mismatch between air and most sound producing materials, most of the ultrasonic transmission wave energy is reflected at the medium interface and only a small amount of energy is propagated through the material. (Kommareddy, Air-coupled ultrasonic measurements in composites, 2003). Therefore, a large amount of energy needs to be transmitted into the material in order to reach the receiving transducer.

3. Through Transmission Testing

To meet the functionality requirements of this project, a technique and testing method known as through transmission will be used. This method involves two transducers: one transmitting unit and one receiving unit. The transducers will need to be placed at opposite sides of the pole, colinear across the diameter of the pole.

The acoustic impedance of air is approximately 415 Rayleigh, compare that to the large acoustic impedance of most wood structures being around $1.57\ X\ 10^6$ Rayleigh

(Fleming, 2005). This impedance mismatch results in only a small fraction of energy being transmitted into the propagation medium. In oak wood, 99.94% of the incidence energy is reflected and only 0.06% is transmitted into the wood (David K. Hsu, 2009). There are multiple points of transmission loss that occur as the energy waves propagate from the transmitter to the receiver in through transmission. As the incident wave enters the first material or medium, a small fraction of the wave's energy is transmitted into the material while the rest is reflected. The process continues as the wave crosses the different mediums and finally reaches the receiving transducer. This process is illustrated in Figure 3.1.1 and 3.1.2 below.

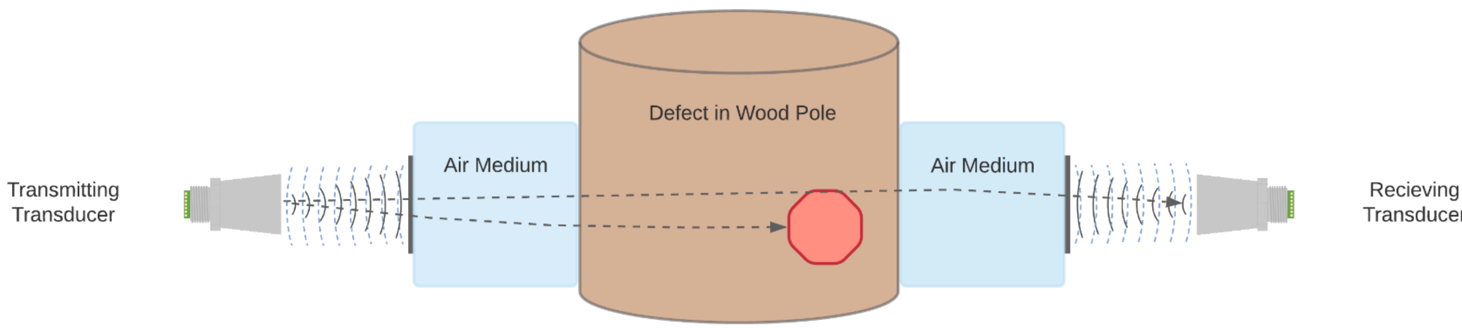


Figure 3.1.1: Through transmission representation for defect detection

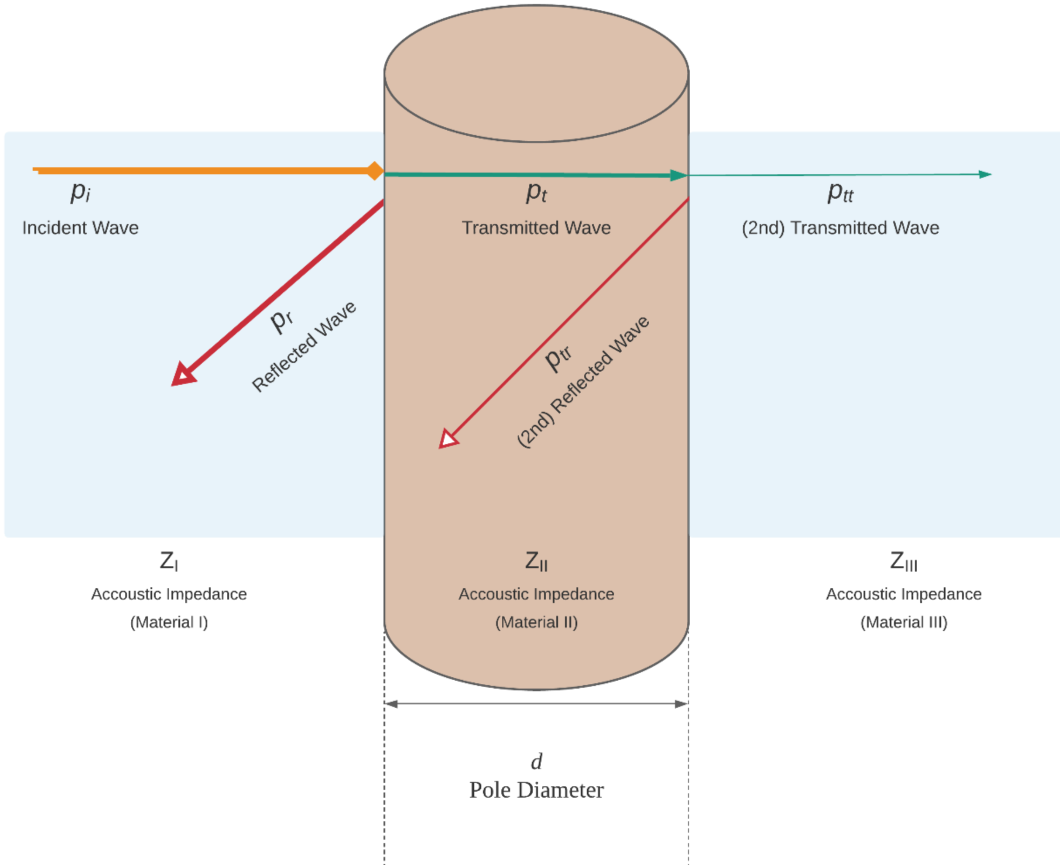


Figure 3.1.2: Through transmission wave transmission and reflection

As stated above, reflected, and transmitted waves are generated as the result of acoustic waves traveling from one medium to another. The amount of energy transmitted from one medium to another depends on the ratio of their acoustic impedances. Wave velocity measurements in a cross section of red-pine utility poles has shown to decrease an average of 20% when encountering a hole or void in the radial direction across the pole (Fernando Tallavo, 2013). Furthermore, ultrasonic waves have been proven to detect decay areas as small as 6 cm in diameter (Tallav´o, 2009).

Given that wood is a cylindrical orthotropic material, uncertainties exist for its elastic, mechanical, and environmental properties. This is associated with evaluation complexities and further consideration regarding wave velocity and attenuation is needed to fully access the condition of the pole.

4. Materials and Methods

Scans will first be established using a baseline measurement showing no defects or degradation and an expression for the transmission coefficient is derived. The recorded time of flight will be taken continuously as the collar traverses up the pole. Any irregularities from inside the pole will affect the transmission amplitude and be measured and compared to the baseline observations. The sound waves will most likely not provide enough energy to reach the receiving transducer if there are any holes or cracks. A decrease in the amplitude of the transmitted signal, compared to the signal of no defects, indicates a flaw (Kaufmann, 2008).

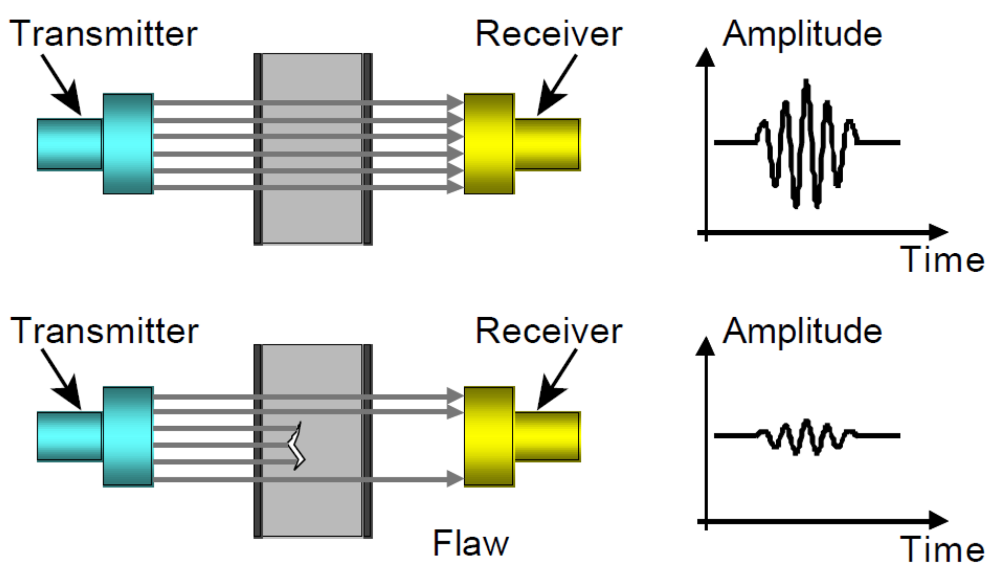


Figure 4.1: Through-transmission flaw detection signals

For our application it is appropriate to record and access multiple measurements and parameters. The measurement categories of time and attenuation domain will provide accurate results for identification and defect characterization. Time domain parameters include time-of-flight and velocity measurements for longitudinal waves.

Attenuation domain provides data on fluctuations from reflected and transmitted signals (Bhardwai, 2002).

Careful consideration must be given to the type of transducer selected as characteristics of a specific frequency, pulse shape, and pulse width of ultrasound propagation vary with material type. For example, a frequency of 50kHz may easily propagate through *Material A*, while making no impact on *Material B*. Furthermore, a frequency of 2MHz may have no problem propagating through both *Materials A* and *B*, but the pulse width would be too large for *Material A* to produce any meaningful results (Bhardwaj, 1987).

Informal testing was conducted on a wooden utility pole by *The Ultran Group, Inc.* They attempted to test for successful propagation using a planar/unfocused NCG50-D50 and S50 transducers that used 50kHz, 100kHz, and 200kHz frequencies with a standard pulser and a high-voltage pulser. Successful propagation through the pole was noted by the 50kHz frequency with increased gain to 84Db from the receiving transducer. The 84dB gain from the receiving transducer produced enough noise to dampen the signal completely so averaging was applied. Although the 50kHz frequency was able to transmit through the pole, it was noted that a larger diameter transducer would produce more profound results for NDE applications on the large diameter pole. The 100kHz and 200kHz frequencies for this experiment were proved to be unsuccessful, but further modifications to signal processing could possibly produce effective results with these frequencies. The test setup is noted in Figure 4.2.1, 4.2.2, and 4.2.3 below (Whetzel, 2021).

Figure 4.2.1: Field test setup

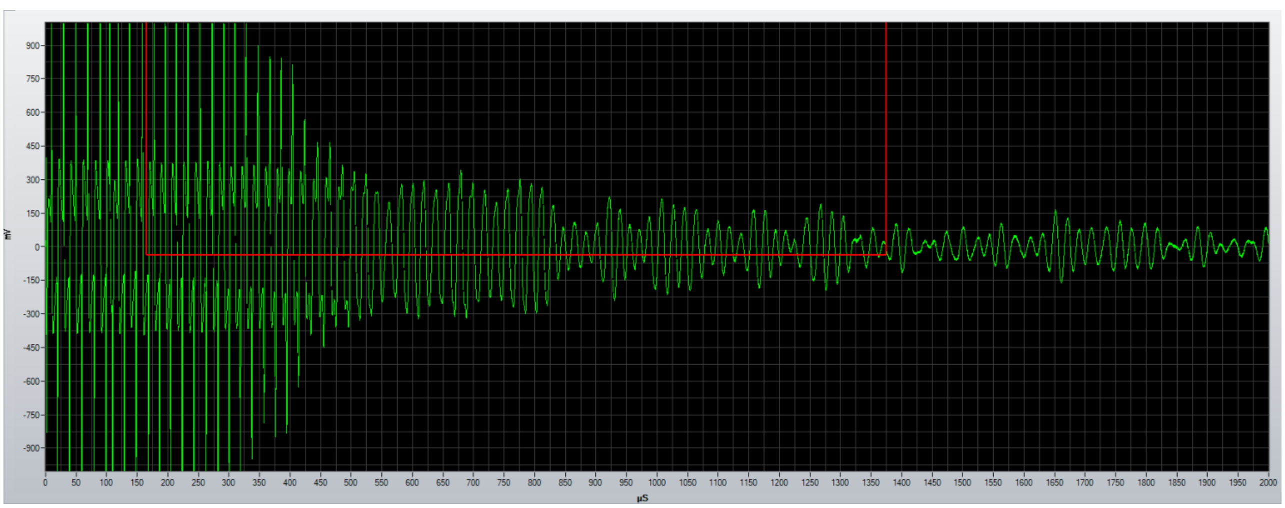


Figure 4.2.2: Received signal (averaged) from a 50kHz frequency high voltage pulser.

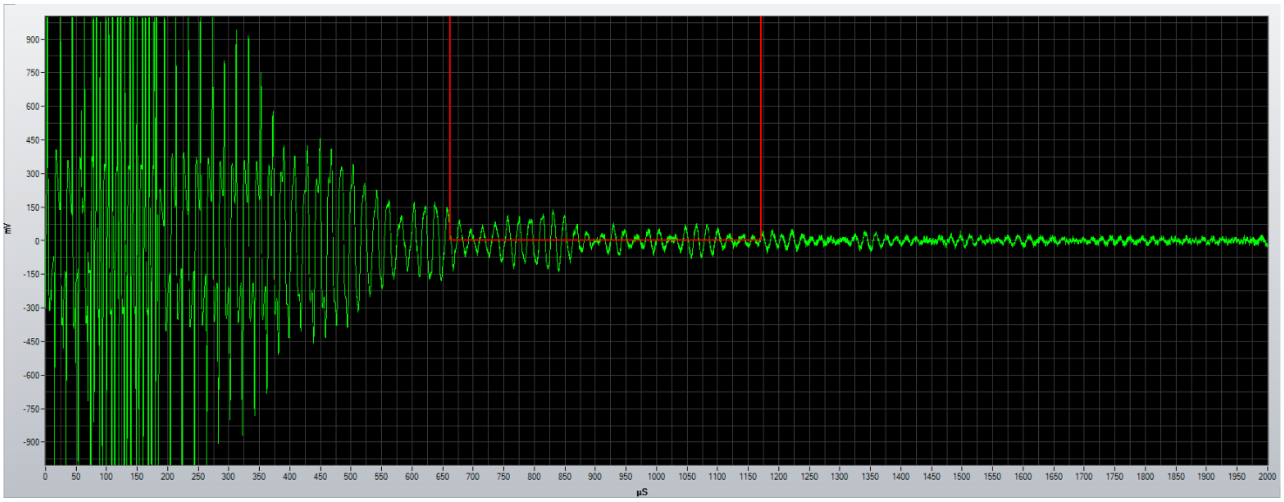


Figure 4.2.3: Received signal (averaged) from a 50kHz frequency standard pulser.

After careful consideration and thorough research, the NCG50-D63 and NCG50-D50 from *The Ultran Group, Inc.* would be an ideal choice for our application. The NCG50-D63 and NCG50-D50 are high-performance piezocomposite non-contact ultrasonic transducers, with nominal frequencies of 50kHz and 63mm & 50mm face diameters. Since successful yet weakened propagation through the utility pole was achieved by two D50s', to ensure increased sensitivity and stronger signal impression we will use the D63 for the transmitting transducer and the D50 for the receiving transducer. Figure 4.3 below shows the basic structure of the NCG series transducers.

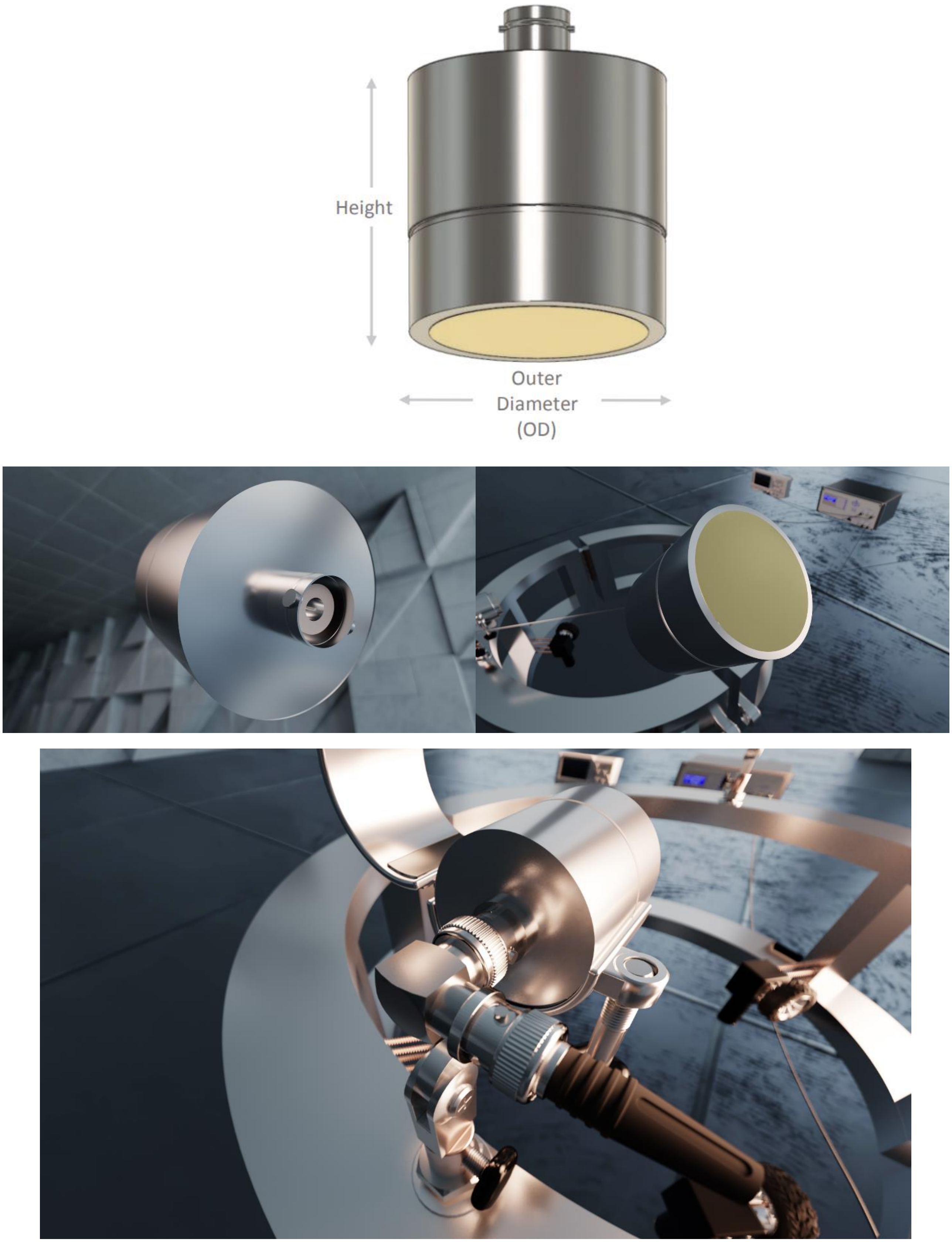
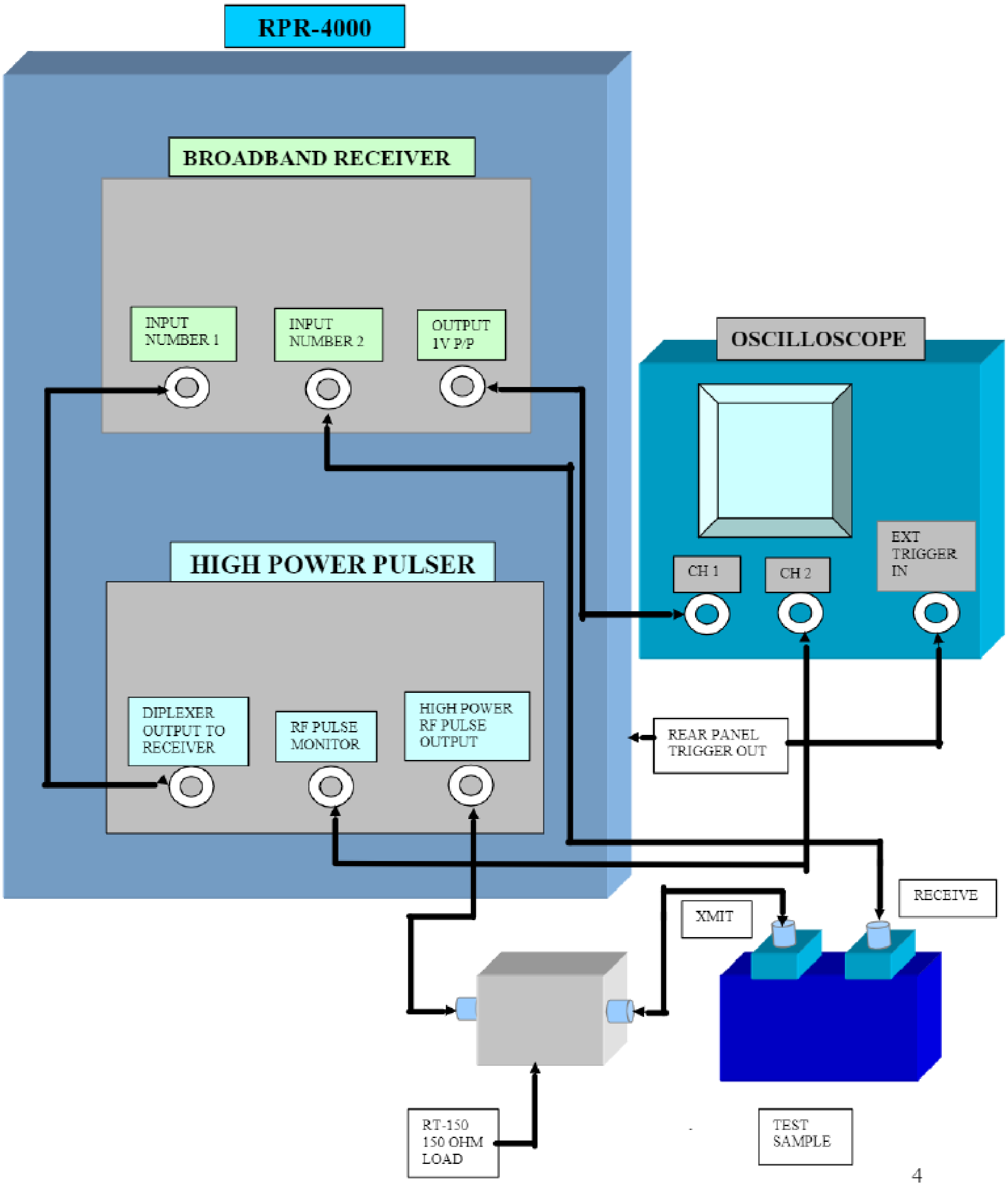


Figure 4.3: NCG500-D19 Ultrasonic Transducer

The testing separation between the transmitter and wooden pole will initially be set to *210 mm* while the receiving transducer's separation width will be *55 mm.* A 390V tone burst will be used to excite the transmitting transducer and the receiving transducer's gain will initially be set to 84dB. Needed adjustments in these initial configurations may need to be made to produce optimum propagation and signal analysis through the full diameter of the pole.

The RPR-4000 High Power Pulser/Receiver from RITEC, Inc. will be used to excite, drive, and receive the signals from the transducers. The transmitting transducer will be connected to the RT-150 Termination via BNC cable before being connected to the high power pulser. The RT-150 reduces reflections that can affect the shape of the toneburst as well as provide more control of the voltage amplitude. The receiving transducer will be connected to the broadband receiver which contains a microprocessor that controls the receiver gain, filter settings, and receiver input. The RPR-4000 has a front panel keypad and menu screens for controlling all the functions of the high-power pulser. The output of the broadband receiver and the RF pulse monitor will be connected to the TDS 2012C Oscilloscope from Tektronix, Inc. Except for the Duplexer (not needed), the following configuration is pictured in Figure 4.4 below.


RPR-4000
BROADBAND RECEIVER
INPUT NUMBER 1
INPUT NUMBER 2
OUTPUT 1V P/P
HIGH POWER PULSER
DIPLEXER OUTPUT TO RECEIVER
RF PULSE MONITOR
HIGH POWER RF PULSE OUTPUT
OSCILLOSCOPE
CH 1
CH 2
EXT TRIGGER IN
REAR PANEL TRIGGER OUT
XMIT
RECEIVE
RT-150 150 OHM LOAD
TEST SAMPLE

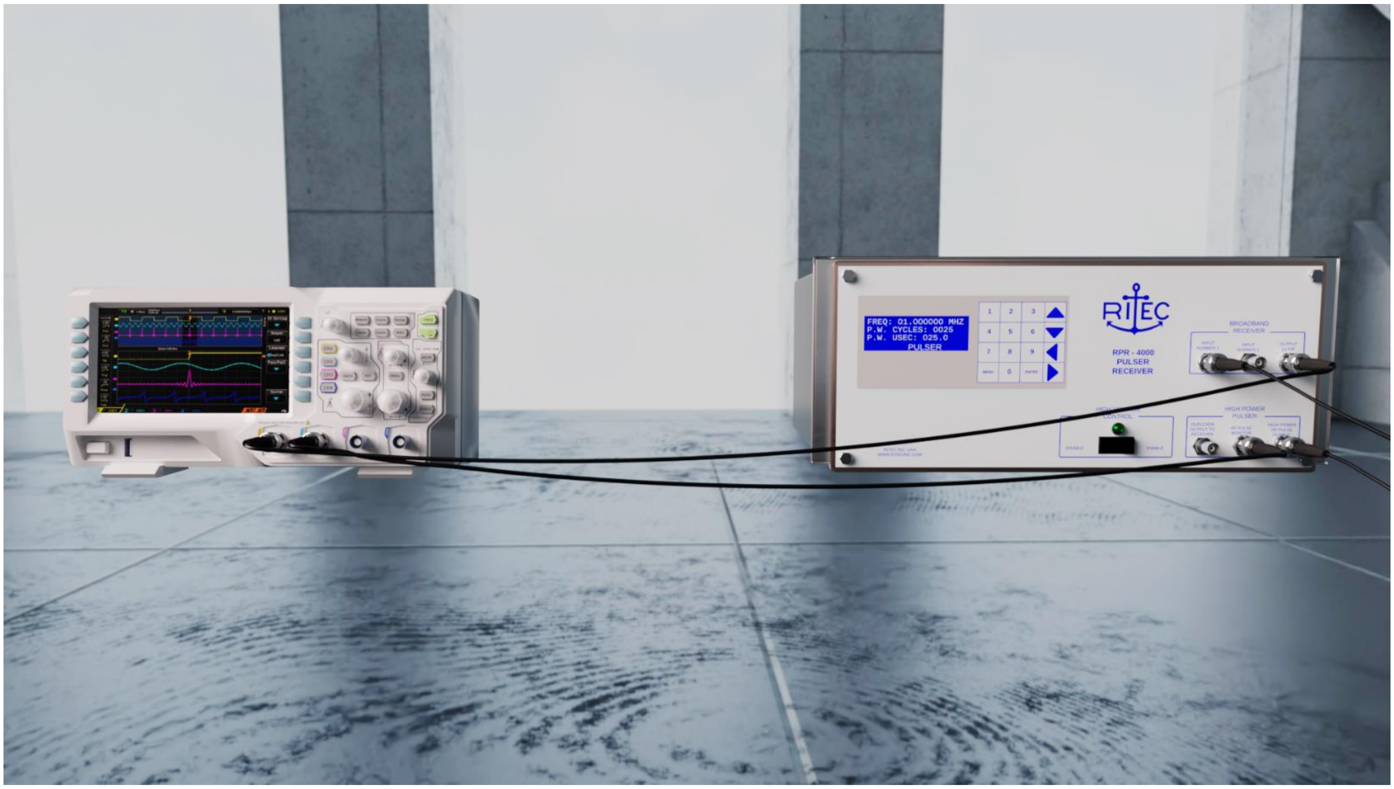


Figure 4.4: The RPR-4000, transducer, and oscilloscope configuration.

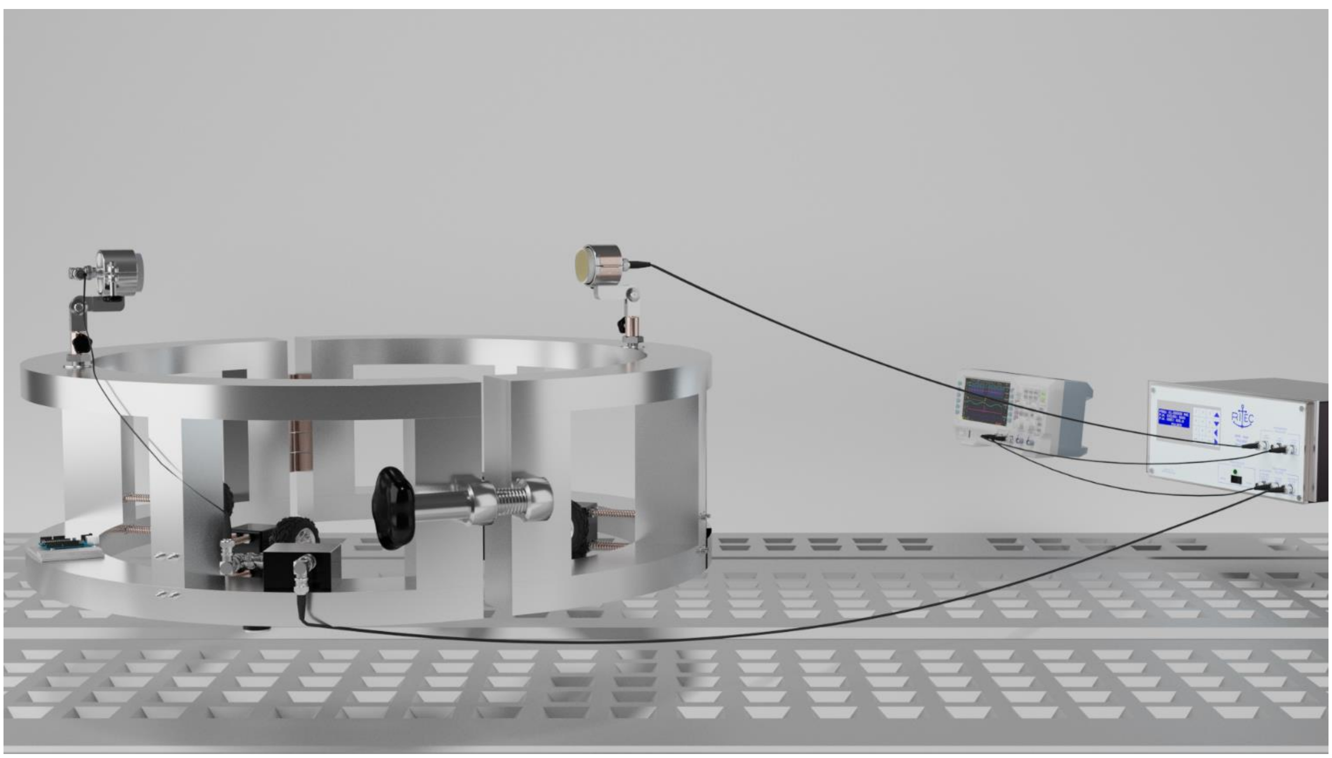


Figure 4.5: Complete RUPIC configuration.

5. Limitations and Future Considerations

Due to the specialized equipment needed to excite the transmitting transducer, amplify the receiving transducer, and display the processed signals, limitations will be enacted on the RUPICs functionality. In order for the RUPIC to fulfill the projects mechanical and functional requirements, the complete ultrasonic sensor sub-system will need to be joined together and mounted on the RUPIC. Because of the extremely high voltage requirements of the pulser/receiver, it is unlikely we will be able to find a battery capable of delivering the power and be light enough to not weigh down the RUPIC.

In a more realistic scenario, the transducers will be the only portion of the sub-system that will be mounted to the collar while the rest of the equipment remains at the base of the pole, on the ground. The connection between the transducers and the pulser/receiver will be maintained by BNC cables measuring approximately 100 ft in length, Figure 5.1 below illustrates this proposed setup.

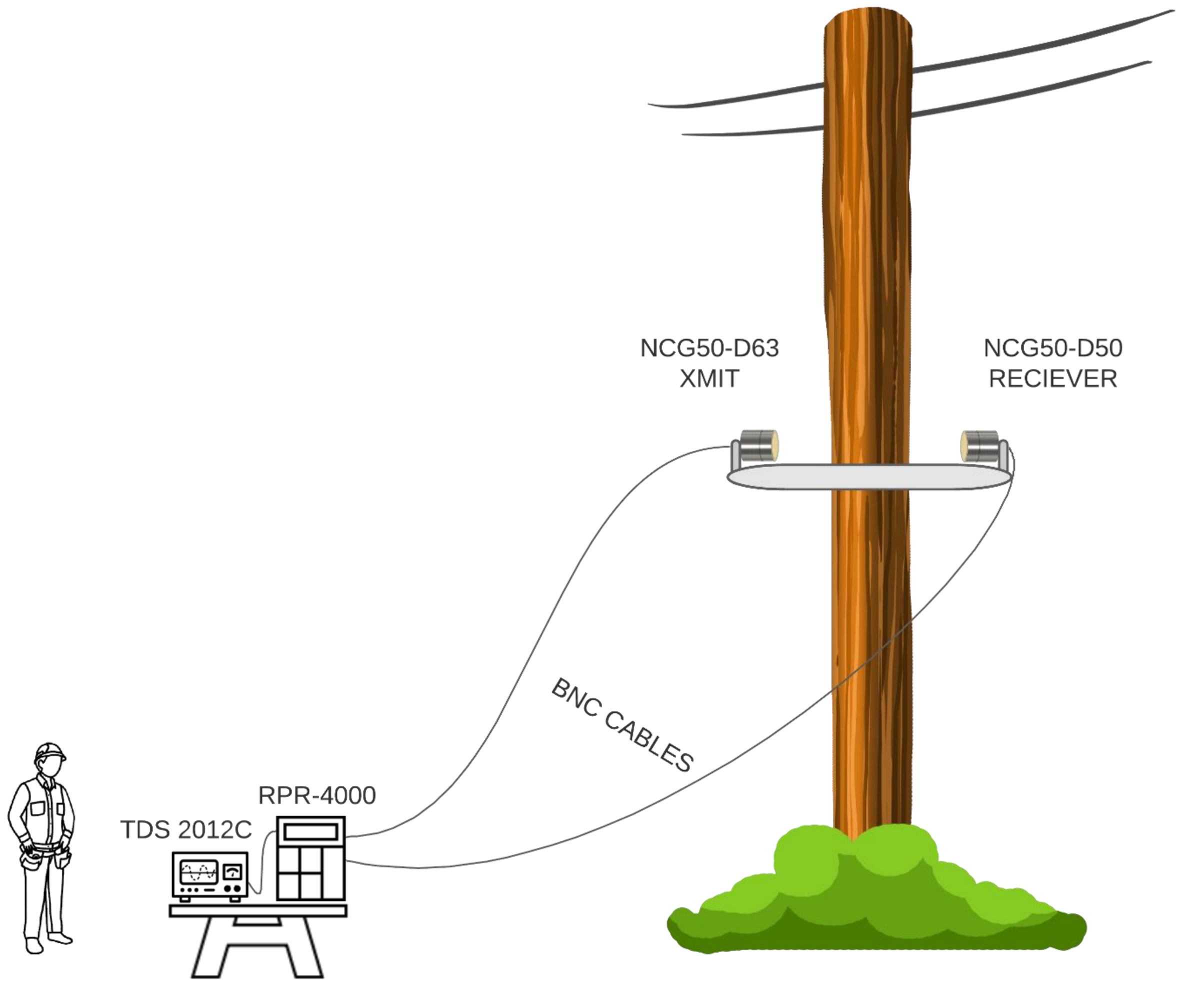


Figure 5.1.1: Proposed field application setup

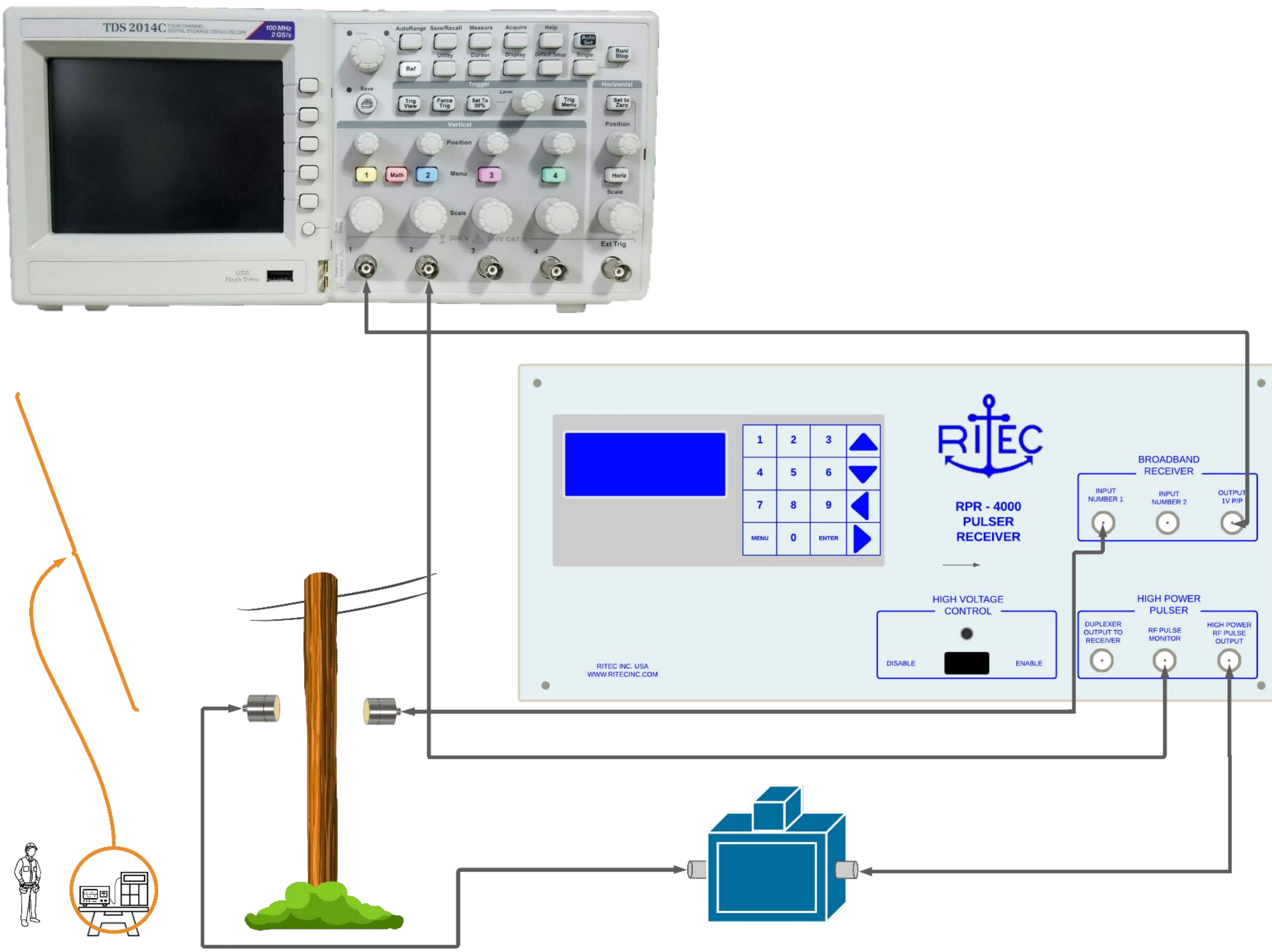


Figure 5.1.2: Proposed field application setup

Although meeting the full requirement and functionality specifications are not possible at this time, future development, optimization, and enhancement will be made on the prototype. Prioritization will be given to identification or production of a battery or mobile power source capable of driving and sustaining the ACUT sensor system. In addition to being able to power the system, it would need to be able to be supported by the strength of the collar so the collar can stay secured to the pole.

Another area of enhancement and functionality would be improvements in the data and signal processing. Added features such as being able to transmit the data (signals) wirelessly to a trained operator on the ground. This will provide real-time signal measurement to the operator enabling him to make a judgement on the status of the pole. Still, the technician would need to be trained in the procedures and methods used for operating an oscilloscope in addition to being able to make the correct judgements in identifying defects. A step forward from human judgements, the implementation of an artificial neural network to make statistically accurate decisions on the condition of the pole would greatly improve the functionality of the collar. Not only would it make decisions faster and more accurately than a human, but it would also negate the need for an operator who is trained to read signals and operate an oscilloscope.

Although oscilloscope signal readings would suffice for defect detection, the transducers also contain the ability to perform C-Scan imaging. A C-Scan image could provide a more clear and definitive approach towards visually recognizing defects that would otherwise be distorted by signal analysis.

6. Conclusion

There are many methods when considering non-destructive evaluation and defect detection of various materials. Ultrasonic propagation provides a means to efficiently evaluate the serviceability of wooden utility poles by detecting defects that otherwise would not be found through visual inspection. Unlike traditional ultrasonic transducers, Air-coupled ultrasonic transducers can be applied to fulfill the functional requirements of the RUPIC.

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