An Experiment to Directly Measure the Optimum Frequency for Thru-The-Earth Communications With Loop Antennas

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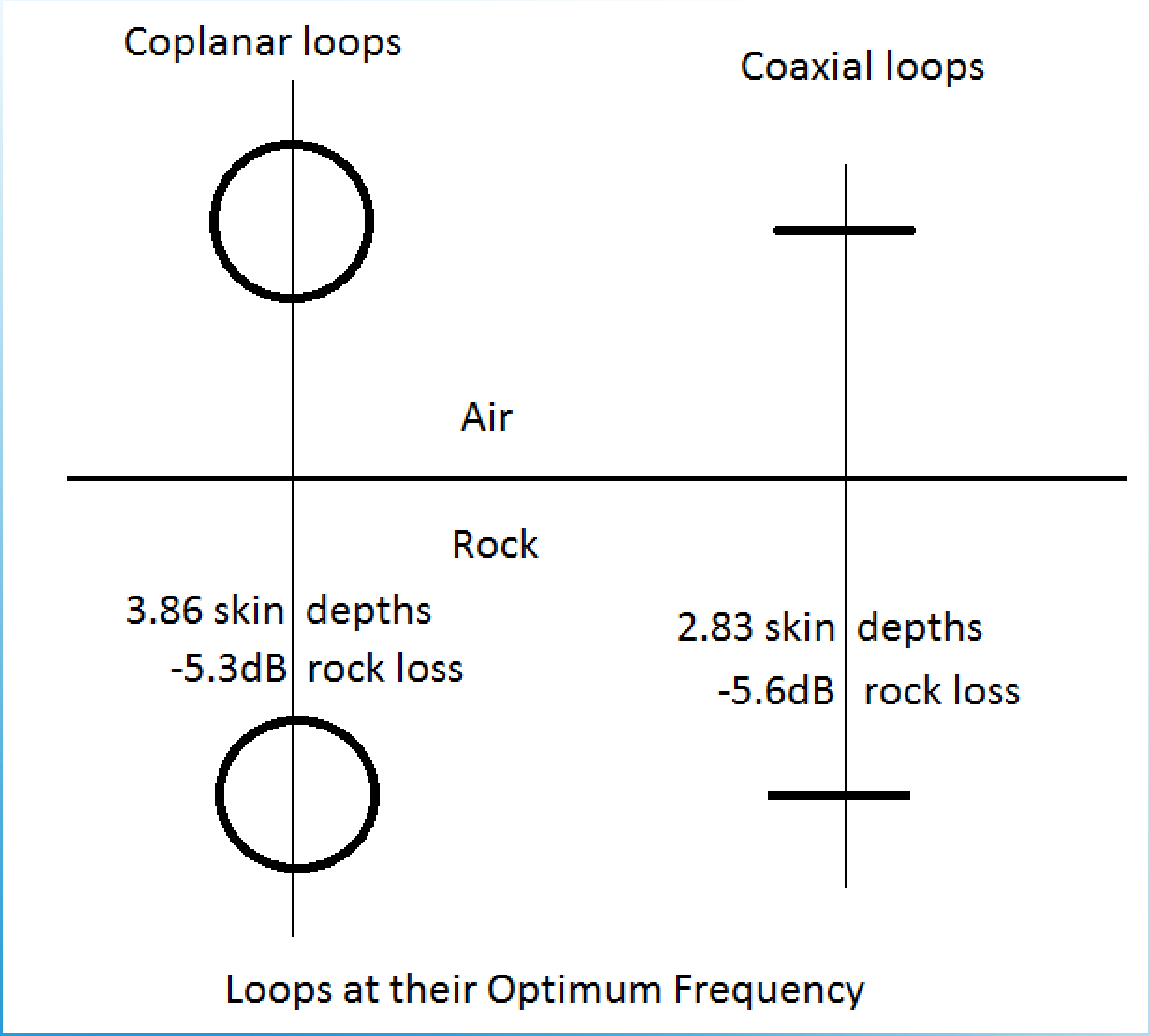
My inspiration came from David Gibson, who lives in the UK, who derived the Optimum Frequency equations in his 2003 PHD Thesis ***Channel Characterisation and System Design for Sub-Surface Communications.*** He proposed, but did not field test, sophisticated broadband equipment to measure Optimum Frequency.

While preparing this talk, I found a 1973 paper online called ***Analysis of Communications in Coal Mines*** by Dr M. D. Aldridge of West Virginia University that coverd this exact topic, including deriving the optimum frequencies, conductivity measurements, and Optimum Frequency measurements both Thru-The-Earth and within several mines.



This slide summarizes Optimum Frequency communication at any depth and rock conductivity.
Above 1 skin depth there is an advantage to coplanar loops

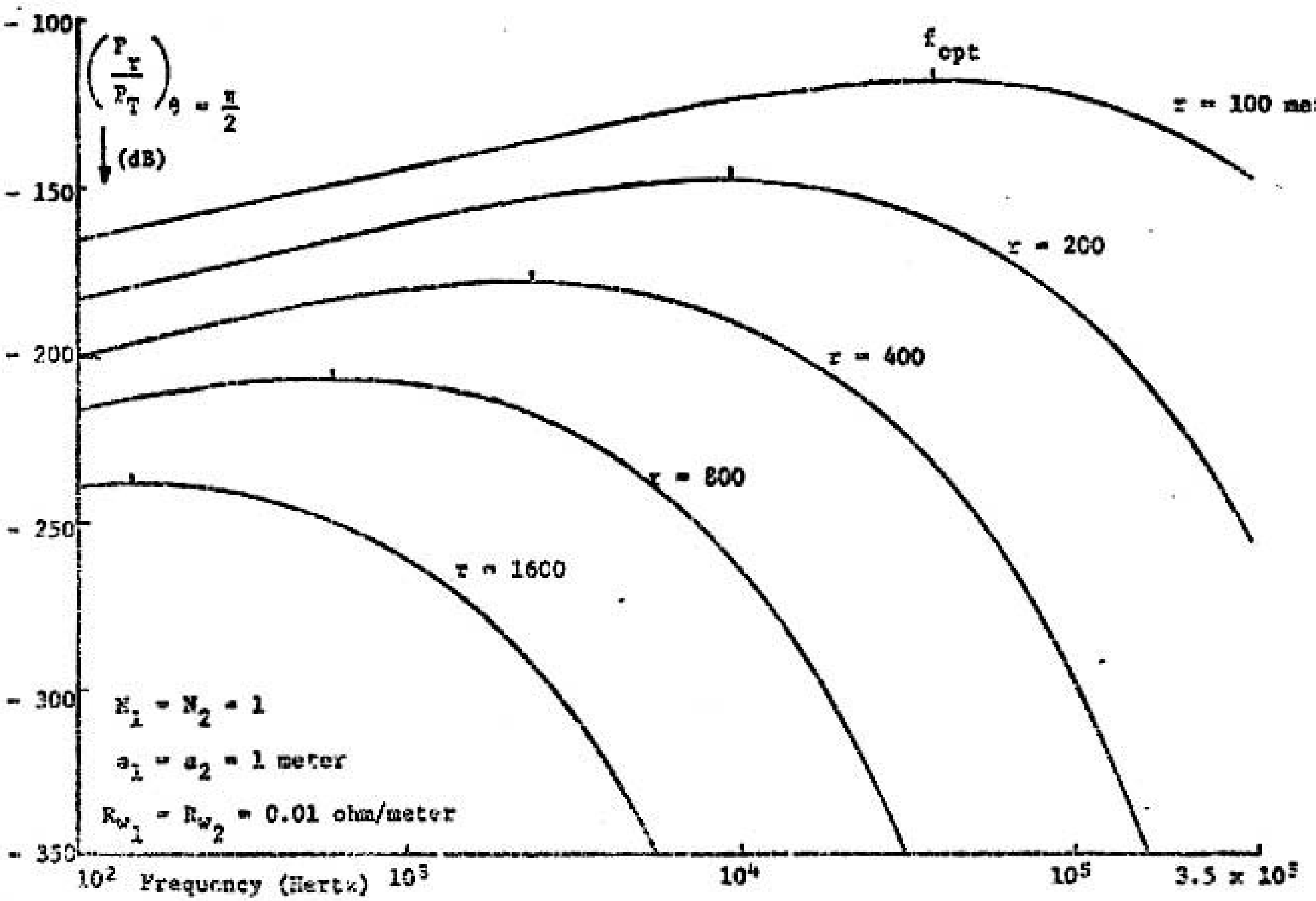


Figure 7
Power Transfer, $\sigma = 0.01$ mho/meter for coplanar loops

From *Analysis of Communications Systems in Coal Mines* by Dr M. D. Aldridge, 1973

Normal damp limestone is a moderately good conductor of electricity. RF penetration decreases with increasing frequency but in loop antennas the received signal voltage increases linearily with frequency. This results in a broad peak in the received signal, giving an optimum frequency.

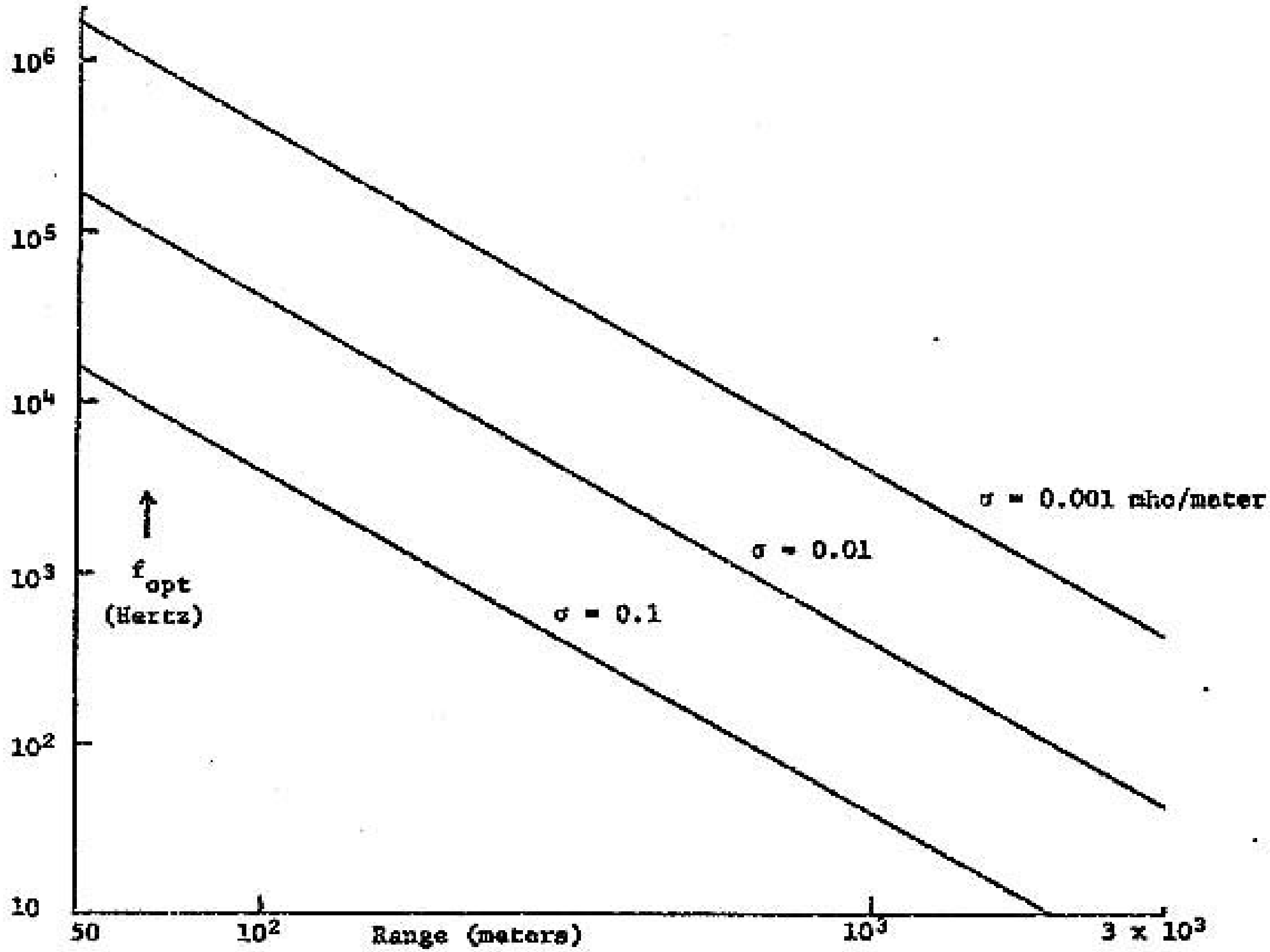


Figure 10
f_{opt} Versus Range, Coplanar Loops

From Analysis of Communications Systems in Coal Mines by Dr M. D. Aldridge, 1973

The optimum frequency drops as the rock becomes more conductive or range increases

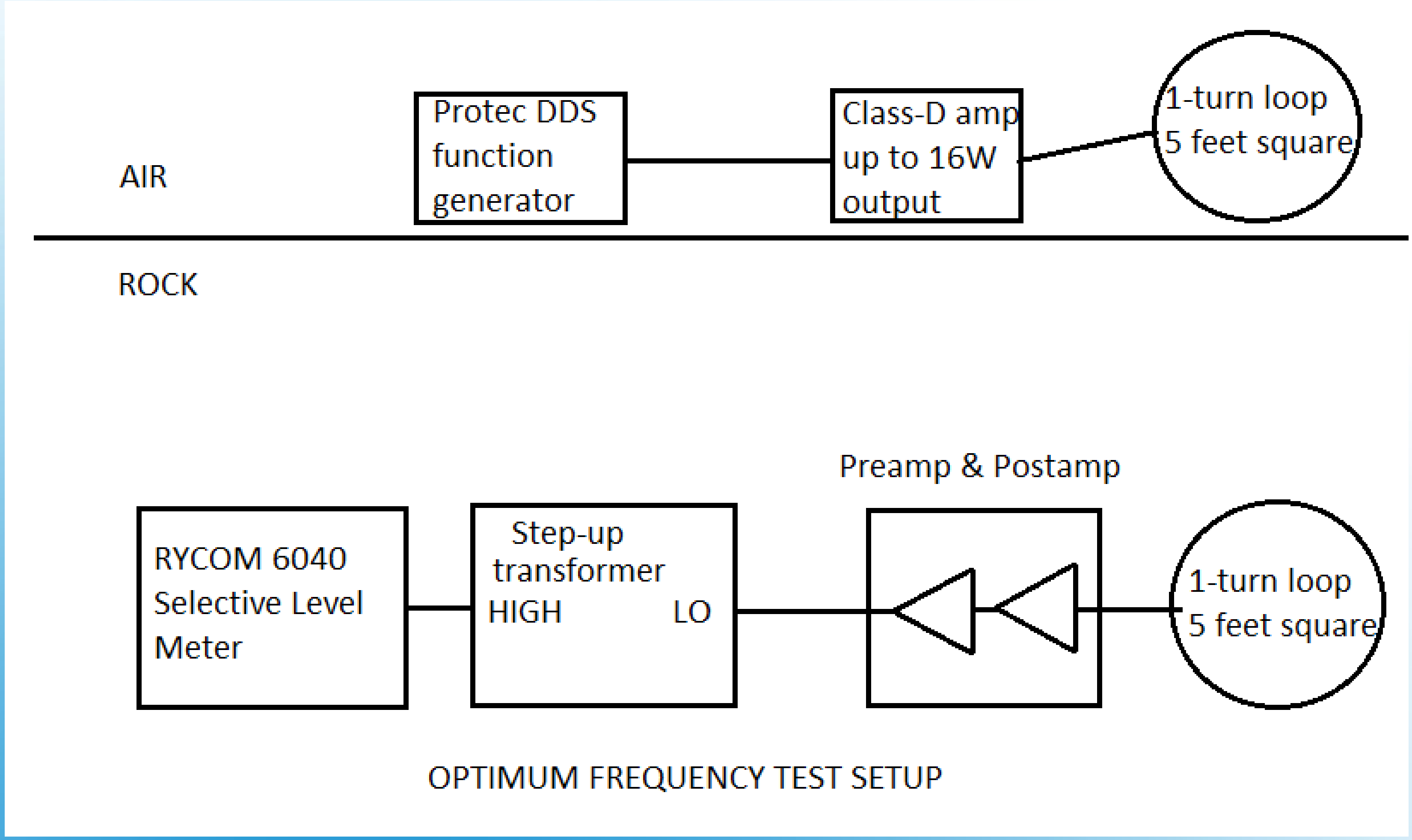
Coplanar loops Optimum Frequency=3774113/(Conductivity x Range squared)

Coaxial loops Optimum Frequency = 2030000/(Conductivity x Range squared)

Frequency in Hz
Conductivity in Siemens/meter
Range in meters

Surprisingly, David Gibson determined that atmospheric noise has little effect on the choice of optimim frequency and can be ignored.

The equation for optimum frequency is pretty simple

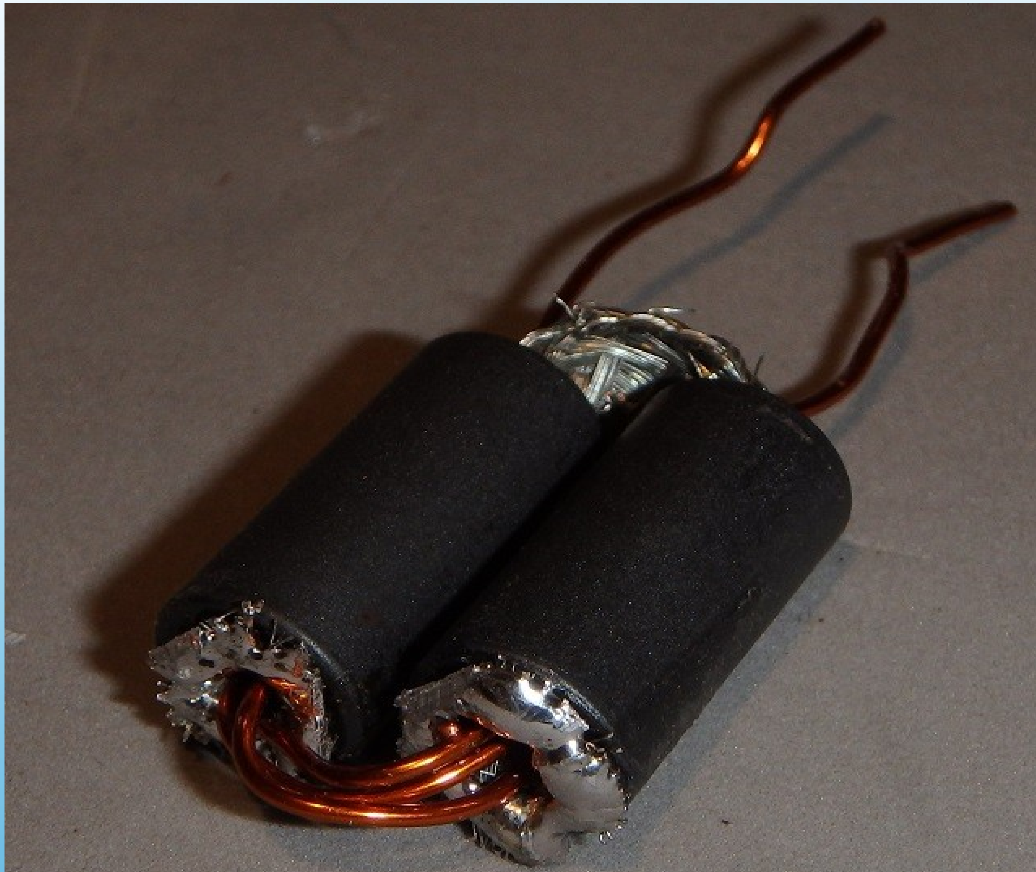


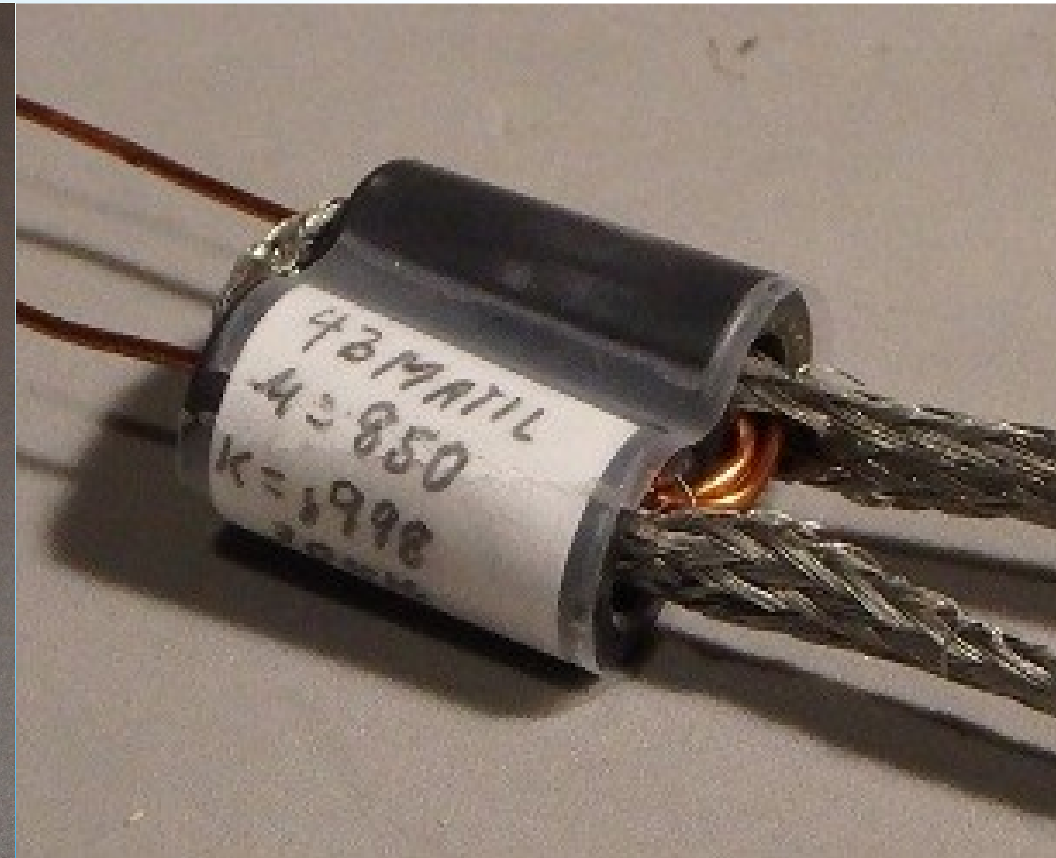
My goal was to directly observe the optimum frequency "peak". I decided to try to build a transmitter to be placed on the surface and a receiver for underground, to minimize received interference. I wanted the transmitted magnetic field to be as constant with frequency as possible, and for the output of the receive loop to rise linearily with frequency.

Early-on, I determined that I could not use broadband (untuned) loops. and that frequency sweeping was impractical.
I needed tuned loop antennas whose series-resonant resistance was constant with frequency. This meant that skin effect had to be minumized.
I chose to use a single turn of Litz wite with 660 turns of #46 wire. I decided to limit my range to 30-500kHz. This wire retains it's DC resistance beyond 500kHz.

My 5 ft (1.5 meter) one turn square loop has a resistance of 0.14 Ohms and an inductance of 9.36uh. This required stepping 0.14 Ohms up to 3.5 Ohms for the Transmitter and to 50 Ohms for the receiver. These transformers were the most challenging part of the design.

Loop Design

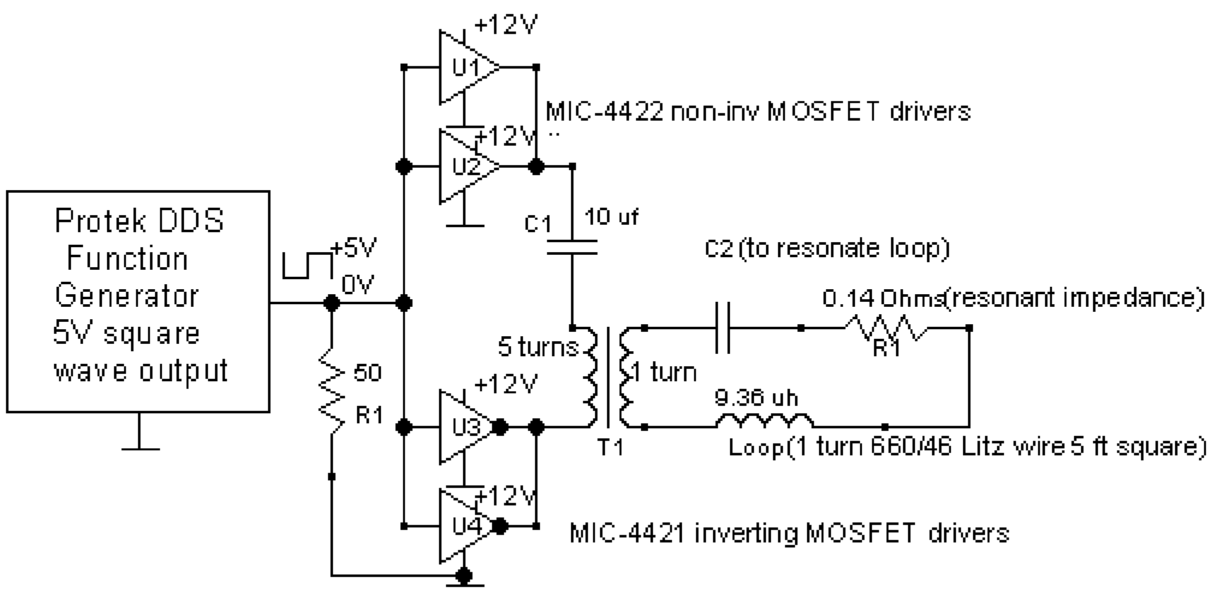




Two ways to build a transformer with a very high coupling factor, which minimizes leakage inductance. The multi-turn winding is inside of the hollow braid except at the ends. Coupling is 0.998 at 30kHz and 0.997 at 500kHz.

H-bridge MOSFET Transmitter

The amplifier generates 11 Amps in loop at 30 kHz, 7.3 Amps at 500 kHz.



Driving a load of 0.14 Ohms is not easy.

The drivers have Ron=0.8 Ohms each, higher than desired.

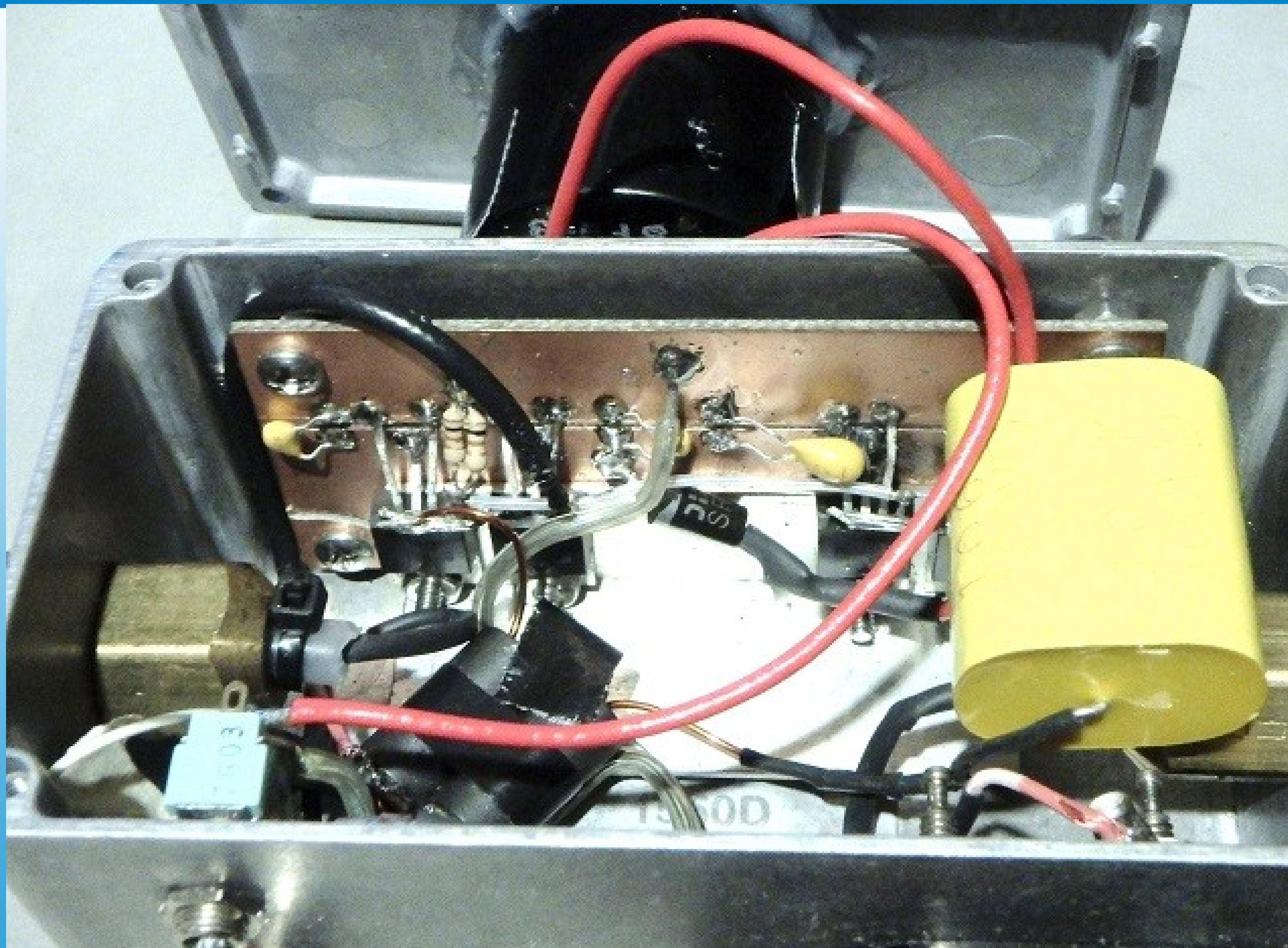
T1 is described in the talk. It uses mix 43 ferrite (u=850). L=3.9 uh for 1 turn.

The litz wire must be carefully soldered to capture all 660 strands.

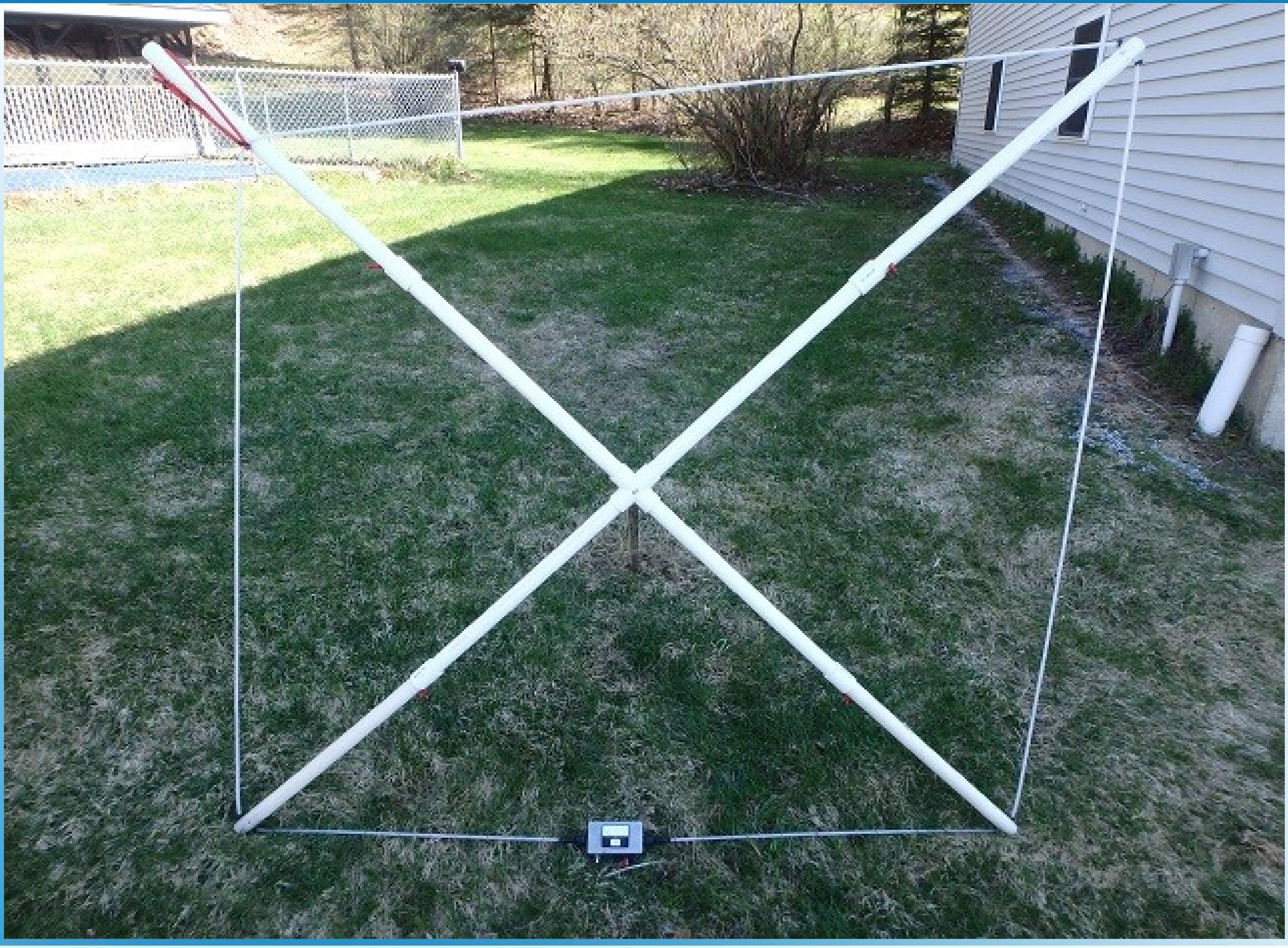
C2 consists of several low loss capacitors in parallel to lower series resistance (ESR).

The H-Bridge Class-D amplifier uses 4 MOSFET gate drivers that I had on hand.
Efficiency is ~80%, which is good given the high Ron of the drivers.

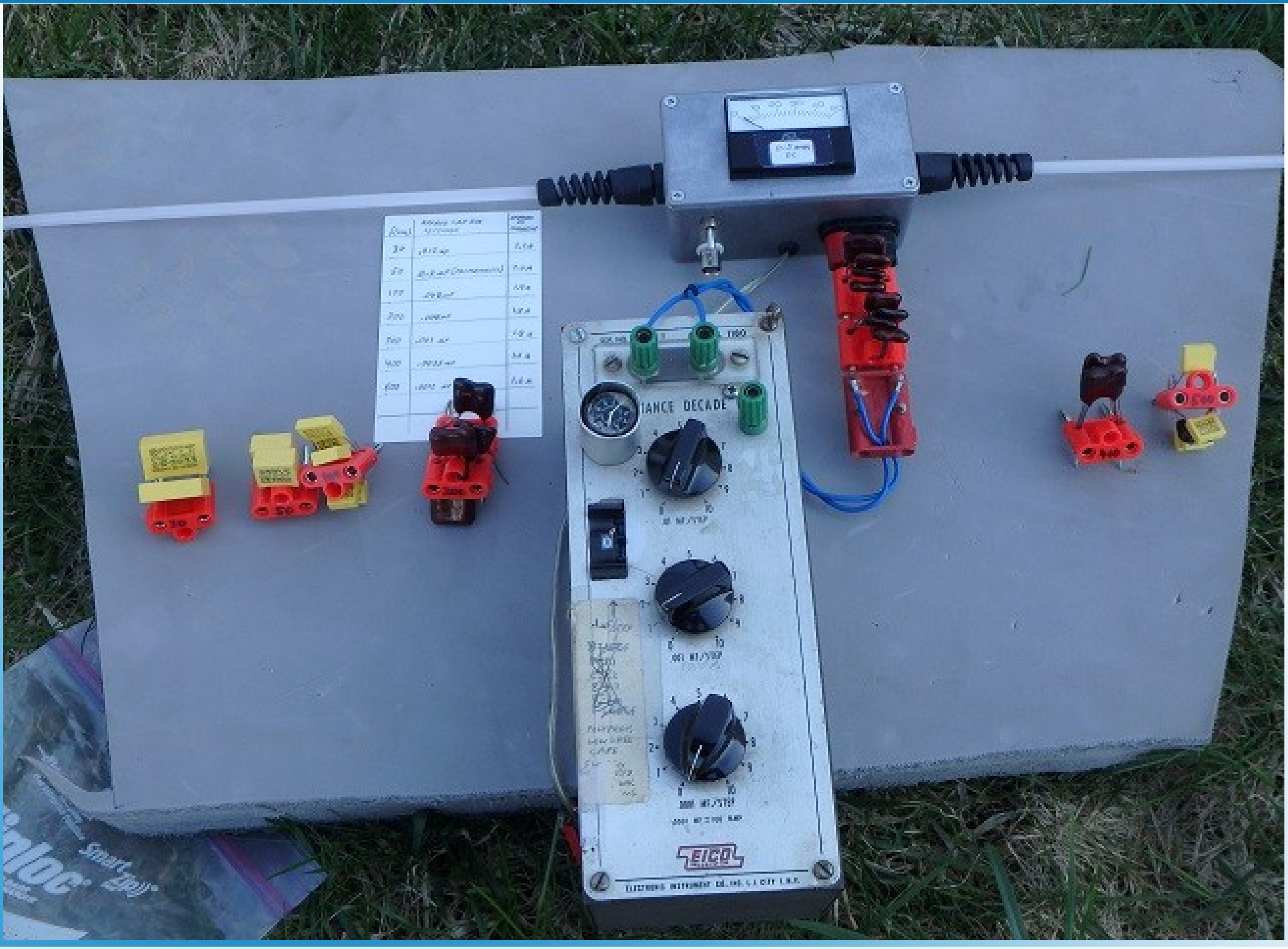
The Class-D amplifier



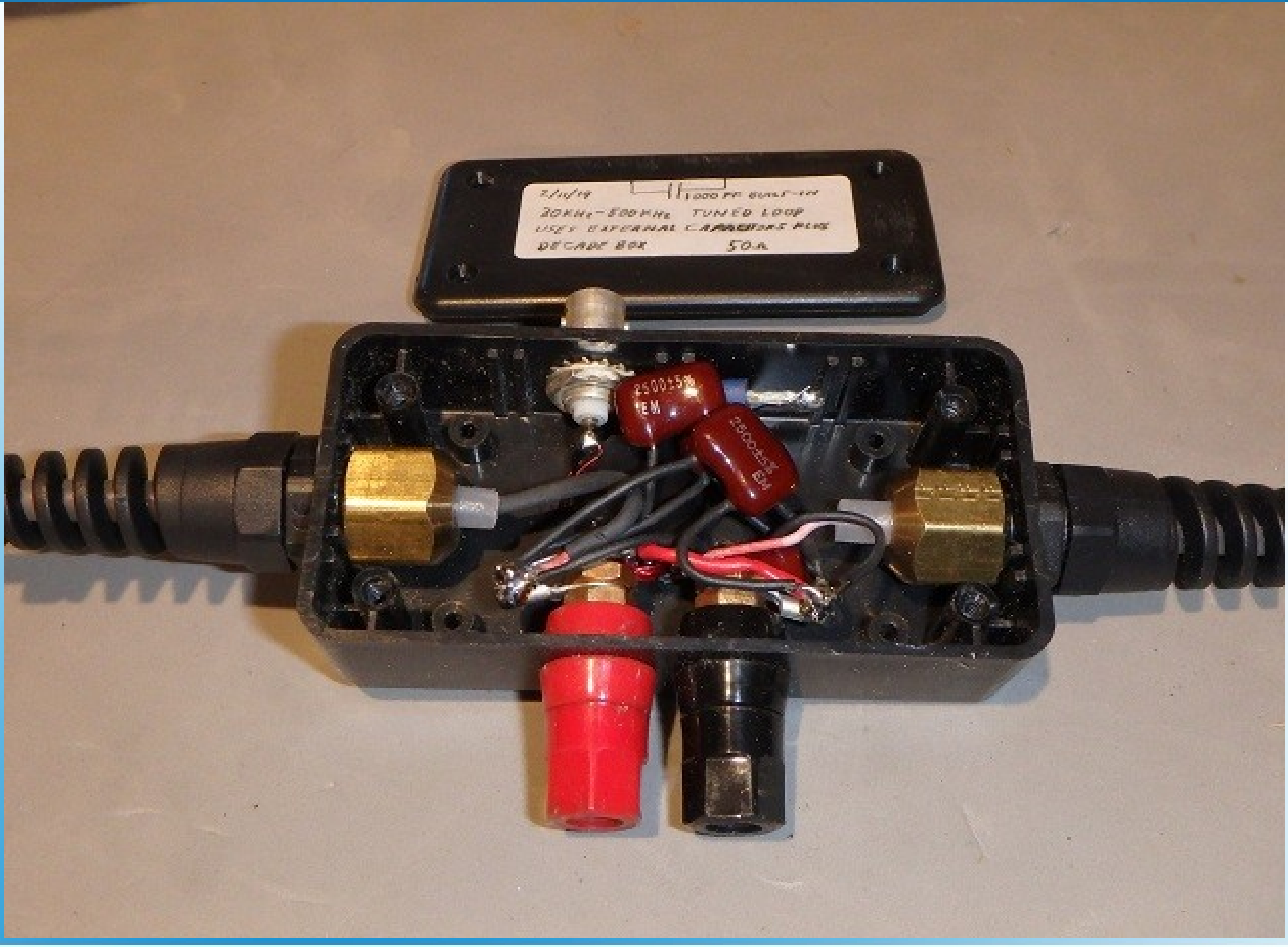
Inside the Class-D Amplifier



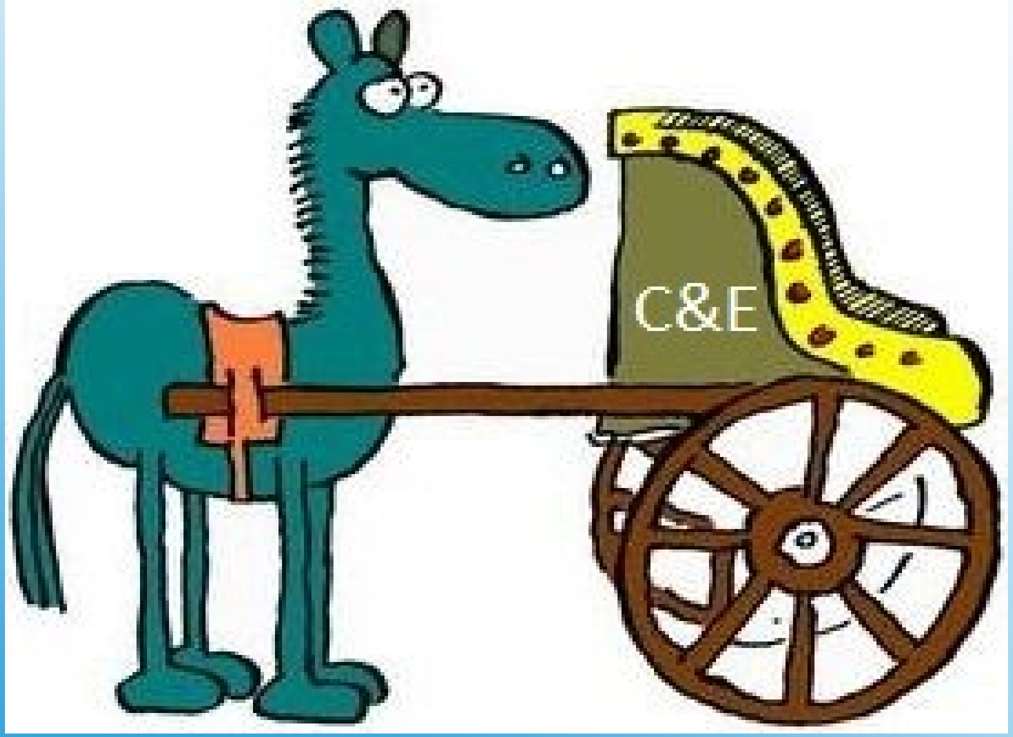
The 5 foot (1.5 meter) square transmit loop with amplifier



Loop tuning requires several low loss capacitors in parallel (mica or polypropylene) To reduce the ESR (Effective Series Resistance) well below 0.14 Ohms. The same setup is used for the receive loop. I picked 7 frequencies 30,50,100,200,300,400 and 500 kHz.



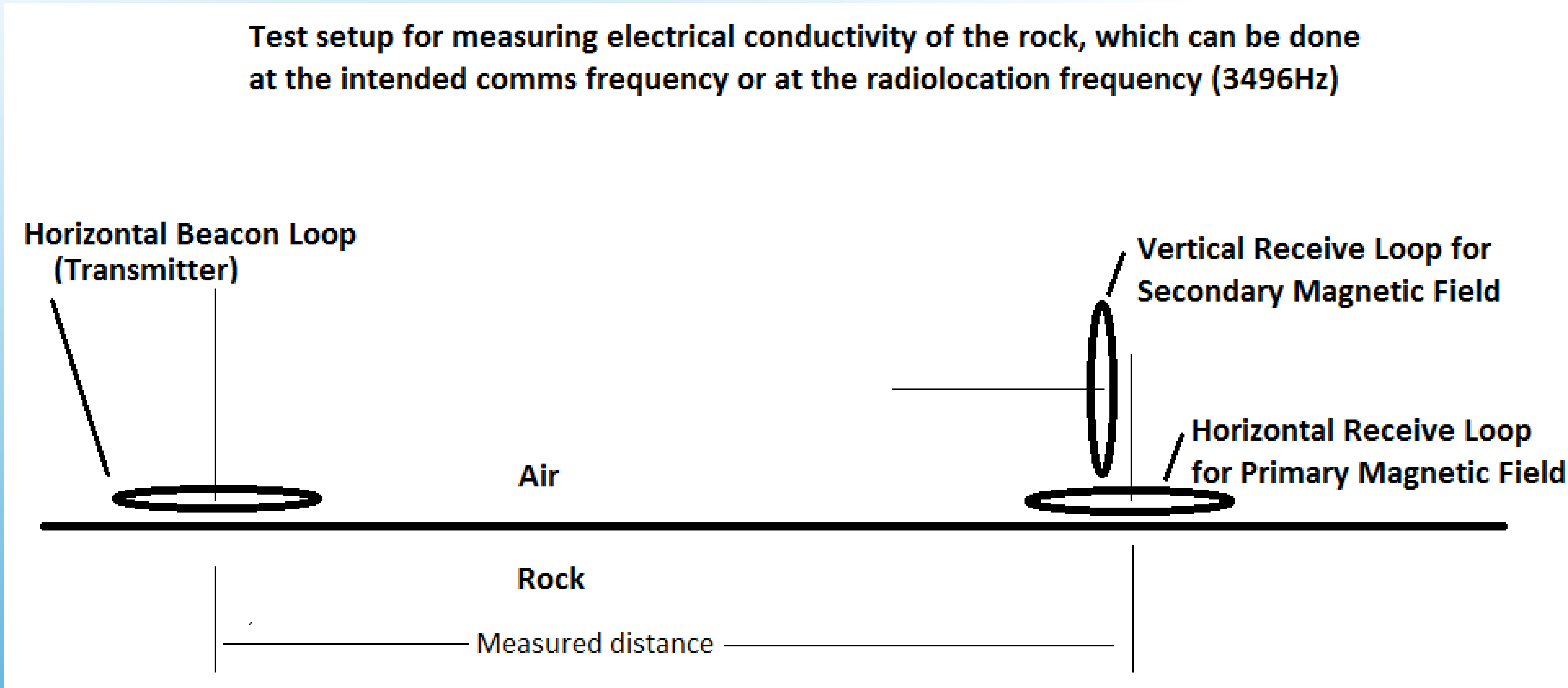
The receive loop is identical and also series-tuned, with a step-up transformer from 0.14 to 50 Ohms (hidden under the capacitors).



A field test of this device will require a separate functioning comms link between cave and surface to coordinate frequency changes and transmit times, which is sort of like putting the cart before the horse.

Fortunately I have a voice SSB comms setup using transverters and Icom IC-703 radios with 5 ft square loops that can operate on both 96kHz and 185kHz that should have the range to do the job.

Before an actual test, I must calibrate the gear on the surface at relatively short range where the ground loss has little effect, recording the received strength at each of the 7 frequencies. I can then calculate a correction table.



And then there is the matter of measuring the average or "bulk" ground conductivity. Ian Drummond In Speleonics 12 devised a simple method that uses the Vertical and horizontal fields at a known distance to calculate the average conductivity to a depth equal to the loop spacing.

A real test in a cave will involve several cavers to carry and set up the gear, which is not light or cave-proof. Both the transmit and receive loops must be re-tuned for each frequency. This gear will interfere with comms and vice versa.I have decided to do more testing before taking this gear into a cave.