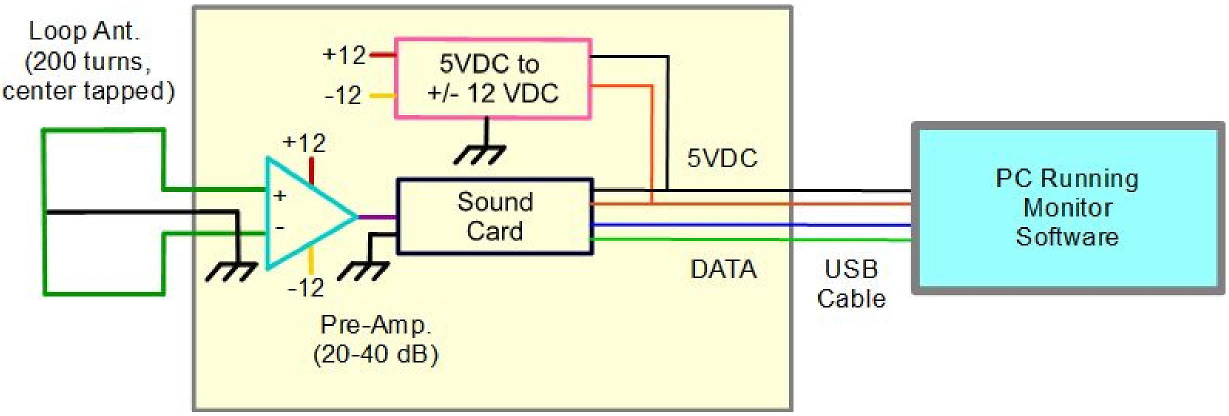
Title: A Portable, Calibrated VLF Field Strength Measurement Receiver and Loop Antenna

Introduction

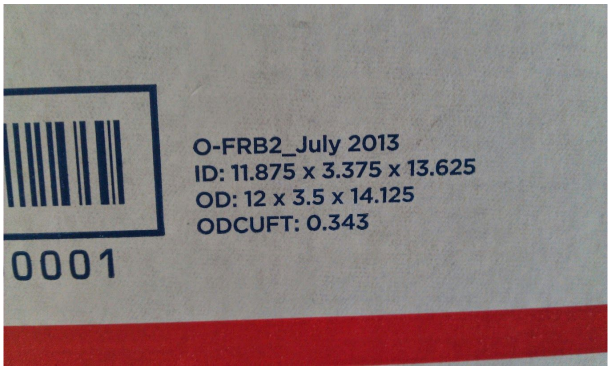
The purpose of this effort is to design and build a calibrated VLF field strength measurement receiver and loop antenna that can be easily shipped to various sites. Topics covered:

- Description of construction and test of initial “first guess” system
- Two possible architectures for the system: Current to voltage amplifier and instrumentation amplifier
- Loop antenna design and construction
- Sensitivity analysis of the chosen instrumentation amplifier realization
- Calibration of the loop antenna
- Conclusions

The system block diagram is shown below.



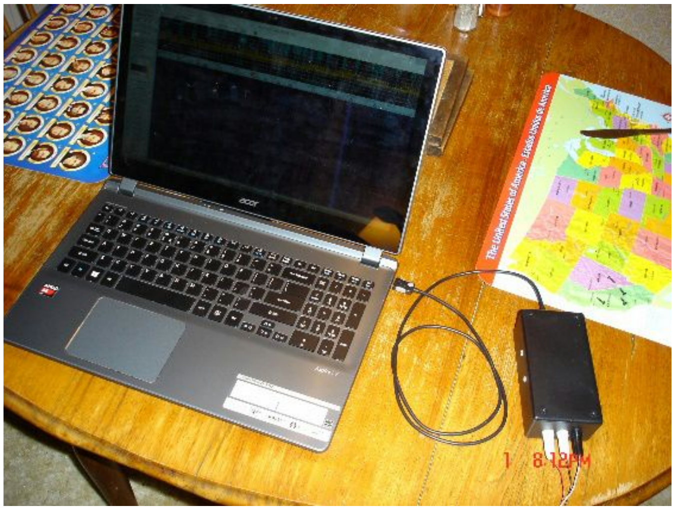
The parts inside the yellow box and the loop antenna can be shipped to the remote site for monitoring. The user will supply the tripod, PC, and monitoring software.



So the box size is the first parameter that affects the design, particularly the loop size. Everything is designed to fit into a standard US Postal Service Priority Mail box.

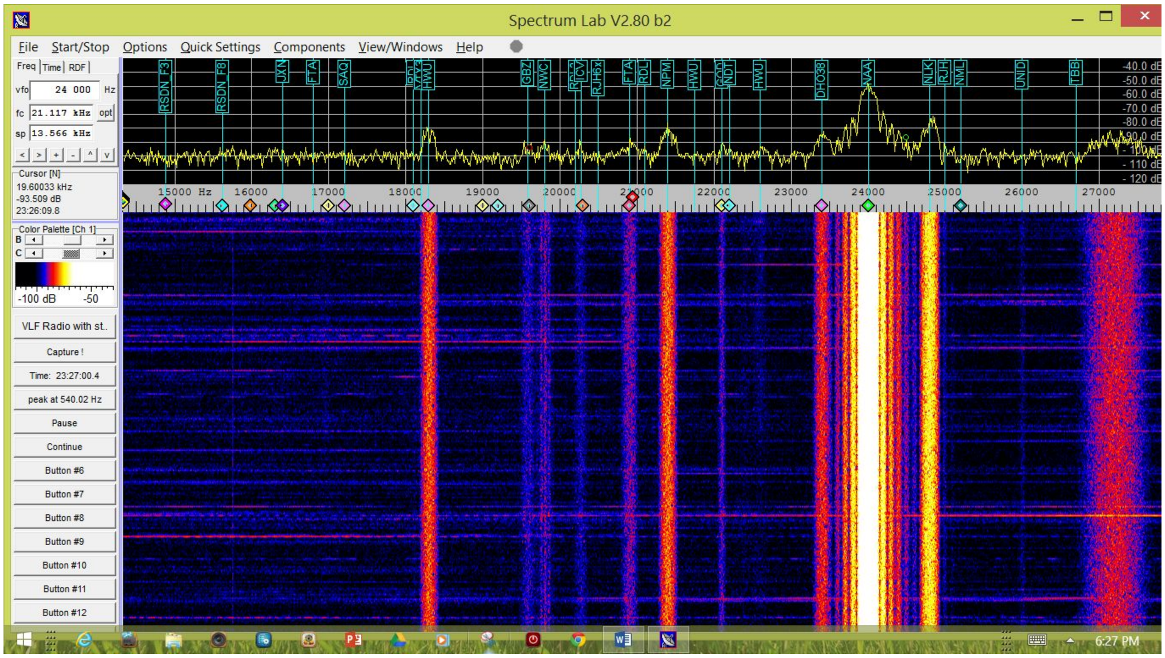
The photos below show the completed version of the setup. The form for the loop antenna is rectangular to fit inside the shipping box. The preamp/soundcard box and cables fit inside the loop antenna form. The loop antenna form is made of a 10.5”x13” form of polystyrene foam insulation board, 2” thick. An opening is cut inside the form to provide a storage location for the cables and interface box.

Loop Antenna



Interface Box and PC

Inside Interface Box



vfo 24 000 Hz

fc 21.117 kHz

sp 13.566 kHz

Cursor [N]
19.60033 kHz
-93.509 dB
23:26:09.8

Time: 23:27:00.4

peak at 540.02 Hz

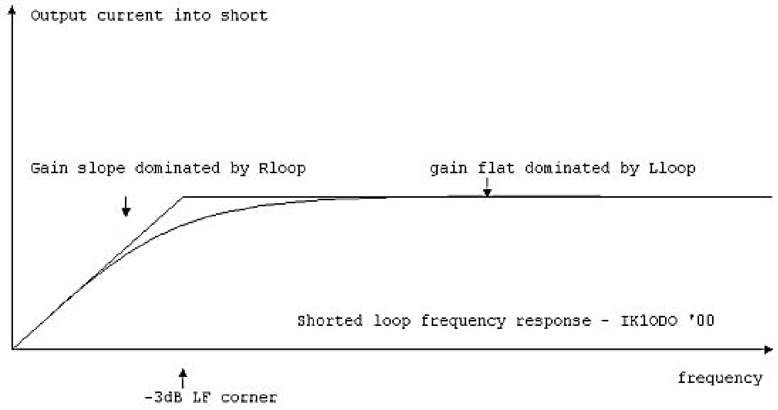
Early Test of Setup; 11/21/14: 11 Stations Received after Sunset, 30 dB Gain Setting

So, the first off the top of my head educated guess for a system at first glance looks like it will meet requirements. The analysis of the design followed construction and initial test of the setup.

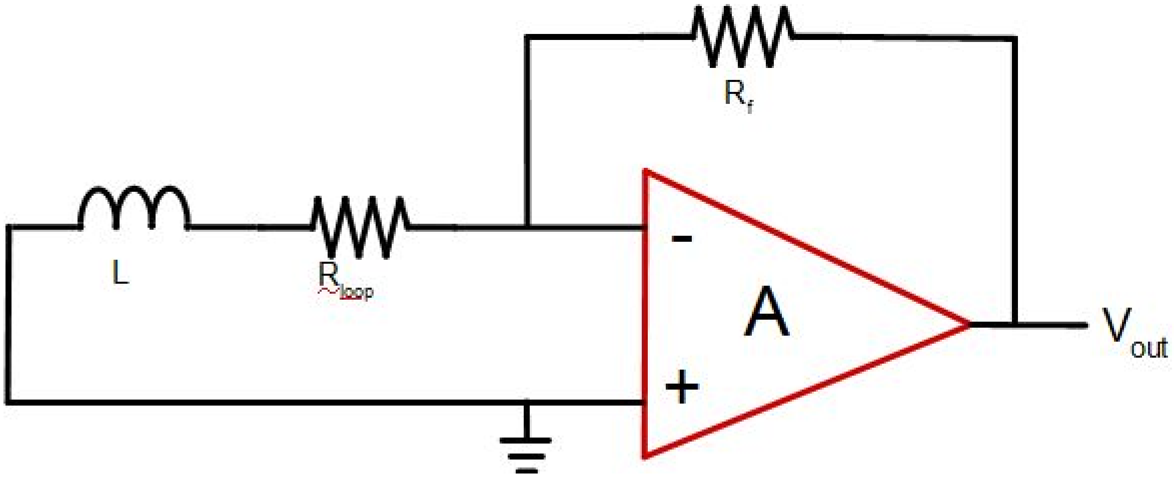
1: System Architecture; Two Possible Ways to Build the System

There are two possible types of amplifier that can be connected to a loop antenna. One is a current-to-voltage (transimpedance) amplifier and the other is a voltage-to-voltage amplifier. The current to voltage amplifier applies a signal short circuit across the loop to maximize the current through the loop. The voltage to voltage amplifier applies a high impedance load across the loop and senses the open circuit voltage of the loop. Virtually no current flows in the loop with this amplifier.

One advantage of the transimpedance amplifier is that the loop is grounded on both ends and is thus protected against electrostatic coupling (proximity effect) from local noise sources. The loop has balanced impedances to ground and need not be shielded. Another advantage

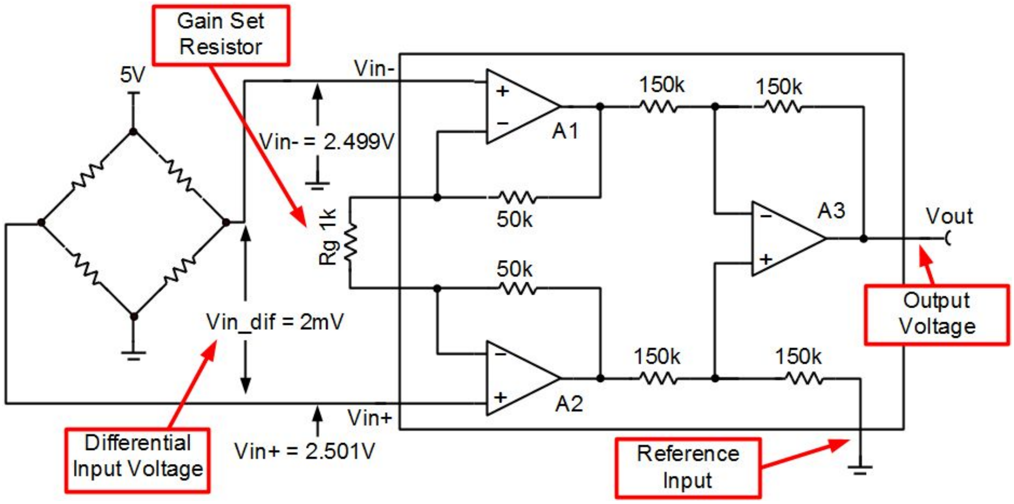


of this configuration is that from a low knee frequency value, the response of the system is independent of frequency. This is advantageous for measuring field strengths at different frequencies. The Stanford VLF group uses this system for its standard VLF receiving setups.



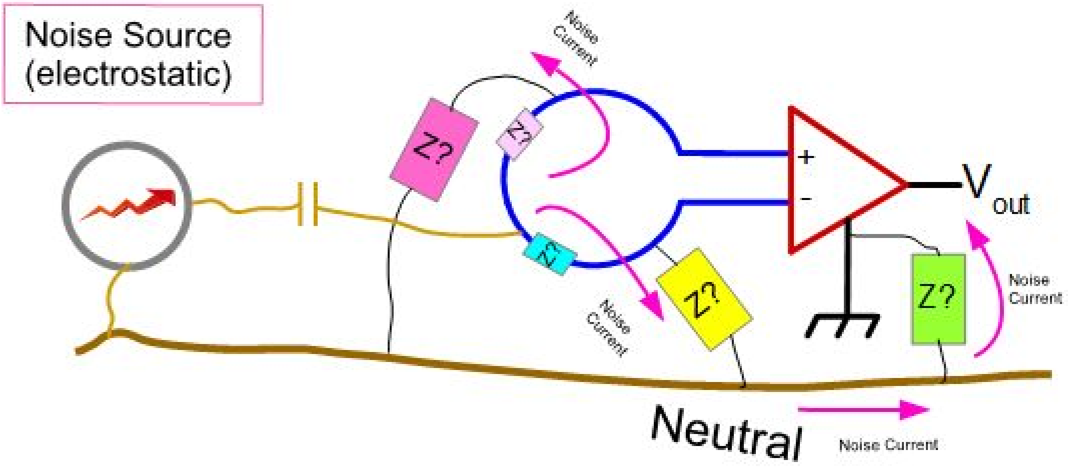
A disadvantage of this configuration is that the opamp must sink a fair amount of current through the feedback resistor to achieve the desired gain. For more explanation see several articles at www.vlf.it. Another disadvantage is that the input impedance is so low that sometimes a transformer is connected between the loop and the amplifier input for a better impedance match.

The high input impedance voltage amplifier is the configuration I built. I used an INA103 instrumentation amplifier (IA) connected to a center tap grounded loop. There is basically no current flow through the loop, as the loop terminals are connected to the IA input which presents a very high impedance to the loop. In effect, only the open circuit voltage of the loop is detected in this setup.



An advantage of this configuration is that if desired the loop can be tuned with a parallel capacitor because the loading is high impedance and a high Q can be achieved. Another advantage is that the gain of the system increases with frequency and this may be desirable in some cases.

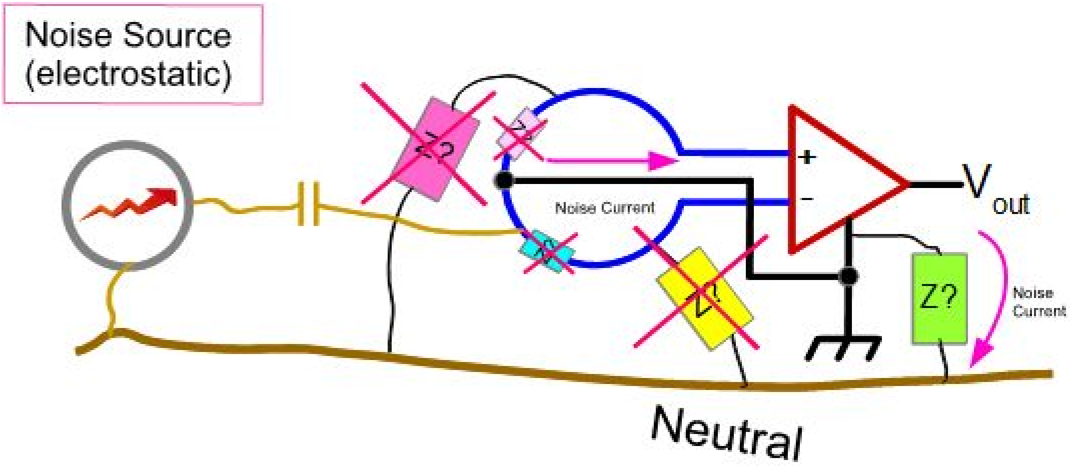
A disadvantage of using a high input impedance amplifier is that if the loop is unbalanced, i.e., the loop does not have equal impedance to ground at both terminals, it will present a differential voltage to the amplifier in the presence of a disturbance from electrostatic (capacitive) coupling. The undesirable result of this is that it will respond to electrostatic local noise sources and the hand effect (also called proximity effect) will come into play. One way around this problem would be to ground both input terminals as in the transimpedance amplifier, but of course this would short out the differential voltage developed by the loop in a magnetic field. A good way to balance the loop is to make a center tapped loop and then ground the center tap. In this way both halves of the loop see the same impedance to ground and electrostatic effects are reduced if not eliminated.



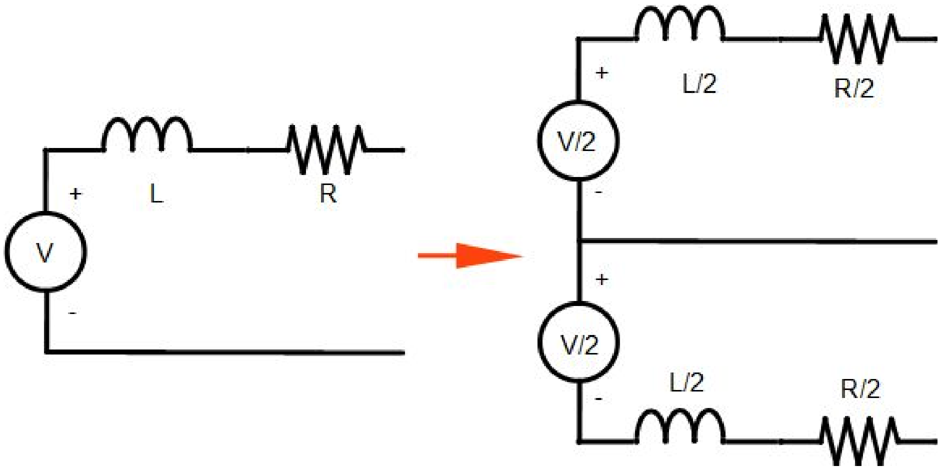
In the figure above, undesired differential voltages can form at the amplifier inputs due to currents flowing through the stray impedances formed between different loop windings and neutral reference. Under these conditions the loop is considered to be *unbalanced* because the output leads of the loop have different impedances to neutral. The currents become a problem because the amplifier reference is also connected to neutral through stray capacitance. The source of these currents is a local noise source that is electrostatically (or capacitively) coupled through stray capacitance to the different parts of the loop. Shielding the loop is one way to stop the problem, but an easier way to deal with this problem is with a center tapped loop.

The center-tapped loop effectively shorts out the stray impedances that are connected to the loop. This has the effect of putting both loop outputs at ground potential with respect to neutral. There is still undesired coupling, but now there's a much smaller potential drop through the unbalanced loop impedances and the undesired effects are greatly reduced. The center tapped loop is the method I chose to improve electrostatic noise coupling immunity for the setup.

When I first tested this setup with an ungrounded loop, I noticed that I had to move the loop at least 12-15 feet away from my monitor laptop because of interference. I could move my hands over the laptop and the noise floor would go up and down 20 dB or so. With the center tapped loop, the baseline was stabilized, and I could place the loop practically next to the laptop and not suffer from interference.



Splitting the loop and grounding the center tap is possible because of the high common mode rejection ratio (CMRR) of the differential amplifier. Note that the instrumentation amplifier has an especially high CMRR and that virtually no current flows into the input terminal because of it's design. Because of this, any voltage within reason may be applied to the center tap and the amplifier still only responds to the differential output voltage of the loop, either center tapped or not. With the center tapped loop grounded , the common mode voltage is zero, which is the best possible case, since even with a finite CMRR, the output voltage of the amplifier is still zero volts. The diagram below shows how the source voltage and impedances of the loop are both divided in half by the center tap.

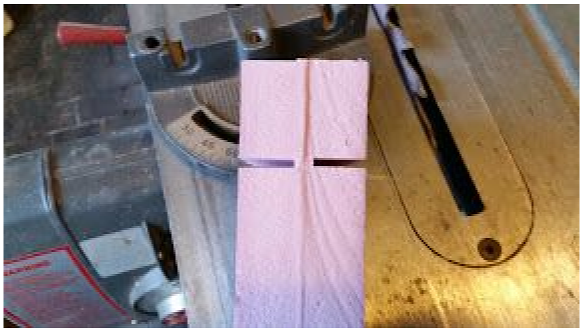


This dividing of the loop parameters has no effect on the operation of the preamp because no current flows in the legs and the V/2 voltages appear in superposition at the differential inputs of the instrumentation amplifier. In most cases of electrostatic interference, the impedance of the stray capacitance is much higher (0.1-10MΩ?) than half the loop impedance (or ~1kΩ in the case of the loop for this setup) and the voltage is dropped to practically nothing across either impedance.

2: Loop Antenna Construction and Design

Using techniques based on reference 1 rectangular loop coil form from 2” thick pink polystyrene insulating board. The easiest way I found to form the material is by cutting it on a table saw. In the past I have used a wire heated with 15-20 A of current flowing through it, but I find it difficult to keep the wire straight and normal to the material surface.

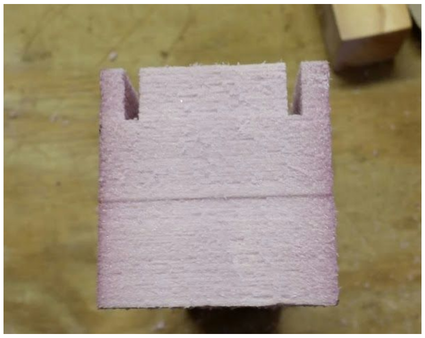
When cutting foam board on a table saw, the material has a tendency to buck and be gouged by the sawblade if the cut is made all the through the material. Instead if the cut is made almost halfway through on one side and then the piece is flipped over and cut on the other side, leaving a ⅛” to ¼” strip connecting the two parts of the material, a nice clean cut can be made.



Then the two parts are broken apart and the remnants of the connecting strip are peeled off. The edge is finished off with a sander to make a nice smooth surface that is ready for hot melt gluing.

Four 3” wide pieces of material are glued together with a hot melt glue gun. While the glue cools and sets over a two minute period or so, the pieces are held square in a form made up of a couple of wood strips screwed to the benchtop.

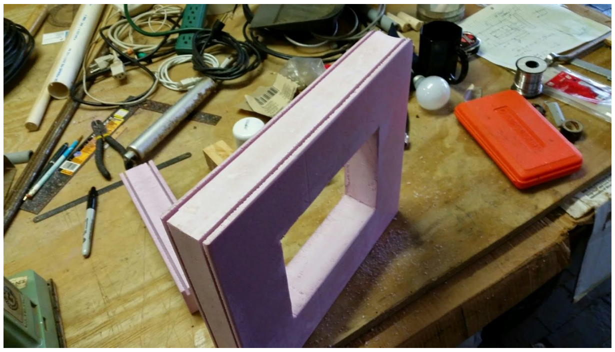
When the rectangular form has set and is rigid, grooves are cut on the table saw to receive the coil windings. Two grooves are made for half of the total windings each. The center tap is brought out between the windings for connection to the preamplifier.



With the grooves made as shown, it’s easy to wind two equal lengths of wire in each groove and bring out the ends of the loop for the center tap and the output terminals. I’ve found that winding the loop on a flat surface is hard because the windings get loose over time in spite of how careful I am to maintain wire tension during the winding process.

I put 100 turns of AWG 28 gauge wire into each slot, connected them together for the center tap and brought out both ends for the output terminals. The dimensions of the loop are: 12”x10-⅜” or 30.5 x 26.4 cm. The area of the loop is therefore 0.081 m^2.

tbd need more photos here of coil end connections



The wire is wound onto the form by clamping the form between two plywood pieces and rotating the form around a wood dowel clamped in a vise.

tbd more pix here of winding process

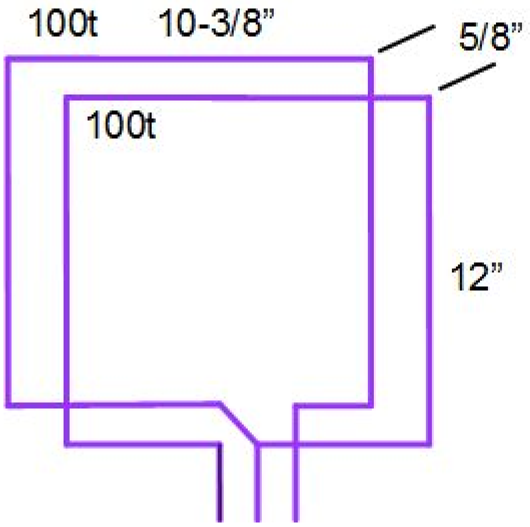
The design of the loop antenna needs to take a couple of parameters into account:

- What is the range of expected signals that will be received?
- What is the thermal noise output from the loop itself due to the resistance of the wire?

These parameters together with the gain and noise levels of the preamplifier will determine the lowest possible magnetic field strength receivable by the system.

The approach I took was to build a coil that I thought would do the required job, do some initial testing with it, and then later analyze the design for performance. Time constraints were the reasons I took this approach. Refinements can come later!

The coil dimensions, no. of turns, etc. are shown in the diagram below.



When using the loop antenna with an instrumentation amplifier, the output voltage at the loop terminals is the important characteristic.

The below equations show how the output loop voltage is calculated. Lab measurements are performed to verify the calculations.

$$V_{rms} = 2\pi f B_{rms}$$

Where
V_{rms} is the open circuit loop voltage
f is the frequency in Hz
B_{rms} is the magnetic flux density of the field causing the open circuit voltage (Loop is assumed to be oriented in the direction for maximum open loop voltage)

Quite often it's desirable to calculate the effective height of the loop. This is a parameter that compares the loop to an equivalent length of wire that responds to the electric field of the source to be measured. This allows the loop to be characterized in terms of electric field strength instead of magnetic field strength.

The math for converting to effective height is as follows:

$$V = h_e E$$

Where
V is the open circuit loop voltage
h_e is the effective height of the loop (or equivalent length of wire of a wire antenna)
E is the electric field strength of the inducing field in units of V/m

h_e is calculated with the following:

$$h_e = \frac{2\pi n A}{\lambda}$$

Where
h_e is the effective height of the loop
n is the number of turns in the loop
A is the area of the loop
λ is the wavelength of the received signal

In the case of the loop used for this project: h_e for 24 kHz is calculated at 0.008 m, or 8 mm!

So it's pretty obvious that a loop antenna is not very sensitive compared to a piece of wire. Why are loops preferred for VLF? A couple of reasons: They are compact, they are directional. And they work just fine with enough gain because of the high ambient noise levels which sets a lower noise floor.

Section 3: System Sensitivity

In this section an estimate of the sensitivity of the system is made, or in other words, what the lowest detectable signal is for the system. I want the most sensitive possible system for a loop that fits into the USPS box. For starters, I want the noise floor of my system below the detectable level of sound card input. Also want a TBD S/N ratio for the lowest detectable signal that my sound card can detect. In addition, TINA-TI is used to simulate the system.

The basic definition of sensitivity for the setup is defined as the lowest magnetic field strength that can be detected. The voltage representing this minimum field strength and its ratio to the system noise determines the sensitivity of the system. Another consideration is the bandwidth of the soundcard receiver. As bandwidth is increased, the noise power increases and the noise voltage increases, but of course the received signal does not increase, assuming its bandwidth is narrower than the receiver bandwidth.

The first limitation on the output loop voltage is the thermal noise from the resistance of the wire of the loop. Next, the noise floor for the amplifier and its associated components are determined. Then, noise contributions of the components are added by root sum of the square. Once all the noise voltages have been added up, the loop open circuit voltage is superimposed on the noise floor to see what amplitude is needed to exceed the noise floor voltage.

The Johnson-Nyquist thermal noise voltage from a resistance is calculated as follows:

$$v_n = \sqrt{4 k_b T R B}$$

Where

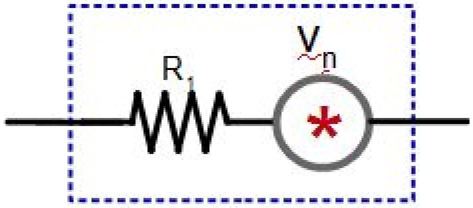
k_b is the Boltzmann's Constant

T is the temperature of the resistor in Kelvin (°K)

R is the value of the resistor

B is the bandwidth of the noise measurement setup (or our VLF receiver in this case)

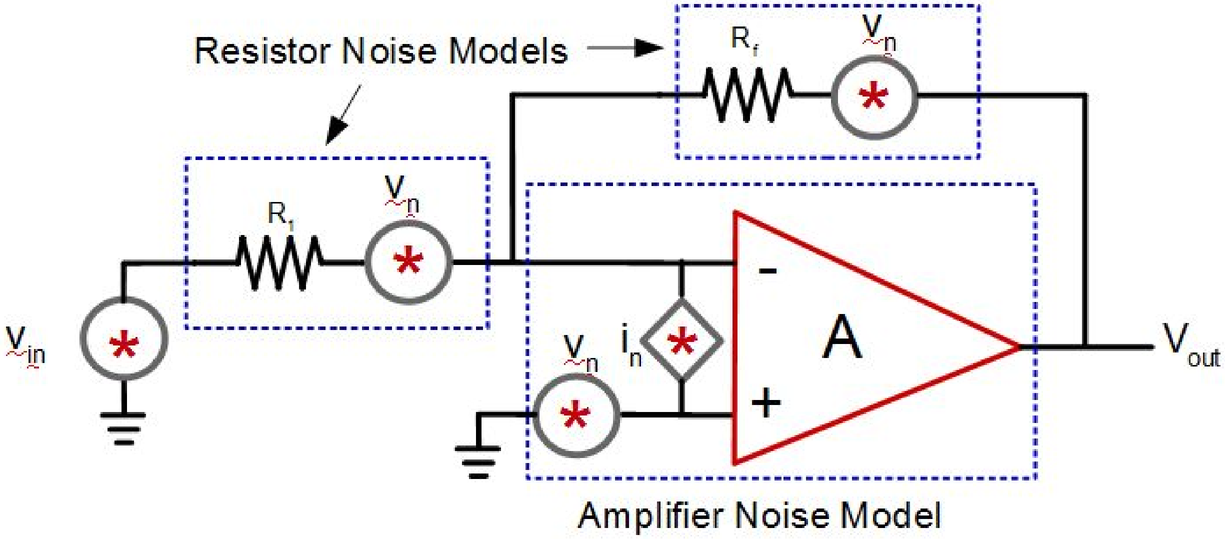
So a resistor can be modelled as an ideal noiseless resistor in series with a noise source of voltage as defined above.



The operational amplifier of the VLF receiver has noise sources which can be modelled as both voltage noise and current noise sources. See the diagram below.

All of the noise sources for a preamplifier and loop antenna can be summed up by the root sum of the square method, since thermal noise is uncorrelated. This means that the noise is gaussian and all noise sources are independent of each other, that is, they have no effect on each other.

For a simple preamp and loop antenna, the various noise contributors are seen below.



The resistor noise sources are calculated from the above formula and the op-amp current and voltage noise sources are read from the op-amp data sheet. In the VLF frequency range the voltage noise source is orders of magnitude greater than the current noise source, so the current noise source can usually be ignored.

Example; For the above op-amp circuit, assume the following apply:

T = 300 K
BW = 100 Hz
R_1 = 1 kΩ

R_f = 100 kΩ
A = 100
$R_{eq} = R_1||R_f$ = 990 Ω
e_n = 55 nV/(Hz)^{½} (@ 24 kHz)
i_n = 100 fA/(Hz)^{½} (@ 24 kHz)

The noise, referred to the op amp input is:

Resistor Johnson/Nyquist noise: $E_{Req} = \sqrt{4k_b \cdot 300 \cdot 990 \cdot 100)}$ = 40.5 nV
Current noise: Negligible, ignore

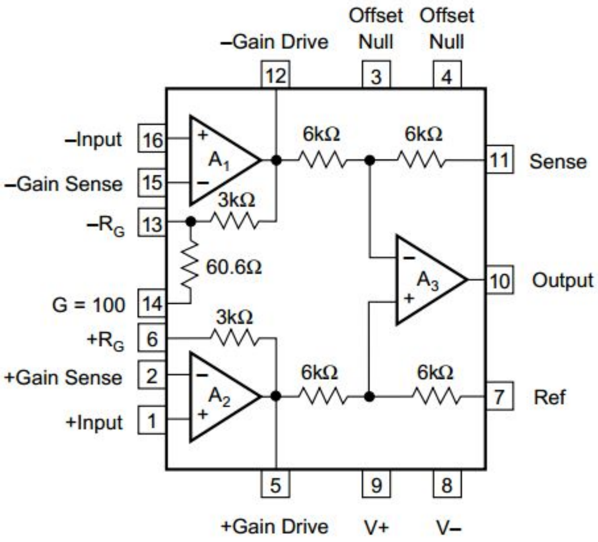
Broadband op-amp noise: (55 nV/(Hz)^{½}) $(\sqrt{100Hz})$ (100) = 55 uV

Total Noise voltage: ~55 uV

So in conclusion, the noise voltage at the output of the amplifier is tbd V. This is an example of how to calculate the noise voltage by hand.

Section 4: INA103 Noise Calculations and Simulation

The INA103 is an instrumentation amplifier (IA). An instrumentation amplifier is a differential input amplifier that has a far better common mode rejection ratio than say a standard differential operational amplifier. In addition it can have a very high gain and the gain is set by one resistor. It uses three op amps typically in the following configuration:



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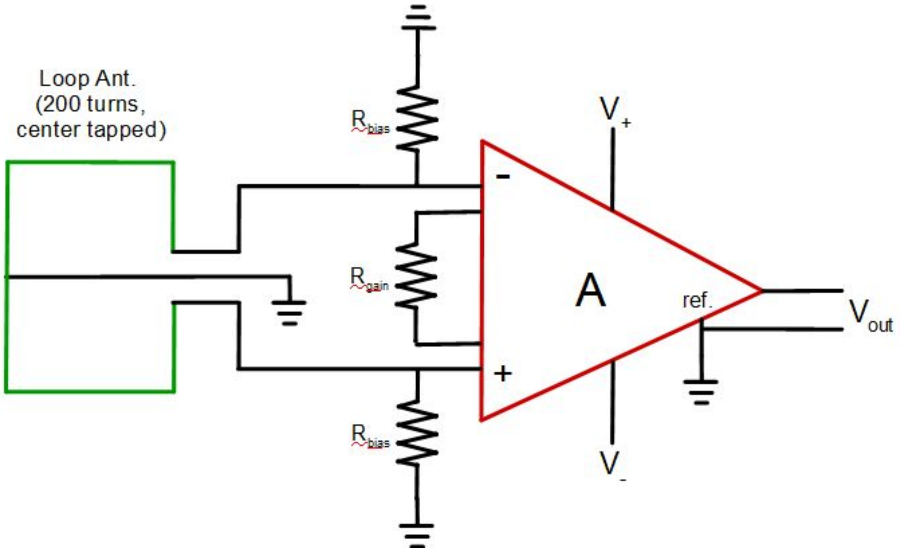
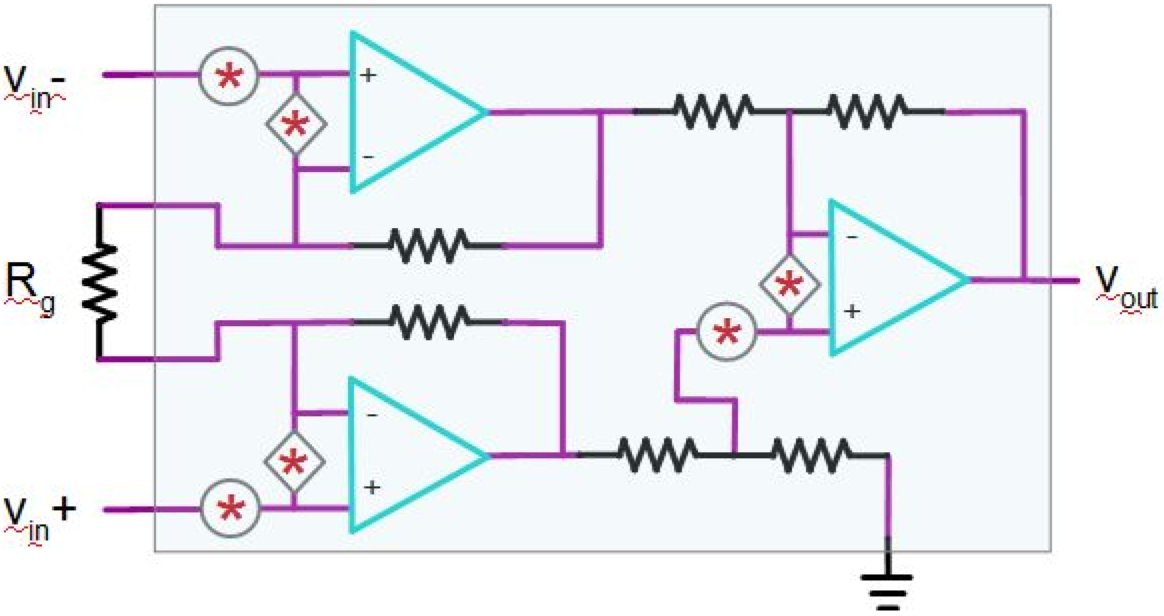
The diagram shows how an IA may be connected to a center-tapped loop.



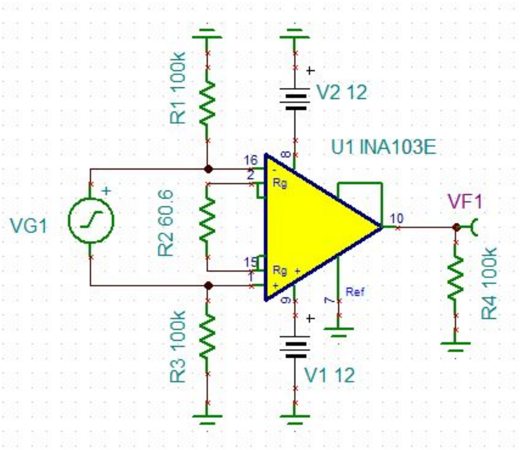


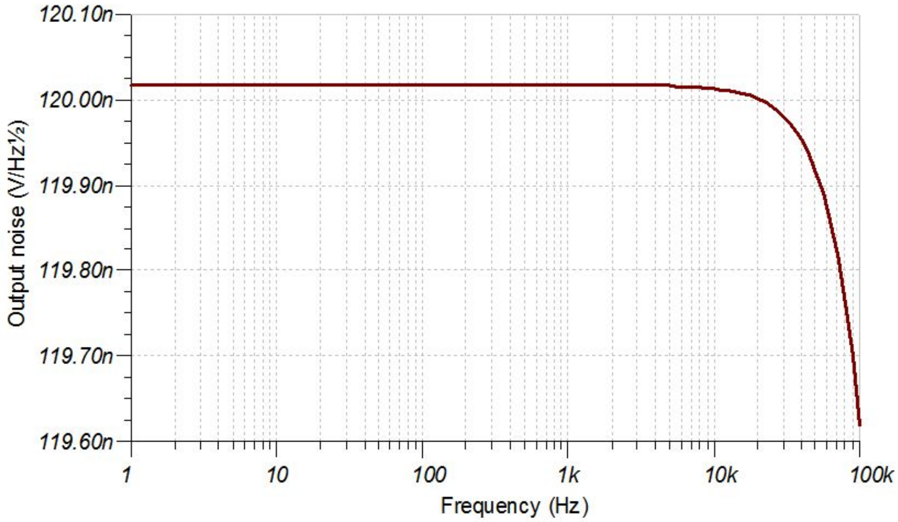
Without going into too much detail, the noise voltage at the output of the IA is a function of the voltage and current noise sources, and the thermal noise of the various resistors. The thermal noise from the DC resistance of the loop antenna should also be included. See Art Kay's book for detailed information on how to hand calculate the noise of the IA. The noise analysis is performed in TINA-TI on the circuit below.

Rg sets the gain of the INA103 according to the formula:

$$Gain = 1 + \frac{6\ k\Omega}{Rg}$$

The internal 60.6Ω resistor is selected to set the gain to 100, or 40 dB. Other valued resistors can be connected across the terminals for other gains. No resistor connected sets the gain to 1 or 0 dB.

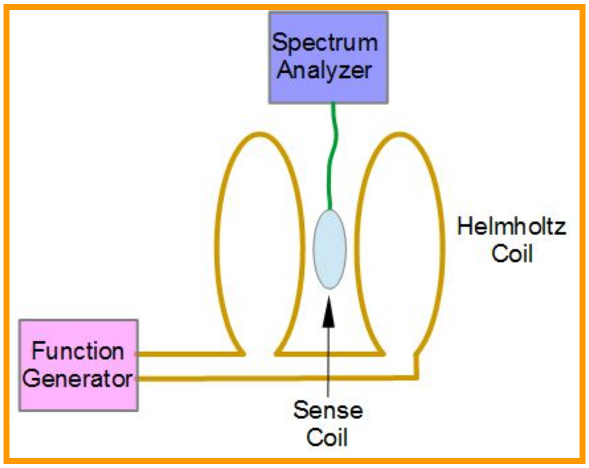


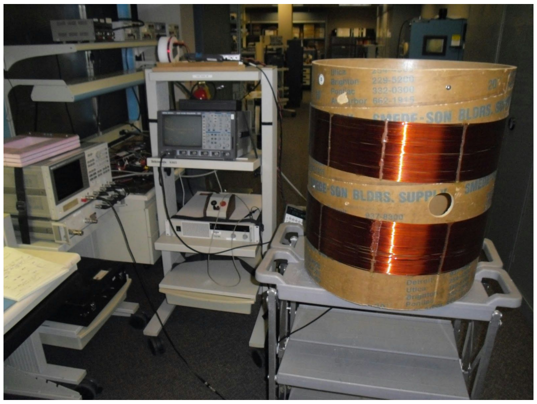


So we can see that the noise spectral density at 24 kHz at the output is 120 nV/(Hz)$^{1/2}$. When multiplied by the square root of our assumed bandwidth of 100 Hz, we multiply 120x10 = 1.2 uV. So this is the noise floor of the preamplifier and the loop antenna must give a signal at the output of let's say 3 db greater than that, or maybe 1.7 uV. This means that the loop output must be 1.7/100 or 17 nV from the resulting magnetic flux density of the received signal. What is the magnetic flux density incident on the loop to generate 17 nV?

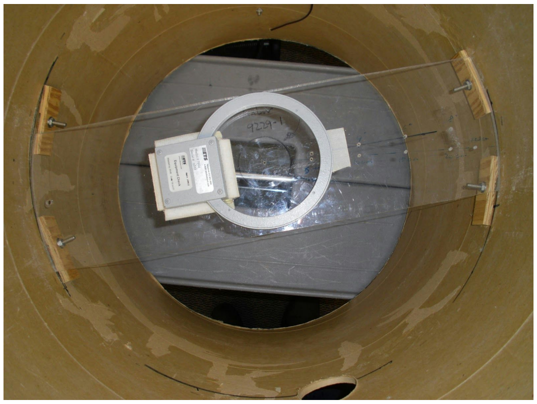
Section 4: System Calibration and Test

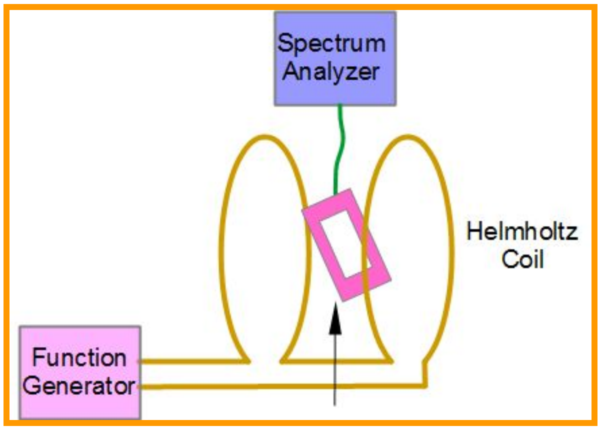
After the setup has been built, tested for function, and noise simulation has been completed, the next steps is to calibrate the loop in the Helmholtz Coil and to develop the antenna factor over frequency for an inputted magnetic field. The Helmholtz setup is seen in the drawing on the left and photo below.

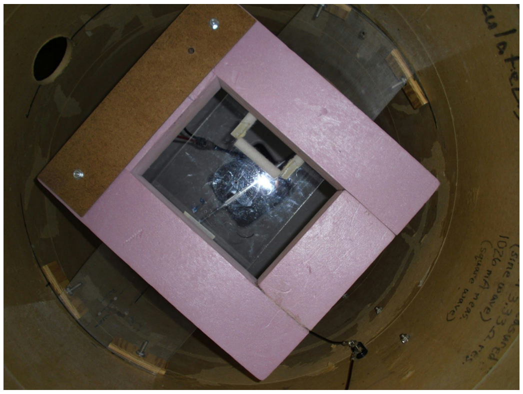




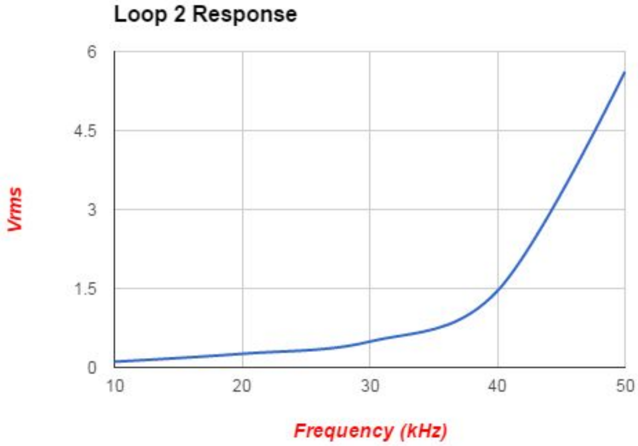
The sense coil and loop antenna measurement setups are seen below.







The loop loop was tested with a 100 dBpT flux density at the frequencies indicated below. The response is approximately linear through 30 kHz and then the effect of the resonance at around 60 kHz is seen. The transfer function works out to about



Section 5: Conclusions and Future Work

A test setup to measure VLF field strengths was developed using a low noise differential amplifier. The setup was tested and having satisfactory results, an analysis of the system was performed to determine the lowest field strength measurable.

The resonant frequency of the loop is somewhat low at around 70 kHz, and it would be desirable to increase this frequency, either by increasing the spacing between the loops or decreasing the number of windings or both.

After improvements have been made, several setups will be built and sent out to volunteers to do field testing.

References

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