Measurement of
Extremely low Frequency Electro-Magnetic fields

Conference Paper

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ABSTRACT.

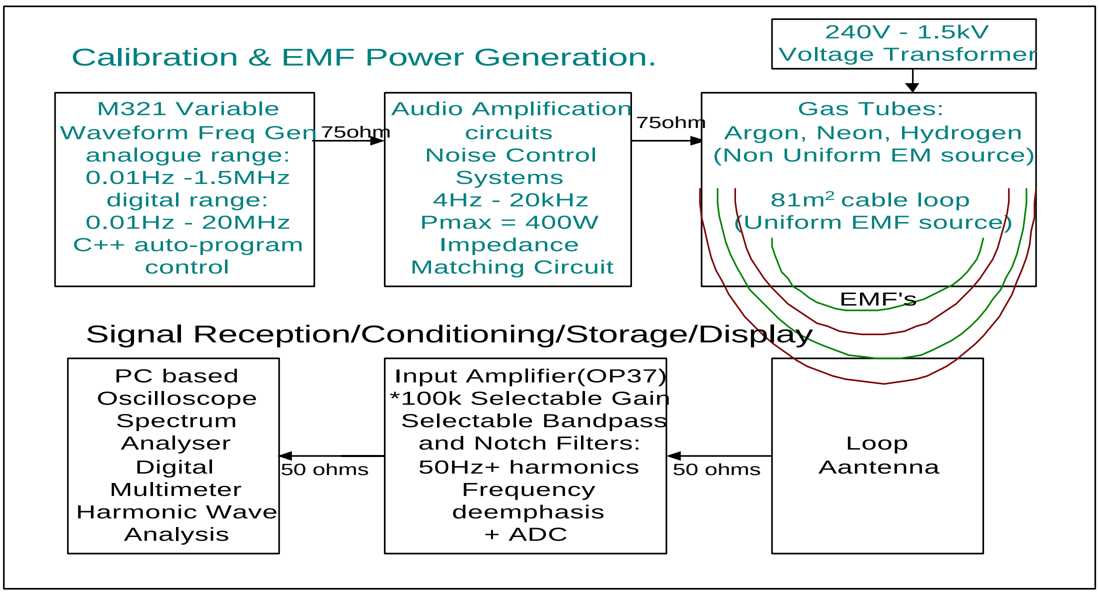
The Loop Antenna, Signal Conditioning Unit and Data Analysis system built was considered because there was no mechanism available for measuring Extremely Low Frequency (**ELF**) signals – the aim of this project.

The system works by the Loop antenna receiving frequencies in the audio range with particular emphasis on the extremely low frequency range of 4Hz to 50Hz**.** The Loop antenna signal is then fed into a purpose built Signal Conditioning Unit(**SCU**) which filters both noise and unwanted signals whilst amplifying the signal of interest.

The signal is then passed to a virtual oscilloscope and spectrum analyser on a notebook computer with capabilities for data recording & logging, analysis, graphical interpretation and presentation. To enable field readings and independence from AC supply, separate power supplies were built for the loop antenna, SCU, and the Analogue to Digital Converter (**ADC**). The results will show that the loop antenna and data analysis and viewing equipment performs within the specified range.

The second half of the system was to build an Electromagnetic Field (**EMF**) generator system able to produce fields with selected frequencies from various types of sources to mimic the EMF's frequently found in the home, industry, and elsewhere. The planned application to ensure that the frequencies of interest were being correctly received by the loop antenna system. A schematic diagram is shown below to illustrate what is contained in the following chapters.

Figure 1. *System Schematic*



1.0 Loop Antenna System for ELF EMF's.

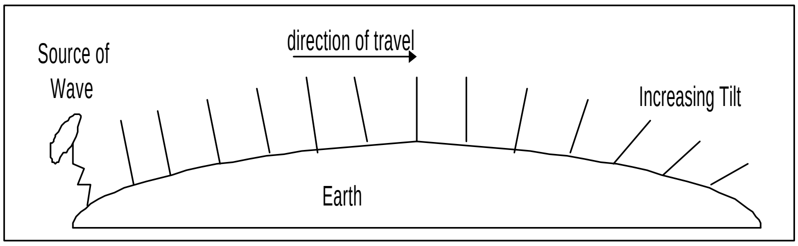
Overview

The Loop antenna is designed from first principles[1] and the calculations are used to build a loop antenna capable of receiving very low frequencies.

1.11 Introduction.

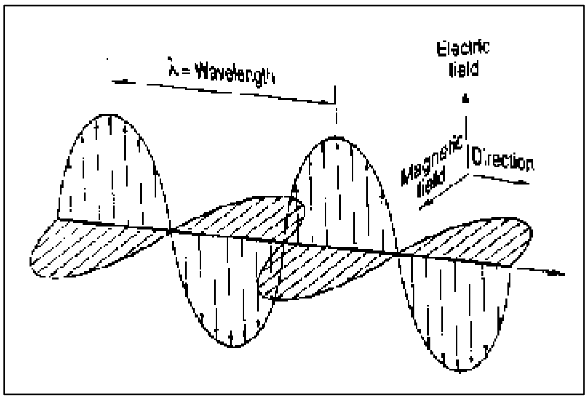
The solar wind has effects on the earth's electromagnetic field such that there are approximately 2000 electric storms produced every hour somewhere on the surface of the planet. These in turn produce an **A**lternating **C**urrent which travels beyond the horizon to form an **E**lectro-**M**agnetic **F**ield (**EMF**) discovered by Schumann in 1952. [2]

Figure 1.11 *Ground wave Propagation*.[3]



A lightning strike, particularly a cloud-to-ground strike dissipates an enormous amount of energy in a fraction of a second. The potential difference between the earth and a cloud that discharges a 500metre strike can be a billion volts, of current up to 500kA, releasing an amount of energy of 100kilowatt hours. As this wave travels between the earth and atmosphere which act as a waveguide, partial cancellation occurs due to ground reflection so the direct line of sight wave is negated by the 180° out of phase reflected wave. This leaves the ground wave as the main form of propagation. Loop antennas are sensitive to polarisation effects but low frequency signals are vertically polarised to minimise currents induced by the ground as they follow and propagate around the earth's curvature. As the waves tilt, the currents increase from the ground causing losses in signal strength. This field of 6 to 50 Hz before the Industrial Revolution was possibly the only **E**xtremely **L**ow **F**requency(**ELF**) planetary wide AC field. The chapter details the construction of an antenna capable of measuring AC fields of this kind.

Figure 1.12 *EMF Electric(B) & Magnetic(H) Waves.*



The brain function is analogous to a frequency generator which produces frequencies between 4 to 20 Hz at a field strength of 10^{-13} Tesla[4] that travel along the nerve pathways to carry out the needs and wishes of the individual. These values are in the same order of magnitude as the AC resonance field of the earth. Whilst EEG's can be used to measure the signals from the brain, the apparatus needed to receive and measure the ambient ELF EMF's, was considered impossible or impracticable to build due to their large wavelengths and small field strengths by the usual electrical, electronic and communication methods and principles inherent in receiver design and signal conditioning units.

This can be illustrated by an example of how to collect a wavelength at 1Hz. A well known equation is $c=f\lambda$. Where: c= speed of light $3*10^8$m/s,

λ = wavelength in metres, f = frequency in Hertz.

Hence $\lambda=c/f=3*10^8=$**300,000km.** The aerial has to be very large.

Secondly, the AC field in question may be of very small magnitudes around 10^{-6} milliGauss $=10^{-9}$Gauss $= 10^{-13}$Teslas: very low orders of field strength.

The sensitivity of the receiving equipment made it necessary to find a place where the ubiquitous power lines and industrial and domestic frequencies did not swamp the location and recording of such low order field strengths beyond the noise floor of the receiver and the limits of analogue filters which are necessary to reduce the power line interference frequency of 50Hz from the desired signal range. Hence, the system required should be able to receive and amplify the signals of interest whilst filtering other signals and interference classed as noise.

These main factors were considered in the process of design and build and gave the following objectives;

- 1) Define problems which have made the construction of a system difficult.
- 2) Determine factors which allow a theoretical measurement model to be built.

- 3) Examine alternatives theoretically and practically in a stage by stage process.
- 4) Develop a theoretical device capable of practical evaluation.
- 5) Build Model.
- 6) Test and Evaluate.

1.12. Theory

ELF's at 1Hz have a wavelength of c=fλ. The magnetism produced by this wave is manifested as a 'field of vectors', that is, any point in the magnetic field has not only a magnitude, but also a direction in space. The four Maxwell equations describe how electric and magnetic vector fields behave and interact. These "fields" are actually forces and motions of space-time continuum. It is said that all the laws of physics can be derived from the Maxwell equations, shown below:

1) $\int_C \overline{B}.d\overline{a} = 0$ **(Gauss)**

2) $\int_C \overline{D}.d\overline{a} = Q$ **(Gauss)**

3) $\int \overline{H}.d\overline{l} = I$ **(Ampere)**

4) $\int \overline{E}.d\overline{l} = \frac{d\Phi}{dt}$ **(Faradays)**

According to Maxwell, an electric field cannot change without creating a magnetic field and vice versa as shown in figure 1.2 above. Electric(E) and magnetic(H) components propagate as waves. The E and H aspects appear 90 degrees apart in space dimensions and in phase in the time dimension. A loop of wire can be used as an antenna to interact with and detect the magnetic aspect of the electromagnetic force. Possible calculations for such a system are shown below.

1.13. Calculations [5]

Magnetic field intensity, H, expressed in units of amperes per meter, produces a magnetic flux density, B, expressed in volt seconds per square meter. Flux is proportional to applied field.

1.11) B = μH, μ expressed in Henrys per meter, is the magnetic permeability of the medium. Let μ equal μ_o, the permeability of a vacuum. This assumption is well justified for air core loops surrounded by non-magnetic media, including air, water, earth.

1.12) $\overline{D} = e\overline{E}$ ε = permittivity, $\overline{E}$ = electric field strength. $\overline{D}$ = electric flux density. Total flux $\int_C \overline{D}.d\overline{a} = Q$ which is the sum of all the points over a closed surface.

In a magnetic field the charge is always zero. This means $\int_C \overline{B}.d\overline{a} = 0$

Where B is the magnetic flux density.

1.13) $\Phi = \frac{1}{N}\int vdt$ $\therefore$ V= N* $\frac{d\Phi}{dt}$

Voltage around a loop is proportional to the rate of change of the amount of **magnetic** flux threading the loop area. When multiple turns are in series, the total voltage is the sum of the individual turns. It can be seen from (3) a motionless loop in a constant dc field produces no voltage. Combining these three equations gives an expression for the terminal voltage of a multi-turn wire loop. The vector normal component of the H field is integrated over the loop area, and differentiated by time.

1.14) V = N$m\frac{d}{dt}\int_C \overline{H}.d\overline{a}$

When the $\overline{H}$ field is uniform over a planar loop, take $\overline{H}$ out of the integral and express its vector normal component as the magnitude times the cosine of the angle between the $\overline{H}$ vector and the loop axis.

1.15) $V = N m \cos \Theta \frac{d}{dt} |H| \int d \bar{a}$

and the integral becomes a simple equation for the loop area.

1.16) $V = \mu N A . \cos \Theta \frac{d}{dt} |H|$

Most of the calculus is solved, but the time derivative of H remains. It can reduce to algebra by examining a discrete frequency (ωt) component of H, with peak amplitude H_0.

1.17) $E = E_O \sin\omega t$

Which transforms equation (6) into:

1.18) $V = eNA\cos\Theta \frac{d}{dt}(E_0 \sin(wt))$

So:

1.19) $V = m.NA\cos\Theta H_0 w \cos(wt)$

Taking the magnitude of the signal, the loop terminal voltage is now an algebraic product of six terms;

1.20) $V = 2\pi\mu NAH_0 f\cos\Theta$ where;

Ho	applied electric field strength in volts/metre
$2\pi\mu$	is a constant
A	loop area in square meters
f	frequency in hertz
$\cos\Theta$	the cosine of the angle between the loop axis and the field.

The product of N and A are the only remaining terms which describe characteristics of the loop itself. This product derived suggests a figure of merit for loop antennas, the "effective aperture", Ae , which is the physical area times the number of turns.

The planar sensitivity of a loop, which is the terminal voltage divided by the applied magnetic field, is now the product of only three terms:

1.21) $\frac{V}{H_o} = 2p.m.f.A_e$ where

$\frac{V}{H_o}$	is the output voltage per unit magnetic field strength applied
2πμ	is a constant $7.89*10^{-6}$ As/(Vm)
Ae	is the effective loop area in square meters
f	is the frequency in Hertz.

Equation (11) shows the problem of loops at low frequencies: as **f approaches zero, so does the loop voltage**. The only recourse is to increase the effective aperture.

Take a wire length of 36000m. For a 1 metre square loop A, the wire length and loop area are:

1.22) Number of complete turns, N = 36000/4 = 9000 turns

So the antenna sensitivity for a fixed wire length is:

1.23) loop area, Ae = N*A=9000m^2

The **d** term appearing in the numerator loop-geometries above denotes a fixed length of wire as a single turn to give maximum sensitivity. A large aperture. Hence, to maximise loop sensitivity:

- **For a fixed number of turns:**
  Sensitivity goes up as loop diameter squared, and up as wire length squared.

- **For a fixed wire length:**
  Sensitivity goes up as the loop diameter, and down inversely as the number of turns.
- **For a fixed loop diameter:**
  Sensitivity goes up as number of turns, and up as wire length.

1.14 Relationships. [6]

For the purposes of design, assume a transmitter of 100Watts (effective radiated power **erp**), 100 miles away.

100miles = 160km=16000m

1.24) Impedance of free space $Z = E/(H\mu_o\mu_R)$ where $Z = 377\Omega$

(1.25) $E = \dfrac{7.02 * \sqrt{erp}}{d}$ [7]

$$\frac{7.02 * \sqrt{100}}{1.6 * 10^{5}} \approx 4.38*10^{-4}\ \mathrm{Vm}^{-1}$$

$$H\mu_o\mu_R = \frac{E}{Z} = \frac{4.38 * 10^{-4}}{377} = 1.164*10^{-6}\ \text{Tesla} = 11.64*10^{-3}\text{Gauss}(\Phi)$$

It is more conventional to express radio waves in terms of E field rather than H field. This will give H for any E in the far field.

To calculate the induced voltage in the loop of inductance L the formulae (16) to (20) assume the self inductance of a circular loop of rectangular cross section. Therefore the square Loop with an internal diameter of 1m (see figure 1.3) must be circled and the circular cross section must be squared.

For a diameter d = 1m

1.26) $\pi r^2 = d^2$

$r = \sqrt{\frac{d^2}{p}} = 56.42\text{cm}$

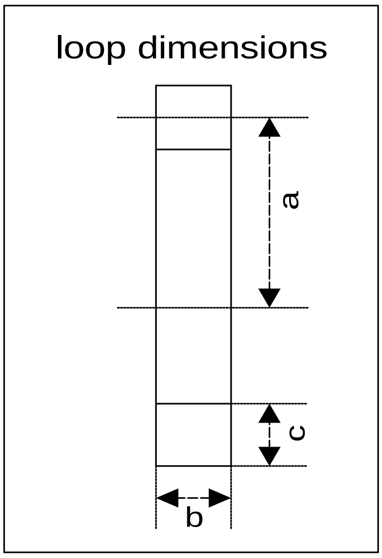
the reverse process for the circular csa to a square:

d_C = 3.5cm for the circle:

$d_S = \sqrt{\pi}.r$ = 3.10179cm is the mean diameter for the square csa.

1.27) $L = 0.001*a*N^2P_o'$ in µH where:[6]

Figure 1.13 *Loop Schematic*



N = number of complete turns on coil,

a = mean radius of the turns to the centre = 57.97cm

b = axial dimension of the cross section = 3.102cm

c = radial dimension of the cross section = 3.102cm

n_b = number of turns per layer $\therefore \sqrt{9000} \approx 95$

n_c = number of layers = 95

p_b = pitch of the winding in the layer = distance between centres of adjacent turns in the layer = 0.05cm

p_c = distance between centres of corresponding wires in consecutive layers = 0.05cm

then the relations exist that

the inductance is a function of the shape of the coil so that two shape ratios such as

$\frac{c}{2a}$ and $\frac{b}{c}$ are involved. For a circular coil of square cross section $\frac{c}{2a}$ may have any desired value between 0&1, but $\frac{b}{c}$ = 1. Using measured values, $\frac{c}{2a}$ = 0.0268

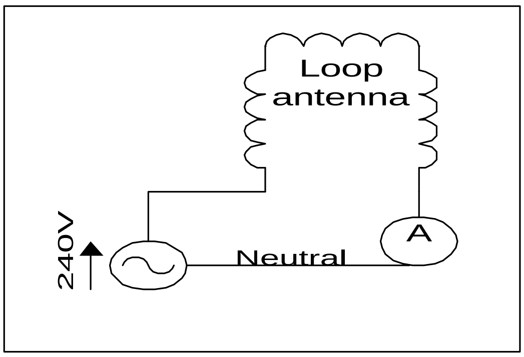
P_o' is a function of $\frac{c}{2a}$ alone and goes to ∞ as $\frac{c}{2a}$ approaches zero. P_o' should then be calculated from

1.28) $P_o' = 4\pi\left[\frac{1}{2}\left\{1+6\left(\frac{c}{2a}\right)^2\right\}\log_e\frac{8}{\left(\frac{c}{2a}\right)^2} - 0.84834 + 0.2041\left(\frac{c}{2a}\right)^2\right] = 48.14.$

L = 0.001*56.42*$(9000)^2$*48 µHenrys = 221H

A test was then conducted using the following circuit to produce a measurement system to find the actual value of impedance of the loop and from that to calculate the actual inductance with the assumption that it is all inductance because this places a minimum estimate on the loop inductance from the results.

Figure 1.14 *Loop Inductance Circuit Test*



Z = V/I = 245/(3.5*10^{-3}) = 70k

$70k^2 - 10k^2 = XL^2$

$\sqrt{XL^2}$ =69282Ω

L = $\frac{69k}{100p}$ =220.5H.

This value of L agrees with the calculated figure.

1.29) V = $L\frac{d\Phi}{dt}$

Induced voltage at a signal of say 1Hz. ($f = T^{-1}$)

$V=220*11.64*10^{-3}*1 = 2.56V$

The proposed coil would give a useable output for the 1Hz wave at lower field strengths. The Oscilloscope has a resolution of 1mV and the Spectrum Analyser has a lower value of –90 dBs. In the Signal Conditioning Unit, the amplifier circuits have an adjustable gain (Chapter 2).

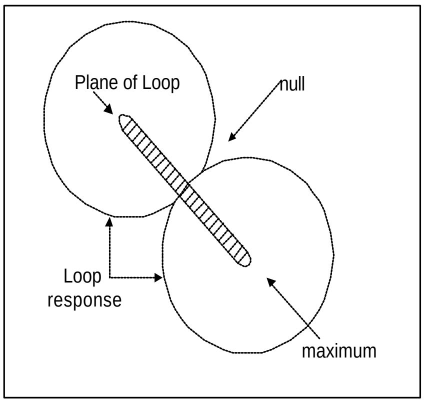
Resonance occurs in the Loop when $(X_L-X_C) = 0$.

1.30) $f_o = \frac{1}{2p\sqrt{LC}}$ For a given f of 100Hz $C = \frac{1}{(2p)^2 L * 100^2} = 11.4nF$

A non-electrolytic Capacitor at 1Hz it is 114.6μF. These values of adjustable loop capacitance C which varies with frequency give a resonance within the range of 1Hz to 100Hz. The resistance of 9.86kΩ gives the Loop a low Q. This was demonstrated by measurement(Chp4) so the system has a fairly even response over the range of desired frequencies.

1.15 Practical Considerations[8]

Figure 1.15 *Directional Sensitivity of Loop Antenna*

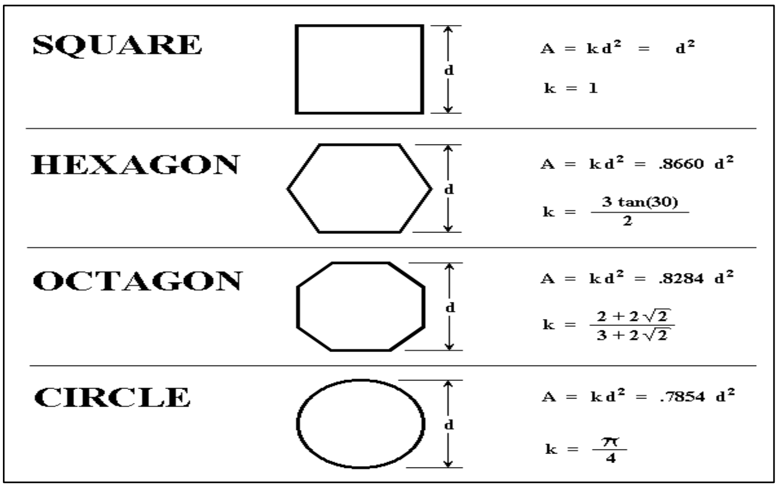


Maxwell states that the higher the frequency the higher the emf induced. Due to the shielding, only the magnetic component of the field passes into the loop. Compared with an isotropic receiver, the directionality of the loop is useful for nulling signals or interference hence lowering the noise floor to pass the signal required into the **S**ignal **C**onditioning **U**nit(SCU) amplifier circuits. The directionality amounts to a >50dB filtering of unwanted signals but this varies with location and number of transmitter sources. The sensitivity of the system to the direction of electromagnetic waves derives from a property of the loop antenna. When a loop of wire that is half as wide as the waves are long from crest to crest is orientated in the direction in which waves travel, a passing wave will induce a current in one direction in the **leading side** of the loop and in the opposite direction in the **trailing side** as shown in figure 1.15. The currents **add** and the maximum voltage appears across the ends of the loop. If the diameter of the loop differs from half the wavelength, the output voltage is less than the maximum but the principle outlined above applies. When the loop is orientated at right angles to the approaching wave opposing currents are induced in the two sides. Destructive interference then occurs and no voltage appears across the terminals.

The loop is enclosed by an **electrostatic shield** so that fluctuations in neighbouring electric fields do not induce spurious voltages. The sensitivity of the loop to signals from various directions when plotted as shown in figure 1.15 takes the form of a figure eight, with maximum signal response in the plane of the loop and minimum or null response at right angles to the plane.

1.16 Loop Construction.

Figure 1.16 *Schematic of Loop. d = 1metre.*



The loop is wound to have two BNC sockets to give an output which takes advantage of the op-amp differential input CMRR. The BNC cables and connectors are insulated and earthed. The loop is shielded with aluminium foil to stop the electric field component of the signal-induced noise. The loop design shown in figure 1.16, has the following features:

1) It is wound randomly with 0.28mm, 32 SWG insulated copper wire.

2) The total wire resistance is approximately 10kΩ

3) Loop inductance and capacitance produce the resonant frequency of the coil.

To enable the calculations of the loop antenna parameters the following factors were considered.

Data for the 0 to 200°C grade 2 polyester 0.28mm copper wire BSEN60317/13 coated with a lacquer.

Table 1.11 Electric Properties.[9]

	Permittivity(ε_r)	Nominal Resistance(per metre)	Conductivity(σ) MSiemens/metre	Frequency [10] limit
Lacquer	3 to 4	10^{10} to 10^{14}	10^{-10} to 10^{-14}	n/a
Copper	1	0.776	$58.582*10^{6}$	10MHz

It is the surface currents or static charge in copper which give the dielectric constant ε_r

Table 1.12 Copper Resistances

Min	0.2676/metre
Nominal	0.776/metre
Max	0.820/metre

Magnetomotive Force F:

1.31) $F_{(50Hz)} = NI_{(50Hz)} = 9000*3.5*10^{-3} =$ 31.5 Amp Turns.

Hence, Reluctance, S:

1.32) $S = \frac{F}{\Phi} = \frac{31.5}{11.64*10^{-3}}$ = 2706Ampere turns/Volt secs

Table 1.13. Magnetic Properties.[11]

	Permeability(μ_r)
Lacquer	1.0000000
Copper	1.0000005
Air	1.0000000

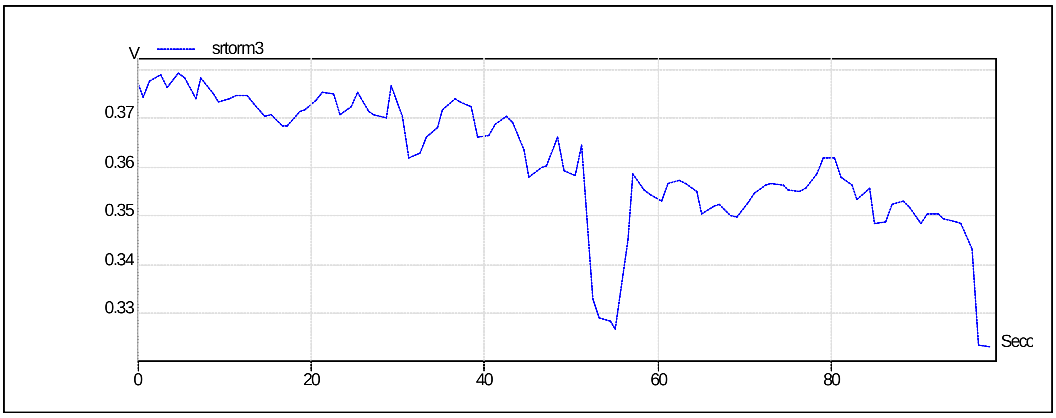
The permeability of the lacquer enamel film μ_r should not affect the magnetic field since it is organic.

This important magnetic property of the loop will vary with signal strength and affect the signal output. However, the effective signal aperture will still produce a relatively large current in the coil for a very small input.

The weights of the Loop and the frame were 22kg and 4kg respectively. They were detachable for ease of portability and the loop being wave-wound allowed flexibility of movement for transportation and position.

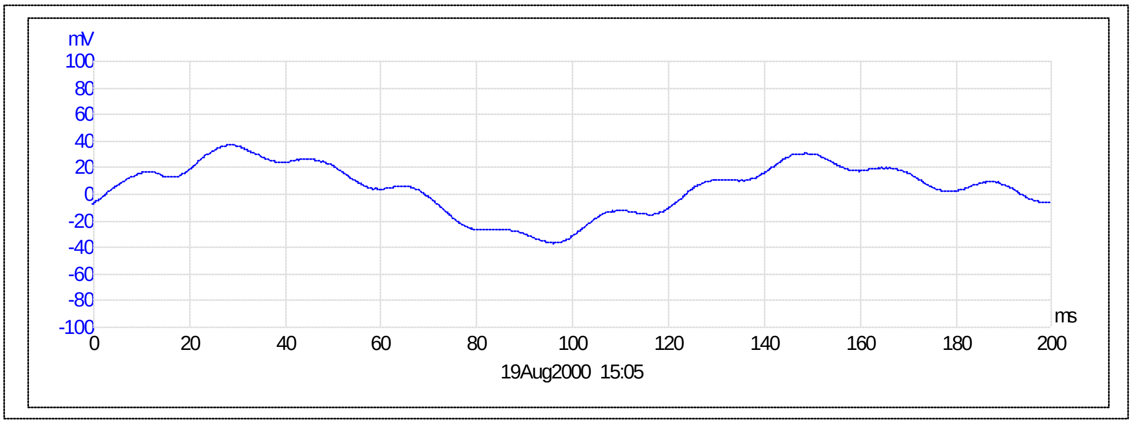
1.17 Results

Figure1.17 *Lightning strike. Graph of Voltage Magnitude against frequency.*



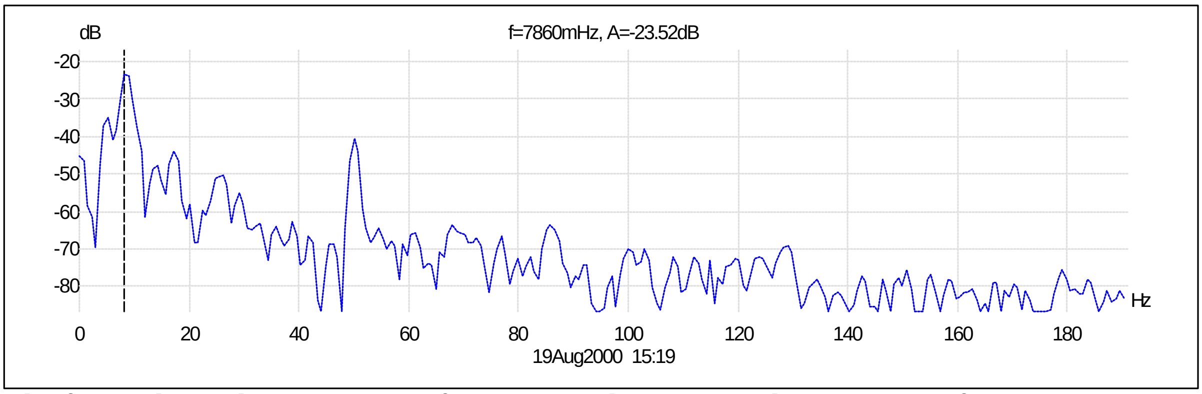
There is a significant rise in the lower frequency spectrum magnitude caused as the lightning strikes. This signal originated within one second of the thunder.

Figure 1.18A Aug2000 *Carlton Moor Trig Point 8.33Hz ±40mV signal.*



The signal was recorded with the loop facing N/S. Middlesbrough (in Cleveland, England) is in the north and the height of Carlton moor Trig point is 800ft. The weather was dry and sunny with a warm breeze. Signals indicated a storm to the west though more than a hundred miles away. Earth currents were measured with a Gauss meter and magnetometer to get background ambience for DC levels. The loop, Signal Conditioning Unit, ADC and Notebook scope and spectrum analyser were checked against a 5 and 50hz signal before measurements were taken. System was operating normally.

Figure 1.18B *Carlton Moor 8.33Hz signal. Loop direction N/S.*



The figure shows the noise corner frequency in the 0 to 2Hz dropping away from zero frequency to a cursor labelled 7.8Hz due to poor cursor resolution, with the 23.5dB signal referenced to one volt. This is actually 8.33Hz and very powerful when compared against the 50 Hz signal at –40dB's. The latter is a good reference point to see that the signal of interest near to a known standard generated by the power companies correct to within 0.1Hz.

1.18 Future Work.

An addition to the system is planned in order that the coil may be extended to 2 intersecting loops, so directionality of signal can be accurately plotted without large rotations through 180° using ADC inputs to distinguish each individual loop signal and thus process this on the virtual Oscilloscope and Spectrum Analyser software. Another test in an anechoic chamber will be expedited for further testing and results. The signal conditioning unit has a good noise rejection ration and it's performance will be extended to higher frequencies from the audio range by user selectable stages to the high frequency(3-30MHz) band. The Oscilloscope and spectrum analyser performance will need to complement this with greater accuracy control over signal analysis.

1.18 Conclusion

The sensitivity of loop antennas at low frequencies has been mathematically derived, and expressed in practical terms. The concept of effective aperture, and how to maximize it has been presented. The system designed was conceived and built with several applications in mind - not least the spiralling levels of electromagnetic fields and their effect on the world we live in. The report aims to calculate and report the effective apertures of the loop antenna, and refer the measurements to a terminal voltage of 100mV at 1Hz. In this way, all geomagnetic/other observations can be converted to a common unit of measure.

1.19 References

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