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Extraction of Electric Network Frequency Signals from Recordings Made in a Controlled Magnetic Field

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ABSTRACT

An Electric Network Frequency (ENF) signal is the 60 Hz component of an AC power signal that varies over time due to fluctuations in power production and consumption, across the entire grid of a power distribution network. When present in audio recordings, these signals (or their harmonics) can be used to authenticate a recording, time stamp the original, or determine if a recording was copied or edited. This paper will present the results of an experiment to determine if ENF signals in a controlled magnetic field can be detected and extracted from audio recordings made with battery and externally powered audio recording devices.

1. INTRODUCTION

Recently there has been an interest in time-stamping and authenticating digital audio signals by extracting the 60 Hz Electrical Network Frequency (ENF) component of the signal that is recorded by every device used within an electrical distribution network. [1]-[6] These networks are common to all buildings and structures served by power generation plants. In the continental United States, most power plants are connected to one of three power grids (Eastern, Western and Texas). [3]

Frequency variations in the power signal over time, due to the differences between produced and consumed power in the entire power grid, can be seen in the ENF component of an audio recording. Recent experiments [2]-[4] have shown that the ENF variations are the same at every place on a grid, but different on each grid. Also, the frequency variations are not repeated over a long period of time, making the ENF signal statistically unique for specific time frames. By comparing the variations in the ENF component extracted from the recording in question to a database of known ENF variations for a power grid, the time of the recording can be accurately determined. [6] In addition, analysis of the ENF component may be used to determine if the audio file was an original or a copy, if it was edited, or if two digital audio files were combined or mixed together.

Because electromagnetic fields are produced in any building with distributed power, or anywhere in the vicinity of external transmission lines, the ENF signal should in theory be present in almost any recording, whether connected to the power distribution network or battery operated. This paper will present the results of an experiment to test whether an ENF signal in magnetic fields of controlled magnetic flux densities can be detected and extracted from audio recordings made with several digital recording devices, both battery operated and powered by 110/120 VAC.

The recording devices were tested by subjecting them to an alternating current (AC) electromagnetic field, generated by connecting the electric power signal to a Helmholtz coil, through a simple resistive network and a variable gain amplifier. The current delivered to the coil was varied by varying the output power of the amplifier, thereby generating magnetic fields of varying magnetic flux density (MFD). The device under test (DUT) was placed in the center of the coil while recording, and the MFD was measured by a magnetometer placed adjacent to the device under test. Because the experiments were conducted in an unshielded room in an urban office building, recordings were also made in the ambient magnetic field of the test environment, to determine if the ENF signal could be detected in recordings made with the devices under test.

2. BACKGROUND

A magnetic field is created by electric charges in motion. A current-carrying conductor will create magnetic field lines lying in planes perpendicular to the conductor. The magnetic field ***B*** is a measure of the number of magnetic field lines per unit transverse area, also known as the magnetic flux density. The SI unit of measure for magnetic flux is the weber (Wb), thus the corresponding unit for ***B*** is webers per square meter (Wb/m^2). Related units are the Tesla (T), which is another name for 1 Wb/m^2, and the Gauss (Gs), which is one-ten-thousandth of a Tesla (10^{-4} T). Magnetic flux density ***B*** is related to magnetic field intensity ***H*** by

$$H = \frac{B}{\mu_0} \qquad (1)$$

where μ_0 is the permeability of free space, a constant equal to $4\pi \times 10^{-7}$ webers per ampere-meter, or Wb/A-m. Thus the unit for magnetic field intensity is amperes per meter, or A/m.

B is a vector quantity, the direction of which is related to the direction of the electric current by the so-called right hand rule: when the thumb of the right hand points in the direction of *i*, the direction of the ***B*** lines are along the right-hand fingers. The magnitude of the magnetic field is inversely proportional to the distance *R* from the conductor, and directly proportional to the current *i*.

Two simple geometries for generating a magnetic field are an infinitely long, straight conductor (which is approximated whenever the distance *R* from a straight conductor is small compared to its length), and a circular loop of radius *R*. The magnitude of the magnetic flux density (MFD) at a distance R is given by

$$B = \frac{\mu_0 i}{2\pi R} \qquad (2)$$

for the straight line and

$$B = \frac{\mu_0 i}{2R} \qquad (3)$$

for the circular loop. Note that the equation for MFD is nearly the same for these two cases, differing only by a factor of $1/\pi$, though the direction of the field in each case is different. The magnetic field lines for the long, straight conductor consists of circular loops around the conductor in planes transverse to the conductor, whereas for the circular loop the magnetic field lines are in planes transverse to the plane of the loop. Thus the two geometries are complimentary in regard to the current and field directions. In both cases, the magnitude decreases inversely as the distance *R* from the conductor increases. The magnetic fields for these two cases are illustrated in Figure 1.

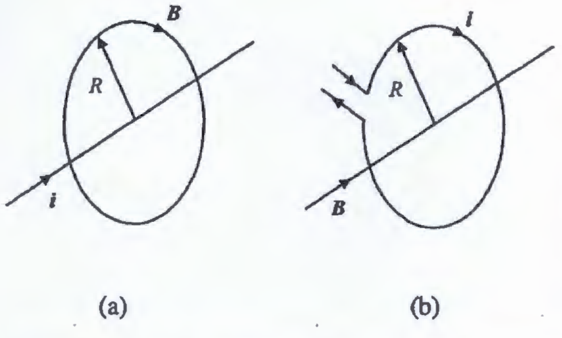

Figure 1. (a) Long, straight conductor and (b) circular loop conductor. These figures show the complimentary relationships of the current ***i***, the distance *R* and the magnetic field ***B*** for each geometry.

Building upon the geometry of a single loop, a Helmholtz coil consists of two identical circular coils of *N* turns each, placed parallel to each other with their axes coinciding at a distance *R* apart, where *R* is also the radius of the coils (see Figure 2).

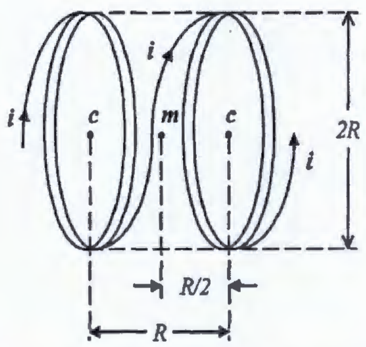

Figure 2. Geometry of a Helmholtz coil.

A current *i* travels through each coil in the same sense, so that the resultant magnetic field in the central region between the coils is reinforced. The magnitude of the axial field at the midpoint *m* on the axis, a distance *R*/2 from each coil, is given by

$$B_m = \left(\frac{16\sqrt{5}}{25}\right)\beta = 1.431\beta \qquad (4)$$

where

$$\beta = \frac{1}{2}\frac{\mu_0 Ni}{R} \qquad (5)$$

Note that equation (5) is simply equation (3), the equation for the MFD of a single loop, multiplied by N, the number of turns. The combined field at the center of either coil *c* is

$$B_c = \left(1 + \frac{\sqrt{2}}{4}\right)\beta = 1.354\beta \qquad (6)$$

which is 94.58 percent of the field at the midpoint *m*. Thus a Helmholtz coil is a practical means of achieving a uniform magnetic field over an appreciable region of space, and was chosen as the means to generate the controlled magnetic field for this experiment. [7] [8]

3. METHODS

The purpose of this experiment was to test whether the ENF signal was present in audio recordings made with a number of battery-operated and/or AC-powered recording devices, when these devices were subjected to the ambient magnetic field in an urban office environment and a controlled magnetic field of varying flux densities.

3.1. Physical Setup

The controlled AC magnetic field was generated from the electrical power signal taken from a 110/120VAC wall outlet, which was transformed from 120VAC to a low-level signal of about 500 mVAC, and gain-adjusted with a Yamaha O2R audio console to a Crown D-150 audio power amplifier which powered the Helmholtz coil A block diagram of the test setup is shown in Figure 3.

The interface to transform the 120VAC signal to a low-level signal was a simple resistive network shown in Figure 4. The output of the interface was split into two paths, one of which was recorded directly to a hard drive using ProTools, and the other which was used to drive a Helmholtz coil to produce the AC magnetic field. By varying the power at the input of the audio power amp, the current through the Helmholtz coil could be varied to produce the desired MFD. The DUT was placed at the midpoint of the axis of the two coils (point *m* in Figure 2), with an AC magnetometer (AlphaLab, Inc. Model UHS) next to it.

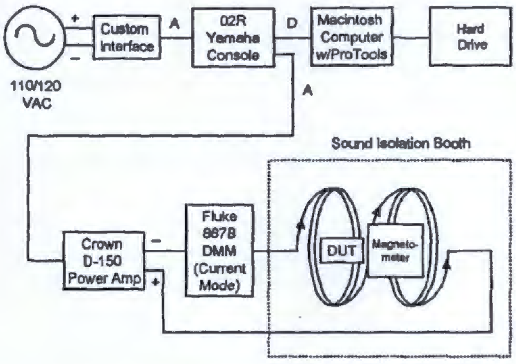

Figure 3. Schematic of test setup. The analog signal paths are labeled 'A,' and the digital signal path is labeled 'D.'

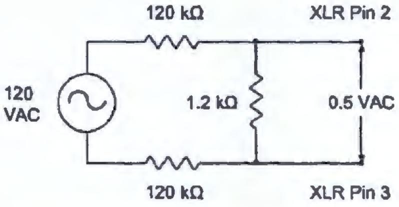

Figure 4. Custom Interface

As noted above, the magnetic field in the region of space between the two coils was uniform to within about 95%, thus the MFD to which the DUT and the magnetometer were subjected could be accurately determined. The current delivered to the Helmholtz coil was measured with a Fluke 867B Multimeter, set to measure AC current. The Helmholtz coil, the magnetometer and the DUT were placed inside an IAC Sound Booth, 2.2 m wide by 2.3 m high by 2.3 m deep, to minimize the level of any acoustic ambient noise present in the recording environment. The recordings of the ENF were all saved as .wav files at 44.1 KHz sample rate and a bit depth of 16 bits.

The recordings with the various devices were done by the authors at the National Center for Voice and Speech, on the fourth floor of the Tramway Building of the Denver Center for the Performing Arts in Denver, CO. The ambient magnetic fields in this urban office setting ranged from 0.4 milligauss (mGs) to about 2 or 3 mGs in the hallways and offices, as measured with the AlphaLabs Model UHS magnetometer in the 3-axis ELF+VLF AC field measurement mode. These measurements were consistent with those reported in studies of the health effects of exposure to extremely low frequency (ELF) magnetic fields in the office environment, which ranged from 1.0 to 6.5 mGs. [9] [10] As reported therein, the sources of the ELF magnetic fields included printers, photocopiers, and the electrical distribution system. Measurements made in our offices could be attributed to similar sources. However, individual measurements near certain pieces of office, laboratory and studio equipment were much higher, and varied with the distance from the equipment (as expected from equations 2 and 3), as shown in Table 1 below. The highest reading of almost 1,200 mGs was obtained directly at the power supply of the Crown D-150 Power Amplifier used to drive the Helmholtz coil in this experiment. For this reason, the power amp was kept at a distance of about 1.5 meters from the coil, the meter and the DUT, outside of the sound booth. In this configuration, the ambient electromagnetic field measured by the magnetometer inside the sound booth was 0.4 mGs, even when the power amp was turned on with no input signal.

Equipment	**Measured MFD**
LCD computer monitors	3-6 mGs
CRT computer monitors	15-30 mGs
Ultra-low temperature freezer (in Tissue Lab)	5-35 mGs
Television monitors	170-300 mGs
Audio Power Amplifier	1000-1200 mGs

Table 1. Measured magnetic flux densities near certain pieces of office, laboratory and studio equipment

Based on the above, three conditions were tested: ambient magnetic field (0.4 mGs), 50 mGs generated magnetic field, and 1 Gs generated magnetic field. The currents corresponding to these MFD values are shown in Table 2.

Current (mA)	MFD (mGs)
0	0.42
5.87 – 6.80	50
118 - 132	1000

Table 2. Current and magnetic flux density values used for this experiment

3.2. Choosing Test Devices

It was decided to use only digital recording devices. Extracting ENF components from analog recordings can be very useful, but there are a couple of drawbacks for this study. The first drawback is assuring correct playback speed in addition to possible wow and flutter on both the record and playback devices. Additionally, in order to extract the ENF component of the analog recording, it must be digitized in real-time, giving the opportunity for a possible second ENF component to present itself. It may be possible to deal with this in a real-life situation. However, for the purpose of simplicity in this test, it was decided to not use analog recording devices. All recorded signals could then be digitally transferred from the DUT to the appropriate software to be analyzed.

It was desired to test a variety of devices of varying cost and where possible, have a few devices that were powered both by batteries and 120VAC to determine if there was a difference in their ENF component.

Since each device would be tested either three or six times for 30 minutes each, there was a need to not have an unmanageable number of devices, therefore, the following six devices were chosen as shown in Table 3. All devices used an electret microphone as an audio input.

This required 6 x 3 or 18 tests for battery powered devices plus 3 x 3 or 9 tests for externally powered devices for a total of twenty-seven, 30-minute tests.

Manu-facturer	Model No.	Record Format	Power Source	Approx Cost
Olympus	WS 100	DSS HQ	Battery	$60
Olympus	DS 330	DSS HQ	Battery External	$175
Machspeed	Trio	8 KHz .wav	Battery	$60
Sony CLIE	PEG-TH55	Sony MD	Battery	$325
Sony- Mini Disc	MZ-M100	44.1 KHz MD	Battery External	$450
Macintosh	Power book G4	44.1 KHz .wav	Battery External	$1,800

Table 3. Test Devices

3.3. Data Analysis

During the tests, two recordings were made simultaneously. One was the electric signal from the wall outlet as described earlier and the other was made using the DUT. Both recordings were started together, requiring two people in our case, since they were in different rooms. Stopping the recordings was automated for the wall outlet recorded to ProTools (Version 5.2, Copyright 1991 – 2001 by Digidesign, Inc.) and manually stopped for the DUT. Therefore, the first task was to convert the DUT recording from its native recording format to a 44.1 KHz wav file and then trim the end of the file to be exactly 30 minutes in length. This was accomplished using Sound Forge 7.0, Copyright 2003, by Sony Pictures Digital Inc.

Then, using the following methodology, spectrograms were made of each recording and analyzed as explained later.

3.4. Making the Spectrograms

There are various methodologies that could be used to make these narrow band spectrograms. The authors do not claim the method used here is the best one, but list the methodology in order for it to be duplicated, if desired. The analysis software used was "DCLive6Forensics," version 6.14, Copyright 1994 – 2005, by Diamond Cut Productions, Inc.

The spectrograms were processed as follows:

1. Load a .wav file
2. Remove the DC Offset using a Highpass Butterworth filter at 20 Hz and a filter slope of 6 dB/Octave under the Filter Menu.
3. Down-sample from 44.1 KHz to 11.025 KHz, using the Change Sample Rate Resolution Command under the Edit Menu.
4. Down-sample from 11.025 KHz to 144 Hz, using the Change Sample Rate Resolution Command under the Edit Menu. NOTE: This is a two-step process because the software does not allow a sample rate conversion from 44.1 KHz to 144 Hz in one pass.
5. Use a Bandpass Filter with Low Frequency 59 Hz, High Frequency 61 Hz, Butterworth Filter with a Filter Slope of 24 dB/Octave under the Filter Menu.
6. Adjust the Spectrogram parameters using the Preferences under the Edit Menu with Linear Frequency Axis, FFT Size 4096, Min. Hz 59.5, Max Hz 60.5 and Color Palette of your choice.
7. Select View Spectrogram under the Forensic Menu.
8. Adjust contrast and brightness of spectrogram.

3.5. Analyzing the Spectrograms

These resulting narrowband spectrograms show the small frequency variations of the ENF around 60 Hz. The resolution of spectrograms is the sample rate divided by the FFT window size or in this case;

$$\frac{144 \quad samples/\sec}{4096 \quad samples} = 0.035 \quad Hz \qquad (7)$$

The first step was to determine if the DUT spectrogram showed evidence of containing an ENF component. Two spectrograms are shown below. Each shows a frequency range from 59.5 – 60.5 Hz on the vertical or *y* axis over 30 minutes on the horizontal or *x* axis. Figure 7 shows no significant ENF component, although there seems to be stronger frequency amplitude at 60 Hz than any other displayed frequency. Compare this to the Figure 8 spectrogram which shows a definite ENF component.

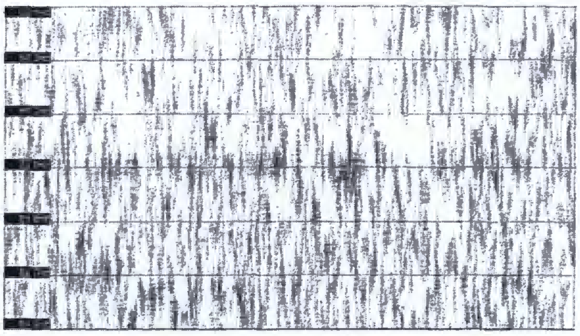

Figure 7. Sony MD, 0 mGs, Battery Powered

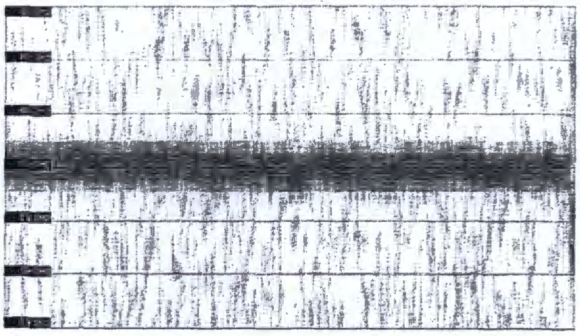

Figure 8. Sony MD, 0 mGs, External Power

The ENF from the wall outlet was recorded simultaneously for comparison to the signal recorded by the DUT. If there was an ENF component from the DUT, it should match the actual ENF information. This comparison was done for each of the individual tests in this experiment. Each ENF component from the DUT did match the true ENF recording, although sometimes noise in the DUT recording made it slightly more difficult to see the similarities, especially when the ENF component level was weak.

Figures 9 and 10 below show the Laptop ENF component and the actual ENF recording while the DUT was exposed to 1 Gs MFD. Similarities between the two are easily observed.

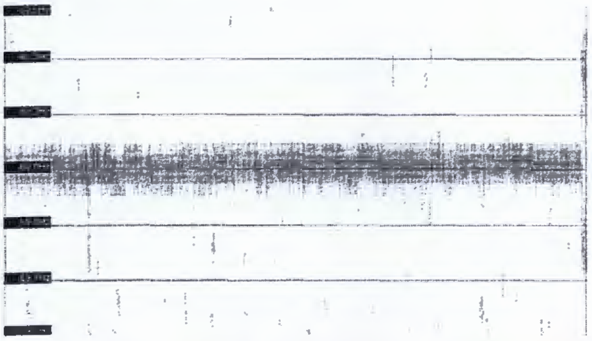

Figure 9. Laptop, 1 Gs, Battery Powered

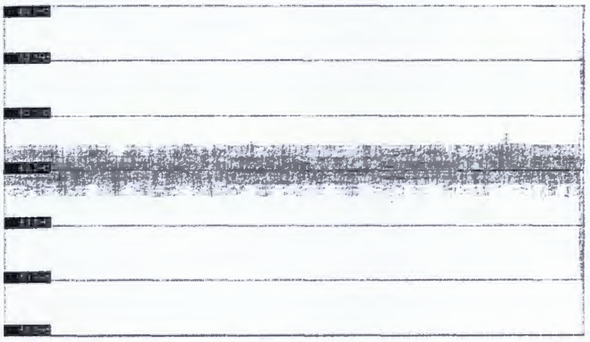

Figure 10. ENF, Laptop, 1 Gs, Battery Powered

4. RESULTS

Table 4 below shows the results of this study. **Yes** means that an ENF component was found in the DUT recording. **No** means that there was not a significant ENF component in the DUT recording.

Device	0 mGs	50 mGs	1 Gs	Comments
WS100 Battery	Yes	Yes	Yes	Sample Rate 0.27% fast
DS330 Battery	No	No	Yes	Sample Rate 0.22% slow
DS330 Ext Pwr	No	No	Yes	Sample Rate 0.22% slow
Trio Battery	No	No	Yes	Sample Rate 0.03% slow
CLIE Battery	No	No	No	
MD Battery	No	No	Yes	
MD Ext Pwr	Yes	Yes	Yes	
Laptop Battery	No	No	Yes	
Laptop Ext Pwr	No	No	Yes	

Table 4. Results

5. CONCLUSIONS

Some definite conclusions are listed below.

1. With the devices tested there was no difference in the ENF component between the ambient MFD and the 50 mGs MFD.
2. The Sony Mini-Disc was the only device where there was any difference in the ENF component between being powered by battery and externally powered.
3. Except for the Sony CLIE, all of the devices had an ENF component with a MFD of 1 Gs.
4. All three of the lesser expensive DUT have less than accurate clock speeds.
5. Even with less than accurate clock speeds, the ENF patterns still follow the actual ENF recording, just at a different center frequency as shown in the spectrograms in Figures 11 and 12.

This experiment primarily tested the effect of the MFD on the DUT. There are however acoustic and electronic sources that may affect the ENF component in recording devices. This test did not have significant input from these sources.

Future research would be helpful in the following areas;

1. More studies of MFD effects on extracted ENF in more situations, more locations and with more devices.
2. Effects of electronic sources on ENF extraction.
3. Effects of acoustic sources on ENF extraction.
4. Usefulness of ENF harmonics.
5. Practical uses of ENF in general.
6. Better and more automated extraction techniques.

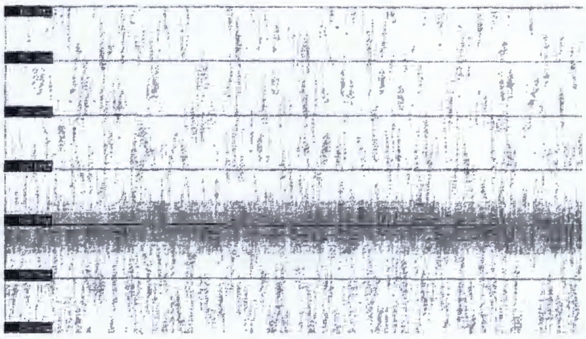

Figure 11. WS100, 0 mGs, Battery Powered

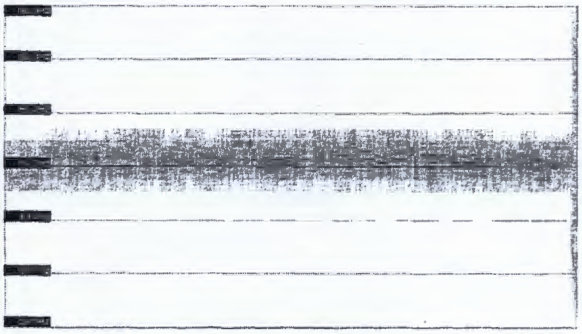

Figure 12. ENF, WS100, 0 mGs, Battery Powered

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