Very Low Frequency Electromagnetic Field Detector with Data Acquisition

Saba A. Hanna, Member, IEEE, Yuichi Motai, Member, IEEE, Steve Ttcomb, Member, IEEE, Walter Varhue, Member, IEEE,

Abstract— Naturally occurring electromagnetic fields in the Very Low Frequency (VLF) spectrum from 1 kHz to 200 kHz are so weak and rare that they are difficult to detect under normal conditions. These natural VLF electromagnetic events occur during thunderstorms, in certain mountain winds, and during earthquakes. On the other hand, man-made VLF electromagnetic fields are stronger, and they have been suspected of causing various types of negative health effects [15],[23]. Typical sources of such VLF emissions include television sets, video display terminals (VDT), certain medical devices, some radio stations, and the Ground wave Emergency Network (GWEN) used for military communications. This paper describes the development of a triaxial “VLF Gaussmeter”, which is a new portable product that is presently unavailable in the market. This electronic instrument can monitor VLF electromagnetic radiation in residential and occupational environments. The “VLF Gaussmeter” is based on a microcontroller with a built-in 10-bit A/D converter and has been designed to measure the magnetic field flux density and frequency across the wide VLF bandwidth (BW). A digitized resolution of 0.2mG is provided in the range of 0.2mG to 2000mG. The meter includes the following features: automatic or manual range selection, data logging, single axis mode, peak hold, RS-232 communication port, true RMS measurements, and analog recorder output.

Index Terms— Biological Effects, EMF, magnetic field measurement, Gaussmeter, VLF.

I. INTRODUCTION

In recent years, the potential deleterious effects of electromagnetic (EMF) pollution have been a growing concern among municipalities and environmentalists. They exist in nature via solar activity, meteorological changes, and biosphere activity. Electromagnetic fields are also generated by man-made means such as high-power electrical equipment and appliances, radiolocation stations, and communication systems. EMF radiation has been linked to the disruption of many biological systems. Some examples include: implications in childhood leukemia [5], calcium transport across cell membranes [2], enhanced DNA synthesis [3], brain wave entrainment [7], inhibition of lymphocyte activity [12], childhood tumors [8], mechanical vibration of brain tissue [4], excessive abortions [6], and chronic stress [13]. These biological effects of ELF and VLF electromagnetic radiation necessitate the development of a hand-held VLF gaussmeter. With a 16 character by two line display, this instrument is able to display both the magnetic field and frequency simultaneously. The magnetic field can be any one of the true RMS vector components of the magnetic flux density: $B_x$, $B_y$ & $B_z$ in milligauss (mG) or the root-mean square: $\sqrt{B_x^2 + B_y^2 + B_z^2}$. This portable gaussmeter has been designed to have a wide dynamic measurement range from 0.2mG to 2000mG, min/max hold, frequency indicator, auto ranging, auditory alarm, and a wide bandwidth frequency response from 1 kHz to 200 kHz. The detection circuit utilizes three orthogonal 47-turns copper loops that will respond to either sinusoidal or complex magnetic field waveforms. The battery-powered gaussmeter is controlled by a microprocessor (PIC18F452) with a 10-bit A/D, 32Kbytes of program memory, 1.5 Kbytes of data memory, and 256 bytes of EEPROM. This system also has standalone EEPROMs that allow up to 32,000 data points to be logged at programmable capture rates. The field measurements are also made available externally through the RS-232 communication port and the analog recorder output. The challenge is therefore to construct this unique magnetic field recording device with high measurement precision and wide BW as a portable standalone meter. Until now none of the commercially available portable meters with this frequency range have included all of features listed above.

This paper is organized as follows. Section II discusses the Related works that already done in the areas of ELF & VLF magnetic field measurements. Section III describes the operation of the gaussmeter including the analog front end, the digital components, and the firmware for the microcontroller Design. Section IV discusses the design and SPICE simulation of the analog subsystem, which incorporates integration,
frequencies ranging from near 0 to 1510 Hz. It has weak ionizing radiation. Non-ionizing radiation consists of Electromagnetism is classified as either non-ionizing or ionizing radiation. Non-ionizing radiation consists of electromagnetic waves below the visible spectrum in the low and high frequency ranges, excluding the very low frequencies, despite their importance in real life. We will discuss in brief some of those papers.

Paper [1] developed a portable dosimeter that has a band pass filter only for 60 Hz cycles, paper [9] discussed the design of a precision gaussmeter, with an ac bandwidth up to 10kHz, the instrument utilizes a hall element probe, single axis, it is not sensitive enough to mG level and it has no data acquisition. Paper [21] developed a stationary system to record the magnetic field from all the sensors on a digital scope and personal computer. Two sets of orthogonal magnetic field sensors applied, ferrite core inductor coil were used as sensors for low frequency magnetic fields from 40 Hz up to 5 kHz, and active loop antennas were used for high frequency magnetic field measurement above 5 kHz. The antenna has a maximum sensitivity of 4 V/mG that was fairly flat above 100 kHz. The antenna response decreases to 1 V/mG at 10 kHz and continues to decrease to a minimum of 0.2 V/mG. Paper [24] presented integrated Microsystems for 3-D magnetic field measurement; the system is based on a multichip module containing three equal channels for the three components of the magnetic field (B_x, B_y, B_z), a microprocessor and a memory. The data stored in the microchip has to be downloaded on a personal computer. This system is valid for low-frequency magnetic fields only.

Based on the above discussion showing the lack of any product similar to our new design in the frequency range it covers. The need in the industrial world for a VLF (very low frequency) Gaussmeter with the unique characteristics mentioned above becomes essential.

II. RELATED WORK IN MAGNETIC FIELD MEASUREMENT

Electromagnetism is classified as either non-ionizing or ionizing radiation. Non-ionizing radiation consists of electromagnetic waves below the visible spectrum [22], with frequencies ranging from near 0 to 10^{15} Hz. It has weak photon energy that cannot break atomic bonds, but it still has a strong effect that is heating [19]. On the other hand, ionized radiation (f > 10^{15}) has sufficient energy to remove electrons from atoms. Included in this part are X-rays, gamma rays, and cosmic rays. This high-frequency radiation is characterized by short wavelengths and high energy.

In general, the non-ionizing part of the electromagnetic spectrum is divided into several ranges: extremely low-frequency fields (0-1000 Hz), very low frequency fields (1-200 kHz), radiofrequency (0.2-300 MHz), microwave (0.3-300 GHz), infrared (0.3-400 PHz), visible light (400-800 PHz) and ultraviolet frequency.

Studying the non-ionizing electromagnetic spectrum, previous papers emphasized mainly on the description of the design of magnetic field monitors and sensors in the low and high frequency ranges, excluding the very low frequencies, despite their importance in real life. We will discuss in brief some of those papers.

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III. GAUSSMETER OPERATION

Fig. 1 shows the top-level design of the VLF Gaussmeter circuits, and Figs. 2 and 3 provide the lower level details. Fig. 3 is a block diagram for the analog front-end of the sensor circuitry associated with each of the three orthogonal coils. The selected signal output from either the X, Y or Z coil is filtered by a unity-gain 100 Hz second order high-pass filter and then fed to the integrator section in order to provide a flat frequency response. The output of the integrator is filtered and amplified consecutively by the 100 Hz second order high-pass and 500 kHz low-pass filters to ensure that only the desired signals are fed to the high-gain amplifier stage. The gain of the final amplifier stage is based on the range selection of 200 mG or 2000 mG. Finally the signal is applied to an AC to DC converter. The DC output from the converter has to be compatible with the 0-5 V range of the analog-to-digital converter.

Table I summarizes the signal path through the analog front-end. Each row shows the voltage levels at the output of each stage for an input signal with a known magnetic field strength and frequency. The input signals were selected to show the signal voltages over the minimum to maximum frequency and the minimum to maximum magnetic field strength with the meter set at the 200 mG scale. For example, the first row shows the voltages for a 0.2 mG input at 1 kHz. The voltage generated by the coil is 3 uV since the coil sensitivity is 15 uV/mG and the magnetic field strength is 0.2 mG.

The 3 uV signal generated by the coil then flows through the rest of the stages in the analog front-end. The output of each stage is shown in Table I and is calculated by multiplying the output of the previous stage by the gain of the present stage. The input signals were selected to show the signal voltages over the minimum to maximum frequency and the minimum to maximum magnetic field strength with the meter set at the 200 mG scale. For example, the first row shows the voltages for a 0.2 mG input at 1 kHz. The voltage generated by the coil is 3 uV since the coil sensitivity is 15 uV/mG and the magnetic field strength is 0.2 mG.

The 3 uV signal generated by the coil then flows through the rest of the stages in the analog front-end. The output of each stage is shown in Table I and is calculated by multiplying the output of the previous stage by the gain of the present stage. To match the input requirements of the A/D converter, the minimum output voltage (Vout in Table I) of the analog front-end must by 5 mV, which corresponds to a meter reading of 0.2 mG. As shown in the second row of Table I, the maximum output voltage must be 5 V, which corresponds to a meter reading of 200 mG. The same process is used to determine the minimum and maximum output voltages at the maximum frequency of 200 kHz. The third and fourth rows of Table I show the detailed calculations for the maximum frequency.
Fig. 1. Top hierarchy model design for the isotropic VLF Gaussmeter

Fig. 2. Block Diagram for the circuit Digital Design.

An 8-bit microcontroller is used for the digital signal processing and for controlling the interface devices and other digital devices in the meter. The meter has two user interfaces, a keypad and an RS232 port, that can be used to select the various features of the meter. The firmware was written in C.
and supports the following features: auto ranging, manual range selection, manual channel selection, offset correction, maximum hold, alarm threshold, data logging, frequency measurement, and a simple control language over the RS232 port.

The RMS output from the analog front end is connected to the input of the 10-bit ADC in the microcontroller. The timing interrupt generator and interrupt handler are configured to sample the ADC every 250 ms. The sample is then scaled and displayed on the LCD if the meter is in single channel mode (x, y, or z). When the meter is in isotropic mode, the microcontroller stores the sampled data and switches input channels after each ADC reading. Since the channels are sequentially sampled, an isotropic measurement can be calculated and displayed every 750 ms.

The frequency counter is based on a dedicated hardware counter that is measured every 1000 ms and the overflow flag is checked every 13 ms. Both time intervals are controlled by the timing interrupt generator and the interrupt handler. The data logging feature stores up to 32,000 data samples in 128 KB of external EEPROM. In single channel mode only the channel being measured is logged. In isotropic mode, the user can set the meter to store only the isotropic measurement or to store the isotropic measurement along with the x, y, and z readings. The data-logging interval can be set in one-second increments from one-second to 2 hours or in one-minute increments from one minute to 6 days.

Listed below is a summary of the additional external hardware required to build the meter and a list of additional features included in the firmware.

<table>
<thead>
<tr>
<th>External devices:</th>
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<tbody>
<tr>
<td>• Keypad – measured every 13 ms with debounce logic</td>
</tr>
<tr>
<td>• RS232 Interface – polled every 13 ms</td>
</tr>
<tr>
<td>• LCD</td>
</tr>
<tr>
<td>• Memory</td>
</tr>
<tr>
<td>• Alarm</td>
</tr>
</tbody>
</table>

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**IV. ANALOG CIRCUIT DESIGN**

**A. Sensor Design**

A multiturn copper coil is used as a field-sensing element for this particular design. A coil element is well suited for this application since the sensitivity is higher than a Hall effect element especially at higher frequencies. According to Faraday’s induction coil theory, a coil of conductive wire can be used as a magnetic flux density sensor. In the presence of a magnetic filed, a voltage $V_{in}$ is induced across the coil and is proportional to the time rate of change (time derivative) of the magnetic flux density [20].

\[
V_{in} = N \left( \frac{d\phi}{dt} \right) \quad (1)
\]

Where

\[
\phi = \int B \cdot dA \quad (2)
\]

**TABLE I.**

**EXPECTED OUTPUT VOLTAGES FROM EACH STAGE OF THE ANALOG FRONT-END AT SCALE 200 mG**

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>5.94718</td>
<td>3.00e-06</td>
<td>3.00e-05</td>
<td>2.98e-05</td>
<td>5.10e-05</td>
<td>1.36e-04</td>
<td>6.92e-03</td>
<td>4.89e-03</td>
</tr>
<tr>
<td>200000</td>
<td>0.04974</td>
<td>6.00e-04</td>
<td>6.00e-04</td>
<td>2.98e-05</td>
<td>5.10e-05</td>
<td>1.36e-04</td>
<td>6.92e-03</td>
<td>4.89e-03</td>
</tr>
<tr>
<td>200000</td>
<td>0.04974</td>
<td>6.13e-01</td>
<td>6.13e-01</td>
<td>3.05e-02</td>
<td>5.22e-02</td>
<td>1.39e-01</td>
<td>7.07e+00</td>
<td>5.00e+00</td>
</tr>
</tbody>
</table>
$dA$: Cross-sectional area inside the coil

If the area within the sensor’s coil is fixed and small, the flux density is assumed to be uniform. Using this assumption, equation (2) becomes:

$$\phi = B \cdot A$$

Substitute this into (1)

$$V_{in} = \frac{N\pi}{4} \cdot \frac{dB}{dt}$$

Where

$$B = B_0 e^{jwt}$$

$$B_0 = |B| = Amplitude, \quad w = 2\pi f$$ is the angular velocity.

Equation (4) becomes

$$V_{in} = \frac{N\pi}{4} \cdot B_0 jw e^{jwt}$$

By taking the magnitude of both sides

$$V = |V_{in}| = \frac{N\pi}{4} d B_0 w = \frac{N\pi}{2} d f B_0$$

$$N = \frac{V}{2\pi f BA}$$

Sensitivity = $V_B = 2\pi fNA$

For this design, the area of the coil is 5.07 $cm^2$, the maximum voltage amplitude is 6 V, the maximum magnetic field is 2000 mG, and the maximum frequency is 2000 kHz. The number of turns for the coil can be found using (7), and the optimal number of turns for this design is 47.

Based on (8), the sensitivities at $f_{min}$ and $f_{max}$ are equal to 15.00 $\mu V/mG$ and 3.00 $mV/mG$ respectively. For comparison, one of the most sensitive Hall sensors only has a sensitivity of 18 $mV/mG$. The coil parameters can also easily be changed to obtain any desired output signal level.

B. Second-Order High Pass Filter Design

Sinusoidal inputs with a frequency greater than the cutoff $f_0$ emerge from the filter with unchanged amplitude, while those inputs with a frequency less than $f_0$ undergo complete attenuation.

The circuit analysis for Fig. 4 draws the final results

$$H\left(\frac{f}{f_0}\right) = \frac{-K\left(\frac{f}{f_0}\right)^2}{1 - (f/f_0)^2 + (j/Q)\left(\frac{f}{f_0}\right)} = \frac{V_0}{V_i}$$

$$k = 1 + \frac{RB}{RA}$$

Where K is constantly referred to as a high frequency gain

$$Q = \sqrt{\frac{mm}{n+1}}$$

$Q$ is a damping factor; it can range from 0.5 to 100, with values near unity by far most common.

$$f_0 = \frac{1}{2\pi RC\sqrt{mn}}$$

A common task is to find suitable component values to achieve a corner $f_0 = 100$ Hz with a dc gain of 4.65 dB and a damping factor of 0.707. The importance of these values will be explained in the final design stage.

Summarized results of these components: $C = 47nF$, $nC = 47nF$, and $R = 24.9 k\Omega$.

Fig. 5 shows the simulation results for the second order high-pass filter, magnitude in dB versus frequency. Note that the low-frequency asymptotic slope is 40dB/dec, indicating that the response of a second-order high-pass is closer to ideal than a first-order filter. The maximally flat or Butterworth response corresponds to $Q = 0.707$, where the magnitude is 3dB below the high-frequency asymptotic value. Above 100 Hz, the response approaches the flat curve that is required for the desired filter bandwidth.
C. Second–Order Low-Pass filter Design

This filter is characterized by a frequency $f_0$ called the cutoff frequency, indicating that the sinusoidal inputs with a frequency less than $f_0$ go through the filter with unchanged amplitude, while those with frequency greater than $f_0$ undergo complete attenuation.

The final equations from Fig. 6 after some algebra can be derived as follow:

$$H(f) = \frac{V_o}{V_i} = \frac{K}{1 - (f/f_0)^2 + (j/Q)(f/f_0)}$$  \hspace{1cm} (13)

$$K = 1 + RB/RA$$  \hspace{1cm} (14)

$$Q = \frac{\sqrt{mn}}{m + 1 + mn(1 - K)}$$  \hspace{1cm} (15)

$$f_0 = \frac{1}{2\pi RC\sqrt{mn}}$$  \hspace{1cm} (16)

A common task is to find suitable component values to achieve the desired values of $f_0$, dc gain, and Q. This design requires $f_0 = 500$ kHz, dc gain = 8.5 dB, and $Q = 0.707$. These requirements will be explained in the section describing the analog frontend.

Summarizing the calculation results: $C=0.01\text{nF}$, $nC=0.005\text{nF}$, $R=24.9\text{ k}\Omega$, $mR=24.9\text{ k}\Omega$, $RB=20\text{ k}\Omega$, and $RA=10\text{ k}\Omega$.

The circuits of Fig. 4 and 6 are connected together. Both gains are added as shown in Fig. 8 to yield a second order wide band-pass flat filter with maximum linearity especially suited to the required bandwidth for this application.
input. For a sinusoidal input, $Ein = v_i \sin wt$, the output is given by:

$$E_{out} = \frac{0.6366v_i R_7}{R_6}$$

(19)

The selection values of $R_7$ for peak and RMS calibration are equal to $1.55R_6$ and $1.11R_6$ respectively. Adding capacitor $C_4$ across $R_7$ causes $U_2$ to act as an average pure DC output. The filter time constant $R_7C_4$ has to be greater than the maximum period of the input signal to have good filtering or averaging without any ripple. In our case the maximum input frequency of the signal is 200 kHz, then $T = \frac{1}{200 \times 10^3} = 5\eta s$, the time constant $R_7C_2 >> 5\mu s$ is needed.

![Fig. 9. Precision AC to DC RMS Converter](image)

For better conversion less than 1%, some cares were taken at the above 125 kHz sine wave input. During construction, the leads should be kept short, the film type resistors values should be kept low, the power supplies should be bypassed with $0.01\eta F$ disc ceramic, the diodes should be reasonably fast and the amplifiers must have low bias currents.

Fig. 10 represents the simulation output result for 5 kHz sine wave input signal. The output conversion is a pure DC that is critical to the input of A/D converter precision.

![Fig. 10. AC to DC RMS Converter Response](image)

**E. AC Integrator Design**

As was discussed previously, this meter has a flat frequency response that measures the true magnitude of the field throughout its range, without regard to the field's frequency. An integrator is needed at the output of the coil to provide a near flat frequency response as shown in Fig. 8. This circuit is needed to integrate AC signals over a reasonable long time and it may not be possible to reset the output to zero periodically. In this case adding a resistor $R_2$ in feedback with $C$ can alleviate the DC offset problem. The advantage of bounding the DC gains with $R_2$ is that the amplifier output will not drift into saturation as shown in Fig. 11. For frequencies greater than $\frac{1}{R_2C_1}$ the response approaches that of an ideal integrator with gain of $\frac{1}{R_1C_1S}$.

![Fig. 11. AC Integrator circuit design](image)

Fig. 12 represents the AC gain response versus frequency. It is clear that the response gain becomes an ideal integrator for the selected bandwidth of the design.

![Fig. 12. Gain Response for AC Integrator](image)

To verify the high frequency operation of the integrator, a SPICE simulation was run with a 100 kHz square wave as the input to the integrator. Fig. 13 shows the expected transient response of this standard integrator test, which is a triangle

![Fig. 13. Integrator Response at 100 kHz input frequency](image)
wave output. The peak of triangle wave is determined by the gain of the integrator and the input waveform. With an input waveform of +/- 5V and an integrator gain of approximately 0.1 at 100 kHz, the expected peaks of the triangle wave are +/- 0.5 V, which matches the simulation results.

**F. Comparator with hysteresis design**

A comparator as shown in Fig. 14 looks at the two voltage signals at its input and determines which of the two signals is the larger. This function comes in extremely handy in detecting high and low voltage limits for frequency counter. A feedback resistor was added to the comparator to eliminate the output chatter. This problem can show up when the input voltage (HIGHGAIN_OUT) is very close in value to the reference voltage (GND). Under these conditions, the comparator’s output may tend to oscillate between states.

![Comparator and Hysteresis circuit design](image)

**V. GAUSSMETER PERFORMANCE**

The prototype development and calibration tests for the VLF Gaussmeter’s field detection circuitry are performed with a Helmholtz coil that provides a known magnetic flux density as a function of the applied current [10]-[11]. In our application, we use a known field of 106mG, and the current is adjusted as we sweep the frequencies to maintain the same magnetic field at the center of the coil. Figs. 14 and 15 show the circuitry of the double-sided board used for development and the final verification tests. The digital components are on the topside of the board to maximize the separation from the analog components that are on the bottom side.

![Development Board - Digital Side](image)

![Development Board - Analog Side](image)

![Computed and Measured Magnetic Field Response for the VLF Gaussmeter versus Frequency](image)

Fig. 17 shows the theoretical and experimental results for the linearity of the magnetic field measurement versus frequency. The linearity error over the measured frequency range was less than 4%.

A second test was done to study the linearity of the meter over a wider frequency range by using a signal generator as the input to the meter. During that test, each time we changed the frequency by a certain ratio, the peak voltage of the signal needed to be adjusted by that same ratio in order to be consistent with the pick up of the coil. Fig. 18 shows the normalized readings versus the frequencies.

![Computed and Measured Magnetic Field Response for the VLF Gaussmeter versus Frequency](image)
VI. CONCLUSIONS

Tradeoffs always exist when an instrument design must be optimized for both high accuracy and high bandwidth (1 kHz-200 kHz). A resultant error less than 4% occurs due noise sources. Some error adjustments could be done within the firmware of the microcontroller. In our case, we ran out of internal memory used to store the firmware in the microcontroller due to the multitude of features implemented. Finally this design can also be done with a proportional frequency response. In this case, the measured magnetic field will be scaled by the frequency of the field.

A portable VLF gaussmeter with high resolution (0.2 mG), good linearity, and a wide frequency bandwidth is useful for measuring man-made electromagnetic fields in work and home environments. Since this meter is a standalone device with data logging capabilities, it can be very useful for monitoring remote areas for health and safety concerns. The frequency indicator and ability to switch between the isotropic mode and single axis mode also make it easier to isolate the source of potentially harmful magnetic fields. With all of these features, this instrument is valuable for health research and epidemiology.

REFERENCES

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