Development and Test of Free Space Electric Field Sensors with Microvolt Sensitivity

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ABSTRACT

We have developed a new solid state electric potential sensor that has over an order of magnitude lower voltage noise than prior state-of-the–art technology. The sensor uses a novel input feedback circuit that enables it to be stable down to DC, and have frequency independent detection sensitivity from 0.01 Hz to 10 kHz. The input voltage noise level at 50 Hz is below 1 μV/√Hz, and when coupled to a 20 cm dipole antenna a coupling efficiency up to 0.75 can be achieved. Using two antennas spaced 50 cm apart, an electric field sensitivity of order 1 μV/mHz$^{-1/2}$ can be achieved outdoors.

Laboratory and field measurements indicate that the environmental noise above 30 Hz may be lower than estimated from atmospheric measurements using previous technology. Below 10 Hz the sensitivity appears to be dominated by noise due to single charged dust impact events. We will discuss the trade-offs in sensor design, the magnitude and spatial coherence of the environmental electric fields close to the ground in the ELF band, and results of recent outdoor tests.

1. Introduction

Many objects of military interest produce quite strong electric fields due to natural electrostatic charging phenomena, such air friction or combustion. In many cases these voltages rise until they reach the local atmospheric breakdown potential of order tens of kV. In addition, most types of heavy electrical machinery involve significant voltages and therefore produce significant electric fields.

Surprisingly, until the present work there was no instrumentation available that could measure extremely low frequency (ELF) free space electric potentials, and therefore ELF free space electric fields, at a comparable sensitivity and convenience level to that achieved by magnetic field sensors. Prior approaches in atmospheric research typically utilized large spherical antennas (≥ 20 cm in diameter) suspended above large metal plates (of order 1 m^2). The best reported sensitivity at sea level using such techniques is of order 70 μV/mHz$^{-1/2}$ at 50 Hz[1]. The only commercially available electric field sensor is the electric field mill, which utilizes rotating metallic vanes to achieve a noise floor at 1 Hz of order 1 V/mHz$^{-1/2}$. The field mill has an

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upper detection frequency of order 25 Hz, limited by the rotation frequency of its vanes. Owing to the lack of convenient, sensitive hardware, electric field detection is a virtually unknown and largely unstudied sensing modality.

2. Measuring the Free Space Electric Potential

Measuring the electric potential of an object is easy to do provided one can make a reasonable electrical contact to it, but no such connection can be made to free space. However, an object placed in an electric field rises to the potential associated with the field at its geometric center. To measure this potential we can connect the object to a charge reservoir and measure the charge that flows onto it, as shown schematically in Figure 1. The accumulated charge is given by the self-capacitance[2] of the object times the potential difference between the object and the charge reservoir. For example, for a potential difference of 1μV sensed by an object (i.e. the antenna) of capacitance 5 pF, the charge to be measured is 5×10^{-18} C, or approximately 30 electrons.

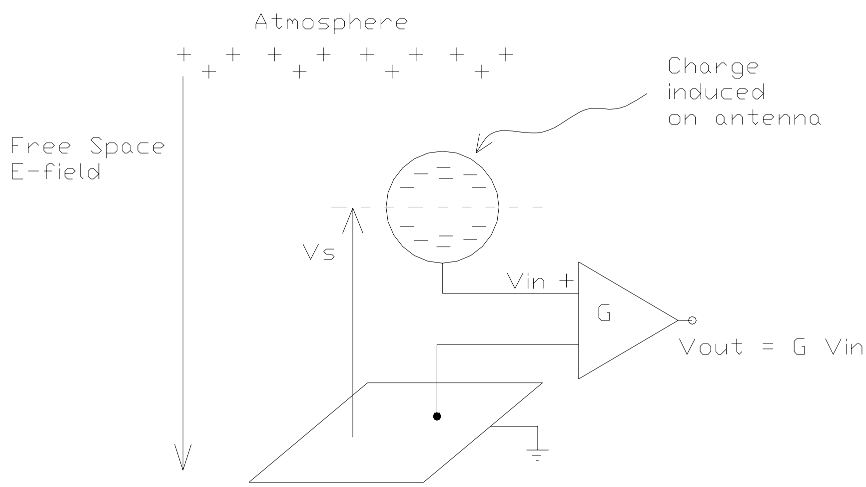

Figure 1. Approach to Measuring the Free Space Electric Potential. Ambient field is shown schematically as being produced by local charges. Charges act to induce the opposite charge on objects within the field. Charge flows from amplifier to object, thereby producing a signal at the amplifier input.

The principal practical difficulty in making a pure capacitive measurement of the free space potential is the input bias current of the amplifier. The measurement circuit diagram is shown schematically in Figure 2. To operate the amplifier an input bias current must flow into the terminals at the amplifier input. However, in the circuit shown in Figure 2 there is no path to provide the input bias current, and so it charges up the capacitance, Cs, of the source (i.e. antenna) being used to sense the potential. The result is that the input has a steady voltage drift. For example, for an input bias current of 0.1 pA (historically a low value for semiconductor amplifiers[3]) flowing onto an antenna capacitance of 5 pF, an amplifier with a gain of 100 would drift off scale (i.e. the output would rise to order 10 V) in around 5 seconds.

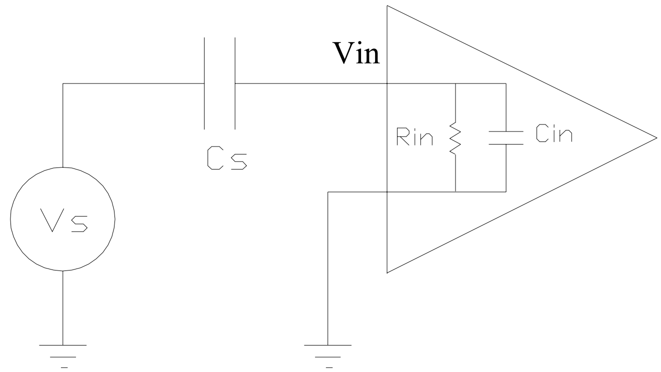

Figure 2. Circuit Diagram for Measuring the Free Space Electric Potential (Represented as a Voltage, V_s, Produced Relative to Ground). C_s is the Capacitance (to Free Space) of the Antenna that Probes the Field. C_{in} and R_{in} are the Input Capacitance and Resistance of the Amplifier

To overcome the drift problem previous techniques have relied on having a resistive path to ground at the input. However, at the impedance levels need to measure free space at sea level, such a path at the input shunts away a large fraction of the input signal to ground, thereby reducing sensitivity. To address this issue QUASAR has developed a combination of novel stabilization and feedback circuits that fully remove the drift due to input bias current[4]. These circuits take advantage of the internal design of the most recent generation of instrumentation amplifier chips, and the very low internal noise levels. With drift canceled we are able to connect the readout circuit directly to a purely capacitive antenna shown in Figure 2.

The circuit in Figure 2 is basically that of an impedance divider with the voltage, V_{in}, at the first stage amplifier input given by: $V_{in} = V_s z_{in} /(z_s + z_{in})$. For the ultra high input resistance, ($R_{in} = 10^{15}\ \Omega$) of presently available amplifiers (so that $\omega R_{in}C_{in}$, $\omega R_{in}C_s >> 1$), the system can produce a flat band frequency response as shown in Equation 1.

$$V_{in} = \frac{j\omega R_{in} C_s}{1 + j\omega R_{in} C_{in} + j\omega R_{in} C_s} V_s = \frac{C_s}{C_{in} + C_s} V_s \qquad [1]$$

Furthermore, the self-capacitance of a metal plate is of order 1 pF times its average dimension in cm, while the input capacitance of present electrometer grade amplifiers is of order 3 pF. Thus is easy to arrange for C_s to be greater than C_{in} so that Equation 1 becomes:

$$V_{in} \approx V_s \qquad [2]$$

thereby yielding the ideal measurement of the electric potential.

To measure the free space electric field it is only necessary to measure the potential at two points, subtract one result from the other and divide by the physical distance, d, between the two points.

$$E = \frac{V_1 - V_2}{d} \qquad [3]$$

The two measurements can be made by different sensors, or by utilizing an amplifier with a differential input. The sensors discussed in this report are differential. Each has two electrodes and thus makes a direct measurement of the ambient electric field.

3. Sensor Specifications and Performance

The response vs. frequency of the present design of QUASAR electric field sensor is shown in Figure 3. The sensor has essentially frequency independent response from 0.5 Hz to 1 kHz. With 2 pF antennas (see Figure 6) the measured coupling efficiency to the external electric field is 0.39 compared to a value of 0.4 predicted by Equation 1. If larger antennas are used the efficiency can easily exceed 0.75. The upper and lower frequency detection cut-offs can be varied by changing the networks used in the input feedback circuit. An earlier version of the sensor was built with a low frequency cut-off of 0.001 Hz (this sensor was used to collect the data shown in Figure 9) and another version had an upper frequency roll-off at 10 kHz. All other data was collected with the sensor with frequency response shown in Figure 3.

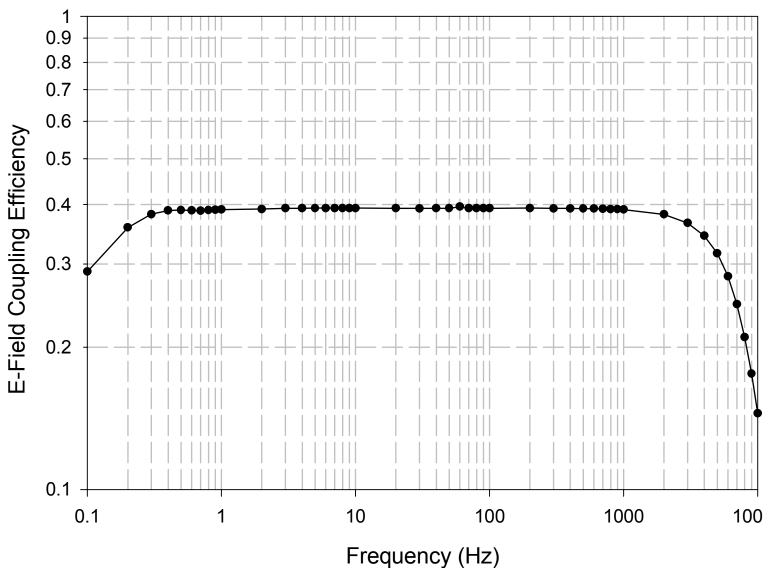

Figure 3. Electric Field Coupling Efficiency vs. Frequency for the Sensor Connected to Antennas with 2 pF Self Capacitance. For Large Antenna Capacitance (~ 10 pF) the Efficiency Approaches 1.

The sensor internal noise referred to its input for the sensor operated in open circuit is shown in Figure 4. Below about 200 Hz the sensor is limited by the effect of its input current noise acting on the antenna impedance, $1/\omega C_s$. Because this impedance increases with decreasing frequency it is responsible for the 1/f-like noise behavior at low frequency. The larger the capacitance of the antenna the smaller low frequency noise in the sensor. For example, for an antenna self-capacitance of 10 pF the current noise contribution is reduced by approximately a factor of 10 over that shown in Figure 4. The data in Figure 4 thus represents the worse case sensor noise for the limiting case of zero antenna capacitance. Above 200 Hz the sensor is limited by its first stage amplifier voltage noise which is 200 nV/√Hz for the sensors used in outdoor tests to date, but can be as low as 25 nV/√Hz depending on feedback circuit configuration.

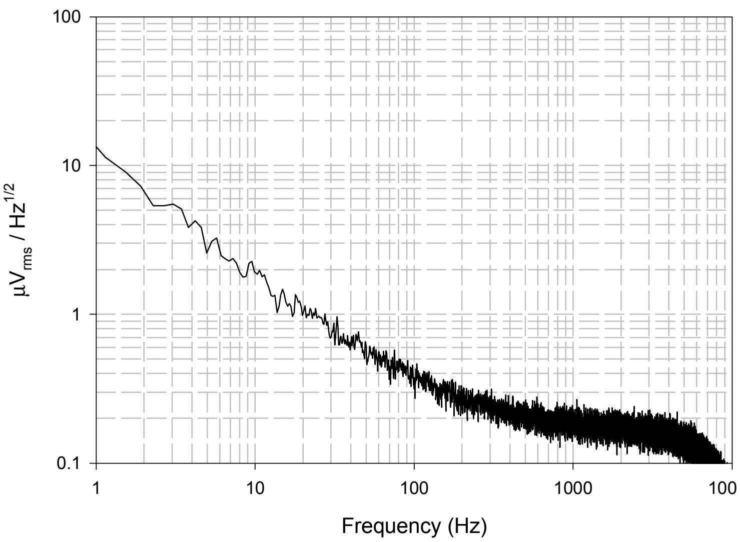

Figure 4. Spectrum of the Internal Voltage Noise for the New Electric Field Sensor

Several views of the new electric field sensors are shown in Figures 5 and 6. Figure 5 shows two sensors with the cover plates of the housing removed. One is a top view showing the main sensor circuit board, the other view shows the integral battery compartment on the rear side of the sensor package. The simplicity, and inherent ruggedness of the sensor is immediately apparent. Figure 6 shows three single axis sensors connected together to measure all three components of the ambient electric field. Also shown are the simple copper plate electrodes used as antennas to sense the local electric potential. The antennas are connected to the sensor electronics using semi-rigid coaxial cable, and have a self capacitance of 2 pF. It is a trivial matter to increase the distance between the sensing points by using a longer cable, or increase the antenna capacitance by using larger plates. In the sensor shown in Figure 6 the effective sensor baseline is about 33 cm. This means that for a noise referred to the sensor input of 1 $\mu V/Hz^{-1/2}$ the electric field detection sensitivity is 8 $\mu V/mHz^{-1/2}$.

Figure 5. View of the Inside of the E-Field Sensor. One Viewed from the Top, One Flipped over to Show the Battery Compartment. Housing is Lightweight Aluminum

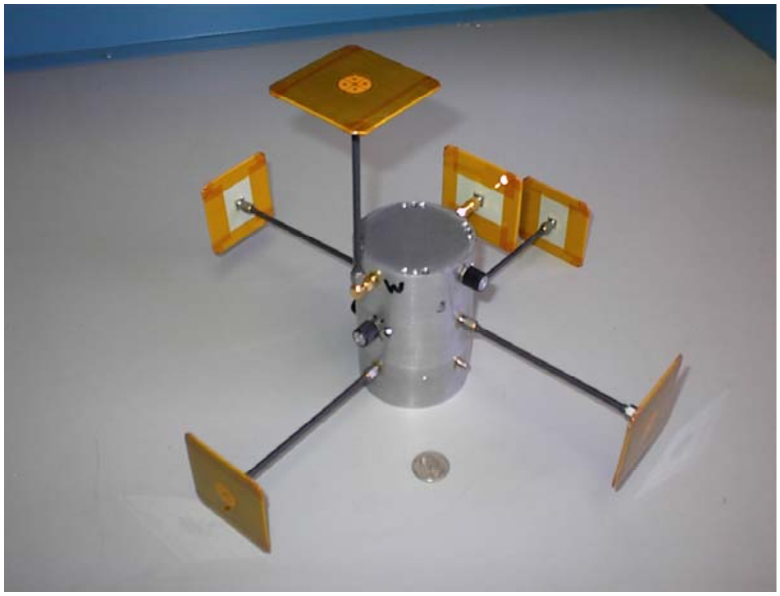

Figure 6. View of the Complete 3-Axis E-Field Sensor Assembly. Sensors are Designed to Bolt Together. Top Sensor Measures the Vertical Field. Antennas are Demountable and Different Lengths can be Inserted via Simple SMA Screw Connectors

The electric field sensitivity can be calibrated by placing the sensors between the plates of a large parallel plate capacitor. Measurements typically agree with the sensitivity calculated from the sensor internal noise and the effective antenna separation to within 5 %.

.1.1 4. Measurements of the Ambient Electric Field Environment

The three axis sensor package is typically mounted about 1.5 m above ground on a standard fiberglass tripod, as shown in Figure 7. The data is collected on a standard laptop computer via a PCMCIA analog to digital converter card. At various times wind baffles have been mounted on a separate stand to prevent mechanical motion due to wind force, and the possible effect of charged dust impacting the sensors. The relative contribution of these effects in the data collected to date has not been determined.

In the frequency range from 10 Hz to 10 kHz, the electric field background noise is predominantly produced by worldwide lightning storms and has virtually the same spectrum as for magnetic noise. Data published by International Telecommunications Union[5] is shown in Figure 8. Owing to the conductivity of the ground, the background electric field is almost completely polarized in the vertical direction, and there appears to be no data available for the background free space electric field noise in the horizontal plane. This lack of data is probably due to two reasons: lack of practical applications, and a (prior) unavailability of sensors with adequate sensitivity to probe free space E-field at levels below 100 $\mu V/mHz^{-1/2}$.

Figure 8 also shows data collected in the vertical and horizontal direction by the new QUASAR electric field sensors on a large undeveloped urban site. Above 100 Hz the E_x and E_y sensors (i.e. in the horizontal plane) operate within a factor of two of their noise floor as measured under fully shielded laboratory conditions. The noise at lower frequency measured in the horizontal plane outdoors is probably due to local space charge around the sensor although it could also be use to atmospheric electromagnetic field noise. The measured electric field in the vertical direction, E_z, agrees well with the projections of the ITU.

Figure 7. Three Axis Electric Field Sensor Suite Deployed in the Field

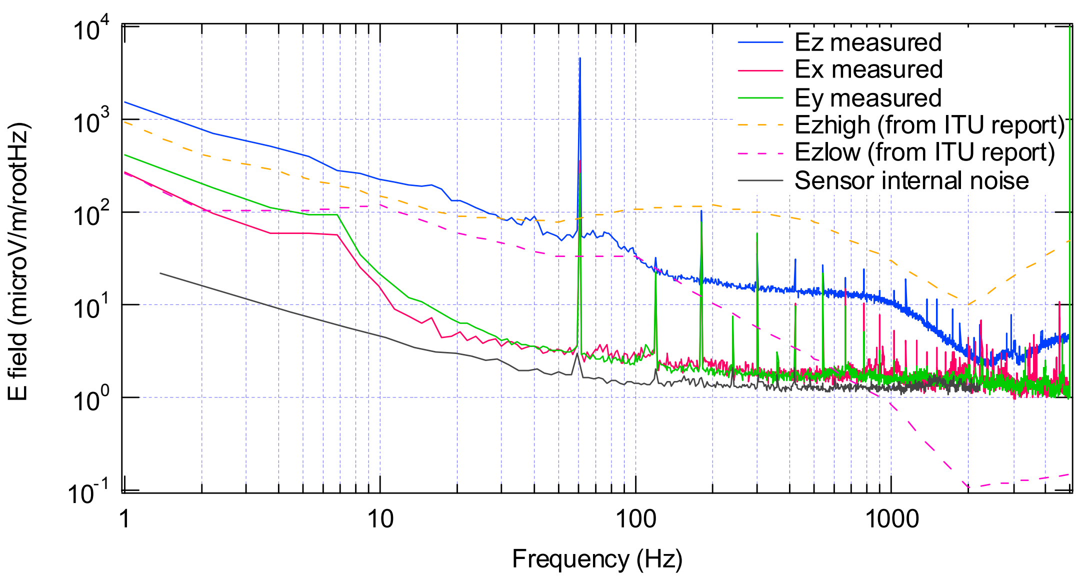

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Figure 8. Published Limits for the Upper and Lower Bounds to the Vertical Electric Field Background Noise, and Data Taken Using the New E-Field Sensors at an Urban Site for the Vertical E-Field, E_z (upper noisy trace) the Horizontal Field, E_x E_y (lower 2 noise traces) and the Sensor Internal Noise (lowest trace).

From this and other data collected with the new sensors, it appears that the background electric field noise in the horizontal plane may be very low. This result may have important consequences for electric field sensing and detection applications. In addition, because of the common long range source for both electric and magnetic field atmospheric noise, it is likely that the electric field noise will have the same spatial coherence over baselines of order several hundred meters as is found for magnetic field sensors. If so this would make gradiometric methods to cancel electric field noise of the same order of effectiveness as is achieved for magnetic sensors

The core sensor electronic readout circuit (modified for lower frequency operation down to 0.001 Hz) was incorporated into a conventional probe for the upper atmosphere by the Space Sciences Laboratory of the University of California Berkeley (UCB-SSL). The complete package was tested alongside a conventional electric field mill in the Arizona desert in June 2001 as part of NASA's Mars Atmosphere and Dust in Optical and Radio (MATADOR) project. The output of the two sensors is shown in Figure 9. The data from the QUASAR/UCB-SSL sensor is denoted DCE and is divided by 10. It is clearly much more sensitive than the electric field mill (denoted by EFM). Note also that although the QUASAR sensor repeatedly hit its output voltage rails, it recovered very quickly from saturation and closely tracks the much less sensitive field mill. Spectral analysis showed that the QUASAR sensor detected both the 20 Hz electric motor used inside the field mill from about 7 m distance, and also 60 Hz emissions from a power substation several miles away.

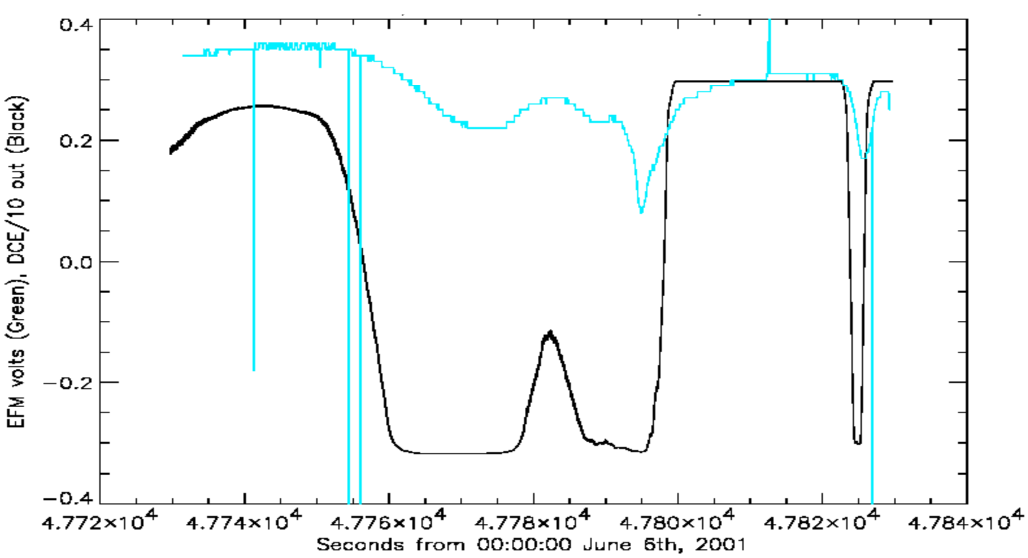

Figure 9. Comparison of the New Electric Sensor (Denoted DCE, dark line, raw voltage data divided by a factor of 10) with an Electric Field Mill (lighter line) Data taken at Marana Az. by the UC Berkeley Space Science Laboratory

.3 5. Possible Applications

The electric field sensors described in this report have only been developed within the last year, and little data has been collected on targets of possible military interest. To illustrate potential applications of electric field sensing we show the electric field signature of a person walking. In Figure 10, the subject started walking (at about 55 arbitrary time units) in straight path from 3 m to about 1.3 m away from a single sensor then continued to a distance about 3 m on the other side. The subject then turned around and walked back. Sensors were operated unshielded without noise cancellation on a laboratory bench. The oscillating signal corresponds to the motion of the legs while walking, and is likely due to a residual static charge carried on clothing, but could also be due to the distortion of the earth's field. The more slowly changing signal is from the torso. This was essentially the closest approach that could be made without saturating the sensors. Based on these results it appears feasible to detect the motion of a human walking from 10 to 20 times greater range than shown in Figure 10.

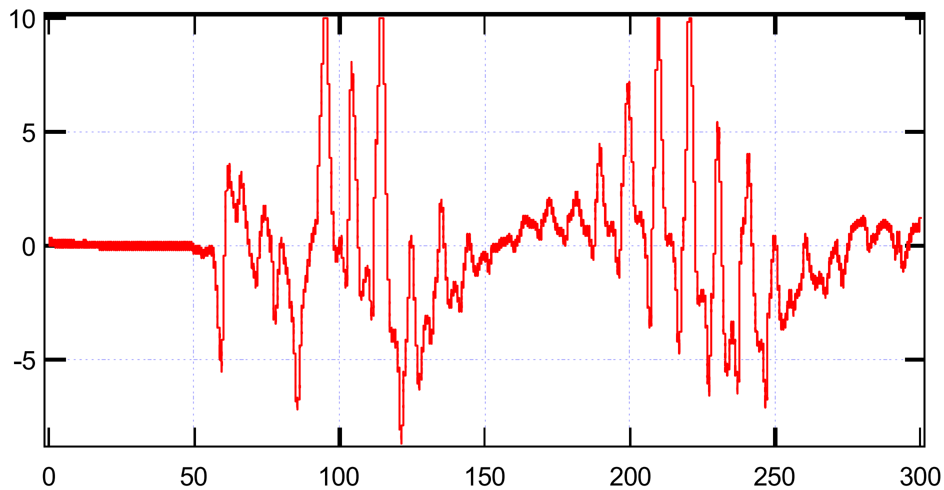

Figure 10. Electric Field Signal of a Person Walking in a Straight Path from 3 m to about 1.3 m at Closest Approach then Continuing to a distance about 3 m on the Other Side. Person then Turns and Walks Back. The vertical axis is –10 V/m to + 10 V/m.

6. Summary

A new type of electric potential sensor has been developed which has the size, weight, cost and simplicity to be used for many types of military sensing applications. It is straightforward to extend the antenna separation to implement an electric field sensor with sensitivity well below 1 $\mu V/mHz^{-1/2}$. Measurements of the horizontal background electric field suggest that above 50 Hz the environmental noise may still be below the present 1 $\mu V/mHz^{-1/2}$ benchmark level set by the new sensors.

Preliminary measurements have shown promise for several new sensing applications that could be done cheaply and with minimal signal processing. It should be noted that to a far field source an electric field sensitivity of 1 $\mu V/mHz^{-1/2}$ corresponds to a magnetic field sensitivity of 3 $fT/Hz^{-1/2}$. Thus, the new electric field sensing technology also has the capability to function as an extremely sensitive magnetic field detection system under certain conditions.

.4 7. Acknowledgements

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.5 8. References

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[1] D. D. Sentman, "Schumann Resonances," in *Handbook of Atmospheric Electrodynamics*, (ed. By H. Volland), CRC Press, Boca Raton, Florida 1995

[2] For an electrically short antenna, (i.e. an object whose baseline is much smaller than the wavelength of interest) the coupling to a free space electric field will be dominated by the self capacitance of the object. The self capacitance is the capacitance of the object to free space. It is calculated by dividing the charge on the object by the voltage calculated by integrating the potential produced by that charge relative to zero voltage at infinity.

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