Capacitive electric field sensors for electromagnetic geophysics

Summary
Over the last ten years, GroundMetrics, Inc., and QUASAR Federal Systems, Inc. (QFS) have developed the first commercial range of geophysical electric (E-) field sensors that couple to the E-field via capacitive coupling. The new type of sensor, known as the eQube™, can easily function in historically challenging, high resistance terrains including desert, frozen ground, gravel and caliche without the need for burial of the electrodes or modification of the ground while still offering performance equivalent to that of conventional porous pot technology. The eQube’s capabilities allow electromagnetic (EM) surveys to be conducted in terrains for which such measurements were previously difficult or not possible, and can simplify and expedite E-field surveys in all terrain types. Telluric cancellation via remote reference further improves E-field data quality. Examples will be shown for comparisons of E-fields measured with our sensors and with extant sensors.

Introduction
Electromagnetic (EM) geophysical methods require accurate and reliable measurement of the E-field in order to characterize the subsurface from the near surface down to several kilometers depth. To date, porous pot or metal electrodes used to measure the E-field have had significant measurement and operational limitations that have prevented reliable E-field data collection in very resistive terrains, such as those covered by ice, tundra, sand, gravel, and caliche (e.g., Thiel, 2000). Yet, many such terrains are very prospective, so the ability to accurately and reliably measure the E-field with land and airborne EM systems opens up new opportunities for EM-led mineral exploration in prospective regions of Australia, Africa, Canada, Chile, Mongolia, Peru, Russia, and the US.

Over the last ten years, GroundMetrics, Inc., and QUASAR Federal Systems, Inc. (QFS) have developed a new type of E-field sensor that employs a chemically inert electrode and directly couples to the electric field via capacitive coupling (Matthews et al., 2005). Unlike other capacitive sensors (e.g., Kuras et al., 2006), our sensors operate down to low frequency (< 0.01 Hz) and have been deployed in a variety of land and marine EM geophysical systems. Our sensor employs ultra-high impedance feedback techniques to provide immunity to changes in ground resistance from 1 Ω to 1 MΩ. In both land and marine tests to date, our capacitive sensors have demonstrated sensitivity equivalent to or better than Ag/AgCl galvanic electrodes, and no measurable degradation in any of the deployed sensors has been observed since initial tests began in 2006.

Figure 1. Circuit for a capacitive electrode (note two electrodes are required to measure the E-field). V_{source} is the potential of interest, R_{e} is the resistance of the earth, C_{couple} and R_{couple} are the electrode contact capacitance and resistance, C_{in} and R_{in} are the amplifier input capacitance and resistance.

Theory for capacitive E-field sensors
Capacitive coupling is a purely EM phenomenon, which, to first order, has no temperature, ionic concentration or corrosion effects, and thus provides unprecedented measurement fidelity. The absence of an electrochemical reaction with the ground can potentially provide an operational lifetime of tens of years, even when exposed to extreme environmental conditions. In addition, ultra-high impedance feedback techniques can be implemented in a capacitive sensor to enhance measurement fidelity even further.

The general measurement circuit architecture for capacitive sensing is shown in Figure 1. The potential of the Earth is represented by the voltage V_{source}. The sensor couples to this potential via the resistance of the Earth, R_{e}, and the electrode coupling impedance represented by the components C_{couple} and R_{couple}. R_{e} is dominated by the ground in the immediate vicinity of the electrode while C_{couple} and R_{couple} are set by the electrically insulating layer on the electrode. The goal is to make the sensor output as independent as possible of changes in the R_{e}, while operating in the regime of zero electrochemical coupling (R_{couple} = ∞). The key issue with designing such a sensor is there is no resistive path to ground at the input to carry the amplifier input bias current. As a result, the current flows onto the electrode capacitance C_{couple}, increasing the voltage at the amplifier input until it saturates. The challenge is to provide a resistive path at the amplifier input (not shown) without essentially shorting the signal into the amplifier. This has been addressed by utilizing a novel
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patented feedback scheme (Krupka, 2004). The result of aiming to operate in the fully capacitive regime over a wide range of $R_e$ is that $R_{in}$ must be very large (> 100 GΩ). However, making $R_{in}$ so large means that the sensor upper frequency response becomes dominated by $C_{in}$. For example, a typical value of $C_{in}$ for a well-designed amplifier circuit connected to a capacitive plate is 10 pF to 20 pF. For $C_{in} = 10$ pF, a ground impedance of 1 MΩ will result in an upper frequency 3 dB point of 16 kHz. Thus, if the ground impedance were to change from 1 MΩ to 100 kΩ due to rainfall, such a sensor could produce gain and phase errors. To address this, GMI has incorporated negative feedback methods that reduce the effective value of $C_{in}$ from ~ 10 pF to less than 0.3 pF.

Example

Figure 2 shows the measured amplitude and phase response of a prototype sensor to a known applied potential in for $R_e$ ranging from 100 Ω to 4 MΩ over frequencies from 0.1 Hz to 100 Hz. The average difference in gain is within 0.2% to 100 Hz while the phase difference is less than 1 mrad to 100 Hz except for very dry sand, for which it is still less than 5 mrad. This property opens the door to E-field sensors that can be permanently installed in very harsh environments and accurately record data even when the ground conditions vary widely over time, for example due to rainfall, temperature (e.g. ice or snow), ground compaction, and ground fissuring.

![Figure 2. Experimental data for a pair of eQube™ sensors measuring the E-field in earth varying from 100 Ω to ~ 4 MΩ. The average difference in gain over the 4 x 10^4 range of resistance is within 0.2% to 100 Hz while the phase difference is less than 1 mrad to 100 Hz except for very dry sand, for which it is still less than 5 mrad.](image)

Conclusions

GroundMetrics and QFS have developed innovative capacitive E-field sensors that, for the first time, enable accurate EM surveys in historically challenging terrains. The ability to accurately and reliably measure the E-fields in land opens up new opportunities for EM-led mineral exploration in prospective regions of Australia, Africa, Canada, Chile, Mongolia, Peru, Russia, and the US. The sensors also enable long-term, permanent E-field monitoring for acid mine drainage, contaminant mapping, enhanced oil recovery (EOR), carbon sequestration, hydraulic fracturing, and infrastructure integrity.
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References


