Fall 10-23-2009

Reduction and Characterization of Error in Low Current Measurements

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Recommended Citation  
Dekany, Justin; Dennison, JR; and Sim, Alec, "Reduction and Characterization of Error in Low Current Measurements" (2009). American Physical Society Four Corner Section Meeting. Presentations. Paper 75.  
https://digitalcommons.usu.edu/mp_presentations/75
Reduction and Characterization of Error in Low Current Measurements

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Abstract

An apparatus has been developed to measure electron transport at a level low enough that radiation induced conductivity is associated with cosmic ray background radiation is of concern. To accurately measure such low currents, typically \(10^{-12}\) A, it is critical to eliminate noise in key components of the hardware setup. Improvements include highly filtered signals, ground isolation and stability, extensive shielding, vibration isolation, and signal averaging. Careful tracking of the error associated with each component in the system and examination of the limitations of each constituent part, allows for precise monitoring of error propagation as improvements are made to the system. Successful implementation of these techniques has pushed the lower current limit of a 29-year-old Keithley 616 low level electrometer to these extreme limits. These methods have been employed to measure the conductivity of high resistivity polymers commonly used in the construction of spacecraft.

Voltage Error \(\Delta V\)

For the programmable medium voltage supply used (Bertan, Model 230-01R; 1 kV @ 15 mA), the instrumental precision is approximately:

\[
\Delta V = (N_{\text{pp}} - 1)^{-1} \times 250 \text{ mV} 
\]

\(N_{\text{pp}}\) is the number of measurements of the current using the electrometer and DAQ card and is given by:

\[
N_{\text{pp}} = \sum_{i=1}^{N} \left[ \frac{1}{2} \left( \frac{\text{current} \text{ at step } i}{} + \text{ current at step } i+1 \right) \right]
\]

The uncertainties in this equation are a combination of uncertainties from the DAQ card and programmable voltage supply. The uncertainty of the instrumental precision is approximately:

\[
\Delta V = (N_{\text{pp}} - 1)^{-1} \times 250 \text{ mV} 
\]

\(N_{\text{pp}}\) is the number of measurements of the current using the electrometer and DAQ card, which is estimated for this data set to be \(250 \text{ mV} \) or \(0.03\%\) based on \(N_{\text{pp}}\).

Use of a battery source greatly reduces the voltage error. The low voltage battery source constructed of twelve nine-volt Duracell Professional Alkaline batteries in series, produces an applied voltage of approximately 102.5 V (minimal linear drift results from slow drain of the batteries). For the low voltage battery source, the instrumental precision is approximately:

\[
\Delta V = (N_{\text{pp}} - 1)^{-1} \times 16 \text{ mV} 
\]

Voltage versus time plot for an experimental data set for LDPE at 100 V for 96 hr at variable temperature. Measured voltage sets at 20 s intervals are shown as grey dots. The blue curve is the smoothed data derived from a binned averaging algorithm designed for unpredictable data sets. The green lines show the statistical variations for the binned/averaged data at 1 standard deviation of the data sets in each bin. The approximately consistent narrow band in the spread of the grey data points bounded by the red curves of about 255 mV corresponds to the estimated instrumental precision from the medium voltage supply and DAQ card, which is estimated for this data set to be \(250 \text{ mV} \) or \(0.03\%\) based on \(N_{\text{pp}}\). The larger, periodic discrete jumps in the voltage of \(\pm 10 \text{ mV}\) with a period of 24 hr are due to daily changes in the room temperature of \(\pm 5 \text{ ºC}\). The daily heating and cooling cycle for the laboratory has been superimposed on the voltage versus elapsed time plot and juxtaposed to the room temperature versus elapsed time plot as confirmation of the temperature effect.

Complete schematic of the Constant Voltage Chamber (CVC) system used in these experiments. It is necessary to generate a complete schematic of the test system in order to identify all potential errors in the system and verify critical connections. A greatly simplified schematic is shown in the upper right.

Conclusions

The fundamental limit to measurement of current or conductivity is the Johnson noise of the source resistance. For any resistance, thermal energy produces motion of the constituent charged particles, which results in what is termed Johnson or thermal noise. Based on a standard formula for peak to peak Johnson noise current:

\[
M_{\text{pp}} = \frac{4 R_{\text{source}} T_{\text{source}}}{R_{\text{source}}} \text{ppm}
\]

where \(M_{\text{pp}}\) is the signal band width approximated as \(0.3(5T_{\text{source}}-1)\). For the lowest \(10^{-12}\) A range of the Keithley 616 electrometer this \(T_{\text{source}}\) is \(3 \text{ ºC}\) and \(M_{\text{pp}}\) is \(5.12 \text{ Hz}\). For a typical LDPE sample at \(-300 \text{ K}, T_{\text{source}}=10^{-12}\) A with a corresponding \(M_{\text{pp}}=6.10^{-12}\) (ppm). This is \(1\%\) of the ultimate instrument conductivity resolution.

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