Laboratory Experiment # 1
ME 303
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Measurement Noise

An Analysis of Sources of Electrical and Magnetic Noise in Measurement Systems and Various Techniques for Mediation

ABSTRACT

Four noise reduction techniques were evaluated by measuring voltage noise in a test measurement system. The use of a differential oscilloscope input was by far the most effective technique for reducing noise. Shorter leads and tightly twisting (40 TPM) leads reduced some noise; however, shielding increased the noise. The most significant noise component was at 60 Hz and higher integer multiples suggesting most of the noise was the result of the AC mains.

INTRODUCTION

Measurement is the result of a series of conversions between physical domains (Skoog et al., 2006). A transducer converts a physical quantity such as pressure into an electrical quantity such as voltage. The voltage is then carried through a set of leads to a data acquisition unit (DAQ) which converts the electrical quantity into a digital one. Even when the variation in the physical quantity it quite small, significant uncertainty can be introduced in any one of the subsequent conversions leading to uncertainty in the final measurement.

The following report will examine the effects of electromagnetic noise on engineering measurement. In particular, at the point where measurement information is flowing as a voltage signal from the transmitter to the DAQ. Electromagnetic noise is present in all real signals. It consists of random voltage fluctuations that sit atop the signal voltage. When these fluctuations becomes sufficient to obfuscate the intended signal, they are called interference (Ott, 1988).

Noise can become a problem on either end of the measurement scale. In precision measurement, even well isolated measurements are subject to shot noise, a noise inherent to the quantized nature of electrons at extremely small currents (Horowitz and Hill, 2015). In industrial measurement, even strong signals can be obfuscated by the many significant noise sources on an industrial site. These include large power distribution transformers and variable frequency drives (Ellis, 2001).

In AC measurements, noise is typically quantified using the signal–to–noise ratio (SNR). This is reported as a log–scale ratio of either the amplitude, peak–to–peak, or RMS voltage of both the signal and noise components (Equation 1).

$$\frac{S}{N} = 20 \times \log\left(\frac{V_s}{V_n}\right) \tag{1}$$

where: V_s = the magnitude of the signal
V_n = the magnitude of the noise

For DC measurement, the SNR can be modified to use the signal mean and standard deviation (Equation 2).

$$\frac{S}{N} = \frac{\bar{x}}{s_x} \tag{2}$$

where: $\bar{x}$ = sample mean (a.u.)
s_x = sample standard deviation (a.u.)

Many techniques exists for reducing signal noise. While noise cannot be completely eliminated, noise can often be reduced to a point where it no longer causes interference. Typical noise reduction techniques include shielding, grounding, balancing, filtering, isolation, separation, orientation, circuit level impedance control, cable design, and active cancellation (Ott, 1988). The following report will expand upon wire length, shielding, cable design, and cancellation.

The first noise reduction technique is the use of short leads. Any wire of sufficient length acts as an antenna picking up stray electromagnetic noise (Skoog et al., 2006). At low frequencies, power lines and transformers produce noise near 60 Hz. At high frequencies, local AM radio stations produce noise near 100 kHz. Shorter wires reduce the effectiveness of this unintentional antenna and with it the magnitude of the noise.

The second noise reduction technique is the user of shielding. Shielding typically consists of a metallic braid or wire that is wrapped around the sensitive conductors within a cable (Skoog et al., 2006). The shield is often connected to ground (i.e. bonded) at one end. Electromagnetic noise that would normally be absorbed by the signal conductors is instead absorbed by the shield, and drained to ground.

The third noise reduction technique is the use of twisted pairs. While the previous techniques reduce electrical noise, twisting reduces magnetic noise (Ott, 1988). The voltage induced in a loop of wire by a changing magnetic field is given by Equation 3. Twisting both minimizes total loop area and produces loops with alternating orientations (i.e. $\theta + n\pi$) such that the voltage induced in one twist is canceled out by the next.

$$V_m = 2\pi BAf\cos(\theta) \tag{3}$$

where: f = frequency of the magnetic field (Hz)
B = strength of the magnetic field (T)
A = loop area (m^2)
θ = orientation of the magnetic field (rad)

The final noise reduction technique is to use a differential DAQ input. When a wire picks up noise it either raises or lowers the signal voltage in a random way. When a differential input is used this still occurs, but the signal is instead defined as the difference between the signal wire and the ground wire. The interference will usually raise or lower the voltage of the signal wire and the ground equally, preserving the difference between the two leads.

EXPERIMENTAL METHODOLOGY

The accuracy and precision of two lab multimeters (RSR MY64) was compared by reading the output voltage of a lab power supply (BK Precision 9110). One measurement was taken with each multimeter at $400\,\mathrm{mV}$ and again at $700\,\mathrm{mV}$. The reading on the power supply was taken as the known value, and error was defined as the difference between the measured value and the multimeter reading. Accuracy was defined as the average error for the two readings, and precision was defined as the difference in error between the two readings. The stability of the multimeter was determined by taking 20 repeat $400\,\mathrm{mV}$ measurements at $10\,\mathrm{s}$ intervals.

Signal noise was measured by sampling a voltage signal through a set of standardized 3 m leads (20 AWG, 600 V, MTW wire; AutomationDirect Part# MTW20WB). A National Instruments Analog Discovery II all–in–one instrument system (ADII) was used throughout the remaining experiments. The voltage supply on the ADII was set to 400 mV (accuracy $\pm 10\,\mathrm{mV}$, $50\,\mathrm{m\Omega}$ output impedance), and the signal was read through a single–ended input (14-bit, $1\,\mathrm{M\Omega}$ input impedance, accuracy $\pm 100\,\mathrm{mV}$, $3.58\,\mathrm{mV}$ resolution). Samples were collected at $1.63\,\mathrm{kS/s}$ for $5\,\mathrm{s}$ ($n = 8192$). Later, the experiment was repeated using a $1\,\mathrm{m}$ lead with 40 twists–per–meter, a grounded shield, and a differential input.

The samples were plotted on a normalized histogram with the bin width set to an integer multiple of the instrument resolution (5x). A Gaussian normal distribution was fitted to the histogram using sample mean and standard deviation (Equation 4).

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \tag{4}$$

where: μ = population mean
σ = population standard deviation
x = sample value

The normality of the samples was assessed by comparing the number of samples within ± 1, ± 2, and $\pm 3\sigma$ of the mean to that predicted by a normal distribution. A Q–Q plot was later used to evaluated the goodness–of–fit visually (Gibbons and Chakraborti, 2014). Any deviation from the center line on the Q–Q plot would indicate a poor fit. Chauvenet's criterion was used to eliminate outliers in normal

Set (mV)	Meter A (mV)	Meter B (mV)
400	407	406
700	705	705
Average Error (mV)	6.0	5.5
Error Differerence (mV)	2.0	1.0

Table 1: Measurements of a known voltage source with two different multimeters.

samples (Equation 5). A fast Fourier transform (FFT) was used to attempt to identify sources of sinusoidal noise in the sample population.

$$DR_o(n) \geq \frac{|x_i - \mu|}{\sigma} \tag{5}$$

Four common noise reduction techniques evaluated by comparing modified leads to a set of standardized $3\,\mathrm{m}$ leads (20 AWG, $600\,\mathrm{V}$, MTW wire; AutomationDirect Part# MTW20WB). The leads were left unterminated at the end farthest from the ADII. The ADII was set to collect $5\,\mathrm{s}$ of samples at $1.63\,\mathrm{kS/s}$ with $1\,\mathrm{V/div}$. Cable length was evaluated by constructing cables 1, 3, and $5\,\mathrm{m}$ in length. Shielding was tested by applying an single–layer shield of aluminum foil to a 3 m cable. The shield was tested with, and without the foil grounded to the ADII system ground. Wire twisting was tested by twisting the leads in a drill chuck to 7, 15, or 40 twists–per–meter (TPW). Finally, differential versus single–ended input was tested by connecting the ground lead to either system ground, or the oscilloscope channel ground. All samples were plotted on a normalized histogram and a Gaussian normal distribution was fitted using sample mean and standard deviation. Because no power was applied, all samples had a mean near zero, and noise was quantified as the standard deviation of all the samples.

Finally, to test the effectiveness of the noise reduction techniques studied above, Part II was repeated with a $1\,\mathrm{m}$ cable, with 40 twists–per–meter, a grounded foil shield, and on a differential input.

RESULTS AND DISCUSSION

Multimeter B was more accurate than multimeter A with an average error of $6\,\mathrm{mV}$ versus $5.5\,\mathrm{mV}$ (Table 1). Multimeter B was also more precise with a difference of errors of $2\,\mathrm{mV}$ versus $1\,\mathrm{mV}$ (Table 1). When selecting instrumentation for a measurement, a precise instrument is more valuable than an accurate one. The repeatable error in a precise instrument, called bias, can often be removed through calibration. Repeated measurements of the same $400\,\mathrm{mV}$ source with multimeter A revealed that the measurement was stable at $407\,\mathrm{mV}$ with no deviation (i.e. a standard deviation of $0\,\mathrm{mV}$). According to Chauvenet's criterion (Equation 5), no outlier data points were removed.

Throughout the following experiments, a standardized $3\,\mathrm{m}$, unshielded, untwisted

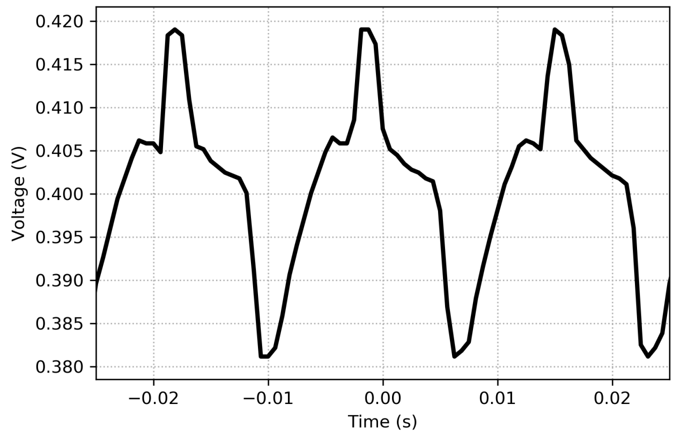

Figure 1: A close–up view of the waveform from the $400\,\mathrm{mV}$ measurement using the standard, unshielded, $3\,\mathrm{m}$ cable. The signal shows a clear sinusoidal component rather than simple, normally distributed noise.

cable was used as a control against which all noise reduction techniques were compared. A reading of $400\,\mathrm{mV}$ source was performed using a single–ended channel of the National Instruments Analog Discovery II data acquisition card. The raw waveform (Figure 1) showed a clear sinusoidal distortion that suggested AC mains noise (Ellis, 2001). A fast Fourier transform (FFT) performed on the signal showed a strong peak at $60\,\mathrm{Hz}$ confirming the source, and several subsequent peaks at integer multiples of $60\,\mathrm{Hz}$ representing higher order harmonics (Figure 2).

When plotted on a histogram, the frequency of sampled voltages differed greatly from that of a Gaussian normal distribution (Figure 3). Bin width was set at 1.28 mV, an even multiple of the resolution of the DAQ ($320\,\mu\mathrm{V}$ at $0.5\,\mathrm{V}/\mathrm{div}$). The number of samples within ± 1, ± 2, and $\pm 3\sigma$ of the mean was compared to the number predicted by a normal distribution (Table 2). A Q–Q plot was created, and deviation from the center–line confirms that the distribution is not normal (Figure 4). A Q–Q plot is essentially an graphical extension of Table 2 except over all quantiles of the dataset (Gibbons and Chakraborti, 2014). Because Chauvenet's criterion (Equation 5) relies on an assumption of normality, the criterion could not be used to remove outliers from this sample.

Measurement noise is the result of both intrinsic and extrinsic sources (Ott, 1988). Typically, noise intrinsic to the measurement appears as a series of normally distributed errors about the measurement mean. Extrinsic noise, however, is AC coupled to the measurement signal and appears as a sinusoid centered about the measurement mean. As is apparent from the raw signal (Figure 1), the major component of the noise is the sinusoidal, extrinsic component. This sinusoidal noise can be modeled as the sum of several sinusoidal components each with their own amplitude, frequency, and phase (Equation 6). When this theoretical model is plotted on a histogram (Figure 5), it maintains the characteristic shape of the raw signal.

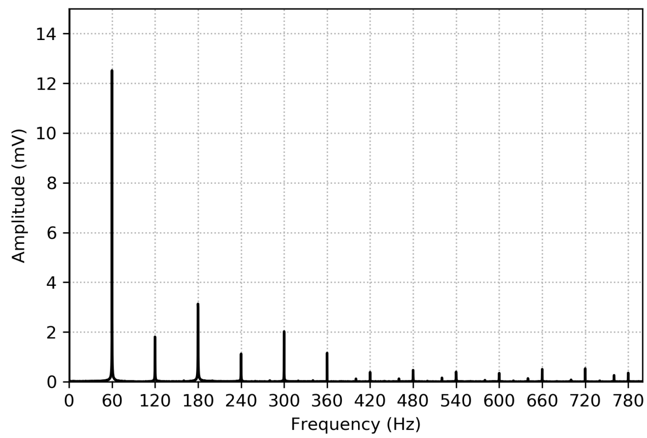

Figure 2: A fast Fourier transform (FFT) of the unshielded, $400\,\mathrm{mV}$ signal shown in Figure 1. The signal shows strong peaks at $60\,\mathrm{Hz}$ and the higher integer multiples indicating AC mains noise and its higher order harmonics are the key noise component.

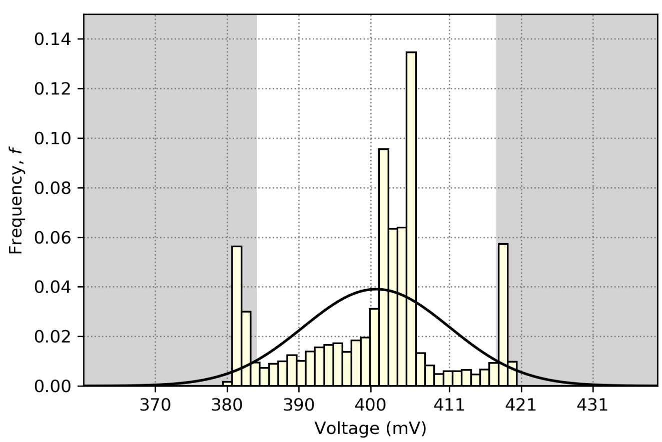

Figure 3: A histogram of the voltage of a $400\,\mathrm{mV}$ DC signal read through a standard $3\,\mathrm{m}$ cable. A normal distribution is fitted to the histogram using the sample mean and standard deviation. Each horizontal grid–line represents one standard deviation from the mean ($400\,\mathrm{mV}$). The non-shaded areas represent the theoretical 90% interval.

	Real	Theoretical	Difference
90%	7460	7373	1.1%
$\pm 1\sigma$	5639	5592	0.8%
$\pm 2\sigma$	8192	7819	4.7%
$\pm 3\sigma$	8192	8169	0.3%
All	8192	8192	0.0%

Table 2: A comparison of the samples observed within so many standard deviations of the mean for the unshielded, $400\,\mathrm{mV}$ measurement as compared to those predicted by a normal distribution.

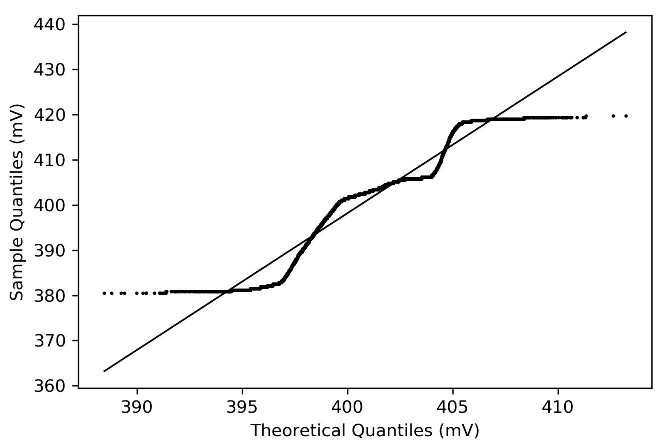

Figure 4: A Q–Q plot used to compare the sample quantiles to the quantiles predicted by a normal distribution. Any deviation from the line represents data that does not approximate a normal distribution. The plotted data set reveals that the sample population has an unusually high number of higher and lower voltages.

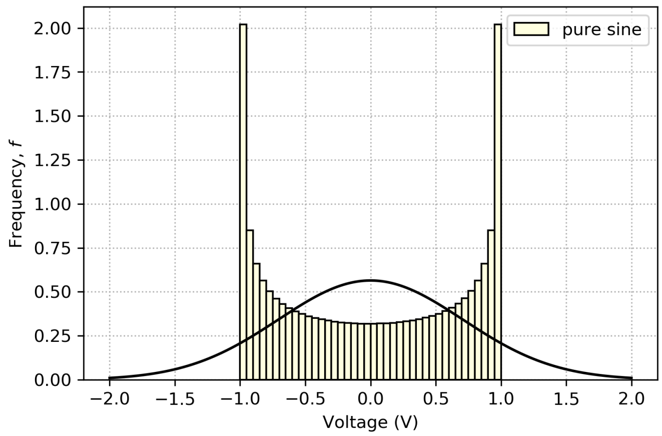

Figure 5: The histogram of a theoretical, pure sine wave with an amplitude of $1\,\mathrm{V}$ and no offset. A normal distribution is fitted to the histogram using the sample mean and standard deviation. As with the raw signal (Figure 1), the voltage extremes are over–represented.

That is, the voltages at the extremes are over–represented in the sample.

$$V = \sum_{i=0}^{n} A_i \sin(\omega_i t + \phi_i) \tag{6}$$

where: A_i = amplitude of noise component
ω_i = frequency of noise component
ϕ_i = phase of noise component

Clearly, even a signal that is known to be fixed such as the $400\,\mathrm{mV}$ signal above does not appear that way by the time it gets to the DAQ. This becomes a problem when the true signal is not known, as is the case with most engineering measurements. The solution is to try to reduce the noise as much as is sensible, and account for any remaining noise in the uncertainty of the measurement.

In order to evaluate the common noise measurement techniques, the signal wire was disconnected from the power supply, and left unterminated. The same 3 m standard cable was used for the following experiments. Cable length significantly affected the quantity of noise present in a signal as measured by the standard deviation (Figure 6). The wire functions as an antenna picking up stray electrical noise in the air (Ott, 1988). As the wire is made longer, it becomes a more effective antenna and picks up more noise. In addition the shape of the noise changed. The noise in the $1\,\mathrm{m}$ cable was nearly normal, whereas the noise in the $3\,\mathrm{m}$ and $5\,\mathrm{m}$ cable began to resemble that of a sinunsoid (Figure 6) vs. Figure 5). This likely represents the shift from intrinsic noise, which is normally distributed, to extrinsic noise, which takes the form of a sinuoid (Ott, 1988).

Shielding introduced additional noise into the signal as compared to control (Figure 7), and grounding the shield at one end only had a small effect on reducing

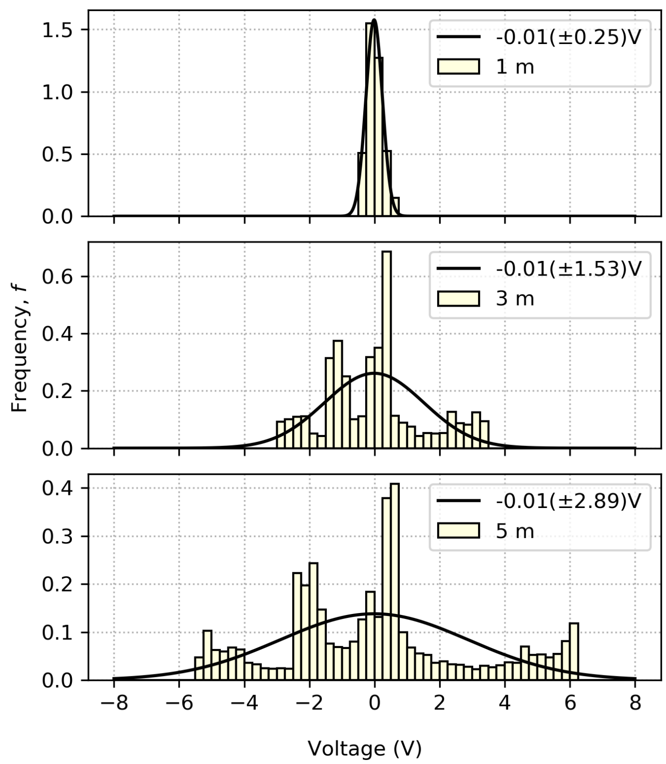

Figure 6: A histogram of the voltage noise in pairs of test leads of various lengths (1, 3, and 5 m). A normal distribution is fitted to the histogram using the sample mean and standard deviation.

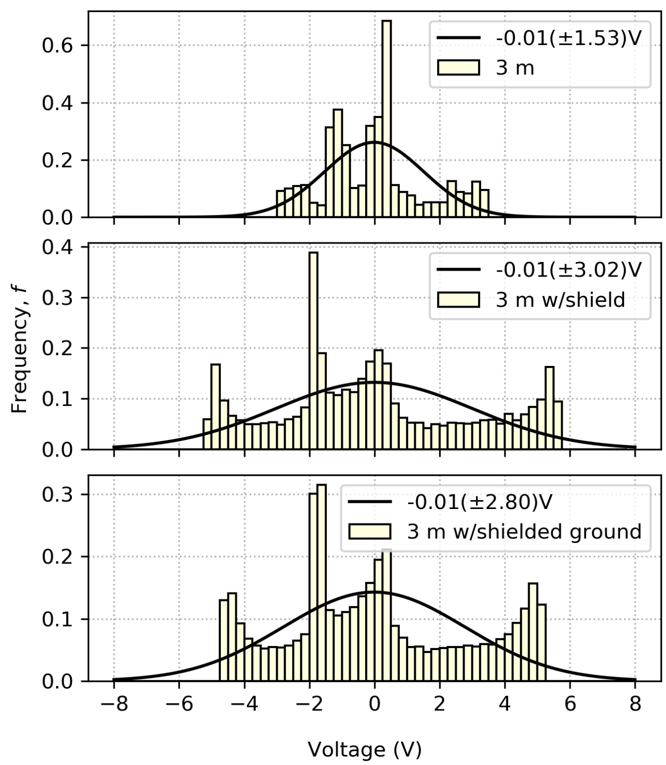

Figure 7: A histogram of the voltage noise in a pair of 3 m leads without shielding, with ungrounded shielding, and with grounded shielding. A normal distribution is fitted to the histogram using the sample mean and standard deviation.

the noise. A similar effect was observed when the signal wire was touched. The additional shielding likely made the wire a more effective antenna causing it to absorb more electromagnetic noise. Shielding *is* a common noise reduction technique in industry; however, the shield used in this experiment may have not been adequate. Industrially, shields typically consist of a continuous foil, braid, or drain wire. Given the construction of the aluminum foil shield used in this experiment, it is very likely that the shield was not continuous down the length of the wire.

Twisting the conductors had a mixed effect on reducing the noise in the signal as compared to control (Figure 8). The loosest twist, 7 twists per meter (TPM), produced a noisier signal, while the tighter twists produced a quieter signal as compared to control. Twisting is a technique that is used to eliminate magnetic noise. The loose twist did not lay flat on the table like the untwisted control did and therefore may have unintentionally had more loop area to pick up magnetic noise.

By far the most effective technique for eliminating noise was using the differential input of the data acquisition card (Figure 9). The differential input allows common

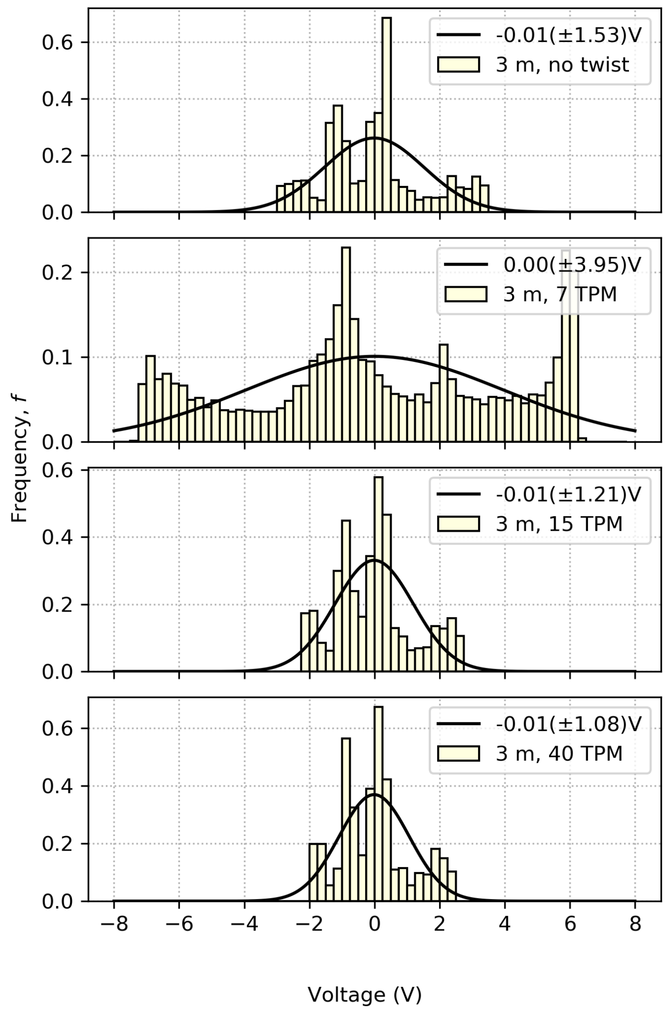

Figure 8: A histogram of the voltage noise in a pair of 3 m leads with no twisting, 7 twists–per–meter (TPM), 15 TPM, and 40 TPM. A normal distribution is fitted to the histogram using the sample mean and standard deviation. Histogram bins were fixed at 25 mV wide.

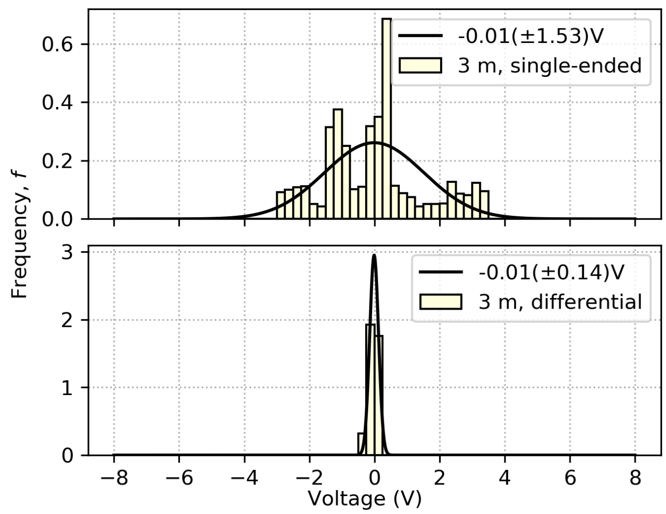

Figure 9: A histogram of the voltage noise in a pair of 3 m leads using both single–ended and differential oscilloscope inputs. A normal distribution is fitted to the histogram using the sample mean and standard deviation. Histogram bins were fixed at 25 mV wide.

mode noise on the ground wire to be rejected. This means that noise that affects both the signal and ground wire equally is blocked out.

In the final experiment a measurement of a 400 mV source was made using the standard 3 m cable and again using all of the noise reduction techniques studied above (Figure 10). Even without noise reduction techniques the lower impedance of the power supply produced a cleaner signal as compared to previous experiment. Regardless, the noise reduction technqique further reduced the noise to below the resolution of the Analog Discovery II.

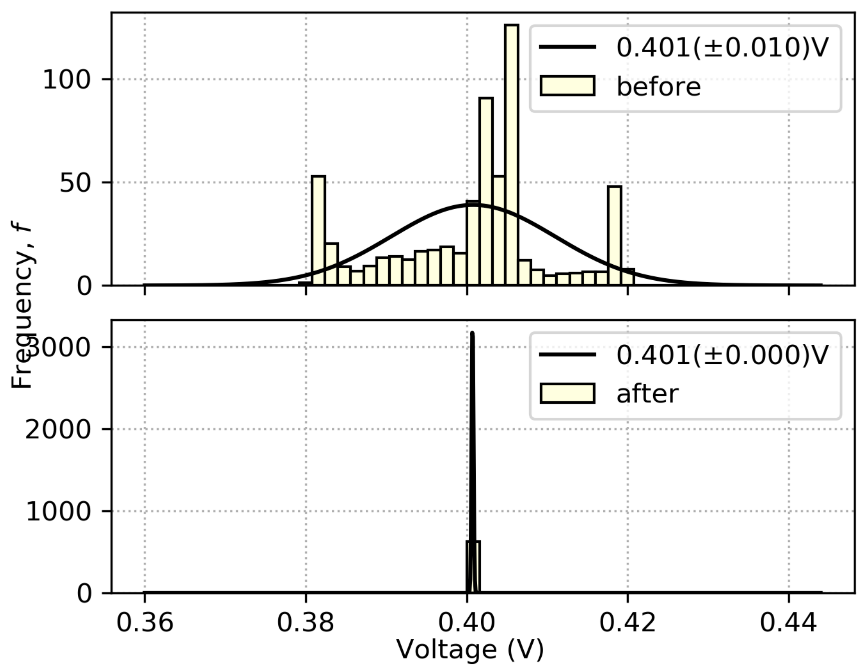

Figure 10: A measurement of a 400 mV know source both before and after noise reduction techniques. The control consisted of a 3 m leads with using a single–ended oscilloscope input. The leads were then reduced to 1 m, twisted to 40 twists–per–meter, shielded with a ground, and read on a differential oscilloscope input. A normal distribution is fitted to the histogram using the sample mean and standard deviation. Histogram bins were fixed at 32 mV wide.

CONCLUSIONS

Short wires, twisting, and differential input decreased the signal noise relative to the 3 m control leads; however, both grounded and ungrounded shielding increased signal noise. The use of a differential input was the most effective noise reduction technique studied reducing the standard deviation of the noise from $\pm 1.53\,\mathrm{V}$ to $\pm 0.14\,\mathrm{V}$. The combined effect of short wires, twisting, shielding, and differential input reduced the noise from $\pm 10\,\mathrm{mV}$ to below the detection limit and the signal–to–noise ratio from 40 to ∞ as compared to control $3\,\mathrm{m}$ leads.

ACKNOWLEDGEMENTS

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APPENDIX A
CALCULATIONS AND CODE

All calculation and plots were performed in Python. A complete, executable code listing along with an electronic copy of this report can be found at `www.github.com/mmolter/ME303/LAB01` withing three days of electronic submission of this report.

APPENDIX B
LOG OF WORK

Below is a log of all hours worked in order to complete this report.

Date	Start	Stop	Hours	Summary of Work
10 SEPT	12 PM	2 PM	2.0	Performed data collection in lab
15 SEPT	2 PM	7 PM	5.0	Repeated experiment with work equipment, different wires, and National Instrument Analog Discovery II.
				Plotted histograms in Python
				Wrote out procedure that was followed.
16 SEPT	12 PM	4 PM	4.0	Reproduced Parts II and IV on Analog Discovery
				Refactored data analysis code in Python
				Tweaked and plotted graphs
				Performed FFT
				Produced histogram of pure sine wave and demonstrated non–normal distribution
				Experimented with box–and–whisker plots
17 SEPT	7 PM	9 PM	2.0	Developed normality testing tools
18 SEPT	12 PM	1 PM	1.0	Worked on writing discussion
18 SEPT	6 PM	9 PM	3.0	Started LaTeXtypesetting
19 SEPT	7 PM	10 PM	3.0	Finished up discussion and submitted
24 SEPT	5 PM	7:30 PM	2.5	Introduction and Methodology.
24 SEPT	9 PM	10 PM	1.0	Rewrote methodology
25 SEPT	12 PM	1 PM	1.0	Fixed some problem with LaTeX
25 SEPT	5 PM	7 PM	2.0	Revised language.
27 SEPT	9 AM	10 AM	2.0	Revised language.
			26.5	Total Hours

Table 3: A log of all hours worked by M. Molter in the completion of this report.