EE431 Lab 2
Experiments with Random Noise
Feb. 10, 2015

For this lab you will use the spreadsheet provided on the class website, http://www.kennethkuhn.com/students/ee431/noise_experiment.xlsx . If you use this file with pre .xlsx versions of Excel you will have to edit the standard deviation computation cells as they do not convert properly to the older forms – change to stddev(…). Non user input cells of the spreadsheet are locked (no password – so you are free to make customizations – but be careful) to prevent accidental corruption. The last part of the lab includes using actual lab equipment to gain hardware experience. The 100 nanosecond time sample used in this lab simulates the operation of the signal generator in lab when set to noise output. This provides you with a way to check your results.

The spreadsheet simulates Gaussian noise by using the simple method of summing 12 uniformly distributed random numbers. That model is not perfect but works very well for students and most applications. The spreadsheet uses 20,000 samples for practical size considerations. That is only 2 milliseconds of time using the 100 ns time sample which is quite short in comparison to time periods that a human would view measured data on instruments. That results in the variance of the measurements being relatively high. To obtain a good representative result, use the median value of fifteen runs for cases where results will vary because of noise. For small sample sizes the median provides a better estimate of the real result than the average.

The spreadsheet has an aid located to the right of the computations for quickly determining the median of your fifteen runs. Start at the top and each time you enter data for the median calculation the spreadsheet will recalculate and you can enter that value on the next row until you have entered 15 values. Be sure to record each of the 15 values in your report.

As an example (your numbers will be different) the first run shows a Vrms/rtHz of 438.3E-6. Enter 438 in the top cell of the median. The spreadsheet recalculates and shows 423.6E-6 and you enter 424 in the next lower cell of the median calculation. The spreadsheet recalculates and shows 419.2E-6. You enter 419 and so on until you have entered 15 values and the number by the Median label is your result when scaled appropriately. Once you have done this the first time you will realize what a time saver this aid is.

For the lab report include plots as noted in the various experiments. It is best to paste the plots as pictures rather than objects. Be sure to label each plot with a brief description that clearly conveys what the plot is showing. An unlabeled plot is meaningless.

Note: computed spreadsheet cells referenced in these instructions have a light orange background to make it easier for you to find them as there are a lot of computational results. All needed spreadsheet user input for each part of the lab is listed in the Setup below each heading. Be sure to enter those values exactly as you see them or your results may have significant error. In various parts you will be asked to compute a certain result and you should

show the computation in your report. In most cases the correct answer is in one of the spreadsheet computational cells (be sure to use the median as necessary) – use that to check your work and learn what you are doing wrong if you initially have errors.

Part 1: Basic measurements with unfiltered noise

Setup: **0** mode, **1.00** Vrms noise, **100E-9** sec. time sample, **5E6** Hz filter, **0** Hz sine wave, **0.0** Vrms sine wave

The noise has a magnitude of 1 Vrms over a 5 MHz noise bandwidth. Compute the spectral density of the noise in Volts/rtHz. Observe and include a copy of the **Waveforms** and **Waveform – zoom** plots. The zoomed plot shows only the first 300 data points which enables you resolve the noise waveform. Press the F9 key a few times to see how the waveform randomly changes.

Looking at the Analysis Noise applied column of the spreadsheet observe that each time the F9 (recalculate) key is pressed that the computed Vrms value (cell F37) of the noise is close to 1.00 volts. The spreadsheet reports the true rms of generated noise over the spreadsheet sample size. Keep in mind that this is a short sample length so the computations won't be perfect. For your report include the individual measured rms values (cell F37) for five runs of the F9 key – no median value for now.

The spreadsheet reports the extreme maximum and minimum values of the noise over the sample size. Those are used to compute the extreme peak-peak noise and then used to compute the extreme ratio of Vpp/Vrms (cell F38). That ratio is typically greater than seven and will exceed eight on some runs of the F9 key. Although the spreadsheet has a theoretical limit of twelve, in reality there is no limit to how high a noise peak could be – although the probability of extreme peaks is extremely low. For your report include the individual Vpp/Vrms values (cell F38) for five runs of the F9 key – no median value for now.

Observe the **Waveforms** plot and note that few noise samples exceed plus or minus 3 volts. That would represent what is known as the main body of the peak-peak voltage and dividing by 6 produces a good estimate of the rms noise voltage – about 1 Vrms – the same as the actual. In viewing the plot you might consider that ~5.5 volts peak-peak to be more representative – the measurement is subjective which is why it is referred to as an estimate. In general we do not attempt to measure noise to extreme accuracy because that takes a long measurement time and is of little improved value compared to a quick quality estimate. For your report visually estimate what you take as the main body of the peak-peak noise on the Waveforms plot included in your report and divide that value by six for your estimate of the rms noise voltage.

Report the spreadsheet calculated noise density voltage (cell F39) and show how it is calculated.

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Part 2: Filtered noise

Setup: **0** mode, **1.00** Vrms noise, **100E-9** sec. time sample, **318E3** Hz filter, **0** Hz sine wave**, 0.0** Vrms sine wave

Note that for this part of the lab that the input noise voltage is 1.00 Vrms over a noise bandwidth of 5 MHz. The noise spectral density is 447 uV per root Hz. This is the input noise voltage to the low-pass filter.

The first filter has an electrical bandwidth of 318 kHz (noise bandwidth of 500 kHz). Calculate the expected rms noise voltage out of the filter and compare that with the spreadsheet measured value in cell C37 using the median of 15 runs. Note the measured Vrms/rtHz value in cell C39 – just pick one representative value – no median. Observe and show the **Waveforms** plot in your report. The larger amplitude signal is the unfiltered input noise and the lower amplitude signal is the filtered noise.

Repeat the above for electrical bandwidths of 31.8 kHz and 3.18 kHz. Did the measured value for the filtered Vrms/rtHz remain essentially constant for each of the three filters?   The answer should be yes – and the computed noise density of the filtered signal might be somewhat higher or lower than the noise density of the raw noise – a consequence of the finite data set. Because of the short data length the results will have significant variance, particularly for the 3.18 kHz filter. Note that the noise voltage is reduced by a factor of 3.16 (square root of 10) or 10 dB each time the filter bandwidth is reduced by a factor of 10. Although the noise voltage is being reduced as the bandwidth is narrowed the noise spectral density remains the same. This means that filtering is not a substitute for design processes to minimize the noise spectral density.

Note: because of the finite data set length the measured value for the filtered Vrms/rtHz becomes inaccurate (and the variance of the results increases) for filter bandwidths less than around 2.5 kHz for the time sample used. Try a bandwidth of 100 Hz and the error will be very visible – the filtered Vrms/rtHz is much lower than true. Be aware that all simulations have limitations. Take care not to jump to wrong conclusions because of some indication in a simulator. Simulations are only a tool or aid to understanding. Only the true math describes reality. Simulators are not a substitute for math.

Part 3: Signal to Noise ratio

Setup: **0** mode, **1.00** Vrms noise, **100E-9** sec. time sample, **5E6** Hz filter, **5,000** Hz sine wave**, 0.2** Vrms sine wave

For this part of the lab you will observe the effect of varying the amplitude of a sine wave signal relative to a wideband noise level. The ratio of the rms signal voltage to the rms noise voltage is known as the signal/noise ratio (abbreviated S/N). The equipment you will be using to look at the signal and noise is your eye – which has some very sophisticated signal processing abilities difficult to replicate in electronics – that allows you to "see" signals of lower magnitude than

the noise. Show **Filtered** plots in your report for the following sine wave amplitudes: 0.2, 0.4, 0.6, 1, 3, 10, and 30 Vrms. It is a lot of plots but the collection paints a good picture of the concept of signal to noise. Because the noise voltage is 1.0 Vrms then these sine signal voltages also represent the signal/noise ratio – label each plot with the S/N value.

For the 0.2 S/N it will be a challenge to detect that the signal is present – press the F9 key a couple of times – you might barely make out a pattern or not. For the 0.4 S/N signal you will see a weak pattern. As the S/N is made larger the sine wave signal will become more prominent.

Note that a S/N of 100 is considered to be poor for audio systems. A S/N of 1000 is considered to be minimally acceptable in audio applications. Good audio systems have a S/N well over 10,000 and perhaps in the 100,000 range. In many signal processing systems the result is not considered valid if the S/N is less than 3.

Part 4: Optimum filtering

Setup: **0** mode, **1.00** Vrms noise, **100E-9** sec. time sample, **1E6** Hz filter, **5,000** Hz sine wave, **0.2** Vrms sine wave

It is obvious that using a low-pass filter will reduce noise. We could practically eliminate noise by utilizing a low-pass filter with a tiny fraction of a Hz of bandwidth but that also eliminates our signal too – no good. Our desired signal must pass through the filter. The critical question that engineers should ask anytime there is some kind of trade-off situation is, "Is there an optimum value?" The answer is almost always yes and it is the job of engineers to determine and utilize that optimum.

The spreadsheet calculates the magnitude response of the filter to the sine wave in cell F40 and the output of the filter to the applied noise in cell F41. The ratio of cells F40/F41 is the signal to noise ratio and is shown in cell C40. These are all pure calculated values that do not depend on the limited size of the random numbers in the spreadsheet so no multiple applications of the re-calculate function (F9) are needed – the result will always be the same.

For all of this part of the experiment the sine wave frequency remains at 5,000 Hz and the amplitude remains at 0.2 Vrms. Only the bandwidth of the low-pass filter is changed.

Start with a low-pass filter bandwidth of 1 MHz and record the following data: Vrms filtered sine, Vrms filtered noise, and Signal/noise ratio. Then repeat for a low-pass filter bandwidth of 100,000 50,000, 20,000, 15,000, 10,000, 6,000, 5,000, 4000, 2000, 1000, 300, 100, 30, and 10 Hz. Show this data as a table in your report and identify the filter cutoff frequency where the signal/noise ratio is highest – i.e. optimum. Note that the lower cutoff frequencies are below what the short segment of data can accurately plot – however, the signal/noise calculation is valid because it does not depend on the data length.   Observe the **Filtered** plot for each of these and see how the noise is reduced down to a point and then the signal reduces more than

the noise as bandwidth is further lowered. For brevity in the report only show the **Filtered** plots for filter cutoff frequencies of 100,000, 5,000 and 2,000 Hz. There should be some discussion in your report to show that you understand the improvement that filtering can make and the results of over-filtering.

It is one thing to hack around with a simulator such as the noise spreadsheet for the lab. Real engineering is to use math to prove a result for all situations. Derive the math to prove your lab result of optimum filter frequency in general. Understand and apply the math that computes the output magnitude of the sine wave from the filter. Understand and apply the math that tells us the rms value of the noise voltage from a given filter. Then compute the ratio and normalize such that only the ratio of the sine wave frequency to the filter cutoff frequency is used. Do that and you will have the proof of the general result. This is a simple algebra problem. There are a number of opportunities for errors and you might have to think a bit about the normalization such that all references to any specific frequency vanishes and only a ratio remains. Discuss that the optimum filter will attenuate the desired signal a bit but that the signal/noise ratio is improved – a good trade-off because the filtered signal can always be amplified back to the desired level.

Note that the above case is very simplistic using a single sinusoid. Real signals are typically complex waveforms and the determination of the optimum filter involves some kind of acceptable tradeoff between fidelity of the desired signal and the amount of noise that can be tolerated. That is a complex process with no unique answer. But the solution comes from understanding the simplistic case in lab.

Part 5: Lab experiment

Go to lab and build the circuit shown in Figure 1 with R = 2K and C = 0.01 uF. Compute the electrical bandwidth of the filter and the noise bandwidth. Using the spectral noise density of your signal generator and the noise bandwidth of the filter, compute the expected rms voltage out of the filter. Measure the rms of the filtered noise voltage using your DVM and compare with your calculation (your calculation and measurement should be around 50 mVrms). If you are off anywhere near a factor of two then most likely you have not properly setup the signal generator – fix whatever is wrong.

Signal generator setup: Set the signal generator to put out 1.00 Vrms noise (this is over a 5 MHz noise bandwidth) open circuited with a source resistance of 50 ohms. Compute the noise spectral density in Vrms/rtHz.

Multimeter (DVM) setup: Set the DVM to measure AC rms and use maximum bandwidth.

Oscilloscope setup: Do not use any kind of auto-set function as that function is not capable of properly configuring the scope for this experiment. Manually set the vertical scale of channel 1 to 50 millivolts per major division and adjust the zero control so that zero volts is on the

centerline, and set the horizontal time base to 200 microseconds per major division. Disable averaging. Set the trigger source to channel 1, trigger level to 0 volts, and no delays. Adjust the trigger controls as needed to obtain continuous sweeps showing the noise waveform when the scope is connected to your filter. All you need to be able to do is make measurements on the main body of the noise as each sweep will have different random data – there are no other waveform details to observe. A screen shot will enable you to observe an individual sweep.

Observe the filtered noise voltage on an oscilloscope and make your best determination of the main body of the peak-peak voltage looking at a continuous display, not a screen capture as that data set is too short for a good measurement (you should manually measure something around 300 mVpp for the main body – the scope reports the extreme peak-peak which is not what we want for this). Report your manually measured value and divide by six to obtain an estimate for the rms noise voltage. That voltage should be similar to the voltage measured on the DVM – don't worry if it is not exact as this is an estimate – but it should be reasonably close. Correct whatever is wrong if not – be sure to check that averaging is disabled if the amplitude is much lower than expected. Show a screen shot of the scope waveform in your report.

Simulate the lab using the spreadsheet and include the **Filtered** plot. You should be able to figure out the necessary settings. The median (15 runs) of the filtered signal in cell C37 should be similar to the measurement on your DVM. The **Filtered** plot and your scope screen shot should be similar in amplitude and character – obviously the waveforms will be randomly different but should have some similarities.
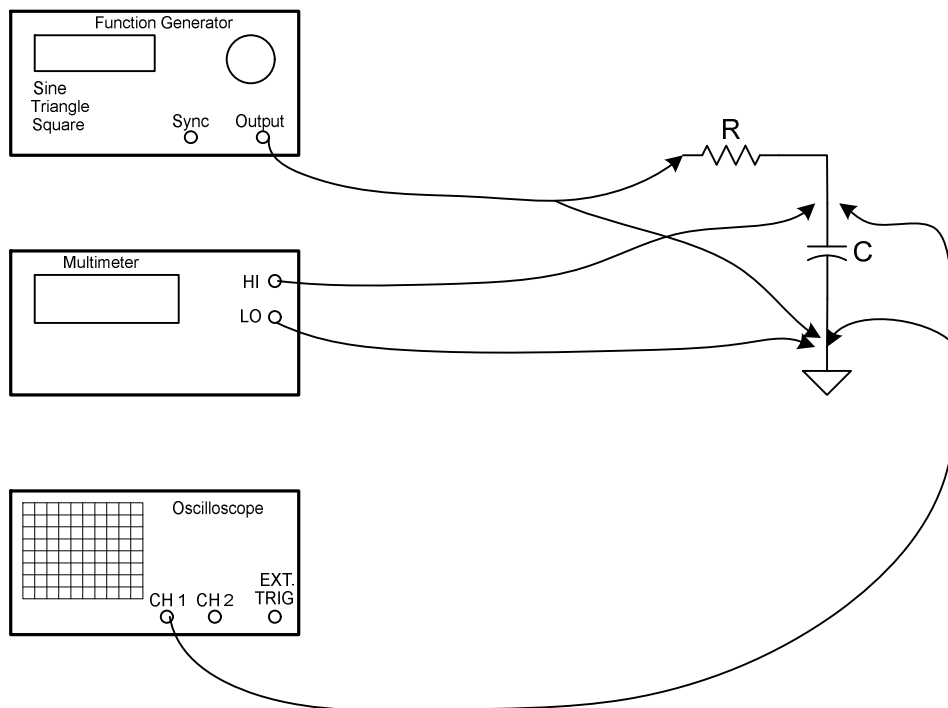

Figure 1: Lab equipment setup