Experiment 19:Small Signal Measurement

From PhysicsLab

Introduction

The success of many physics experiments hinges on the ability to measure small signals. Most experiments today use electronics to convert signals into voltages, which are then recorded. Often, the amount of power going into a measurement must be very low in order not to alter the result by overheating, damaging, or otherwise distorting the specimen. The “smallness” of a signal can arise because of intrinsic smallness of the physical change, or from trying to measure a change in a very small specimen, or because one is trying to measure in a challenging environment where access to the sample is restricted.

The Faraday Effect in SF-59 glass, encountered in the previous experiment, gives a concrete example of a small signal for the purposes of this lab. Many materials have even smaller Verdet constants than this glass. A table of selected Verdet constants is available in the CRC Handbook of Chemistry and Physics (also online at [1] (http://www.hbcpnetbase.com/articles/12_24_88.pdf)). In addition, it is often of interest to measure the Faraday effect in structures which are much smaller than the glass rod used previously – which becomes challenging since the measured polarization change was proportional to the length of the sample.

Object

Continue the examination of the Faraday Effect using the AC technique from the previous lab, with an improved method of signal detection to allow even smaller optical polarization changes to be observed.

Measure the Faraday signal for a liquid having a small Verdet constant, such as methanol.

Procedure

AC amplitude measurement, method 1.

The end of the Faraday lab is the jumping-off point for this experiment. First, reconnect the apparatus to reproduce the AC Faraday Effect measurement for glass done previously. Observe the AC Faraday signal on the oscilloscope and record its amplitude using the digital voltmeter set to measure AC volts.

For the measurement of AC voltage above, the digital voltmeter passes its input through a high-pass filter to remove DC, and then rectifies the remaining signal to determine an amplitude, by time-averaging the rectified signal over some interval using a low-pass filter. There are several drawbacks to using such a meter: the user does not have control over the high-pass filter frequency setting; the user does not control the time constant of the low-pass filter for integration; and the minimum voltage resolvable by the meter is not very small (here, 0.1 mV).

The steps beyond this are to use the modules on the right hand side of the TeachSpin front panel, to measure the AC amplitude in a more controlled way.

AC amplitude measurement, method 2.

Use the “Detector” module to rectify the AC signal. For the first step, the switch in the lower right corner of the module should be set at the “Amplitude Detector” position. Connect the output of the bandpass filter to the input of the detector module. The output of the detector can now be inspected with the oscilloscope. It should look like a rectified sine wave. There is amplification in this module, which can be set to gain values between 2X and 2000X . (Keep the maximum output voltage below about 2V, however, to ensure the signal does not become distorted.) Record your observation in your notebook.

In order to record a DC voltage proportional to the amplitude of the signal, the output from the detector can now be connected to the Low-Pass Filter-Amplifier (LPFA), that will integrate over many cycles of the rectified waveform. Adjust the time constant of the filter, and describe how your observations change. Additional gain can be introduced with the LPFA, if needed.

At this juncture, the main shortcoming of the measurement is the fact that any unwanted noise making it through the bandpass filter also gets rectified by the detector, and can contribute random and systematic error to the measurement. There is one additional step we can take to improve upon this.

From a conceptual viewpoint, if our filtering scheme only uses our knowledge of the frequency of the signal, and does not also take advantage of the fact that having a reference waveform allows us to measure the phase of the signal relative to the reference, then we are essentially throwing away information, and missing an opportunity for greater signal to noise. This was a very fundamental insight made by R.H. Dicke in the 1940s. “Phase sensitive” measurements of many kinds have been introduced, and steadily grown in importance, ever since.

“Lock-in” detection uses phase information to eliminate much of the remaining noise getting past the bandpass filter. Imagine multiplying one sine wave by another, having the same frequency and phase. The product contains a DC value, proportional to the amplitude of each component wave. Multiplying one pure sine wave by just about anything else, however, will lead to a result with a time-average of zero. (Note that this includes multiplying the sine wave by a cosine wave at the same frequency, that is, by the same wave phase shifted by 90"). The lock-in detector in effect multiplies the signal by a reference waveform of a specific phase, creating what amounts to a “super bandpass filter”.

Any source of signal interference (noise) which is not “coherent” with the reference, that is, which has a phase which varies randomly compared to the phase of the reference wave, will in principle average to zero over time.

AC amplitude measurement, method 3.

For lock-in detection you must switch the detector module over to lock-in mode (lower right toggle switch), and supply a reference waveform to the reference input. The reference wave comes from the right-hand output of the Reference Oscillator, but must first pass through the Phase Shifter to make its phase adjustable, relative to that of the signal. See Figure 1 for the typical connections at this juncture.

First, inspect the output of the lock-in detector on the oscilloscope, for a case where the signal to noise is good. When the phase shifter is adjusted to the desired setting, the output should be very similar to that from the Amplitude Detector case. It might have the opposite polarity, but this can be reversed by changing the phase shift by 180° .

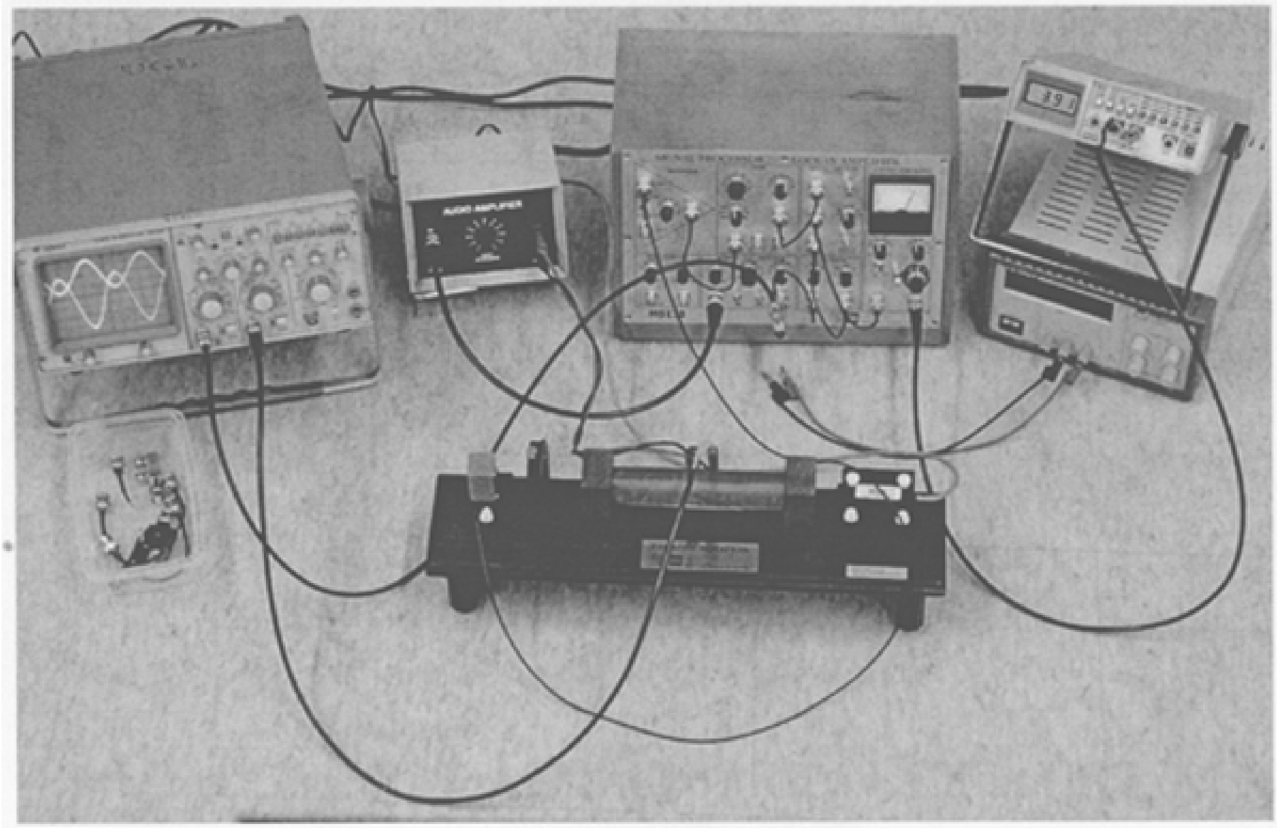

Figure 1. Configuration for measurement of the AC Faraday signal using the lock-in detector. Channel 1 of the oscilloscope is teed to the reference output of the lock-in, and is used to trigger the scope. Channel 2 is monitoring the AC voltage across the solenoid. The other connection from the "BNC tee" on the reference oscillator goes through the phase shifter and then into the reference input of the lock-in detector. The phase is adjusted for maximum response (corresponding to the reference "in-phase" with the signal). The output of the detector goes to the low-pass filter amplifier, from which the reading can then be made using the analog panel meter or by connecting to the Fluke meter set to read DC volts. [Note: the BNC adapteris shaped like an "F" here, but these adapters are usually "T" shaped, hence the name.]

The AC lock-in detection method allows one to detect extremely small Faraday rotations, and thus small Verdet constants, or to make the observations using small magnetic fields. Using the attenuator dial of the Audio Amplfier, reduce the amplitude of the AC excitation to the point where the signal is comparable to the noise ("signal to noise ratio" of approximately 1). From this, determine the corresponding mimimum value of polarization rotation that you are able to detect. Express the answer in microradians.

For use in the analysis, you should also calibrate the overall gain of the lockin by applying a known (amplitude measurable on the oscilloscope), small signal at the input, and measuring the resulting output signal (amplitude, voltage). Such a signal can be taken directly from the Reference Oscillator controllable amplitude output. The divide by 100 switch of the reference oscillator must also be used to reduce the amplitude to a small enough level.

Various liquids exhibit the Faraday effect and their constants can be measured with this apparatus. A glass cell with flat optical ends and a filling tube at one end will hold an appropriate liquid sample. Make required measurements in order to determine the Verdet constant for a liquid of your choice (check with the TA for suitability and availability). Do you have enough sensitivity to distinguish between the Verdet constants of different liquids, such as methanol and water?

Note that with the fluid cell, unlike the glass rod, the sample is not all in a region of approximately constant magnetic field; part of the sample is even outside the solenoid. This requires an additional analysis step in the determination of the Verdet constant, which also requires a measurement of the axial magnetic field profile.

<u>Questions</u>

1. Explain why you must become increasingly careful about the filter frequency setting as you go to higher *Q*.
2. Develop a data analysis algorithm for extracting *V* from the liquid cell measurements. Note that the Faraday effect is a linear function of the magnetic field.

Appendix A

A short tour of the modules of the TeachSpin Signal Processor / Lock-in Amplifier

Reference Oscillator. This module has two outputs and no external inputs. The two outputs have the same frequency (the frequency is variable, see switch and dial which together control it), and different amplitude.

The left output has a controllable amplitude. You can adjust the amplitude with the dial, and also attenuate it by a factor of 100 using the "÷100" switch. You can also change the left output waveform from sinusoidal to square, if necessary.

The right output has a fixed amplitude. This output is used to create the “reference wave” for the lock-in detector. When using an oscilloscope to monitor signals in conjunction with the lock-in instrument, it is helpful to use a BNC coaxial connector adapter (provided) which allows two output connections to be made to the fixed amplitude output terminal of the Reference Oscillator, instead of just one. The additional output can be connected to Channel 2 of the oscilloscope. Triggering the oscilloscope on this Channel 2 waveform will keep the phase of the waveform stable on the screen and let you more easily inspect low amplitude signals using Channel 1.

Preamplifier. This module has differential inputs, and one output which is the difference between the two inputs, multiplied by the gain. You will just use one input. The three position switches dictate whether a particular input is DC coupled (meaning it amplifies DC as well as AC signals), AC coupled only, or grounded (GND, meaning the input is tied to “zero”).

[Aside: why is it called a “pre” amplifier? It is usually best to introduce signal amplification through a chain of amplifier stages, rather than all at once. Any amplifier inevitably contributes some extra noise, in addition to amplifying the input signal and input noise. The first stage amplifier is the most crucial link in the chain, and is traditionally referred to as a preamplifier. It can be selected for characteristics that will minimize the amplifier contribution to overall system noise.]

Filter. This module has one input and three outputs. The bandpass output is most useful to us here. The behaviour of the bandpass filter is controlled by the numbered settings on the switch labeled “*Q*”. “*Q*” refers to the quality-factor of the filter, which is approximately the ratio of the frequency at the *peak* of transmission through the filter, to the full-width at half-maximum *range* of frequencies transmitted by the filter. As *Q* becomes larger, the filter characteristic becomes sharper, and a narrower range of frequencies passes through the filter. The peak frequency set point is determined by the Frequency Range switch and the Freq. Fine dial in combination. Tune the Filter frequency relative to the signal frequency (which is set by the Reference Oscillator) and note what happens.

Lock-in / Amplitude Detector.

There is just one output here, what comes out of it is determined by the position of switch to toggle between lock-in detector and amplitude detector. The amplitude detector is a rectifier, a simple way to determine the strength of an AC signal (and still very useful in many circumstances) but with the disadvantage that it also rectifies AC noise. The lock-in detector requires the reference input to be connected to the output of the phase shifter.

Conceptually, the different modules can be grouped into three separate categories: sources, signal conditioners, and detectors.

The Reference Oscillator (left output) is the origin of the modulation applied to the experiment to generate the signal of interest. The Reference Oscillator and Phase Shifter together are your "reference source" (needed by the instrument for the lock-in detector only).

The Preamplifier and Filter are for "signal conditioning". You can increase the amplitude of very small signals with the preamplifier, and you can selectively remove noise with the filter.

Phase Shifter. The phase shifter allows you to control the relative phase of the signal and the reference wave at the lock-in detector. You may notice that the phase shifter output amplitude varies somewhat with the fine phase setting, as well as with frequency. This is the nature of the analog circuit for the phase shifter, and does not impair performance of the lock-in.

When the signal is in phase with the reference, the lock-in detector output will look very similar to the amplitude detector output (provided the signal amplitude is not too small), for example:

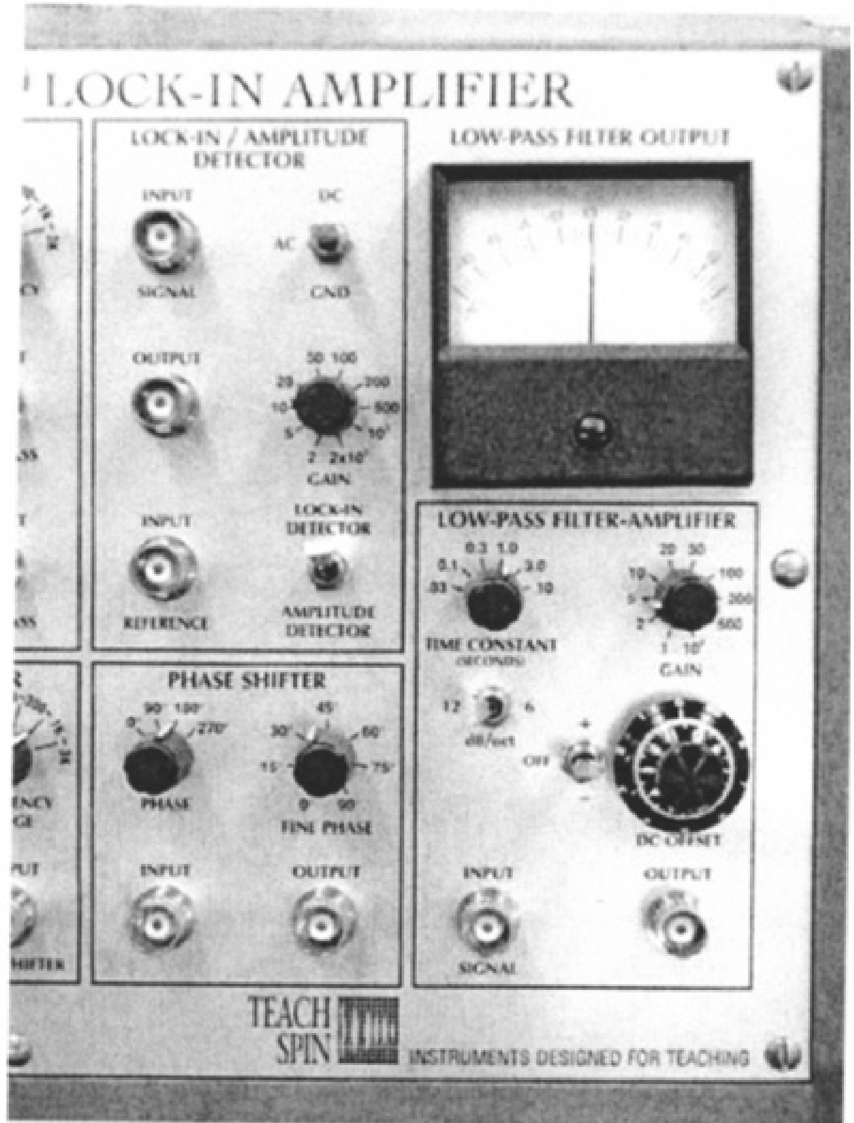

Figure A1: A photo of the right half of the TeachSpin SP-LIA front panel.

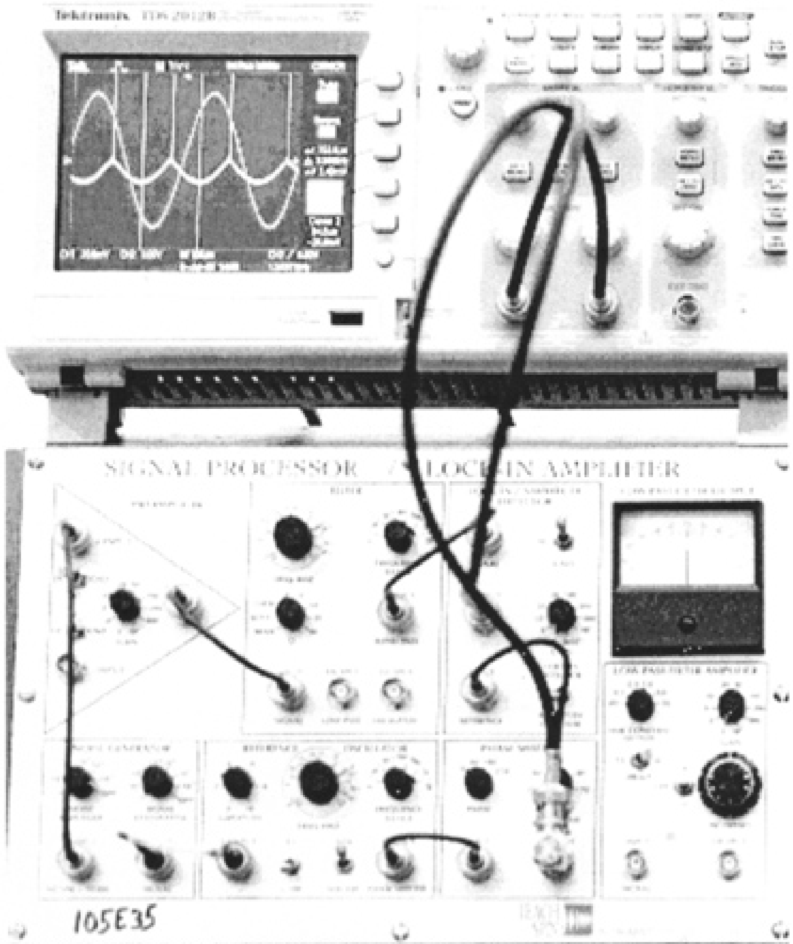

Figure A2: An illustration of how the detector output appears on an oscilloscope (provided the signal is much larger than the noise). The yellow trace is the amplitude detector output, and the blue trace is the waveform from the reference oscillator (which here happens to be taken from the output of the phase shifter, using the output-splitting BNC adapter). The two oscilloscope channels are set for very different vertical sensitivities: 1.0 V/div for channel 2 (the reference), and 20.0 mV/div for channel 1 (the detector output). The scope trace is triggered from channel 2.

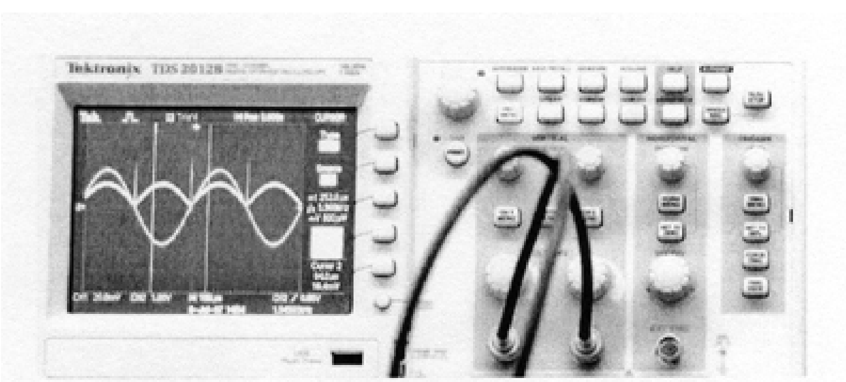

Figure A3

The time-average of the output will yield a voltage proportional to the amplitude of the signal.

When the reference is 90 degrees out of phase with the signal, the lock-in detector output will be something like this:

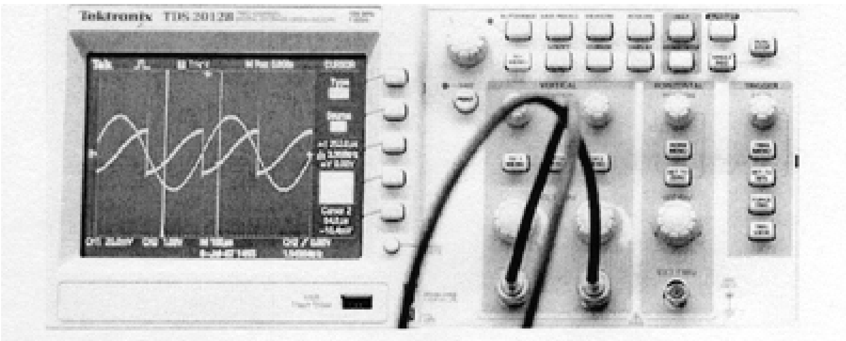

Figure A4

The time-average of this output will be nearly zero (expected, for the out of phase component).It is important to realize that if you are measuring an unknown signal, performing two measurements, the first at an arbitrary initial reference phase, the second with the reference phase 90 degrees from that value, is always sufficient to determine both the magnitude (absolute value of the amplitude) of the signal, and its phase relative to the reference. For an arbitrary setting of the reference phase, the lock-in detector output will probably look something like this:

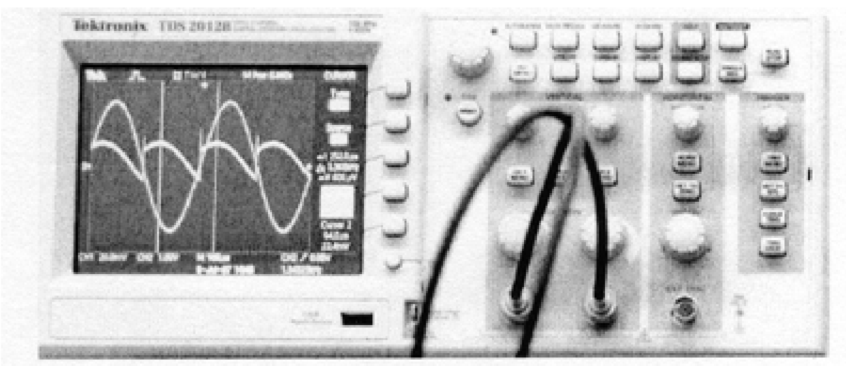

Figure A5

Low-Pass Filter-Amplifier (LPFA). Finally you are ready to obtain a “DC” voltage that will correspond to your signal amplitude. The LPFA integrates the detector output with a selectable long time constant, typically a fraction of a second. You can add additional gain at this stage also if necessary. The 6 or 12 dB/octave switch determines the steepness of the low-pass filter attenuation with increasing frequency. 6 dB/oct cuts the amplitude in half for every factor of two increase in frequency above the rolloff. This is the characteristic of a standard RC filter. 12 dB/oct is the sharpest rolloff you can obtain with analog electronics.

The output of the LPFA is measured with a meter (either a digital voltmeter connected to the BNC output or, if the signal is large enough after multiple gain stages, the analog meter on the front panel).

Appendix B

Signals and Noise

The notion of “small signal” might at first seem arbitrary – can’t we simply use amplifiers to turn small signal into big ones, and then measure them? In practice there are always unavoidable sources of noise competing for attention, attempting to swamp out small signals. The real gauge of the sensitivity of a measurement comes from the signal-to-noise ratio, or SNR. Raw amplification will not increase SNR if the noise is amplified as much as the signal; in fact, amplifiers always add some noise of their own, and care must be taken to ensure that this contribution is negligible, when possible.

The noise on an electrical signal may have many origins. It can arise from fluctuations associated with thermal energy (known as “Johnson noise” in the case of electrical signals); from the fact that the signal being detected comes from discrete entities, electrons, and not a continuum (known as “shot noise”; the same is also true of photons.) Because noise is random, the time-honoured manner for increasing SNR is “averaging” – if you integrate over time, the signal accumulates faster than the noise because of partial self-cancellation in the integrated noise. Usually multiple sources of noise are present, and they add in quadrature if they are independent and random, just as in our considerations of error analysis. Likewise there can be systematic sources of small signal measurement error, one form of which is “crosstalk” that can cause a non-zero “background” level and might be mistaken for the actual signal of interest if the experimentalist does not perform enough checks.

Arguably the most insidious form of noise is “$1 / f$” noise (sometimes also called flicker noise), which has the characteristic that it becomes larger at lower frequencies. Broad classes of fluctuations behave in such a manner that the amplitude of the changes become larger in proportion to the time scale over which you measure. All of the possible origins of this so-called $1 / f$ noise have not been determined, but it is a ubiquitous occurrence. Sometimes it is associated with the experimental apparatus, sometimes with the sample itself; and the frequency scale over which this noise is important varies a lot from case to case. When $1 / f$ noise is dominant, integrating for a longer time does not improve SNR and the averaging strategy is kiboshed.

$1 / f$ noise in particular can mean that trying to measure small signals as “DC” voltagescan be a very poor strategy. An excellent alternative is to somehow modulate the signal at a frequency where the $1 / f$ noise is relatively unimportant, and perform an “AC” measurement. Robert Dicke realized at MIT in the mid-1940’s that the very best way to measure an AC signal was not just to record its amplitude, but also to measure its phase – the latter being possible if you use a “reference” AC signal to keep track of the phase. The lock-in amplifier was born, transforming small signal measurement forever.

One natural question is, how small can these signals become, before you can’t measure their amplitudes reliably anymore? For a 1V signal, you can resolve the amplitude to perhaps 1 part in 1000 using just the oscilloscope. A 1mV signal is more challenging – you might still see it clearly using the “averaging” mode of the oscilloscope, but the amplitude uncertainty is probably of order 10%. But what if the signal is only $1\mu V$ or $1nV$ in amplitude? The lock-in amplifier makes such measurements straightforward for AC signals. The lock-in is also adept at extracting AC signals from within a noisy background, of great utility independent of the absolute signal magnitude.

References

1. R.H. Dicke, “The Measurement of Thermal Radiation at Microwave Frequencies”, Review of Scientific Instruments 17, 268 (1946). First application of lock-in detection.
2. Horowitz P. and Hill W. 1989 "The Art of Electronics", Second Edition, Cambridge Univ. Press Description of various types of signal processors, as well as a good discussion of noise.
3. Moore, J.H., Davis, C.C., Coplan, M.A. 1989 "Building Scientific Apparatus" Second Edition, Addison - Wesley