Lock-in Amplifier Exercise for Spectropolarimetry

T.V. Chavez, S.F. Schrubbe, Q. Rice and W.D. Brandon

The University of North Carolina at Pembroke

Abstract

Occasionally a scientist is faced with the dilemma of measuring very low voltage signals of the order of a microvolt, or even nanovolts. Naively, one might assume such signals can be amplified using a traditional chain of operational amplifiers. However, the result of doing so might amount to a waste of time. Why? – NOISE. When the signal of interest is amplified, so is the accompanying noise. Essentially one will not be able to distinguish the signal of interest from the background noise. In this type of situation, one solution is to employ a measurement technique referred to as phase sensitive detection (PSD) with a lock-in amplifier (LIA). Here is a brief outline of the theory, as well as a very straight-forward exercise involving several instruments found in a typical electronics laboratory, in addition to an optical chopper and a lock-in amplifier, to elucidate the power of phase sensitive detection.

Basic Theory

Signals and Noise

Frequency dependence of noise

- Low frequency ~ $1/f$ noise ("pink noise")
  - Examples: temperature (0.1 Hz)
  - pressure (1 Hz)
  - acoustics (10 -- 100 Hz)
- High frequency ~ constant = white noise
  - Examples: shot noise
  - Johnson noise
  - spontaneous emission noise

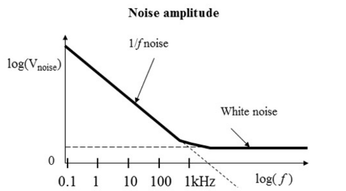
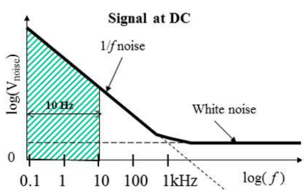
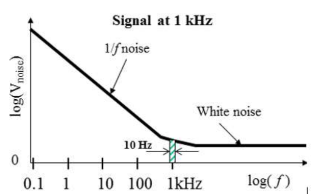


Fig. 1a) Noise depends on signal frequency, f. Note that the noise is worst at DC (pink noise), but better at high f (white noise). Most signals are DC – this is a problem!

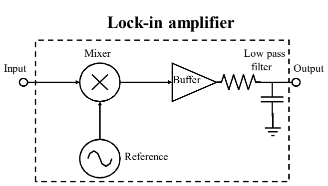




In these figures a 10Hz bandwidth of noise is compared at DC (1b, left figure) and 1 kHz (1c, right figure). It is evident that high frequency measurements contain much less noise than their low frequency counterparts.

LIA 1 : Phase Sensitive Detection

- Signal frequency should match reference frequency
- Reference = $\sin(2\pi ft)$ and Signal = $\sin(2\pi ft + \phi)$
- ϕ is signal phase shift
- Mixer (or multiplier): Product ~ $\cos(\phi)$ - $\cos(2\pi ft)$ "DC part"
- Low pass filter integrates out modulated noise



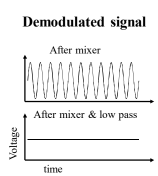
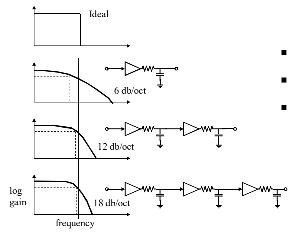


Fig. 2a) (left) is the basic schematic of the apparatus. Fig 2b) (right) shows the effect of a low pass filter

Basic Theory (continued)

LIA 2: Low Pass Filters (more)



- For weak signal buried in noise
- Ideal low pass filter blocks all except signal
- A real filter uses cascaded low pass filters as shown in the figure to the left.

Figure 3) Comparing the effectiveness of different low pass filter arrangements

Experimental Demonstration

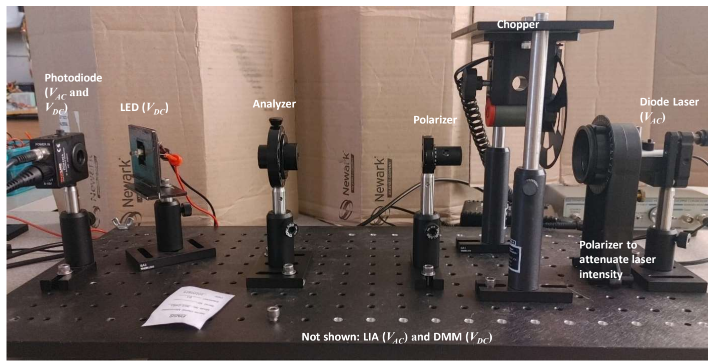
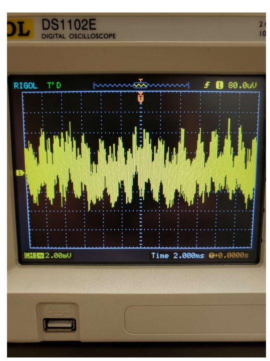
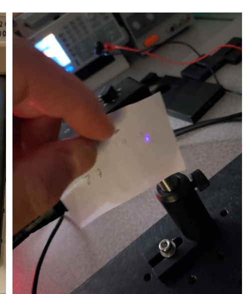
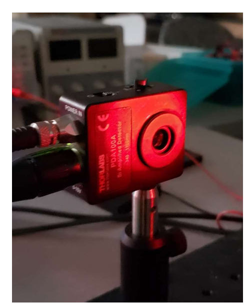


Figure 4) Above shows our apparatus minus our measurement devices

To demonstrate the effectiveness of phase sensitive detection we designed, constructed, and then implemented an apparatus affording a straight-forward experiment serving two main purposes. The first is a transparent method explicitly demonstrating to undergraduate students how signals buried in noise may be accurately measured using a lock-in amplifier. The second is a measurement at the foundation of spectropolarimetry – the Law of Malus.







From Left to Right:
Figure 5. The noisy light source that was generated from our experiment
Figure 6. The signal beam on our photodetector with the LED off
Figure 7. The red LED illuminating the photodetector is ~ 1000 times more intense than the blue laser shown in Figure 6. The red LED provides the noise from which the much weaker blue laser signal must be accurately measured.

Experimental Demonstration (continued)

Apparatus for the detection of signals buried in noise (LIA/Malus Apparatus)

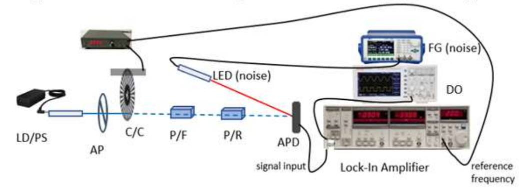


Figure 8) Complete diagram of apparatus

LD/PS: Laser Diode with Power Supply / Signal beam
AP: Attenuating Polarizer
C/C: Chopper with Controller (f ~ 1 kHz)
P/F: Polarizer with Fixed angle
P/R: Polarizer in Rotation mount (the Analyzer)
LED/FG/N: Laser Diode with Function Generator (output random Noise)
APD: Amplified Photodiode
DO: Digital Oscilloscope
LIA: Lock-In Amplifier

Tuning the analyzer angle, θ, in ten-degree increments (from 0-200 degrees), while recording the intensity, I (lock-in amplifier display), a "cosine squared distribution" ensues – the Law of Malus: $I = I_0 \cos^2\theta$ as shown below in Figure 9.

The light sources are configured so that the LED intensity (noise) is 10^3 – 10^5 times the laser intensity (signal of interest), to emphasize the lock-in phase detection abilities. The LIA "filters" the LED signal (noise) since it is completely out of phase with the chopped laser signal at a frequency of around 270 Hz.

This experiment allows students to get hands on experience with phase sensitive detection using the lock in amplifier, data analysis (analyzing the Malus fit), optical components (polarizers, LEDs, lasers, photodiodes), and electronics (mechanical choppers, LIAs, function generators and power supplies). Students are exposed to some underlying principles of spectropolarimetry-based measurements and provided the opportunity to develop the foundation for higher-level experiments including magneto-optic induced optical activity (e.g., Faraday Rotation).

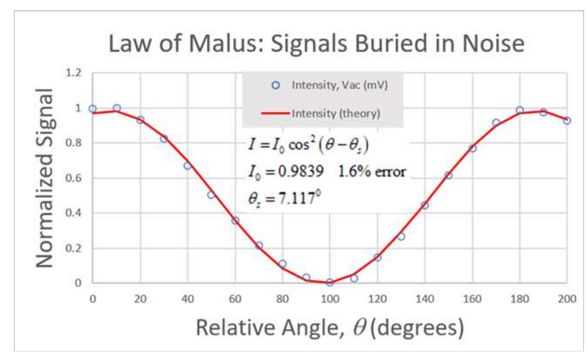


Figure 9) The graph of the normalized data, showcasing the Malus fit.