Characterization of infrared detectors

Evan M. Smith, Guy Zummo, R. E. Peale
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Quick Start Guide

- Before doing this experiment, first align the system first with the LEDs supplied to insure proper alignment for maximum signal. Then calibrate the blackbody with the thermocouple by placing the thermocouple *just* inside the aperture of the BB. You want to know the temperature of your source. The BB should reach temperatures of up to 150℃. With the BB calibrated and aligned, measure the signal with the detector and finely adjust the alignment for maximum signal.
- Heat up the blackbody slowly and record the PbSe signal output as a function of detector temperature. Record this data for a wide range of temperatures and plot the results. You can do this before any calculations.
- Do not run more than 120 V into the blackbody
- Be careful with the optics. Do not drop them or touch them with your fingers
- Check the calibration on the thermocouple. Don't be surprised if it is a few degrees off. This should be fine, but keep your data consistent.
- Transmission data for the bandpass filters and the lens are available on the ThorLabs website.
- The peak spectral response for the PbSe detector is somewhere between 1×10^5-2×10^5 V/W at 4μm wavelength.

<u>Introduction</u>

Common types of infrared detectors include photodetectors and bolometers. Photodetectors detect by observing the change in their electrical properties due to optical excitation of electron-hole pairs across the band gap of a semiconductor. A bolometer is a detector of infrared radiation based on the measurement of a *thermally* induced resistance change caused by small temperature increases from absorbed infrared radiation.

A two-dimensional detector array allows infrared imaging, which is useful for "night vision" based on the infrared radiation that objects *emit*, rather than by the sunlight that they *reflect*. They have a wide range of applications, including defense, surveillance, security, and emergency response. The amount of radiant energy an object emits depends on its temperature and emissivity, according to blackbody radiation theory. Thus, detector signal is a measurement of an object's temperature, if its emissivity is known.

A detector's output signal is always a voltage. For a photo*diode*, this may be the voltage drop across a load resistor that a photocurrent passes through. Here, the photocurrent is generated at the junction of a semiconductor diode, where photons are absorbed to create electron-hole pairs, which are separated, and the current driven, by the diode's built-in field. Or, a voltage change may be measured across the terminals of a photo*conductor*, which is biased by a constant current, due to the change in conductivity caused by infrared-created charge carriers. A voltage is measured similarly across the terminals of a bolometer, except that the mechanism of its resistance change is thermal.

The ability to image an object requires that the induced voltage exceed the noise level. A measure of the sensitivity of a detector is its "Noise Equivalent Temperature Difference (NETD)". This is the temperature difference between object and background that gives a voltage response equivalent to the noise voltage level. NETD is considered a more meaningful measure of sensitivity than is the detector's responsivity, which is the ratio of output voltage to incident radiant power (V/W), since in principle noise may bury the signal even for a highly responsive detector.

Noise has several causes. There are fluctuations in the background radiation, in the temperature of the device, in the applied current through photoconductors and bolometers, and electronic noise in circuits that amplify and record the signal. Detectors are even susceptible to mechanical vibrations. The best detector has both high responsivity and low noise, giving high signal-to-noise ratio (SNR), or small NETD. Small NETD is good.

A related quantity that characterizes the detector, independent of the imaging optics, is the Noise Equivalent Power (NEP). This is the infrared power incident on a detector that results in a SNR of 1 at a specified noise equivalent electronic bandwidth. The smaller the bandwidth, the smaller the NEP.

In this experiment, you will measure the NETD of a detector and compare your measurement to predictions based on given detector specifications such as NEP.

Objectives
1) Determine the NETD of the given commercial PbSe detector.
2) Using the value for NETD determined experimentally, determine the Noise Equivalent Power (NEP) of the device and compare to the manufacturer-provided detector specifications.
3) Use the detector's specified spectral responsivity and band-pass filters to measure infrared emission power of a blackbody source at several different temperatures and within different wavelength bands. Compare your results with expectations from Planck's formula.

Materials
- Blackbody source
- Optics: 1 lens, 2 filters
- Detector
- Chopper
- Thermocouple
- Oscilloscope
- Power Supplies

Experimental procedures
Objective 1: Set-up to measure NETD
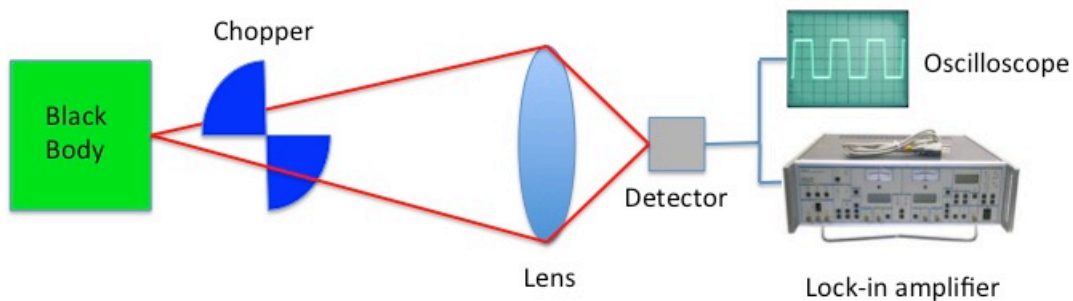*See ASTM E1543 (2011) for the full standard from which this is derived*

Fig. 1. Experimental set up.

Fig. 1 above presents a schematic for the experimental measurement of NETD. An area A_s of a blackbody held at a constant temperature is imaged onto a detector with an infrared-transparent lens. A chopper at room temperature alternately blocks the view of the black-body. Filters may be used to limit the spectral bandwidth of the source.
The blackbody (BB) is positioned horizontally, with the radiation emitted in all directions from its aperture. See Appendix A for optical set-up considerations.

Task 1. Work out the mathematics and ray diagrams of the optical set-up for your report and presentation.

Measurement using an oscilloscope
The detector output goes to an oscilloscope. You can directly view the signal on the oscilloscope by measuring the peak-to-peak voltage with the scope in DC

coupling. The noise is measured with the oscilloscope by blocking the light from the blackbody and recording the trace, which should look like a thick, flat line. The RMS value of the noise is given by

$$V_{RMS} = \sqrt{\overline{(V_i - \overline{V})^2}} \qquad (4)$$

where V_i is the ith value of voltage, and $\overline{V}$ is the average value of the voltage. The term in the square root is called the *variance.*

Measurement using a lock-in

If a lock-in is available, the rms signal is given by the "R" output. You have to multiply the lock-in output by 2.818 ($2\sqrt{2}$) to get the same peak-to-peak signal value observed for the square wave on the oscilloscope. You can measure the noise on the lock-in amplifier by selecting the x-noise and y-noise button on the display. As with the oscilloscope, measure the noise with the signal blocked. The magnitude of the total RMS noise will be $\sqrt{x_{noise}^2 + y_{noise}^2}$. Note that this will be a smaller number than measured on the oscilloscope because the lock-in has a much narrower bandwidth centered at the chopping frequency. This bandwidth can be selected as 1 Hz or 10 Hz, and it can be further reduced by averaging. See Appendix C for a discussion of noise bandwidth.

Task 2: Determine NETD for your detector and optical set-up.

NETD is calculated as a ratio of temperature difference to signal-to-noise ratio according to

$$NETD = \frac{T_{BB} - T_{ref}}{SNR} \qquad (5)$$
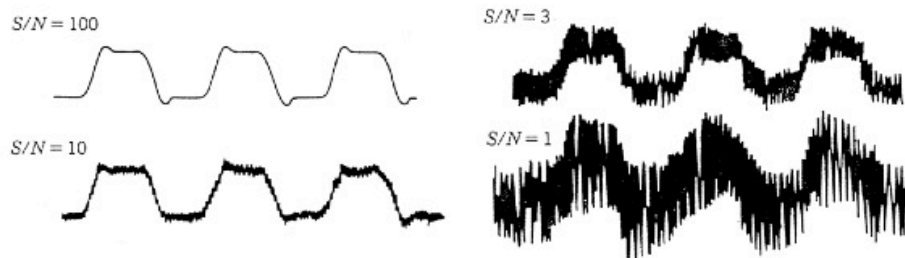
Fig. 2. Chopped oscilloscope traces with different SNR.

In Fig. 2, the signal given is the difference between the upper and lower voltage levels in the chopped wave (amplitude), and the noise is the rms amplitude of the variations in the wave that at frequencies other than the chopping frequency. Noise that is faster than the chopping frequency, as pictured in Fig. 2 is easy to quantify. Noise may also occur more slowly than the chopping frequency, and this can be seen as fluctuations in the average voltage level.

Objective 2: Calculation of NEP and NETD

NETD is not specified for the detector, because it depends on the fore-optics used to collect the signal and deliver it for absorption by the detector. For example, optics that are optimized for collection will produce a lower NETD. Instead, detector data sheets specify noise equivalent power (NEP), which is the absorbed power that results in unity signal-to-noise ratio within a specified electrical bandwidth Δf.

Many noise sources are "white", so that if the detection system had infinite bandwidth, the sum of the noise over all frequencies would be infinite. However, all electronic systems have finite bandwidth, and electronic filters are often used to limit the bandwidth further. The noise power density scales with the electronic bandwidth, so the noise voltage appearing on the oscilloscope scales with the square root of the bandwidth. Therefore, NEP is specified per root bandwidth. Determination of bandwidth is described in Appendix C for both oscilloscope and lock-in, namely

$$NEP = \frac{Incident\ Power}{SNR\ \sqrt{\Delta f}} \tag{6}$$

The incident power on the detector is

$$\Delta P = \frac{\partial L}{\partial T}\Delta T \times A_s \times \frac{A_{mirror}}{o^2} \times \tau \tag{7}$$

where dL/dT is is the differential radiance contrast between the background and the blackbody, A_s is the area of the blackbody aperture that is imaged onto the detector, A_{mirror} is the surface area of the focusing mirror, o is the object distance between the blackbody and the mirror, and τ is the transmission of the atmosphere and any imaging optics.

Using Eq. 6 and 7, determine the relationship between NEP and NETD for this system.
What is the NEP given the NETD you measured?
Compare to the nominal NEP given in the detector data sheet. How far off is your measurement in %?
Given the spectral responsivity of the detector and the measured signal voltage, determine what the absorbed power should be. How does this compare to the power calculated in Eq. A14? What is the reason for this discrepancy?

Objective 3: Measurement of radiance vs. temperature
With the same experimental set-up as objective 1, change the temperature of the blackbody and determine how this affects the power absorbed by the detector. Add in a band-pass filter and measure the signal again, now calculating the radiance under a more specified wavelength range and a known value for transmission.

Compare your results to the Stefan-Boltzmann Law and the blackbody curve.

Appendix A: Optical Set-up and Signal Optimization

The power incident on a detector depends on the power emitted by the source and the optical system. A system with no collection optics at all is defined schematically in Figure 1. An area element A_s of a source emits infrared that falls on a detector with active area A_d. The source radiance L in units of Watts/cm²-sr is the power emitted per unit source area per unit solid angle. If the detector is distant r from the source, then the detector subtends a solid angle $\Omega_d = \frac{A_d}{r^2}$. For large r, so that none of the source elements is far off the optical axis, this solid angle is approximately the same for all area elements of the source, as indicated in the figure by the red and black lines. Integration over the entire source area gives the total power incident on the detector

$$P = L\, A_s\, \Omega_d \qquad . \qquad\qquad (A1)$$
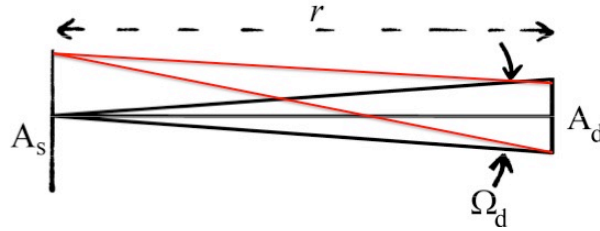

Fig. A1. Schematic of detector and source with geometrical parameters.

A lens is needed for image formation on detector arrays. Moreover, the lens aperture $A_{lens} > A_d$ collects more light due to its larger subtended solid angle. A schematic is presented in Fig. A2, which indicates 3 important solid angles, namely

$$\Omega_1 = \frac{A_{lens}}{o^2}, \quad \Omega_2 = \frac{A_s}{o^2}, \quad \Omega_3 = \frac{A_i}{i^2} \qquad\qquad . \qquad (A2)$$

Rays from the extreme edges of the object pass undeflected through the center of the lens to the extremes of the image. These rays are indicated by red lines Fig. A2, which shows that $\Omega_2 = \Omega_3$. The power emitted by the source and collected by the lens is

$$P = L \times A_s \times \Omega_1 = L \times A_{lens} \times \Omega_2 = L \times A_{lens} \times \Omega_3 \qquad (A3)$$

where the second equality holds by Eq. A2 and the third by $\Omega_2 = \Omega_3$.

Fig. A2. Schematic of source and detector with imaging lens.

In our experiment, the BB has finite size, though in applications the scene is large. If the object distance o is small, the magnification $|m| = i/o$ will be large, and the image of the BB will overfill the detector $A_i > A_d$. Although overfilling means that some of the available BB radiation is wasted, this is the condition that you want, because in practice the image of a scene always overfills a single detector in an array.

In your experiment, for the provided foreoptic with focal length f, you must determine the optimum o and i values. You need two equations. The thin lens equation $1/i + 1/o = 1/f$ is used to insure an image of the scene is formed at the detector plane. The magnification equation $|m| = i/o$ is used to insure that the image of the BB overfills the detector, or $A_i > A_d$, or $A_{BB} * m^2 > A_d$. Obviously, you need to know the BB and detector areas.

The following calculation is instructive for choosing o and i in such a way that the desired overfill condition is met without losing too much collected power. When overfilling, the power incident on the detector is given by Eq. A3 multiplied by the ratio of the detector and image areas,

$$P = L \times A_{BB} \times \Omega_1 \times \frac{A_d}{A_i} = L \times A_{BB} \times \frac{A_{lens}}{o^2} \times \frac{A_d}{A_i} \tag{A4}$$

The magnification is related to area ratios by

$$m^2 = \frac{i^2}{o^2} = \frac{A_i}{A_o} \tag{A5}$$

which reduces Eq. A4 to

$$P = L \times A_{lens} \times A_d \times \frac{1}{i^2} \qquad . \tag{A6}$$

Using the thin lens equation to find it in terms of o,

$$P = L \times A_{lens} \times A_d \times \left(\frac{1}{f} - \frac{1}{o}\right)^2 \tag{A7}$$

On the other hand, if the imaging lens is placed too far from the blackbody, then the magnification will be too small, and the image of the BB will underfill the detector. Though all of the light collected by the lens is incident on the detector in this case, the larger o means the lens subtends a smaller solid angle from the point of view of the source, so that less of the emitted light is captured by the lens. In the limit that a

BB of finite area is infinitely distant from the lens, no signal will be collected at all! In the underfilled case, the power incident on the detector is

$$P = L \times A_{BB} \times \frac{A_{lens}}{o^2} \qquad\qquad (A8)$$

Note that this power goes to zero as o approaches infinity.

The above discussion indicates that there is an object distance for a finite BB, where the signal on the detector is maximized. This occurs when the area of the BB image exactly matches the area of the detector, as we will show. Equations (A7) and (A8) become equal in this case. Fig. A3 presents a calculation of $P/(L\,A_{lens})$ from these two equations as a function of object distance for the case that f = 25 mm, A_{BB} = π (5 mm)^2, and A_d = π (2 mm)^2 For these geometrical parameters, the object distance for maximum collection is 150 mm, or about 6 inches. The power function is rather sharply peaked about this position, but it is clearly better to err on the side of an o that is too small (over-filled case) than on the side where o is too large (under-filled case). Having o too small by as much as 25 mm (1 inch) causes only 10% decrease in the amount of light incident on the detector.
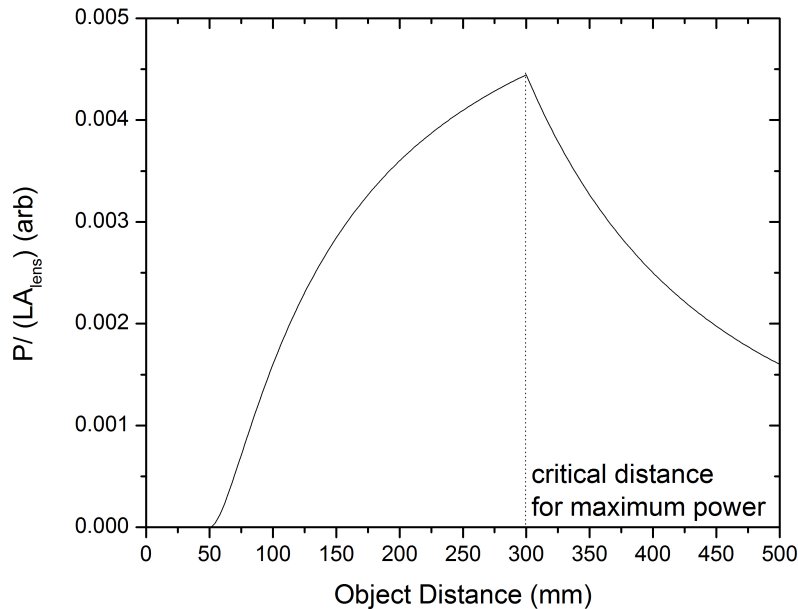

Fig. A3. Plot of the unitless ratio of power incident on the detector to the product of source radiance and lens area as a function of the object distance o. The lens focal length is 50 mm, the BB diameter is 5 mm, and the detector dimension is 2x2mm².

Appendix B: Radiance

Planck's Law gives the blackbody spectral radiance as [1]

$$L_\lambda = \frac{2hc^2}{\lambda^5\left[e^{\frac{hc}{\lambda kT}}-1\right]} \quad \frac{Watts}{cm^2\ sr\ \mu m} \tag{B1}$$

This is the power per unit source area emitted into a unit solid angle per unit wavelength interval. The total radiance L in W cm^{-2} sr^{-1} within a finite wavelength range at a given temperature is found by integrating Eq. B1 with the substitution $x = \frac{hc}{\lambda kT}$, giving

$$L = +\frac{2k^4T^4}{h^3c^2}\int_{x2}^{x1}\frac{x^3}{e^x-1}dx \quad , \tag{B2}$$

which can be solved numerically. The temperature used here is the blackbody temperature. If we integrate over all wavelengths, the find the total radiance

$$L = \frac{\sigma}{\pi}T^4 \quad , \tag{B3}$$

which is the power per unit source area per unit solid angle, where σ is the Stefan-Boltzmann constant $\sigma = \frac{2\pi^5k^4}{15h^3c^2}$ (5.67 x 10^{-8} W m^{-2} K^{-4}). This assumes a Lambertian emitter where the radiance is proportional to cos (θ), where θ is the angle with respect to the surface normal. Integrating over a hemisphere gives

$$L = \sigma T^4 \quad , \tag{B4}$$

which is the Stefan-Boltzman Law.

The radiance changes with T according to

$$\frac{\partial L}{\partial T} = +\frac{2k^4T^3}{h^3c^2}\int_{x2}^{x1}\frac{e^x x^4}{(e^x-1)^2}dx \quad . \tag{B5}$$

Note that the integration variable is also a function of T. For small ΔT we may write

$$\Delta L \approx \left.\frac{\partial L}{\partial T}\right|_{BB}\Delta T \tag{B6}$$

for the radiance difference between blackbody and background.

The optical transmission τ influences the power incident on the detector, and this is a function of the atmosphere and the optics. Thus, from Eq. A4 and B6, the change in incident power resulting from a change in source temperature is

$$\Delta P = \left.\frac{\partial L}{\partial T}\right|_{ref}\Delta T \times A_s \times \frac{A_{lens}}{o^2} \times \tau \quad , \tag{B7}$$

where A_s is the area of the black body that is imaged exactly onto the area of the detector. This is less than A_{BB} due to overfilling, and you determine it using the magnfication equation.

Eq. B7 is an approximation that is only valid for ΔT < 40°C. For a more accurate incident power, calculate ΔL by integrating Eq. B2 at the backround temperature and the blackbody temperature, and take the difference between these two. You may use the website listed below to help with this integration.

For a very useful radiance calculator, check out:
https://www.sensiac.org/external/resources/list_calculators.jsf

References Cited
1. Dereniak, E.L and Boreman, G.D. Infrared Detectors and Systems. John Wiley and Sons, New York, 1996.

2. Datskos. *Performance of Uncooled Microcantilever Thermal Detectors*. Review of Scientific Instruments Vol 75 No 4, p. 1134-1148 (2004)

3. Niklaus, Frank. *MEMS-Based Uncooled Infrared Bolometer Arrays-A Review*. Proceedings of the SPIE edited by Chiao et.al. (2007), Vol. 6836

Appendix C Noise bandwidth[1]

The noise equivalent bandwidth Δf is the width of a flat bandpass filter that passes the same amount of noise power as the circuit used to make the measurement. It can be determined by analysis of the time-dependence of the detector circuit. A Fourier transform of the time dependence gives the voltage transfer function R(f), which is the signal response (or noise response) as a function of frequency. In other words, we are observing the noise present at each frequency. The noise equivalent bandwidth can be determined as

$$\Delta f = \int_0^\infty \left| \frac{R(f)}{R(f=0)} \right|^2 df \qquad (C1)$$

For a square-pulse signal, the noise voltage as a function of time can be written as

$$v(t) = v_0 \, rect(\frac{t-t_0}{\tau}) \qquad (C2)$$

where τ is the integration time and we utilize the rectangle function (gate or pulse function)[2]. The Fourier transform of Eq. C2 gives

$$\left| \frac{R(f)}{R(f=0)} \right| = \left| \frac{\sin{(\pi f \tau)}}{\pi f \tau} \right| \qquad (C3)$$

Plugging Eq. C3 into Eq. C1 and solving the integral gives $\Delta f = \frac{1}{2\tau}$. Therefore the noise bandwidth is related to the total integration time of the measurement apparatus.

Digital oscilloscope

To determine the noise equivalent bandwidth on the oscilloscope, you must determine first the sampling frequency. This is the minimum time difference between one data point and the next. On the digital oscilloscope, there are 250 data points per division. If the time per division is set to 10 ms, then the sampling frequency will be 10ms/250 = 40 μs, corresponding to a frequency of 25 kHz. The noise equivalent bandwidth is half of this value, or 12.5 kHz. (If you output your data to a CSV file, the sampling frequency will be listed.)

Lock-in

A lock-in amplifier has the capability of having a much shorter noise bandwidth. This can be determined by the integration time set by the time constant on the amplifier. If the integration time is long, then the amplifier has a better opportunity to hone in on the right frequency. This means that the noise floor will decrease; however the noise bandwidth will increase.

It was already shown above that the integration time and the noise bandwidth are related mathematically, what follows is more of a visual argument.

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[1] Information taken from lectures of Dr. Glenn Boreman, also found in Dereniak and Boreman (reference listed above)

[2] The rectangle function is defined as
$\Pi = 0 \; for \; |x| > \frac{1}{2} , \frac{1}{2} \; for \; |x| = \frac{1}{2}, and \; 1 \; for \; |x| < \frac{1}{2}$

In Fig. C1 we see a representation of the square wave signal with a period T. Overlaid on this representation is two noise voltages at two different frequencies, one at the same frequency as the signal (that is, at f=1/T) and the other at a slightly different frequency (f+df). A lock-in amplifier is designed to suppress any voltages outside of the reference frequency, but the determination of which signals are at the reference must be related to the integration time. If the integration time were dτ (that is, just a signal point) then all frequencies would contribute, as it is impossible to determine frequency from a single data point in time. If there were an infinite integration time, then only the desired frequency would remain, as all others would diverge eventually. Any time constant $\tau \geq \frac{1}{2\Delta f}$ would damp out noise components outside of the bandwidth. Therefore we have $\Delta f \leq \frac{1}{2\tau}$, where we would consider the maximum value at $1/2\tau$ as the noise equivalent bandwidth.
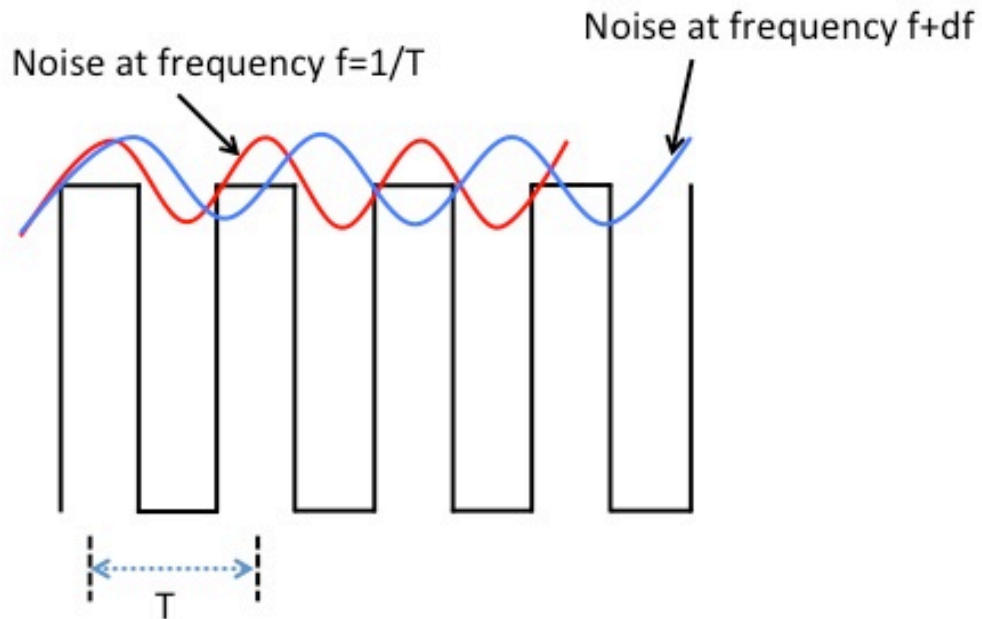

Fig. C1. Representation of the signal voltage, as a square wave, with two noise voltages overlaid. As the time constant increases, the range of frequencies at the desired frequency decreases.

Appendix D: Theory of Operation

Lead salt detectors (PbS and PbSe) are among the oldest and most versatile uncooled infrared detectors, first developed in the 1930s and used extensively in World War II. A photoconductor is a piece of semiconductor that has a current passing through it. When optical radiation of a specific range of wavelength falls on the device, energy is transferred to electrons in the valence band, which causes them to transition to the conduction band, increasing the number of free electrons and holes in the material. This transition only occurs if the photon energy is greater than the effective energy gap, 0.42 eV for PbS and 0.23 eV for PbSe (both at room temperature—decresing the temperature of the device decreases this bandgap, which allows the detectors to sample a higher wavelength with greater response). Thus, there can be a direct relationship between the conductivity of the material and the power of incident light.
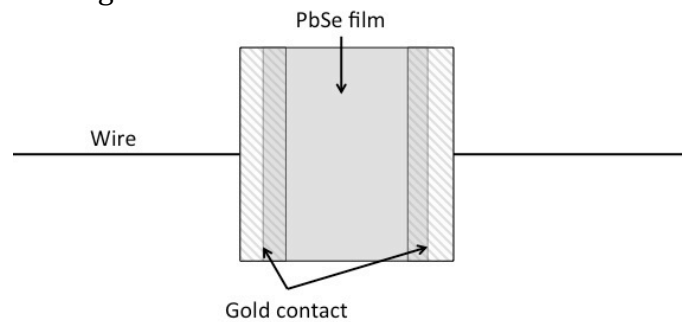

Fig. 1: Simple layout of a PbSe detector.

The detector used in this experiment is a PbSe photoconductor. A simplified diagram is shown in Fig. 1. Here, a thin film (~100s nm) of polycrystalline PbSe is deposited on an insulating substrate (quartz or glass). The area of this film is 2x2mm^2. On either end are gold electrodes that form good electrical connections to the PbSe film on one side and wires on the other. This detector can be connected to a bias voltage source, ground resistor, and output voltmeter as shown in the schematic in Fig. 2. The output voltage will be related to the resistance of the film as

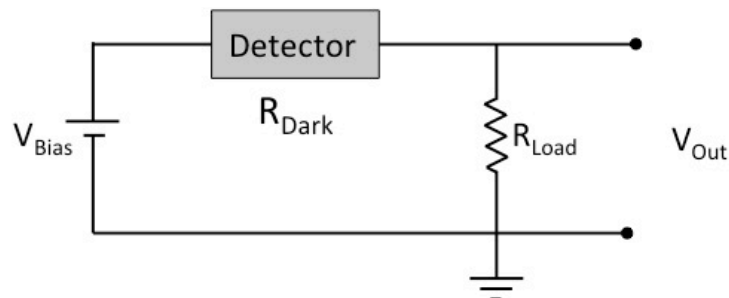$$V_{Out} = V_{Bias} \times \left(\frac{R_{Load}}{R_{Dark} + R_{Load}} \right)$$ (1)

Fig. 2 A schematic of a simple circuit designed to measure the resistance of a photoconductor. Note that this circuit would not be ideal due to high levels of noise.

Differentiating Eq. 1 with respect to R$_d$, we find

$$dV_{out} = -\frac{R_{Load}V_{Bias}}{(R_{Dark}+R_{Load})^2}dR_{Dark} \, ,$$

(2)

which gives the change in output voltage as a function of change in detector resistance. Because the measurement made with a photoconductor is a voltage, the responsivity of this type of device is generally given in Volts/Watt.

In order to obtain an AC signal $f_c = \frac{1}{2\pi \tau_r}$ make a measurement of incident power, the signal must be modulated. In other words, the difference in resistance in the detector correlates to a blocked and unblocked state of the signal, achieved with an optical chopper, and is observed by a difference in output voltages. A chopper will reduce the detector responsivity according to

$$\frac{R_f}{R_0} = \frac{1}{\sqrt{1+(2\pi f_c \tau)^2}} \, ,$$

(3)

where f_c is the frequency of the chopper, τ is the rise time of the detector (time for the PbSe structure to change resistivity; ~35 μs in this case), R_f is the responsivity of the detector with a chopper and R_0 is the responsivity with no chopper. As seen in Eq. 3, a chopping frequency of 600 Hz results in less than a 1% loss in responsivity; 8 kHz cuts the responsivity in half.

Typical photodetectors, including this one, are connected to a preamplifier circuit to boost the output signal $V_{out} = \left(1 + \frac{R_f}{R_i}\right)*I_s R_D$ itional noise above the detector noise. An example of the preamplifier circuit is shown in Fig. 3.

Amplifier Model