

September 3, 2014

Laboratory #2 Guide: Measuring the Lamp/Monochromator Output Spectrum

Introduction

In the last lab we did a simple exercise to introduce students to the major components in our optical breadboard set-up, and used a simple LabVIEW (LV) program to acquire data relating to the time constant of a chopped thermopile detector. A wavelength near the peak output of the lamp was selected to maximize the signal. The data was analyzed using Igor Pro Software (IP). Thus, students were exposed to three key elements of the laboratory course; LV, IP, and several pieces of hardware and instrumentation.

In order to understand how light interacts with condensed matter/solid state materials and devices one needs to understand in detail the qualities and quantities of the light associated with the source. In the laboratory, we are concerned with the output of the lamp/monochromator combination and, to a lesser degree, the lenses and other optical components that may be employed in an experimental set-up. We want to understand the power and photon number distribution as a function of wavelength.

In this lab we will characterize the output of the monochromator/lamp combination as a function of wavelength. This activity will further build-up our core capabilities in LV so that more complicated experiments related to photovoltaic devices and materials can be done as the course progresses. Also, a detailed characterization of the light source will be required for a variety of future experiments and analyses.

Initial Goals of Lab #2: Characterize the Output of the Lamp/Monochromator Combination

You will construct a LV program that will step the monochromator from an initial to a final wavelength at selected intervals (e.g. from 900 nm to 300 nm, at 10 nm steps). The thermopile detector will be used to measure the power at each wavelength. The data will be plotted and recorded.

Concepts

The lamp is a blackbody source, much like the Sun, that generates a broad distribution of wavelengths. The monochromator selects a fraction of this output depending on the position of the internal diffraction grating and the width of the slits. The output power will be a function of the slits used, the optical throughput of the monochromator, and the intensity of the lamp. The transmission characteristics of the lenses can also be important in some cases, but we will neglect these issues here. The output can be specified in terms of Watts/cm²-nm, or # photons/cm²-nm since the energy of a photon equals hc/λ . The "cm²" term refers to the area over

which the photons are incident. We will not specify this area now, but consider it to be a constant for the experiments done in the lab, so long as no optical components are moved during measurements that will be compared. The “nm” refers to the optical bandwidth of the monochromator, and depends on the slit width – see the accompanying lecture notes.

Experimental Steps

1. Start at the end of Lab #1 (basically, steps 2 – 10 of Lab Guide #1), which boil down to:
 - a. Establish communication with the monochromator (MC) (Note that COM Port 4, rather than 7, may be operational for communications with the MC).
 - b. Establish data acquisition from thermopile through the USB 6009.
 - c. Set-up and align optical components to maximize signal. Though you may wish to have the Chopper operating to do this, it will not be used for this experiment.
2. Open a new VI in LV. On the BD, pop-up on the Function Palette, go to Exec Control, and place a While Loop in the BD. Wire an indicator to the “i” terminal (aka, the counter). Go to the front panel and run the VI. Note the behavior of the Numeric indicator on the FP. Press Stop to end.

****Helpful Hint: Control-E switches back and forth between the FP and the BD****

3. Return to the BD, and Exec Control within the Function Palette, and drop in a Time Delay. Set to 1 s, and run the VI again. Note and understand the new behavior of the Numeric indicator on the FP.
4. Return to the BD, replace the time delay with a DAQ Assist (DA). Set it up to acquire data from the Thermopile. Note that the settings you provide to the DAQ assist will act as a time delay. Remember these in case you need to change them. Even better, wire up front panel controls for the key Rate and # of Samples inputs.
5. Return to the BD, pop-up on Function Palette and expand it with the small arrow at the bottom. Then, go to Mathematics\Prob&Statistics and drop in the Mean VI. Wire the data output of the DA to the input of the Mean VI. The data stream should convert to the correct type automatically. Bring the output all the way to the right hand wall of the While loop, and enable indexing on the block connection that appears.
6. Run the “i” terminal to the While loop wall and enable indexing as well.
7. Outside of the While loop, on the right hand side, create a Bundle element (you can use the search function on the Function Palette to find this, or expand the Function Palette, go to Programming\Cluster, and select Bundle), and wire up

the “i” array and the mean array to the inputs to form a cluster of two one dimensional arrays. Now wire the output of the Bundle to an XY graph. Run the VI to make sure the output is properly updated.

Hint: With contextual help on, you can always place the cursor over an item of interest and learn more about it **

8. To store the data, take the two arrays and form a new two dimensional array (use Build Array in Programming\Array). Then couple the new two dimension array to Write to Spreadsheet File (located in Programming\File I_O). Run the VI and make a test data file. Open the file and look at the organization of the data. It’s likely you’ll see two rows of data in N columns. At this point the data cannot be easily read into Igor Pro, so transpose the two dimensional array before it is written to the File using Transpose Array (in Programming/Array).

*****Hint: Whenever writing data to a file, inspect the file to make sure the data is written in the format that you will need later, and that the acquired data is the same as the written data.*****

9. Now add a Goto11x.vi within the While loop. Create a control for the Initial Wavelength on the front panel. Use the “i” terminal to act as an indexer that can be multiplied to increment the wavelength according to an interval control that can be created on the front panel. Use the natural updating of the While Loop to control updating of the values written to Goto11x.vi. You can stop the While Loop manually with the provided button, or use logic to stop the scan when the final wavelength is reached. At this point, you should be able to collect the needed data to finish the report for this lab.

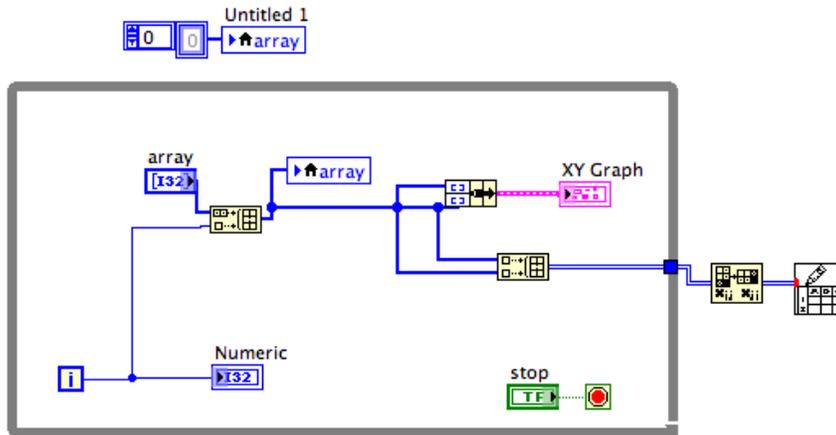
10. **Additional activity:** You have noticed that the data and graph are not updated until the loop is exited. It would be preferable to observe the data while it is being collected. Besides being more satisfying, the data collection can be abandoned earlier if something is not quite correct. However, more complicated programming is required to update the data on the screen. One approach that may work is shown in the screen shot below. Note that in this example we are simply plotting the “i” array versus itself, for demonstration purposes. The same thing could be implemented for the separate voltage and wavelength arrays that our program is creating. The key difference from what was implemented previously is that the arrays are built-up within the While Loop using an Array variable and associated Local Variables that can be specified as Read Local or Write Local. (Local Variables can be created from the Programming\Structures palette for an already-created variable). The 1-dimensional array variable is wired into a Build Array, as is the “i” terminal. You can pop-up on the Build Array and set it to concatenate data. The Array is initialized before the loop to be all zeros by writing in an array full of zeros into a write local Array variable. During execution, the “i” (or wavelength, or voltage) values are added to the Array. The output with the added value is then used to

replace the previously existing Array via a second write local Array variable. This process continues until the loop is exited. The two arrays can then be bundled directly to the graph, which now can reside within the While Loop. The data is written to the file outside of the loop. Note that, in this case, indexing is not enabled for the wire that goes through the While Loop wall.

Note that other approaches are possible as well. One which was discussed in lab includes the use of Shift Registers (see video introduction here: <http://www.ni.com/gettingstarted/labviewbasics/shiftregisters.htm#ShiftRegisters>). See the 2nd screen shot below for the basic arrangement for populating an array using a Shift Register. No matter what approach you take it is important to do thorough testing to insure that the data you wish to save is the correct and in the right format.

Report (Draft version due Tuesday Sept. 16)

Report on your measurement setup and results, and present a plot of the power output of the Lamp/Monochromator in units of W/nm and in photons/s-nm for two different slit widths.



Building an array using the Local Variable for an array, and the Build Array function.

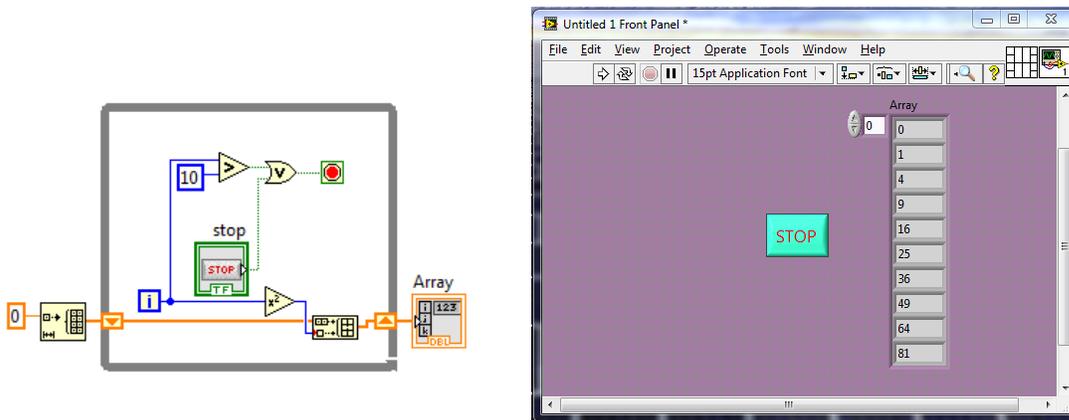


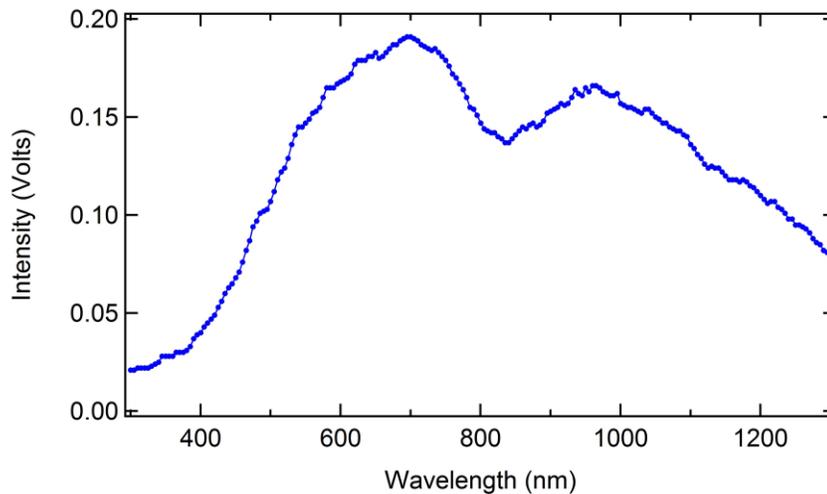
Figure 1. Building an array using a Shift Register. The FP displays the values (in this example, values = i^2) within the array.

Laboratory #2 – continued: Measuring the Spectrum Using Lock-in Detection

Introduction

In the first part of Lab #2 (Sept. 9th), we used LabVIEW to control the output wavelength of the monochromator, focused the light onto the 2M thermopile detector, and recorded data using the USB-6009 Analog-To-Digital input. Most of you are using “ai0” as your input channel, which refers to “Analog Input 0”.

The goal was to measure the output spectrum of the lamp/monochromator system, and to do so for two different entrance-exit slit widths (e.g., 2.4 mm and 1.2 mm). Your data likely resulted in a graph similar to this one, in terms of Volts vs. Wavelength:



Measured output spectrum (example only).

In this 2nd part of Lab #2, you will refine your measurements in order to determine the actual shape of the lamp spectrum – before it interacts with the monochromator’s optics which include the diffraction grating and the mirrors. Note that we still will not concern ourselves with the actual total lamp intensity, but just the accurate determination of the *shape* of the spectrum – i.e., the spectral distribution of lamp power as a function of wavelength.

There are two key aspects in which your measurements will advance compared to those you made in the first part of Lab 2 (the portion reported on in your draft report due Sept. 16): one concerns the measurement technique, and the other concerns the correction of the measured spectrum to account for the diffraction grating’s wavelength-dependent efficiency:

- A. You will implement use of the Lock-In Amplifier (LIA) to generate and record a signal from the thermopile detector.

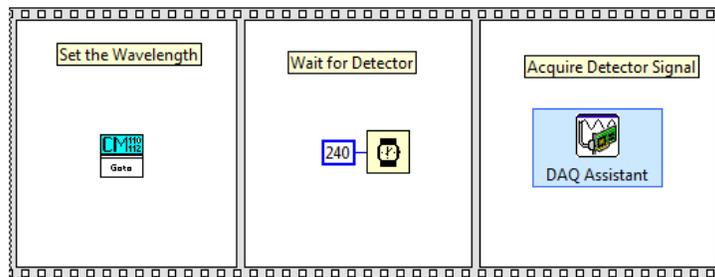
- B. You will use the diffraction grating efficiency curve available on the web site to correct your measured spectrum. After correction, you'll have a more accurate accounting of the lamp's spectral distribution.

Review of Two Other LabVIEW Concepts

Use of a Sequence Structure can provide important timing control to a LabVIEW .vi. Specifically, the Sequence Structure enables you to control the order in which your program's actions run. Viewing this short video will demonstrate the value of sequence structures:

<http://www.ni.com/academic/students/learn-labview/execution-structures/>

For most .vi's last week, the While loop contained two functions – incrementing the wavelength of the CM 110, and recording a data value from the detector. Unless you programmed some interdependence in your data flow, it is in general impossible to predict the order in which the two operations occur. For our measurements, we ideally want to (1) set the monochromator wavelength, (2) allow the detector to “settle” (wait 2-3 time constants), and (3) acquire data from the detector. To control such timing, you could use this approach (a Flat Sequence is shown though a Stacked Sequence is essentially identical but takes less room on the BD):

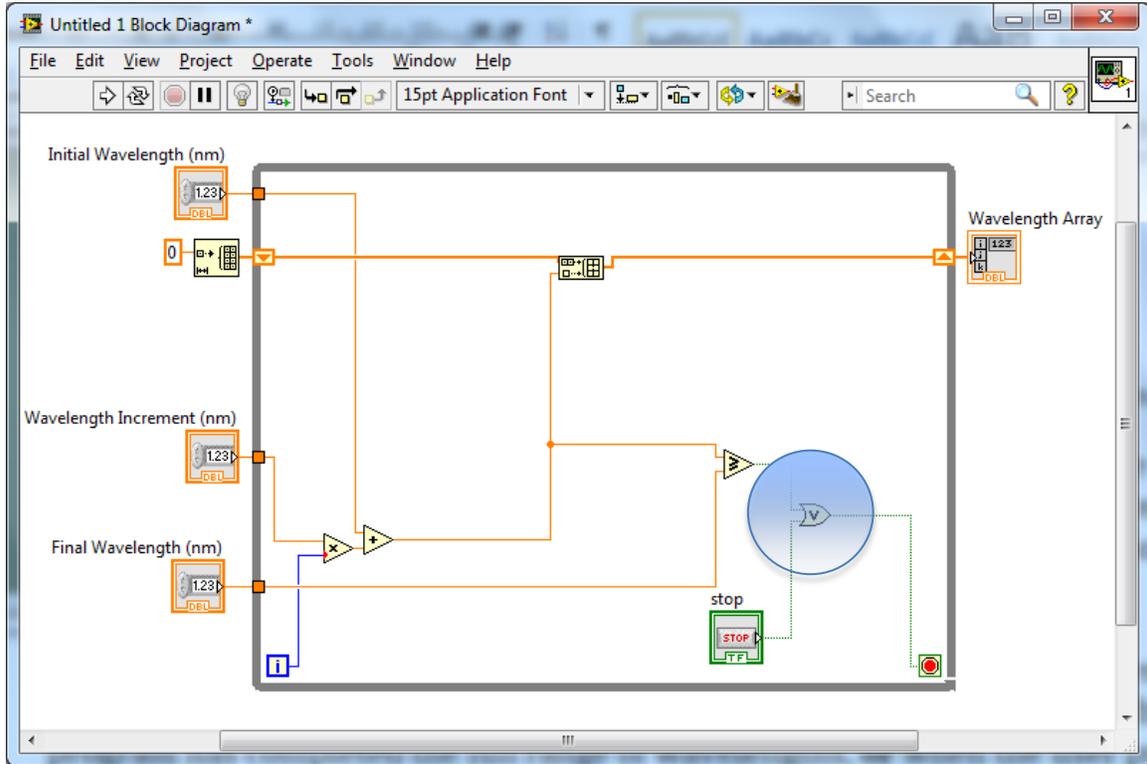


Flat Sequence Structure, in which the frames of the sequence are performed in order from left to right.

The steps are not fully wired in the picture above, but each frame is commented at the top to clarify what step is being performed (you'd of course have to wire them for full functionality). Enclosing such a sequence structure within a While loop enables you to continually repeat these three steps, which execute from left to right.

Another concept concerns Boolean operators, such as the logical “Or” operator. For many programs, you may want to be able to save your data either when the program has completed the full range of wavelengths, **or** when the user presses the Stop button on the FP (as opposed to the “terminate” button within the VI operation toolbar). In this case, the While loop's Stop button would be wired with an Or operator as shown below. Note that LabVIEW has a huge number of features, and if

you can imagine an operation, then you can likely find a way to create and control the operation.



The **Or** operator (circled in this screenshot) allows one to Stop the execution of the While Loop when either the Stop button is pressed, **Or** the Set Wavelength equals or exceeds the Final Wavelength value. One would normally have a subsequent step (either using a sequence structure or positioning the data flow to a “write file” operation outside the While Loop.

The Next Set of Goals of Lab #2: Characterize the Output of the Lamp/Monochromator Combination Using Lock-In Detection

Using lock-in detection enabled by the SR510, you will measure the lamp output spectrum over the range of 300 nm to 1500 nm. Subsequently, you will use Igor Pro to correct the data for losses expected due to the wavelength dependence of the efficiency of the diffraction grating. Lastly, you will determine the approximate temperature of the lamp using Wien’s Law.

To start toward these goals, you will alter the hardware configuration to connect the amplified thermopile detector signal to the ‘A’ input of the SR510 lock-in amplifier (LIA). You will digitize the SR510 Output signal (proportional to the amplified detector voltage) using LabVIEW and the USB-6009 – stepping the CM110 wavelength as before allows you to record the output spectrum. You can likely modify your existing LV program, or if you wish, you can start a new .vi.

Concepts (read this section prior to starting the Experimental steps)

The lock-in amplifier (see reference file on web site -- <http://astro1.panet.utoledo.edu/~relling2/teach/4580.6280.2014/About LIAs.pdf>) allows one to measure *the amplitude of a signal modulated at a constant frequency*. For example, a signal arising from a light detector that is optically chopped will produce a signal modulated at the optical chopping frequency. Note that the manual for the SR510 is included in hardcopy with each experimental setup. You should understand the SR510 front panel controls (the physical front panel, not a .vi front panel!) – see info starting on p. 8 of the manual.

As mentioned above, the diffraction grating has an efficiency associated with it. The efficiency of the grating is relatively good around 500 nm, and significantly worse around 1000 nm. The grating's efficiency is a simple average of the 'S' and 'P' efficiency curves shown in Lecture #2, because the light emitted from the lamp is unpolarized. To determine the lamp's actual spectrum (as it enters the monochromator from the left) from the spectrum measured after the light exits the monochromator, you'll have to think through the effect of the diffraction grating on the measured data. This guide will show you an easy way to perform math on a wave in Igor Pro.

Lastly, the concept of blackbody radiation will be applied to determine the approximate temperature, in K, of the lamp. If you have not done so, read through the Wikipedia entry on Black-body radiation: http://en.wikipedia.org/wiki/Black-body_radiation . More detail follows below.

Experimental Steps

1. Power up the lamp and monochromator, and use the USB-6009 to confirm that you are able to see a signal (without the chopper) from light incident on the thermopile detector. Now switch to the 0.3 mm set of slits, exercising care to insert them all the way so that the proper wavelength exits the CM 110.
2. As an aside, recall that the Model 1010 amplifier has a gain of 1000x. This means that for a measured signal amplitude of 0.01 V, or 10 mV, the signal generated by the detector is just 10 μ V.



3. Now disconnect the BNC cable from the adapter leading to the USB-6009 input, and connect it to the 'A' Signal Input on the SR510. Ensure that the rocker switch on the Signal Inputs section is set to A. Turn on the power to the SR510.

4. Insert the optical chopper into the path of the light beam, and run it at 2 Hz or slightly higher frequency. Using 1 Hz presents problems for the SR510 to lock into the signal, while very high chopping frequencies limit the signal amplitude since the time constant of the detector is < 100 ms. Ensure that the REF OUTPUT from the front of the Optical Chopper controller is connected to the Reference Input of the SR510. The SR510 uses this signal to define the modulation frequency of the signal it will amplify and then send to the output. The LIA amplifies the portion of the signal at the modulation frequency, while suppressing electrical signals (such as noise) that occur at *any other frequency*. You're now ready to look for the signal on the LIA.

First, keep an eye on the OVLD light – if the signal is too large, adjust the Sensitivity to larger values (e.g., from 1 μ V to 1 mV, or from 1 mV to 200 mV) until the OVLD light is off. Ultimately, you'll want the signal during each measurement to vary within a single sensitivity range, i.e. without exceeding the maximum of the range.

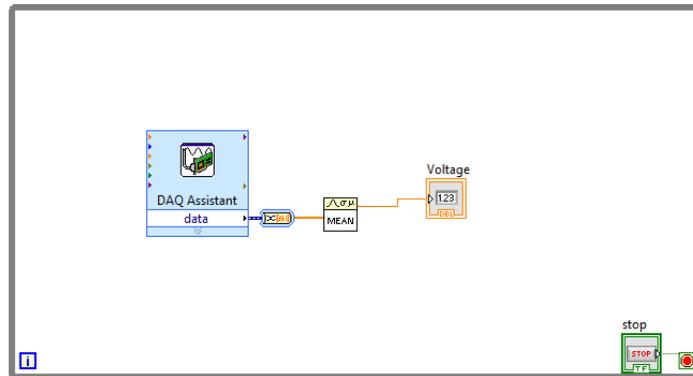
Another key setting on the LIA concerns the Time Constant, which as you may suspect determines the response time with which the LIA settles on the actual signal value. If you set the TC to 3 s, you'll need to wait 3 s for the LIA to respond within the range of e^{-1} ($\sim 63\%$) of the actual signal; waiting 2.5-3 times the Time Constant is appropriate. A reasonable TC setting while trying to find the signal and zero the phase is 1 s or 300 ms. You can set the POST Time Constant to 0.1 s.

In order to properly measure the signal amplitude using the LIA, one must "zero the Phase" as follows. Adjust the Fine control under Phase, until the signal on the needle reads zero. Once you reach this point, changing the phase by 90° using the 90° button on the Phase settings will result in the signal (i.e., on the needle or the digital meter) changing to either positive or negative of the maximum possible value. For convenience, you'll want the signal to be > 0 , so adjust the phase by either $+90$ or -90 as needed. Once you have the phase adjusted correctly for signal maximum, confirm that blocking the beam with a card results in a signal of 0 mV.

***** Hint: Restarting or changing the position of the chopper likely will result in a loss of the phase information and you will need to re-zero the phase on the SR510. Ensure the phase is set correctly before you start acquiring data. Changing the CM 110 wavelength setting, or the LIA sensitivity or time constant will not affect the phase.

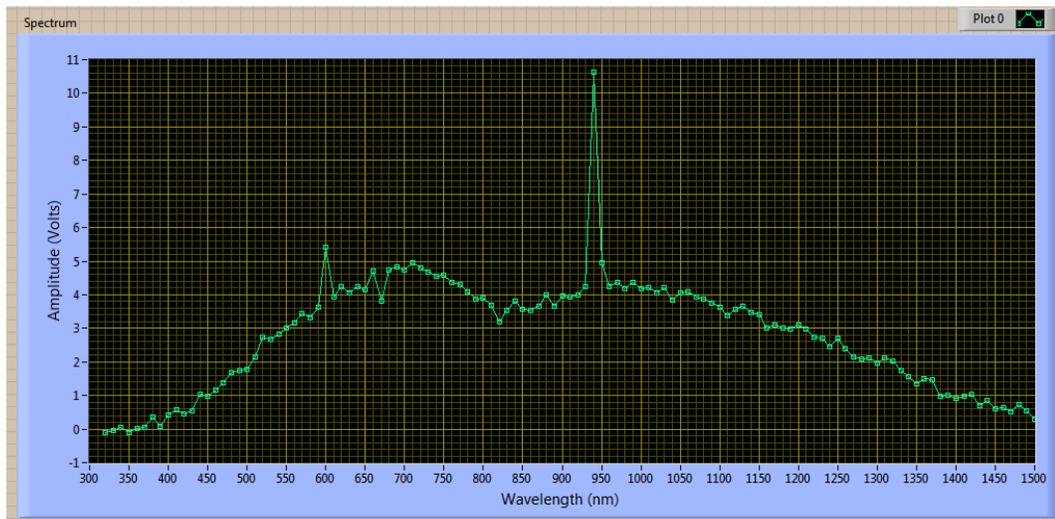
5. By now (perhaps with a little assistance), you should be able to confirm that you have a signal, generated by light incident on the thermopile detector, that when blocked returns the needle and digital read-out on the SR510 to 0.0 mV. The next step is to establish the ability to read the data from the SR510

into the computer using LV. To do this, read in the SR510 manual about the Output connection on the LIA. This output can be connected to the same ai0 channel on the USB-6009 as used previously, and you can measure the value using DAQ Assistant. The signal amplitude may be quite different from what you measured directly out of the Model 1010 amplifier, since now the LIA also plays a role in the signal. You can quickly investigate the signal amplitude using a program similar to this one (or just by using Max):



- Now you're ready to use the LIA and the rest of your setup to measure the spectral dependence of the output intensity – i.e., what is the Intensity vs. Wavelength? Acquire high quality data over as large a spectral range as possible (300 nm to 1500 nm). If your data looks good, try reducing the slit size; conversely, if you're having trouble getting a good spectrum, you may need to use the next larger slit size. Remember that when you change the signal amplitude, you'll need to adjust the LIA sensitivity setting so that you're using as much of the sensitivity range as possible.

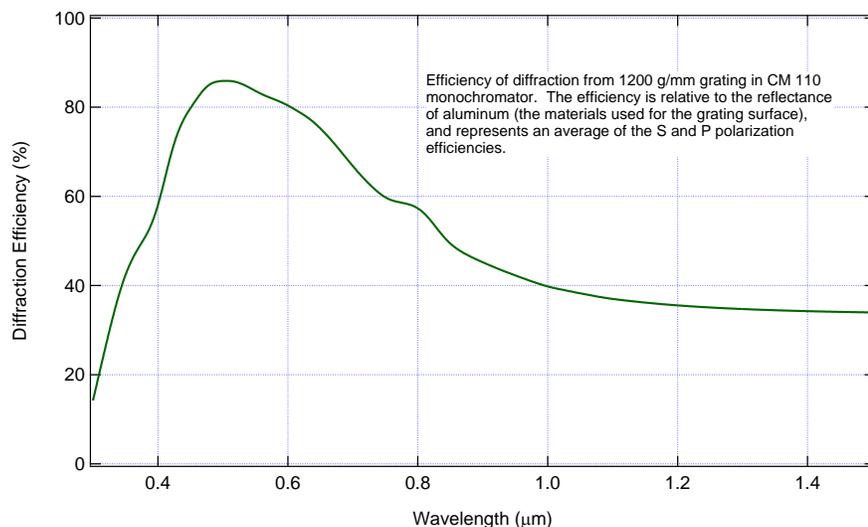
One of the setups yielded the spectrum below when using 300 μm slit widths, a 1 s time constant, and a sensitivity setting of 500 μV :



The sensitivity is notable; if you tried to obtain such data using the “direct”

measurement, you'd see significantly larger noise in the spectrum. Note that there are a couple wavelengths affected by noise. This may very likely be connected to a controllable event – i.e., the detector is quite sensitive and if you motion with your hand, or someone walks by, these radiant sources may influence the measurement. So be aware of this possible pitfall.

7. Your LabVIEW program should be configured to save your data. Once you have that aspect working correctly, acquire high quality data with a 5 nm spacing (or smaller). Use the smallest slit size that allows you to get good data within about a 10 minute scan. You can adjust the time constant for the LIA to reduce noise (greater than 3 s is inordinately long, since you should wait several LIA time constants prior to reading the LIA Output value. Try to use no larger than a 0.6 mm slit width for the entrance and exit slits on the CM110. Record 1 or 2 high quality spectra from 300 nm to 1500 nm, and save these data as text files (.lvm or similar).
8. Now we'll apply the diffraction grating correction. Note that the grating efficiency is measured relative to the reflectance of aluminum, which is not ideal for our purposes since Al does show decreased reflectance around 830 nm: <http://en.wikipedia.org/wiki/File:Image-Metal-reflectance.png>



Load the data file ([available on the course web site](#)) into Igor Pro using “Load Delimited Text...”, and assign suitable wavenames for Wavelength and Efficiency, e.g. *wl* and *eff*. Graph the data so that you know how the efficiency varies with wavelength over the region of your measurements of the lamp spectrum. The data file includes data for every 1 nm from 300 nm to 1500 nm – that’s 1201 points.

Now also load your spectrum data file into waves, using names assumed here to be *specx* and *specy*. Most likely, you’ll find a couple of problems trying to graph these two curves at the same time: namely, one spectrum uses nm (or Å) and the other uses microns. Not a big deal – let’s switch them both to nm.

Here's how to switch the x data wave from μm to nm: Since there are 1000 nm per μm , we can multiply the grating efficiency x wave values by 1000. The easiest way to do this is at the command line, where you type:

```
wl *= 1000
```

Another way to accomplish the same thing is to type:

```
wl = wl * 1000
```

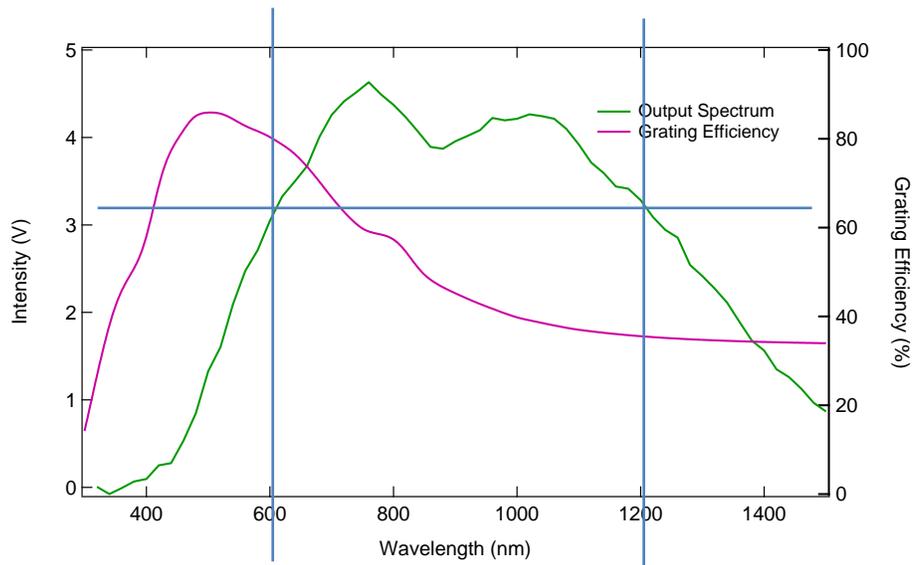
Since many of you save the wavelength data for your measurements in terms of Angstroms, you'll also need to correct that x data to nm. Now we have both curves in terms of x-values (wavelengths) measured in nm. OK, another problem concerns the amplitude of the two y-wave curves. Graphing these two curves on the same plot is straightforward in Igor Pro.

When creating a New Graph, click the "More Choices" button in the wave selection dialog box, and you'll see this: now select the first Y Wave (eff) and the corresponding X Wave (wl), and click Add.

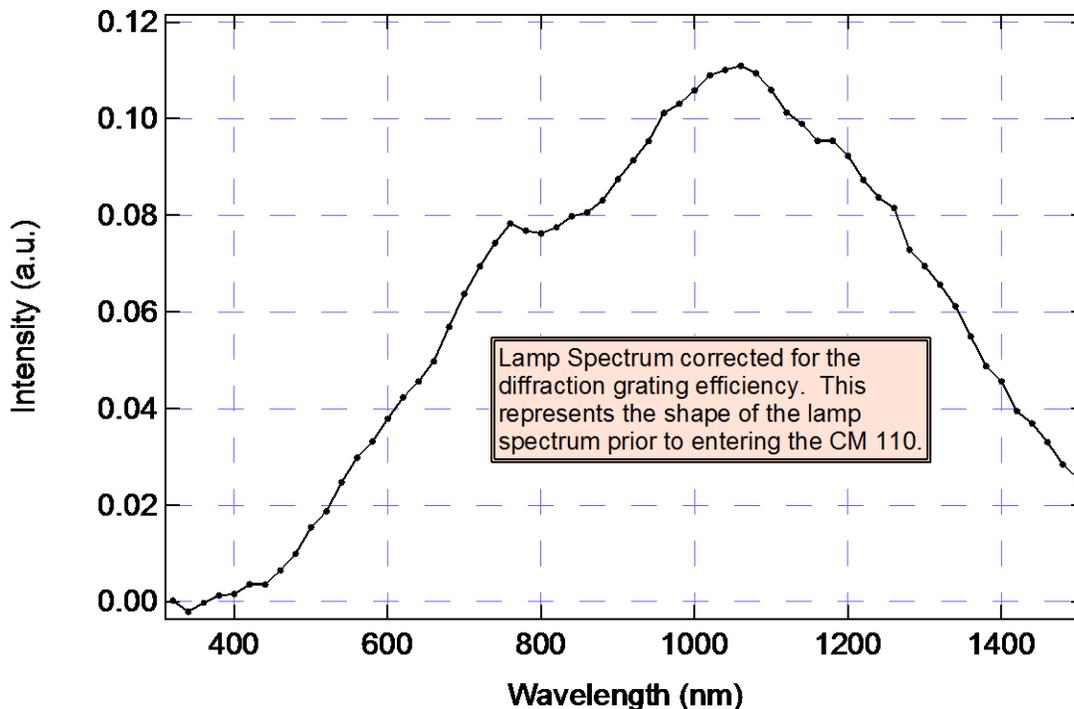
Next, select the 2nd Y Wave (specy) and the 2nd X Wave (specx), and then assign the Y Wave to Axis 'right' instead of 'left'. Click "Do It", and you'll see the graph with two red lines, and separate Y axes labels at left and right.



Give the curves different colors, add a legend, and label the graph axes which will also define for us which axis pertains to which curve. Include this graph in your Report, with a suitable caption.



9. Now for a thought experiment (all experiments require thought, but this one is all thinking). Consider the intensity of light emitted from the monochromator at 600 nm and at 1200 nm. Based on the graph above, these two wavelengths have similar signal intensity. Consider the influence of the diffraction grating on the output spectrum. How does the intensity at 600 nm *before the diffraction grating* (I_{600}) compare to the intensity at 1200 nm *before the grating* (I_{1200})? The answer to this question will tell you whether you need to *multiply* your spectrum by the grating efficiency curve, or *divide* by the grating efficiency curve. Think through this and tell us your answer during lab. We'll make sure you're on the right track, but this is the kind of thinking you need to master to perform careful experiments.
10. So now you'd like to multiply (or is it divide?) the measured spectrum by the correction file. Use Control-i to to set the A cursor on one curve and the B cursor (square) on the other curve. Next, can go to the Analysis menu, then choose Wave Arithmetic. Note that although the the point spacing for *specx* may be 5 nm rather than the 1 nm spacing used for *wl*, under the Help for Wave Arithmetic it states that "If X values do not coincide, linear interpolation is done to get values at the same X. The X value used is that of the result. If the result is a new wave, the X values are copied from the A cursor wave." Plot the resulting spectrum on a new Graph, and annotate the graph to indicate that the data are corrected for the grating efficiency. See an example below:



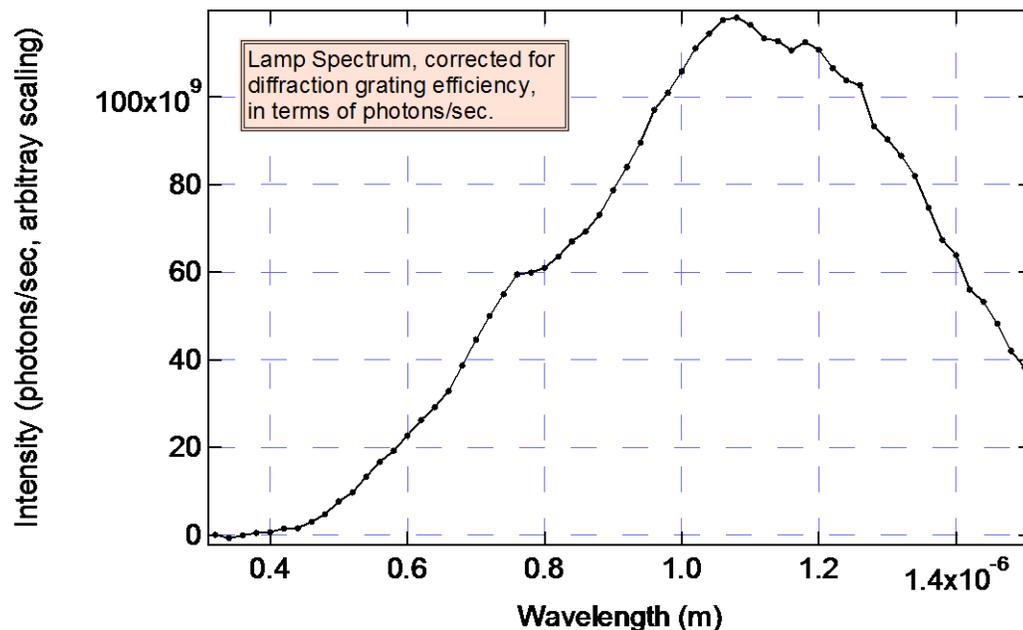
Rename your new waves as *specxcorr* and *specycorr*, and notice that the peak of the spectrum has shifted to longer wavelength.

11. The spectrum of light emitted by the tungsten halogen bulb is close in shape to a blackbody emission spectrum, defined by the temperature of the bulb filament. Much like a glowing ember in a fire, the filament emits radiation (light at a wide range of wavelengths) such that the lower the filament temperature, the longer the wavelength of the peak of the emission.

Convert the corrected spectrum from Volts to values proportional to photons/s. As before, you need not concern yourself with the area of the detector. Recall that the detector produces a voltage proportional to the incident power, specified by the Responsivity). Since this is a linear relationship dependent on energy incident on the detector per unit time, and since we are using a fixed slit width on the monochromator, we do need to correct for the fact that an equivalent amount of energy corresponds to different numbers of photons depending on the wavelength. To determine the relationship, start with the equation relating the energy of a photon to its wavelength: $E = hc/\lambda$. As you increase the wavelength from λ_1 to λ_2 , for the same amount of energy you need to increase the number of photons by the ratio of λ_2/λ_1 . Therefore, multiply the spectrum intensity by λ using the Igor Pro command line:

```
specycorr = specycorr * specxcorr
```

Plotting this spectrum (proportional to photons/sec) shifts the peak to a longer wavelength, which makes sense since photon energy decreases with increasing wavelength.



12. Now you're ready to compare the spectrum to that of a blackbody radiator. We can fit the spectrum to that of a blackbody curve in the units of **spectral photon flux** (with units of $photons/(time \cdot area \cdot \Delta\lambda)$):

$$\frac{dN}{dt} \propto \frac{B}{\lambda^4 (e^{hc/\lambda kT} - 1)}$$

While it is possible in Igor Pro to fit the data to the above blackbody radiation curve to extract the temperature (T) of the lamp spectrum, the limited range of wavelengths and the lack of a correction file for the reflectance of aluminum makes this difficult in this case. However, since Wien's Displacement Law relates the peak wavelength to the blackbody temperature, we can refer to it to determine the temperature corresponding your measured spectrum:

$$\text{Wein's Law: } \lambda_{peak} = \frac{2.8978 \times 10^6 \text{ nm} \cdot \text{K}}{T}$$

One can determine the T corresponding to the peak in the corrected spectrum from the above equation. Determine the wavelength corresponding to the peak of your spectrum using a QuickFit gauss; the Command window will show the Gaussian fit results, and the x0 value provides the peak wavelength with the uncertainty. Follow this exercise, and provide the estimated lamp temperature as part of your Lab Report. In an upcoming lab, we'll fit the Sun's spectrum to the actual blackbody radiation function to determine the effective temperature of the Sun.

Compare your spectrum acquired using LIA detection to your spectrum acquired using direct digitization of the detector output (last week's method). To prepare a graph showing how the data compare, use the raw data (not the corrected data), in terms of voltage. Normalize each curve so that the amplitudes scale from 0 to 1 V, and label the y-axis "Normalized Intensity". Comment on advantages and disadvantages of using the SR510 in the experiment, referring to topics such as signal-to-noise ratio, speed (duration) of the measurement, ability to handle the lower light levels using smaller slits (and how the spectral resolution changes), etc.