Diffraction (E8)

Objectives

- Analyze the diffraction pattern of a single slit. Measure the width of the slit.
- Analyze the interference-diffraction pattern of two slits. Measure the width of the slits and their separation.

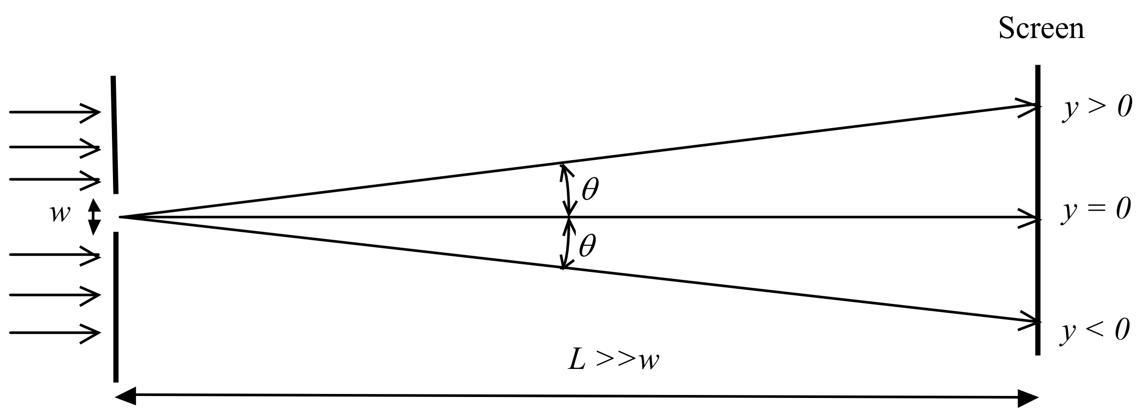
Theory

Diffraction occurs whenever obstacles or apertures limit a portion of a wave front. It is a superposition of many waves at a given point. Diffraction may be observed for all kinds of waves (e.g., electromagnetic waves, sound waves, etc.). Because of the superposition of many waves, the diffracted waves may bend around obstacles or edges, or create patterns of alternating high and low amplitudes (e.g., bright and dark fringes or spots).

The diffraction may be described using the **Huygens' principle**:
Every point on a wave front acts as a source of tiny wavelets that move forward with the same speed as the wave; the wave front at a later instant is the surface that is tangent to the wavelets.

Single-Slit Diffraction Pattern.

Waves passing through a narrow slit of width w produce a single-slit diffraction pattern that includes the central maximum (bright spot) and other bright spots separated by dark spots. The typical experimental setup is shown below.



The diffraction pattern dark spots (intensity minima) occur for the following condition.

$$\frac{wy}{\lambda L} = m \quad \text{or} \quad y = m\frac{\lambda L}{w} , \quad \text{where } m = \pm 1, \pm 2, ... \tag{1}$$

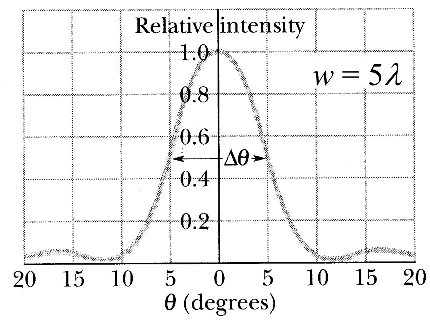
The two dark spots in the center ($m = \pm 1$) are separated by the distance Δy_w on the screen.

$$\Delta y_w = y_{m=1} - y_{m=-1} = \frac{\lambda L}{w} - \left(-\frac{\lambda L}{w}\right) = \frac{2\lambda L}{w} \tag{2}$$

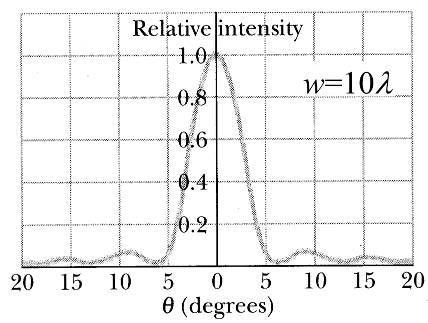
Measuring the distance between the first order dark spots Δy_w and measuring the distance between the slit and the screen one may calculate the width w of the slit.

$$w = 2L\frac{\lambda}{\Delta y_w} \tag{3}$$

Examples of the single-slit diffraction patterns are shown below.

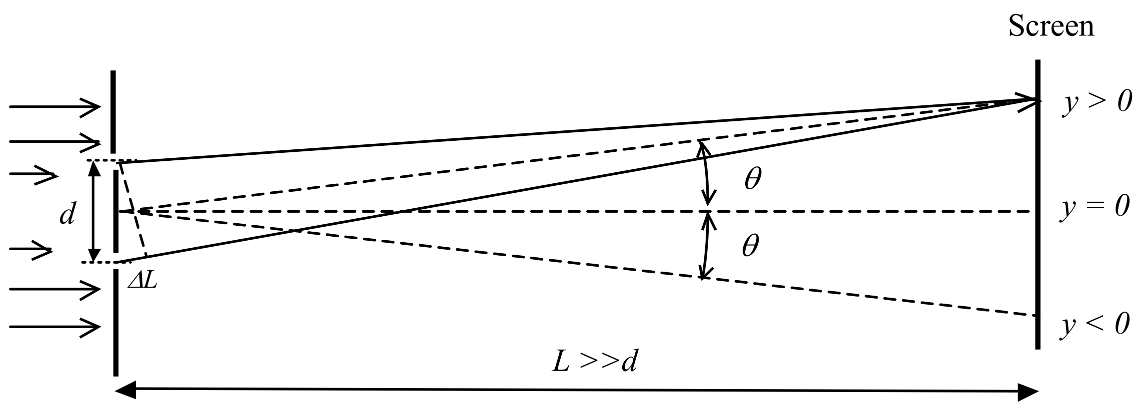


(b)



Interference Pattern for Two Narrow Slits.

The typical experimental setup is shown below.



The light passes through two very narrow slits. The superposition (interference) of two synchronized, point-like sources creates a pattern of alternating dark and bright spots on the screen. The above drawing is not to scale. Usually, the distance between the two slits L and the screen is much larger than the separation between the slits d (i.e., $L>>d$). Let us measure the position y of the bright and dark spots on the screen from the center of the screen. The center spot ($\theta = 0°$) will always have position $y = 0$.

Bright spots on the screen (also called a constructive interference) occur when the distance from this spot to one of the slits differs from the distance to the other slit by an integral number of wavelengths $m\lambda$. It is described by the following equation.

$$\Delta L = d\sin\theta = m\lambda \qquad m = 0,\pm1,\pm2,\pm3,... \tag{4}$$

$$L >> y \quad \Rightarrow \quad \sin\theta = \frac{y}{\sqrt{L^2+y^2}} \cong \frac{y}{L} \quad \Rightarrow \quad y = mL\frac{\lambda}{d} \qquad m = 0,\pm1,\pm2,... \tag{5}$$

Dark spots or destructive interference occurs when the distance from this spot to one of the slits differs from the distance to the other slit by: $\lambda/2,\ 3\lambda/2,\ 5\lambda/2...$

$$\Delta L = d\sin\theta = \left(m+\frac{1}{2}\right)\lambda \qquad m = 0,\pm1,\pm2,\pm3,... \tag{6}$$

$$L >> y \quad \Rightarrow \quad \sin\theta = \frac{y}{\sqrt{L^2+y^2}} \cong \frac{y}{L} \quad \Rightarrow \quad y = \left(m+\frac{1}{2}\right)L\frac{\lambda}{d} \qquad m = 0,\pm1,\pm2,... \tag{7}$$

The distance Δy_d between the two neighboring dark spots in the center of the screen is equal to:

$$\Delta y_d = y_{m=0} - y_{m=-1} = \frac{1}{2}L\frac{\lambda}{d} - \left(-\frac{1}{2}L\frac{\lambda}{d}\right) = L\frac{\lambda}{d} \tag{8}$$

Measuring the distance between the two neighboring dark spots (or two neighboring bright spots) in the center Δy_d and measuring the distance between the slit and the screen L one may calculate the distance d between the slits.

$$\Delta y_d = L\frac{\lambda}{d} \quad \Rightarrow \quad d = L\frac{\lambda}{\Delta y_d} \tag{9}$$

Interference-Diffraction Pattern for Two Wide Slits.

Waves passing two slits, each of width w and a distance d apart, display the two-slits interference pattern with the amplitude modulated by the single-slit diffraction pattern. It is a combination of the single-slit pattern and the double-slit pattern. The picture below (Fig. 1.)

shows the diffraction pattern for a single slit and the diffraction pattern for two slits both having the <u>same width</u> as the single slit.

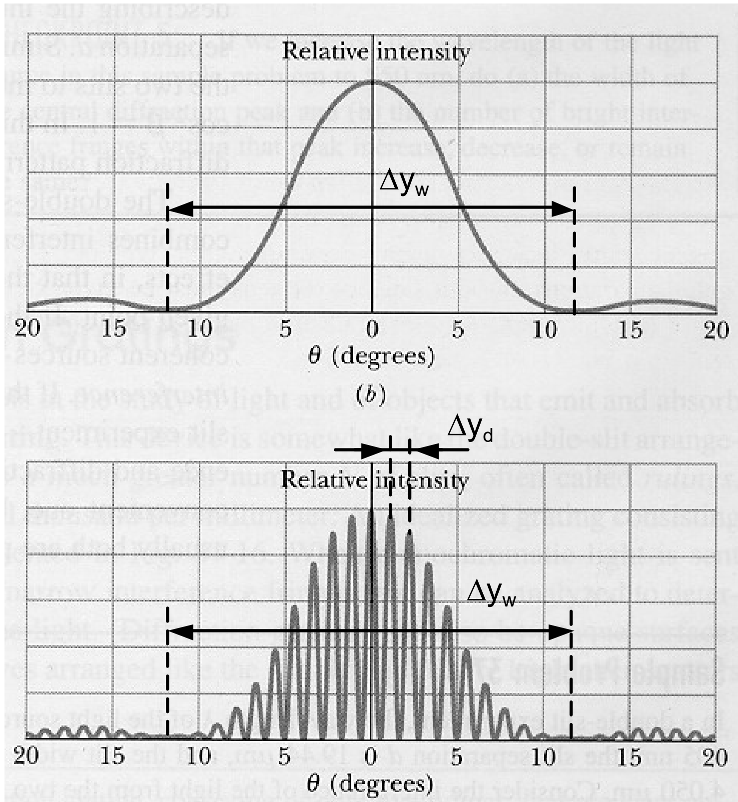


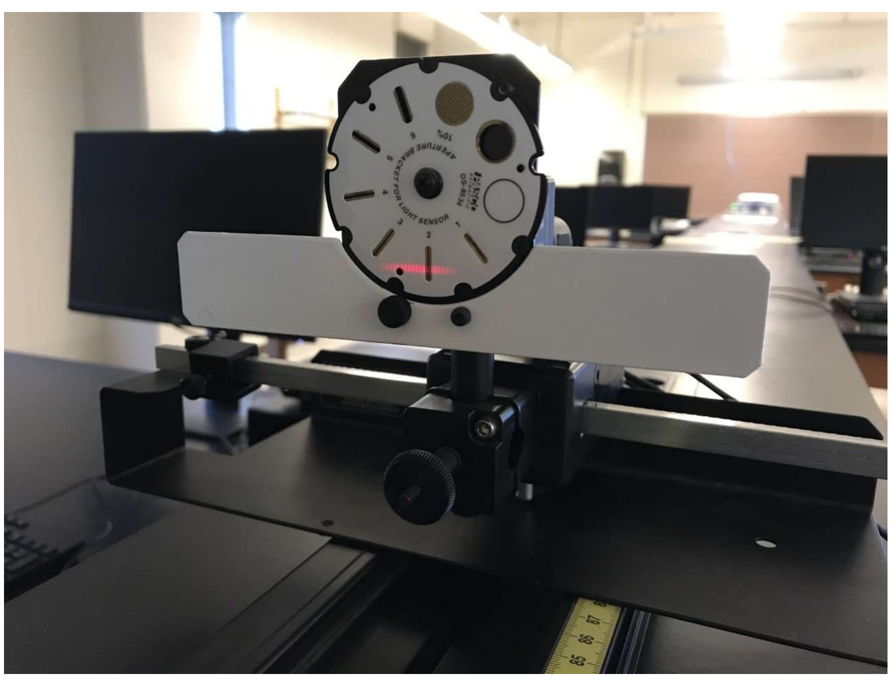
Fig. 1.

Procedure.

Activity 1: Diffraction Pattern of a Single Slit.

The experimental setup includes the optics bench, red and green diode lasers, light sensor with the aperture bracket and two disks with various sizes of single and double slits. The whole setup is shown on the following picture.


DANGER

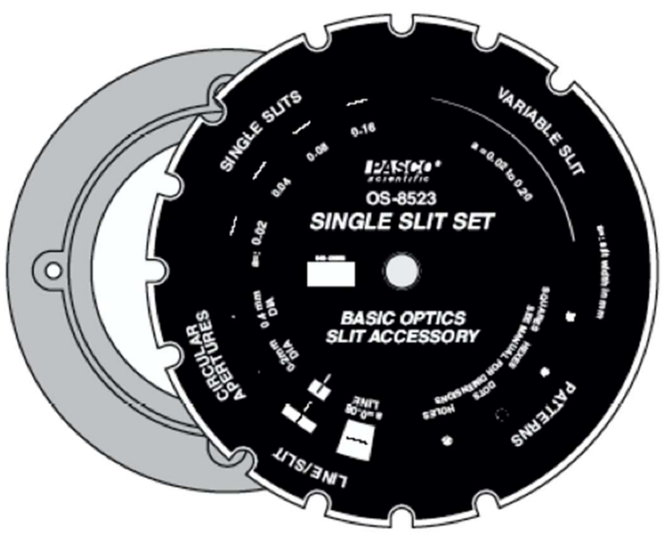

10%
APERTURE BRACKET FOR LIGHT SENSOR

Warning: DO NOT LOOK INTO THE LASER BEAM!

The laser beam will not hurt your hand, but if you look directly into the laser beam, it could be harmful to your eyes.

Before you start collecting data check the **initial settings**:

- Make sure that the data interface is turned on.
- The rotary motion sensor should be connected to the DIGITAL CHANNEL 1 (yellow plug) and DIGITAL CHANNEL 2 (black plug).
- The "HIGH-SENSITIVITY LIGHT SENSOR" should be connected to the ANALOG CHANNEL A. Set the "Gain" slide on the top of the light sensor to "**1**" (minimum sensitivity).
- The **red diode laser** should be turned on. The red light from the diode laser has the average <u>wavelength</u> λ_{red} = 670 nm. (1 nm = $1*10^{-9}$ m)
- The aperture disk in front of the light sensor should be **set to aperture slit #2**, i.e., 0.2 mm wide. In other words, the <u>laser light should go through the slit aperture #2</u>.
- The "SINGLE SLIT SET" accessory disk should be located in front of the laser and set to a single slid with the nominal width $a_{nom.}$ = 0.16 mm. The laser light should go through the $a_{nom.}$ = 0.16 mm slit.

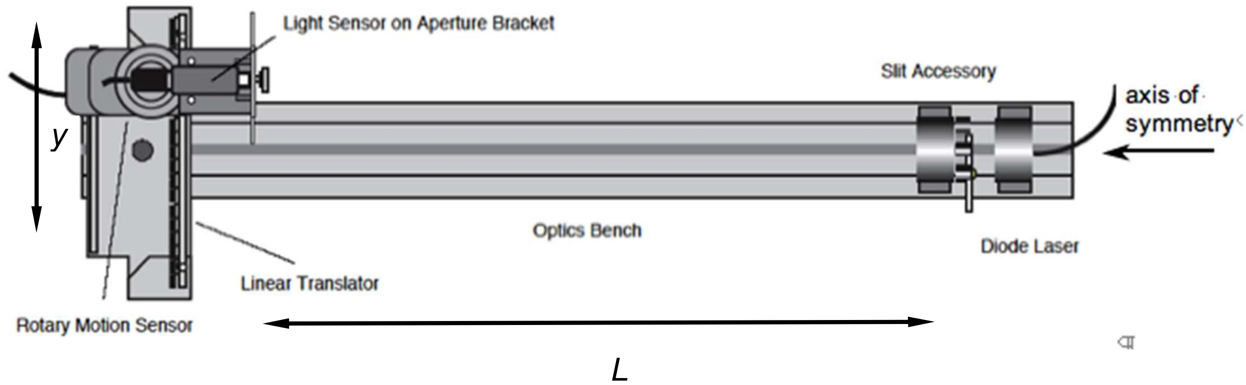


Diffraction pattern of a single slit with red light.

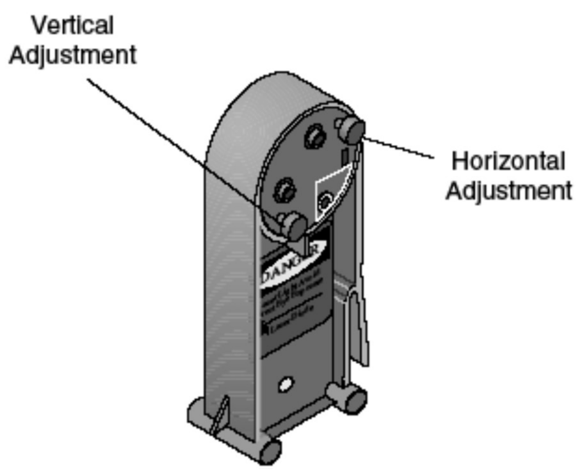
1.1. Login in to Brightspace and find files for experiment E8.

1.2. Download the document "E8, Activities 1-2" and open it. The application "Capstone" should open with configuration ready for Activity 1.

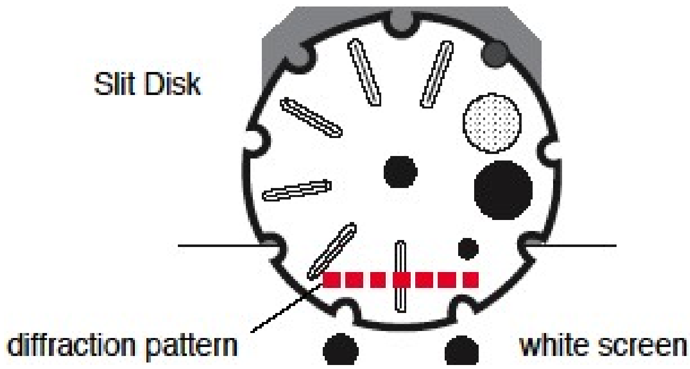
1.3. Turn on the laser and **adjust the direction of the laser beam**. The rotary motion sensor and the light sensor are attached to a device called the linear translator that allows using the rotary motion sensor for measuring the linear position of the light sensor. As the light sensor light sensor moves left or right, the translator combined with the rotary motion sensor measures the position of the light sensor. The light sensor can move in the direction that is perpendicular to the direction of the optics bench.



Check if the brightest spot of the diffraction pattern is pointing at the light sensor. If not, then use the laser's horizontal adjustment (see the picture below) to move the pattern left or right.



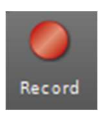
1.4. When the horizontal alignment is done go to vertical adjustment. The diffraction pattern should spread horizontally and should go through the center of the vertical slit located in front of the light sensor. See an example on the picture below. To make the pattern horizontal, rotate the slit disk frame.



1.5. Measure the distance ***L* between the disk with slits and the light sensor**. *L* should be between 0.75 m and 0.90 m. Remember that for the <u>red diode laser</u> λ_{red} = 670 nm. 1 nm = $1*10^{-9}$ m

1.6. Verify that the "SINGLE SLIT SET" accessory disk should be located in front of the laser and set to a single slid with the nominal width $a_{nom.}$ = 0.16 mm.

1.7. Move the light sensor to the leftmost position (when looking from the laser side of the optics bench). There is a small stopper on the linear translator, which is approximately 5.0 cm from the symmetry axis. This (y = -0.050 m) is going to be a **starting position** for all measurements.

1.8. Click on the 

button. Initially, you should not see any data. **Slowly and steadily** move the light sensor from its initial position to make a 10 cm scan. Once you get to the point that is located at 5 cm from the center, but on the other side of the optics bench (y = +0.050 m), the data acquisition stops automatically. The whole scan should take ~30 seconds. You may get a smooth motion when instead of pushing the whole light sensor assembly you try to rotate the disk on the top of the rotary motion sensor. The direction of the sensor's motion is perpendicular to the light beam. That way, we get the graph of light intensity vs. position (in perpendicular direction to the beam). Without any slits we would simply observe a single bright spot in the center of the screen without any other patterns. When the computer finish collecting data points, move the light sensor back to the starting position. If computer does not start collecting data when you move the sensor, then <u>try reversing direction of the motion</u> (this could happen when the rotary motion sensor was accidentally installed upside down).

Once the laser beam goes through a slit (or a pair of slits), then it diffracts creating more complicated patterns on the screen. The light sensor measures the light intensity changes and sends that information to the computer for visual representation in form of light intensity graph. Using the intensity graph, we can perform quantitative analysis of the diffraction pattern, not just observe it.

1.9. You should see two graphs on the monitor. The upper graph shows the intensity of the light versus the position of the light sensor $I(y)$. The lower graph shows the log $(I(y))$. The log scale has one very important advantage. It shows more clearly, where the light intensity minima are located. The positions of the minima on the log scale are the same as for the linear scale. **Print** this graph #1.

1.10. Using the log $(I(y))$ graph measure the distance Δy_w between the first order diffraction minima (dark spots). Using Equation (3) find the measured width w of the single slit. Remember that $\lambda_{red} = 670$ nm.
What is the percent difference between the measured value and the nominal width of the slit?
What is the ratio of the measured width of the slit to the wavelength of the laser light?
What should happen to the diffraction pattern if we would reduce the w/λ_{red} ratio? (*Hint*: see the Theory section)

1.11. Gently rotate the "SINGLE SLIT SET" to get the laser light through the next slit with the nominal width $a_{nom.} = 0.08$ mm. Check if the diffraction pattern spreads horizontally. Repeat the measurements (steps 1.7 – 1.10) for this wider slit. **Print** this graph #2.

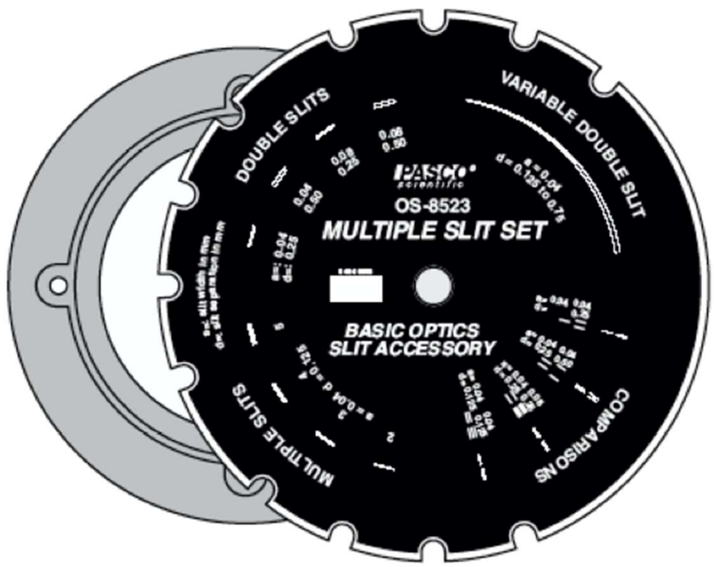
1.12. Using the log$(I(y))$ graph measure the distance between the first order diffraction minima Δy_w. Find the measured width w of the single slit. Remember that for the red laser $\lambda_{red} =$ 670 nm.
What is the percent difference between the measured and the nominal width of the slit?
What is the ratio of the measured width of the slit to the wavelength of the laser light?

1.13. Gently rotate the "SINGLE SLIT SET" to get the laser light through the next slit with the nominal width $a_{nom.} = 0.04$ mm. Check if the diffraction pattern spreads horizontally. Change the "Gain" slide on the top of the light sensor to "10". Repeat the measurements (steps 1.7 – 1.10) for this wider slit.

1.14. Using the log$(I(y))$ graph measure the distance between the first order diffraction minima Δy_w. Find the width w of the single slit.
What is the percent difference between the measured value and the nominal width of the slit?
What is the ratio of the measured width of the slit to the wavelength of the laser light?

Activity 2: Interference-Diffraction Pattern of Two Slits.

2.1. Remove the "SINGLE SLIT SET" accessory disk from the optics bench and replace it with the disk called "MULTIPLE SLIT SET". That one contains several "DOUBLE SLITS" as well as some other configurations of multiple slits. Remember that for the red diode laser λ_{red} = 670 nm.



2.2. Measure the distance L between the disk with slits and the light sensor. It should be between 0.75 m and 0.90 m.

2.3. Use the same software as for Activity 1. Change the aperture disk in front of the light sensor to slit #2, i.e., 0.2 mm wide. In other words, the laser light should go through the slit aperture #2.

2.4. Gently rotate the "MULTIPLE SLIT SET" to get the laser light through the slit with the nominal width $a_{nom.}$ = 0.04 mm and the nominal separation between slits $d_{nom.}$ = 0.25 mm. Check if the interference-diffraction pattern spreads horizontally. Change the "Gain" slide on the top of the light sensor to "10". Repeat the measurements (steps 1.7 – 1.10) for this pair of slits. **Print** this graph #3.

2.5. Using the log(I(y)) graph measure the distance between the first order diffraction minima Δy_w. Find the measured width w of the single slit. Remember that λ_{red} = 670 nm. If you are not sure how to read Δy_w and Δy_d, then check Fig.1 in the Theory section.
What is the percent difference between the measured and the nominal width of the slit?
Using the log(I(y)) graph measure the distance between the interference minima Δy_d. Find the measured separation d between the two slits.

What is the percent difference between the measured and the nominal value of the separation between the two slits?

2.6. Is the distance between the first diffraction minima similar to that for the single slit with the same width? ($a_{nom.}$ = 0.04 mm, Activity 1)

2.7. Gently rotate the "MULTIPLE SLIT SET" to get the laser light through the next slit with the nominal width $a_{nom.}$ = 0.04 mm and the nominal separation between slits $d_{nom.}$ = 0.50 mm. Check if the interference-diffraction pattern spreads horizontally. Repeat the measurements (steps 1.7 – 1.10) for this pair of slits. **Print** this graph #4.

2.8. Using the log($I(y)$) graph measure the distance between the first order diffraction minima Δy_w. Find the measured width w of the slit.

What is the percent difference between the measured value and the nominal width of the slit?

Using the log($I(y)$) graph measure the distance between the interference minima Δy_d. Find the measured separation d between the two slits.

What is the percent difference between the measured and the nominal separation between the two slits?

2.9. **Turn off the laser**. Restore the initial conditions, i.e., remove the holder with diffraction grating and attach the holder with the "SINGLE SLIT SET" at the distance of 0.90 m from the screen.

Make sure to complete the following tasks:

You must submit the answers to the prelaboratory questions online. (3.5 points)

1. Four printouts from *Activities 1* and *2*. (4*1 = 4 points)
   (Title and write your name and those of your partners on each graph.)
2. Your completed Data Sheets. (2.5 points)
3. Return the completed lab report to your lab TA.