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NEW TECHNOLOGIES FOR UNDERSTANDING OF OPTICS: "TRAVELING ON THE CREST OF A WAVE"

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Abstract

Optics experiments, that show some important aspects of physical optics were performed to motivate students to obtain quantitative relations in the form of phenomenological laws. These experiments, tested with high school students and in a course for physics teacher education, are bricks of a teaching learning sequence.

The experiments require simple and inexpensive material or tools readily available in a well-equipped teaching laboratory.

Diffraction patterns are produced by monochromatic light coming from a commercial laser diode. To measure light intensity we propose three different methods:

- a traditional "manual" measurement of the alternating maxima and minima;
- a microcomputer based laboratory tools (MBL) measurement;
- a "digital camera" based measurement.

In the latter case the photo camera is used as a light detector. Here we discuss how digital photos can be extremely useful in physics research and teaching. Computer analysis of these "live photos" allows to measure the wavelength and intensity of light at different points and to extract detailed data about diffraction or interference patterns.

Specific software was developed with our students in order to treat the experimental data and to compare them with the theoretical predictions.

1. Introduction

In a paper of ten years ago the Physics Education Group at the University of Washington reported the results of an investigation of student understanding of single-slit diffraction and double-slit interference. They write "Results from an investigation of student understanding of physical optics indicate that university students who have studied this topic at the introductory level and beyond often cannot account for the pattern produced on a screen when light is incident on a single or double slit. Many do not know whether to apply geometrical or physical optics to a given situation and may inappropriately combine elements of both. Some specific difficulties that were identified for single and double slits proved to be sufficiently serious to preclude students from acquiring even a qualitative understanding of the wave model for light [1].

These results confirm some previous researches that have investigated student understanding of the nature of light by analyzing responses in a variety of contexts [2-6]. Many of these studies have focused upon ''misconceptions'' or ''alternative frameworks''.

In order to improve the student understanding of physical optics we are working on a teaching learning sequence about the wave nature of the light. In order to design this sequence we made some choices: (i) teachers should offer students an overview of the wide-ranging phenomenology of geometrical and physical optics, from reflection and refraction to diffraction and polarization; (ii) experiments should be performed to motivate students to obtain quantitative relations in the form of phenomenological laws; (iii) teachers should emphasize the role of a physical theory and its capability of interpreting the experimental data and of encompassing the results of a previous theory. The sequence of topics is organized into three parts: (1) introductory experiments and observations about reflection and refraction (quantitative measurements of the Snell law); (2) diffraction and interference: first observations and definition of descriptive quantities, then quantitative measurements; (3) light polarization first observations, then quantitative measurement of the Malus law.

The experimental activities play a central role in the sequence since they are the starting points on which to construct an interpretation of the different considered phenomena. These experiments were designed with the aim of motivating students to obtain quantitative relations in the form of phenomenological laws and overcoming specific learning difficulties.

Most of the activities were conducted among high school students enrolled in a program devoted to orient students before the choice of their universities studies. All ideas indeed emerged in the so-called ‘Scientific degrees project’ involving high school students inside the environment of the physics university *Alessandro Volta* of Pavia for labs activities. During their forth year of high school (age of students 17-18 years), students are introduced to two different ways of thinking about the behavior of light. The high school teachers usually present first the geometrical optics based on the ray model. Thus the students study reflection and refraction, draw ray diagrams, and solve numerical problems for a variety of simple optical systems. Later, in physical optics, the students learn that light is a transverse electromagnetic wave that propagates in the space (wave model). They are taught the concepts and formal representations that are used to predict and explain diffraction, interference, and polarization. The experiments of the sequence have been proposed to the students at the end of the forth year of high school.

In the past it was very difficult both to have in high school labs a monochromatic coherent light source and to measure the intensity of the light with good approximation. The latter problem can be now solved by using Interfaced Communication Technology (ICT). ICT use for teaching science has increased dramatically in recent years and has proved to be a very effective tool in a variety of situations. In particular, computers equipped with data acquisition systems have increased the level of hands-on experimental activity in science laboratories at both secondary school and university. Supported by a variety of sensors such as voltage, current, light, force and temperature, these systems have shown to be pedagogically effective, particularly where high level learning skills are concerned [7-10]. The most popular commercially available low-cost data acquisition systems include those supplied by Vernier [11], PASCO [12], CoachLab [13] and ComLab [14]. Pupils understanding of basic physics concepts can be significantly improved by the use of such utilities in an interactive and ‘hands-on’ approach.

In the following we focus on a single experimental problem by considering different way to approach it.

In particular, in section 2 we present the physics content to be explored. In section 3 we describe the experiments about diffraction from single an double slits and three different methods to measure the diffraction pattern. Main features of the different methods are discussed.

2. The physics content

Measuring of the interference and diffraction patterns produced by light passing through single and double narrow slits is a classic undergraduate physics experiment that dramatically confirms the wave nature of light. To determine the form of a diffraction pattern, we have to consider the phase and amplitude of each of the Huygens waves at each point in space and then find the sum of them.

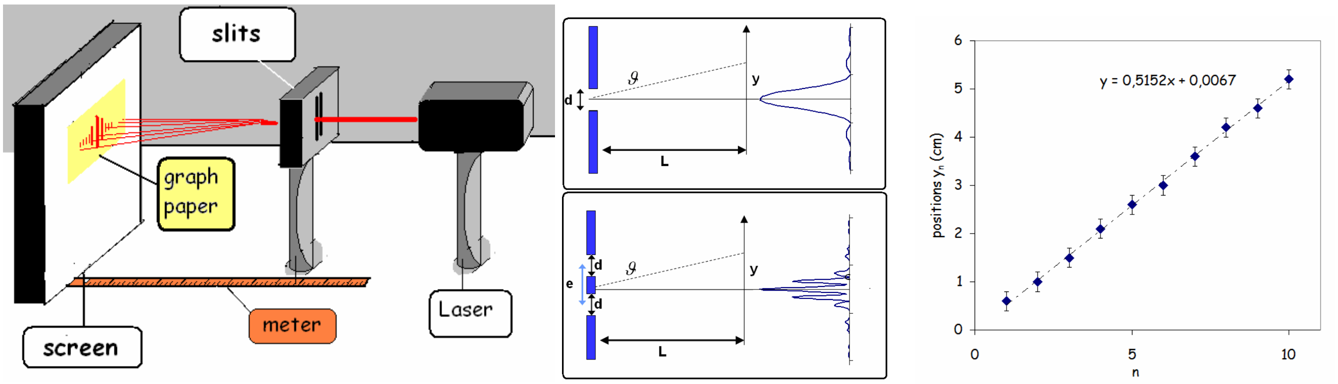

Figure 1. (left panel) the experimental setup. Diffraction patterns are produced on a screen by monochromatic light coming from a commercial laser diode. The screen is fixed at a distance L<1 m from the slits. We fix a sheet of paper on the screen. (middle panel) a schematic plot of the single and double slit experiments with the notation considered in the text. (right panel) a typical measurements performed by the students; the position of the first 10 minima of a single slit diffraction pattern.

Consider a single slit experiment in which light of wavelength λ is diffracted by one slit of width d. The experimental setup is schematically reported in Fig.1 (left panel). The intensity at a point on the screen (at a distance *L* from the slit) $I(\vartheta)$ associated with an angle ϑ is given by the equation:

$$I(\theta) = I_0 \frac{\sin^2 \mathrm{x}}{\mathrm{x}^2}, \tag{1}$$

where I_0 is the intensity at center of the diffraction pattern, $x = (\pi d/\lambda) \sin \vartheta$, $\sin \vartheta = y/L$ and *y* is the coordinate along the screen (see the middle panel in Fig.1).

For a single slit, the minima in the diffraction pattern occur at positions that satisfy the condition $y_n = \pm n\lambda(L/d)$, with $n = \pm1, \pm2, \ldots$.

Consider a double slit experiment in which light of wavelength λ is diffracted by two slits each of width *d* and separated by a distance *e*. In this case, the intensity at a point on the screen associated with an angle ϑ is given by the equation:

$$I(\vartheta) = I_0 \frac{\sin^2 \mathrm{x}}{\mathrm{x}^2} \cos^2 \delta, \tag{2}$$

where I_1 is the intensity at center of the diffraction pattern and $\delta = (\pi e/\lambda) \sin \vartheta = (\pi e y)/(\lambda L)$. Thus the double slits interference pattern is actually a single slit diffraction pattern superimposed on interference pattern for two very narrow slits (see the middle panel in Fig.1). For a double slit, the minima in the interference pattern occur at positions that satisfy the condition $y_n = \pm\lambda(L/e)(n+1/2)$ with $n = 0, \pm1, \pm2, \ldots$. Notice that eqs (1) and (2) are valid only for large distances, $L >> d^2 / \lambda$ (Fraunhofer diffraction).

3. Experiments

In the following we describe three different methods to perform the same kind of experiment. Each method focuses on different aspects and develops complementary students experimental skills. In this way students directly measure all the relevant quantities to explore the effectiveness of the wave model of light.

In each experiment a commercial laser diode is used as light source because of its small divergence angle, but also because of monochromatic light avoids the complication of the colour dispersion. Thus the light source used in the experiments is a 5 mW laser diode at wavelength λ=650 nm. Such sources are commonly available as pointers or pattern projectors and provide a coherence length up to some centimeters, which is enough for our configuration.

3.1. Traditional manual measurement

The students carry out a traditional manual measurement of the alternating maxima and minima by using graph paper and pencil. They can also move the screen by changing the distance between the screen and the slits and use slits with different width.

The experiment does not require a dark environment. It was presented by a group of students also as exhibit in a didactical exhibition. The experimental setup is shown in Fig.1 (left panel).

In order to analyze the data acquired in a measurement session we developed with the students a specific program by using a spreadsheet-software (Excel). Since students have often difficulty in understanding how interference and diffraction patterns are formed, and how different parameters (slit separation, wavelength, and distance between slits and screen) can affect the pattern, two Excel worksheets are devoted to reproduce the theoretical plots of *I*(θ) according to the variations of *L*, d and *e* (in our experimental setup λ is fixed).

For each measurement session, after choosing the appropriate physical parameters, the students started the program in order to compare the results with the theoretical prediction in real time.

A third Excel worksheet is devoted to the analysis of the experimental data. In this case, when *L* is fixed, by performing a measurement of the minimum positions on the screen, the students were able to evaluate the width of the slits.

In this way the experimental apparatus can be seen as a device able to measure the geometrical dimensions of a micro-object. Thus the student measured the hair thickness of many visitors at the didactical exhibition. In Fig.1 (right panel) the position of the minima as measured by the students is shown.

3.2. MBL based measurement

In order to improve the quality of students experiments on physical optics we used a simple methodology that exploits the advantages of MBL labs and digital techniques to record diffraction patterns. In fact, with this experiment not only the position but also the intensity of the peaks of the diffraction pattern are measured by means of the coordinated use of two sensors. We used, in particular, the light sensor (photo diode or PASCO PS2106A) to measure the intensity of the light and a motion sensor to measure the relative positions of minima and maxima in the diffraction pattern. DataStudio software records and displays the data acquired by the sensors and plots the intensity versus position graphs. The experimental setup is shown in Fig.2 (left panel).

Measurements for single slit and double slits were recorded and the intensity profiles were analyzed by fitting the experimental values with the theoretical curves in the Fraunhofer approximation [15].

First we use a photo diode as light sensor by measuring the light dependent voltage as a function of the position along the linear bar.

Two filters are adopted to attenuate the intensity of the source in order to measure all the intensity profiles for a single slit diffraction avoiding saturation phenomena due to the high difference in intensity between the central peak and those lateral one. In Fig.3 (left panel) we report the results.

Next measurements were performed by using PASCO photo and motion sensors connected to a DataStudio interface running DataStudio software. The plot of the light intensity (and the logarithm of it) as a function of the position along the linear bar is reported in Fig.3 (right panel) for a double slit diffraction.

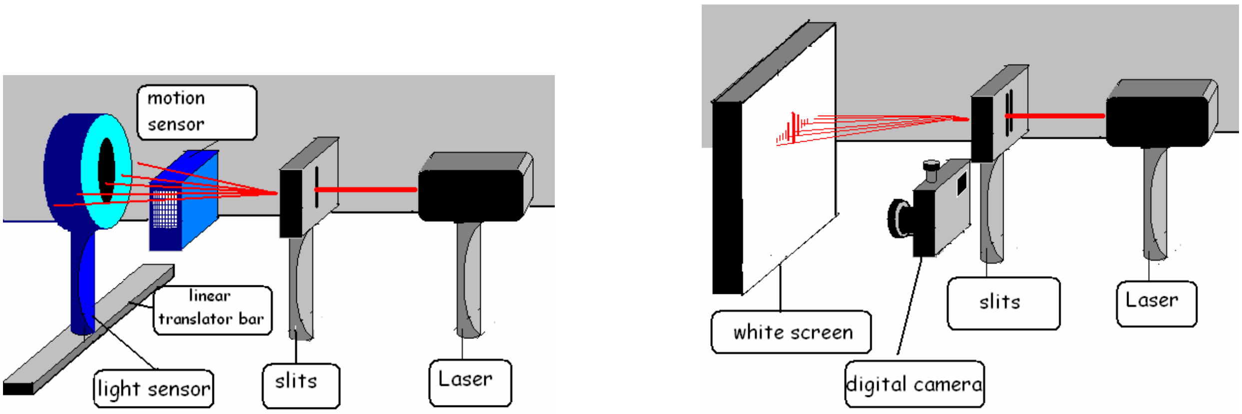

Figure 2 (left panel) Diffraction patterns are produced by monochromatic light coming from a commercial laser diode. A light sensor moves along a linear translator bar fixed at a distance L<1 m from the slits. A motion sensor measures the light sensor positions. Signals from the light sensor and motion sensor are processed by a computer. (right panel) Diffraction patterns are produced by monochromatic light coming from a commercial laser diode. A white screen is fixed at a distance L<1 m from the slits. A digital camera is fixed between the screen and the slits while the acquired images are processed by a computer.

3.3. "Digital camera" based measurement

The use of digital image techniques to demonstrate basic concepts in physics was initiated in the 1990s [16-21] and it is now increasing due, mostly, to the low cost of digital cameras and the development of digital image processing software [22]. In our measurements, the digital image of the whole pattern is acquired by the camera and processed.

The experimental setup to obtain images of the diffraction patterns is shown in Fig.2 (right panel). Photos of the diffraction patterns produced by monochromatic light on a white screen are acquired by using a digital camera. The computer is used for visualizing, storing, and analyzing the images. A digital image consists of an array (rectangular matrix) of pixels distributed in rows and columns.

Each pixel is a combination of primary colors red, green, and blue (RGB channels roughly follow the color receptors in the human eye). The RGB images are 24-bit, i.e. each channel has 8 bits, for red, green, and blue. It follows that each pixel is an array of 3 values (RGB color intensities) between 0 and 255.

The computed intensity pattern is got then from an algorithm managing each single pixel RGB values contained in each digital image. Finally the latter is compared with the theoretical intensity diffraction pattern superimposed to them.

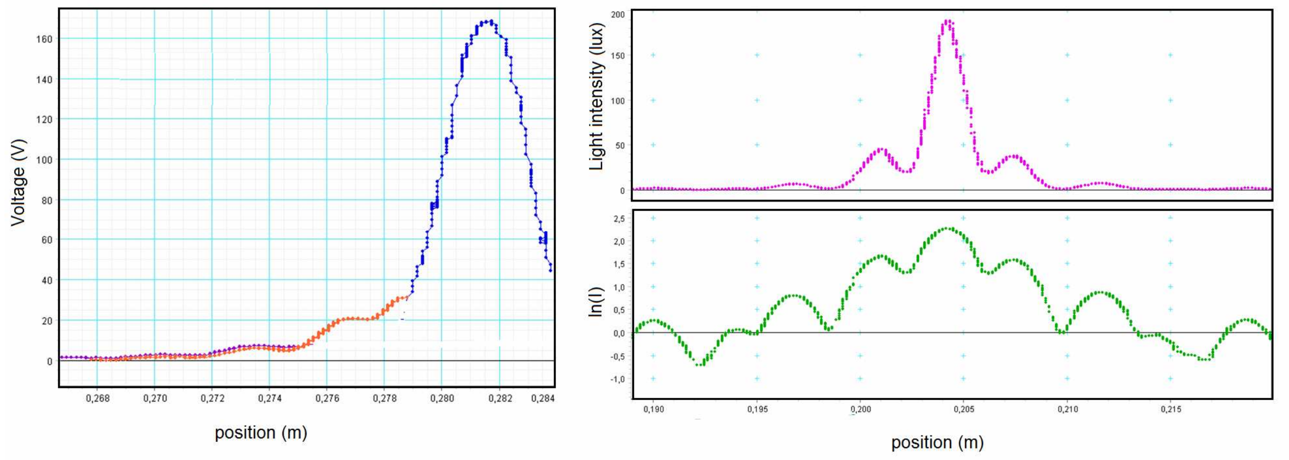

Figure 3 (left panel) Plot of the resulting intensity profile of the single slit diffraction pattern obtained by using a photodiode as light sensor. Two optical filters have been used to make visible the entire pattern due to the extremely high difference in intensity between the central peak and those lateral to avoid saturation phenomena. (right panel) On the top a plot of the resulting intensity profile of the double slit diffraction pattern obtained by using a PASCO sensor PS2601A. Optical filters have been used to explore again all the diffraction pattern. On the bottom a plot of the logarithm of the intensity reported in the top panel emphasizes the presence of several peaks.

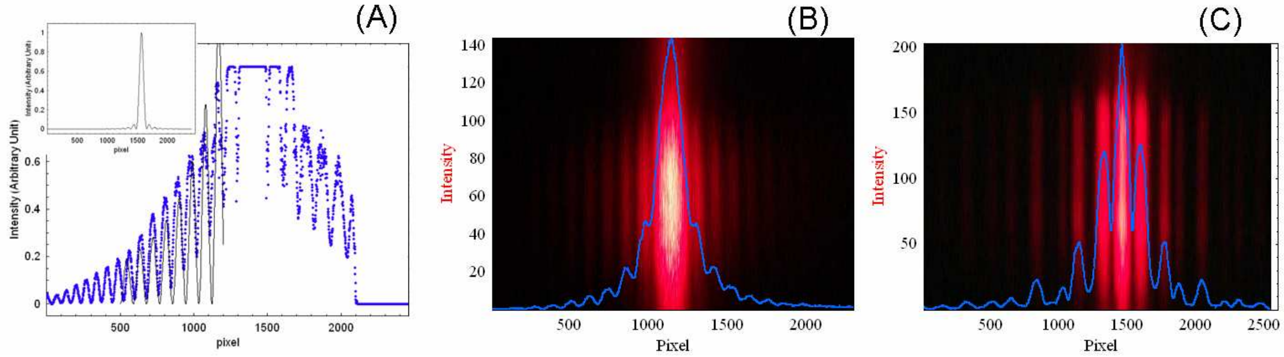

Figure 4 (A) Plot of the resulting intensity profile of the single slit diffraction pattern (L~0.8m, d~0.1mm) with an ad-hoc exposure time. Notice that the intensity of the bright central maximum can not be measured due to saturation, while the intensity of many side peaks is correctly represented. (B) Plot of the resulting intensity profile of the single slit diffraction pattern superimposed to the digital photo captured with auto-setting in the exposure time. The bright central peak results automatically reduced in intensity below the sensor saturation threshold.(C) Plot of the resulting intensity profile of the double slit diffraction pattern superimposed to the digital photo. In this case saturation of the central peak does not occur and the interference peaks are visible.

It is important to note a technical problem related to the peak intensity saturation. Due to the extremely high difference in the diffraction pattern between the intensity of the central maximum and the intensity of the lateral peaks, as previously discussed, image saturation can occur depending by the camera setting. If the camera presents an auto-setting in the exposure time, the relative intensities of the peaks are correctly represented only for lateral side maxima, while the bright central peak results automatically reduced in intensity below the sensor saturation threshold. On the contrary, an ad-hoc adjustment of the time exposure allows obtain images where many side peaks are correctly captured while the bright central maximum is saturated (see the panel (A) of Fig.4).

The concept is fundamental particularly in the double slit experiment where several interference maxima can fall inside the single slit diffraction profile maxima. With an auto-setting camera all the interference maxima inside the single diffraction maximum profile can be made visible however the theoretical profile do not agree anymore (see Fig.4 right panel). These plots were compared with the ones obtained by the students by using a spread-sheet software and the limits of the digital camera based measurements were widely discussed.

4. Conclusive remarks

We have reported on three simple methods to perform quantitative experiments concerning the Fraunhofer diffraction, tested with high school students.
The first method is based on a traditional manual measurement of the position of alternating maxima and minima.
This traditional approach is surely the most simple and inexpensive. Good quantitative measurements were obtained about the position of peaks just by using an hair (as a scattered center) and a commercial laser diode. This experiment can be carried out also in an enlightened environment and with a source-screen distance below 1m. The use of ad-hoc prepared Excel sheets allows a real time comparison of the experimental data with the theoretical prediction, improving the students understanding of the wave model of light.
The second method have the advantage of reproducing the intensity profiles of the diffraction patterns. The one based on a photodiode or a PASCO sensors requires specific tools and it is thus more expensive (even if these tools are now often available in a well-equipped teaching laboratory).
The third method is based on the use of a digital photo camera and on computer image processing. Quantitative data on light intensity can be easily obtained, avoiding the use of filters, which diminish the intensity and cause the loss of information about the diffraction pattern.
By employing this methodology students can quickly and routinely record diffraction patterns. Simple calibrations allow them to convert pixel numbers to position values with a high degree of accuracy. This technique can also be used for other photometric applications.
After the experiments, most of the students overcame their learning difficulties as was also tested by their performances at the end of the year. Students were able not only to show the results of the experiment to their peers during an exhibition, but also to explain them the physical interpretation of the experimental results. Moreover, from the interviews with students, carried out by us after the course, we could argue to what extent this experience was for them involving and amusing.

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