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Introduction to Fundamental Concepts of Spectroscopy Using the Lhires III Spectrograph

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Abstract: This article proposes and analyzes the use of the high-resolution Lhires III spectrograph as a pedagogical tool for teaching-learning concepts of optical spectroscopy. A methodology was developed and it was tested in a population of 20 students from different engineering programs at the Technological University of Pereira, Colombia. The methodology was implemented through a guide, which describes the 3 experiments that are part of the methodological proposal. Upon completion of the guide, students were asked to respond to a test. The Hake gain coefficient was used to measure the learning evolution of students and verify the methodology proposed in this study. 85% of the students affirmed they would like to explore in more depth the concepts of spectroscopy. Although more analysis may be required to verify the findings, these preliminary results show the experiments carried out with the Lhires III allow students to strengthen knowledge acquired in the classroom, fostering interest in science both at high school and university levels.

Keywords: Fundamental Concepts of Spectroscopy, Lhires III Spectrograph, Science Education, Teaching-Learning

Introduction

One of the common questions that is found in teacher training processes and in different methodologies to improve science education, is “How can we teach science in order to make a significant impact?” This question seeks to promote concrete discussions that provide theoretical and practical elements for the teaching and learning of the sciences and, where it is possible, to demonstrate necessary and fundamental relationships between conceptual, social and cultural elements of the actors involved in this process (Ortega, 2007). To understand the problem of science teaching, specifically physics, it is necessary to look for the cause and effect of the problem situation in the teaching-learning process of this science (Arruda and Marín, 2001). The lack of motivation of students in the learning of physics calls for, as a central point, the need for a new paradigm supported by scientific methodology and pedagogical tools that bring the concepts of physics to students in ways that differ from traditional methodologies as proposed by several authors (Kuhn, 1998; Savery, 2001; Hmelo-Silver, 2004; Goh, 2014).

The program’s activity guide represents an application of the constructivist model of science learning. Basic ideas underlying the development of these programs are to encourage the construction of knowledge by students and to familiarize them with some characteristics of scientific work. The activities included in the program guide may be varied but can be classified into three main categories according to Gil and Martínez (1987): Initiation activities (sensitization of the subject, explanation of the ideas that the students possess, etc.), development activities (introduction of scientific concepts, repeated management of concepts, detection of errors, hypotheses foundation, connection between different parts of the subject, elaboration of experimental designs, etc.) and finishing activities (synthesis, schematics, conceptual maps, learning, etc.).

The 2015 Program for International Student Assessment (PISA), an assessment that measures 15-year-old students’ reading, mathematics and science literacy every three years, focused on science literacy for its data collection. A person with knowledge in science knows and is willing to participate in a reasoned discourse on science and technology. This discipline plays an increasingly important role in our economic and social growth. Science knowledge requires the skills to: Scientifically explain a range of natural and technological phenomena, evaluate and design research and interpret data to draw appropriate scientific conclusions (OECD, 2016). In 2015, the highest-scoring countries in Latin America were Argentina, in the position (38), Chile (44), Uruguay (47), Costa Rica (55), Colombia (57), Mexico (58) and Brazil (68). Colombia scored 416 in the area of science, compared to the average of 493 in the OECD countries. 15-year-old Colombian youths scored more than 70 points lower than the students of Portugal and Spain and between 20 and 60 points lower than the students of Chile and Uruguay, only scoring higher than the students of Mexico, Brazil, the Dominican Republic and Peru (OECD, 2016). According to the PISA results, we see how science education in countries like Colombia is poor. According to statistics from the Colombian government, basic science has been on the decline in the last 5 years. Only 0.3% of Colombian students graduated with degrees in physics, mathematics, biology and/or chemistry (Mineducación, 2014; El Colombiano, 2015). The apathy for science is due, among other things, to the lack of tools that stimulate its study. Because of this, it is important to familiarize students with the investigative process in such a way that they can identify the physical phenomena that are part of their everyday environments and in this way build knowledge to apply to their scientific study (El Espectador, 2013; ICFES, 2007).

Teaching optical spectroscopy allows students to be astonished by the nature of light, to question it and to acquire the necessary tools to problem solve during a guided program offered by the teacher. Because of this, laboratory practices are a didactic component that strengthen the investigative process (Duch, 1996; Restrepo, 2005). In the instrumentation for the teaching of physics, there is different equipment for performing spectroscopy experiments in engineering and basic sciences. The equipment available has drawbacks. In general, the equipment is formed by individual pieces. For instance, the Leybold brand spectrometer measures spectra of noble gases and metal vapors (Leybold). Unfortunately, this equipment is highly specialized and runs the risk of not being properly handled and can be easily damaged since the lamps provided by this equipment are placed manually in a support to be fed by a source. If the lamp breaks, students will be exposed to toxic gases, like mercury. Also, the grid is not fixed and can fall and be damaged by poor handling. For the above reasons, students perform this experiment in fear of an accident and learning is compromised. Another tool used to teach science in a didactic classroom is the Red-Tide USB-650 of Ocean Optics Company (OceanOptics). This device is designed mainly for experiments in chemistry. It's effective in that it allows the observation of spectral lines of different lamps in the optical range. However, these spectral lines come out in low resolution. In general, teachers don't have access to good equipment to teach spectroscopy.

The Lhires III spectrograph, being a compact and portable, resolves the aforementioned problems and can be an essential piece of laboratory equipment to enable students to learn high-concept science in a more meaningful way. The Lhires III spectrograph allows students to observe the emission lines of different lamps and observe solar spectrum (like a rainbow), a natural source of radiation. In turn, this tool gives students the opportunity to identify, in everyday life, the concepts of emission and absorption of light. Observing the diffraction of light at different wavelengths is something that fascinates students. The emission and/or absorption lines of these spectra are like fingerprints and are unique to each chemical element (Harrison, 2011). Furthermore, the study of these spectra allows to learn the chemical composition, temperature, density and radial movement of a star (Robinson, 2007; Kaler, 2011).

Using the Lhires III spectrograph, a teacher's guide was made to facilitate the teaching-learning of some of spectroscopy's most fascinating concepts. The guide was tested in a population of 20 students (divided into 10 groups) of different engineering programs at the Technological University of Pereira. This guide included the following experiments: Fraunhofer diffraction through a rectangular slit, observation of spectral lines of neon and argon emission lamps and observation of absorption lines of the solar spectrum. A software called Lambda for Lhires III was also developed to support the realization of the experiments and the SBIG ST-i color camera was used to capture the spectra.

The objective of the present work is to show a didactic way to strengthen the knowledge and to enhance the students' abilities in the area of sciences, arousing their curiosity about physics using the Lhires III spectrograph. This instrument is an excellent tool to support the teaching of physics. It should be part of educational projects to promote the learning of physics and spectroscopy and to increase public interest of science both at school and university levels (Thizy *et al*., 2008), critical for countries like Colombia where science levels are below the average of OECD countries (OECD, 2016).

Methodology

The methodology presented in the following article proposes the introduction to some fundamental concepts of spectroscopy using the Lhires III spectrograph of the French brand Shelyak Instruments. A general diagram of the proposed methodology can be seen in Fig. 1. For this purpose, an activity guide was developed which was tested with 10 groups of students from different programs of the UTP's fifth semester. In this semester, students are already familiar with the principles of light and the laws of optics, concepts that are learned in a regular course of physics III. Figure 2 shows an image of the Lhires III spectrograph of the Astronomical Observatory of the Technological University of Pereira (AOTUP), which was used in this study.

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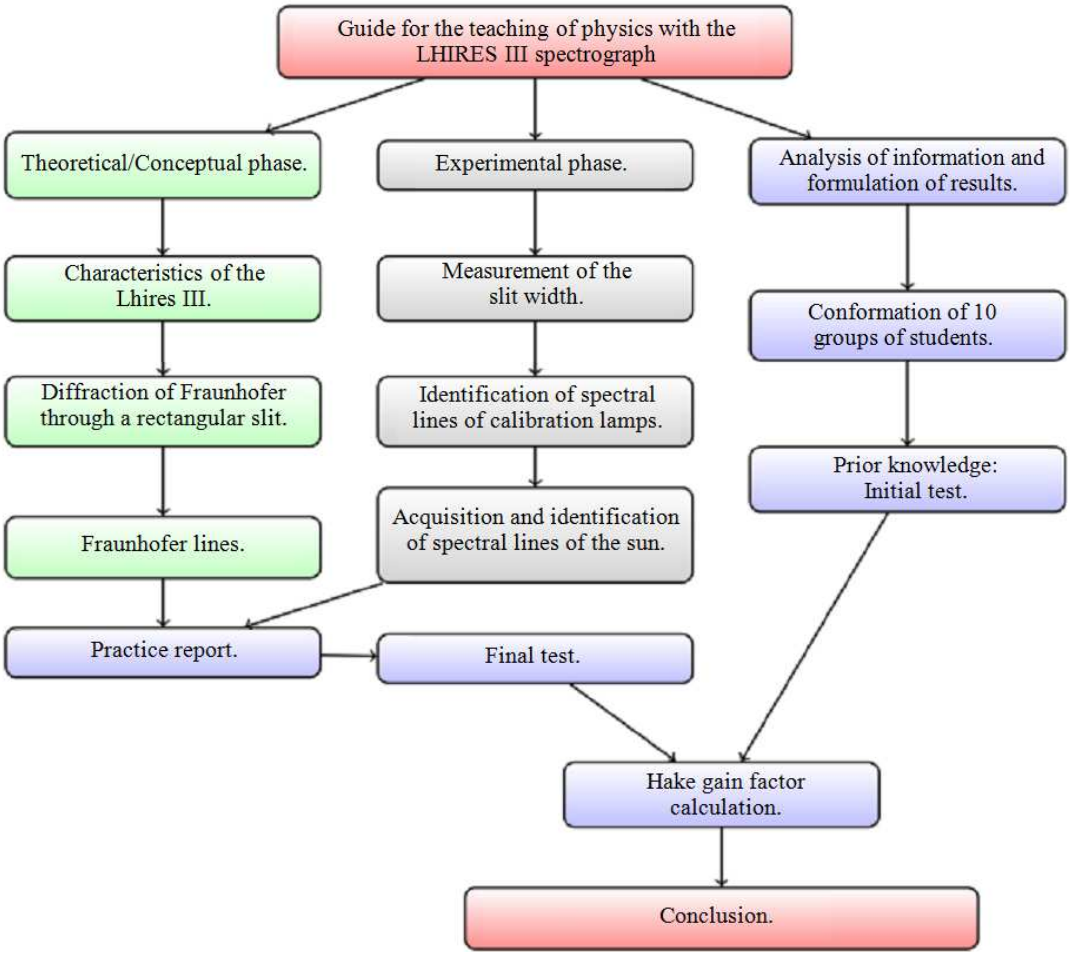


Fig. 1: Flow chart of the proposed methodology

Fig. 2: Lhires III spectrograph of the AOTUP

Table 1: Summary of the experimental part of the proposed guide

Measurement	Objectives	Equipment	Time
Slit width	To measure the width of the slit of the spectrograph using the principle of Fraunhofer diffraction.	- Lhires III spectrograph. Monochromatic laser. Measuring tape.	120 min
Spectral lines	To observe the spectral lines of neon and argon lamps, calculating the position of the micrometric screw for the observation of these wavelengths.	- Lhires III spectrograph. Sbig ST-i camera. Computer. Software Lambda for Lhires III.	120 min
Solar spectrum	To photograph and identify some of the Fraunhofer lines using the Sbig ST-i camera.	- Lhires III spectrograph. Sbig ST-i camera. Computer. Software Lambda for Lhires III.	90 min

The guide consists of three phases:

- A theoretical-conceptual phase in which the main features of the Lhires III spectrograph are explained, as well as its internal design and how to use the Lhires III to observe the Fraunhofer lines of the solar spectrum and the Fraunhofer diffraction through a rectangular slit. The Hake gain factor is used to measure the evolution of student learning
- An experimental phase that consists of 3 components (Table 1). Students are given an explanation of the materials they will work with and how they should assemble the equipment and perform the experiments. In this phase, the student creates his own learning environment, with the teacher as a facilitator
- The third phase consists in the analysis of information and formulation of results. At this stage, each group relates what was learned in the first two phases, discussing the concepts involved during the development of the experimental set-up, thus enhancing collaborative learning

The groups took about an hour and a half to contextualize the theoretical-conceptual phase of the guide (phase 1), then proceeded to execute the experimental phase. To perform the experiments measurement protocols were defined.

Diffraction through a Slit

Measuring the width of the slit is an easy practice. To perform this, it is possible to apply the laws of optics.

Measurement Protocol

- First, the students remove the slit base from the spectrograph Lhires III
- Then, they carry out the assembly shown in Fig. 3a. By passing a monochromatic beam of light from a laser through the slit a diffraction pattern is presented (Fig. 3b). The slit is placed at an arbitrary distance (a distance of 100 cm is recommended). At the bottom, a flat projection screen is located
- Students are able to observe how a diffraction pattern is presented with a bright central zone, bordered by alternating dark and bright bands as shown in Fig. 4
- After that, students measure the distance from the center of the diffraction pattern to the minimums x with a tape measure
- Finally, students use Equation 1 to measure the width of the rectangular slit:

$$a = \frac{D\lambda}{x} \tag{1}$$

Where:

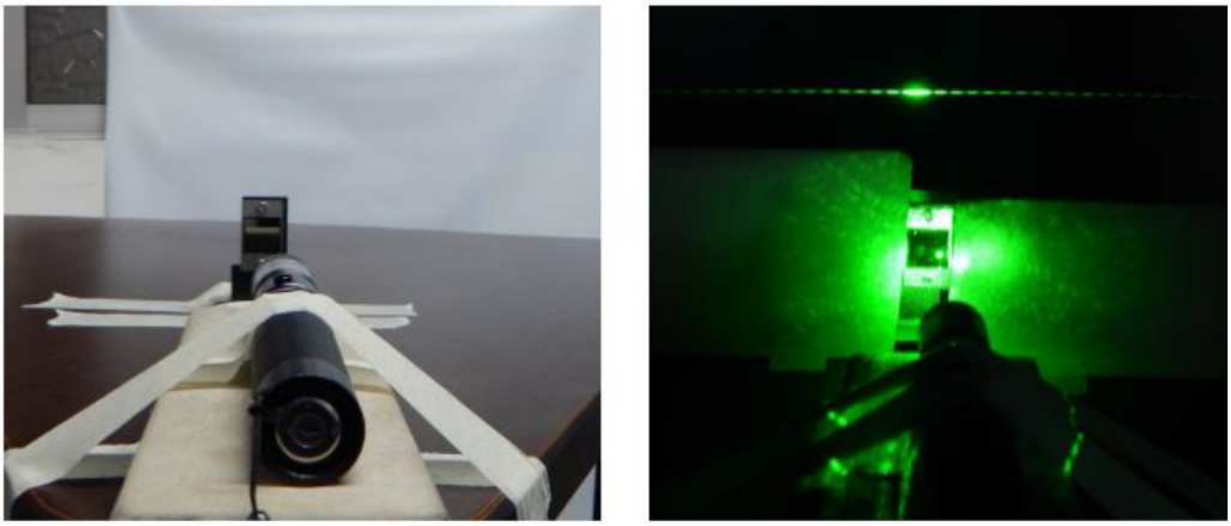
a = The slit width (μm)
λ = The wavelength of the laser (nm)
D = The distance from the slit to a flat area
X = The distance from the center of the diffraction pattern to the first minimum

Measurement of Spectral Lines

For this exercise, it is necessary to use the software Lambda for Lhires III which was developed in the AOTUP.

Measurement Protocol:

- Here, each group enters the values of the wavelengths of the neon and argon calibration lamps in the Lambda for Lhires III software
- Then, students calculate the position in which the micrometer screw of the Lhires III spectrograph should be placed for the observation of these wavelengths
- Later on, students connect the camera to the PC and run the CCDSoft software
- After the software is running, each group places the micrometer screw in one of the calculated positions and takes a picture. A bright line can be seen near the center of the image. The assembly is shown in Fig. 5
- Students compare the observed field with that of the Lambda for Lhires III software and, if necessary, they move the micrometer screw until centering the line on the image
- Next, students write down the observed position values and calculate the error with respect to the calculated position
- Finally, students make a graph of wavelength Vs observed position and discuss the results



(a) (b)

Fig. 3: (a) Experimental setup for slit width measurement; (b) Diffraction pattern observed

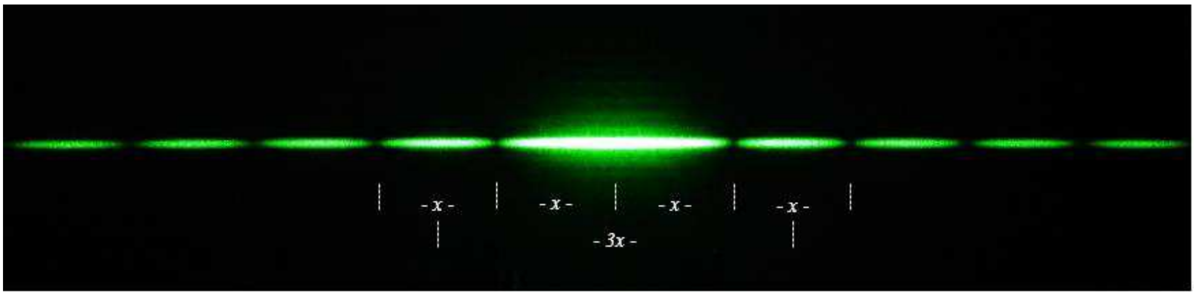


Fig. 4: Maximum and minimum of the diffraction spectrum

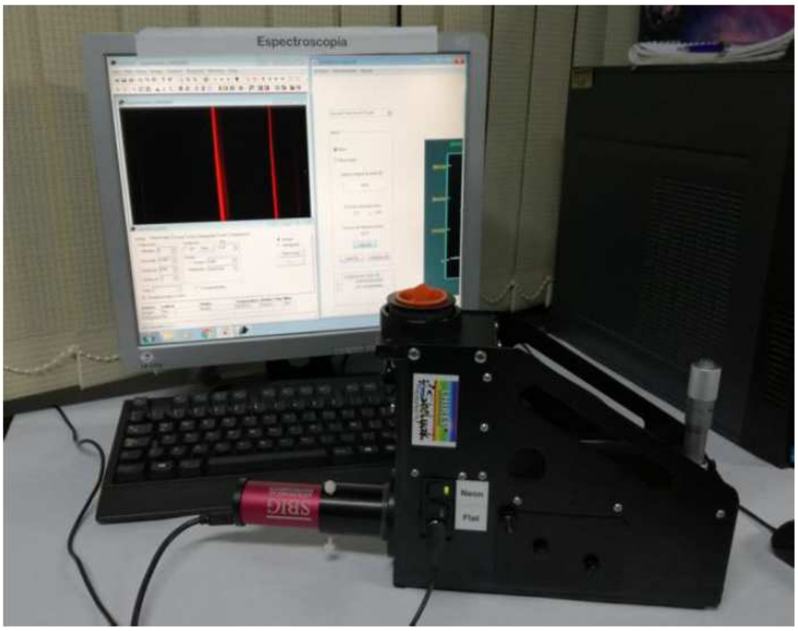


Fig. 5: Assembly for the measurement of spectral line

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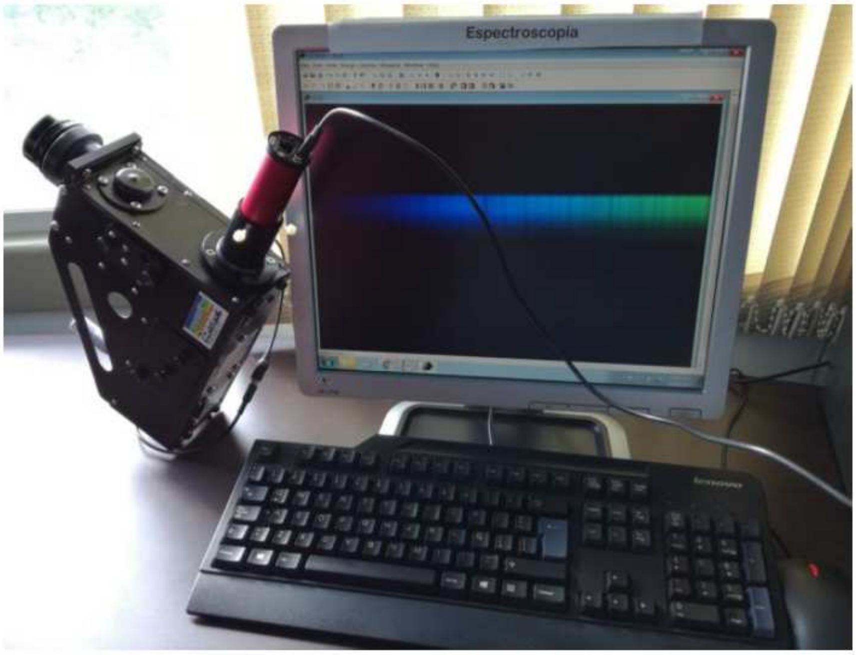


Fig. 6: Assembly for the measurement of the solar spectrum

Observation of the Solar Spectrum

Measurement Protocol:

- On a sunny day, students have the opportunity to observe the spectrum of the sun. A small slit must be made in a piece of paper and placed in the input of the spectrograph. This is done to minimize the entrance of light to the Lhires III
- After that, students enter the values for the wavelengths corresponding to some of the main lines of Fraunhofer in the software Lambda for Lhires III. Then they calculate the position in which the micrometer screw of the Lhires III spectrograph must be placed for the observation of these wavelengths
- Then, students place the micrometer screw in one of the calculated positions and take a picture. A dark line is seen near the center of the image. If necessary, they move the micrometer screw until centering the line on the image. The assembly of this experiment is observed in Fig. 6
- Finally, students write down the values of the observed position and calculate the error with respect to the calculated position

For the development of the first two parts of this phase, the groups took two hours on average. For the last part, one hour. The high cloudiness of the city of Pereira was the main problem that slowed down the groups in order to perform this last exercise.

Results and Discussion

Every group was asked to report results and analysis of each of the experiments. In this study, we present the results and analysis of one of the working groups which was chosen at random (the results and analyses of the other groups is available as supplementary material).

Measurement Results (Slit Width)

Table 2 shows the results obtained in this experiment. Using Equation 1, students found the respective slit width values for each measured x value. The measurement of the slit width is a key point in the instrumentation of the Lhires III. Its nominal width, according to the manufacturer, is 25 µm. The average value of the slit width calculated by the students was 23.83 µm, which differs by approximately 1.20 µm according to the manufacturer's specifications. This irregularity is due to the fact that the manufacturing process of the slit is not rigorous and the manufacturer recommends making a measurement of this parameter as exact as possible, since a wider slit would reduce the resolution of the spectra, while a thinner one would decrease the luminous flux (Shelyak Instruments, 2006).

Results of Spectral Lines Measurement

The results obtained are shown in Table 3. In most cases, the position of the screw had to be adjusted to center the image on the line of the indicated wavelength and thus register this as the actual position of the micrometric screw.

The spectra of the argon and neon calibration lamps, respectively, are shown in Fig. 7 and 8. Both spectra were taken with the ST-i camera after calculating the positions of the micrometric screw for each of the characteristic emission lines (Table 3).

Using the data in columns 2 and 5 of Table 3, the students plotted a graph to correlate the wavelength with the position of the micrometric screw. This was done using the Matlab Curve Fitting tool, finding a polynomial relation of order 2, so the position of the micrometric screw with respect to the wavelength is not linear (Fig. 9). Two calibration lamps were used in order to have wavelengths throughout the visible region of the electromagnetic spectrum and thus have a wavelength ratio and the real position of the micrometric screw as accurate as possible. For the identification of these lines, students used the spectral line databases of the National Institute of Standards Technology (NIST, 2009) and National Optical Astronomy Observatories (NOAO).

Table 2: Measured values for calculating the slit width of the Lhires III spectrograph

Measurement	Measurement (cm)	x (cm)	D (cm)	λ (nm)	a (μm)
x	2.3	2.300	100	532	23.13
x	2.3	2.300			23.13
2x	5.0	2.500			21.28
2x	4.8	2.400			22.17
3x	6.8	2.267			23.47
3x	6.7	2.233			23.82

Table 3: Real and calculated positions of the micrometer screw for characteristic lines of the calibration lamps of the Lhires III spectrograph

Element	Wavelength (Å)	Calculated position (mm)	Uncertainty (%)	Real position (mm)	Error (%)
Ar	4158.59	12.20	0.02	12.22	0.16
Ar	4348.07	12.72	0.01	12.74	0.16
Ar	4764.86	13.90	0.01	13.95	0.36
Ar	5187.75	15.13	0.01	15.18	0.33
Ne	5400.56	15.77	0.01	15.77	0.00
Ne	5852.49	17.16	0.01	17.20	0.23
Ne	6143.06	18.09	0.01	18.12	0.17
Ne	6402.25	18.93	0.01	18.96	0.16
Ne	6752.83	20.09	0.02	19.94	0.75
Ar	6965.83	20.81	0.03	20.82	0.05

Table 4: Calculated screw position data for different Fraunhofer lines

Fraunhofer Lines	Wavelength (Å)	Composition	Calculated Position (mm)	Uncertainty (%)	Real Position (mm)	Error (%)
B	6867	O_2	20.47	0.08	20.50	0.15
C	6563	H_α	19.46	0.05	19.47	0.05
D	5896	N_a	17.30	0.04	17.28	0.12
b	5184	M_g	15.12	0.04	15.16	0.26
F	4861	H_β	14.17	0.04	14.21	0.28
G	4340	H_γ	12.70	0.04	12.70	0.00

Fig. 7: Emission lines of the argon lamp of the spectrograph Lhires III

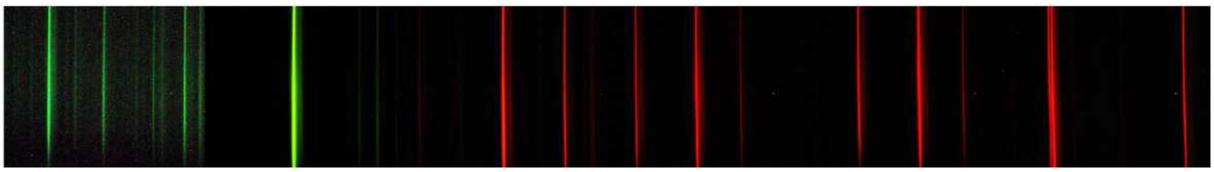


Fig. 8: Emission lines of the neon lamp of the spectrograph Lhires III

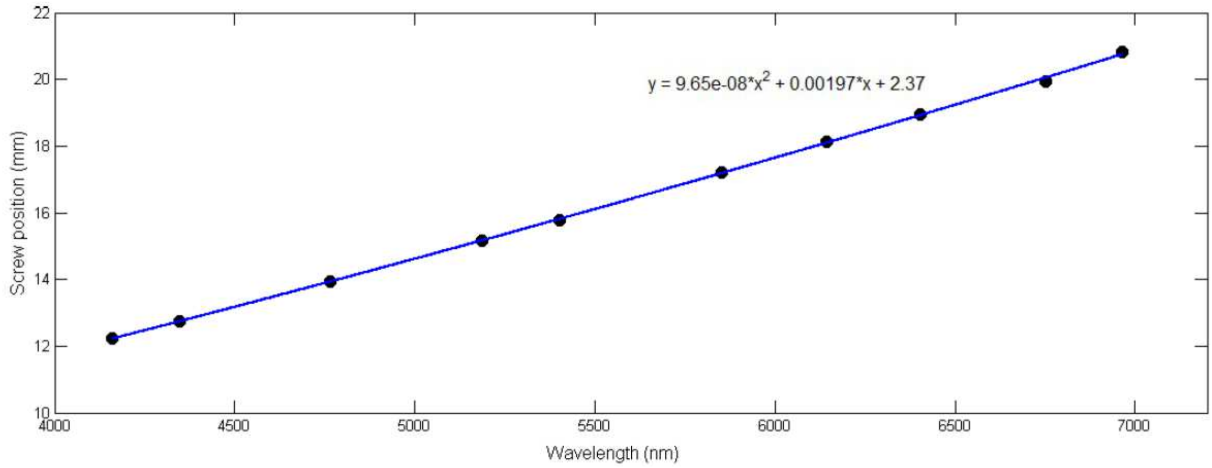
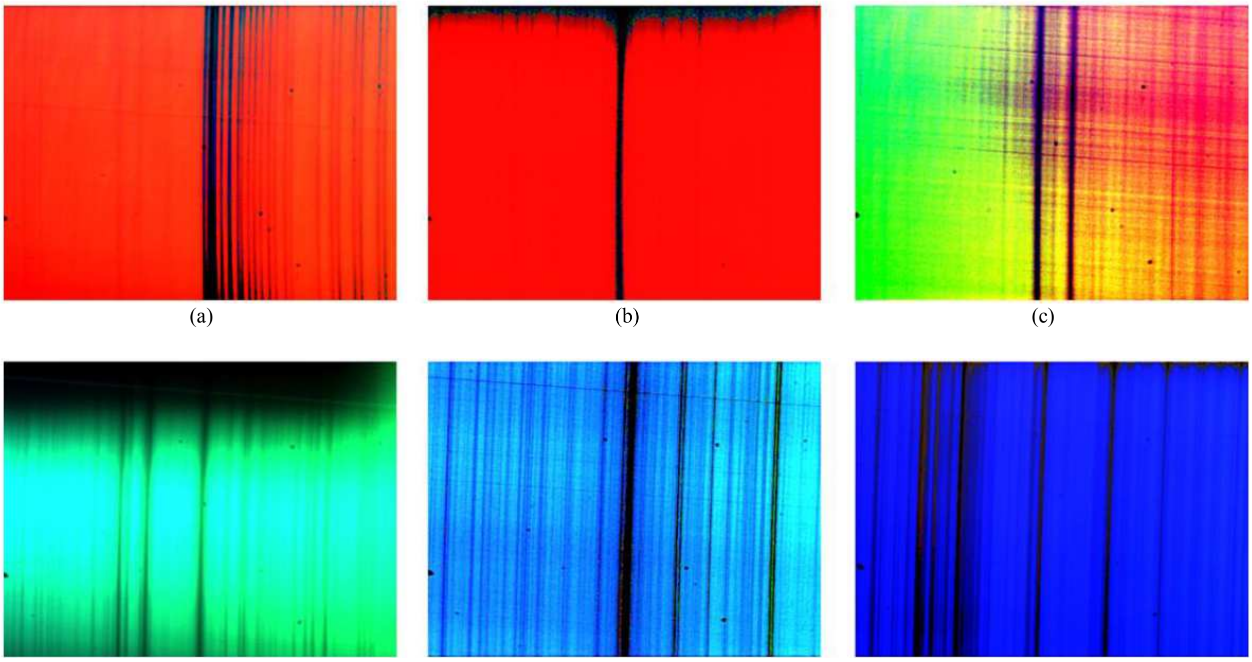


Fig. 9: Calibration curve of the Lhires III spectrograph



(a) (b) (c) (d) (e) (f)

Fig. 10: Absorption lines of the sun (a) line B, (b) line C, (c) line D, (d) line b, (e) line F, (f) line G

Results of Solar Spectrum Observation

Observing the solar spectrum is one of the most interesting practices for students. The light that is generated in the interior of the sun passes through its atmosphere and, depending on the sun's chemical composition, selectively absorbs certain wavelengths. The result is that the spectrum of sunlight obtained by a diffraction grating has dark bands called Fraunhofer absorption lines. Laboratory experiments show that different types of atoms and ions absorb light at different wavelengths (Eisberg, 1963; Thornton and Rex, 2006). Comparing these laboratory results with the absorption wavelengths observed in the solar spectrum, astronomers are able to deduce the chemical composition of the sun's atmosphere. This same technique is used to perform chemical analyses of galaxies that are millions of light-years away (Sears *et al*., 2009).

Table 4 shows the data obtained from the calculation of the position of the micrometric screw of the absorption lines wavelengths of the solar profile, with the respective uncertainty provided by the software Lambda for Lhires III. The percentage error in the calculation is also shown, which was found by the students. Figure 10 shows the images taken with the ST-i camera of the Fraunhofer lines of the solar spectrum (see Table 4).

Hake Gain Factor

This is a parameter that takes values between 0 and 1, where 0 represents no learning, while 1 corresponds to the maximum learning possible that a student can achieve. The Hake gain factor allows educators and investigators to measure the learning evolution of a group of students to whom a teaching strategy is applied, regardless of the state of the previous knowledge of each individual. Likewise, it helps verify whether a teaching methodology is positive, considering the previous knowledge of the student (Hake, 1998).

For this, a test was developed and taken by all the students before and after the activity, in order to validate the guide proposed in this study (a detailed description of the test available from author as supplementary material). By means of Equation 2, the Hake gain factor was calculated, obtaining a value of 0.78, which indicates that the applied teaching strategy allowed a high conceptual gain of the fundamentals of the spectroscopy among the students:

$$h = \frac{post - pre}{100 - pre} \tag{2}$$

Where:
h = The Hake gain factor
$post$ = Indicates the average score of the final test
pre = the average score of the initial test

Both tests rated from 1 to 100.

In the third phase of the guide, students were asked to report on aspects such as: Objectives of the experiment, introduction, methodology, analysis of results, conclusions and general comments about the experience. The following are among the most common conclusions and comments on the part of the students:

Most of the students had difficulties in correctly taking the measurement of the micrometer screw of the spectrograph.

Others presented confusion when measuring the minimums of the Fraunhofer diffraction pattern.

The majority of students were surprised to see that the solar spectrum is not continuous and that it displays a series of dark lines called absorption lines of Fraunhofer. This experiment was the preferred by the students.

In addition, they argued that the Lhires III spectrograph is an instrument that allows them to perform different spectroscopy experiments in a quick and simple way.

Despite the fact there are not enough findings about the use of spectrographs as educational tool, we found that the Lhires III, being an instrument designed for astronomical research, is an excellent tool to support the teaching of physics and nurture the public interest of science (Thizy *et al*., 2008).

Students' perception towards the proposed guide to learn the concepts of spectroscopy using the Lhires III was very positive. 85% of the students said that after following the activity guide they would like to delve further into the concepts of spectroscopy.

For future studies, it is suggested to take more experimental data, in order to validate the significance of the proposed guide as a tool to introduce fundamental concepts of spectroscopy using the Lhires III spectrograph. This can be achieved broadening the group of students that participate in the study, not limiting it to engineering students but also including non-engineering and non-university students.

Overall, this study serves as preliminary evidence on the versatility of the Lhires III as a pedagogical tool and demonstrates applicable research relevant to educational practices in a public university from a middle-income country.

Conclusion

The Lhires III spectrograph, an instrument designed for astronomy, was used to develop a methodological teaching proposal, which was implemented through a guide to introduce concepts of spectroscopy in a didactic way to university students of different engineering programs of the Technological University of Pereira, Colombia. During the experimental phase, the students had difficulties measuring the minimum of the diffraction pattern as well as interpreting the measurement of the micrometric screw. The Hake gain factor of 0.78 indicated a high conceptual gain of the acquired learning. In addition, 85% of the students affirmed that they would like to deepen the concepts of spectroscopy.

The Lhires III spectrograph is a scientific tool that can serve as a pedagogical tool. It motivates students to apply classroom learning in the real world, increasing interest. This differs from the traditional methodology and fosters a more solid and deeper knowledge of physics, a critical issue for countries like Colombia where science levels are below the average of OECD member countries.

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Author's Contributions

Ivan Dario Arellano Ramirez: He is the correspondence author of this paper. His main contribution is in the preparation, writing and publication of this manuscript.

Angelica Maria Guapacha: Her main contribution is in the preparation and development of the proposed guide. She also conducted the data collection and designed the protocol of the experiments among the students for this study.

Jairo Alberto Aguirre Galvis: He contributed in preparing and reviewing this manuscript. He was also involved in the data analyses, literature review and methodological writing.

Ethics

The authors declare this article is original and contain unpublished material. Hence, no conflicts of interest to disclose.

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