The Spectrograph:
A Prototype for a Digital Spectrometer

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Abstract

Optical spectroscopy is a conceptual referent which links classical and modern Physics. This paper will consider how an educational path has to involve students in interpretative activities. Experiments can allow one to highlight the link between energy levels in atoms and discrete light emissions. After analysing several commercial devices and apps for mobile devices, our Physics Education Research Unit from Udine University (Italy) designed and created a digital spectrometer using a simple webcam and implemented the various functionalities which can be connected to PCs via USBs. Both hardware and software have been designed in order to obtain spectral images of various sources and the digitised spectrum. The hardware allows the use of different diffraction grating, coloured and optical filters and an optical goniometer, whilst the software is designed to allow calibration and qualitative and quantitative measures of wavelengths. We will describe this system in detail as well as some experimental activities which can be carried out by secondary school students and freshmen in biotechnology.

Keywords: Digital spectrometer, optical spectroscopy, physics education

Introduction

Modern physics is now integrated in all European secondary school curricula and its teaching requires an effective approach to create a culture that links new theories with instruments and methods related to physics. A thematic area which provides an experimental basis of modern atomic theory is optical spectroscopy. Both from a historical and conceptual point of view, it represents a bridge between classical and modern physics, offering an important disciplinary contribution to the epistemological plan of physics. Quantized emission and absorption of radiation are basilar concepts representing the main investigative tool for light-matter interaction, thus optical spectroscopy is a context in which the role of energy is indispensable when describing physical processes.

Optical spectroscopy is an experimental context to validate models through indirect measures - for example, in the case of atomic models highlighting the link between luminous emissions and atomic energy levels. Students can therefore gain competence in specific inquiry modalities employed in physics.

Experiments and educational devices used to perform optical spectroscopic measurements are amongst the most significant and feasible; however, existing experimental proposals are quite limited and often implemented in expensive and complicated devices - such as the so-called “black box” - that do not allow students to understand the mechanisms and principles of functioning. Indeed, obtaining optical spectra of luminous sources is quite easy: a CD or a cheap diffraction grating are widely available and the produced spectra can be captured with a digital camera or a Smartphone and analyzed - quantitatively or qualitatively - with specific apps.

Different educational proposals (Luo & Gerritsen, 1993; Ouseph, 2007; Scheeline, 2010; Amrani, 2014; Onorato et al., 2015) including simple experiments of optical spectroscopy that allow qualitative and quantitative measures have been developed in order to stimulate students’ functional understanding concerning spectra formation and measurement. These experiments represent important educational activities contributing to the learning process concerning both disciplinary and methodological aspects, but they have been designed and implemented in specific and limited contexts. Generally speaking, laboratorial educational proposals are offered in the form of commercial devices, and teachers have the task of integrating them in a coherent educational path.

The Physics Education Research Unit at Udine University (IT) aims to develop an educational path on optical spectroscopy in which students are directly involved in experimental and interpretative studies. Laboratory activity is essential and new technologies allow new opportunities to teach and learn physics, as already discussed in the case of the educational path on optical diffraction from a single slit (Gervasio & Michelini, 2009; Michelini & Stefanel, 2015). From this perspective we developed a prototype for a digital spectrometer implementing some proposals based on ICT (Information and Communication Technologies), making use of a webcam and specifically-designed software which allows qualitative and quantitative analysis of a digitised spectrum. After having analysed the main available commercial devices and apps performing spectroscopic analyses, we decided to develop a complete low-cost technical solution that will be illustrated below with examples of significant measures.

Some Existing Proposals

The *PASCO PS-2600* wireless spectrometer (figure 1, left) integrates a CCD sensor upon which the spectra of light, ranging between 380 and 980 nm, of a certain source is registered. Light is guided to the dispersive element that creates the spectrum by means of an optic fibre. With the use of either a USB or a Bluetooth connection, the software automatically shows the emission spectrum as a function of the wavelength, with no need for calibration (figure 1, right). Obtained spectra, with a resolution of about 3 nm, can be compared with discrete reference spectra. The device also allows the analysis of absorption and fluorescence spectra as a test tube with the sample can be inserted in it. Absorption spectra are obtained by illuminating the sample with a reference white LED light while fluorescence spectra are obtained by illuminating the sample with light of 405 or 500 nm. The absorbance curve is automatically shown and the user has only to perform automatic actions.

Figure 1. ***PASCO PS-2600*** **digital spectrometer (left) (https://www.pasco.com/prodCatalog/PS/PS-2600_wireless-spectrometer/index.cfm) and user interface (right).**

The *RSPEC EXPLORER SYSTEM* digital spectrometer (figure 2, left) is a spectrometer which uses a focusing element, rather than an optic fibre. A diffraction grating is placed in front of a webcam which is connected to a PC via a USB port. Once the webcam is pointed towards the source, the software allows for the registration of the whole image of the frame with a spectrum range between 390 and 700 nm. Users can select the portion of the frame where the spectrum is present. The software digitalises it and provides a graph in which the intensity - in arbitrary units

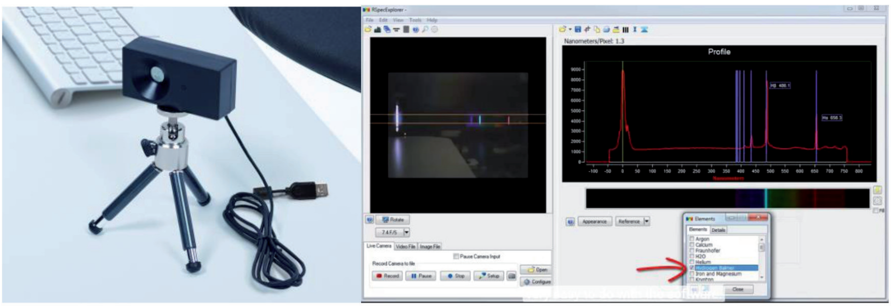

Figure 2. RSPEC EXPLORER SYSTEM digital spectrometer (left) (https://www.fieldtestedsystems.com/) and user interface (right).

- is shown as a function of the wavelength. The pitch of the grating is fixed, as well as its distance from the CCD sensor: it is enough to line up the image of the source with a reference to automatically and uniquely associate a position along the pixel array with a specific wavelength (figure 2, right). The good quality of measurements, with a resolution of about 3 nm, makes it possible for one to compare the recorded spectra with reference ones.

Despite the good performances and the high quality of the two aforementioned devices, they are quite similar to "closed boxes" that do not allow the user to approach the physics of the measurement or to change the experimental condition as it is not possible to change the diffraction grating or use any kind of filters. Absorption measurements are automatically generated by the software as well as the calibration which is an important phase of the measuring process,
However, a digital analysis of recorded images obtained from a Smartphone is allowed by certain mobile apps namely *LEARNLIGHT SPECTROSCOPY*, *SPECTRA UPB, LIGHT SPECTRA LITE* and *ASPECTRA MINI*. A diffraction grating is enough to produce the image of an emission spectrum that can be analysed but a precise calibration is possible only in few cases. Those apps make it possible to obtain graphs of intensity as a function of the position along the spectrum, i.e. in different positions of the digital image (figure 3).

SPETTROGRAFO is a new system that combines the simplicity of use of existing commercial devices and the feasibility of the analysis algorithms with new functionalities that allow for a better control of the measuring process thereby ensuring more accurate readings.

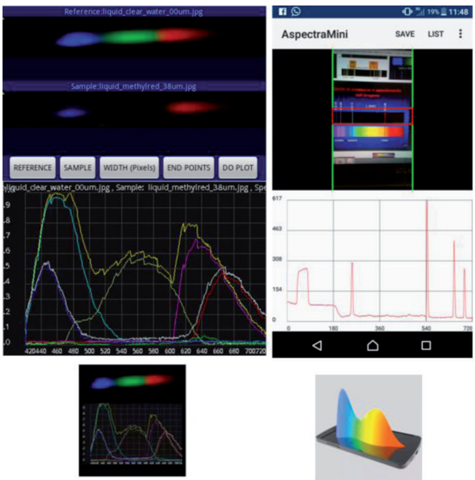

Figure 3. User interfaces and logos of two apps performing spectroscopic measurements. *LEARNLIGHT SPECTROSCOPY* (left) and *ASPECTRA MINI* (right).

The *Spettrografo* System

Both hardware and software components of the designed and produced prototype will be described below. It allows for measurements of optical spectra obtained by diffraction grating with different pitches. Our goal was to create a low-cost device allowing quantitative and accurate analysis of discrete, continuous and band spectra.

Hardware

The equipment is assembled in a very simple way: a commercial webcam is inserted inside an aluminum case (6cm x 6cm x 6cm) mounted on an adjustable tripod (figure 4). The webcam has a resolution of 640x480 pix interpolated by a 1.2 Mpix CCD and it focuses on images from 15 cm to infinity. The field of view is 60° and the frame-rate is 60 fps. A support allows the diffraction grating to be placed in front of the webcam. The digital image registered on the sensor is sent to a PC via a USB connection. Gratings with pitches of 1000 lines/mm and 500 lines/mm can be used, both allowing spectral analysis ranging between 380 nm and 700 nm. 1000 lines/mm grating allows one to see only the first diffraction order with a resolution of 1.3 nm/pix, while with 500 lines/mm the second order is visible, but the resolution decreases to 2.6 nm/pix. A couple of Polaroid filters can be inserted in front of the webcam to tune the intensity of the source, avoiding the saturation of the sensor. Coloured filters can also be also inserted to study selective absorption of colours (figure 4). The device can be used with extended light sources, making use of an external slit, working as a diaphragm.

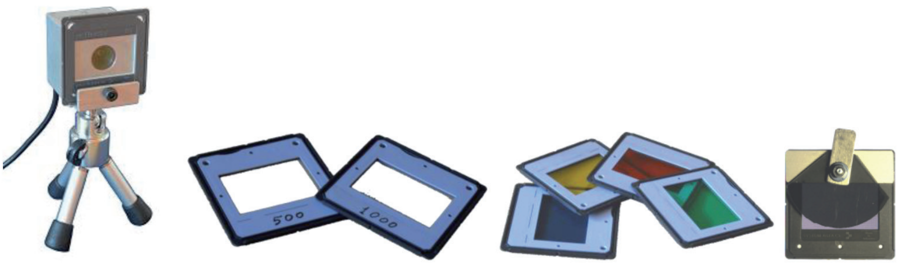

Figure 4. *SPETTROGRAFO* system (left) and accessories: diffraction gratings, coloured and Polaroid filters (right).

Software

Software was developed through the use of Microsoft "*framework.NET* " using C# language. As shown in figure 5, it allows one to visualise the image captured by the webcam, containing both the source and its spectrum, and to select the area needed to be analysed (reproduced in the upper right of the user interface). Digitisation of the spectrum occurs making a sum of the digital information of each pixel (proportional to the incident intensity) along every column. The intensity as a function of the position along the spectrum in the graph in the lower right of the user interface is represented in arbitrary units and it is proportional to the mean intensity incident on the pixels of a same column.

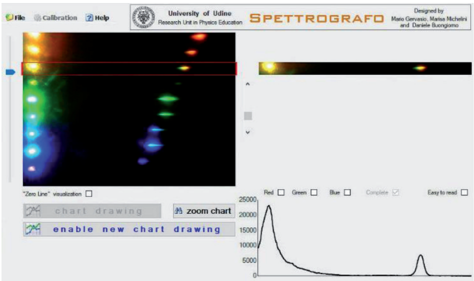

Figure 5. Main user intrface. Recorded image by the webcam (left) from which it is possible to select the area to be analyzed (source + spectrum) that is automatically digitalyzed in a graph (bottom right). In this example the source is a column of LEDs observed with a 1000 lines/mm grating.

It is possible to switch to a calibrated graph, in which the horizontal axis represents an energy or wavelength scale: it is enough to select the employed diffraction grating in the user panel (this information fixes the pixel-wavelength or energy relationship) and a calibration source can also be used. A secondary panel allows for these operations to be done. After having calibrated the system, quantitative measurements can be performed and a reference spectrum appears under the graph showing an eV energy scale. Two movable markers allow the user

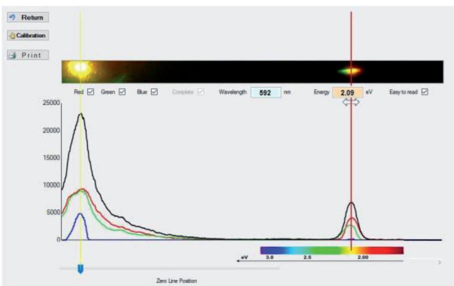

Figure 6. Calibrated yellow LED spectra.

to mark the position of the image (0th order) as well as a generic position along the spectrum of the 1st order, resulting in a univocal measure of wavelength (expressed in nm) or energy (expressed in eV) (figure 6). Data can be exported in tabular form allowing further analysis with a spreadsheet.

Examples Of Measures

The *SPETTROGRAFO* system allows qualitative and quantitative measurements of continuous spectra from incandescent lamps, discrete spectra from gas discharge or fluorescent lamps, band spectra from LEDS and absorption spectra. To perform a measurement, it is enough to target the source with the device (figure 7), eventually screening it through a panel with a slit. No optical bench is needed; it is enough to assure the alignment between source, grating and sensor in a way that the spectrum is horizontal with respect to the array of pixels. Here we describe some examples of measurements that can be performed with the device.

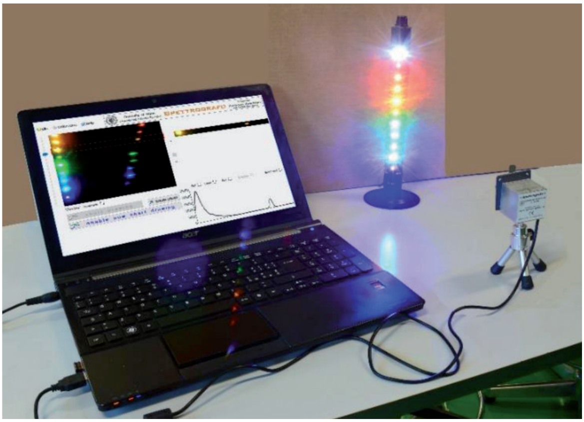

Figure 7. *SPETTROGRAFO* connected to PC, pointing the source.

Spectral lines

The shape of the slit shielding the light of a gas discharge lamp is reproduced in different colours and in different positions on the CCD sensor, showing the source spectrum. Once it has been digitised, is possible to observe and measure the position, width and relative intensity of the various emissions (figure 8). The spectral features can be recorded as a wavelength or energy value. As an example, some visible wavelengths in cadmium and helium spectra have been measured and they are reported in table 1, against standard values.

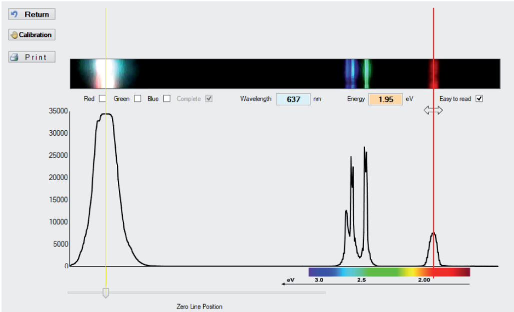

Figure 8. Spectra of a cadmium gas-discharge lamp.

Table 1. Measure of the main emission lines of Cd and He performed with *SPETTROGRAFO* compared with standard values (https://www.nist.gov/pml/atomic-spectra-database).

Cadmium			Helium		
λ_{meas} (nm)	λ_{std} (nm)	Δ%	λ_{meas} (nm)	λ_{std} (nm)	Δ%
639	643.85	0.75	656	667.82	1.77
506	508.58	0.51	577	587.56	1.80
480	480.00	0.00	496	501.57	1.11
469	467.81	-0.25	471	471.31	0.07
-	-	-	447	447.15	0.03

Spectral lines - optical goniometer

An alternative modality of performing measurements with a *LUCEGRAFO* system is to place it on a rotating base: the diffraction grating is no longer placed in front of the sensor, but it is fixed on a support at the center of the rotating base (figure 9). The system thus functions as an optical goniometer. Different spectral emissions are thus observed as a function of the diffraction angle α, represented by the angle of rotation of the sensor around the grating, which has pitch d. The angle is measured on a graduated scale with a sensibility of 1°. Wavelengths are evaluated with the formula to the various orders m:

$$d \cdot \sin\alpha = m \cdot \lambda$$

In this modality no calibration procedure is needed, except for the 0^{th} angle that has to correspond to the position of the source. A movable marker, appearing on the image acquired by the sensor is used as a reference while the system rotates. In this way, apart from performing qualitative measures on different spectra, the angular and symmetrical features of diffraction grating phenomena are highlighted. In the following, measurements taken in optical goniometer modality on the spectrum of a blue LED with a 500 lines/mm grating are shown (table 2).

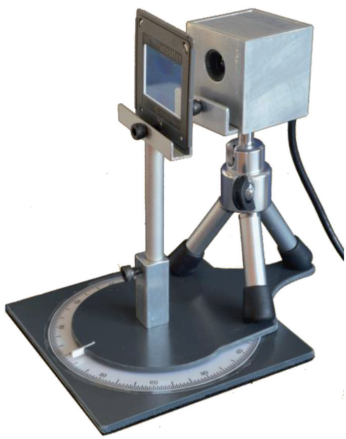

Figure 9. SPETTROGRAFO system used as an optical goniometer.

Table 2. Measure of the wavelength associated to the peak emission of a blue LED.

m=1		m=2		m=-1		m=-2	
α	λ (nm)	α	λ (nm)	A	λ (nm)	α	λ (nm)
13°	449.9	27°	454.0	13°	449.9	27°	454.0

Transmissivity curve

A white light source, as a LED, is used to obtain a reference spectrum (figure 10, left) which is modified if a coloured filter is placed in front of it (figure 10, right). Software allows to extract data in a tabular form that can be further analysed with a spreadsheet in order to quantitatively evaluate the absorbance in various zones of the spectrum. This way, the intensity of the reference spectrum as a function of the n^{th} column of the pixel array ($I_0(n)$) and the intensity of the absorption spectrum ($I(n)$) as well as the quantity $T(n)= I(n)/I_0(n)$ can be calculated, representing the fraction of the transmitted light, i.e. the transmittance of the filter (figure 11).

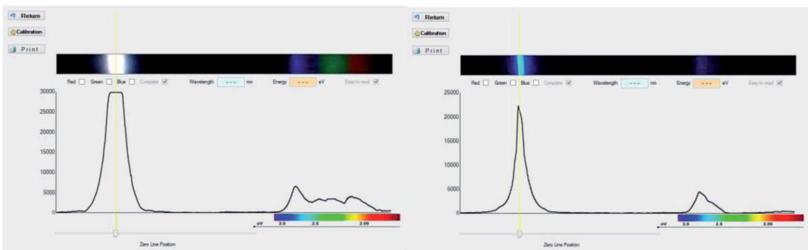

Figure 10. White LED spectra, chosen as a reference (left) and absorption spectrum having placed a blue filter in front of the source (right).

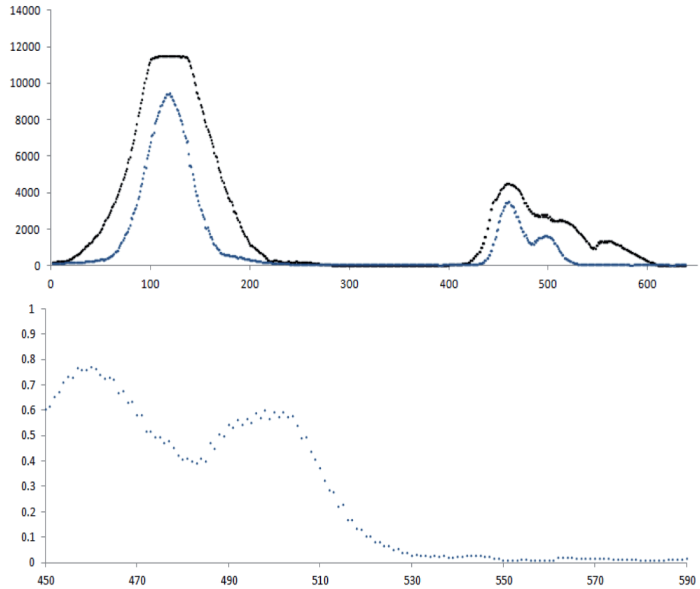

Figure 11. Elaboration with a spreadsheet: light spectrum from a white LED compared with the spectrum of the same light passing through a blue filter. Abscissa values refer to the column of pixel; on the left the peak due to the source is visible (top) and transmittance of a the blue filter (bottom).

Conclusions

After having analyzed potentialities and limits of some commercial digital spectrometers and mobile APPs, we highlighted the main needs for an effective educational laboratory apparatus for optical spectroscopy which also stress the importance of the calibration process, the insight into the physical processes accounting for the observations and the possibility to change the grating and data acquisition modality. A simple digital device, *SPETTROGRAFO*, has been designed and created; it allows real-time study of diffraction phenomena with subsequent analysis of optical spectra of different light sources. This system consists of a commercial webcam, to be connected via USB to a PC, inside an aluminum case. Different diffraction gratings can be placed in front of it, as well as Polaroid filters to dim the source luminosity, or coloured filters to study selective absorption of colours. Virtual images of spectra are recorded on the CCD sensor of the webcam and observed with the aid of a specifically designed software. It is therefore possible to perform qualitative observations concerning shape and main features of different kind of spectra: continuous, discrete and/or bands to various diffractive orders, according to the used grating. Real-time observations of the modification of a spectrum with the presence of a coloured filter can also be observed. Calibration occurs via software by selecting the used diffraction grating or with the aid of a calibration source with known wavelength (e.g. a laser). In this way a column of pixels is assigned to a specific wavelength, or energy, allowing quantitative measures with an error margin of less than 5%, depending mostly on the alignment between source and detector. Recorded spectra are digitalized in a graph representing luminous intensity as a function of the wavelength, or energy in arbitrary units proportional to the luminous intensity on a portion of the sensor. This device can be mounted on a rotating base allowing one to measure the diffraction angle and thus quantitatively evaluate the wavelength, as in the classical experiment of the optical goniometer, with an error margin of less than 5%.

The *SPETTROGRAFO* prototype for a digital spectrometer, offers itself to be used both in secondary school educational labs and in university introductive physics courses, thanks to its relative inexpensiveness, to its user-friendliness and to the possibility of exploring the functional role of every component of the measure setup. The device avoids the "closed box" problem: it allows students to develop a functional understanding, which is one of the main goal of an educational lab. Observations and measures of spectra allows one to characterize different kinds of luminous sources, elements and absorption mechanisms.

Up to now the device has been presented to a group of 10 secondary school teachers who used them in the context of "National School for Teachers on Modern Physics" within IDIFO6 project[1] held in Udine University (IT) in September 2017. In the same IDIFO6 project, the device was used in the educational lab for freshmen in biotechnology as a part of a wider didactical innovation project and it has also been implemented in Masterclass and CLOE (Conceptual Lab of Operative Explorations) activities held in Udine University between the period of January-March 2018 for secondary school students in the framework of a wider school-university collaboration project.

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Bio-notes

Daniele Buongiorno holds a Bachelor's degree in Physics (2011, University of RomaTre, Roma, IT) and a post-graduate degree in Physics (specialization in Astrophysics, 2015, University of RomaTre, Roma, IT). He is a third-year PhD student in Physics Education at the University of Udine (IT), within the Department of Mathematics, IT and Physics, and the Physics Education Research Unit. His research field addresses the educational significance of optical spectroscopy. His main interests include the interpretation of links between spectral lines and discrete energy levels, students' interpretative models and strategies, and the role of processes and apparatuses which can lead to the formation of a vertical educational path from primary pupils to university.

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