DOI: 10.1478/AAPP.99S1A22

AAPP | Atti della Accademia Peloritana dei Pericolanti
*Classe di Scienze Fisiche, Matematiche e Naturali*
ISSN 1825-1242

Vol. 99, No. S1, A22 (2021)

# EXPERIMENTAL USE OF MOBILE APPS IN PHYSICS EDUCATION

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ABSTRACT. Mobile devices have nowadays become familiar instruments of our daily lives. Due to the presence of more and more sophisticated and precise environmental sensors and to the development of more and more user-friendly APPs able to read and analyse data, the interest in the educational context of smartphones, the number of proposals and their quality have rapidly increased in the last years. Our research group in physics education promoted various activities in which students, in the role of "active researchers", tested some of the available APPs and used them to perform qualitative and quantitative experiments with the aim to improve learning. Here we suggest some significant experimental activity that our partners-student performed with his/her smartphone and low-cost equipment on sound, acceleration, optics and spectroscopy.

## 1. Introduction

Laboratory activities and experimental explorations are excellent opportunities for active learning in physics and for increase the fertile intellectual challenges in the learning process (Viennot 2014). The use of smartphone sensors through specific APPs for measurements stimulate curiosity and personal involvement in phenomena exploration offering a new way to employ a familiar device (Vogt *et al.* 2011; Kuhn *et al.* 2013; Buongiorno *et al.* 2017; Longo *et al.* 2016; Buongiorno *et al.* 2018). Our research group in physics education from Udine University promoted mobile APPs as a context for integrating new technologies in teaching/learning physics in secondary schools (Hammond and Assefa 2007; Kuhn *et al.* 2011). Secondary students interested in a working experience with us were encouraged to select the best APP for specific measurements, analysing features of the available ones, work on data collection campaigns and experiments they deemed significant for learning. The basic idea was to consider students as partners in a challenge involving the study of a problem, the analysis, the programming of operational phases, the investigation, the evaluation as well as the planning and the realization of prototypes and experiments using low-cost equipment. The goal concerned how to promote educational innovation through the integration of new technologies in traditional teaching by the BYOD "Bring Your Own Device" paradigm. In the following, the main significant experimental activities performed by 16-17 years old students on the study of motion, sound and optics are described in order

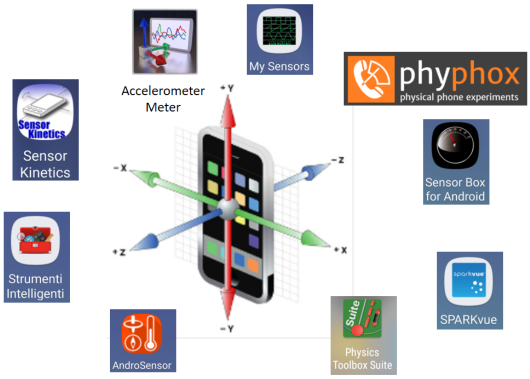


FIGURE 1. Examples of APPs able to read sensors data.

to allow students to re-propose them in physics class, to improve them or simply to try to perform the measures on their own, integrating the curricular activities.

## 2. Smartphones and sensors

Modern mobile devices, smartphones in particular, are nowadays equipped with lots of environmental sensors able to perform quantitative and qualitative measurements. The adjective "smart" is due to the presence of those sensors, allowing the device to act responsively to external stimuli as well as to perform measurements able to satisfy the needs of the users. In order to quote some examples: flipping the device leads to rotate the screen, approaching an object to the device results in turning off the screen, an high temperature is notified to protect the device, the GPS records positions and tracks, the magnetic sensors can turn the device into a compass, microphones can record sounds and voices, and so on. Sensors have become cheaper and cheaper in the last years and now all smartphones have them built-in even if they are quite useless for daily use of the devices. Nevertheless, they are able to perform very precise measurements of physical quantities (acceleration, angular velocity, pressure, temperature, luminosity, magnetic field, sound intensity) and the existence of various (available for free) APPs able to read sensors data and to display them in a user-friendly way open the possibility to use a smartphone as a "portable physics laboratory". Among the available APPs some of them are able to access all the sensors (Fig.1), while others are more specific and they are devoted to specific ones (accelerometers, microphones or light sensors) performing specific measurements and displaying dedicated plots or tables.

Examples of elementary but significant measurements will be described in the following. Experiments are divided by topic, in particular topic A: sound, topic B: motion and acceleration and topic C: optics. By means of free APPs, interested people can perform the activities and interpret the experimental results.

**2.1. Topic A: sound.** The sound that enters the smartphone's microphone can be analysed very deeply using numerous APPs; in particular, three APPs can be employed to perform measures on sound: Frequency Sound Generator, Sound Oscilloscope and Sound Analyzer.

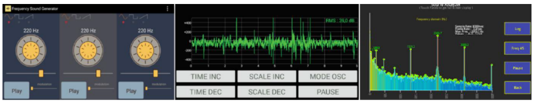

FIGURE 2. Main user interfaces of the three APPs on sound: Frequency Sound Generator, Sound Oscilloscope and Sound Analyzer.

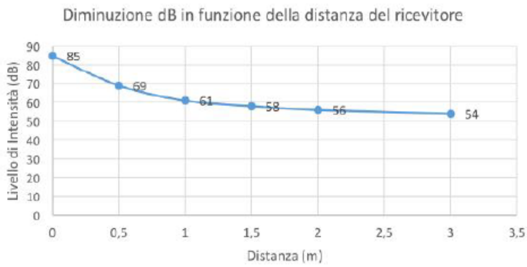


FIGURE 3. Using a smartphone and a specific APP it is possible to measure the diminishing of the intensity level as a function of the distance. Data collection and analysis performed by students from scientific lyceum M. Flaminio – Vittorio Veneto, Italy in the scholastic year 2016/17.

Frequency Sound generator allows to generate up to three acoustic signals at the same time varying their amplitude and frequency individually; Sound Oscilloscope is an oscilloscope emulator for acoustic signals: it shows the intensity as a function of the time, while Sound Analyzer allows performing analysis both in time and in frequency domain, and shows in real-time the sonograms. (Fig.2).

It is possible to measure the attenuation of a sound as a function of the distance between the source and the receiver. The source can be a smartphone generating a sound with constant amplitude (using Sound Generator) and the receiver can be a second smartphone using Sound Oscilloscope measuring the sound intensity, in deciBels (dB). As expected, the intensity level is attenuated if the distance increases, according to the law stating that the intensity decreases with the inverse of the square of the distance ($I = I_0/d^2$). The plot in Fig.3 shows, as a function of the distance, the intensity measured in dB (every smartphone uses this unit of measure for intensity). To be noticed that since the intensity in dB is defined as the logarithm in base 10 of the intensity, the functional relation should be more similar to a logarithmic graph (Fig.3).

Sound Analyzer (Fig.4) allows visualizing in real time and contemporary the actual sound wave (the evolution of the waveform with time), the actual spectrum (the intensities of the various frequencies composing the sound, *i.e.*, the Fourier transform of the signal) and the spectrogram (the time evolution of the frequencies with the relative intensity by means of a colour code. We can first explore how different sound are composed in terms of frequencies with experiments aimed at clarifying the difference between frequency, intensity and timbre: a single frequency (produced with Sound Generator) produces a sinusoidal waveform and a single peak appears in the spectrum. Common sound sources, such as

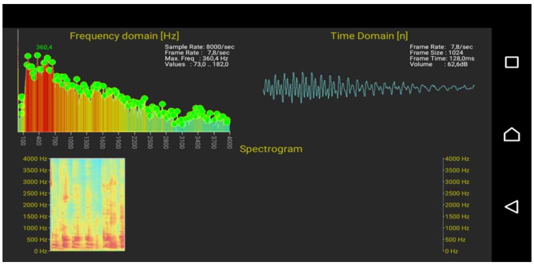


FIGURE 4. The APP Sound Analyzer allows the analysis of the sound, showing the spectrum, *i.e.*, the intensities of the various frequencies (top left), the actual time shape (top right) and the spectrogram, i.e. the evolution of the intensities of the various components with time (bottom). Intensities of the various components are plotted using a colour scale.

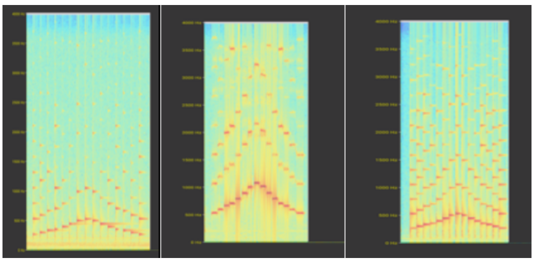

FIGURE 5. The same musical scale performed with different instruments. The spectrogram allows highlighting the different harmonics and their evolution with time. The idea for this exploration and data collection are ascribed to students from scientific lyceum M. Flaminio – Vittorio Veneto, Italy in the scholastic year 2016/17.

bottles, xylophones, small tubes, and the human voice can be used to identify how they are composed by various frequencies and how the intensity of each is.

It is also possible to analyse a spectrogram of the sound performed to put in evidence what means timber: the frequency spectrum around the main frequency (musical note) due to the different materials and/or shape of the source (instrument). This highlights the characteristics components (harmonics) of every instruments. Performing musical scales with piano, flute, guitar allows displaying the spectrograms dynamically and in overlap with the musical performance (Fig.5).

Other experimental activities were described in various publications (Parolin and Pezzi 2013; Gomez-Tejedor *et al.* 2014; Hirth *et al.* 2015; Kasper *et al.* 2015; Parolin and Pezzi 2015; Yavuz 2015).

**2.2. Topic B: motion and accelaration.** Every smartphone is equipped with three independent accelerometers measuring accelerations along the three orthogonal axes x, y and z. Each accelerometer consists of a measurement of the inertial mass of a little body attached to a spring; the elongation of this spring is converted into an electrical signal depending by

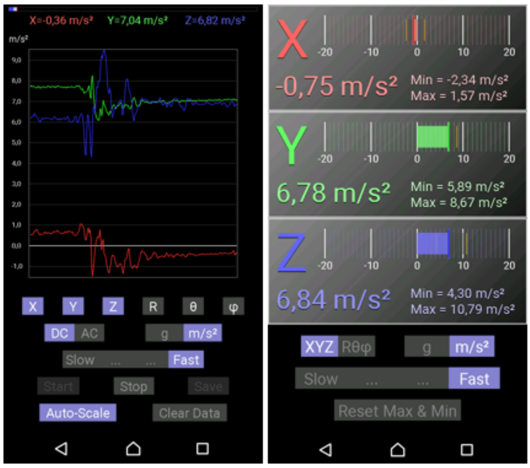


FIGURE 6. Measurements of acceleration using Accelometer Meter APP.

means of a known function to the acceleration undergone by the mass and therefore by the smartphone itself. Different APPs shows data in graphical or numerical form (Fig.6).

In Fig.7 is shown how different APPs offer measurements called respectively "acceleration", "accelerometer" and "gravity acceleration"; a clarification is needed: the measurements referred to the "gravity field" is non-zero even if the device is at rest and does not vary with its motion conditions. Vice versa, the measurements referred as "acceleration" varies only if the device moves with an acceleration (non-rectilinear uniform motion), as well as the measurements of the "accelerometer". In particular, it can be observed that when the device is at rest, the accelerometers measured an acceleration of about $9.8 m/s^2$, which could be varied by varying the state of motion of the device, which did not however affect the "gravity field" measurements. This suggest a reflection on the role of mass as property of bodies to interact with an entity called "gravity field" which has a vector nature and which is present in every point of space. The evidence that all the masses fall with the same acceleration can be experimentally proved and it makes sense of the presence of the field as an entity present in the well-defined value space and with the dimensions of an acceleration. It is useful to focus on the evidence, initially unexpected, that the measurements referred to the "accelerometer" size were null in free fall, a consequence of the fact that a mass in free fall has no weight being in a non-inertial system in free fall. The role of the reference frame can be analysed by orienting the smartphone (when stationary) so that the measured value of the gravity field was identically zero on two of the three axes and maximum on the third. The algebraic sign allowed to determine the direction of the axes.

In order to study the free fall motion, it is useful to make the following preliminary observation. With the stationary device on a table, the measurement of the gravitational field $g_x = g_y = 0$ and $g_z = -g$ is returned, which allows us to conclude that all measuring instruments are immersed in a uniform gravity field of intensity $9.81 N/kg$ pointing downwards. A suitable way to examine the free fall motion is to suspend the smartphone at a certain height and then drop it. To avoid damaging the device, a soft object (a pillow) is placed at the end


FIGURE 7. User interface of the "AndroSensor" APP. Note how the reading of the data collected in real time by the accelerometers is translated into the three quantities called respectively "ACCELEROMETER", "GRAVITY" and "LINEAR ACCELERATION".

of the fall section. In this case, the smartphone has a dual function: it acts both as a body in free fall and as a measuring instrument, allowing you to determine the fall time during which the measured apparent acceleration is zero. It is possible to determine the value of acceleration $g$ or the height of fall adopting the laws of uniformly accelerated motion (Fig.8). In fact, for an object moving in a straight linear trajectory with constant acceleration $a$, the position $x$ with respect to the initial one $x_0$ and with initial velocity $v_0$ varies with the time interval $\Delta t$ from the starting motion according to the following expression:

$$x(t) = x_0 + v_0 \Delta t + 1/2a(\Delta t)^2 \tag{1}$$

If the smartphone is dropped from rest ($v_0 = 0$) and the acceleration is the gravitational one ($a = g$), the displacement $h = x(t) - x_0$, i.e. the height from which the smartphone is dropped, can be obtained by:

$$h = 1/2g(\Delta t)^2 \tag{2}$$

It is thus possible to evaluate the height $h$ measuring the free-fall time extracting from the graph (knowing the value of $g = 9.81 m/s^2$) or alternatively, trying to evaluate $g$ measuring directly the height $h$ (Fig.8).

Another possibility offered by accelerometers is to measure the dynamical friction coefficient $\mu$ between the smartphone and the surface on which it is moving studying the motion along an inclined plane. It is known that the friction force that opposes the motion on an inclined plane is (Fig.9):

$$F_f = \mu N = \mu mg \cos\theta \tag{3}$$

Where $N = mg\cos\theta$ is the module of normal component of the weight force ($\theta$ is the angle of the inclined plane).

Throwing the smartphone upwards along the plane the resulting acceleration turns out to be (Fig.9, left):

$$a_u = \frac{F}{m} = \frac{F_{w,p} + F_f}{m} = gsin\theta + \mu g \cos\theta \tag{4}$$

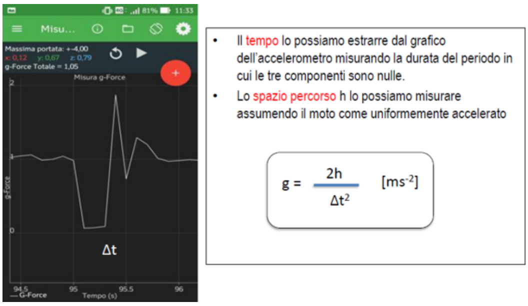


FIGURE 8. Free fall experiment of a smartphone. Data collection and analysis performed by students from scientific lyceum L. da Vinci – Treviso, Italy in the scholastic year 2017/18.

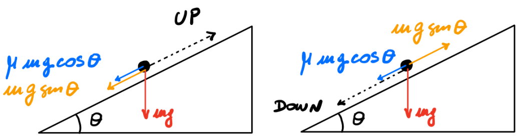


FIGURE 9. Motion along an inclined plane: upwards (left) and downwards (right).

Where $F_{w,p}$ is the parallel component of the weight force with respect to the plane. Once the smartphone accelerates downwards, it undergoes an acceleration (Fig.9, right):

$$a_d = \frac{F}{m} = \frac{F_{w,p} - F_f}{m} = gsin\theta - \mu g \cos\theta \tag{5}$$

Both can be measured with the smartphone itself (notice that it is not necessary to know its mass $m$) and it is possible to evaluate their difference:

$$\Delta a = a_u - a_d = 2\mu g \cos\theta \tag{6}$$

It is thus possible to evaluate the dynamical friction coefficient $\mu$ (measuring the angle $\theta$) using the formula:

$$\mu = \frac{\Delta a}{2g\cos\theta} \tag{7}$$

**2.3. Topic C: optics and spectroscopy.** Optics and spectroscopy experiments deal with properties of the light, in particular measures of optical path (refraction measurements); light intensity (photometric measurements) and chromatic analysis of the light (spectroscopic measurements) could be performed. In the following, some example of measures will be described. APPs able to perform optics measurements are based on the analysis of "recorded quantity of light": photometric measurements rely on the light flux incident on the light sensor (usually placed above the smartphone screen), while spectroscopic measurements rely on measuring the quantity of light incident on a specific area of the CCD sensor analysing a digital image (taken with the smartphone camera).


FIGURE 10. APP Light Meter.

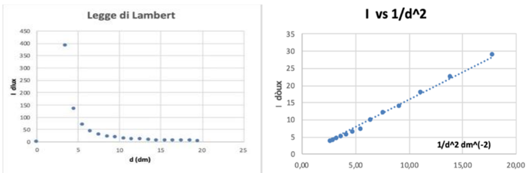


FIGURE 11. Data analysis of light intensity versus distance. The second graph represents the linearized relationship. Data collection and analysis performed by students from scientific lyceum L. da Vinci – Treviso, Italy in the scholastic year 2018/19.

**2.3.1.** *Lambert's law.* Lambert's law (the reduction of the perceived light intensity with the inverse of the square of the distance between the detector and the light source) can be performed using the luminosity sensor also known as "luxmter" implemented in various APPs (in Fig.10 one of them is shown).

Recording the collected light intensity $I$ at increasing distances $d$, the study of the characteristics of the phenomenon can be done. The experience could reveal unexpected difficulties in data interpretation: the proportionality between $I$ and $1/d$ squared can be controlled linearizing the relationship between $I$ and $1/d^2$ (Fig.11) and by interpolating the data with a straight line passing through the origin.

Moreover, it can be noticed that the data corresponding to short distances do not belong to the straight line passing through the origin and it can be concluded that "Lambert's law is valid only if the distance between the source and the light detector is sufficiently large. Otherwise other physical phenomena intervene which make the light intensity vary with different law". This behaviour of light intensity $I$ at short distance $d$ from source can be further interpreted by considering the not-point shape effect of the used source (the pointier the shape, the more accurate is the linear relationship).

**2.3.2.** *Malus' law.* Light transmitted through a couple of Polaroid filters as a function of the angle between them can be investigated with the use of a light sensor. A light source is needed to illuminate the couple of filters from the bottom and the smartphone with its sensor has to be placed above them. (Fig.12, left). The law stating that the relation between

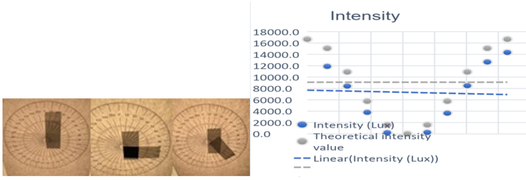


FIGURE 12. Experimental setup to test Malus' law (left) and data analysis of light intensity transmitted through a couple of Polaroid filters as a function of the angle between them (right). Data collection and analysis performed by students from scientific lyceum L. da Vinci – Treviso, Italy in the scholastic year 2019/20.

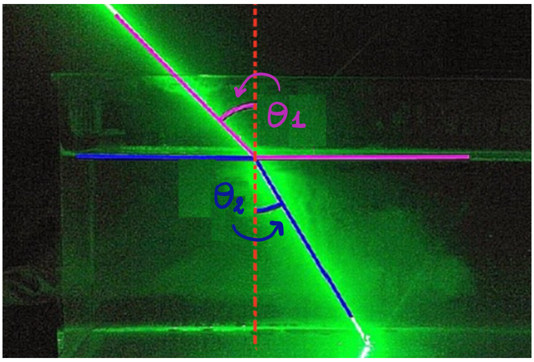


FIGURE 13. A laser beam highlights the refraction of light. Data collection and analysis performed by students from scientific lyceum L. da Vinci – Treviso, Italy in the scholastic year 2019/20.

the two quantities is of the form "cosine squared of the angle" $I(\theta) = I_0(\cos\theta)^2$ is known as "Malus' law" (Fig.12, right).

**2.3.3.** *Snell's law.* An experiment on optics that is not based on light intensity measurements, but on an analysis of a digital image is the measurement of the index of refraction of a material. When a beam of light passes through the separation between two transparent medium (Fig.13) with different index of refraction, its path changes direction according to the Snell law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{8}$$

For air $n_1 \simeq 1$, so:

$$n_2 = n = \frac{\sin\theta_1}{\sin\theta_2} \tag{9}$$

Pointing a laser beam towards the free surface of a (Fig.13) and varying the incidence angle $\theta_1$, it is thus possible, using the camera of the smartphone and performing angular measurements (also using dedicated APPs as Angulus, Protractor e Angle Meter) measuring the indexes of refraction of different materials, for example water (Tab.1).

TABLE 1. Measurements of the water index of refraction using three different APPs.

| **Used APP** | **Measured index of refraction *n* of the water** |
|---|---|
| Angulus | 1.25 |
| Protractor | 1.80 |
| Angle Meter | 1.73 |
| Average *n* | 1.59 |

**2.3.4.** *Spectroscopy measurements.* How to analyse the chromatic structure of light? As Newton shows, white light can be divided in different colours by a prism. A diffraction grating (a device with close engravings on its surface) can be also used to separate the colour components of a light beam thanks to the phenomenon of diffraction, which is a pattern distribution depending on the colour: the series of obtained colours is named "light spectra". Assuming a wave model for light, a wavelength $\lambda$ characterizing the colour is diffracted at an angle $\theta$ (Fig.14, top right) according to the formula:

$$d \sin\theta = m\lambda = mhc/E^{1} \tag{10}$$

Where $d$ is the distance between the engraving on the grating. It is possible to measure the wavelength $\lambda$ and/or the energy $E$ of a specific colour, measuring the angle at which it is diffracted (Fig.14, top left). The relationship between colour of a component radiation and the associated energy build the bridge between the emitted light and energy level of emitting matter, Optical spectroscopy in fact a way in which we can analyse the matter components. The identity card of each atom is his spectrum. Simple APP gives us the opportunity to carry out an optical spectroscopy. A spectroscope is a tube with a grating mounted on one side and a diaphragm on the other one in order to create a beam of light to be analysed (Fig.14, top right). It is possible to self-build a diffraction grating using a CD and removing the reflective surface. The obtained grating has $d = 1.67\mu m$. Putting it at the end of a small tube it is possible to build a spectroscope. By putting your little self-made spectroscope tube in front of the camera lens of your smartphone device, it is possible to collect a digital image of a light spectrum available and use it with the selected APP. Simple spectroscopes can be easily built and coupled with every smartphone (Fig.14, bottom).

Three mobile APPs are able to perform semi-qualitative measurements of light spectra. Two of them, SpectraUPB and AspectraMini are available only for Android devices, while the third, Light Analyzer, is available for both Android and iOS devices (Fig.15). The role of the various APPs consists in constructing the spectral profile, provided to the user in the form of a plot in which the intensity of the light is reported as a function of the long pixel position or spectrum. The APP Light Analyzer (Fig.16) is the one that allows the best control over the calibration, while the other two only allow to obtain the spectral profile considered, without obtaining any information on the wavelengths involved. However, with

[1]h and c are Planck's constant and the speed of light respectively. The last equality links the value of a wavelength with the corresponding value in energy.

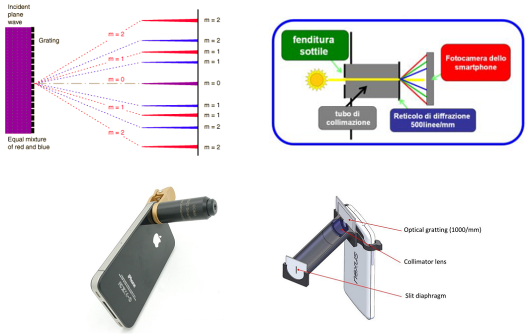


FIGURE 14. Practical use of a diffraction grating.

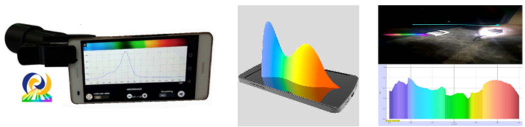

FIGURE 15. Spectroscopy APPs: SpectraUPB, AspectraMini e Light Analyzer.

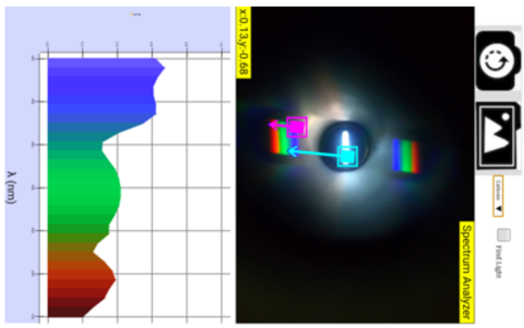


FIGURE 16. Interface of the APP Light Analyzer: the user has the possibility to select the position of the zero order of diffraction (blue marker), the blue end of the spectrum (corresponding to 400*nm*, purple marker) and the direction along which to extract the spectral profile, reported in real time at the bottom of the screen. In this way a spectrum calibrated in wavelength is obtained.

the use of the smartphone it is possible to obtain the light spectra of various light sources, highlighting the differences in the chromatic structure of the emitted light.

## 3. Conclusions

Mobile devices are nowadays very familiar objects discovered as real "tools" for doing science. Their use allows integrating technical and methodological skills with those of study, to explore technical characteristics of multimedia devices available in common smartphones.

The fascinating world of music can be explored by means of the powerful formal (as Fourier transform) and technical instruments (signal analysis) of physics, building competences of scientific citizen. The use of accelerometers and digital interfaces for the measurement of gravity acceleration offer the opportunity to reflect on the meaning of the laws of dynamics: the meaning of a gravitational field compared to the idea of remote action , as well as the role of the reference frame and in particular of the principle of inertia. In fact, the "surprise" of zero acceleration for bodies in free fall activates the discussion of the meaning of this result. This experience stimulate the discussion, the deepening and the clarification of the conceptual distinction between mass and weight (in particular apparent weight) of a body, as well as activate reflections on the concepts of force, gravitational field, gravitational and inertial mass, as well as on mass measurement methods. Simple methods based on angle measurements offer the opportunity to explore reflection and refraction in real world. The light intensity measurement by means of free APP for mobile open a world on physical optics, as the real dependence of light intensity from the distance from a source: the power and limit of the usual approximation, as Malus' law for light polarization. It is a great opportunity to reflect on the limits of validity of certain laws (Lambert's law) and the interpretation of the differences between the collected data and expected data (verification of Malus' law or of Snell's law). The use of electronic devices has allowed everyone to get involved and feel more involved in the learning process. The use of the APPs make it possible to perform measurements in real world and impossible in the school laboratory, allowing us to independently manage the experiments.

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Paper contributed to the international workshop entitled “New Horizons in Teaching Science”, which was held in Messina, Italy (18–19 november 2018), under the patronage of the *Accademia Peloritana dei Pericolanti*

Manuscript received 24 June 2020; published online 30 September 2021