Classical Experiments revisited: Smartphone and Tablet PC as Experimental Tools in Acoustics and Optics

P Klein[1,3], M Hirth[1], S Gröber[1], J Kuhn[1] and A Müller[2]

[1]University of Kaiserslautern, Department of Physics/Physics Education, Erwin-Schrödinger-Str. 46, 67663 Kaiserslautern, Germany
[2]University of Geneva, Faculty of Sciences/Physics Section and Institute of Teacher Education, Pavillon d'Uni Mail (IUFE), Boulevard du Pont d'Arve 40, 1211 Geneva, Switzerland
[3]Corresponding author: pklein@physik.uni-kl.de

Smartphones and Tablets are used as experimental tools and for quantitative measurements in two traditional laboratory experiments for undergraduate physics courses: The Doppler effect is analyzed and the speed of sound is determined with an accuracy of about 5 % using ultrasonic frequency and two smartphones, which serve as rotating sound emitter and stationary sound detector. Emphasis is put on the investigation of measurement errors in order to judge experimentally derived results and to sensitize undergraduate students to the methods of error estimates. The distance dependency of the illuminance of a light bulb is investigated using an ambient light sensor of a mobile device. Satisfactory results indicate that the spectrum of possible smartphone experiments goes well beyond those already published for mechanics.

1. Introduction
Mobile phones and smartphones have more and more become tools for everyday life – for us and for students in particular. Furthermore, mobile devices can "enrich educational opportunities for learners in diverse settings" [1, p.5].

We pick up this idea and integrate such mobile devices – especially smartphones and tablet computers –in undergraduate physics courses for the purpose of gathering and analyzing real data. Several sensors, such as microphones, acceleration sensors, field strength sensors, light intensity sensors and GPS receivers qualify these kinds of devices to conduct a large number of quantitative measurements and therefore enable them to serve as new, inexpensive experimental tools in physics education.

Some first examples discussing experimental possibilities of smartphones in physics have been presented in recent years, mostly focusing on mechanics or on the usage of the acceleration sensor of these devices [2-7]. Contributions concerning some other topics of physics education are rare [8-12].

In the following, we describe two traditional laboratory experiments with smartphones and a Tablet Computer illustrating low-cost techniques for analyzing physical content: In a first step, smartphones are used as experimental tools to analyze the Doppler effect and to determine the speed of sound. In a second step, the distance dependency of the illuminance of a light source is investigated.

2. Studying the Doppler effect with smartphones
The acoustic Doppler effect is an experience in everyday life for everyone. Out of several articles about the Doppler effect [13-15], we consider the idea of a rotating sound source [13,14] as a good example to model the passing by of an sound emitting source. In the following, we will determine the speed c of sound using smartphones as emitter and detector in a less complicated experimental setup compared to [14].

2.1 Theoretical Background
Consider a sound source with emission frequency f_e which moves on a straight line towards or away from a sound detector at rest. Let $0 < u < c$ be the velocity modulus of the sound source, then the frequency shift Δf between emission frequency f_e and detection frequency f_d is given by

$$\Delta f = f_d - f_e = \pm f_e \frac{1}{\frac{c}{u} \mp 1} \qquad (1)$$

The upper signs (combination of plus and minus) correspond to approaching and the lower signs (minus and plus) correspond to a receding source.
Now consider that the sound source rotates on a disk with constant velocity modulus u and the detector is placed within the rotation plane. A continuous frequency band will appear due to the permanently changing relative velocity between emitter and detector. Figure 1 illustrates that the maximum detection frequency $f_{d,max}$ and the minimum detection frequency $f_{d,min}$ are measured when the velocity vector is directed towards or reversely to the sound detector, respectively.
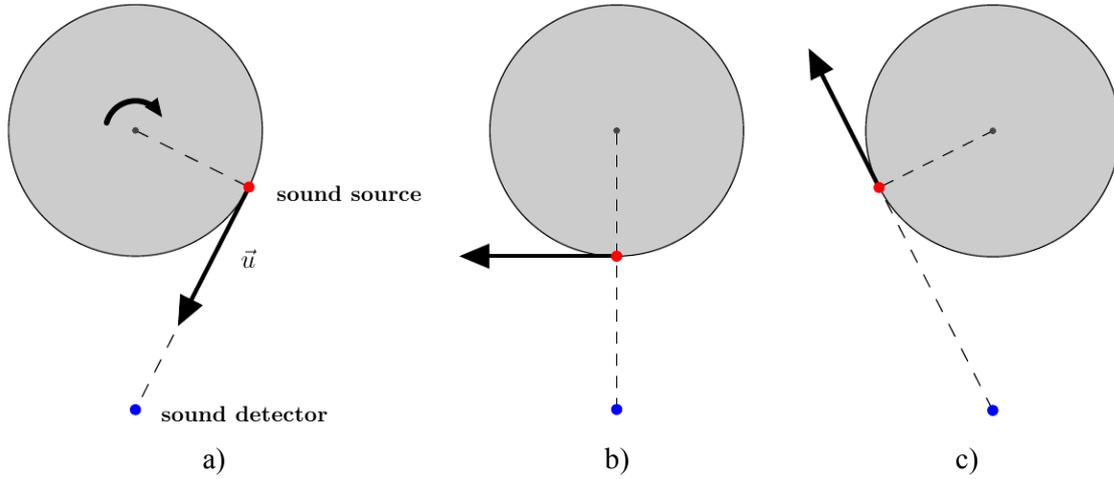
Figure 1. Position of sound emitting source (red dot) in three cases: a) Maximum frequency $f_{d,max} > f_e$ is measured during approach; b) No frequency shift is measured, $\Delta f = 0$ Hz; c) Minimum frequency $f_{d,min} < f_e$ is measured during recession.

The speed c of sound can be determined from equation (1) by

$$c = \frac{u}{1 - \dfrac{f_e}{f_{d,max}}} = \frac{u}{\dfrac{f_e}{f_{d,min}} - 1} \qquad (2)$$

Note that we neglect any changes of the experimental conditions (such as non-constant angular velocity of the rotating disc, fluctuating temperature and fluctuations in emission frequency). In the following, we reverse the Doppler effect in the sense that we derive c from the detected Doppler shifts.

2.2 Experimental setup
Figure 2a shows the experimental setup: A smartphone is fixated on a motor-driven rotating disc (with speakers in distance $r = 0.2$ m from point of rotation). The app "Audio Kit" [16] allows to produce emission frequencies f_e up to 19 kHz (figure 2d). We chose an emitting frequency of $f_e = 19$ kHz which can be motivated by three reasons: First, ambient noise does not disturb the measurement. Second, students will not be annoyed with constant perceivable emitted sound. Third, high frequencies allow using low rotation velocities, see (1). The velocity modulus

$$u = \frac{2\pi r n}{t} = \frac{2\pi r}{T} \qquad (3)$$

of the sound source is determined by measuring the period T from $n = 100$ revolutions during time t. To detect the signals, a second smartphone is placed in the rotational plane near to the disk. While the source is rotating, the application Spektro:skop [17] continuously measures and graphs the spectrum, see figure 2c. This data can be saved and exported as a CSV – file subsequently to evaluate the measurements in detail and to focus on the interesting part of the spectrum (near 19 kHz), see figure 3c. Note that the relevant part of the spectrum is not disturbed by ambient noise which typically occurs up to 15 kHz. Furthermore, note that the app Spektro:skop measures the sound pressure level in units of dBFS (decibel full scale): 0 dBFS refers to the maximum possible digital level (signal saturation). Just as the dB scale, dBFS is a logarithmic scale and signals with higher sound pressure result in lower (negative) values.
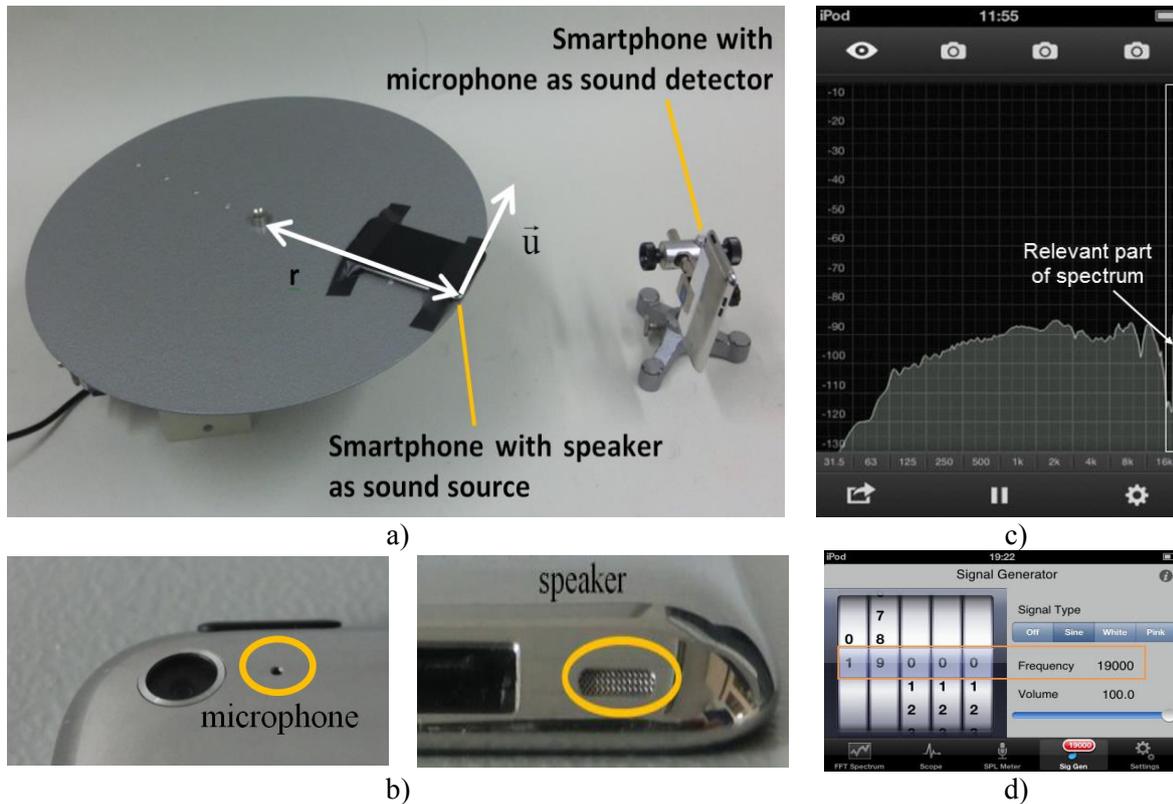
Figure 2. a) Experimental setup (r = 0.2 m), b) positions of microphone and speaker (Apple iPod touch), c) App "Spektroskop" as FTTspectrometer: x-axis shows the frequencies on a logarithmic scale, y-axis shows sound pressure level in dBFS (see text for explanation), d) App "Audio Kit" as signal generator

Remark: In our setup, we use iOS devices (Apple) because there are applications (apps) available which provide an export of measured frequency spectra. To this date, there are no equivalent Android applications known to us which provide this feature. Note that some apps (iOS- and Android-based) might measure and graph frequency spectra but exportation is restricted to figures instead of data sheets.

2.3 Results
Figure 3 shows the frequency spectra of three velocity moduli u and of the resting sound source:

(i)   S*pectral width*. The faster the velocity modulus u, the larger is the resulting spectral width (see equation 1).

(ii)   *Intensity drop*. The drop of the broad frequency spectra provides a determination of the maximal and the minimal frequency measured during experiment. Since even the frequency spectrum of the resting sound source is detected with an inaccuracy, this transfers to the spectra of the rotating sound sources. In consequence, the spectrum drop is not a sharp line but the measured maxima and minima still provide satisfactory results.

(iii)   *Asymmetry*. The different intensity maxima at the left and right edges of the spectra are caused by the orientation of the sound source in relation to the detector during approach and recession, respectively (see figure 2a).
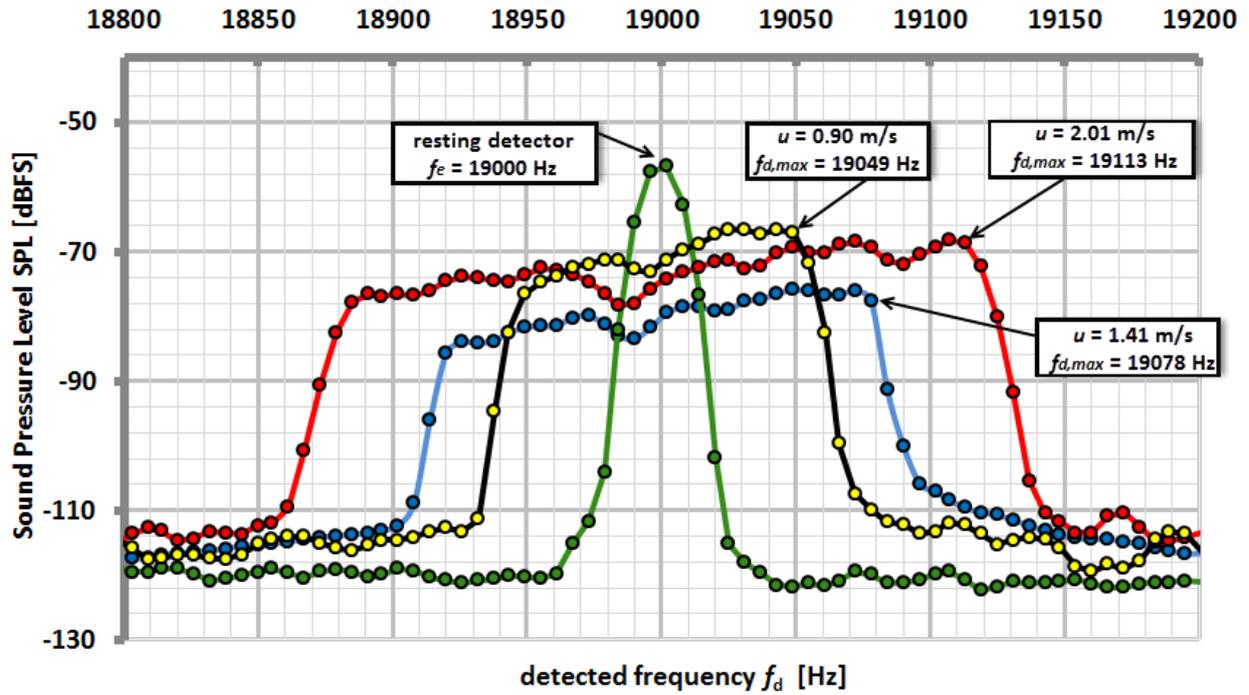
Figure 3. Measured frequency spectra of the sound source at rest (green line) and during rotation. Three different velocity moduli u were triggered.

In table 1, the speed c of sound is calculated for three velocity moduli u using maximum detection frequencies $f_{d,max}$ found in figure 3.

Table 1. Determination and errors of speed c of sound.

u (m/s)	$f_{d,max}$ (Hz)[a]	c (m/s)[b]	$\Delta c/c$ (%)[c]	$(c-c_r)/c_r$ (%)[d]
0.90	19049	350.0	13,0	2.0
1.41	19078	344.9	8,8	0.6
2.01	19113	340.0	7,0	0.9

[a]values from figure 3.
[b]calculated by equation 2.
[c]measurement uncertainty calculated by equation 4a.
[d]deviation from bibliographical reference $c_r = 343$ m/s ($\vartheta = 20\ °C$).

The deviation of c from bibliographic reference is about 2%. The measurement uncertainty $\Delta c/c$ was calculated by use of the Gaussian error propagation law:

$$\frac{\Delta c}{c} = \frac{f_e}{f_{d,max} - f_e}\frac{\Delta f_{d,max}}{f_{d,max}} + \frac{\Delta T}{T} \approx \frac{\Delta f_{d,max}}{f_{d,max} - f_e} + \frac{\Delta T}{T} \tag{4a}$$

For absolute errors $\Delta f_{d,max} = 6$ Hz, given by the frequency difference of adjacent data points measured by Spektro:skop, and $\Delta T = 0.01$ s estimated from $\Delta t = 1$ s for $n = 100$ revolutions of the disc, the total measurement uncertainty is about 10 %.

The first addend in equation 4 shows that small shift frequencies $f_{d,max} - f_e$ caused by small velocity moduli u result in large errors Δc. On the other hand, increasing angular velocity results in a larger error caused by the second addend in equation 4 since T becomes smaller. Therefore, working with lower emitting frequencies, for example $f = 6$ kHz, requires large angular velocities to observe a sufficient frequency shift $f_{d,max} - f_e$ but may require more complex time measurement methods to reduce ΔT.

We further estimate the variation of $c \sim \sqrt{\vartheta}$ due to changes of temperature ϑ:

$$\left| \frac{\partial c}{\partial \vartheta} \right| \Delta \vartheta = \frac{\Delta \vartheta}{2\vartheta} c \sim \frac{5K}{600K} c \approx 0.01c \qquad (4b)$$

Compared to the contributions of (4a), these variations can be neglected.
In conclusion, our results correspond with theory within given error limits (table 1). These limits are rather broad despite precise measurement techniques (note that, e.g. $\Delta f / f < 0.1\%$).

3. Distance dependency of the illuminance of a light source

Smartphones or tablet computers are often equipped with an ambient light sensor (ALS) in order to adjust the brightness of the display based on how much ambient light is present in the purpose of optimizing battery life [18]. Quantitative photometric measurements are possible because several apps allow reading out the sensor data in real-time. In the following, we discuss the measurement principle of the ALS and provide basic information about the photometric quantities we need to conduct a standard experiment for the physics classrooms: We investigate the distance dependency of the illuminance of a light source.

3.1 Theoretical Background

The number of quantities and units representing light measurement is large and one loses track to definitions rapidly. Instead of presenting an overview about the relationships between several quantities, we start our theory based on the measurement principle of the ALS:

An ALS uses a photodiode with a prefixed filter in order to adjust its spectral sensitivity to the brightness sensitivity of the human eye (the so-called *luminosity function*). The measured quantity is the luminous flux Φ per unit area A, the so-called illuminance E

$$E = \frac{\partial \Phi}{\partial A} \qquad (5)$$

in units of cd sr/m² = lux. Illuminance is the physical quantity of what the human eye perceives as *brightness*. Given a light source with isotropic intensity $I(\Omega) = I_0$ where Ω denotes the solid angle, it is well-known that E follows an r^{-2} law, i.e.

$$E(r) = \frac{I_0}{r^2} \qquad (6)$$

For sufficiently large distances ($r \geq 20$ cm, experimentally determined for the light source in own setup, see sect. 3.3), (6) e.g. is valid for a light bulb, which we demonstrate in the following.

3.2 Experimental Setup

A light bulb and a mobile device (Samsung Galaxy Tab 2 equipped with an ALS [19]) are both placed on an optical bench in a darkened room as seen in Figure 4. It must be ensured that the center of the ALS is located at the same height as the light bulb. Note that the sensor is sensitive to illuminance changes of approximately 5 lux which is less than 1 % of the absolute values measured in this experiment. Hence, uncertainties of measurement are not caused by the sensors' accuracy but for example by deviations from vertical alignment of the mobile device. Such deviations may result in lower values since a smaller effective detection surface is illuminated ("cosinus-law"). Therefore, a level balance helps to keep vertical alignment as needed.
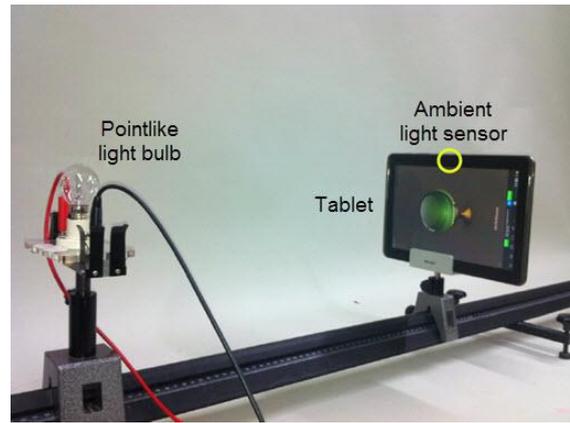
Figure 4. Experimental setup to measure distance dependency of the illuminance of a light bulb.

3.3 Results

In order to verify (6), illuminance E is plotted against r^{-2} as shown in figure 5. For sufficient large distances, the data points lie on a straight line as expected and the coefficient of determination is high. For small distances (≤ 20 cm), the spatial extension (deviation from a point source) and directional characteristics from the light source cannot be neglected. Hence, deviations from the r^{-2} law increase as the distance becomes smaller.
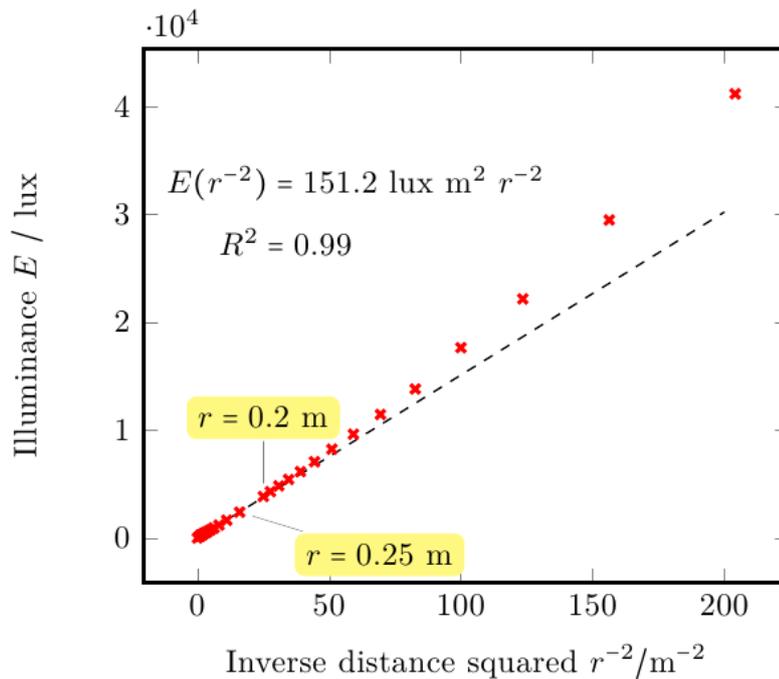

Figure 5: Measured illuminance E versus r^{-2} (red data points) and regression line for the far-field ($r \geq 25$ cm, black) to proof the inverse squared law. Distance r varied from 7 cm to 20 cm in steps of 1 cm (near-field) and from 25 cm to 115 cm in steps of 5 cm.

4. Discussion

We presented two classical experiments using smartphones as experimental tools: first, an analysis of the acoustic Doppler effect, including its use for measuring the speed of sound; second an investigation of the r^{-2} dependence of the illuminance of a light source.

In conclusion, both experiments show that using a mobile device could at least have two main advantages: First, the experimental setup indicates how traditional measurement techniques can be extended by mobile devices offering sufficient measurement accuracy. With smartphones as stand-alone devices, the experimental setup can be less complicated compared to traditional measurement techniques and may thus foster students' understanding. Second, being everyday tools, mobile

devices allow students to measure physical quantities in everyday life and compare them at different places in their environment. It remains to study the effects mobile devices have on students' learning behavior – a research subject rather unexplored yet. Within our N.E.T.-project (New Media Experimental Tools), we investigate the motivational and cognitive benefits students achieve when conducting scientific experiments with mobile devices [20].

Acknowledgements

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[20] See http://www.physik.uni-kl.de/kuhn/forschung/net/ [02/2014] for further information.