RESEARCH ARTICLE | JULY 24 2023

A version of Buys Ballot experiment for quantitative proof of the Doppler effect in students' laboratory work, adapted to online conditions FREE

Zsuzsa Sárközi ; Alpár-István-Vita Vörös

AIP Conference Proceedings 2843, 050013 (2023)
https://doi.org/10.1063/5.0150800

A Version of Buys Ballot Experiment for Quantitative Proof of the Doppler Effect in Students' Laboratory Work, Adapted to Online Conditions

Zsuzsa Sárközi[1, a)] and Alpár-István-Vita Vörös[1, 2]

[1] *Babeș-Bolyai University, Physics Department (str. Mihail Kogălniceanu nr. 1, 400084, Cluj-Napoca, Romania).*
[2] *Apáczai Csere János Highschool (str. I.C. Brătianu nr. 26, 400074 Cluj-Napoca, Romania).*

[a)] Corresponding author: susana.sarkozi@ubbcluj.ro

Abstract. There are many possible ways to experimentally test the Doppler effect. Last year's epidemic forced us to transform the laboratory practices for online conditions at university level physics education. We performed a similar experiment as Buys Ballot's and recorded it for student's online laboratory work: we placed a loud, single-frequency sound source on a moving car and recorded the sound near the road while the car was passing with constant speed. The source was a smartphone connected to a loudspeaker. The digital recording was then analyzed by students in the frame of online laboratory work using the "phyphox" application on their smartphones (but any other frequency analyzer app could have been used). A sample calculus for the speed of the car and the estimation of the errors of measurements is also presented. The scientific processing of a dataset is almost as useful for students as it would be for a laboratory experiment conducted in attendance education. The advantage here is that they could deal with a phenomenon which previously was not included among the laboratory themes, although it is interesting and has a large variety of applications. Highlighting the importance of the Doppler effect and the good practices in other countries, we recommend to include this topic in the Romanian high school physics curriculum as well.

MOTIVATION AND CHALLENGES IN THE DESIGNING OF ONLINE LABORATORIES

During the online learning/teaching process forced by the pandemic, it was a real challenge to replace student's laboratory work by something similar, by which we can attain the same purpose, namely to prepare students for conducting real experiments (to collect, process and interpret scientific data as well as to communicate the results).

For the General Physics Laboratory and for the Mechanics I - II laboratories, the teaching staff at our university prepared video-recordings of the usual laboratory experiments. These video files were used by students for data acquisition. Some experiments were rethought as home experiments. For the online laboratory work we had to take into account which tools can our students have at home: in addition to a ruler or a measuring rod, they probably have a watch and a cell phone that they can use during their lab practice. The mobile phone application "phyphox" [1] was of great help. Students determined gravitational acceleration from the measurement of the period of a thread pendulum and also studied centripetal acceleration using phyphox. Other experiments were transformed in such a way, that students had to figure out, based on the calculus of theoretical maximal relative errors, how to set the parameters of an experiment in order to achieve a certain precision of the result. In our opinion one of this kind of laboratory work is sufficient, merely because it is too theoretical and it does not involve any measurements.

The situation raised a question: Is there something important/interesting that we were not used to measure in the laboratory, but could be done online? One obvious experiment that otherwise would need a lot of space is the acoustic longitudinal Doppler effect experiment, in a similar way as Buys Ballot has performed it in 1845 [2].

It has to be mentioned that there are many other possible realizations of the Doppler effect experimentally in the laboratory, the majority of those described in educational physics papers using Doppler effect for measuring something

Proceedings of the TIM20-21 Physics Conference
AIP Conf. Proc. 2843, 050013-1–050013-6; https://doi.org/10.1063/5.0150800
Published by AIP Publishing. 978-0-7354-4594-9/$30.00

else (i.e. the frequency of a pendulum, acceleration, the speed of sound) [3,4]. There are also various experimental setups described in the literature (confront [5] and references therein).

For our purpose, we needed the simplest setup. We have found some sound registrations on the internet which could be used for measurements at first sight, such as Formula 1 registrations, where there is one single car moving on a straight part of the track. The problem here is, that there are multiple frequencies in the sound of the engine and in addition, one cannot be sure, that the movement of the car is uniform. Among the MITK12Videos on youtube, designed by a group from Massachusetts Institute of Technology, there is also one about the Doppler effect, in which they eventually repeat Buys Ballot's experiment with the use of a trumpet in a moving car. It was designed for the demonstration of the effect, not for measurements, unfortunately. Thus, if we wanted a real set of measurements, we had to register the phenomenon for various parameters, like different frequencies of the source and different, well-known speeds of the source. A detailed description can be found in the third section.

We "met" our students for the online laboratory work on the Discord platform because at that time it was the only one to provide the conditions which mimicked real laboratory work, so that the students were divided into groups of two or three, and the teacher, as well the students, could have free movement between the groups.

DOPPLER EFFECT IN THE PHYSICS CURRICULA

Although at the time C.A. Doppler deduced (in 1842) that this effect of frequency-change must exist, his theory was not very plausible as it was not common for sound or light sources to travel at speeds at which the effect could have been easily detected by human senses. Nowadays, of course, we encounter this effect almost every day: it is noticeable that every time as a vehicle approaches us, the moment it passes us, the sound of the vehicle suddenly switches to a lower frequency. Even after the experimental demonstration of the Doppler effect (DE) in 1845 by C.H.D. Buys Ballot, no application has been foreseen at that time, but today there are far-reaching consequences of the DE in terms of technical progress. The DE is utilized in many technical applications, such as medical diagnosis (imaging, determination of the blood flow rate through the ultrasound DE, or the determination of the heart rate of the fetus) and therapy. The optical DE is used in several other areas: in radar systems, in meteorological forecasts, for astronomical observations, but also when keeping contact with satellites orbiting the Earth. It is well known that the expansion of the universe was established based on DE, and this also provides the basis for our current theory of how the universe has formed. David Nolte [6] provides us with a detailed historical background of the phenomenon and with a brief summary of today's Doppler spectroscopy. Based on all these, we recommend that it is such a fundamental phenomenon that it should be included in every physics curricula which contain a chapter regarding waves.

The European Space Agency (ESA) has a successful video explaining the longitudinal Doppler effect [7], which could serve as a basis for its introduction as a curriculum, but there are also plenty of lesson plans already available on the internet, which can help teachers to prepare the subject for the class.

As a simple demonstration experiment it can be done purely mechanically by using a flexible pipe with one end rotated, or with a single tone generator (on a mobile phone for instance) while swinging it overhead in a mesh.

In France DE is included as curriculum for certain special classes and it is also a theme for the graduation exam [8], in South-Africa DE has recently been introduced in the curriculum [9], in Germany DE has been proposed to be introduced and a methodology was elaborated [10]. Romanian high school physics curriculum [11] does not include the topic of Doppler effect. Browsing the 11th grade textbooks from Romania we noticed that, in spite of that, in one of them DE is treated as exercise [12], and in another textbook DE is mentioned in two technical applications without clarifying the phenomenon [13].

IMPLEMENTATION OF BUYS BALLOT'S EXPERIMENT FOR ONLINE LABORATORY CONDITIONS

As usually, before performing their laboratory work, students read the theoretical basis of the experiment and the working method for their measurements. This did not change in the framework of online conditions.

Students were provided with a brief description which contained mainly the link towards phyphox.org in order to get the app, and the well-known Doppler formula for the observed frequency in various source / observer situations:

$$f_o = \frac{1 \pm \frac{v_o}{c}}{1 \mp \frac{v_s}{c}} f_s, \tag{1}$$

where f_o and f_s are the observed and the source frequency, v_o and v_s denotes the velocities of the observer and the sound source with respect to the medium in which the sound propagates, and c is the speed of the sound in that medium. The upper operations are valid when the observer or the source is approaching, and the lower ones are valid when they are moving away. Students also got a link towards a movie specially edited from multiple sound recordings of the acoustic DE.

The experiments were performed and registered outdoors. The temperature of the air was -7 °C. As sound source, a mobile phone with a tone generator and a loudspeaker placed on a car were used (Fig. 1), while the car was moving on a straight road at different speeds (30, 50 and 70 km/h according to the speedometer on board). So, the frequencies of the approaching and receding sound source are easy to be distinguished also by ear.

FIGURE 1. The sound source: a mobile phone with a tone generator and a loudspeaker placed on a moving car

The video compilation begins with the recorded sound of the resting source relative to the air and observer (two different frequencies, 1100 Hz and 1500 Hz), followed by a set of recordings of the same sound source in motion. Students were asked to use the phyphox application, the Audio Spectrum analyzer with the History tab, where the peak frequency is plotted versus time for each 10 ms timeframe. The whole recording can be analyzed at once. Data can also be exported for further analysis. As it is shown in Fig. 2, the greater the speed of the car, the greater the frequency difference between the approaching and receding sound source. The frequency value for a given point can be easily read using the "Pick data" button.

After analyzing the frequencies for different situations, students are required to calculate the speed of the car in each situation. They have to express the speed of the source from eq. (1). There are three different possibilities:

- using the frequencies of approaching and resting sound source

$$f_a = \frac{1}{1 - \frac{v_s}{c}} f_s, \tag{2}$$

which leads to

$$v_s = \frac{f_a - f_s}{f_a} c \tag{3}$$

- using the frequencies of receding and resting sound source

$$f_r = \frac{1}{1 + \frac{v_s}{c}} f_s \tag{4}$$

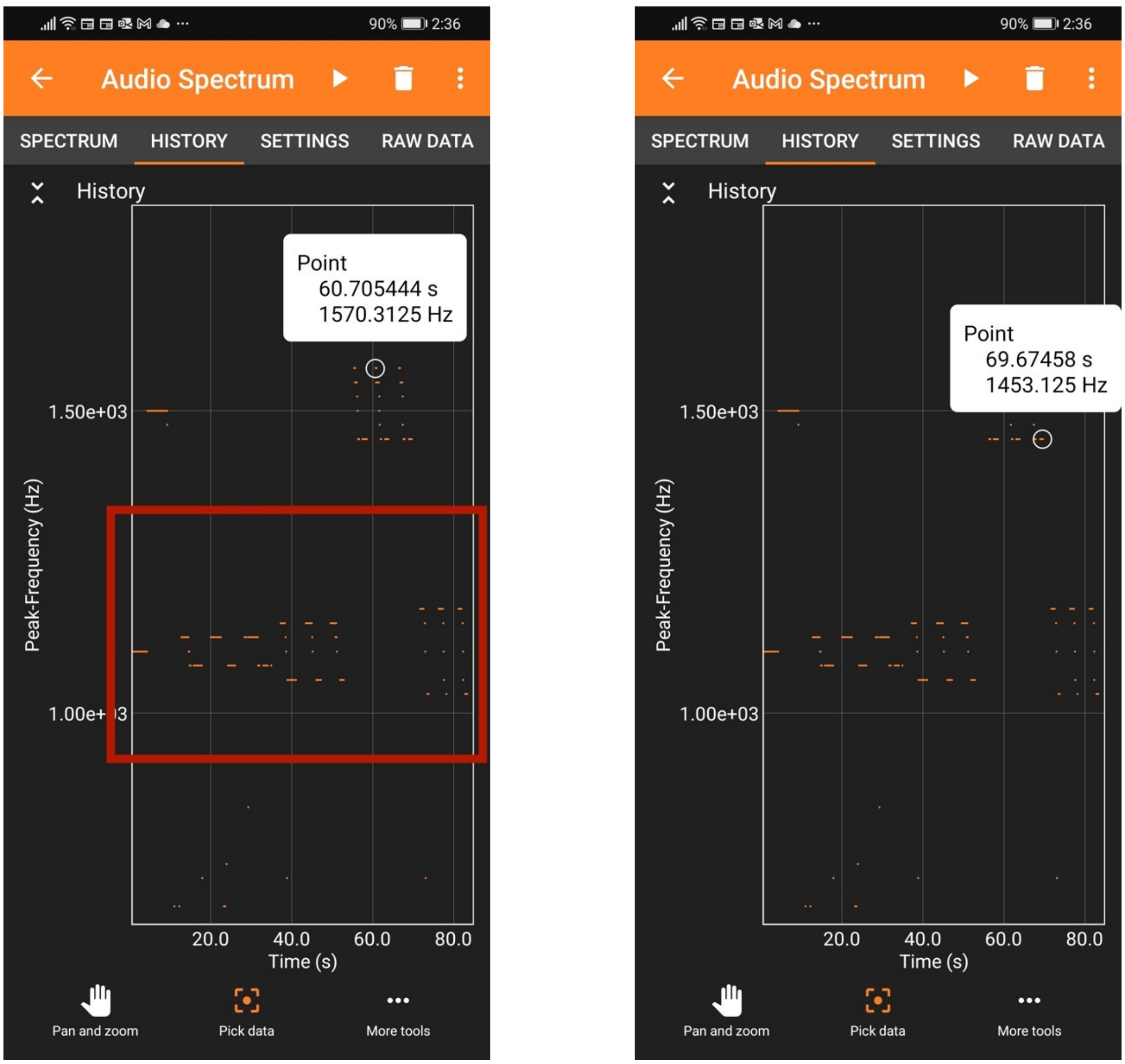
one obtains

$$v_s = \frac{f_s - f_r}{f_r} c \tag{5}$$

- using the frequencies of approaching and receding sound source, by dividing eq. (2) by eq. (4), and expressing the speed of the source, results

$$v_s = \frac{f_a - f_r}{f_a + f_r} c \tag{6}$$

As usual, the measurement data are entered in a table, together with the calculated physical quantities. Such a table of measurements is given below (Table 1). Here, for the speed of the sound the value of 327 m/s was used, a value obtained according to the temperature [14].



(a) (b)

FIGURE 2. Screenshots of a measurement of peak frequencies versus time with phyphox. On part (a) in the thickened frame one can see the increasing Doppler-shift as the speed of the source is increasing. Around the value of 1500 Hz there is a DE for one single velocity of the source. On part (a) the frequency of the approaching source is readable, while on part (b) the frequency of the receding source is shown

The table contains also the greatest possible errors for each speed, calculated as percentage $\left(\frac{\Delta v_s}{v_s}\right)_{max}$ and also in absolute value $(\Delta v_s)_{max}$, presuming that the precision of reading frequencies with the application cannot be worse than $\Delta f = 5$ Hz:

$$\left(\frac{\Delta v_s}{v_s}\right)_{max} = \frac{\Delta c}{c} + \frac{\Delta f}{f_a - f_r} + \frac{\Delta f}{f_a + f_r}, \tag{7}$$

$$(\Delta v_s)_{max} = v_s \cdot \left(\frac{\Delta v_s}{v_s}\right)_{max}. \tag{8}$$

Usually, such a measurement table has to contain the actual error of the measurement as well, which means the difference between the average value and the value calculated for each single measurement. In this case all frequency measurements for a certain speed of the source gave the same result. We have to note that according to the measurements reported by several students, there were some offsets in the measured frequencies (even for the case of resting source) which we attribute to the use of different electronic devices on which the sound was played and then analyzed. When the same device was used, there were no differences between the frequencies measured for the same speed at all.

TABLE 1. Example of students' measurement table. Here f_s, f_a and f_r denotes the frequency of the resting, of the approaching and of the receding source respectively. The velocity of the source v_s was calculated according to eq. (6). The greatest measurement errors were calculated according to eq. (7) and eq. (8).

speed nr.	f_s	f_a	f_r	v_s		$\left(\frac{\Delta v_s}{v_s}\right)_{max}$	$(\Delta v_s)_{max}$	
	Hz	Hz	Hz	m/s	km/h	%	m/s	km/h
1.	1102	1125	1078	7.0	25	22.1	1.5	6
2.	1102	1148	1057	13.9	50	11.4	1.6	6
	1500	1570	1453	12.7	46	9.2	1.2	4
3.	1102	1172	1031	20.9	75	7.9	1.7	6

According to the set of measurements presented in Fig. 2 and Table 1, the sound source was moving with three different velocities in the experiments: (7.0±1.5) m/s, (13.1±0.9) m/s, and (20.9±1.7) m/s, which corresponds to (25±6) km/h, (47±3) km/h and (75±6) km/h. This shows a good match with the selected speed values, shown on the car's speedometer. For the second speed there are two sets of measurements at two different frequencies. That leads to a greater precision of the result, as the result has to be in the intersection of the two intervals. Examining the values obtained in m/s and in km/h, it turns out that it is also a great exercise for students to get used to the correct number of decimal places the result should be.

CONCLUSIONS

We have implemented a new students' laboratory work adapted to online conditions. Doppler effect was realized outdoors using a mobile phone and a loudspeaker as sound source on a moving car. Digital recording of the acoustical Doppler effect was used for data acquisition via mobile phone applications (mainly phyphox) for the first-year students online laboratory work. The data collected led students to the determination of the speed of a car (as moving sound source) and the estimation of measurements errors.

Doppler effect is ubiquitous in daily life, also as a directly perceptible acoustic phenomenon or as technical applications. Nevertheless, there is no mention of this effect in the Romanian high school physics curriculum. Therefore, we recommend the introduction of "Doppler effect", at least as an optional topic in the Mechanical Waves chapter.

ACKNOWLEDGMENTS

The publication of this article was supported by the 2021 Development Fund of the UBB. We are also grateful for the help of our student András Kisjancsi and of his team, who performed and recorded the outdoor experiments.

REFERENCES

1. S. Staacks, S. Hütz, H. Heinke and C. Stampfer, Phys. Educ. **53**, 045009 (2018).
2. E.J. Jonkman, Ultrasound in Med. & Biol. **6**, 1–5 (1980).
3. T. Stonawski and T. Gálik, Phys. Educ. **52**, 015002 (2017).
4. R. Gagne, The Physics Teacher **34**, 126–127 (1996).
5. J.A. Gómez-Tejedor, J.C. Castro-Palacio, J.A. Monsoriu, Eur. J. Phys. **35**(2), 025006 (2014).
6. D. Nolte, Physics Today **73**(3), 30–35 (2020).
7. https://www.esa.int/ESA_Multimedia/Videos/2014/07/Doppler_effect_-_classroom_demonstration_video_VP0
8. ***, Le Bulletin officiel de l'éducation nationale, de la jeunesse et des sports no. 46 (3 déc. 2020), (https://www.education.gouv.fr/bo/20/Hebdo46/MENE2033175N.htm)
9. M. Mosabala, Mediterranean Journal of Social Sciences **5**, 207–212 (2014)
10. M. Strasser, *Der Doppler-Effekt in der Schule. Ein Demonstrationsexperiment für den Physikunterricht*, (GRIN Verlag, München, 2020), pp. 1–28.
11. ***, Programe şcolare pentru ciclul superior al liceului, fizică clasa a XI-a, Ordinul Ministrului Educației și Cercetării nr. 3252/13/02.2006, Anexa nr. 2., București, (2006). https://www.isjcta.ro/wp-content/uploads/2013/06/Fizica_programa-F1_F2_clasa-a-XI-a_a-XII-a.pdf
12. J. Tellmann, B. Darvay, Z. Kovács, *Fizika F1 Tankönyv a XI. osztály számára* (Ábel Kiadó, Cluj-Napoca, 2006), pp. 84–87.
13. S. Bratu, A. Motomancea, I. Apostol, *Fizică - Manual pentru clasa a XI-a F1* (Editura Didactică și Pedagogică R.A., București, 2006), pp. 94, 163.
14. https://www.weather.gov/epz/wxcalc_speedofsound