Abstract. In this article we set out to design, develop and test didactic experiments for the determination of the speed of sound in the air and to compare the didactic efficacy of these experiments. Firstly, we analysed the methods based on measuring the time interval after which the sound reflected by an obstacle is detected. Secondly, we presented the methods of measuring the time of flight of an acoustic wave front between two detectors (microphones). The first category of didactic experiments (echo recording) contains sound speed determinations using an ultrasonic sensor connected to an Arduino processing board, the reflection on one end closed tubes and the reflection on walls situated within a large distance from the sound source. The second category of didactic experiments (time of flight recordings) contains determinations using a data acquisition device (NIDAQ).

Key words: Sound, speed, Ping sensor, Arduino, tube, microphone, echo, data acquisition device, LabVIEW, Audacity.

1. INTRODUCTION

A very important teaching-related aspect of the experimental activities associated with the study of Acoustics concerns the measuring the speed of sound through the air. Literature in this field comprises a series of studies [1,2,3], such as the study of Berg and Courtney [4] about the echo-based method of measuring the speed of the sound, the determinations performed by Litwhiler and Lovell [5] with the help of a computer sound card and a LabVIEW software application, as well as the determinations made by Carvalho et al. [6] with free software application, such as Audacity.

However, such studies do not perform a comparative analysis of these methods in order to test the efficiency of each one. That is why this paper brings forward a new approach, by testing a wide methodical spectrum and emphasizing, comparatively, the quality factors that differentiate the degree of efficiency of these methods. The factors that we made reference to were: the financial investment needed to acquire the experimental materials, the time required to perform the experiment, the minimum digital competence level of the students, the time for data processing and last, but not least, the precision of the measurements performed.
2. DETERMINATION OF THE SPEED OF SOUND THROUGH THE AIR USING THE ECHO-BASED METHOD

The common principle of these methods consists in emitting a sound wave towards a wall and receiving the echo produced (Fig. 1). Measuring the time lag ($\Delta t$) between the moment when the sound was emitted and the moment it was received we can calculate the speed of the sound ($v_s$) based on the mathematical relation:

$$v_s = \frac{2 \cdot \Delta d}{\Delta t}$$  \hspace{1cm} (1)

where $\Delta d$ represents the value of the distance between the sound source and the wall.

![Fig. 1 - Schematic representation of the methodic principle used to determine the speed of sound through the “echo-based method”. The colored versions can be accessed at http://www.infim.ro/rrp/](http://www.infim.ro/rrp/)

This method of determining the speed of sound in the air was used for three different distances: short distance (cm), medium distance (m), long distance (dozens of meters).

2.1 Determining the Speed of Sound in the Air through Echo-Based Methods Using a Short Range Ultrasonic Sensor

We used an ultrasonic sensor Ping connected to a development Arduino board (Fig. 2).

![Fig. 2 - Experimental scheme for a short range ultrasonic sensor. The colored versions can be accessed at http://www.infim.ro/rrp/](http://www.infim.ro/rrp/)
This sensor has a range of action from 2cm to 3m. The functional control of the sensor is done through an application uploaded on Arduino. Therefore, the sensor is programmed to emit an ultrasonic impulse (on the 40 kHz frequency) and detect the echo produced by an object situated on the direction of the ultrasonic flow. The application measures the time lag emission-reception \( \Delta t \) and, knowing the distance relative to the object \( \Delta d \), can determine \( v_s \) according the relation (1). The aspects associated with the experimental setup, the diagram of the application and the results obtained can be seen in the images below (Fig. 3, Fig. 4, Fig. 5 and Fig. 6).

![Experimental setup](http://www.infim.ro/rrp/)

![Experimental values obtained](http://www.infim.ro/rrp/)

```
void setup() {
  Serial.begin(9600);
}

void loop() {
  float duration, spd;

  pinMode(pingPin, OUTPUT);
  digitalWrite(pingPin, LOW);
  delayMicroseconds(2);
  digitalWrite(pingPin, HIGH);
  delayMicroseconds(5);
  digitalWrite(pingPin, LOW);

  Serial.print("duration = ");
  Serial.println(pingTime, "f");
  Serial.print("spd = ");
  Serial.println(spd, "f");
  Serial.print("v_s = ");
  Serial.println(spd / duration, "f");
}
```

![Sequences from the Arduino application diagram](http://www.infim.ro/rrp/)
We performed measurements of $v_s$ for different distances between the sensor and the objects situated in its vicinity, under various conditions of temperature and humidity of the surrounding environment.

The experimental results of $v_s$ for different acoustically reflective physical environments are illustrated in Table 1. We used the following notations: $\Delta d$ - distance; $\Delta t$ - time; $v_s$ - sound speed; $v_{sr}$ - reference value sound speed; $v_{sm}$ - medium value sound speed; $v_{srm}$ - medium value reference sound speed; $\varepsilon$ - measurement error; $\varepsilon_m$ - medium measurement error; $\varepsilon_r$ - relative measurement error; $\varepsilon_{rm}$ - medium relative error; $\theta$ - temperature; $RH$ - relative humidity index.

The reference values of the speed of sound through the air, were established using the relation (2):

$$v_{sr} = (331 + 0.600 \cdot \theta) \frac{m}{s}$$

**Table 1**
Experimental results of $v_s$ for different acoustically reflective physical environments

<table>
<thead>
<tr>
<th>Material</th>
<th>$\Delta d$ (cm)</th>
<th>$\Delta t$ (μs)</th>
<th>$v_s$ (m/s)</th>
<th>$v_{sr}$ (m/s)</th>
<th>$v_{sm}$ (m/s)</th>
<th>$v_{srm}$ (m/s)</th>
<th>$\varepsilon$ ($\frac{m}{s}$)</th>
<th>$\varepsilon_m$ (%)</th>
<th>$\varepsilon_r$ (%)</th>
<th>$\theta$ (°C)</th>
<th>$RH$ (%)</th>
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<tbody>
<tr>
<td>PVC</td>
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<td>337.3</td>
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<td>339.8</td>
<td>347</td>
<td>7.2</td>
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<td>22</td>
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<tr>
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<td>589</td>
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<td></td>
<td></td>
<td>26</td>
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<tr>
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<td>584</td>
<td>339.6</td>
<td>346.6</td>
<td>338.7</td>
<td>347</td>
<td>8.3</td>
<td>8.06</td>
<td>2.39</td>
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<td>79</td>
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<td>2975</td>
<td>336.1</td>
<td>344.2</td>
<td>338.9</td>
<td>347</td>
<td>8.3</td>
<td>8.06</td>
<td>2.39</td>
<td>26</td>
<td>68</td>
</tr>
<tr>
<td></td>
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<td>338.9</td>
<td>346.6</td>
<td>341.2</td>
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<td>344.2</td>
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<td>338.3</td>
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<td>Concrete</td>
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<td>7092</td>
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<td></td>
<td>240</td>
<td>14088</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>32</td>
<td>79</td>
</tr>
</tbody>
</table>
Figure 7 illustrates the dependence of the values $v_s$ on the temperature $\theta$ of the surrounding environment.

$$v_s = v_s(\theta)$$

The experimental values variation obtained for different flat materials, for a given temperature, is determined by the dispersion of the ultrasonic flow with the increase of distance and by the ultrasonic reflection coefficient of the material the reflective panel is made of.

Analysing the graphic of dependence $v_s = v_s(\theta)$ for the plastic reflective wall (Fig. 8) we deducted a medium value of its slope $m = 0.575$ rather close to the value $m = 0.600$ associated to the reference speed value graph from the same diagram. Therefore, the equations of the two lines $v_s = v_s(\theta)$ and $v_{sr} = v_{sr}(\theta)$ are:

$$\begin{cases}
  v_{sr} = 331 + 0.600 \cdot \theta \\
  v_s = 326 + 0.575 \cdot \theta
\end{cases}$$

(3)
The analysis of the experimental data on the thermal interval (22 ± 32°C) indicates a medium value measured for the sound speed \( v_{\text{sm}} = 338.9 \frac{m}{s} \) related to the medium value reference \( v_{\text{srn}} = 347 \frac{m}{s} \). With a relative medium error \( \varepsilon_{\text{rm}} = 2.32\% \), we deduce the fact that such measurements have a good precision, adapted for didactic purposes.

2.2 Determining the Speed of Sound in the Air through Echo-Based Methods on a Medium range distance

In this experiment we used a small section tube \((cm^2)\) of known length \( L \), closed at one end. At the other end of the tube we placed a sensitive microphone, connected to the sound card of a computer (Fig. 9).

![Diagram of tube closed at one end with labels: S - acoustic source, M - microphone, PC - computer, L - length, Emitted wave, Reflected wave.]

Fig. 9 - Experimental scheme using a tube closed at one end. The colored versions can be accessed at [http://www.infim.ro/rrp/](http://www.infim.ro/rrp/).

An acoustic signal was generated next to the microphone. The acoustic wave emitted was detected by the microphone and turned into an electric signal, digitally processed by sound editing software installed on a PC (Audacity – free audio editor). The acoustic wave front propagated towards the inside of the tube and, when reaching its closed end, reflected back towards the microphone. The microphone recorded a second signal, which was sent to the computer. The time interval between the two detected signals was calculated from the graphic analysis of the electrical wave forms displayed in the window of the audio editing software. Knowing the length of the acoustic reflection tube \((L)\) and the time interval between the main wave front and the reflected one \((\Delta t)\), the speed of the sound \((v_s)\) was calculated based on the relation:

\[
v_s = \frac{2 \cdot L}{\Delta t}
\]  

We performed experiments using tubes made of different materials (PVC, metal), having different values of the cross-sections and of their lengths (Fig. 10, Fig. 11, Fig. 12 and Fig. 13).
In the following diagrams (Fig.14, Fig.15 and Fig.16) we can observe a few results from the set of experimental data obtained:

**Fig. 10** - Experimental setup using a PVC tube (L=1m). The colored versions can be accessed at [http://www.infim.ro/rrp/](http://www.infim.ro/rrp/).

**Fig. 11** - Experimental setup using a long PVC tube (L=3m). The colored versions can be accessed at [http://www.infim.ro/rrp/](http://www.infim.ro/rrp/).

**Fig. 12** - Experimental setup using an aluminum tube (L=0.85m). The colored versions can be accessed at [http://www.infim.ro/rrp/](http://www.infim.ro/rrp/).

**Fig. 13** - Experimental setup using a copper tube (L=1m). The colored versions can be accessed at [http://www.infim.ro/rrp/](http://www.infim.ro/rrp/).

**Fig. 14** - Experimental results for a PVC tube. The colored versions can be accessed at [http://www.infim.ro/rrp/](http://www.infim.ro/rrp/).

**Fig. 15** - Experimental results for an aluminum tube. The colored versions can be accessed at [http://www.infim.ro/rrp/](http://www.infim.ro/rrp/).
The experiments were performed in various conditions of the thermodynamic atmospheric parameters: temperature and humidity. The obtained results can be visualised in Table 2.

**Table 2**

Experimental results for \( v_s \) obtained for tubes of various materials closed at one end

| Material     | \( L \) (cm) | \( \phi \) (cm) | \( \Delta t \) (ms) | \( v_s \) (m/s) | \( v_{sx} \) (m/s) | \( v_{sm} \) (m/s) | \( \varepsilon = |v_{sm} - v_{sx}| \) (m/s) | \( \varepsilon_m \) (m/s) | \( \varepsilon_{rm} \) (%) | \( \theta \) (°C) | \( RH \) (%) |
|--------------|--------------|-----------------|---------------------|-----------------|-------------------|-------------------|---------------------------------|-----------------------------|------------------|--------------|-------------|
| PVC tube     | 100          | 5               | 5.76                | 347.2           | 346               | 346.6             | 1.73                            | 0.49                         | 0.57             | 25           | 55          |
|              | 100          | 2               | 8.66                | 346.4           | 348.5             | 348.23            | 2.02                            |                             |                  |              |             |
|              | 200          | 1.5             | 11.55               | 346.02          | 350.6             | 346               | 1.73                            | 0.49                         | 0.57             | 29           | 64          |
| Metallic     | 100          | 1               | 5.73                | 349.04          | 349.04            | 349.4            | 3.04                            | 0.87                         | 0.81             | 32           | 70          |
| tube - Al    | 87           | 3               | 5.01                | 347.3           | 347.3             | 346               | 1.3                             | 0.37                         | 0.37             | 25           | 55          |

The notations \( L \) and \( \phi \) correspond to the lengths and to the diameters of the selected tubes.

One could notice an insignificant dependence of the value \( v_s \) on the tube section \( S \) or its length \( L \). However, the resolution of the reflection diagram is more visible for long tubes with a wider section. The experimental data, recorded in the thermal interval \( (25 \pm 32°C) \), indicate a medium measured value of the speed of sound \( v_{sm} = 347.6 \frac{m}{s} \) related to a medium reference value \( v_{sx} = 346.7 \frac{m}{s} \). The presence of a value \( \varepsilon_m < 1\% \) leads to the conclusion that such an experimental method is recommended for high precision measurements of the speed of sound in the air.
2.3 Determining the Speed of Sound in the Air through Echo-Based Methods on a Long Range Distance

As a sound source we used a balloon (containing air at high pressure) situated near a directive microphone (having a parabolic reflector) facing the wall and connected to the sound card of a computer. The sudden release of the air contained in the balloon generates an acoustic wave which propagates omnidirectionally. The acoustic disturbance is detected by the microphone in two stages: at first, directly and, a little later, through reflection on a wall situated at an established distance $\Delta d$ (Fig. 17).

![Diagram](image)

Fig. 17 - Experimental scheme using the echo-based method on a wall. The colored versions can be accessed at [http://www.infim.ro/rrp/](http://www.infim.ro/rrp/).

The audio editing software displays the wave forms of the two signals in a time domain diagram. Knowing the distance acoustic source – wall $\Delta d$ and determining the time interval $\Delta t$ between the direct signal and the reflected signal allows us to apply the formula (1) and determine $v_s$.

The experiments were performed outside (schoolyard) using the sound reflection on the wall of a building (school) (Fig. 18 and Fig. 19).

![Setup (front view)](image)

Fig. 18 - Experimental setup (front view).

![Setup (back view)](image)

Fig. 19 - Experimental setup (back view).
In Fig. 20 there is an example of an Audacity diagram containing a recording $\Delta t = 0.099\text{s}$ for the spatial interval $\Delta d = 17\text{m}$.

![Fig. 20 - Time interval recording $\Delta t$. The colored versions can be accessed at http://www.infim.ro/rrp/](image)

In Table 3 one can observe aspects of the experimental recordings.

**Table 3**

Experimental results of $v_s$ obtained using the “echo on a wall” method

| Area                | $\Delta d$ (m) | $\Delta t$ (ms) | $v_s$ (m/s) | $v_{sr}$ (m/s) | $v_{vm}$ (m/s) | $\varepsilon = \frac{|v_{vm} - v_{sr}|}{v_{vm}}$ (m/s) | $\varepsilon_s = \frac{v_{vm} - v_{sr}}{v_{sr}}$ (%) | $\theta^\circ$ (C) | $RH$ (%) |
|---------------------|----------------|-----------------|-------------|---------------|---------------|-------------------------------------------------|-------------------------------------------------|---------------|----------|
| Outdoor (schoolyard)| 17             | 9.9             | 343.43      | 344.6         | 346           | 3.5                                             | 1.01                                            | 25            | 65       |

The experiments took place in constant temperature and atmospheric pressure conditions. The method has a good accuracy, in direct proportion to the sensitivity and acoustic directivity of the microphone in use. The medium value of the speed of sound $v_s = \frac{342.5\text{m}}{s}$ is rather close to the reference value $v_{sr} = \frac{346\text{m}}{s}$. The presence of multiple echoes requires a high resolution analysis of the wave forms associated with the signals recorded by a microphone, in order to establish the precise temporal interval needed to determine $v_s$.

### 3. METHODS BASED ON DETERMINING THE TIME OF FLIGHT

Through these methods we can determine the value of the time interval $\Delta t$ in which an acoustic wave front emitted by a source placed next to a microphone is
propagated towards another microphone situated at a distance $\Delta d$ from the first. The acoustic signals detected by the microphones are digitally processed through a specialized software so that we can measure the time lag between them: $\Delta t$. Knowing the values of $\Delta d$ and $\Delta t$ we can determine $v_s$ based on the relation:

$$v_s = \frac{\Delta d}{\Delta t}$$ (5)

### 3.1. Determining the Time of Flight using Walkie-Talkie Stations (Outdoor Method)

This method uses two walkie-talkies, a microphone with a parabolic reflector and an overpressurised balloon. The walkie-talkie stations were configured on the same communication channel. The microphone was connected to a laptop on which the sound recording and editing application Audacity was used (Fig. 21). Two operators were needed for the successful completion of this experiment. One of them moved with a walkie-talkie and with the balloon at a considerable distance (a few hundred meters) from the place where the other operator was located. The latter placed the walkie-talkie near the microphone and started the sound recording application (Fig. 22, Fig. 23 and Fig. 24). The sudden release of air from the balloon (through explosion) generated an acoustic disturbance that was detected by the walkie-talkie and transmitted, through the radio communication channel, to the other station. This station emitted a signal upon reception which was detected and recorded by the parabolic microphone. After a time interval $\Delta t$, the acoustic wave front arrived, propagated through the air. This second signal was also recorded.

Analysing the graphic which contains the recorded wave forms we determined, with a good degree of accuracy, the value of $\Delta t$ (Fig. 25). Measuring the distance between the two walkie-talkies ($\Delta d$), we calculated the value of the speed of sound based on the relation (5).

![Experimental scheme for determining the time of flight using walkie-talkies.](http://www.infim.ro/rrp/)

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**Fig. 21** - Experimental scheme for determining the time of flight using walkie-talkies. The colored versions can be accessed at [http://www.infim.ro/rrp/](http://www.infim.ro/rrp/).
Table 4 contains a few experimental results.

**Table 4**

Experimental results of $v_s$ using the outdoor method

| $\Delta d$ (m) | $\Delta t$ (s) | $v_s$ (m/s) | $v_{ir}$ (m/s) | $v_{sm}$ (m/s) | $\varepsilon = \left| v_{sm} - v_{ir} \right|$ (m/s) | $\varepsilon_r = \left| \frac{v_{sm} - v_{ir}}{v_{ir}} \right|$ (%) | $\theta (\circ C)$ | RH (%) |
|----------------|----------------|-------------|----------------|---------------|---------------------------------|---------------------------------|---------------|--------|
| 300            | 0.885          | 339         | 345.4          | 336.6         | 9                               | 2.6                             | 25            | 63     |
| 375            | 1.115          | 339         | 345.4          | 336.3         |                                 |                                 |               |        |
| 450            | 1.345          | 334.6       | 345.4          | 336.6         | 9                               | 2.6                             |               |        |
The recordings performed under constant pressure, temperature and humidity led to a medium value of $v_s = \frac{336.6 m}{s}$, related to a reference value $v_{sr} = \frac{345.4 m}{s}$. The method employed is efficient (relative error $\varepsilon_r = 2.6\%$) and interesting, because it emphasizes two speeds at which the information may propagate: the radio waves speed (speed of light) and the acoustic wave speed (speed of sound). The resolution $\Delta t$ (between the two detected signals) is good, due to the high distance travelled by the acoustic wave front.

3.2 Method of Determining $\Delta t$ using a Data Acquisition Device (Indoor Method)

In this experiment the two microphones for sound detection were set up at a distance of a few meters from each other. We used two data channels from the data acquisition device NIDAQ 6008. The signals detected by the microphones were amplified and acquired by the data entry channels, being digitally processed using LabVIEW Signal Express. As an acoustic signal source we used an overpressurized balloon. The explosion of the balloon near one of the microphones generated an acoustic wave that propagated towards the other microphone (Fig. 26, Fig. 27 and Fig. 28).

![Experimental scheme for determining $\Delta t$ using a data acquisition device](http://www.infim.ro/rrp/)

Fig. 26 - Experimental scheme for determining $\Delta t$ using a data acquisition device. The colored versions can be accessed at [http://www.infim.ro/rrp/](http://www.infim.ro/rrp/).

![Experimental setup](http://www.infim.ro/rrp/)

Fig. 27 - Experimental setup. The colored versions can be accessed at [http://www.infim.ro/rrp/](http://www.infim.ro/rrp/).

![DAQ signal recording](http://www.infim.ro/rrp/)

Fig. 28 - DAQ signal recording. The colored versions can be accessed at [http://www.infim.ro/rrp/](http://www.infim.ro/rrp/).
The analysis made by the data acquisition device allows the measurement of the time interval in which the acoustic disturbance travels between the two detectors (Fig. 29 and Fig. 30).

One can notice in Table 5 examples of experimental recordings.

| $\Delta d$ (m) | $\Delta t$ (ms) | $v_s$ (m/s) | $v_{sr}$ (m/s) | $\varepsilon = |v_{sm} - v_{srm}|$ (m/s) | $\varepsilon_r = \frac{|v_{sm} - v_{srm}|}{v_{srm}}$ (%) | $\theta$ (°C) | RH (%) |
|---------------|----------------|-------------|----------------|---------------------------------|---------------------------------|-------------|--------|
| 1             | 2.84           | 352.11      | 350.57         | 2.17                            | 0.6                             | 29          | 70     |
| 2             | 5.71           | 350.26      | 348.4          |                                 |                                 |             |        |
| 4             | 11.45          | 349.34      | 348.4          |                                 |                                 |             |        |

The medium measured value of the speed of sound through this method was $v_s = 350.57 \frac{m}{s}$, related to a reference value $v_{sr} = 348.4 \frac{m}{s}$. The relatively small error (under 1%) makes this method suitable for high precision measurements of the value $v_s$.

4. CONCLUSIONS

The conclusions of the comparison involving the experiment-based methods presented in this article can be drawn based on the data found in Table 6. We used quality indexes for the methodical evaluation criteria present in the table (L-low, M-middle, H-high). We proceeded to attribute values to those indexes, ranging on a scale from 1 to 10, as follows: L – interval $1 \div 4$; M – interval $5 \div 7$; H – interval $8 \div 10$.

The score for the applicability of each method in Physics Education was
calculated based on the formula:

\[ S = \frac{DA}{VFI + TPE + DCR + DPT} \]  

(6)

The variables present in the algebraic structure of the formula are illustrated in Table 6 and the graphic representation in Fig. 31.

**Table 6**

<table>
<thead>
<tr>
<th>Methodical evaluation criteria</th>
<th>Methods</th>
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<td>Echo Ultrasounds</td>
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<td>Financial investment value</td>
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<td>Digital competences required</td>
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<td>(DCR)</td>
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<td>Data processing time (DPT)</td>
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<td>Score for method applicability in class (S)</td>
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<td>0.375</td>
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</tbody>
</table>

Fig. 31 - Methodology rating. The colored versions can be accessed at [http://www.infim.ro/rrp/](http://www.infim.ro/rrp/).

Analysing the values of S for the echo-based method, we concluded that the experiments based on ultrasonic echoes rank first, followed closely by the tubes experiments. In what concerns the time of flight method, the leading experiments are those involving the use of a data acquisition device (NIDAQ). Whichever of these methods can be successfully applied in Physics Education, conveying results that allow for both a qualitative and quantitative approach in the sound speed measuring experiments. All in all, as we have shown in previous studies [7, 8], in line with the findings of other authors [9,10], the role of experiments in the teaching of physical concepts or phenomena is of outmost importance, arising
students’ awareness and curiosity towards the topics that are investigated.

REFERENCES