Walkie-talkie measurement for the speed of radio waves in air

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Abstract

An affordable handheld emitter-receptor device which is suitable for the direct estimation of the velocity of radio-waves in air is presented. The velocity of radio-waves is measured by the direct time of flight method, without needing any tedious and precise settings. Results for two measurement series are reported. Both results estimates the accepted value of radio-waves in air with less than 16% error. The method can be used with success during a field-trip or picnic and it is appropriate for both high-school and university level student projects.

I. INTRODUCTION

The speed of electromagnetic waves in vacuum is one of our fundamental constants. The fact that its value is independent from reference frames holds the key to special relativity and defines the presently used length unit in the International System (SI). Due to the extremely big value of this velocity (c $\approx 3\cdot 10^8$ m/s), and due to the fact, that most of the detectors and emitters have a relatively slow reaction time, it's measurement proved to be rather difficult by using direct flight of time methods[1,2]. Nevertheless many successful direct measurements have been done both for light rays and for radio waves in air[3−10]. The majority of these experiments use a delicate experimental setup, and it is not advisable for students projects without supervision. In normal coaxial and optical cables the measurements can be done relatively easily by using a high frequency signal generator and a good oscilloscope[11,12]. Another alternative is to use interconnected computers and play with the "ping" command on cables with different length[13]. These experiments are rather useful in high-school and university laboratories. The drawback is however that there are not open-air experiments, diminishing their pedagogical strength. Indirect measurements based on interference and/or the estimation of the frequency and wavelength are also possible[14−18]. This can be realized by an affordable setup[16], the problem is that their pedagogical value is limited by the fact that there are not direct methods. The speed of radio-waves can be also estimated by many other indirect methods. One of them is the use of the naturally occurring lightning discharges in the troposphere, which generates radio waves with low frequency and small propagation attenuation in the Earth's atmosphere[19]. Another possibility is to use the resonance frequency of an LRC circuit[20].

Here we present a simple walkie-talkie apparatus that can be built with a modest budget (around 150 USD), and which is appropriate for obtaining a direct estimate by the flight of time method for the speed of electromagnetic waves in air. The measurement method and data collection is also straightforward, so it is a good candidate for high-school projects and demonstrations.

II. EXPERIMENTAL APPARATUS

Nowadays there exists a large variety of affordable transceiver chips, that can operate on the Industrial, Scientific and Medical (ISM) license-free radio-frequencies bands and which are optimal for sending and receiving data[21]. These chips are the ones that are usually used in commercial and cheap walkie-talkie systems. By using these chips one can construct simplified transmitters and receivers that are able to communicate with simple pulse sequences and are able to measure with a good precision the time-lag between emitting a signal and receiving the response to it.

Two simple Emitter - Receiver (ER) devices were built based on these transceiver chips. One of the ERs is connected to a computers USB port, continuously sending the measured time-lag data. The heart of the ERs is the integrated circuit with the codename RFM12BP, made by HOPE Microelectronics Ltd. This is suitable both for sending and receiving data, so the same circuit is fitted in ER1 and ER2. The RFM12BP is a cheap ISM integrated circuit which is perfect for being used in such experiments[22]. It can work on three different frequencies: 433 MHz, 868 MHz, 915 MHz. Depending on the geographic location and state regulations, one can select the operating frequency, so that it should be in the license-free ISM band. For example in most of Europe and Russia the 433 MHz and 868 MHz frequencies are free to use and for the American continent the 915 MHz frequency is OK. The RFM12BP chip is widely used in remote controls, for wireless communications and for data collection purposes. Details for the construction of the ERs and the computer interface are given in[23]. In[23] we also give the programs used for data collection and processing.

On Figure 1 we present the used equipments. The ERs are powered with 12V DC voltage, supplied in our experiments from two Uninterruptible Power Supplies (UPS). The ERs are sending and receiving (communicating) a data package of 1 byte. They are able to emit and detect a total of 30-40 data packages per second. The ER which is connected to the computer (from now on ER1) sends a package to the other (ER2). After ER2 detects the package coming from ER1, it responds with another data package. If the response package returns to ER1, it records the time elapsed between the original package and the response with a 1/8 μs accuracy. The recorded time is sent than to the computer, where it is registered. If ER1 doesn't detect a response package, it will emit another signal. The communication protocol is very similar with the classical "ping" protocol in computer networks. The function of the ERs (function meaning which is the emitter, and which is the receiver) is defined by the settings of the micro-controller that can be be found on the circuit. According to those settings, one of the ERs will be in a master state, while the other one will be in a slave state. This means, there is a master/slave type of connection between the ERs, the master being the one which emits the data packages, and the slave being the one which responds to the emitted data packages. Both ERs are running a program written in C++, which actually governs their communication. The algorithmic representation of their communication is sketched in Figure 2. From here we learn the following simple operation protocol: ER1 sends a signal, and starts the clock. If this signal reaches ER2, then ER2 responds with another 1 byte length signal. When the response signal reaches ER1, this stops the clock, writes the elapsed time to a file on the attached computer, and sends another signal, starting the clock again.

Once we know the distance between ER1 and ER2, it is possible to estimate the speed of the electromagnetic waves in open air. Everything seems straightforward, unfortunately however (as it is usual with experiments) the problem is not that simple due to several reasons:

1. The constructed ERs are of short range, they are able to communicate only on distances less than 3 kilometers. Under such conditions the electromagnetic waves pass from ER1 to ER2 and back in a very short time period (of the order of microseconds). The time-accuracy of $1/8$ μs of the equipment is barely satisfactory for the measurements. For improving the results we will measure many flight times and analyze them statistically. In our experiments for each particular position of the ERs, we recorded continuously the flight-times for approximatively 15 minutes. This means that we process roughly 20 000 different measuring results for each particular distance.

2. The worst problem arises from the fact that the largest part in the communication time of the ERs result not from the finite spread-time of the electromagnetic waves, but from the delay in the ERs. It takes orders of magnitude longer for the ERs to emit and receive data, than for the signal to pass. Under such conditions a simple measurement on one fixed distance is useless, and we need to make relative measurements to eliminate the delay time of the apparatus. We consider thus measurements on different distances and consider the difference between these flight times. Assuming that the

average delay on the ERs is the same every time, differences between the mean flight times are due to the finite velocity of the radio waves in air. The easiest method to estimate the correct value of the velocity is to plot the average recorded total delay as a function of the distance between the ERs. Considering a linear regression on these points, the tangent of the slope will give the inverse value of the velocity of the radio-waves in air.

3. Another problem, with the devices built by us is that for the same position of the ERs, with a small occurrence rate the recorded flight times have unexpectedly high values. In other words this means that the distribution of the flight times for one fixed location does not show a simple normal distribution around a mean value. Instead of one peak we get other well-separable and much smaller peaks which are shifted with a constant offset (Figure 3a). These smaller peaks can be nicely observed if we use logarithmic axes for the distribution functions (Figure 3b). Although the occurrence rate of the flight-times values leading to the second and higher level peaks of the distribution are small, they might still strongly affect the statistical interpretation of the data. Calculating thus a simple mean for the observed flight times could be seriously biased by these rare events. The situation is not so gloomy however, since the good news is that these peaks are clearly separable. Averages can be thus computed solely on flight-times belonging to the first peak, and in such manner rare-events are taken out from the statistics. The obtained peculiar distribution function of the flight-times can be interpreted in the following way: there are always additive noises on the analog components in the devices, these are responsible for the observed normal distribution. Seemingly, there are also errors on the digital components. The fact that the successive peaks are delayed with a characteristic delay-time (τ_d) suggests errors of the frame-synchronization algorithms acting on the transceiver chip. Such effects are present in other wireless communications as well.

4. The wave-length of the radio-waves used by us is relatively short, in consequence the effects of reflexion might be significant. To avoid this, we must do the measurements in an open field. In such cases however, there are no convenient electric networks available to operate the ERs and the computer. The solution is to carry two fully loaded PC batteries (UPS) to the selected measuring locations and to use a notebook

instead of a desktop computer.

5. Due to the fact that we make our measurements in an open field, and the distance between the two ERs can be of the order of kilometers, the direct measurement of the relative distances becomes also a problem. The easiest method is to locate the exact GPS coordinates of ER1 and ER2 by using a mobile GPS locator. This is commonly available nowadays even on cell-phones. Then, with these coordinates one can easily determine the distance between the two geographical points by using the freeware Google Earth program. In case of short distances (10-50m) we measure the distance directly by using a measuring tape. Naturally, the double of this distance is used for approximating the round-trip of the wave-packages.

III. EXPERIMENTS

For performing the measurements, we have found a suitable open field close to our university town Cluj-Napoca (Romania). The 433 MHz frequency band was used to operate our walkie-talkie devices. We made measurements in two different occasions using convenient and nearby locations. In both experiments we have chosen a suitable place for the base-camp, a place from where one could go to a fairly long distance (2-3 km) by car and remaining still in sight. We left the ER1, one of the UPS and a notebook at the campsite. ER2 and the other UPS were transported by car to different distances. The communication between the teams (one staying at the camp and the other one being in the car) was done by using mobil-phones. For every chosen distance we let the ERs to communicate with each other for about 15 minutes, during which we recorded the flight-times times of the emitted and received packages. For each location where we made measurements, the GPS coordinates were recorded and later we calculated the exact distances between the two ERs from these data. In every measuring spot we recorded the GPS coordinates at least 5-6 times, and we used an average of these coordinates, eliminating thus the imprecisions of our GPS system. The spots used for the measurements are sketched on Figure 4, a figure which is realized by using Google Earth. We estimated that the error for determining the exact position is of the order of 20m, which means that the round-trip distance was determined with an error of ± 40m.

IV. DATA PROCESSING AND RESULTS

During the measurements several thousands of flight-times were recorded for each distance (the ERs were communicating approximately 15 minutes). First, we have eliminated those data that did not fit in the first peak of the distribution function (see Figure 3). By this we have eliminated the rare events influenced by errors on the digital components and obtained normally distributed data. For this data we calculated then the characteristic mean. The error was estimated from the standard deviation of the used data divided by the square root of their number. The mean flight time for each measurement with the characteristic error-bars was plotted as a function of the distance between ER1 and ER2. Results obtained for the two measurement series are plotted on Figure 5. The obtained trend can be reasonably well approximated with a linear fit. The steepness of this fit will give in both cases an estimate for the inverse velocity of the radio waves.

By using the error bars on both axis (estimated distance and mean flight-time) we can determine also a maximal (plotted with dotted lines) and minimal slope (plotted with dashed lines) fit, leading to a confidence interval for the obtained velocity. With this simple data processing procedure the result are the following: for the first series of measurements (a) we got from the best fit $c_1 = 3.08 \cdot 10^8$ m/s and the confidence interval $c_1 \in [2.58, 4] \cdot 10^8$m/s and for the second experiment (b) we get the best value $c_2 = 3.46 \cdot 10^8$m/s with the confidence interval $c_2 \in [2.95, 4.14] \cdot 10^8$m/s. The obtained best fit values approximates in both cases the accepted value of the velocity of electromagnetic waves in air ($c \approx 2.99 \cdot 10^8$ m/s) with an accuracy of less than 16%. The accepted value is in both cases in the given confidence interval.

V. CONCLUSIONS

We presented here a simple and affordable handheld emitter-receptor device that can be build in high-school or university labs with a modest budget and can be used to estimate the speed of radio-waves in air. The experiments are made in open-air and seemingly such project is fun for the students. The measurement method and data processing is quite straightforward and can be understood with high-school level physics and mathematics knowledge. The apparatus is easy to handle, it is reliable and thus not necessitate fine tuning or precise setting. After making two series of measurements with this apparatus we have estimated in both cases the velocity of radio-waves in air with less than 16% error.

Acknowledgments

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Figures

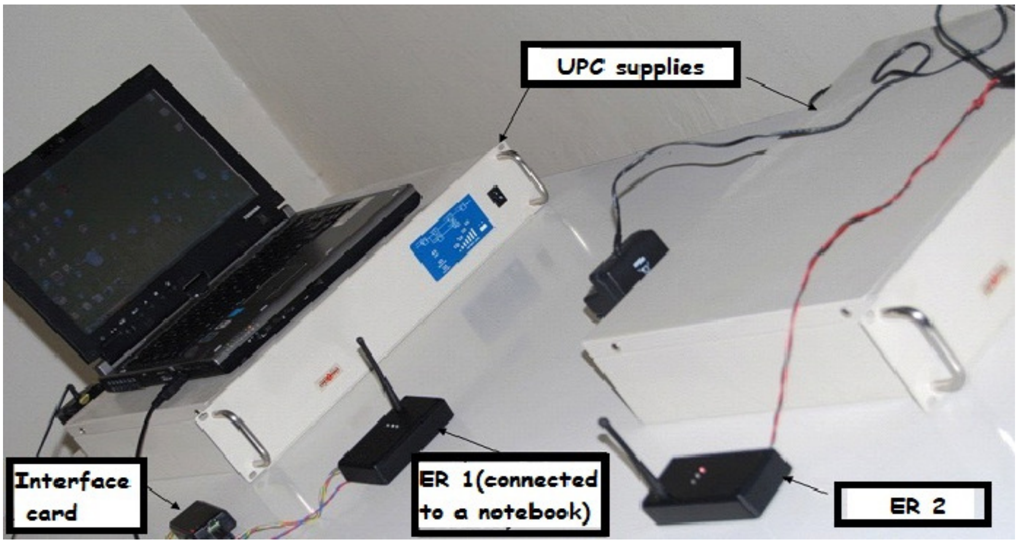

FIG. 1: Measurement apparatus. The ERs used for the measurements, the two uninterruptible power supplies (UPC) and a notebook used for collecting the data.

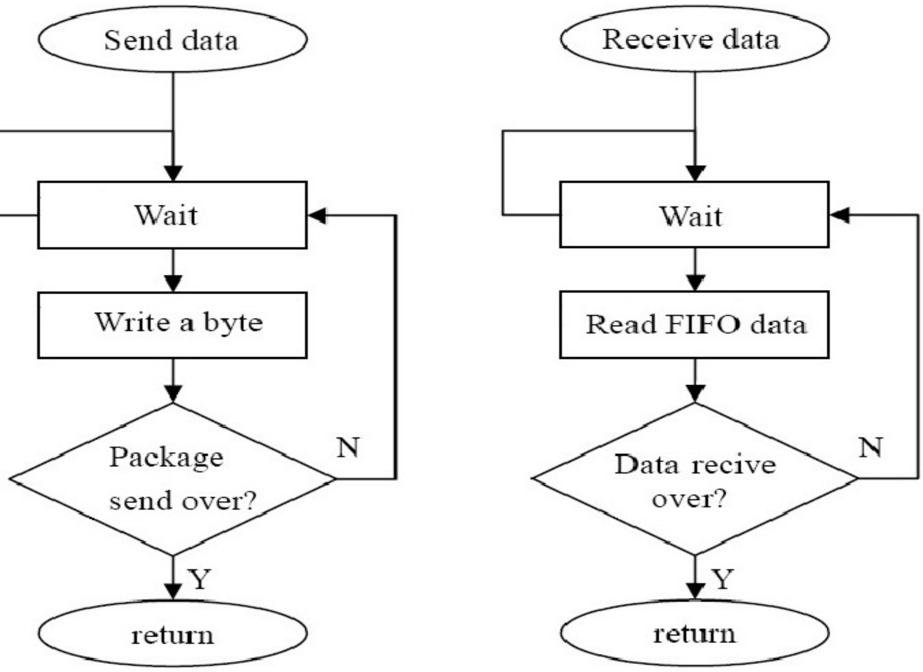

FIG. 2: Flowchart for the transmitter-receptor system.

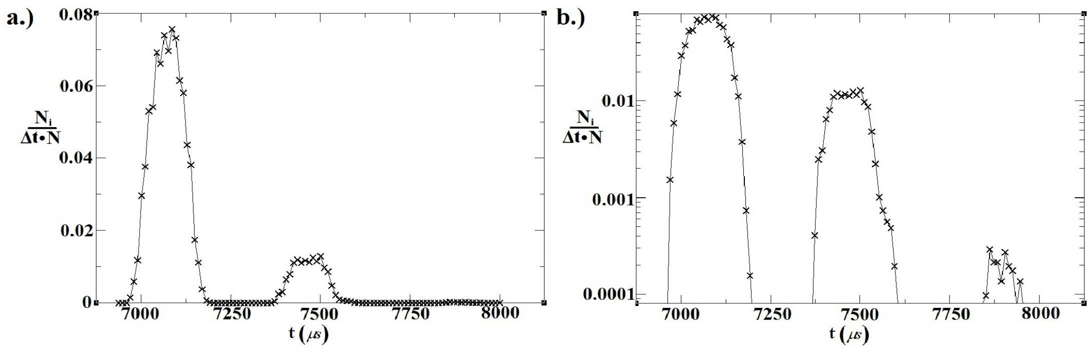

FIG. 3: (a) Distribution of the recorded flight-times for a fixed position of the ER's. (b) The same distribution using a logarithmic vertical scale, where the smaller peaks are also visible.

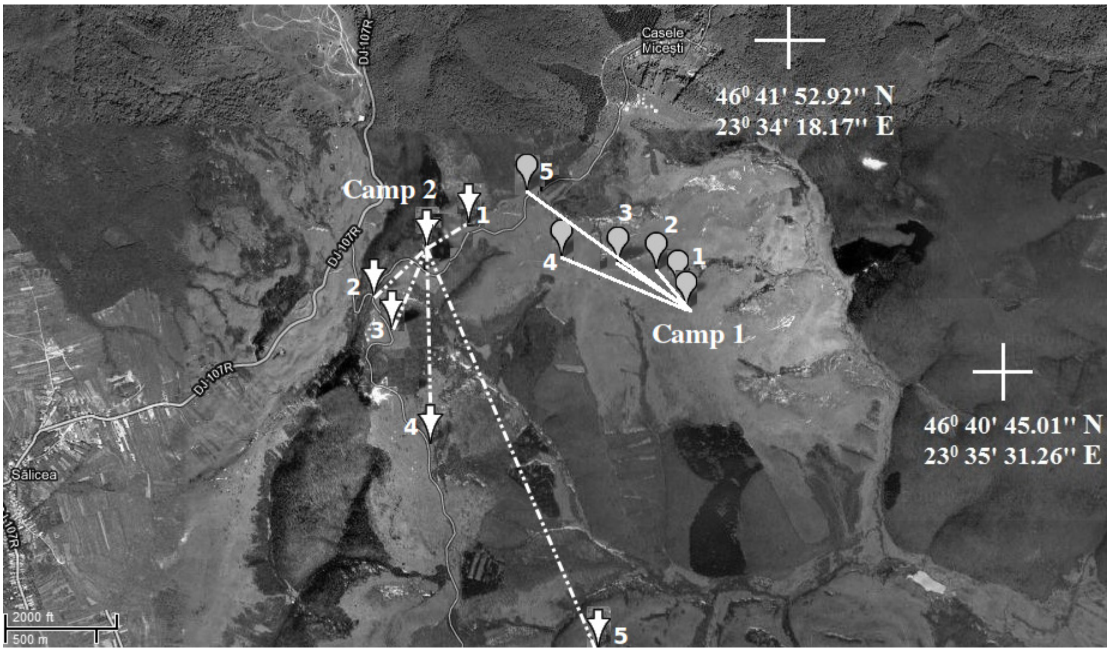

FIG. 4: Google Earth satellite map showing the locations for the two measurements series.

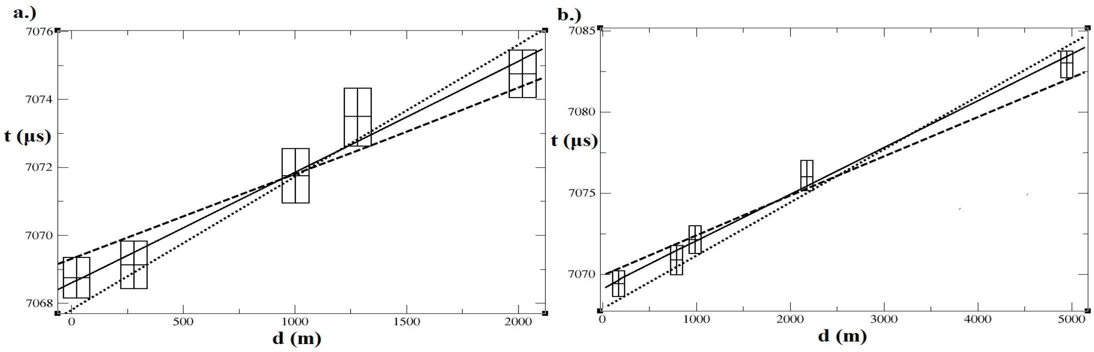

FIG. 5: Measurement results (average flight-time as a function of distance between ERs) for both the first (a) and the second (b) experiment. Error-bars and rectangular confidence intervals are given for each result. Continuous line indicates the best fit. Dotted lines indicates the maximal slope and dashed line indicates the minimal acceptable slope. For experiment (a) the best fit gives: $3.08 \cdot 10^8$m/s, the maximal acceptable slope leads to $2.58 \cdot 10^8$m/s and the minimal acceptable slope gives $4.01 \cdot 10^8$m/s. For experiment (b) the best fit indicates: $3.46 \cdot 10^8$m/s, the maximal acceptable slope yields $2.95 \cdot 10^8$m/s and the minimal acceptable slope gives $4.14 \cdot 10^8$m/s.