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

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Abstract

A handheld emitter–receiver device suitable for the direct estimation of the velocity of radio waves in air is presented. The velocity of radio waves is measured using the direct time-of-flight method, without the need for any tedious and precise settings. The results for two measurement series are reported. Both sets of results give an estimate of the velocity of radio waves in air that is within an error of 16% of the accepted value. 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.

Introduction

The speed of electromagnetic waves in vacuum is one of our fundamental constants. The fact that its value is independent of the reference frames holds the key to special relativity and defines the unit of length currently used in the international system of units (SI). Due to the extremely large value of this velocity ($c \approx 3 \times 10^8$ m s^{-1}) and due to the fact that most of the detectors and emitters have a relatively slow reaction time, its measurement using direct time-of-flight methods proved to be rather difficult [1, 2]. Nevertheless many successful direct measurements have been carried out for both light and radio waves in air [3–10]. The majority of these experiments have used delicate experimental setups, which would not be suitable for students to use without supervision. In normal coaxial and optical cables the measurements can be made 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 of different lengths [13]. These experiments are useful in high-school and university laboratories. The drawback is, however, that these are not open-air experiments, which diminishes their pedagogical advantage. Indirect measurements based on interference and/or the estimation of the frequency and wavelength are also possible [14–18]. This can be realized using an affordable setup [16], but the problem is that their pedagogical value is limited by the fact that they are not direct methods. The speed of radio waves can also be estimated through many other indirect methods, such as by using naturally occurring lightning discharges in the troposphere, which generate 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 on a budget of around 150 US dollars, and which is appropriate for obtaining a direct estimate of the speed of electromagnetic waves in air with the time-of-flight method. The measurement methods and data collection are also straightforward, so this is a good candidate for high-school projects and demonstrations.

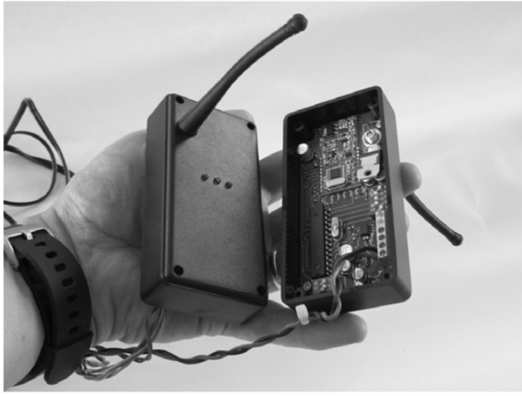

Figure 1. The used emitter–receiver (ER) devices and the circuit board used.

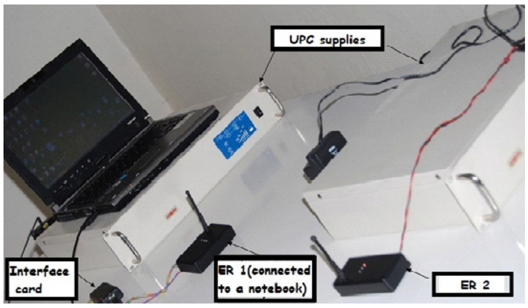

Figure 2. Measurement apparatus: the ERs used for the measurements, the two uninterruptible power supplies (UPC) and a notebook used for collecting the data.

Experimental apparatus

There are now many affordable transceiver chips that can operate on industrial, scientific and medical (ISM) licence-free radio-frequency bands and which are optimal for sending and receiving data [21]. Commercial walkie-talkie systems normally use these chips. By using them we can construct simplified transmitters and receivers that are able to communicate with simple pulse sequences and can measure with 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 (figure 1). One of the ERs is connected to a computer's USB port, continuously sending the measured time-lag data. At the heart of the ERs is the integrated circuit 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 use in such experiments [22]. It can work on three different frequencies: 433, 868 and 915 MHz. Depending on the geographic location and state regulations, we can select the operating frequency, so that it is in the licence-free ISM band. This should always be checked carefully. For example, in most of Europe and Russia the 433 and 868 MHz frequencies are free to use and for the American continent the 915 MHz frequency is available. The RFM12BP chip is widely used in remote controls, for wireless communications and for data collection. Details of 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.

In figure 2 we present the equipment used. The ERs are powered with a 12 V 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 connected to the computer (from now on ER1) sends a package to the other ER (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 an accuracy of $1/8$ μs. The recorded time is then sent to the computer, where it is registered. If ER1 does not detect a response package, it will emit another signal. The communication protocol is very similar to the classical 'ping' protocol in computer networks. The function of the ERs (i.e. which is the emitter and which is the receiver) is defined by the settings of the micro-controller that can 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 that there is a master/slave type of connection between the ERs, the master being the one that emits the data packages and the slave being the one that responds to the emitted data packages. Both ERs run a program written in C++, which actually governs their communication. The algorithmic representation of their communication is sketched in figure 3. From here we learn the following

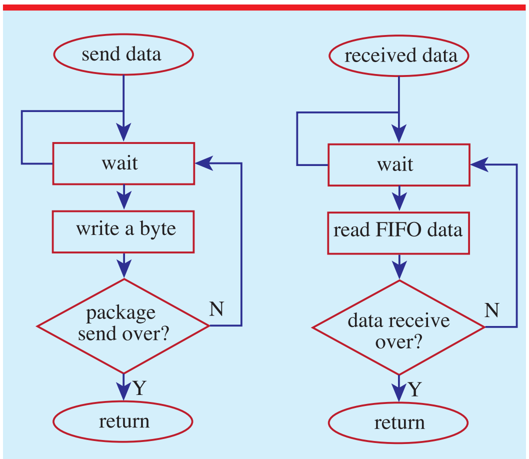

Figure 3. Flowchart for the transmitter–receiver system.

simple operation protocol. ER1 sends a signal and starts the clock. If this signal reaches ER2, then ER2 responds with another signal of length 1 byte. 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 air. Everything seems straightforward; however, (as is usual with experiments) for several reasons the problem is not that simple.

(i) The constructed ERs are of short range, they are able to communicate only over distances of less than 3 km. Under such conditions the electromagnetic waves pass from ER1 to ER2 and back in a very short time (of the order of microseconds). The $1/8$ μs time-accuracy of the equipment is barely satisfactory for the measurements. To improve the results, we measure many flight-times and analyse them statistically. In our experiments, for each particular position of the ERs, we recorded the flight-times continuously for approximately 15 min. This means that we processed roughly 20 000 different measured results for each particular distance.

(ii) The greatest problem arises from the fact that the major part of the communication time between the ERs results 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 at one fixed distance is useless and we need to make relative measurements to eliminate the delay time of the apparatus. Therefore, we consider measurements at different distances and consider the differences between these flight-times. Assuming that the average delay on the ERs is the same every time, the 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.

(iii) Another problem with the devices built by us is that, for the same position of the ERs, if the occurrence rate is low 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 easily separable and much smaller peaks that are shifted by a constant offset (figure 4(a)). These smaller peaks can be nicely observed if we use logarithmic axes for the distribution functions (figure 4(b)). Although the occurrence rates of the flight-time values leading to the second and higher level peaks of the distribution are low, they might still strongly affect the statistical interpretation of the data. So the calculation of a simple mean for the observed flight-times could be seriously biased by these rare events. However, the situation is not quite so gloomy, since the good news is that these peaks are clearly separable. Averages can thus be computed solely on flight-times belonging to the first peak and in such a manner rare events are taken out of the statistics. The obtained peculiar distribution function of the flight-times can be

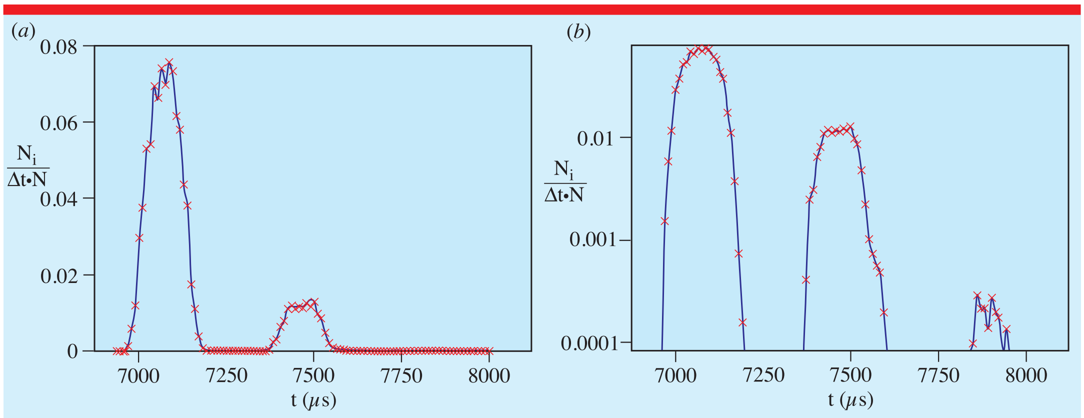

Figure 4. (a) Distribution of the recorded flight-times for a fixed position of the ERs. (b) The same distribution using a logarithmic vertical scale so that the smaller peaks are also visible.

interpreted in the following way: there are always additive noises on the analogue components in the devices, these are responsible for the observed normal distribution. Seemingly, there are also errors in 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.

(iv) The wavelength of the radio waves used by us is relatively short and as a consequence the effects of reflection might be significant. To avoid this problem, we must perform the measurements outside. 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.

(v) As we are taking our measurements outside and the distance between the two ERs can be of the order of kilometres, the direct measurement of the relative distances also becomes a problem. The easiest method is to locate the exact GPS coordinates of ER1 and ER2 by using a mobile GPS locator. This is now commonly available, even on mobile phones. Then, with these coordinates we can easily determine the distance between the two geographical points by using the freeware Google Earth program. In the case of short distances (10–50 m) we measure the distance directly using a measuring tape. Naturally, twice this distance is used to approximate the round-trip of the wave-packages.

Experiments

To perform the measurements, we found a suitable field close to our university town of Cluj-Napoca (Romania). The 433 MHz frequency band was used to operate our walkie-talkie devices. We took measurements on two different occasions using convenient and nearby locations. In both experiments we chose a suitable place for the base-camp, a place from where we could go a fairly long distance (2–3 km) by car and still remain in sight. We left the ER1, one of the UPSs and a notebook at the base-camp. ER2 and the other UPS were transported by car to different locations. Communication between the teams (one staying at the base-camp and the other one being in the car) was by mobile phone. For every chosen distance we let the ERs communicate with each other for about 15 min, during which time we recorded the flight-times of the emitted and received packages. For each location, the GPS coordinates were recorded and later we calculated the exact distances between the two ERs from these data. At every measuring spot we recorded the GPS coordinates at least five–six times and we used an average of these coordinates, thus

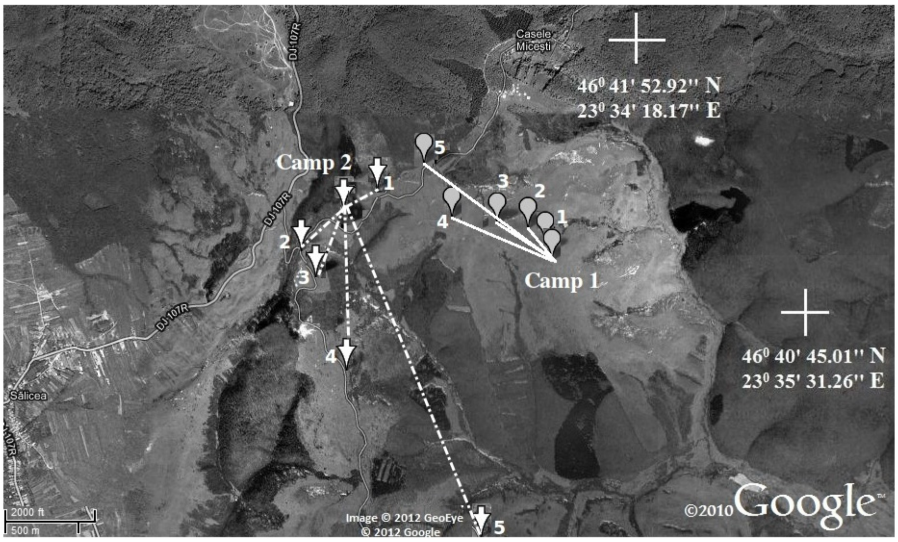

Figure 5. The Google Earth satellite map showing the locations of the two measurement series. © 2012 Google.

eliminating the imprecision of our GPS system. The spots used for the measurements are sketched in figure 5, which was produced using Google Earth. We estimated that the error in determining the exact position is of the order of 20 m, which means that the round-trip distance was determined with an error of ±40 m.

Data processing and results

During the measurements several thousands of flight-times were recorded for each distance (the ERs were communicating for approximately 15 min each time). First, we eliminated those data that did not fit into the first peak of the distribution function (see figure 4). In this way we eliminated the rare events influenced by errors in the digital components and obtained normally distributed data. For these data we then calculated the characteristic mean. The error was estimated from the standard deviation of the data used divided by the square root of their number. This error (as is clearly visible in figures 4 and 6) is orders of magnitude higher than the $1/8\ \mu$s resolution of the receiver. It is, thus, the main source of error in the results. The mean flight-time for each measurement with the characteristic error-bars was plotted as a function of the distance between ER1 and ER2. The results obtained for the two measurement series are plotted in figure 6. The obtained trend can be reasonably well approximated by 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 axes (estimated distance and mean flight-time) we can also determine a maximal (plotted with dotted lines) and minimal (plotted with dashed lines) slope fit, leading to a confidence interval for the obtained velocity. With this simple data-processing procedure the results are as follows. For the first series of measurements (a) we got from the best fit $c_1 = 3.08 \times 10^8$ m s^{-1} and the confidence interval $c_1 \in [2.58, 4] \times 10^8$ m s^{-1} and for the second experiment (b) we obtained the best value $c_2 = 3.46 \times 10^8$ m s^{-1} with the confidence interval $c_2 \in [2.95, 4.14] \times 10^8$ m s^{-1}. In both cases the obtained best fit values approximate the accepted value of the velocity of electromagnetic waves in air ($c \approx 2.99 \times 10^8$ m s^{-1}) with an error of less than 16%. The accepted value is in both cases within the given confidence interval.

Conclusions

We presented here a simple handheld emitter–receiver device that can be built in high-school or university laboratories on a modest budget and can be used to estimate the speed of radio waves in air. We performed our experiments outside, which meant that the project was more enjoyable for the students. The measurement

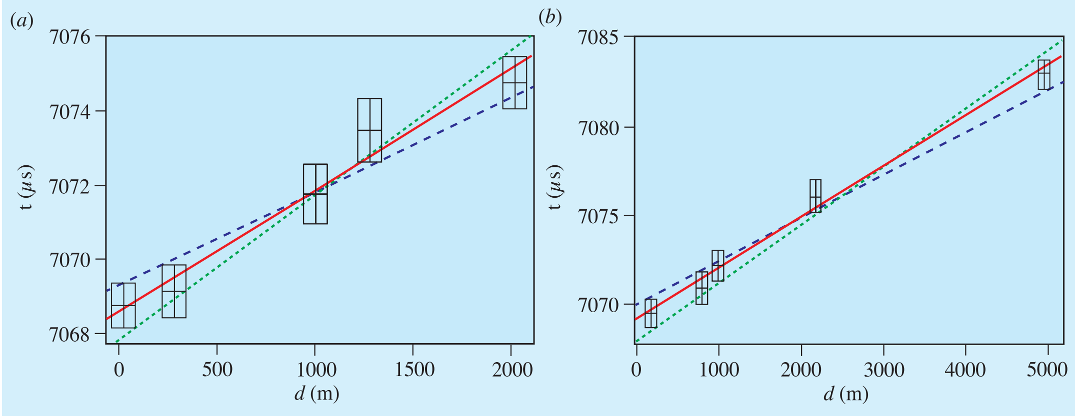

Figure 6. Measurement results (average flight-time as a function of distance between ERs) for both the first (a) and the second (b) experiment. Error-bars and rectangular confidence intervals are given for each result. The continuous line indicates the best fit. Dotted lines indicate the maximal slope and the dashed line indicates the minimal acceptable slope. For experiment (a) the best fit gives: 3.08×10^8 m s^{-1}, the maximal acceptable slope leads to 2.58×10^8 m s^{-1} and the minimal acceptable slope gives 4.01×10^8 m s^{-1}. For experiment (b) the best fit gives 3.46×10^8 m s^{-1}, the maximal acceptable slope yields 2.95×10^8 m s^{-1} and the minimal acceptable slope gives 4.14×10^8 m s^{-1}.

methods and knowledge of data processing are quite straightforward and can be understood with knowledge of high-school-level physics and mathematics. The apparatus is easy to handle and reliable, and thus does not need 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.

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