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# An improved version of the "extraordinary tabletop speed of light apparatus"

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# LETTERS TO THE EDITOR

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## Johannes Vermeer and *The Guitar Player*: Observations on the vibrating guitar string's edge

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Around 1672, the celebrated Dutch artist Johannes Vermeer (1632–1675) painted his famous picture *The Guitar Player*, which is displayed in London's Kenwood House (Fig. 1). Described as "easily the most important of all seventeenth-century guitar pictures,"[1] it depicts a young woman playing a baroque guitar, a musical instrument which was becoming increasingly popular at that time. Of particular note here, however, is the observation that "perhaps the most subtle technique is reserved for the painting of the instrument's strings. If carefully observed, we find that some of them are strongly blurred to suggest vibration in a quite unconventional manner which finds few parallels in seventeenth-century painting. Thus, Vermeer has painted movement rather than substance."[2]

Fig. 1. Johannes Vermeer, *The Guitar Player*. Oil painting, c. 1672. London: Kenwood House. Image courtesy of English Heritage.

Yet what appears not to have been noticed before is that Vermeer has shown the edges of these vibrating strings to be more prominent and darker than their centers (Fig. 2), a feature sometimes observed during introductory laboratory experiments. Thus, Vermeer seems to have been extraordinarily perceptive when observing the precise behavior of the plucked or strummed strings of the guitar, and his observation has subsequently been corroborated by means of photography, as seen, for instance, in the vibrations of a modern classical guitar visualized in slow motion in Fig. 3.

Surprisingly, however, physicists' studies on the vibrating guitar string and its transverse standing waves, and art historians' descriptions, rarely refer to or illustrate the prominent appearance of the edges of the guitar strings during their rapid movements which Vermeer had depicted.

What accounts for these prominent edges? There is an extensive literature on the physics of vibrating guitar strings,[3] and most likely is a simple explanation relating to the sinusoidal wave-like oscillations which constitute the standing waves of the vibrations.[4] Thus, "The speed [of the vibrating string] varies throughout the cycle…[and] is zero at the extremes of the motion and is a maximum as the oscillator passes through its equilibrium position."[5] As a result, therefore, the vibrating string spends more time at the periphery, i.e., at its edges, and consequently appears relatively prominent, compared with when the string traverses the centre where its movement is more rapid.

Four hundred years ago, Johannes Vermeer will not have known about sinusoidal wave-like oscillations. But his wonderful painting *The Guitar Player* reveals his hitherto unrecognized remarkable powers of observation on the behavior of the guitar's vibrating strings.

Fig. 2. Johannes Vermeer, *The Guitar Player*, detail.



  

Fig. 3. Classical guitar strings vibrating when song is played in slow motion; still from video. Credit: iStock, photo maradek.

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[1]F. V. Grunfeld, *The Art and Times of the Guitar: An Illustrated History of Guitars and Guitarists* (Collier Macmillan, London, 1969), p. 116.
[2]A. Rech, "Musical instruments in Vermeer's paintings: The guitar," in *Essential Vermeer 2*, edited by J. Janson. Accessed April 1, 2026. http://www.essentialvermeer.com/.
[3]N. H. Fletcher and D. T. Rossing, *The Physics of Musical Instruments*, 2nd ed. (Springer, New York/London, 1998).
[4]P. Perov, W. Johnson, and N. Perova-Mello, "The physics of guitar string vibrations," Am. J. Phys. **84**(1), 38–43 (2016).
[5]J. S. Rigden, *Physics and The Sound of Music*, 2nd ed. (Wiley, New York/Chichester, 1985), p. 16.

# An improved version of the "extraordinary tabletop speed of light apparatus"

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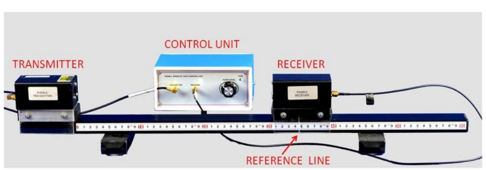
A revised version of the phase-comparison apparatus for the determination of the speed of light $c$ in free propagation[1] is described. As in the previous version, its most significant feature is the display technique employed, namely the nulls of an acoustic signal.

The modulation frequency of the laser beam has been increased to 1 GHz, by far the highest value employed in educational devices, thereby allowing a significant improvement in the precision of the determination of $c$. This enhancement also enables a reduction in the overall size of the apparatus, making it possible to measure the distance traveled by light in only 0.5 ns, corresponding to approximately 15 cm. In an accurate operating mode, the receiver position can be determined with an uncertainty of 0.5 mm. This corresponds to an uncertainty of approximately 0.3% in a single determination of c.

The theory of the operating principle, the overall signal processing, and the mechanical structure are identical to those of the previous 434 MHz apparatus. The setup is completely self-contained and requires no external power supply (the internal battery is rechargeable by USB), no oscilloscope, no optical bench, generator, or auxiliary optical components. It is pre-aligned. The three units—the transmitter, the receiver, and the control unit—are interconnected by single signal cables that also carry their respective power supplies.




Owing to the recent availability of specialized high-frequency integrated electronic modules, the construction of the apparatus has been greatly simplified, requiring only a minimal number of soldering operations on discrete components and the wiring of the power supply to the various modules. Furthermore, the overall cost of the device has been significantly reduced because of the low cost of the components.

The only aspects that inevitably still require mechanical fabrication and assembly are the guide rail, the transmitter and receiver housings, the laser alignment system, and the installation of the photodiode together with the radio frequency and low frequency modules inside the control unit.

The transmitter is kept fixed on the left of the rectangular guide. The modulated laser light beam it emits reaches the photodiode in the receiver unit at right, which may precisely and smoothly slide along the guide. A scale graduated in centimeters and millimeters on the side of the guide makes it possible to precisely determine the intervals $D_k$ ($k = 1, 2, \ldots$) between the successive receiver positions of null of the acoustic display signal along the guide. It has been shown[1] that the speed of light $c$ is given by $c = 2D \cdot f$, where $D$ is the arithmetic mean of the $D_k$ and $f$ is the modulation frequency (1 GHz).

Other determinations are possible, such as the determination of the speed of light in transparent or semi-transparent media, as well as the rapid determination of their refractive index, even of very thin samples. For example, the change in the speed of light as it passes through a microscope slide is easily detected and can be audibly perceived. Straightforward studies on how the refractive index of a solution in volumes as small as a few cubic centimeters depends on factors such as solute concentration, temperature, and so on are also possible, as well as the determination of the speed of signals in a cable, or the demonstration of the optical Doppler effect with infinitesimal transmitter or receiver velocities in comparison to $c$.

## SUPPLEMENTARY MATERIAL

Please click on this link to access the supplementary material, which includes all construction details. Print readers can see the supplementary material at https://doi.org/10.60893/figshare.ajp.c.8545740.

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[1]G. Pegna, "An extraordinary tabletop speed of light apparatus," Am. J. Phys. **85**(9), 712–720 (2017).