The One-Way Velocity of Light Is Measurable Without Synchronized Clocks and Two Clocks Are Synchronizable Without One-Way Light Signals

Charles Nissim-Sabat*

Northeastern Illinois University, Chicago, U.S. (emer.)

ABSTRACT

The one way velocity of light is measurable with only one clock and this measurability invalidates Reichenbach’s Conventionality of Synchronization thesis. Systematic measurements of the isotropy in optical barrier penetration and of the mean decay lengths of unstable particles can determine the one way velocities of light and of particles. Presently, everyday experience, standard laboratory practices, and experiments with synchronization-independent results in these two areas indicate that the one-way velocity of light is the same as its round trip velocity. Also, the Special Relativity Postulate allows the synchronization of two isochronous stationary clocks by using a single moving isochronous clock without knowing the one way velocity of light. Thus, the Conventionality of Synchronization thesis is invalid on several grounds.

Keywords: one-way velocity of light; clock synchronization; frustrated total internal reflection; conventionality of synchronization; optical barrier-penetration.

*nissimsabatc@gmail.com
I. INTRODUCTION

Numerous extremely precise experiments have confirmed the predictions of Special Relativity. The fundamental “Postulate” of Special Relativity is often stated as:

*For all inertial observers (a) the laws of physics are the same and (b) the velocity of light, c, is the same.*

Yet, there has been uncertainty about clause (b): what is meant by the velocity of light? Is it the velocity for a one-way trip between two points or that for a round-trip?

When Einstein\(^1\) introduced Special Relativity (‘SR’), he stipulated that, given two clocks A and B, at rest with respect to each-other in vacuo in field-free space, if a light signal is emitted at A at time \(T_0\), reflected at B back to A, and received there at time \(T_\text{r} \), the clocks are synchronized by setting the time when the signal reached B as \(T_B = (T_\text{r} − T_0)/2\). Einstein thus assumed that the one-way velocity (‘OWVL’) from A to B must equal OWVL from B to A, i.e. that both OWVLs equal \(c\), the round-trip velocity of light (‘RTVL’). On this basis, Einstein derived the Lorentz transformations. I designate Einstein’s synchronization procedure as ‘standard SR,’ ‘light’ as any beam of electromagnetic radiation, \(f\) the frequency of light, and \(\lambda = c/f\) its ‘round-trip wavelength.’

Throughout, ‘synchronization’ refers to spatially-separated clocks at relative rest.

Reichenbach\(^2\) and followers, notably Edwards,\(^3\) Winnie,\(^4\) and Giannoni,\(^5\) have maintained that: (1) the standard SR synchronization procedure is merely *an arbitrary convention* because, they claim, one can measure only light’s RTVL \(c\), while one may have or choose that OWVL equals \(c_+\) in an arbitrary \(+x\) direction and \(c_-\) in the \(-x\) direction, with a parameter \(\zeta\) describing this *reciprocal asymmetry*, \(-1 \leq \zeta \leq 1\), where

\[
c_+ = c/(1-\zeta),
\]

\[(1a)\]
\[ c_- = c/(1+\zeta), \]  

(one of these velocities can be as high as infinity while the other is as low as \(c/2\)) and synchronize clocks accordingly, with RTVL = \(c\) for any distance; (2) on the basis of this ‘R-synchronization’ one can derive \(\zeta\)-dependent Lorentz transformations consistent with the kinematics of standard SR;\(^3\)\(^4\) (3) every one-way velocity is conventional,\(^4\) i.e. for any object one can measure only its round-trip velocity \(v\) while, with \(\beta=v/c\), the object has any one-way velocity \(v_\pm\) in the \(x_\pm\) directions,

\[ v_\pm = v/(1 \pm \beta \zeta); \]  

and, (4) one can identify synchronization-dependent and synchronization-independent quantities and the laws of classical SR physics must be stated in synchronization-independent terms.\(^5\) (References 2 through 5 use a notation different from mine but equivalent to it.)

Thus, Reichenbach introduced a ‘R-limited’ second clause for SR’s Postulate stating “the round-trip velocity of light is the same for all inertial observers and” (since OWVL cannot be measured) “regardless of what \(\zeta\) is chosen (or happens) to be, the results of all experiments will always agree with standard SR. In effect, Reichenbach conflated two issues: clock synchronization and the one-way velocity of light.

Initially, this Conventionality of Synchronization (‘CS’) thesis was adopted by many philosophers but now some argue it is nonsensical to speak of speed: “To understand Relativity, we have to expunge all ideas of things having speeds, including light.” Maudlin.\(^6\) Yet, in the next paragraph, Maudlin speaks of “two [things] in very rapid relative motion.” Einstein and Reichenbach would agree that there nothing is more rapid than light.

Since Reichenbach, several theories concerning the speed of light have been proposed, some of these postulate a reciprocal or other anisotropy in OWVL, and many experiments
have been performed, but, so far, no asymmetry in OWVL has been detected and no experimental approach capable of measuring it has yet been proposed. Inasmuch as the CS thesis postulates a continuous distribution $c/2 < OWVL < \infty$, a cluster of reliable measurements consistent with $OWVL = c$ would invalidate the CS thesis but, also, so does the mere possibility of such measurements.

The CS fundamental contention that OWVL is immeasurable can be tested by systematic experiments in two areas that so far have been ignored in this regard: optical barrier-penetration and the mean decay-lengths of unstable particles. Everyday experience, standard laboratory practices, and quantitative experiments in these areas indicate that OWVL is isotropic and equals $c$ but a program of measurements in opposite directions along three non-coplanar axes is required to demonstrate isotropy.

Independently, I introduce a conventionality-independent method of clock synchronization based directly on the R-limited SR Postulate.

Thus, clock synchronization and the one-way velocity of light are separate issues that can be resolved separately. The proposed experiments can be used to test other theories regarding OWVL, e. g. theories claiming the choice of OWVL is a mere gauge transformation.

All above authors have confined their discussion to non-quantum special-relativistic physics and I do likewise, emphasizing light-propagation in three dimensions, the mean decay-lengths of unstable particles, and the wave nature of light.

In Section II, I point-out that the results of experiments aiming to test the isotropy in OWVL must be stated in synchronization-independent terms. Using only one clock and considering light-propagation in two or three dimensions, I show that, if the CS thesis is correct at all, the nature of any anisotropy in OWVL is strictly limited and that establishing
isotropy of OWVL requires establishing its isotropy along three non-coplanar axes. Finally, I show why some experimenters claiming to prove OWVL is isotropic actually fail to do so.

In Section III, I note that everyday observations of the wave behavior of light, standard laboratory practices, and precise measurements of optical barrier-penetration and of the mean decay-lengths of unstable particles all indicate that OWVL is isotropic. These observations require one clock or none at all. Further measurements in these areas may establish isotropy.

In Section IV, using three isochronous clocks, i.e. a moving clock together with two stationary collinear clocks, I show that the R-limited SR Postulate, allows conventionality-free synchronization of the stationary clocks.

**II. DIFFICULTIES IN FORMULATING EXPERIMENTAL METHODS FOR TESTING THE CONVENTIONALITY OF SYNCHRONIZATION THESIS.**

(a) *Arrival Time Differences for Light Signals Emitted Simultaneously.*

The CS thesis must duplicate the predictions of standard SR. This imposes strict limitations on the CS thesis when applied to light motion in two or three dimensions. This Section uses only one clock, so synchronization is irrelevant.

CS allows one to choose $\text{OWVL} = \infty$ along a line segment AB, but can it do the same for a non-collinear segment BC and also for the segment AC forming the triangle ABC? A signal from A taking the ABC path would arrive at C at the same time as one taking the AC path, violating causality. Also, one can choose $\text{OWVL} < c$ for two segments, but not three.

To satisfy CS, the time difference for ABC vs AC paths in a plane must be the same as that predicted by standard SR and the same for light taking the CBA path vs the CA path. Finally, the round-trip time in either direction must equal the perimeter divided by $c$. 


One may proceed as follows. Choose any straight line as the X axis where $\zeta$ is unknown. In the $+x$ direction $\text{OWVL}=c/(1-\zeta)$, in the $-x$ direction $\text{OWVL}=c/(1+\zeta)$ (Eqs. (1a) and (1b)). Any odd function $c(\theta)$, $0<\theta<\pi$, describing the angular dependence of OWVL, $dc(\theta)/d\theta \leq 0$, and $[(c(\theta))^{-1}+(c(\theta+\pi))^{-1}]=2/c$, satisfies causality. For instance, consider

$$c(\theta)=c/(1-\zeta \cos \theta), \quad n = 1, 3, 5, \ldots$$  \hspace{1cm} (2)

Consider, in vacuo in field-free space on the X,Y plane, a right triangle formed by points A at (0,0), C at (x, y), and B at (0, x), with $r=[x^2+y^2]^{1/2}$ designating the distance AC and $\cos \theta = x/r$. A is a light source, B a clock, and C a mirror. One may think that for light signals emitted simultaneously at A, $c(\theta)$ can be determined from the arrival time difference for signals from A to B vs signals from A to C to B.

When two signals are emitted simultaneously from A, the clock at B reads an unknown time $t_B$. Given Equation (2), $T_{ACB}$, the arrival time at B for the A-C-B signal is $t_B + (r/c)(1-\zeta (x/r)^n) + y/c$, for the A-B signal the arrival time is $T_{AB} = t_B + (x/c)(1-\zeta)$.

The arrival times difference at B is

$$T_{ACB}-T_{AB}=(r+y-x)/c-\zeta r(x/r)^n-x]/c$$  \hspace{1cm} (3)

and the round-trip time:

$$T_{ACB}+T_{BA}=(r+y+x)/c-\zeta r(x/r)^n-x]/c.$$  \hspace{1cm} (4)

The CS thesis requires that all measurements accord with standard SR. Thus, the arrival-time difference between paths and the round-trip time must depend ONLY on the round-trip velocity of light, $c$: the CS thesis is valid only if $n=1$ in Eqs. (3) and (4). For all $\zeta$,

$$c(\theta)=c/(1-\zeta \cos \theta).$$  \hspace{1cm} (5)

If Eq. (5) applies, time (or phase) of arrival differences for simultaneously-emitted light rays taking different paths between two points are independent of OWVL. This holds for any
path geometry. Given Eq. (1c), for all cases where particles or light signals have RTV $v$, Eq. (5) must be generalized to

$$v(\theta) = v(1 - \beta \zeta \cos \theta). \quad (6)$$

Equations (5) and (6) were derived differently by Nissim-Sabat\(^8\) whose analysis of time or phase of arrival experiments, given Eqs. (5) and (6), is summarized below, sub-section (d).

**(b) The Only Possible Expression for $c(\theta)$ under the CS Thesis is $c(\theta) = cl/(1 - \zeta \cos \theta)$.

Consider again the ACB triangle with $c_r = cl/(1 - k)$ being a possible OWVL along AC, $c$ the velocity along CB, and $cl/(1 + \zeta)$ (Eq. 1b) that along BA. Then the round-trip time is

$$T_{ACB} + T_{BA} = (r + y + x)/c - (kx / \cos \theta - \zeta x)/c, \quad (7)$$

which, according to Eq. (5), equals $(r + y + x)/c$. So $k = \zeta \cos \theta$, $c_r = cl/(1 - \zeta \cos \theta)$, Eq. (5).

**(c) Extension to Three Dimensions.

Consider a triangle AC’B congruent to the triangle ACB described but extending in a plane XY’ that intersects the XY plane at an arbitrary angle. The source at A broadcasts simultaneously in the C and C’ directions and the CS thesis requires a simultaneous time of arrival at B for both signals. Therefore $c(\theta) = cl/(1 - \zeta \cos \theta)$ applies to any arbitrarily chosen XY plane. This $c(\theta)$ azimuthally symmetric function fully describes what the CS thesis allows as the only possible reciprocal anisotropy of OWVL in three dimensions.

From the above, OWVL is $c$ along any axis Y’ orthogonal to the X axis, i.e. along the whole YZ plane. Therefore, OWVL is $c$ in any direction orthogonal to the one where its anisotropy is, or chosen to be, maximal. Therefore, one needs measurements along three non-coplanar axes to prove OWL is isotropic and it is best that, for each axis, these measurements be made simultaneously in both directions. (See also Sec. III A (e) 2)

Note that all of the above conclusions are independent of the value of $\zeta$ and of the straight
line chosen for the X axis.

(d) Formulating Tests of the CS Thesis Using Synchronization-Independent Quantities.

1. Kinematics. Relevance of Eqs. (5) and (6) to the analysis of several kinematical experiments is treated in detail by Nissim-Sabat\textsuperscript{8} who has shown that one cannot determine OWVL by using Doppler shifts or by measuring time or phase differences when two light rays are emitted simultaneously and then recombined after each ray passes through different media (glass, water, etc...), or generates a pulse in a cable.

This counterintuitive fact is sometimes overlooked. For instance, Dryzek and Singleton\textsuperscript{9} claim to have measured \( OWVL = c \) for photon pairs produced in opposite directions by positron annihilation at rest from a source midway between two counters. The pulses from each counter are then transmitted by cable to a coincidence circuit and the authors find maximum coincidences when the cables have equal length. They note the controversy concerning OWVL for photon travel in air but they tacitly assume that OWV for signals along their cables is independent of direction. What they have shown is that Eqs. (5) and (6) are valid.

Thus, if \( c(\theta) = c/(1-\zeta \cos \theta) \), OWVL cannot be measured by an arrival-time differences experiment but SR is valid. If, in fact, \( c(\theta) \neq c/(1-\zeta \cos \theta) \) in such an experiment, SR is not valid but one can measure OWVL by systematic measurements of arrival time differences for light travel between two points along different paths. Yet, given the ubiquitous use of light signals for land surveys, if \( c(\theta) \neq c/(1-\zeta \cos \theta) \), it would have been observed.

Also, Winnie\textsuperscript{4} has derived \( \zeta \)-dependent Lorentz transformations that, independently of \( \zeta \), duplicate the standard SR kinematical conclusions about space-contraction, time-dilation, etc… Whatever OWV may be, all SR predictions depend only on RTV.
2. Dynamics and Electromagnetism. One is just as restricted here. In a thorough analysis, Giannoni distinguishes between synchronization-dependent quantities and synchronization-independent ones, and, among the latter, between $\zeta$-contravariant and $\zeta$-covariant expressions for vectors and tensors. Scalar products of these last quantities are synchronization-independent and, therefore, measurable quantities.

It has been suggested that one measure OWV when a particle traverses a semi-circular path in a magnetic cavity by measuring its momentum, $p=mv$, before and after, $(m=\text{rest mass}, \gamma=(1-v^2/c^2)^{-1/2})$. Giannoni has shown that mass is as much synchronization-dependent (‘sync-dependent’) as $v$, the sync-dependent velocity, both depending on $\zeta$. In a particle’s circular motion both mass and velocity change while $p$ remains constant. Momentum conservation in a collision requires that momentum be sync-independent but measuring it does not determine the one-way velocity.

Synchronization-dependence of mass is easily shown. Consider a $\pi^+/\pi^-$ pair produced by $K^0_{\text{short}}$ decay with total $p=0$ in the pair center-of-mass system. The pions have velocities $v_\pm$ along the $x_\pm$ directions and, presumably, momentum $p_\pm=m_\pm v_\pm$ with $v_\pm$ given by Eq. (3). Winnie has shown $\gamma_\pm=(1-\gamma^2/c^2)^{-1/2}$ a $\zeta$-scalar. Since we must have $p_+ = p_-$ along the $x$ axis,

\begin{equation}
m_\pm = m (1 \mp \beta \zeta).
\end{equation}

Consequently, \((\text{Kinetic Energy} \pm) = m_\pm \gamma \ c^2\) is not a $\zeta$-scalar.

Giannoni extended his analysis of synchronization-dependence to Electromagnetism.

A proposed test of the CS thesis must show that the sync-independent quantities to be measured will yield a value for $\zeta$ or for another sync-dependent quantity, i.e. that the CS thesis is not self-consistent. See Equations (13), (14d), and (15c) below.
III. EVERYDAY OBSERVATIONS AND EXPERIMENTS ON HAND INDICATE THAT THE ONE-WAY VELOCITY OF LIGHT IS ISOTROPIC.

This Section discusses the wavelength-dependence of optical barrier penetration and the one-way-velocity dependence of the mean decay-lengths of unstable particles in flight, areas where we have data which indicate isotropy in OWVL. If re-analyzed or pursued further, they may demonstrate isotropy in OWVL. Interestingly, a flurry of measurements in these areas came about just before the thorough development of the CS thesis by Winnie and Giannoni. Also, everyday observations of the wave properties of light and routine laboratory practices invalidate the CS thesis.

A. A ONE-WAY MEASUREMENT OF THE WAVELENGTH OF LIGHT IS POSSIBLE AND IT YIELDS THE ONE-WAY VELOCITY OF LIGHT.

After outlining general requirements for a wavelength-based measurement of OWVL, I discuss the reduction in the transmitted intensity when one interposes a variable-width transparent airgap in light’s path between two transparent blocks. It relies solely on Maxwell’s electrodynamics.

(a) General Considerations for the Determination of a Reciprocal Asymmetry in the Wavelength of Light of a Given Frequency.

This sub-section discusses the determination of a directional asymmetry in OWVL by the measurement of the change, at a specific frequency, of the light intensity transmitted through a system. Replacing $c$ by $\lambda$ in Eqs. (1a) and (1b) yields the direction-dependent $\lambda_+$ and $\lambda_-$. Note that

$$\frac{1}{\lambda_+} - \frac{1}{\lambda_-} = -2\zeta/\lambda$$  \hspace{1cm} (9)

The usual definition of ‘wavelength’ as the distance, at a given time, between two
successive peaks of the wave amplitude implies one has absolute synchronization. I propose instead an instrumentalist definition of wavelength: one determines, for a system that acts as a filter, the frequency (and thus the wavelength) where one finds sizeable attenuation of the transmitted intensity, and then one determines whether this attenuation depends on the value of an identifiable length $\lambda$ in the system. One must verify that this attenuation depends on the wavelength rather than the frequency: frequency is independent of the medium of propagation, wavelength is not. Intensity can be measured by a single clock as the number of photons/sec. and thus is independent of synchronization. The proposed method should be implemented simultaneously in opposite directions.

Note that, given Eq. (5), when light from a source at $x=0$ traverses two parallel slits in a screen at $x=s$ and produces two light rays that recombine at a point $x=b$, the wavelength determined by the phase difference at $b$ between the two rays is independent of OWVL: this measurement does not yield an “average $\lambda$” in the $+x$ direction.

While the CS thesis allows visible light to have infinite wavelength in some direction, this is precluded by everyday observations: as has been noted in this regard, one can see light passing through a pinhole independently of light’s direction.

(b) Maxwellian Theory for the Wavelength of Light Transmitted through an Airgap.

Snell’s law of refraction predicts that when visible light passes from a medium with a refractive index $n_1$ into one with an index $n_2$, $n_1 \sin \phi_1 = n_2 \sin \phi_2$, with the angles measured with respect to the orthogonal to the interface. If $n_1 > n_2$ there is a critical angle $\phi_c$ for the $n_1$ medium where $\sin \phi_c = 1/ n_1$ while $\phi_2 = \pi/2$, beyond which there is total internal reflection. For a glass/air interface, where for glass $n_1=1.50$ and for air $n_2= n_o=1$, $\phi_c$ is 42°.

For $\phi_1 > \phi_c$, in order to satisfy the boundary conditions for the $\mathbf{E}$ and $\mathbf{B}$ fields at the
interface, we have a surface (or ‘evanescent’) wave propagating along the interface with wave fronts orthogonal to the interface. A wave of initial intensity $I_1$ is transmitted through the interface with intensity $K e^{-\kappa d}$ where

$$\kappa = \frac{4\pi}{\lambda_a} \left\{ (n_1 \sin \phi_1)^2 - (n_2)^2 \right\}^{1/2},$$  \hspace{1cm} (10a)$$
d is the distance light penetrates into the interface, $\lambda_a$ the round-trip wavelength in air, $K$ a constant, and $\kappa = 2.2/\lambda_a$ at $\phi_1 = 45^\circ$ for a glass/air interface.\(^{10}\) The light transmitted through a parallel airgap of width $A$ between two glass blocks has intensity

$$I_T(A) = K I_1 e^{-\kappa A} = K I_1 e^{-2.2 A / \lambda_a},$$  \hspace{1cm} (10b)$$
an effect called \textit{frustrated total internal reflection} (‘FTIR’) or \textit{optical barrier penetration}.

Equation (10b) is valid for all $A$ when $E$ is normal to the plane of incidence but valid only if $A > \lambda_a$ for $E$ parallel to that plane, where, for $A < \lambda_a$, $I_T$ is roughly constant. I consider only $E$ normal to the plane of incidence. FTIR has also been observed at microwave frequencies.\(^{11}\)

\textbf{(c) The CS Thesis and the Wavelength of Light Transmitted through an Airgap.}

Given Eq. (5), Snell’s law holds under the CS thesis.\(^8\) Giannoni\(^5\) has adapted Maxwell’s electrodynamics to the CS thesis and shown that Maxwell’s equations hold for light propagating in the $x_\pm$ directions according to Eqs. (1a) and (1b). Eq. (10a) becomes:

$$\kappa_\pm = \left(\frac{4\pi}{\lambda_{a\pm}}\right) \left\{ (n_1/n_2) \sin \phi_1 \right\}^2 - 1\right\}^{1/2},$$  \hspace{1cm} (11a)$$
where $\kappa_\pm = 2.2/\lambda_{a\pm}$, for $\phi_1 = 45^\circ$ and a glass/air interface. With initial intensities $I_{I\pm}$ and $E$ normal to the plane of incidence, the intensities transmitted through an airgap of width $A$ are:

$$I_{T\pm}(A) = K I_{I\pm} e^{-\kappa_\pm A / \lambda_{a\pm}} = K I_{I\pm} e^{-2.2 A / \lambda_a}. $$  \hspace{1cm} (11b)$$

With equal initial intensities $I_{I\pm}$, the ratio $R$ of the transmitted intensities is:

$$I_{T+}(A)/I_{T-}(A) = R = \exp \left(-2.2 A \lambda_a / \lambda_+\right) / \exp \left(-2.2 A \lambda_a / \lambda_-\right).$$  \hspace{1cm} (12)$$

Given Eq. (9), $R = e^{d A \zeta / \lambda a}$ and $\zeta$, the parameter for the reciprocal asymmetry, is:
\[ \zeta = \lambda_d \frac{(ln \, R)}{4.4 \Lambda}. \] (13)

Therefore, measurement of the transmitted intensity through an airgap of known width, Eq. (10b), yields the wavelength of light traversing the airgap and the ratio of transmitted intensities in opposite directions yields the reciprocal asymmetry parameter, Eq. (13).

Note that the CS thesis predicts light can have infinite wavelength in some direction and, in that direction, it would never be attenuated when passing through an airgap.

(d) **Experiments on the Wavelength of Light Transmitted Through an Airgap.**

Excellent agreement between Eq. (10b) and experimental data for $3\lambda_a < \Lambda < 8\lambda_a$ was found by Coon\textsuperscript{12} counting the number of photons transmitted through an airgap vs the gap’s width for a parallel airgap between two glass prisms. The same agreement with Eq. (10b) was found by Smartt,\textsuperscript{13} Bergdahl,\textsuperscript{14} and Voros and Johnsen.\textsuperscript{15} All these experiments accord with standard SR. Coon\textsuperscript{12} observed a $2 \times 10^3$ attenuation through the airgap. Thus, FTIR is a very effective band-reject filter for short wavelengths.

(e) **Relevance of These Experiments to the Conventionality of Synchronization.**

Did the above four experiments test the CS thesis?

1. **FTIR is relevant to the CS thesis.** One may think that Section II suggests that it is not! In these experiments bundles of light rays are emitted from a source and recombined at a detector, just as in Section II. Yet, Section II pertains to the relative phase of the individual rays. FTIR provides another datum: diminution in the number of transmitted photons yielding the wavelength $\lambda_T$ of the light traversing an airgap. For each experiment, $\lambda_T = \lambda_a$, i.e. \textit{OWVL through the airgap is c.}

2. **These experiments test the CS thesis.** Each experiment separately? Arguably not. Sec IIc shows one must have OWVL=$c$ along some plane in space. Perhaps, inadvertently,
each group chose a direction along that plane for its experiment and so did all the other FTIR researchers who have performed similar experiments, all with the same result. Bertolotti et al.\textsuperscript{10} (p. 35) give a (partial) list of eleven such experiments. Yet, not only does each individual experiment measure OWVL but, as a whole, they provide a cluster of measurements consistent with OWVL=\(c\) for light traversing an air-gap while the CS thesis predicts a continuous distribution \(c/2 < \text{OWVL} < \infty\). The CS thesis is invalidated on two counts.

3. FTIR experiments address other theories concerning the velocity of light. Eq. (5) entails that, under the CS thesis, the wavelength of light may change with direction. An apparatus remaining stationary in the laboratory still partakes of the earth’s rotational motion and \(\theta\) in Eq. (5) changes with time, \(15\circ/hour\) for a light path along a parallel. This entails a change in \(\kappa_{z}\). We do not know how long each experiment lasted nor the orientation of the apparatus, but the graphs of intensity vs wavelength in Refs. 12 and 15 show a wavelength uncertainty of \(0.05\lambda_a\) for each data point, with excellent accord with the — \(2.2A/\lambda_a\) exponent in Eq. (10b). The data suggest that the time-dependent \(z \cos\theta\) term in Eq. (5) is at most 0.05. A thorough re-analysis of past experiments may yield a definitive value for OWVL.

FTIR has been observed since Newton’s rings but no directional dependence has ever been reported.

(f) Proposed Experiment to Measure Simultaneously \(\lambda_+\) and \(\lambda_-\), and, Thus, \(c_+\) and \(c_-\).

The apparatus used by Coon\textsuperscript{12} can easily be adapted for a simultaneous measurement of \(\lambda_+\), \(\lambda_-\) and, thus, \(c_+\) and \(c_-\). The Coon apparatus consists of (a) a cube comprising two transparent rectangular prisms (index \(n_1\)), with the oblique surfaces facing each-other forming (b) a variable-width \(A\) parallel gap filled with a transparent medium (index \(n_2\)). One measures, one photon at a time, in opposite directions, the optical intensity transmitted
through the system as a function of the gap-width $\Lambda$ from sources of identical monochromatic constant-intensity parallel light beams with velocities $c_+$ and $c_-$, wavelengths $\lambda_+$ and $\lambda_-$, and $\mathbf{E}$ normal to the plane of incidence. At $\phi_i = 45^\circ$ with respect to the gap, are the beams’ incident, transmitted, and reflected beams in the medium of index $n_1$. Photomultiplier tubes detect the transmitted and reflected photons. Requiring anti-coincidence between these detectors allows reduction of noise.

Experimenters should use media with different $n_1$ and/or a gap with different $n_2$ and verify that the same value of $\zeta$ is obtained, thus demonstrating that the attenuation upon traversal through the gap depends on the wavelength of the light rather than its frequency. Determination that OWVL is isotropic requires simultaneous measurements along three non-coplanar axes. The small bulk of the apparatus makes this method especially appropriate.

**B. DETERMINATION OF ONE-WAY VELOCITIES FROM THE MEAN DECAY-LENGTHS OF UNSTABLE PARTICLES**

**(a) The Mean Decay-Lengths of Unstable Particles Can Determine One-Way Velocities, Thus Establishing That the CS Thesis Is Not Self-Consistent.**

The $\zeta$-dependent Lorentz transformations that Winnie$^4$ has derived show that, independently of $\zeta$, the standard SR conclusions about space-contraction and time-dilation still hold. Regardless of what its OWV may be, all SR predictions depend only on the body’s RTV. If clock C has OWV $v_+$ with respect to clock C’, the time-dilation between the two clocks is given by its RTV $v$, which, CS claims, is the only measurable velocity. A particle’s expected lab-lifetime $t_{\text{LAB}}$, depends on $v$, its travel-time depends on $v_+$, while its expected mean decay-length is $t_{\text{LAB}}v_+$. Yet, Eqs. (1a) through (1c) show no one-to-one correspondence between RTV and OWV. This conundrum is resolved if the one-way velocity is the same as
the round-trip velocity. The mean decay-length of unstable particles allows the measurement of one-way velocity and proves that this is the solution to the conundrum.

Standard SR\textsuperscript{16} predicts that if a clock S with RTV $v$ measures a time $\tau_S$ (its ‘proper time’) for travel from A to B, the travel time $t_{LAB}$ measured by stationary clocks at A and B is

\[ t_{LAB} = \gamma \tau_S. \]  

(14a)

Consider a well-collimated burst S of charged unstable particles of lifetime $\tau$ produced by an accelerator. $\tau$ is defined in the particles’ rest frame. For muons and positive pions, it can be measured easily with a single clock. The number of particles in the burst $N_S(t_S)$ decreases as $e^{-ts/\tau}$ where $t_s$ is measured in the burst rest frame. Thus, $N_S(t_S)$ is sync-independent. One can select particles with a unique momentum $p$ using crossed E and B fields. According to the CS thesis, $p = m\gamma v_{(ExB)}$, $v_{(ExB)}$ being the selected round-trip velocity.\textsuperscript{5}

The burst then passes first counter A and then counter B which determine the number of particles $N_A$ and $N_B$ the burst comprises as it passes them. $N_A$ and $N_B$ are sync-independent and the same in the burst and lab frames. The lab distance between A and B is $X$. Set $\Pi(X) = N_B/N_A$. In the burst rest frame, $t_s$ is the time for travel from A to B, $\Pi(X) = e^{-ts/\tau}$ and:

\[ t_s = -\tau \ln \Pi(X). \]  

(14b)

According to the CS thesis and SR, $t_{LAB} = \gamma t_S$, Eq. (14a). The lab time $t_{LAB}$ for that travel is:

\[ t_{LAB} = -\gamma \tau \ln \Pi(X). \]  

(14c)

In the lab frame, the velocity, $v_{LAB} = X / t_{LAB}$, is:

\[ v_{LAB} = X (\gamma \tau \ln \Pi(X))^{-1}. \]  

(14d)

$v_{LAB}$ is a one-way velocity, stated in sync-independent terms. Measurements\textsuperscript{17, 18} are often stated in terms of the mean decay-length $\mathcal{L}$, which, in a sync-independent form, is

\[ \mathcal{L} = \gamma \tau v_{LAB} = -X / \ln \Pi(X). \]  

(14e)
(b) Routine Laboratory Practice with Unstable Particles Invalidates the CS Thesis.

Back in the 1960’s, high-energy physicists (myself included) were blissfully ignorant of the CS thesis and set up their experiments at a safe distance from the particle source but within the distance predicted by Eq. (14e). For particles selected to have $\beta =0.99$, Eq. (1c) allows $0.503v < v_+ < 100v$. If we had known about particles of known lifetime traveling an unknowable distance, the course of particle physics would have been very different. Probably, some accelerators would not have been built. Since 1960, countless experiments on many beamlines with various particle lifetimes and energies have found that $v_{LAB}$ as determined by the decay process is the same, within experimental error, as the velocity selected by crossed $\mathbf{E}$ and $\mathbf{B}$ fields ($v_{(\mathbf{E}\times \mathbf{B})}$). In the well-known Eq. (14d), $X$, $\tau$, $\gamma$, and $II(X)$ are sync-independent quantities. Thus, $v_{LAB}$, the one-way velocity of the particles, supposedly a sync-dependent quantity, is a measurable quantity and this measurability ipse makes the CS thesis not self-consistent. Moreover, while in conflation of measurements of the mean decay-lengths of unstable particles the variance is usually less than $10^{-3}$, thus indicating $|\zeta|<10^{-3}$, the CS thesis allows $-1 \leq \zeta \leq 1$.

As discussed in Sect. II(f), experimental confirmation of the invalidation of the CS thesis requires systematic re-analysis of past data regarding the dependence of the mean decay-length on the direction of the beam line. Reported decay-lengths are conflations of many measurements. One should compare measurements at different accelerators.

IV. CLOCK SYNCHRONIZATION USING A MOVING CLOCK.

CS thesis advocates have maintained the impossibility of synchronizing spatially separated clocks. Winnie has shown that a proposed slow clock transport synchronization
method, wherein two clocks are synchronized next to each other and then slowly moved apart, relied on isotropy of OWVL. No one has considered clock synchronization by using a moving clock.

The method of measuring one-way velocities discussed in Sec. III.B relies on unstable particles constituting moving clocks. This suggests using an ordinary moving clock in a Gedankenexperiment to measure one-way velocities.

Again, the $\zeta$-dependent Lorentz transformations,\(^4\) independently of $\zeta$, duplicate the standard SR conclusions about time-dilation and length-contraction. In an arrangement similar to the one in III.B above, consider a clock/signal-generator S, at $x<0$, on a rail parallel to and at a negligible distance from the X-axis. S is initially collinearly at rest with respect to lab-bound stationary clocks A and B, a distance $\delta$ apart on the X-axis. Observers $O_A$, $O_B$, and $O_S$ control the clocks A, B, and S, respectively. They have measured $\delta$ by appropriate means. Clocks S, A, and B are light-clocks\(^{19}\) wherein light bounces between mirrors a distance $L$ apart. The clocks’ time unit is $2L/c$, the time for round-trip travel of a signal inside the clock. At relative rest, all three clocks are isochronous as can be checked by interchanging light signals with frequency $f_S$.

Next, clock S assumes a constant OWV $\nu_+$ towards A and B, in such a manner such that, for clock S, $L$ is unchanged. Observers $O_A$, $O_B$, and $O_S$ are inertial observers before and after S assumes the velocity $\nu_+$. Preservation of isochrony between clocks S, A, and B after S begins its travel derives directly from the CS-modified SR Postulate ---the round-trip speed of light is the same for all inertial observers. As S approaches A and B, all observers continue broadcasting at the frequency $f_S$. $O_A$, $O_B$, and $O_S$ measure the RTV $\nu$ of S (the only velocity one can measure) from the Doppler shifted\(^{16}\) frequency $f_R$ of the interchanged signals:
\[ f_R = f_S (1 + \beta)/\gamma, \] (15a)

whence the observers determine \( \gamma \), \( \gamma = (1-v^2/c^2)^{-1/2} \), which Winnie proved one must use in SR calculations.

When S passes A, O_A and O_S initialize their clocks, \( t_S = t_A = 0 \). As S passes B, O_S notes the reading of clock S, \( \tau_S \), communicates it to O_B and, given Eq. (13a), O_B sets clock B to read

\[ t_B = \gamma \tau_S. \] (15b)

Clocks A and B are now synchronized in a conventionality-independent manner and one can measure the one-way velocity of light.

In fact, O_S can measure the one-way velocity of the burst \emph{en passant}, by noting that, in the lab frame, the travel distance is \( \delta \), the travel time is \( \gamma \tau_S \), and the one-way velocity \( v_{LAB} \) is

\[ v_{LAB} = \delta/\gamma \tau_S. \] (15c)

Given the isochrony of clocks S, A, and B, the proposed method allows synchronization of two clocks distant from each other and, hence, measurement of OWVL. Both Einstein and Reichenbach could have adopted it. It is extendable to an arbitrary number of collinear clocks.

**VI. CONCLUSION**

Contrary to Reichenbach’s contention that the one-way velocity of light is merely conventional, the one-way velocity of light is measurable. Using optical barrier penetration, one can measure the wavelength of light and, hence, its one-way velocity. Also, the mean decay length of unstable particles allows measurement of the particles’ one-way velocity. In both cases, the measurability itself invalidates Reichenbach’s thesis. For both cases, presently available data indicate isotropy in the one-way velocity of light, supporting standard SR. Independently, relativistic time-dilation allows using a moving clock to
measure one-way velocities. Finally, with a moving clock isochronized with two other stationary clocks, one can synchronize these two clocks without knowing any one-way velocity. Therefore, clock synchronization and one-way velocities are separate issues and, concerning each issue, Reichenbach’s Conventionality of Synchronization thesis is invalid.

ACKNOWLEDGEMENT

I am grateful to Gerald Marsh and Robert Stehman for their most valuable encouragement over many years.

REFERENCES

1 Albert Einstein, “Zur Elektrodynamik bewegter Koerper,” Annal. der Phys. (Leipzig) 17, 891–921 (1905). English translation in Hendrik A. Lorentz, Albert Einstein, Hermann Minkowski, and Hermann Weyl, The Principle of Relativity. (Dover, New York, 1923).

2 Hans Reichenbach, The Philosophy of Space and Time (Dover, New York, 1957). First published in German under the title Philosophie der RaumZeit-Lehre (1927).

3 Edwards, W. F., “Special Relativity in Anisotropic Space,” Am. J. Phys. 31 (7), 482–489 (1963).

4 John A. Winnie, “Special Relativity Without One-way Velocity Assumptions II,” Phil. Sci. 37 (2), 223–238 (1970).
5 Carlo Giannoni, “Relativistic Mechanics and Electrodynamics Without One-Way Velocity Assumptions,” Phil. Sci. 45 (1), 17–46 (1978).

6 Tim Maudlin, Philosophy of Physics: Space and Time. (Princeton University Press, Princeton, 2012). p. 68.

7 Anderson R., Vetharianam J., and Steadman G.E., “Conventionality of Synchronization, Gauge Dependence, and Test Theories of Relativity,” Phys Reports 295, 93-180 (1998).

8 Charles Nissim-Sabat, “Can One Measure the One-Way Velocity of Light,” Am. J. Phys. 50 (6), 533-536 (1982).

9 Jerzy Dryzek and Douglas Singleton, “Test of the Second Postulate of Special Relativity Using Positron Annihilation,” Am. J. Phys. 75 (8), 713-717 (2007).

10 Mario Bertolotti, Concita Sibilia, and Angela Guzmán, Evanescent Waves in Optics: An Introduction to Plasmonics. (Springer, Berlin, 2017). p. 45-51.

11 Eugene Hecht: Optics, 2d ed. (Addison-Wesley, Reading, 1966). p. 106-107.

12 Coon D. D.: “Counting Photons in the Optical Barrier Experiment,” Am. J. Phys. 35 (3), 240 – 243 (1966).

13 Olaf Bryngdahl, “Evanescent Waves,” J. Opt. Soc. America, 59, 1645-1649 (1969).
14 Smartt R. N.: “A Variable Transmittance Beam Splitter,” Appl. Opt. 9, 970-971 (1969).

15 Zoltan Voros and Rainer Johnsen, “Simple Demonstration of Frustrated Total Internal Reflection,” Am. J. Phys. 79 (7), 746 – 749 (2008).

16 Wolfgang Pauli, Theory of Relativity (Pergamon, Oxford, 1958). p. 11-19.

17 Rossi B. and Hall B., “Variation of the Rate of Decay of Mesotrons with Momentum,” Phys. Rev. 59 (3), 223-228 (1941).

18 Durbin R. P., Loar, H. H., and Havens, W. W., ”The Lifetimes of the π⁺ and π⁻ Mesons,” Phys. Rev. 88 (2), 179–183 (1952).

19 Charles Misner, Kip Thorne, and John Archibald Wheeler, Gravitation (W. H. Freeman, San Francisco, 1973). p. 397.