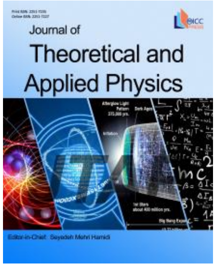

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Research Article

The One-Way Light Speed May be Measurable: Non-Equivalence of the Lorentz Transformations and Transformations that Preserve Simultaneity and Spacetime Continuity

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Abstract

Based on our analysis of the GPS and other physical effects, we confirm the well-known view that the Lorentz transformations (LT) fail to interpret light propagation along a closed moving contour. We show in detail that, with the LT based on light speed invariance, in the standard linear Sagnac effect a photon traveling at the local speed c cannot cover the whole closed contour in the measured interval T. Thus, the LTs imply a breach in spacetime continuity related to the adoption of relative simultaneity. Making use of internal synchronization procedures a priori not equivalent to Einstein synchronization, in principle it is possible to test Lorentz and light speed invariance and confirm, or not, the contended equivalence between relative and absolute simultaneity.

Keywords: One-way speed of light, Sagnac effect, Relative simultaneity, Lorentz invariance, Foundations of relativity theory

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1. Introduction

With Einstein's theory of special relativity (SR) of 1905, light is assumed to propagate in empty space at the same one-way speed c relative to any inertial observer in motion. Light speed invariance is reflected by the Lorentz transformations (LT) associated to standard SR. In treating with light speed, Einstein adopted a procedure for synchronizing two clocks, A and B, spatially separated by the distance L, assuming that the one-way light speed coincides with the average round-trip light speed $c = 2L/T$, where T is the time interval in the light round-trip from a clock to the other and back. With Einstein synchronization, clock B is set at $t = L/c$ when reached by light from A. However, after more than a century of evolution, the interpretation of the foundations of the theory has changed and presently we find in mainstream physics journals that light speed is considered to be conventional [1], since the observable constant speed c in the second postulate of SR is no longer the one-way light speed, but "the round-trip speed of light (i.e., the average speed of light during the round-trip from A to B and then back to A)".

In fact, Einstein synchronization procedure was soon criticized by epistemologists [2-5]: since the one-way speed from A to B can be different from the return speed from B to A, the one-way speed is left undetermined and arbitrary (conventional). In agreement with the requirement of Einstein synchronization, in 1977 Mansouri and Sexl [6] introduced their generalized coordinate transformations where the one-way speed depends explicitly on the arbitrary synchronization parameter ε:

$$
\begin{aligned}
&t^{'} = \frac{t}{\gamma} - \frac{\varepsilon x^{'}}{c^2} = \gamma\left[t(1+\frac{\varepsilon v}{c^2} - \frac{v^2}{c^2}) - \frac{\varepsilon x}{c^2}\right] \\
&t^{'} = \gamma(t - \tfrac{vx}{c^2}) \qquad \text{LT } (\varepsilon = v) \\
&t^{'} = t/\gamma \qquad \text{ST } (\varepsilon = 0) \\
&x^{'} = \gamma(x - vt), y^{'} = y, z^{'} = z \\
&c^{'} = c^{'}(\varepsilon) = \frac{dx^{'}}{dt^{'}} = \frac{c}{1 + v/c - \varepsilon/c}
\end{aligned}
\tag{1}
$$

The transformations (1) from frame S to S$^{'}$ in relative motion with velocity v take on different names depending on the chosen value of the parameter ε. With $\varepsilon = v$, we have the standard Lorentz transformations (LT); with $\varepsilon = 0$ we obtain the Selleri transformations (ST) [9-13] based on absolute simultaneity.

The time transform of the LT and ST differs by the value of ε only. If the speed of light is c on frame S, it is $c' = c'(\varepsilon)$ on S′. Light speed invariance, $c' = c$, holds for the LT only. The ST have been used by many physicists, although under different names and, originally, they have been denoted as the Tangherlini transforms [8], and later as ALT [14-16], or LTA [17-34], etc., where the letter A indicates that the (Lorentz) transformations adopt conservation of simultaneity (i.e. absolute simultaneity).

Supporters of standard special relativity (SR) claim that there are no paradoxes associated with the LT and that the term "paradox" may appear when we make erroneous use of them. Still, since the term "paradox" is widely used in literature, we keep it here even though it may simply indicate an erroneous use of the LT. Nevertheless, the supporters of SR adhering to the conventionalist view agree that the transformations ST interpret all the relativistic effects of the theory and that the ST can be used, in lieu of the LT, to describe the Sagnac effect and "solve" the Selleri [9-11] and other paradoxes [6, 35, 1, 36-39]. The implications of the optical effects of the Sagnac type have been discussed by several physicists [40-51].

The main argument of conventionalists for claiming that the LTs are still valid, even if the paradoxes of the LT can be more easily interpreted or "resolved" with the ST, is that the LT and ST differ by the arbitrary synchronization parameter ε only [6], and thus they are physically equivalent and interchangeable. The argument is based on the common property of the transformations (1) (pointed out and proven by Mansouri and Sexl [6] and other physicists [7]) that any "internal" synchronization procedure adopted in an inertial frame turns out to be equivalent to Einstein synchronization. As an example of this property we mention the clock transport procedure and other procedures using moving rods [6, 7]. Therefore, the use of the other transformations of (1) differing from the LT by the arbitrary parameter ε but with the same physical time dilation and length contraction, requires implicitly the use of an "external" synchronization procedure. In this way, the transformations (1) offer a conventional alternative for the interpretation of a physical effect but, according to the conventionalist view, this alternative does not invalidate the result that the observable local one-way light speed is c as foreseen by Einstein or any equivalent synchronization.

Nevertheless, we must consider that the interpretation of SR has been evolving, and now we are faced with the possibility that the one-way light speed may be tested, as indicated in Refs. [25-27, 30, 31], just to mention a few. The reason why all the internal synchronization procedures are not necessarily equivalent to Einstein synchronization, is also explained in Ref. [31] and discussed in section 2. In short, the argument in Ref. [31] is that in a given inertial frame we may realize a physical system with two classically entangled, simultaneous, and spatially separated events, one at A and the other at B with AB = L, which are preset in the system.

Hence, the preset simultaneity can be exploited to synchronize two spatially separated clocks without the need of sending information from A to B, or vice versa, as instead it occurs with the use of light signals in Einstein synchronization or with clock and rod transport, both of which are influenced by the relativistic effects of time dilation and length contraction.

As discussed in Ref. [31], this preset classical simultaneity is unrelated to Einstein’s or Einstein-equivalent synchronization procedures based on the transport of physical information.

Instead, it is analogous to the simultaneity implicit in the entanglement of a two-particle quantum system, where the collapse of the wave function determines simultaneously

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the spin orientation of the two particles, in agreement with Bell's theorem and as recently verified experimentally [32]. The possibility of measuring the one-way speed of light within the relativistic framework has been considered by Nissim-Sabat in 2021 [33]. The author shows that the one-way velocity of light is measurable without synchronized clocks and clocks are synchronizable without one-way signals.

The approach of Nissim-Sabat differs from ours and, although these themes require further studies, it is worth mentioning that his results agree with the ones we derive using the procedure based on classical entanglement [31]. In conclusion, with the internal synchronization of Ref. [31], or other suitable internal procedures that, at least in principle, are not equivalent to Einstein synchronization, we may discriminate experimentally, the different transformations (1) and test Lorentz and light speed invariance. In this scenario, the light speed c' in (1) is not a conventional physical quantity, and it represents the local differential speed in the inertial frame S′. The purpose of our article is to show that, in general, the LT and ST may not be physically equivalent and actually may represent two different physical realities that can be differentiated experimentally. The main novelty of our article consists in adopting, to corroborate our claim, the internal synchronization described in Refs. [31] and [26], which, in principle, is not equivalent to the one of Einstein. Hence, differently from what is usually considered in the literature, we deal with transformations LT and ST as not necessarily being equivalent. Our procedure can be applied to interpret several optical experiments that involve light speed propagation and test space isotropy, such as, the circular Sagnac effect [56]; the Michelson-Gale experiment [57]; the Global Positioning System (GPS) [53, 54]; the Wang-Sagnac linear effect [58], [59]; the experiments determining the variation of the Earth's rotation [60]. All these experiments can be considered to be equivalent to the effects of the Sagnac type [26], [29] and, thus, we may limit our interpretation and discussion to the GPS and the linear Wang-Sagnac effect as representing the experimental evidence of all of them. We present first the interpretation of the results achieved with the Global Positioning System (GPS), which indicate agreement with the ST but not with the LT. The fact that the LT fail when Einstein synchronization is applied to a moving closed contour is well known and is the reason why relativists adhering to the conventionalist view adopt the ST in lieu of the LT. Then, we make some general theoretical consideration regarding the symmetry the LT and ST and, finally, consider in detail the special case of light propagation along a linearized moving closed contour. For the latter case, we corroborate the result that the use of the LT in interpreting the GPS and the circular and linear Sagnac effects, implies non-conservation of spacetime continuity in some inertial frame, while continuity is preserved in every inertial frame with the ST. Furthermore, we mention other examples, discussed in depth in the literature, where the two transformations foresee different observable results. Still, although the physical effects considered favour the adoption of the ST versus the LT, we do not exclude the possibility that the result of the test of Lorentz and light speed invariance based on internal synchronizations such as that considered in Ref. [31] may confirm the equivalence with Einstein synchronization and, correspondingly, the validity of the conventionalist thesis.

2. Interpreting the GPS equation for clock synchronization assuming an internal synchronization procedure not equivalent to the one of Einstein

In the literature there are very many articles interpreting the circular Sagnac effect within the relativistic scenario. However, save for a few exceptions, all these interpretations are based on the single-frame assumption that in the chosen inertial frame S the one-way light speed is c.

Thus, to the first order in v/c, these interpretations are valid also in Newtonian physics and the LT are not discriminated against any other transformations. The challenge is to interpret consistently these optical effects in the succession of the inertial frames S′ instantaneously comoving with the measuring device on the contour, as done by several authors [9-11, 12, 22].

We show below the results corresponding to the interpretations of the LT and ST. In the rotating frame of the Earth, the clock synchronization equation, which has been confirmed by experiment and which represents light travel time determined using two GPS clocks, can be used to derive light speed in any direction. Thus, with results valid to the first order in v/c, a light signal travels a coordinate distance $d\sigma'$ in the time dt' given by Ashby [53]:

$$dt' = \frac{d\sigma'}{c} + \frac{2\omega}{c^2} dA_z' = \frac{r' d\phi'}{c} + \frac{\omega}{c^2} r'^2 d\phi' \qquad (2)$$

where the last term, valid for light propagation along the circumference of radius $r' = r$ of the Earth's circular section perpendicular to the rotation axis, is derived considering that the infinitesimal area dA_z' is the quantity $r'^2 d\phi'/2$ and $d\sigma' = r'd\phi'$. Therefore, for two clocks, A and B, synchronized by the GPS and located along the circumference of radius r, the time interval $dt' = c^{-1} r'd\phi'(1 + \omega r'/c)$ taken by the light ray sent from A to reach B, corresponds to the local light speed c' in the rotating frame of the Earth given by:

$$c' = \frac{r' d\phi'}{dt'} = \frac{c}{1 + \omega r'/c} = \frac{c}{1 + v/c} = c - v \qquad (3)$$

If any "internal" synchronization is equivalent to Einstein synchronization, the result (3) corresponds to having the clocks in the inertial frame S′, instantaneously comoving with the segment $r'd\phi'$, as being "externally" synchronized with the clocks at rest in the Earth Centered Inertial (ECI) frame S. However, as mentioned in the Introduction and discussed below, it is feasible to adopt an internal synchronization that is not equivalent [31] to the one of Einstein.

Then, the observable light speed c' in (3) represents the possible related outcome whenever this alternative synchronization is performed in the inertial frame S′ instantaneously comoving with the segment $r'd\phi'$. Since, at least in principle, this alternative synchronization is not necessarily equivalent to Einstein synchronization, it may very well support transformations based on conservation of simultaneity and, in this case, the light speed in the expression (3) is not a conventional, externally synchronized quantity, but represents the local differential speed c' along the segment $r'd\phi'$ in agreement with Ashby's equation [53].

To clarify the consequence of the result (3) we consider now the inertial frame S′ with its x' axis tangent to the circumference and moving at the tangential speed $v = \omega r$ relative to the ECI frame S. Let us suppose that there is a pole, or stick, of length $\Delta L'$ at rest on and comoving with frame S′. For the two clocks A and B at the extremities of the arc $s' = r\Delta\phi'$ and with AB = $r\Delta\phi' = \Delta L' << 2\pi r$, the arc length $s' = r\Delta\phi'$ can be thought of as being instantaneously comoving with $\Delta L'$. As seen from the ECI frame S, a light ray traverses the moving $\Delta L'$ from A to B in the interval $\Delta t = \gamma^{-1}\Delta L'/(c - v)$. The time transformations of the LT and ST between the inertial frames S′ and S, are respectively,

$$\Delta t'_{LT} = t'_B - t'_A = \gamma(\Delta t - v\Delta x/c^2) = \frac{\Delta L'}{c}$$

$$\Delta t'_{ST} = t'_B - t'_A = \frac{\Delta t}{\gamma} \simeq \frac{\Delta L'}{c'} = \frac{\Delta L'}{c - v} \qquad (4)$$

where, for the LT, $\Delta x = c\Delta t$ in (4).

To the first order in v/c, the verified GPS synchrony is precise enough to foresee the local speed $c' = c - v$ of (3), in agreement with the predictions (4) of the ST but not the LT, which may not fully account for the observed results under certain interpretations of the GPS synchronization [54].

Objection of the conventionalists to the conclusion that the LTs are disproved by the GPS synchronization.

The claims of conventionalists [6, 35, 1, 36-39] are: any internal synchronization procedure (such as clock transport) is equivalent to Einstein's; synchronization is arbitrary; the one-way light speed is conventional and the LT and ST are equivalent. Thus, on account of the arbitrariness of synchronization and the equivalence of the LT and ST, the LT are not disproved by the GPS "external" synchronization.

Our reply to the conventionalists' objections:

a) Not every internal synchronization is equivalent to Einstein's. We highlight the recent procedure by Spavieri [30, 31], consisting of a rod of length AB = L stationary on an inertial frame and rotating uniformly about its symmetry axis L parallel to the x axis. When the rod is not rotating, on the two cross sections of the rod, we can identify two points, point A* at A and point B* at B, that are in phase being aligned on the A*B* line parallel to the x axis . When the rod is in uniform rotational motion and in absence of torsional stresses, the points A* and B* are still in phase [30, 31]. Then, the rod built-in synchrony implies that the rotating points A* and B* will cross simultaneously any axis perpendicular to the AB direction and the simultaneity of the two events can be exploited to internally synchronize two clocks, one at A and the other at B. Since this rotating rod synchronization procedure represents an internal synchronization not ineludibly equivalent to Einstein's, we infer that the LT and ST are not necessarily equivalent and thus, at least in principle, the one-way light speed may be measurable.

Moreover, confirming that synchronization is not arbitrary, there are other ways that can lead to the measurements of the one-way light speed, shown in Refs. [23, 25, 27]. The conclusion that the LT and ST are not always physically equivalent is corroborated also by the other arguments presented below in sections 3-5.

b) If the LT and ST were equivalent, we should expect that both can provide an equivalently consistent interpretation of the GPS and the effects of the Sagnac type. However, one of the problems of the LT consists in the well-known fact (recognized even by conventionalists [1, 35]) that Einstein synchronization fails when applied to a moving closed contour [9-12, 17-63]. If, with Einstein synchronization, the local light speed is c along the circular contour of the Sagnac effect (or the GPS), by integrating the first of the Eqs. (4), the distance AB = $2\pi r$ will be traversed by a counter-moving light signal, performing a round trip starting from A and returning to A≡B, in the interval $T' = 2\pi r/c$. Nevertheless, the correct value is $T' = 2\pi r/(c + v)$, as observed in the Sagnac effect and as a result of the GPS evidence. Hence, Klauber [62, 63] is right when pointing out that with Einstein synchronization the clock A is out of synchrony with itself.

Moreover, that the GPS and Sagnac results favour the ST over the LT, is not due to the fact that rotating frames are not inertial, as in the case of the GPS and the circular

Sagnac effect (a point highlighted also by Engelhardt [34]). Indeed, the mentioned difficulties of the LT emerge even when dealing with inertial systems as in the case of the linear Sagnac (Wang et al. [58, 59]) effect. To prove our view and for the convenience of the reader, we discuss in detail in section 4 the linear Sagnac effect, showing that the well-known result that Einstein synchronization fails in describing light propagation along closed contours, is linked to the imposition of light speed invariance along the whole closed contour when adopting the LT. No problems arise adopting the ST. Finally, that the LT are ST are not equivalent and predict different results, can be shown explicitly with the reciprocal linear Sagnac effect [28, 29] and other cases discussed below.

3. The symmetry of transformations

The role of symmetry represents an important theoretical argument endorsing the view that, in general, relative simultaneity (and the LT) is not compatible or exchangeable with absolute simultaneity (and the ST). In the literature, we have found no discussions about this fundamental aspect from physicists adhering to the conventionalist view. Regarding the LT, we know that the Thomas-Wigner rotation is present whenever a pair of Lorentz transformations involving non-collinear velocities is composed. In the context of atomic physics, and exploiting the symmetry of the transformations along the electron orbit, Jackson [55] applies these successive Lorentz transformations in his derivation of the Thomas precession, showing that it is foreseen by the LT. Yet, in Ref. [28] Spavieri and Haug take into account the different symmetries of relative and absolute simultaneity and, following Jackson's derivation using the ST, show that, due to the different symmetry, the LT and ST provide different results. This outcome confirms the notion that the LT and ST are in general not physically equivalent because, fundamentally, the LT form a symmetry group, a Lie group of symmetries of the spacetime of SR, while the ST do not form a group (Selleri explicitly states "the inertial transformations [ST] form a quasi-group." [10]).
Our claim is that, the contended equivalence between relative (LT) and absolute simultaneity (ST), has no general validity and is limited to the special case of the arbitrary synchronization involving two spatially separated clocks and making use of Einstein synchronization procedure. However, as well known and pointed out above, Einstein synchronization fails [56, 9-15, 17-63] for light propagation along a moving closed contour (such as the Sagnac effects) where a single clock may be used to measure the round-trip time interval. Hence, the conventionalist view seems to have some limits because the LT and ST are not interchangeable in general. Thus, if and whenever the ST are successfully used to solve paradoxes of standard SR [35, 1, 39], it seems to represent a conceptual error the claim that also the LT are validated [12, 21-29].

4. The linear Sagnac effect: Spacetime continuity requires to adopt conservation of simultaneity with the corresponding local speed $c = c(v)$ along the moving optical fiber

In its linear form, the Sagnac effect of Figure 1 has been verified by Wang et al. [58, 59] in 2003. We consider here the special case of a single counter-propagating photon that leaves the clock C* and returns to it after the round-trip proper time interval T. Our purpose here is to verify whether the photon can traverse in the observed time interval T the whole contour of length $2\gamma L \simeq 2L$ traveling at the local speed c in every section of the contour.

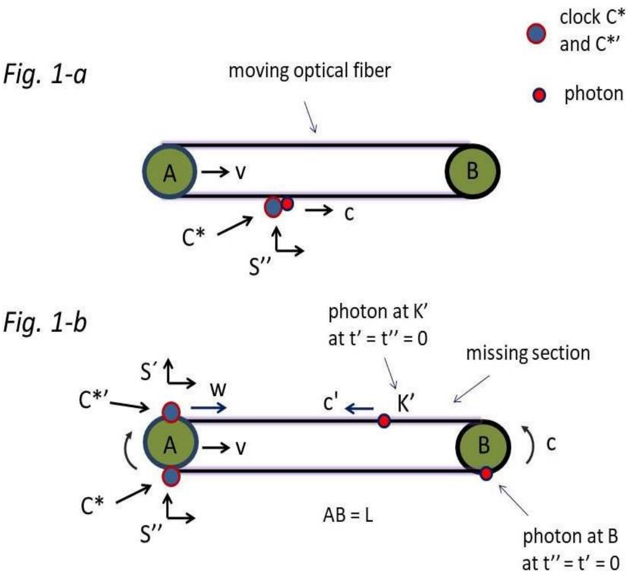

Figure 1. Figure 1-a. In the linear Sagnac effect, the optical fiber slides on the two pulleys A and B at speed v relative to the rest frame S of the pulleys. Clock C* is at rest on the inertial frame S″ from where the pulley frame AB is seen in motion with velocity v, while the photon leaving C* is counter-moving at speed c along the fiber. Figure 1-b. Clock C*′ is at rest on the inertial frame S′, being S′ and S″ in motion with opposite velocities v relative to the frame AB of the contour, while coinciding at A at $t' = t'' = 0$. As observed from C* on frame S″, the photon emitted from C* on the fiber lower section reaches B when A reaches C* and covers at speed c the distance L/γ in the interval T_{out}. After the photon at B has moved on the upper section, according to the LT and due to relative simultaneity, as seen from frame S′, the photon is already at K′ at $t' = 0$ and covers the shorter distance $\gamma L(1 - v/c)^2$ in the return trip. The "missing" section $K'B = c\delta t' = 2\gamma(v/c)L$ has not been covered for $t' > 0$

We focus on the special case when the device C* moves from the lower to the upper section in the interval T, as discussed in detail in Refs. [21, 22, 24]. To simplify the calculations, it is convenient to assume that the interval η, taken by C* to move around the pulley of radius R, while moving from the lower to the upper fiber section, is negligible and much less than T. However, with a complete linearization of the problem, it is simpler to deal with two clocks in uniform motion, where the first clock C* is placed on the lower fiber section comoving with the inertial frame S″, and the second clock C*′ is placed on the upper section comoving with the inertial frame S′. C*′ is synchronized with C* when the two clocks coincide at the pulley A.

The round-trip T measured by C* and C*′ comoving with the fiber is evaluated below, but is generally easily evaluated in the lab rest frame of the pulleys and the standard result is [21, 22, 24]:

$$T = \frac{2\gamma L}{\gamma^2(c+v)} = \frac{2\gamma L(1-v/c)}{c} \tag{5}$$

where T is an invariant quantity independent of the initial position C* along the contour.

We can see from the relation (5) that the two expressions for T correspond to two different lengths representing the possible distance traversed by the photon:

i) The first expression for T in (5) stands for the interpretation of the observer with the clock comoving with the fiber of length $2\gamma L$, where $\gamma^2(c + v)$ is the average speed of light along the moving contour. As measured by an observer comoving with the fiber, in a round trip the photon covers the whole distance $2\gamma L$, which represents the invariant length of the fiber.

ii) The second expression stands for the interpretation from the lab rest frame of the pulleys, or any other single inertial frame, where the light speed is assumed to be c. This single-frame interpretation is valid (to the first order in v/c) even in Newtonian physics and thus does not discriminate the LT against any other transformations, such as the ST. Moreover, it does not reveal whether the one-way speed of the photon is c, locally, along a particular moving section of the contour. As seen from the lab frame, or any other single inertial frame, at the speed c in the chosen frame, the distance traversed by the photon is $2\gamma L(1 - v/c) < 2\gamma L$ because, in the interval T, the clock C* has traveled the distance $vT \simeq 2L(v/c)$, which is not covered by the photon. Obviously, as claimed by Sagnac [56], Selleri [9-11], Gift [12], Spavieri et al. [21, 29] and many other physicists [14-20, 35, 1], the average speed $\simeq c + v$ seen from C* comoving with the fiber is inconsistent with an invariant local light speed c along the whole fiber of length $\simeq 2L$. As shown in detail below, at the local speed c along the fiber and in the interval T, the photon can cover the distance $\simeq 2L(1 - v/c)$ only, which is less than $\simeq 2L$ and thus misses to cover the remaining section $\simeq 2L(v/c)$ in the observable interval T. If instead the photon covers the whole length $\simeq 2L$ of the fiber at the local speed c, as required by the LT, for the clock C* comoving with the fiber the resulting interval would be $T_c \simeq 2L/c$, contrary to observation.

Proceeding with our derivation, we denote by $c^{''} = c_g^{''}$ the "ground" local light speed on S″. Then, $c_g^{''}$ represents the "ground" local light speed along the fiber ground section that is at rest on $S^{''}$ on the lower section, as measured by clocks at rest on $S^{''}$. Similarly, we denote by $c^{'} = c_g^{'}$ the ground local light speed on S′. A priori, c'' and c' do not necessarily coincide, depending on the theory and corresponding synchronization.

As a way to check the consistency and completeness of the theory, with the LT or the ST, we need to verify:

a) the ground local speed on both the lower and upper sections, and:

b) the ground total length covered by the photon in the proper interval T.

In general, it is impossible to determine a) and b) with a description from a single inertial frame of reference, but in our case it is possible to do it by using two inertial reference frames. We must stress here that the result (5) is independent of the initial position of C* along the closed contour and the results of the derivation considered below are valid for any choice of the initial position, including the case when C* keeps in uniform motion in the lower (or upper) section of the fiber during the whole interval T. However, for our purpose and for simplicity, we find it convenient to consider the special situation where C* moves from the lower to the upper section while the photon performs a round trip in the interval T. We begin by considering the consistency of the LT.

Description from S″ using the LT.

With C* initially on the frame S″ of the lower section (Figure 1-a), the initial position of C* relative to A, can be chosen in such a way (AC* = $X = (v/c)L/\gamma$) that the counter-propagating photon leaving C* reaches B when, simultaneously, A reaches C*, as indicated in Figure 1-b. Assuming $c^{''} = c_g^{''} = c$ as seen from C* on the clock frame S″, the time interval taken by the photon to reach B is,

$$T_{out}^{''} = T_{out} = \frac{L^{''}}{c^{''}} = \frac{L}{\gamma c} \tag{6}$$

which is the same time interval $T_{out} = X/v$ taken by A to reach C*. Since L'' and c'' are "ground" kinematical quantities measured on S″, the fiber ground length covered at speed $c^{''} = c_g^{''} = c$ by the photon in the out trip T_{out} from C* to B, is $L^{''} = L_g^{''} = \gamma^{-1}L$. For the return trip on the upper section, the situation is shown in Figure 1-b, where the second clock C*′ is comoving on the fiber upper section with the frame S′, traveling with velocity v relative to the arm AB. Clock C*′ is set at $t' = t'' = 0$ at point A when coinciding with C*. Obviously, the time intervals measured by C*′ after $t' = 0$ are the same

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intervals that C* would measure after having moved to the upper section.

With the corresponding LT (see Refs. [21, 22] and some of its relations with the AB frame S given in the Appendix of the present paper), the relative velocity between S″ and S′ turns out to be given by $w = 2v/(1 + v^2/c^2) \simeq 2v$. From the equation $wt'' = L/\gamma - ct''$, the return trip time interval seen from S″ is

$$T''_{ret} = \frac{L}{\gamma(c+w)} = \frac{\gamma_w L(1-v/c)}{\gamma c(1+v/c)}$$
$$T_{ret} = T'_{ret} = T - T''_{out} = \frac{T''_{ret}}{\gamma_w} = \frac{\gamma L(1-v/c)^2}{c} \quad (7)$$

where the proper interval $T_{ret} = \gamma_w^{-1} T''_{ret}$ is equally foreseen by the time transforms (1) of the ST and LT.

The interval (7) has been evaluated from the single frame S" assuming with the LT that the one-way light speed along the upper fiber section is still the invariant c. To verify the conditions a) and b) along the upper fiber section, we need to consider that the one-way ground light speed might be not c along the upper section and we must evaluate $c' = c'_g$ and $L' = L'_g$ from the rest frame S′ of clock C*′. Hence, we have to consider the following:

Description with the LT involving the frame S′.

The return trip $T'_{ret} = L'/c'$ is given by (7) but, according to the LT, the return light speed is the invariant c on S′ and we have $T'_{ret} = L'/c'$, the interval T'_{ret} being measured at $t' \geq 0$. Then, for the observer on S′,

$$AK' = L' = cT'_{ret} = \gamma L(1-v/c)^2$$
$$= \gamma_w L/\gamma - c\delta t' < L \quad (8)$$

where in (8) the term $\delta t' = 2\gamma v L/c^2$ represents the "time gap" from S′ to S″ due to relative simultaneity foreseen by the time transform of the LT. The total ground path covered at speed c by the photon, with $L'' = L''_g$ on S″ and $L' = L'_g$ on S′, is exactly,

$$L''_g + L'_g = \gamma^{-1}L + \gamma L(1-v/c)^2$$
$$= 2\gamma L - c\delta t' < 2L \quad (9)$$

Hence, at the invariant local speed c on both lower and upper sections, the photon does not cover the whole fiber length $2\gamma L$ in the round-trip interval T. In fact, according to standard SR and due to the effect of relative simultaneity, the section BK′ = $c\delta t'$ has been covered in the past, at $t' < 0$. Then, by assuming light speed invariance with the LT, result (9) implies that the section BK′ has not been covered in the measured interval T_{ret}' (for $t' > 0$). Thus, according to the LT, the spatial distance covered is $2L - c\delta t'$, less than the total ground fiber length $\simeq 2L$. Since in the proper interval $T_{out} + T_{ret}$ and at speed c, the photon covers the sections $L''_g + L'_g$ only, the "missing" path BK′ = $2\gamma vL/c = c\delta t'$ has not been covered and the use of the LT entail a breach of spacetime continuity.

Imposing spacetime continuity in deriving T.

In the return trip from B to C* on the upper section, clock C*′ measures the observable interval $T_{ret} = L'/c'$ from the instant $t' = 0$, when it coincides with A, to the moment when the photon reaches it. Although c' and L' are undetermined, light propagation along the closed contour imposes a constraint: spacetime continuity requires the total ground length of the fiber to be $2\gamma L$. Since the distance $L'' = \gamma^{-1}L$ has been covered in the out trip, the remaining distance,

$$L' = 2\gamma L - L'' = \gamma^2\left(1+\frac{v^2}{c^2}\right)\frac{L}{\gamma} = \gamma_w \gamma^{-1} L$$

must be covered at speed c' in the return trip. With the help of (7) and (12) we find,

$$T_{ret} = \frac{L'}{c'} = \frac{\gamma_w \gamma^{-1} L}{c'} = \frac{\gamma L(1-v/c)^2}{c}$$
$$c' = \gamma_w^2(c+w) = \frac{c}{1-w/c} \quad (10)$$

Result (10) corresponds to the synchronization parameter $\varepsilon = 0$ in the approach of Mansouri and Sexl [6] for the transformations from S″ to S′ in terms of the synchronization parameter ε, implying that the resulting synchrony, reflecting the interpretation of the linear Sagnac effect consistent with spacetime continuity, is the one of the ST with absolute simultaneity. With c' given by (10) on S′, and $c'' = c$ on S″, the total ground length covered is $cT_{out} + c'T_{ret} = \gamma^{-1}L + \gamma_w\gamma^{-1}L = \gamma^{-1}L + \gamma(1 + v^2/c^2)L = 2\gamma L$, as expected. If the one-way speed is assumed to be c in the lab frame S of the pulleys (instead than in S″), along the moving sections of the fiber we find $c(v) = \gamma^2(c + v)$.

5. Other considerations showing the nonequivalence between the ST and the LT

Does the Sagnac effect need to be interpreted in the framework of General Relativity?

There are researchers [40-52] working on similar topics in rotating frames who claim that the Sagnac type of effects can only be explained within general relativity–that is, that neither the Lorentz nor the Absolute transformations are sufficient without the inclusion of general-relativistic arguments. These authors [40-52] believe that general relativity provides a more complete description that accounts for effects beyond just rotation, such as

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gravitational waves and acceleration. While it may be described using the formalism of general relativity, we argue the Sagnac effect is purely special relativistic in nature, arising from the intrinsic kinematical effects easily describable from inertial frames.

The approach of general relativity to the circular Sagnac effect [56] seems unnecessary and is easily dismissed following the realization of the linear Wang-Sagnac effect [58, 59], as the counter-propagating beams in the linear Sagnac setup can be made sufficiently long that the acceleration effects at each end become negligible. Furthermore, the measuring device (clock or interferometer) in the linear effect may always move with uniform velocity during the photon's round trip interval, *T*, defined by Eq. (5), thereby excluding non-inertial effects. Since the experimental results and the theoretical predictions show that the full Sagnac effect in its linear realization is completely equivalent to the circular Sagnac effect, the non-inertial effects that, supposedly, exist in the circular Sagnac effect and may need the use of general relativity, are absent or negligible in the linear effect. This equivalence implies that non-inertial effects cannot be the origin of Sagnac-type effects. Hence, the realization of the linear Wang-Sagnac effect [58, 59] effectively rules out the view that Sagnac-type effects can only be explained within the framework of general relativity.

It must be pointed out that, contrary to the famous Michelson-Morley experiment that gives a null result (favoring light speed invariance, $c' = c$), the circular Sagnac effect [56], the Michelson-Gale experiment [57], the Global Positioning System (GPS) [53, 54], the Wang-Sagnac linear effect [58, 59], and the experiments determining the variation of the Earth's rotation [60], all provide evidence of light speed variance ($c' \simeq c \pm v$). The interpretive difficulties of these effects within the context of relativity theory (both special and general) are widely recognized by physicists. These difficulties are attributed to the failure of Einstein synchronization and the Lorentz Transformation (LT)–which are based on relative simultaneity–when applied along the moving closed contours inherent in the mentioned effects of the Sagnac type. The only viable and consistent theoretical interpretation found by physicists so far has been to adopt a synchronization method that conserves simultaneity, as an alternative to Einstein's. This approach was originally suggested by Sagnac [56] and subsequently championed by Selleri [9-11] and numerous other physicists [12-31].

The reciprocal linear Sagnac effect.

The analysis by Spavieri and Haug [28, 29] of the reciprocal linear Sagnac effect, indicates that the LT and ST foresee different values for the round-trip observable *T*. As mentioned above, if *X* is the initial distance of the clock C* from the pulley A, *T* is independent of *X* in the standard linear Sagnac effect (5). However, for the reciprocal effect, these authors find that $T = T(X)$ is *X*-dependent for the LT, while *T* is invariant and *X*-independent for the ST. Then, the two transformations are not equivalent and represent different physical realities in this case, invalidating the argument of general equivalence claimed by conventionalists.

The well-known failure of Einstein synchronization along closed moving contours.

Note that the problem arising by using Einstein's procedure for synchronizing clocks and using the LT along a closed contour has been pointed out more than 50 years ago by Landau and Lifshitz [64] by stating:

"However, synchronization of clocks along a closed contour turns out to be impossible in general.

In fact, starting out along the contour and returning to the initial point, we would obtain for dx^o a value different from zero ". The well-known failure of Einstein synchronization along closed moving contours has been discussed by several authors [56, 9-15, 17-63] and, according to Klauber [62], when applied on a closed moving contour it amounts to a clock being out of synchronization with itself.

However, Landau and Lifshitz clarify that "The impossibility of synchronization of all clocks is a property of the arbitrary coordinates system, and not of the spacetime itself." Hence, although by adopting the LT the impossibility of synchronization along a closed contour does not necessarily reflect a problem with spacetime itself, the adoption of the ST allows for the possibility of the synchronization of all clocks without the difficulties arising with the LT. Thus, as shown in the case of the linear effect of Figure 1, the requirement of spacetime continuity for the photon covering the whole fiber length $2\gamma L$ in the interval T, supports conservation of simultaneity (ST) versus relative simultaneity (LT).

A preset simultaneity implicit in the quantum entanglement of the spin of two particles.

As discussed also in Ref. [31], the collapse of the wave function simultaneously determines the spin orientation of the two particles, in agreement with Bell's theorem and as recently verified experimentally [32]. This result favours the notion of a preset simultaneity in physical systems that can be achieved without sending information from point A to the spatially separated point B. Hence, with the classical entanglement of Ref. [31] it is conceivable to realize an internal clock synchronization procedure not equivalent to Einstein's.

6. Conclusion

The major and straightforward difference between the LT and the ST is that they make different light speed predictions in the frame S′ of the measuring clock in the case of the GPS [53, 54] and the related circular Sagnac effect of Ref. [56], the linear WangSagnac effect [58, 59], and particularly the reciprocal linear Sagnac effect [28, 29]. All these optical effects, including the Michelson-Gale experiment [57] and the experiments determining the variation of the Earth's rotation [60], can be interpreted consistently and avoiding the problems inherent to the LT, if the ST based on conservation of simultaneity and spacetime continuity are adopted.

On account of the several arguments presented above, we consider that there is evidence showing that the LT and ST may not be physically equivalent and, thus, it may be feasible to discriminate experimentally between the LT and ST. Making use of internal synchronization procedures such as the one considered in Ref. [31] a priori not equivalent with Einstein synchronization, in principle it is possible to test Lorentz and light speed invariance and confirm, or not, the contended equivalence between relative and absolute simultaneity.

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Availability of data and materials

Not applicable (this manuscript does not report data generation or analysis).

Conflict of interests

The authors declare no conflicts of interest.

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Appendix

$$x' = \gamma_w(x'' - wt')$$

$$t' = \gamma_w(t'' - \frac{wx''}{c^2})$$

$$w = 2v/(1 + v^2/c^2) \tag{11}$$

$$\gamma_w^{-1} = (1 + w^2/c^2)^{1/2}$$

$$\gamma_w = \gamma^2(1 + v^2/c^2)$$

$$\gamma_w(1 + w/c) = \gamma^2(1 + v/c)^2 = \frac{1 + v/c}{1 - v/c} \tag{12}$$

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