Research Article

The One-Way Light Speed Is Measurable: Nonequivalence of the Lorentz Transformations and the Transformations Preserving Simultaneity and Spacetime Continuity

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Based on our analysis of the GPS and other physical effects, we confirm the well-known view that the Lorentz transformations (LT) fail in interpreting 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 cannot cover the whole closed contour in the measured interval T. Thus, the LTs imply a breach in spacetime continuity related to the "time gap" due to relative simultaneity. Our results invalidate Mansouri and Sexl's conventionalism of the speed of light and the contended equivalence between relative and absolute simultaneity[1].

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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 with standard SR. In treating 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

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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[2], 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's synchronization procedure was soon criticized by epistemologists[3][4][5][6]: 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[1] introduced their generalized coordinate transformations where the one-way speed depends explicitly on the arbitrary synchronization parameter ε:

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

The transformations (1) from frame S to S$'$ in relative motion with velocity v, are the LT with $\varepsilon = v$, and the ST with $\varepsilon = 0$ are the Lorentz transformations based on absolute simultaneity. The time transform of the LT and ST differs by the value of 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 (e.g., Tangherlini transforms[7], Selleri transforms[8][9][10][11], ALT[12][13][14], LTA[15][16][17][18][19][20][21][22][23][24][25][26][27][28], etc.).

Supporters of standard special relativity agree that the STs 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[8][9][10] and other paradoxes[1][29][2][30][31][32][33][34]. Their main argument for claiming that the LTs are still valid, even if the paradoxes of the LT need to be "solved" with the ST, is that the LT and ST differ by the arbitrary synchronization parameter ε only[1], and thus are physically equivalent and interchangeable.

The purpose of our Letter is to show that the LT and ST are in general not physically equivalent and actually represent two different physical realities. To corroborate our claim, we present first the interpretation of synchronization achieved with the global positioning system (GPS), which indicates agreement with the ST but not with the LT. Then, we make some general theoretical considerations regarding the symmetry of 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 a violation of spacetime discontinuity, while continuity is preserved with the ST. Furthermore, we mention other examples, discussed in depth in the literature, where the two transformations foresee different observable results.

2. Interpreting the GPS equation for clock synchronization

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 given by Ashby[35]

$$dt' = \frac{d\sigma'}{c} + \frac{2\omega}{c^2} dA'_z = \frac{r' d\varphi'}{c} + \frac{\omega}{c^2} r'^2 d\varphi', \tag{2}$$

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 is the quantity $r'^2 d\varphi'/2$ and $d\sigma' = r' d\varphi'$. Therefore, for two clocks, A and B, synchronized by the GPS and located along the circumference of radius r, the time interval $dt' = c^{-1} r' d\varphi' (1 + \omega r'/c)$ 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,

$$c' = \frac{r' d\varphi'}{dt'} = \frac{c}{1 + \omega r'/c} = \frac{c}{1 + v/c} = c - v. \tag{3}$$

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 Earth-centered inertial (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 $s' = r\Delta\varphi'$ and with AB = $r\Delta\varphi' = \Delta L' << 2\pi r$, the arc length 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,

$$\begin{aligned} (\Delta t')_{LT} &= t'_B - t'_A = \gamma(\Delta t - v\Delta x/c^2) = \frac{\Delta L'}{c} \qquad (4) \\ (\Delta t')_{ST} &= t'_B - t'_A = \frac{\Delta t}{\gamma} \simeq \frac{\Delta L'}{c'} = \frac{\Delta L'}{c - v}, \end{aligned}$$

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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, suggesting that the LTs are invalid[36].

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

The claims of conventionalists[1][29][2][30][31][32][33][34] 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[27], 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 the absence of torsional stresses, the points A* and B* are still in phase. 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 rod synchronization procedure represents an internal synchronization not necessarily equivalent to Einstein's, we infer that, in principle, the LT and ST are not equivalent and thus the one-way light speed is 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.[21][23][24]. The conclusion that the LT and ST are not 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 inconsistencies of the LT consists in the well-known fact that Einstein synchronization fails when applied to a moving closed contour[8][9][10][11][15][16][17][18][19][20][21][22][23][24][25][26][27][28][29][30][31][32][33][34][35][36][37]

[38][39][40][41][42][43]. If the local light speed is c along the circular contour of the Sagnac effect (or the GPS), with Einstein synchronization and by integrating the first of the equations (4), the distance AB = $2\pi r$ will be traversed by a countermoving 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[42][43], 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 favor 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[28]). Indeed, the mentioned difficulties of the LT emerge even when dealing with inertial systems, as in the case of the linear Sagnac[39][40]) 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 violation of spacetime discontinuity of the LT when light speed invariance along the closed contour is imposed. Finally, that the LT and ST are not equivalent and predict different results can be shown explicitly with the reciprocal linear Sagnac effect[25][26], 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's[37] applies these successive Lorentz transformations in his derivation of the Thomas precession, showing that it is foreseen by the LT. Yet, in Ref.[25], 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,

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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] do not form a group."[9]).

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 the Einstein synchronization procedure. However, as well known and pointed out above, Einstein synchronization fails[38][8][9][10][11][12][13][14][15][16][17][18][19][20][21][22][23][24][25][26][27][28][29][30][31][32][33][34][35][36][37][38][39][40][41][42][43] 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, contrary to the conventionalist claim, the LT and ST are not interchangeable in general and thus, if and whenever the ST are successfully used to solve paradoxes of standard SR[29][2][34], it is a conceptual error to claim that also the LT are validated on account of their equivalence with the ST[11][19][20][21][22][23][24][25][26].

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

In its linear form, the Sagnac effect of Fig. 1 has been verified by Wang et al.[39][40], 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. 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.[19][20][22]. 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 . 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$^{*\prime}$ is placed on the upper section comoving with the inertial frame S$'$. C$^{*\prime}$ is synchronized with C* when the two clocks coincide at the pulley A.

The round-trip T measured by C* and C$^{*\prime}$ 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[19][20][22],

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

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

We can see from the relation (5) that there are two different lengths representing the possible distance traversed by the photon. The first expression for T in (5) stands for the interpretation from 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, considering the distance $2\gamma L$ covered by the photon as invariant when measured along the fiber. The second expression stands for the interpretation from the lab rest frame of the pulleys where the light speed is c. As seen from the lab frame, or any other single inertial frame, at the speed c 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[38], Selleri[8][9][10], Gift[11], Spavieri et al.[19][20][21][22][23][24][25][26] and many other physicists, 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 using two inertial reference frames. Hence, for our purpose, it is

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convenient to consider the following 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 (Fig. 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 Fig. 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 Fig. 1-b, where the second clock C$^{*\prime}$ is comoving on the fiber upper section with the frame S$'$, traveling with velocity v relative to the arm AB. Clock C$^{*\prime}$ is set at $t' = t'' = 0$ at point A when coinciding with C*. Obviously, the time intervals measured by C$^{*\prime}$ after $t' = 0$ are the same intervals that C* would measure after having moved to the upper section.

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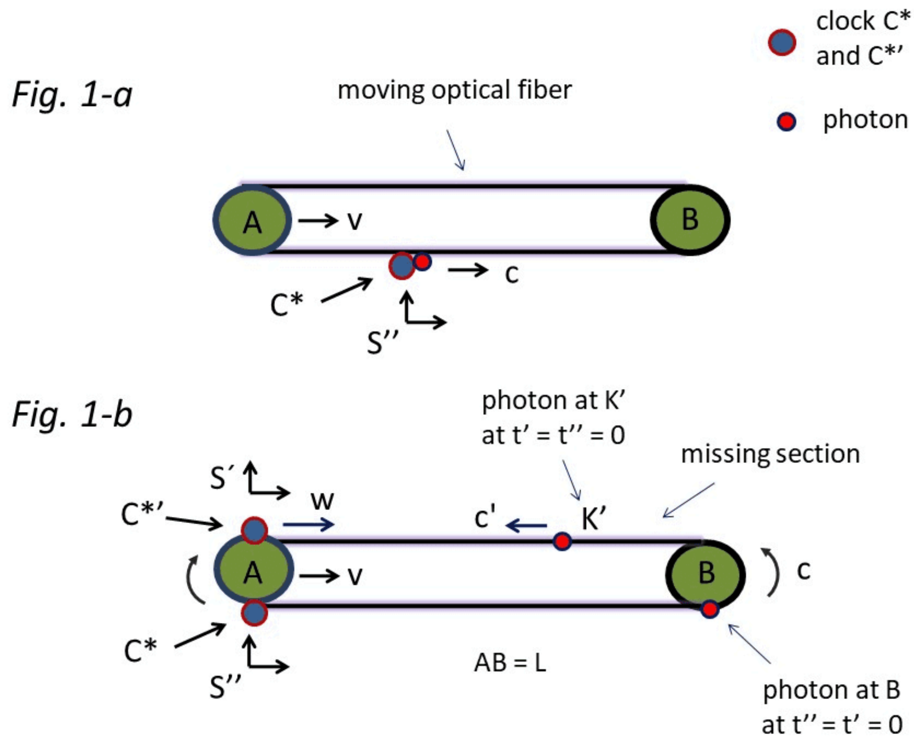

Figure 1. a) In the linear Sagnac effect, the optical fiber slides on the two pulleys A and B at speed v relative to the rest frame S of the pulleys. Clock C* is at rest on the inertial frame S$''$ from where the pulley frame AB is seen in motion with velocity v, while the photon leaving C* is counter-moving at speed c along the fiber. **b)** Clock C$^{*\prime}$ 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 $t' > 0$.

With the corresponding LT[19][20], 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,

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

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

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

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,

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

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$' = 2\gamma v L/c = c\delta t'$ has not been covered, and the use of the LT entails 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$^{*\prime}$ 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,

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

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

$$\begin{aligned} T_{ret} &= \frac{L'}{c'} = \frac{\gamma_w \gamma^{-1} L}{c'} = \frac{\gamma L(1-v/c)^2}{c} \\ c' &= \gamma_w^2(c+w) = \frac{c}{1-w/c}. \end{aligned} \qquad (10)$$

Result (10) corresponds to the synchronization parameter $\varepsilon = 0$ in the approach of Mansouri and Sexl[1] 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 that 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 of 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.

The reciprocal linear Sagnac effect. The analysis by Spavieri and Haug[25][26], 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 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.

Violation of spacetime continuity. Note that the spacetime discontinuity of the LT has been pointed out more than 50 years ago by Landau and Lifshitz[44] 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

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zero . . ." .

The statement by Landau and Lifshitz is an indication of the failure of Einstein synchronization along closed moving contours[44][8][9][10][11][12][13][15][16][17][18][19][20][21][22][23][24][25][26][27][28][29][30][31][32][33][34][35][36][37][38][39][40][41][42][43]. Thus, as shown in the case of the linear effect of Fig. 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) and invalidates relative simultaneity (LT).

6. Conclusions

In short, considering the various inconsistencies of the LT in relation to the Sagnac effects and the other several arguments presented above, there is sufficient evidence showing that the LT and ST are not physically equivalent. 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 cases of the GPS (and the circular Sagnac effect) and the linear Sagnac effect.

Appendix

Relations used in the derivation of the results of section 4:

$$x' = \gamma_w \left(x'' - wt'\right) \quad t' = \gamma_w \left(t'' - \frac{wx''}{c^2}\right) \qquad (11)$$

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

$$\gamma_w = \gamma^2 \left(1 + v^2/c^2\right) \qquad (12)$$

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

Notes

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