

# Non-Invariant One-Way Speed of Light: Advancing the Selleri Transformations

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## Abstract

In a recent paper [1], the author shows that in spacetime physics, the Selleri transformations (STs) are viable alternatives to the Lorentz transformations (LTs) of special relativity. However, the STs predict a non-invariant one-way speed of light which implies a violation of the foundational light speed invariance principle of special relativity. We confirm the correctness of this prediction of the STs using two independent and experimentally implemented procedures within the Global Positioning System (GPS): the range equation, and the clock synchronization equation. The predicted light speeds of both the LTs and the STs are further tested by applying them in the derivation of the ITU time transfer equation. The finding is that the STs do not require a supplementary correction as do the LTs. These light speeds are also applied to the Michelson-Gale experiment (configured in a local inertial frame) showing that the STs reproduce the observed fringe shift, a result further confirmed through direct timing using GPS clocks. The LTs are unable to address this experiment since they predict constant light speed in the arms of the apparatus and hence a null result as occurs in the Michelson-Morley experiment. Finally, we show that despite their different light speeds, the STs, like the LTs, accurately reproduce relativistic beaming, a well-established physical effect in high-energy physics. These results directly confirm light speed non-invariance that **invalidates** the light speed constancy postulate of special relativity and indicate that the STs provide a more accurate and complete framework for relativistic physics than the LTs.

## Keywords

Lorentz Transformations, Selleri Transformations, One-Way Light Speed, GPS Synchronization Equation, GPS Range Equation, Time Transfer, Michelson-Gale Experiment, Relativistic Beaming

## 1. Introduction

The **principle of the constancy of the speed of light** is a foundational postulate of special relativity that leads directly to the Lorentz transformations (LTs) [2]. This concept, inspired by the null result of the Michelson-Morley experiment [3], is a cornerstone of modern physics. Throughout the past century, many experiments conducted on the Earth have sought to detect light speed variations from directional, diurnal, or seasonal changes, consistently pushing the limit on anisotropy to the exceptionally low value  $\delta c/c < 10^{-18}$  [4]-[7]. This overwhelming evidence for light speed isotropy has led to its widespread acceptance and incorporation into the 1983 SI definition of the meter.

However, Zhang has determined in a thorough review [8] that these high-precision tests fundamentally confirm two-way light speed constancy, and that one-way light speed constancy remains **unconfirmed**. The accurate measurement of one-way light speed generally requires synchronized separated clocks and continues to be a subject of investigation, particularly within the context of Earth-based and satellite-based measurement systems. The operational realization of such synchronized clocks became possible with the emergence of the Earth-Centered Inertial (ECI) frame in the latter part of the 20<sup>th</sup> century, in which light travels at constant speed. As a result, accurate synchronized atomic clocks are today deployed in the global positioning system (GPS) [9] and provide an operational framework within which one-way light propagation times can be measured on the surface of the Earth. When these synchronized clocks are used to determine one-way light propagation times, direction-dependent time differences emerge. Marmet [10] and Kelly [11] for instance, reported time differences for light traversing the same path eastward and westward, from which they deduced light speeds  $c - v$  eastward and  $c + v$  westward relative to the Earth's surface, where  $v$  is the rotational speed at the particular latitude. Similar results have been determined by Gift using the CCIR clock synchronization equation [12] and the GPS range equation [13].

Earlier, experimental evidence by Saburi *et al.* [14] involving two-way satellite communication between the USA and Japan, demonstrated significant transmission time differences. Unequal circumnavigation times for signals travelling in opposite directions around the Earth were also directly measured by Allan *et al.* [15], though both of these groups interpreted this as light speed isotropy *with a time difference arising because of rotation*. Collectively, these results suggest that the one-way speed of light is not constant in all directions on the Earth's surface, thereby challenging a key tenet of special relativity. This interpretation has also recently appeared in Choi's relativistic analysis of the Michelson-Gale experiment where he states "the one-way speed of light is anisotropic in inertial frames" [16].

The Selleri transformations (STs) [17]-[19] provide a coherent theoretical framework for describing such direction-dependent propagation effects. These transformations connect a preferred frame  $S$  (such as the ECI frame) to a moving inertial frame  $S'$  and have been shown to accurately reproduce a wide array

of relativistic phenomena, including length contraction [17], time dilation [17], two-way light speed constancy [18], the null results of Michelson-Morley and Kennedy-Thorndike experiments [18], the Doppler effect [20], aberration [20], and the Sagnac effect [21]. The STs have also been successfully applied to relativistic dynamics [22] and electromagnetism [23], and importantly, can accommodate superluminal signals without causal paradoxes [24]. A recent analysis by the author [1] indicates that the STs offer a consistent approach to resolving certain conceptual paradoxes and can naturally yield the clock synchronization equation used in the GPS. In contrast, within the standard Lorentz framework, the derivation of this equation requires the introduction of a “Sagnac correction” from outside the formalism of the theory. The important phenomenon of Thomas precession correctly predicted by the LTs was for the first time also derived using the STs and these transformations completely resolved the right-angle lever paradox that has been an unresolved issue for the LTs for more than 100 years [1].

Thus, the STs reproduce the confirmed predictions of the LTs while also succeeding where the LTs do not. A key distinction is the prediction by the STs of a *non-invariant* one-way light speed [17]-[19]. While this is consistent with the observations of Marmet [10], Kelly [11], Gift [12] [13], Saburi *et al.* [14], Allan *et al.* [15] and Choi [16] mentioned earlier, it represents a direct violation of the light speed invariance postulate of special relativity. Because of the foundational nature of this postulate in modern physics, this prediction of light speed non-invariance is thoroughly examined and provided with robust experimental support in this paper. To this end, we first derive one-way light speed using the LTs and the STs and test these predicted speeds using two independent tests based on core GPS technology: 1) the experimentally confirmed GPS range equation; 2) the experimentally confirmed GPS synchronization equation. We then apply this light speed prediction of the STs in the straightforward derivation of the International Telecommunications Union (ITU) time transfer equation, as well as in the successful analysis of the 1925 Michelson-Gale experiment, both of which the LTs are unable to accomplish. We complete the study by demonstrating that the STs, despite their different light speed prediction, accurately account for the phenomenon of relativistic beaming as do the LTs, indicating their broad applicability.

The Lorentz and Selleri transformations, which are the basis of the discussion on light speed in this paper, are here stated. We consider an inertial system  $S$  with coordinates  $x, y, z, t$  in which the speed of light is  $c$ , and another inertial system  $S'$  having coordinates  $x', y', z', t'$  which is moving at velocity  $v < c$  relative to  $S$  along the x-axis, the two systems  $S$  and  $S'$  being coincident at  $t = t' = 0$ .

#### Lorentz Transformations (LTs)

Assuming 1) the principle of relativity and 2) the principle of light speed constancy in all inertial frames, the Lorentz transformations which relate coordinates in the two inertial frames  $S$  and  $S'$  are given by [2]

$$x' = \gamma(x - vt), y' = y, z' = z \quad (\text{L1})$$

$$t' = \gamma \left( t - \frac{vx}{c^2} \right) \quad (L2)$$

where  $\gamma = 1/\sqrt{1-v^2/c^2}$ . Note that an inertial frame  $S$  where light speed is  $c$  is like all other inertial frames  $S'$  which, because of the light speed constancy postulate, also have light speed  $c$ . In the context of the Lorentz transformations therefore,  $S$  is not a preferred frame and  $v$  is the relative velocity between the two frames.

### Selleri Transformations (STs)

Using 1) experimentally confirmed two-way light speed constancy in all inertial frames and 2) experimentally confirmed clock retardation by the usual velocity-dependent factor, the Selleri transformations which relate coordinates in the two inertial frames  $S$  and  $S'$  are given by [18]

$$x' = \gamma(x - vt), y' = y, z' = z \quad (S1)$$

$$t' = t/\gamma \quad (S2)$$

where  $\gamma = 1/\sqrt{1-v^2/c^2}$ . Here, the inertial frame  $S$  is, in general, the only inertial frame where light speed is  $c$  and therefore in the context of the Selleri transformations, is a preferred frame. The Earth-Centered Inertial (ECI) Frame, which is a critical component of the very successful GPS [9], is an example of such a frame.

## 2. One-Way Light Speed

The LTs are derived using the light speed invariance postulate, while Selleri [18] showed that the STs give light speed  $c' = c/(1 + \beta \cos \theta')$  where  $\beta = v/c$  and  $\theta'$  is the angle between the light propagation direction and the direction of the moving frame. In this section, we derive light speed  $c'$  relative to the moving frame predicted by these two transformations then subject these predictions to test by determining light speed using two components of GPS technology.

### Light Speed Predicted by the LTs

A light ray is beamed at an angle  $\theta$  with the  $x$ -axis in frame  $S$ . Let the resulting velocity in frame  $S'$  be  $c'$  at an angle  $\theta'$  with the  $x'$  axis. The components of the light velocity  $c$  in  $S$  are  $u_x = c \cos \theta$  and  $u_y = c \sin \theta$ . Using velocity composition under the LTs, the components of the light velocity in  $S'$  are given by

$$u'_x = \frac{u_x - v}{1 - vu_x/c^2} = \frac{c \cos \theta - v}{1 - v \cos \theta/c} \quad (1)$$

$$u'_y = \frac{u_y \sqrt{1-v^2/c^2}}{1 - vu_x/c^2} = \frac{c \sin \theta \sqrt{1-v^2/c^2}}{1 - v \cos \theta/c} \quad (2)$$

Therefore, the velocity  $c'$  in  $S'$  is given by

$$\begin{aligned} c'^2 &= u'^2_x + u'^2_y = \left( \frac{c \cos \theta - v}{1 - v \cos \theta/c} \right)^2 + \left( \frac{c \sin \theta \sqrt{1-v^2/c^2}}{1 - v \cos \theta/c} \right)^2 \\ &= \frac{c^2 + v^2 - 2vc \cos \theta - v^2 \sin^2 \theta}{(1 - v \cos \theta/c)^2} \end{aligned} \quad (3)$$

Noting that

$c^2 + v^2 - 2vc \cos \theta - v^2 \sin^2 \theta = c^2 - 2vc \cos \theta + v^2 (1 - \sin^2 \theta) = (c - v \cos \theta)^2$ , equation (3) reduces to

$$c' = \sqrt{\frac{c^2 (1 - v \cos \theta / c)^2}{(1 - v \cos \theta / c)^2}} = c \quad (4)$$

This shows that the LTs predict light speed  $c' = c$  in any direction in frame  $S'$ . This of course corresponds to the well-known light speed invariance postulate of special relativity.

### Light Speed Predicted by the STs

Consider a light ray that propagates at an angle  $\theta$  with the  $x$  axis in frame  $S$ . Let the resulting velocity in frame  $S'$  be  $c'$  at an angle  $\theta'$  with the  $x'$  axis. The components of the light velocity  $c$  in  $S$  are  $u_x = c \cos \theta$  and  $u_y = c \sin \theta$  and the components of the light velocity  $c'$  in  $S'$  are  $u'_x = c' \cos \theta'$  and  $u'_y = c' \sin \theta'$ . Using velocity composition under the STs [23], the components of the light velocity in  $S'$  are given by

$$u'_x = \frac{u_x - v}{1 - \beta^2} = \frac{c \cos \theta - v}{1 - \beta^2}, \quad u'_y = \frac{u_y}{\sqrt{1 - \beta^2}} = \frac{c \sin \theta}{\sqrt{1 - \beta^2}} \quad (5)$$

Therefore

$$\begin{aligned} c'^2 &= u'^2_x + u'^2_y = \frac{(c \cos \theta - v)^2}{(1 - \beta^2)^2} + \frac{c^2 \sin^2 \theta}{1 - \beta^2} \\ &= \frac{c^2 \cos^2 \theta + v^2 - 2vc \cos \theta + c^2 \sin^2 \theta - v^2 \sin^2 \theta}{(1 - \beta^2)^2} \end{aligned} \quad (6)$$

This reduces to

$$c'^2 = \frac{c^2 + v^2 - 2vc \cos \theta + v^2 \cos^2 \theta - v^2}{(1 - \beta^2)^2} = \frac{(c - v \cos \theta)^2}{(1 - \beta^2)^2} \quad (7)$$

Hence

$$c' = \sqrt{\frac{c^2 (1 - \beta \cos \theta)^2}{(1 - \beta^2)^2}} = \frac{c(1 - \beta \cos \theta)}{1 - \beta^2} \quad (8)$$

The angle  $\theta'$  can be found using

$$\cos \theta' = \frac{u'_x}{c'} = \frac{c \cos \theta - v}{1 - \beta^2} \bigg/ \frac{c(1 - \beta \cos \theta)}{1 - \beta^2} = \frac{\cos \theta - \beta}{1 - \beta \cos \theta} \quad (9)$$

which reduces to

$$\cos \theta' = \frac{\cos \theta - \beta}{1 - \beta \cos \theta} \quad (10)$$

This yields

$$1 + \beta \cos \theta' = 1 + \frac{\beta(\cos \theta - \beta)}{1 - \beta \cos \theta} = \frac{1 - \beta^2}{1 - \beta \cos \theta} \quad (11)$$

from which we get

$$1 - \beta \cos \theta = \frac{1 - \beta^2}{1 + \beta \cos \theta'} \quad (12)$$

Using (12) for  $(1 - \beta \cos \theta)$  in (8) gives the final result

$$c' = \frac{c(1 - \beta \cos \theta)}{1 - \beta^2} = \frac{c}{1 + \beta \cos \theta'} \quad (13)$$

Equation (13) for light speed predicted by the STs is that given by Selleri [18]. It is anisotropic and therefore different from that predicted by the LTs in (4) which is isotropic.

In the two sub-sections to follow, we test these light speed predictions of the LTs and the STs by determining light speed using two aspects of GPS technology. A common objection to any claim of anisotropic one-way light speed is that such measurements are convention-dependent, since the synchronization of distant clocks requires a simultaneity convention. However, the methods presented here employ the very successful GPS, where clock synchronization is achieved operationally through signal timing in the frame of the surface of the Earth or Earth-Centered Earth-Fixed frame, using a clock synchronization algorithm discussed by Ashby [9] that was derived based on the underlying ECI frame and published by the CCIR in 1990. This algorithm produces operationally synchronized clocks in the GPS and is therefore a well-defined and accurate procedure, not an artifact of a chosen convention.

Another issue concerns the fact that special relativity was originally formulated in inertial frames while the surface of the Earth is inherently non-inertial. This situation has not prevented application of the theory in many terrestrial tests such as the Michelson-Morley experiment, the Kennedy-Thorndike experiment and the various versions of these and other experiments that support the theory. In these many cases, no issue is ever raised about the non-inertial nature of the Earth causing the inapplicability of these relativity-supporting experiments. What is unscientific and therefore unacceptable however is that when experimental results don't accord with special relativity, supporters of the theory often claim inapplicability of those cases as tests of special relativity because of the non-inertial nature of the Earth's surface. This is done, despite the fact that no such objections are ever raised in relativity-supporting experiments which have also been performed in the same frame of the Earth's surface.

On this matter, Rindler ([2], p 36) argues that while there are no infinite inertial frames where Special Relativity can be applied, we can identify **local inertial frames** by appropriately restricting the region under consideration such that it is approximately inertial. He states, "It is to these frames (or other frames not differing too much from these frames) that [special relativity] is applied in practice, and with great success." This means that in what follows, the surface of the rotating Earth can be treated as a co-moving approximately inertial frame by confining considerations to suitably restricted regions we refer to as **local inertial frames**.

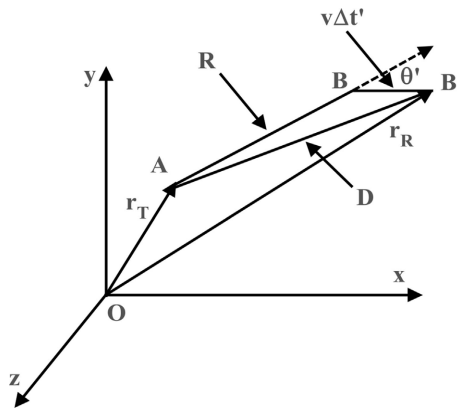
### 2.1. Light Speed Using the GPS Range Equation

GPS signals propagate at the constant speed  $c$  in the ECI frame and this is codified in the GPS range equation given by ([25], p 41)

$$|\mathbf{r}_r(t_r) - \mathbf{r}_s(t_s)| = c(t_r - t_s) \tag{14}$$

Here  $t_s$  is the time of transmission of an electromagnetic signal from a source,  $t_r$  is the time of reception of the electromagnetic signal by a receiver both times (determined using synchronized clocks),  $\mathbf{r}_s(t_s)$  is the position of the source at the time of transmission of the signal and  $\mathbf{r}_r(t_r)$  is the position of the receiver at the time of reception of the signal. In the rotating frame of the Earth, the GPS range Equation (14) has been rigorously confirmed by experiment and is used every day in the successful operation of the GPS. It is therefore an established characteristic of the ECI frame that can be used to determine light travel time and hence one-way light speed on the surface of the Earth.

Consider a light signal transmitted from a point  $A$  on the surface of the Earth at position  $\mathbf{r}_T$  and GPS time  $t_T$  travelling at velocity  $c$  relative to the ECI frame to a receiver at another point  $B$  on the surface of the Earth at position  $\mathbf{r}_R$  and GPS time  $t_R$  and whose velocity because of the rotation of the Earth is  $\mathbf{v}$  relative to the ECI frame at the particular latitude. Let  $\theta'$  be the angle between the direction of propagation of the signal and  $\mathbf{v}$  which can be represented as shown in **Figure 1**. Here  $R$  is the initial distance between the transmitter and the receiver and since the signal arrives at the receiver at time  $t_R$ , then for the signal transmission interval  $\Delta t' = t_R - t_T$  the receiver experiences a displacement  $\mathbf{v}\Delta t'$  to position  $B'$  (**Figure 1**).



**Figure 1.** Light beam propagates from  $A$  to  $B'$  on the Surface of the Earth.

$$\mathbf{D} = \mathbf{R} + \mathbf{v}\Delta t' \tag{15}$$

where  $\mathbf{D} = \mathbf{r}_R(t_R) - \mathbf{r}_T(t_T)$  and using range Equation (14) we get

$$|\mathbf{D}| = c\Delta t' \tag{16}$$

By taking the vector dot product we can write

$$\mathbf{D} \cdot \mathbf{D} = (\mathbf{R} + \mathbf{v}\Delta t') \cdot (\mathbf{R} + \mathbf{v}\Delta t') \quad (17)$$

This gives

$$\Delta t'^2 c^2 = R^2 + 2\mathbf{v} \cdot \mathbf{R}\Delta t' + v^2 \Delta t'^2 \approx R^2 + 2\mathbf{v} \cdot \mathbf{R}\Delta t' = R^2 \left( 1 + \frac{2\mathbf{v} \cdot \mathbf{R}\Delta t'}{R^2} \right), v \ll c \quad (18)$$

Taking the square root gives

$$c\Delta t' = R \left( 1 + \frac{2\mathbf{v} \cdot \mathbf{R}\Delta t'}{R^2} \right)^{1/2} \approx R + \frac{\mathbf{v} \cdot \mathbf{R}\Delta t'}{R} \quad (19)$$

Rearranging we get

$$\Delta t' = \frac{R}{c} \left( 1 - \frac{\mathbf{v} \cdot \mathbf{R}}{cR} \right)^{-1} = \frac{R}{c} + \frac{\mathbf{v} \cdot \mathbf{R}}{c^2} = \frac{R}{c} + \frac{vR \cos \theta'}{c^2} \quad (20)$$

Using the distance  $R$  between the two positions at the time of transmission of the signal, the light speed  $c' = R/\Delta t'$  relative to the surface of the Earth is given by

$$c' = \frac{R}{\Delta t'} = \frac{R}{\frac{R}{c} + \frac{vR \cos \theta'}{c^2}} = \frac{c^2}{c + v \cos \theta'} = \frac{c}{1 + \beta \cos \theta'} \quad (21)$$

This reduces to

$$c' = \frac{c}{1 + \beta \cos \theta'} \quad (22)$$

Equation (22) determined using the GPS range Equation (14) confirms Equation (13) predicted by the STs. It is a generalization of light speed results derived by Gift [13] using the range equation. It is not the light speed  $c' = c$  predicted by the LTs in (4) and required by the principle of light speed constancy. *Note that the region under consideration can be treated as a local inertial frame by restricting the distance  $R$ .*

## 2.2. Light Speed Using the GPS Synchronization Equation

In the frame of the surface of the Earth, a light signal travels a distance  $d\sigma'$  along the Earth's surface in the time  $dt'$  given in differential form by ([9], p 8)

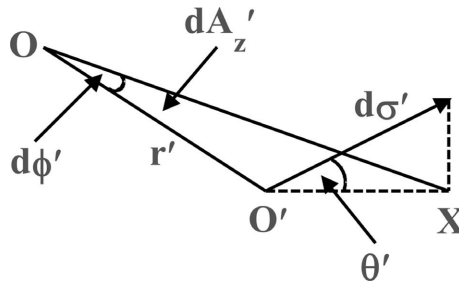
$$dt' = \frac{d\sigma'}{c} + \frac{2\omega_E}{c^2} dA'_z \quad (23)$$

Equation (23) leading to “the total time required for light to traverse some path”, has been confirmed by experiment and is the basis of ground-clock synchronization [9]. It was derived in [1] using the light speed predictions of the two transformations in order to demonstrate a clear difference between the LTs and the STs. Here we use Equation (23) to determine one-way light speed on the surface of the Earth and thereby test the correctness of the light speeds predicted by the LTs and the STs. In Equation (23),  $\omega_E$  is the angular velocity of the Earth and  $dA'_z$  is the infinitesimal area in the rotating frame that is swept out by a line connecting the axis of rotation to the light pulse and projected onto a plane parallel to the equa-

torial plane. Also, the ECI frame corresponds to frame  $\mathcal{S}$  and a local co-moving inertial frame on the surface of the rotating Earth corresponds to frame  $\mathcal{S}'$ . In **Figure 2**,  $O$  is on the axis of the Earth,  $O'$  is on the surface and  $dA'_z$  is parallel to the equatorial plane. By noting that the infinitesimal area  $dA'_z$  is the quantity  $r'^2 d\phi'/2$ , (23) becomes

$$dt' = \frac{d\sigma'}{c} + \frac{\omega_E r'^2 d\phi'}{c^2} \tag{24}$$

Therefore, the light speed  $c'$  in the rotating frame of the Earth is given by



**Figure 2.** Distance  $d\sigma'$  travelled by the light signal.

$$c' = \frac{d\sigma'}{dt'} = \frac{d\sigma'}{\frac{d\sigma'}{c} + \frac{\omega_E r'^2 d\phi'}{c^2}} \tag{25}$$

Let the angle between the direction of the light signal travelling on the surface of the Earth and the line of latitude  $O'X$  at that point be  $\theta'$  as shown in **Figure 2**. Then it follows that

$$r' d\phi' = d\sigma' \cos \theta' \tag{26}$$

Since  $v = \omega_E r'$  is the speed of the earth's surface at the particular latitude, using (26), (25) becomes

$$c' = \frac{d\sigma'}{\frac{d\sigma'}{c} + \frac{v d\sigma' \cos \theta'}{c^2}} \tag{27}$$

This reduces to

$$c' = \frac{c}{1 + \beta \cos \theta'} \tag{28}$$

Thus, the light speed in the Earth's rotating frame determined using the time Equation (23) is one-way light speed  $c' = c/(1 + \beta \cos \theta')$  relative to the surface of the Earth given in (28), as determined in Equation (22) using the GPS range Equation (14) and predicted by the STs in (13). It is not light speed  $c' = c$  predicted by the LTs in (4) and required by the principle of light speed constancy. *Note that since the distance travelled by the light is an infinitesimal length  $d\sigma'$ , the region involved is located within a local inertial frame.*

For eastward light transmission over distance  $l$ , integrating Equation (23)

over a fixed path length  $l$  gives transmission time  $t_E$  as [12]

$$t_E = \frac{l}{c} + \frac{lv}{c^2} \quad (29)$$

where  $v$  is the surface velocity at the particular latitude. For westward light transmission over the same distance, Equation (23) gives time  $t_W$  as [12]

$$t_W = \frac{l}{c} - \frac{lv}{c^2} \quad (30)$$

Equations (29) and (30) yield a time difference  $\Delta t' = t_E - t_W \neq 0$  between two signals travelling east and west over a fixed distance  $l$  as  $\Delta t' = 2lv/c^2$  establishing that **light travels faster west** at speed  $c_W = l/t_W = c + v$ , **than east** at speed  $c_E = l/t_E = c - v$ , **between fixed points on the surface of the Earth**. What this means is that for well over a century, scientists have missed the fact that one-way light speed is anisotropic in the frame of the surface of the Earth.

Thus, for two signals travelling in opposite directions between San Francisco and New York which are at about the same latitude, measurement of this time difference can be conducted using GPS clocks to give a predicted time difference of  $\Delta t' \approx 28$  ns as discussed by Marmet [10]. This means that light travelling from San Francisco to New York takes about 28 ns longer than light travelling from New York to San Francisco. This occurs because as the signal travels eastward at speed  $c$  in the non-rotating ECI frame, the Earth (along with New York) will have rotated to the east, away from the approaching signal resulting in the additional 14 ns compared with propagation on a non-rotating Earth. If the signal goes the other way from New York to San Francisco, the Earth (along with San Francisco) will move toward the arriving signal and thereby cause the light propagation time to be shortened by 14 ns. Ashby [9] and Kelly [11] have discussed the similar case of two light signals that circumnavigate the Earth in opposite directions along the equator for which  $\Delta t' = 414.8$  ns. This light speed anisotropy as detected on the surface of the Earth is **consistent** with the results of the earlier experiment by Saburi *et al.* [14], who reported a transmission time difference with a mean value of 328 ns, between signals propagating in both directions from locations in USA and Japan via a geostationary satellite. In all these cases, the Earth's rotation as light travels at speed  $c$  relative to the ECI frame fully accounts for these east-west light speed differences observed on the surface of the Earth.

### 3. Applications

In this section, having derived and tested light speed predictions for the LTs and the STs, we now apply them to three real-world situations: 1) Time Transfer; 2) the Michelson-Gale Experiment; 3) Relativistic Beaming.

#### 3.1. Time Transfer

Time Transfer is a process where electromagnetic signal transmission through space is used to communicate information about time. The method is based on a

relativistic time transfer algorithm published by the International Telecommunications Union (ITU) that has been rigorously tested and verified [26]. It is part of a standard procedure employed in time comparisons between separated laboratories on the rotating Earth and is widely accepted [27]-[30]. The basic method uses electromagnetic signal transmission from a satellite to a ground receiver which is moving at speed  $v$ , the rotational speed of the Earth at the particular latitude. Here, the moving frame  $S'$  is the rotating surface of the Earth, and the preferred frame  $S$  is the ECI frame.

Thus consider an electromagnetic signal transmitted from a GPS satellite at position  $r_t$  and GPS time  $t_t$  travelling at speed  $c$  relative to the ECI frame to a ground receiver whose position at GPS time  $t_r$  is  $r_r$  and whose velocity because of the rotation of the Earth is  $v$  relative to the ECI frame. Let  $\theta'$  be the angle between the direction of propagation of the signal and  $v$  which can be represented as shown in Figure 3. Here,  $R$  is the initial distance between the satellite and the receiver. If the signal arrives at the receiver at time  $t_r$ , then for the signal transmission interval  $\overline{\Delta t} = t_r - t_t$ , the receiver experiences a displacement  $v\overline{\Delta t}$ . For signal travel at speed  $c$  within the ECI frame from satellite to receiver in time  $\overline{\Delta t}$ , the signal transmission interval  $\overline{\Delta t}$  (excluding gravitational effects) published by the ITU ([26], p 11, Equation (35)) is given by

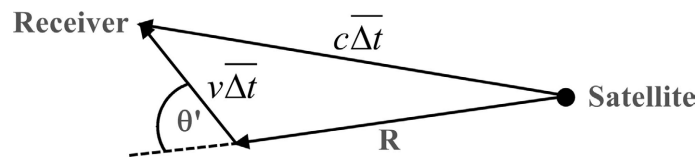


Figure 3. Light propagation from a satellite to earth-based receiver.

$$\overline{\Delta t} = \frac{R}{c} + \frac{v \cdot R}{c^2} \tag{31}$$

where  $R = r_r - r_t$ . The time interval  $\overline{\Delta t}$  in (31) for light travelling from the orbiting satellite to a ground-based receiver has been fully tested and verified and is routinely used in time comparisons. From Figure 3,  $v \cdot R = vR \cos \theta'$  and hence (31) becomes

$$\overline{\Delta t} = \frac{R}{c} + \frac{vR \cos \theta'}{c^2} \tag{32}$$

Because of the short duration of the signal transmission, the ground-based receiver location can be treated as a local inertial frame enabling use of the LTs and the STs to derive (32).

**Derivation Using the LTs**

Using the initial distance  $R$  between the satellite and the receiver and the predicted light speed  $c' = c$ , light transmission time  $\overline{\Delta t}$  is given by

$$\overline{\Delta t} = \frac{R}{c'} = \frac{R}{c} \tag{33}$$

This Equation (33) derived using the light speed  $c' = c$  predicted by the LTs is not the time transfer Equation (31) given by the ITU equation  $\overline{\Delta t} = \frac{R}{c} + \frac{\mathbf{v} \cdot \mathbf{R}}{c^2}$  since the term  $\mathbf{v} \cdot \mathbf{R}/c^2$  is absent. This term must be introduced as a “correction” from outside the formalism of the theory in order to prevent time transfer errors arising in the use of Equation (33) [28]. The light speed prediction  $c' = c$  is therefore unable to derive the ITU time transfer equation.

#### Derivation Using the STs

Using the initial distance  $R$  between the satellite and the receiver and the predicted light speed  $c' = c/(1 + \beta \cos \theta')$ , light transmission time  $\overline{\Delta t}$  is given by

$$\overline{\Delta t} = \frac{R}{c'} = \frac{R}{c/(1 + \beta \cos \theta')} = \frac{R(1 + \beta \cos \theta')}{c} = \frac{R}{c} + \frac{R\beta \cos \theta'}{c} \quad (34)$$

This reduces to

$$\overline{\Delta t} = \frac{R}{c} + \frac{R\beta \cos \theta'}{c} = \frac{R}{c} + \frac{vR \cos \theta'}{c^2} \quad (35)$$

which can be written as

$$\overline{\Delta t} = \frac{R}{c} + \frac{\mathbf{v} \cdot \mathbf{R}}{c^2} \quad (36)$$

This is the time transfer Equation (31). Thus, the light speed  $c' = c/(1 + \beta \cos \theta')$  predicted by the STs produces the ITU time transfer equation, naturally incorporating the term  $\mathbf{v} \cdot \mathbf{R}/c^2$ . It should be noted that while general relativity also accounts for the term  $\mathbf{v} \cdot \mathbf{R}/c^2$  in the time transfer equation, this requires the full machinery of a curved spacetime description in a rotating frame. However, the simpler framework of the STs yields the complete time transfer equation without recourse to external corrections as with the LTs or the more complex formalism of general relativity.

### 3.2. Michelson-Gale Experiment

In this second application, we apply the light speed predictions of the LTs and the STs to the Michelson-Gale experiment shown in **Figure 4** [31]. This experiment involved a large rectangular evacuated ring ABCD fixed to the surface of the Earth with a size that enabled detection of the Earth's rotation. Two light beams from a single source S were sent around the ring in opposite directions and upon return combined in an interferometer I. The longer arms were aligned in the east-west direction along lines of latitude and separated by a distance  $h$ . (A smaller rectangle at one end that produced no significant phase shift provided a reference point for the fringe patterns in the interferometer.) Because of the Earth's rotation, the arm AB of length  $l_2$  at latitude  $\phi_2$  which is nearer the equator moves with speed  $v_2 = v_E \cos \phi_2$  (relative to the ECI frame) which is faster than the speed  $v_1 = v_E \cos \phi_1$  of arm CD of length  $l_1$  at latitude  $\phi_1 = \phi_2 + \delta\phi$  where  $v_E$  is the Earth's surface speed at the equator. This speed and length differences cause a time difference between the time travel of the counter-propagating beams with the beam going in the direction ABCDA taking longer than that going in the di-

rection ADCBA. While the original experiment occupied a large area ( $\sim 0.2 \times 10^6$  m<sup>2</sup>), modern Michelson-Gale systems using ring-laser technology can occupy an area of less than one square meter (0.748 m<sup>2</sup>) [32]. This area is less than that occupied by the 1887 Michelson-Morley experiment ( $\sim 2.25$  m<sup>2</sup>) where application of special relativity is accepted, and hence constitutes a **local inertial frame** where the LTs can be applied. We therefore locate the experiment in such a **local inertial frame** to ensure applicability of the LTs and thereby negate objections that the experiment involves a non-inertial frame such that the LTs cannot be applied.

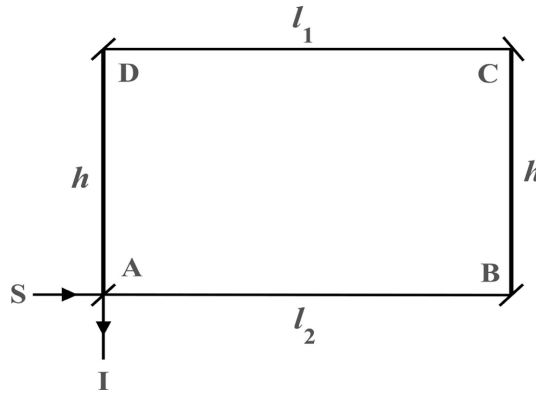


Figure 4. Simplified structure of michelson-gale experiment.

**Analysis Using the LTs**

Using the LTs, with the apparatus located in a local inertial frame, the predicted light speed (4) in all the arms of the system is  $c' = c$ , as it is in the arms of the conceptually similar Michelson-Morley experiment, and therefore there will be zero time difference  $\Delta t' = 0$  between the counter-propagating beams and hence zero fringe shift  $\delta = 0$ . This is inconsistent with the positive fringe shift in the actual experiment [31]. This failure of the LTs perhaps explains why this experiment is rarely if ever found in special relativity textbooks! Choi [16] has recently provided what he refers to as “relativistic analysis” of this experiment using anisotropic light speeds but his analysis does not directly involve the LTs and hence does not alleviate the difficulty presented by this experiment for these transformations. The formalism of general relativity is usually used in the analysis of this experiment.

**Analysis Using the STs**

Using light speed Equation (13) of the STs, the one-way light speeds for light travelling in the west-east and east-west directions are given by

$$c'(0^\circ) = \frac{c}{1 + (v/c)\cos 0^\circ} \approx c - v \quad \text{and} \quad c'(180^\circ) = \frac{c}{1 + (v/c)\cos 180^\circ} \approx c + v \quad \text{respec-}$$

tively. Therefore, the time  $t_1$  for the clockwise beam to traverse the long arms of the ring is given by

$$t_1 = \frac{l_1}{c - v_1} + \frac{l_2}{c + v_2} \tag{37}$$

The time  $t_2$  for the anti-clockwise beam to traverse the long arms of the ring

is given by

$$t_2 = \frac{l_2}{c - v_2} + \frac{l_1}{c + v_1} \quad (38)$$

The STs predict light speed  $c'(90^\circ) = \frac{c}{1 + (v/c)\cos 90^\circ} = c$  for a light signal travelling in a northern direction and  $c'(270^\circ) = \frac{c}{1 + (v/c)\cos 270^\circ} = c$  for a signal travelling a southern direction. As a result, there is no time difference for light signals travelling in the north-south arms of the system. Hence the time difference  $\Delta t' = t_2 - t_1$  is then

$$\Delta t' = \frac{l_2}{c - v_2} + \frac{l_1}{c + v_1} - \frac{l_1}{c - v_1} - \frac{l_2}{c + v_2} = \frac{2(l_2 v_2 - l_1 v_1)}{c^2} \quad (39)$$

Let the eastern ends of the two long arms lie along the same line of longitude and so too the western ends in which case  $l_1 = l \cos \phi_1$  and  $l_2 = l \cos \phi_2$  where  $l$  is a fixed distance at the equator.

Then (39) becomes

$$\Delta t' \approx \frac{2(l_2 v_2 - l_1 v_1)}{c^2} = \frac{2lv_E}{c^2} (\cos^2 \phi_2 - \cos^2 \phi_1) = \frac{2lv_E}{c^2} (\cos^2 \phi_2 - \cos^2 (\phi_2 + \delta\phi)) \quad (40)$$

Using  $\cos(\phi_2 + \delta\phi) = \cos \phi_2 \cos \delta\phi - \sin \phi_2 \sin \delta\phi$  in (40) gives

$$\Delta t' \approx \frac{2lv_E}{c^2} \left( \cos^2 \phi_2 - [\cos \phi_2 \cos \delta\phi - \sin \phi_2 \sin \delta\phi]^2 \right) \quad (41)$$

Noting that since  $\delta\phi$  is very small,  $\sin \delta\phi \approx \delta\phi = h/R$  where  $R$  is the Earth's radius,  $\cos \delta\phi \approx 1$  and  $v_E = R\omega$  where  $\omega$  is the angular velocity of the Earth we have

$$\Delta t' \approx \frac{2lv_E}{c^2} (2 \cos \phi_2 \cos \delta\phi \sin \phi_2 \sin \delta\phi) = \frac{4v_E hl \cos \phi_2}{c^2 R} \sin \phi_2 \quad (42)$$

This reduces to

$$\Delta t' = \frac{4\omega hl_2}{c^2} \sin \phi_2 = \frac{4\omega A}{c^2} \sin \phi \quad (43)$$

where  $A = hl_2$  and  $\phi_2$  is written as  $\phi$ . The corresponding fringe shift  $\delta$  is given by

$$\delta = \Delta t' \frac{c}{\lambda} = \frac{4\omega A}{c\lambda} \sin \phi \quad (44)$$

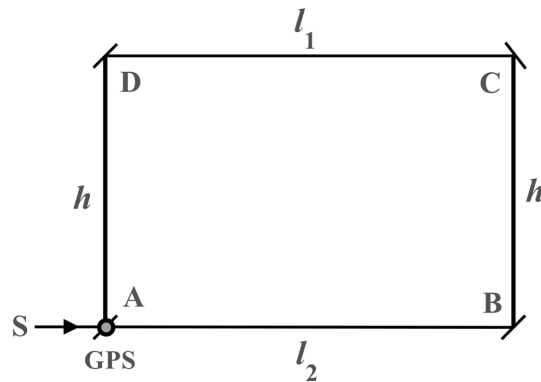
where  $\lambda$  is the wavelength of the light. Michelson and Gale in 1925 [31] confirmed Equation (44) and reported a measured fringe shift of  $\delta = 0.230$ , whereas the LTs yield  $\delta = 0$ .

### Michelson-Gale Experiment Using GPS Clocks

It is possible to use the GPS clocks via Equation (23) to directly determine the time difference in the Michelson-Gale experiment. Let there be a GPS clock at A to measure the time difference between counter-propagating beams. Consider a clockwise beam traveling the path ADCBA. In **Figure 5**, using the GPS clock

synchronization Equation (23), the GPS clocks give the travel time for light traveling north-south along the arms AD and BC in either direction as  $h/c$  where  $h$  is the arm length (since  $A'_z = 0$ ). Again using Equation (23), the time to traverse arm DC is given in Equation (29) as  $t_{DC} = \frac{l_1}{c} + \frac{l_1 v_1}{c^2}$  and the time to traverse arm BA is given in Equation (30) as  $t_{BA} = \frac{l_2}{c} - \frac{l_2 v_2}{c^2}$  where  $v_1$  and  $v_2$  are respective surface speeds. Hence the time  $t_1$  for clockwise light transmission measured by the GPS clock at A is

$$t_1 = \frac{l_1}{c} + \frac{l_1 v_1}{c^2} + \frac{l_2}{c} - \frac{l_2 v_2}{c^2} + 2\frac{h}{c} \tag{45}$$



**Figure 5.** Michelson-Gale experiment using GPS clock technology.

Similarly, the time  $t_2$  for anti-clockwise light transmission measured by the GPS clock at A is

$$t_2 = \frac{l_2}{c} + \frac{l_2 v_2}{c^2} + \frac{l_1}{c} - \frac{l_1 v_1}{c^2} + 2\frac{h}{c} \tag{46}$$

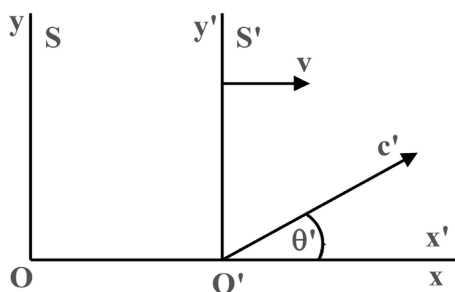
Therefore, the time difference  $\Delta t' = t_2 - t_1$  is given by

$$\Delta t' = t_2 - t_1 = 2\frac{l_2 v_2}{c^2} - 2\frac{l_1 v_1}{c^2} = \frac{2(l_2 v_2 - l_1 v_1)}{c^2} \tag{47}$$

Equation (47) is Equation (39) that leads to  $\Delta t' = \frac{4\omega A}{c^2} \sin \phi$  where  $\phi$  is the latitude of the experiment,  $\omega$  is the angular velocity of the Earth, and  $A$  is the area covered by the arms of the system. This is the time difference between counter-propagating beams in the Michelson-Gale experiment and corresponds to Equation (43) determined using the STs. Here again, a modern version of the Michelson-Gale experiment using GPS clock technology can be conducted in a reduced area similar to that used in the Michelson-Morley experiment corresponding to a local inertial frame. Therefore, no issues regarding the experiment being in a non-inertial frame can be legitimately raised in attempts to argue against the direct applicability of the LTs.

### 3.3. Relativistic Beaming

In this final case, the STs are applied to the phenomenon of relativistic beaming. This is a high-speed phenomenon where a rapidly moving source emits light and the angle of propagation appears reduced when viewed from a stationary frame. This phenomenon is well known in high-energy physics and is normally derived using the LTs [33]. We show here that it can also be derived using the STs, even though their light speed prediction  $c'_s = c/(1 + \beta \cos \theta')$  in (13) is quite different from the light speed prediction  $c'_L = c$  of the LTs in (4). We consider a light source fixed at  $O'$  in frame  $S'$  and therefore moving at a velocity  $v$  relative to frame  $S$ . It emits light rays in frame  $S'$  at an angle  $\theta'$  to the  $x'$  axis, and we must determine the angle  $\theta$  at which a stationary observer in  $S$  would see the ray. Let the velocity of the light ray in frame  $S'$  be  $c'$  as shown in **Figure 6**.



**Figure 6.** Light source at origin  $O'$  in  $S'$  emitting light ray at angle  $\theta'$ .

For the STs, the velocity  $c'$  of the light ray in  $S'$  is not necessarily equal to  $c$ . The components of the light velocity in  $S'$  are  $u'_x = c' \cos \theta'$  and  $u'_y = c' \sin \theta'$ . Using velocity composition [23], the components of the light velocity in  $S$  are given by

$$u_x = u'_x(1 - \beta^2) + v = c' \cos \theta' (1 - \beta^2) + v \quad (48)$$

and

$$u_y = u'_y \sqrt{1 - \beta^2} = c' \sin \theta' \sqrt{1 - \beta^2} \quad (49)$$

Noting that the light velocity in  $S$  is  $c$ , the angle  $\theta$  is easily found to be

$$\cos \theta = \frac{u_x}{c} = \frac{c' \cos \theta' (1 - \beta^2) + v}{c} = \frac{\frac{c}{1 + \beta \cos \theta'} \cos \theta' (1 - \beta^2) + v}{c} \quad (50)$$

This reduces to

$$\cos \theta = \frac{\frac{c}{1 + \beta \cos \theta'} \cos \theta' (1 - \beta^2) + v}{c} = \frac{\cos \theta' (1 - \beta^2)}{1 + \beta \cos \theta'} + \beta \quad (51)$$

giving

$$\cos \theta = \frac{\cos \theta' + \beta}{1 + \beta \cos \theta'} \tag{52}$$

Note also that  $\tan \theta = \frac{u_y}{u_x} = \frac{c' \sin \theta' \sqrt{1 - \beta^2}}{c' \cos \theta' (1 - \beta^2) + v}$  giving

$$\tan \theta = \frac{\sin \theta' \sqrt{1 - \beta^2}}{\cos \theta' + \beta} \tag{53}$$

Equations (52) and (53) derived using the STs, are exactly the equations derived using the LTs for relativistic beaming which have been experimentally confirmed ([33], pp: 155-157).

### 4. Conclusions

In this study, a rigorous theoretical and experimental examination of the one-way speed of light was undertaken, comparing the light speed prediction of the LTs with that of the STs. The result is that the non-invariant light speed

$c' = c/(1 + \beta \cos \theta')$  predicted by the STs, and not  $c' = c$  predicted by the LTs, has been confirmed with empirical data codified in the GPS range equation and the GPS synchronization equation. **It follows therefore that the principle of the constancy of the speed of light, which has been a foundational (but unconfirmed) postulate in special relativity and modern physics for more than a century, is wrong!**

We further confirmed this anisotropic light speed by successfully applying it in the derivation of the ITU time transfer equation without the need for the “Sagnac correction”. We also applied non-invariant light speed in the complete analysis of the Michelson-Gale experiment. This confirmation was strengthened by a novel approach using synchronized GPS clocks to directly measure the time difference in the experiment, yielding a result consistent with both the STs and the 1925 experiment. The LTs predict constant light speed in all arms of the apparatus (configured in a local inertial frame) and therefore give a null result, which is contrary to what is observed. Finally, we showed that the STs account for relativistic beaming, a phenomenon usually derived using the LTs. These results are summarized in **Table 1**.

**Table 1.** Summary of results of key tests.

Test	Prediction of LTs	Prediction of STs	Test Result
One-Way Light Speed	Isotropic: $c' = c$	Anisotropic: $c' = c/(1 + \beta \cos \theta')$	GPS (Equation (22), (28)): $c' = c/(1 + \beta \cos \theta')$
Time Transfer Delay	$\overline{\Delta t} = \frac{R}{c}$	$\overline{\Delta t} = \frac{R}{c} + \frac{\mathbf{v} \cdot \mathbf{R}}{c^2}$	ITU: $\overline{\Delta t} = \frac{R}{c} + \frac{\mathbf{v} \cdot \mathbf{R}}{c^2}$
Michelson-Gale Fringe Shift	$\delta = 0$	$\delta = \frac{4\omega A}{c\lambda} \sin \phi$	M-G: $\delta = \frac{4\omega A}{c\lambda} \sin \phi$
Relativistic Beaming	$\cos \theta = \frac{\cos \theta' + \beta}{1 + \beta \cos \theta'}$	$\cos \theta = \frac{\cos \theta' + \beta}{1 + \beta \cos \theta'}$	$\cos \theta = \frac{\cos \theta' + \beta}{1 + \beta \cos \theta'}$

In order to place the present results in a broader context, **Table 2** summarizes tests of the Lorentz and Selleri transformations discussed in [1], in which the STs are shown to provide consistent results. Here the LTs are unable to resolve the Selleri paradox and the right-angle lever paradox, and the clock-synchronization algorithm derived using the LTs requires the introduction of a “Sagnac correction” which is external to the theory. This clock synchronization result in particular means that clock synchronization in the GPS can be achieved by using the confirmed non-invariant light speed  $c' = c/(1 + \beta \cos \theta')$  predicted by the STs with no “correction”, and not with incorrect constant light speed  $c' = c$  predicted by the LTs, since then serious errors arise as discussed in [9] and [1] requiring correction.

**Table 2.** Summary of results of tests from [1].

Test	LTs	STs
Selleri Paradox	Unresolved	Resolved
Clock Synchronization	Needs “correction”	Correctly predicted
Thomas Precession	Correctly predicted	Correctly predicted
Right-Angle Lever Paradox	Unresolved	Resolved

Therefore, the synchronization time determined by integrating (23) over the light path is simply the time required for light to travel between ground clocks at the **correct** light speed  $c' = c/(1 + \beta \cos \theta')$ . This applies to short distances such as within the confines of a laboratory (local inertial frame) or over large distances such as between San Francisco and New York or around the world. The interpretation by Ashby [9], Saburi *et al.* [14] and Allan *et al.* [15] that the time determined using (23) is that required for light to travel between clocks at constant speed  $c' = c$  with a “correction” added because of the rotating Earth, maintains the incorrect light speed constancy postulate by attributing the time difference to frame rotation. The alternative interpretation presented here attributes it directly to direction-dependent light speed on the surface of the Earth, which the two GPS tests have confirmed is the correct light speed.

The results summarized in these two tables, underpinned by the ground-breaking contributions of Selleri and others [18]-[24], show that the STs reproduce the confirmed successes of the LTs while offering complete accounts in cases where the LTs do not. Indeed, using Selleri’s “equivalent” set of transformations [18], the STs were identified by Selleri using the Sagnac effect [18], counter-propagating beams on a rotating disc [19], and recently by Gift using clock retardation in an inertial frame [1], as the **correct** solution to the central problem of determining the relationship between coordinates in two inertial frames.

Thus, the **Selleri Transformations** offer a mathematically rigorous, internally consistent and physically coherent framework that is applicable to both modern systems such as the GPS and time transfer technology, and classical systems such

as the Michelson-Gale and the Michelson-Morley experiments. Their asymmetrical nature leads to a natural asymmetry in their predictions and hence the absence of the paradoxes that beset special relativity. They are able to address the full range of relativistic phenomena and associated experiments, from time dilation, transverse Doppler and the Sagnac effect, to Thomas precession, relativistic collisions and electrodynamics. In this regard, the reader is referred to a monograph by the author titled “*A Modern Approach to Spacetime Physics*” [34], published on the centenary of the very consequential Michelson-Gale experiment, that contains a comprehensive discussion on the **Selleri Transformations** and their application in all aspects of relativistic physics.

### Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

### References

- [1] Gift, S.J.G. (2025) Light Propagation and Alternative Space-Time Transformations. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **481**, Article ID: 20250470. <https://doi.org/10.1098/rspa.2025.0470>
- [2] Rindler, W. (2006) *Relativity Special, General and Cosmological*. 2nd Edition, Oxford University Press.
- [3] Michelson, A.A. and Morley, E.W. (1887) On the Relative Motion of the Earth and the Luminiferous Ether. *American Journal of Science*, **3**, 333-345. <https://doi.org/10.2475/ajs.s3-34.203.333>
- [4] Müller, H., Herrmann, S., Braxmaier, C., Schiller, S. and Peters, A. (2003) Modern Michelson-Morley Experiment Using Cryogenic Optical Resonators. *Physical Review Letters*, **91**, Article ID: 020401. <https://doi.org/10.1103/physrevlett.91.020401>
- [5] Herrmann, S., Senger, A., Kovalchuk, E., Müller, H. and Peters, A. (2005) Test of the Isotropy of the Speed of Light Using a Continuously Rotating Optical Resonator. *Physical Review Letters*, **95**, Article ID: 150401. <https://doi.org/10.1103/physrevlett.95.150401>
- [6] Eisele, C., Nevsky, A.Y. and Schiller, S. (2009) Laboratory Test of the Isotropy of Light Propagation at the  $10^{-17}$  Level. *Physical Review Letters*, **103**, Article ID: 090401. <https://doi.org/10.1103/physrevlett.103.090401>
- [7] Nagel, M., Parker, S.R., Kovalchuk, E.V., Stanwix, P.L., Hartnett, J.G., Ivanov, E.N., et al. (2015) Direct Terrestrial Test of Lorentz Symmetry in Electrodynamics to  $10^{-18}$ . *Nature Communications*, **6**, Article No. 8174. <https://doi.org/10.1038/ncomms9174>
- [8] Zhang, Y.Z. (1997) *Special Relativity and Its Experimental Foundations*. World Scientific.
- [9] Ashby, N. (2003) Relativity in the Global Positioning System. *Living Reviews in Relativity*, **6**, Article No. 1. <https://doi.org/10.12942/lrr-2003-1>
- [10] Marmet, P. (2000) The GPS and the Constant Velocity of Light. *Acta Scientiarum*, **22**, 1269-1279.
- [11] Kelly, A. (2005) *Challenging Modern Physics*. BrownWalker Press.
- [12] Gift, S.J.G. (2010) One-Way Light Speed Measurement Using the Synchronized Clocks of the Global Positioning System (GPS). *Physics Essays*, **23**, 271-275.

- <https://doi.org/10.4006/1.3361840>
- [13] Gift, S.J.G. (2012) A Simple Demonstration of One-Way Light Speed Anisotropy Using Global Positioning System (GPS) Technology. *Physics Essays*, **25**, 387-389. <https://doi.org/10.4006/0836-1398-25.3.387>
- [14] Saburi, Y., Yamamoto, M. and Harada, K. (1976) High-Precision Time Comparison via Satellite and Observed Discrepancy of Synchronization. *IEEE Transactions on Instrumentation and Measurement*, **25**, 473-477. <https://doi.org/10.1109/tim.1976.6312267>
- [15] Allan, D.W., Weiss, M.A. and Ashby, N. (1985) Around-the-World Relativistic Sagnac Experiment. *Science*, **228**, 69-70. <https://doi.org/10.1126/science.228.4695.69>
- [16] Choi, Y. (2024) Relativistic Analysis of the Michelson-Gale Experimental Result. *Scientific Reports*, **14**, Article No. 9956. <https://doi.org/10.1038/s41598-024-60515-7>
- [17] Selleri, F. (1995) Space, Time, and Their Transformations. *Chinese Journal of Systems Engineering & Electronics*, **6**, 25-44.
- [18] Selleri, F. (1996) Noninvariant One-Way Velocity of Light. *Foundations of Physics*, **26**, 641-664. <https://doi.org/10.1007/bf02058237>
- [19] Selleri, F. (1997) Noninvariant One-Way Speed of Light and Locally Equivalent Reference Frames. *Foundations of Physics Letters*, **10**, 73-83. <https://doi.org/10.1007/bf02764121>
- [20] Puccini, G.D. and Selleri, F. (2002) Doppler Effect and Aberration of Light from the Point of View of Absolute Motion. *Il Nuovo Cimento*, **117**, 283-293.
- [21] Selleri, F. (2004) Sagnac Effect: End of the Mystery. In: Rizzi, G. and Ruggiero, M.L., Eds., *Relativity in Rotating Frames*, Springer, 57-77. [https://doi.org/10.1007/978-94-017-0528-8\\_6](https://doi.org/10.1007/978-94-017-0528-8_6)
- [22] Selleri, F. (1996) Noninvariant One-Way Velocity of Light and Particle Collisions. *Foundations of Physics Letters*, **9**, 43-60. <https://doi.org/10.1007/bf02186208>
- [23] Buonaura, B. (2004) Maxwell Equations and Inertial Transformations. *Foundations of Physics Letters*, **17**, 627-644. <https://doi.org/10.1007/s10702-004-1118-8>
- [24] Selleri, F. (2006) Superluminal Signals and the Resolution of the Causal Paradox. *Foundations of Physics*, **36**, 443-463. <https://doi.org/10.1007/s10701-005-9028-6>
- [25] Ashby, N. (2002) Relativity and the Global Positioning System. *Physics Today*, **55**, 41-47. <https://doi.org/10.1063/1.1485583>
- [26] International Telecommunication Union (2012) Relativistic Time Transfer in the Vicinity of the Earth and in the Solar System, Recommendation ITU-R TF.2018.
- [27] Nelson, R.A. (2011) Relativistic Time Transfer in the Vicinity of the Earth and in the Solar System. *Metrologia*, **48**, S171-S180. <https://doi.org/10.1088/0026-1394/48/4/s07>
- [28] Ashby, N. (2004) The Sagnac Effect in the Global Positioning System. In: Rizzi, G. and Ruggiero, M.L., Eds., *Relativity in Rotating Frames*, Kluwer Academic Publishers, 11-28.
- [29] Petit, G. and Wolf, P. (2005) Relativistic Theory for Time Comparisons: A Review. *Metrologia*, **42**, S138-S144. <https://doi.org/10.1088/0026-1394/42/3/s14>
- [30] Blanchet, L., Salomon, C., Teyssandier, P. and Wolf, P. (2001) Relativistic Theory for Time and Frequency Transfer to Order  $c^{-3}$ . *Astronomy & Astrophysics*, **370**, 320-329. <https://doi.org/10.1051/0004-6361:20010233>
- [31] Michelson, A.A. and Gale, H.G. (1925) The Effect of the Earth's Rotation on the Velocity of Light, II. *The Astrophysical Journal*, **61**, 140-145. <https://doi.org/10.1086/142879>

- [32] Bilger, H.R., Stedman, G.E., Poulton, M.P., Rowe, C.H., Li, Z. and Wells, P.V. (1993) Ring Laser for Precision Measurement of Nonreciprocal Phenomena. *IEEE Transactions on Instrumentation and Measurement*, **42**, 407-411. <https://doi.org/10.1109/19.278592>
- [33] Christodoulides, C. (2016) *The Special Theory of Relativity*. Springer.
- [34] Gift, S.J.G. (2025) *A Modern Approach to Spacetime Physics*. Nova Science Publishers, Inc. <https://doi.org/10.52305/atlx2621>