Chapter 5

On the Anisotropy of the Speed of Light on a Rotating Platform

5.1 Introduction

The term "inertial frame of reference" in physics refers to an idealised concept. Our knowledge of physics in inertial frames has always been obtained in frames having small but non-zero acceleration. Indeed it is well-known that no perfectly inertial frame can be identified in practice. It is therefore expected that physics in non-inertial frames will go over smoothly to that in inertial frames in the mathematical limit of zero acceleration. In some recent papers [1, 2] Selleri observes that the existing relativity theory fails our expectations on that count. In this connection Selleri poses a paradox concerning the speed of light as measured by an observer on board a rotating turn-table. If two light beams from a common source are sent along the rim of a rotating disc in opposite directions and the round-trip speeds (c_+ for counter-rotating and c_- for co-rotating beams) for these two light beams are measured, it will be found from simple kinematics, that the ratio of these speeds $\rho = c_+/c_-$ is only a function of the linear speed v of disc at its edge and it differs from unity if $v \neq 0$. This observation finds its support in the well known Sagnac effect [3, 4] which is manifested in the experimentally observed asymmetry in the round-trip times of light signals co-rotating and counter-rotating with the interferometer.However, since the rotating turn-table is not an inertial frame, one might initially not be inclined to consider the observed anisotropy of light propagation with respect to this frame a startling result as such. But Selleri then considers a situation where one gradually increases the radius of the disc and at the same time allows the angular velocity ω of the same to get decreased proportionately in such a way that the linear speed $v = \omega R$ of the periphery remains constant. The edge of the disc can then be thought of approaching (locally) an inertial frame since, in the limit the centripetal acceleration $a = v^2/R$, tends to zero. [1] In an inertial frame ρ must strictly be unity since, light propagation is considered to be isotropic in such a frame according to the special relativity (SR). However Selleri shows that the ratio ρ on board the rotating disc does not change in the limit process provided v remains constant and therefore will continue to differ from unity as long as v is finite. A discontinuity in the behaviour of ρ as a function of acceleration is thus predicted. This is certainly paradoxical in the light of the observations made in the beginning of this section. We hereafter refer to it as the Selleri paradox (SP). SP has so far met with evolving but inadequate responses. For example in one paper Rizzi and Tartaglia [6] observe that the "calculations of Selleri are quite careful" and the "paradox cannot be avoided if it is maintained that the round-trip on the turn-table corresponds to a well defined circumference whose length is univocally defined". It appears that the authors of Ref. [6] cannot accept the global anisotropy of light speed in the frame of reference of the rotating disc and hold that because of the "impossibility of a symmetrical and transitive synchronization at large", the notion of whole physical space on the platform at a given instant is conventional. Their final conclusion is that the counter-rotating and co-rotating light beams travel different distances with respect to the *frame of the disc* in such a way that the *global* ratio ρ remains unity. The view point towards the resolution of SP also finds its endorsement in a later paper by Tartaglia [7]; although in a subsequent

[1] There is a scope for confusion here. Although an element of the disc will have zero acceleration in the limit considered, an observer on the turn table would be able to detect its rotation since the latter is an absolute concept. In an article Klauber [5] even claimed that there would be, for example a change of mass of a particle on the disc due to a general relativistic effect which can be seen to depend only on the circumferential velocity and not on the acceleration. This effect would even enable one to determine in principle the rotational motion of the platform from local measurements alone!

paper Rizzi and Tartaglia [8] somewhat retract from the past position and allow an observer at rest on the disc to consider a notion of its unique circumference in the "relative space of the disc" and hence endorse the view that light propagation can be anisotropic in the reference frame of the rotating turn-table. In conjunction with Budden's observation [9] the authors then correctly identify the root of the paradox and hold that the basic weak point of Selleri's arguments lies in equating the global ratio ρ of the speeds of light propagating in opposite directions along the rim with the local ratio ρ' of the same at any point on the edge of the disc. The latter ratio is always equal to unity if Einstein synchrony is used in any local inertial frame instantaneously comoving with the element of the rim at the point concerned (such frames will hereafter be referred to as momentarily comoving inertial frames (MCIF))and therefore SP does not pose any harm to SR.

However, Selleri's argument regarding the equality of two ratios ρ and ρ' is based on a symmetry argument (rotational invariance) but the authors of Ref. [8] do not clearly state what is precisely wrong with Selleri's symmetry reasoning. Further the arguments by the authors although correct, are blurred by their ambivalent observations (in the same paper) that the global ratio ρ itself comes out to be unity (a) if the time measuring clock is suitably corrected to "account for the desynchronization effect" or (b)if the space is suitably defined according to "geometry of Minkowskian spacetime". Note that (b) is the reiteration of their earlier stand in this regard [6, 7].

In Refs. [1, 2] Selleri raises another matter in connection with SP. In light of conventionality of (distant) simultaneity (CS) thesis of SR, the author discusses the conventionality issue on a rotating turn-table and argues that not the Lorentz transformation (LT) but the relativistic transformation with absolute synchrony (which is one of the many possible synchronization conventions for which light propagation is anisotropic) only correspond to the correct expression for ρ (see Eq. (5.2.16) later). In a recent paper Minguzzi [10], whose view we share, briefly addresses the issue. The author agrees that isotropic convention (standard synchrony) can be unsuitable in certain situations but maintains that the possibility of anisotropic conventions does not imply any inconsistency of SR. However SP has not been discussed therein in its entirety.

To sum up it may be said that the responses to SP so far available in the literature are not fully satisfactory. We therefore hold that the paradox which poses a challenge to the very foundations of SR by questioning its self consistency, deserves to be given a fuller treatment. Indeed there are many subtle issues concerning SP. For example it will be seen in Sec. 5.3 that the paradox not only undermines the standard relativity theory but also denies the basic tenet of the CS thesis. The purpose of the present paper is to re-examine Selleri's arguments in the light of the CS thesis and provide a resolution of SP in a novel way by recasting the paradox in the classical world (see Sec. 5.4). It will however be argued that while both the self-consistency of SR and the CS thesis remain unchallenged, SP has a merit in that if properly interpreted in the light of reasonings presented in this paper, the whole issue will throw new light on various related issues like the question of time on rotating platform, desynchronization and its debated role in the explanation of Sagnac effect [11, 12].

We organize the paper as follows. Before we present our main arguments in Sec. 5.4 and onwards, the CS thesis will be discussed (in Sec. 5.3) in the context of the paradox. However in order to set the stage we will briefly reproduce in Sec. 5.2 the arguments of Selleri leading to SP. In Sec. 5.5 the issue of desynchronization vis-a-vis the Sagnac effect will be addressed and finally in Sec. 5.6 the standard synchrony and absolute synchrony will be compared upholding Selleri's point of view in this regard [13, 14].

5.2 The Paradox

Suppose a light source is placed at some fixed position Σ on the rim of the turn-table and two light signals start from Σ at the laboratory time t_{01}, and are constrained (by allowing them for example, to graze a suitably placed cylindrical mirror on the rim) to travel in opposite directions in a circular path along the periphery of the disc. Let that, after making the round trips, the counter-rotating and co-rotating light flashes reach Σ at times t_{02} and t_{03} respectively.

As seen from the laboratory, the counter-rotating light signal travels a distance shorter than the circumference L_0 by the amount

$$x = v(t_{02} - t_{01}), \tag{5.2.1}$$

where $v = \omega R$ is the linear speed of the disc at its periphery. Similarly the co-rotating light beam has to travel a distance larger than L_0 by the amount

$$y = v(t_{03} - t_{01}). \tag{5.2.2}$$

From simple kinematics it therefore follows that

$$L_0 - x = c(t_{02} - t_{01}) \tag{5.2.3}$$

$$L_0 + y = c(t_{03} - t_{01}), \tag{5.2.4}$$

where L_0 is the disc's circumference as seen from the laboratory. From equations (5.2.3) and (5.2.4) and using equations (5.2.1) and (5.2.2) one readily obtains the round-trip times for counter-rotating and co-rotating signals respectively as

$$t_{02} - t_{01} = \frac{L_0}{c(1+\beta)} \tag{5.2.5}$$

and

$$t_{03} - t_{01} = \frac{L_0}{c(1-\beta)}. \tag{5.2.6}$$

By taking the difference of these times, one may note here that the delay between the arrival of the two light signals at the point Σ is obtained as

$$\Delta t_s = t_{03} - t_{02} = \frac{2L_0\beta}{c}\gamma^2, \tag{5.2.7}$$

where $\gamma = (1-\beta^2)^{-1/2}$, $\beta = v/c$. As an aside remark, it may be noted that (5.2.7) is nothing but the well-known delay time of classical Sagnac Effect. The relativistic formula for Sagnac delay can easily be obtained by noting that Δt_s in Eq. (5.2.7) is not the time as measured on board the platform and hence time dilation effect has to be considered. By multiplying both sides by $\gamma^{-1} = (1-\beta^2)^{-\frac{1}{2}}$ one obtains the relativistic formula for Sagnac delay as

$$\Delta\tau_s = \frac{2L_0\beta}{c}\gamma, \tag{5.2.8}$$

where $\Delta\tau_s = \gamma^{-1}\Delta t_s$ denotes the delay time as measured on board the turntable.[2].

Suppose now that a clock C_Σ is placed on the disc's rim at Σ so that it co-rotates with the platform and also let t denotes the time of C_Σ. When the disc is in motion, according to Selleri, the laboratory time t_0 and t may be assumed to be related, most generally as

$$t_0 = tF_1(v, a). \tag{5.2.9}$$

Similarly for the circumference also Selleri assumes a relation between L_0 and the proper circumference L as

$$L_0 = LF_2(v, a), \tag{5.2.10}$$

[2]The controversial issue of the appearance of the relativistic γ-factor in the Sagnac formula has been discussed in detail vis-a-vis the Ehrenfest paradox in Chap. 3. However Eq. (5.2.8) is the most widely quoted one. See also Ref. [15, 16]

where F_1 and F_2 are some functions of the linear velocity $v = \omega R$ and the acceleration $a = v^2/R$ of the edge of the disc.

Although, from the widely accepted hypothesis of locality [6, 11] it is evident that these functions are nothing but the usual time dilation and length contraction factors

$$F_1 = F_2^{-1} = \gamma, \tag{5.2.11}$$

however, Selleri keeps open the possibility that F_1 and F_2 may depend on the acceleration as well.

Inserting equations (5.2.9) and (5.2.10) in equation (5.2.5) and (5.2.6) one gets the following times of flight of the counter-rotating and co-rotating light signals as measured on board the disc,

$$t_2 - t_1 = \frac{L}{c(1+\beta)} \frac{F_2}{F_1}, \tag{5.2.12}$$

$$t_3 - t_1 = \frac{L}{c(1-\beta)} \frac{F_2}{F_1}. \tag{5.2.13}$$

The round-trip speeds for these beams are therefore given by

$$c_+ = \frac{L}{t_2 - t_1} = c(1+\beta)\frac{F_1}{F_2}, \tag{5.2.14}$$

$$c_- = \frac{L}{t_3 - t_1} = c(1-\beta)\frac{F_1}{F_2}. \tag{5.2.15}$$

Consequently the ratio of these light speeds turn out to be

$$\rho = \frac{c_+}{c_-} = \frac{1+\beta}{1-\beta}. \tag{5.2.16}$$

Selleri now argues that since no point on the rim is preferred, the instantaneous velocities of either signals at any point of the rim must be the same, and therefore, the above ratio ρ is true not only for the global light velocities but also for the instantaneous velocities at any point on the rim. Now, as pointed out in section 1, if we consider that $R \to \infty$ and $\omega \to 0$ in such a way that v, the linear speed of any element of the circumference remains constant, so that the centripetal acceleration $a \to 0$, any short part of the circumference can be thought of as an inertial frame of reference in the limit. However, the ratio ρ does not change as long as v is kept constant. Hence, a discontinuity results in the behaviour of ρ as a function of acceleration ($\rho = \rho(a)$), since as $a \to 0$, but not equal to zero, ρ continues to differ from unity, but if $a = 0$, SR predicts that ρ must be equal to unity! In Fig. 5.1, the ratio ρ is plotted as a function of acceleration for rotating platforms of constant peripheral velocity and decreasing radius. The black dot ($\rho = 1$) represents the prediction of the SR and this is discontinuous with the values of ρ of the rotating platforms [17].

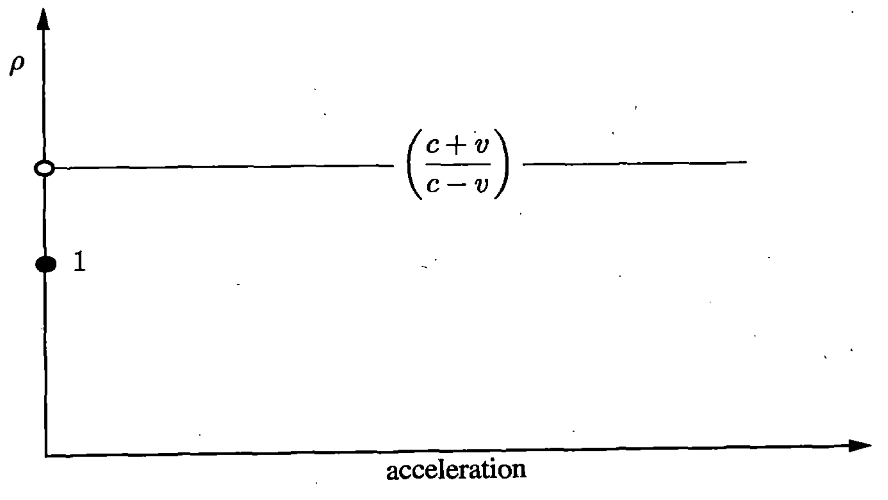

Figure 5.1: The ratio ρ versus acceleration of rotating platform

It may be argued that the above gedanken experiment with infinitely sized disc is impossible to perform since the times of flight of the co-rotating and counter-rotating light beams whose ratio we are currently interested in, would become infinite and therefore unmeasurable [18]. However it is enough to note that if the radius of the disc is increased arbitrarily from a finite value and at the same time v is kept constant by suitably adjusting the angular velocity no tendency for the ratio ρ getting diminished would be seen although the acceleration of a point on the circumference gets reduced arbitrarily in the process.

It is worthwhile to mention in this context that recently Wang et-al [19] has obtained a travel time difference $\Delta t = \frac{2vL}{c^2}$ between two counter-propagating light beams (indicating $\rho \neq 1$) in a uniformly moving fibre where v is the speed of the light source or the detector (comoving with the fibre) with respect to the laboratory and L in the length of the fibre (see Sec. 2.8.2). The experiment has been performed using a fibre optic conveyer(FOC) where two light beams leaving a source travels in opposite directions through an optical fibre loop which is made to move with uniform speed like a conveyer belt by a couple of rotating wheels separated by a distance. The interesting feature of the FOC arrangement is that here the observer (*i.e.* the source or the detector) is attached to one of the straight-fibre segments and therefore moves with *uniform velocity* along a straight line. Experimental observation together with a symmetry argument (similar to that used by Selleri in the rotating disc context) may lead one to infer that the statement $\rho \neq 1$ is also valid *locally* in a segment of uniformly moving fibre indicating *local* anisotropy in the speed of light in vacuum[3] with respect to an inertial observer! Such an outcome which apparently follows from a symmetry argument is also paradoxical if one believes in SR. Although the purported scope of the present paper restricts us to deliberating on SP in its original form and consequent issues following a few responses it has received, the arguments that will be used in the following sections will equally apply to the paradox in the FOC context as well.

[3]As suggested by Wang et-al, here we have assumed that experiment using FOC with a hollow core would give the same result. Indeed the result $\rho = \frac{1+\beta}{1-\beta}$ remains valid in this case since the simple minded analysis presented in this section leading to the equation also applies to this situation

Indeed all Selleri wanted to achieve was to obtain an inertial observer with respect to whom $\rho = \dfrac{1+\beta}{1-\beta}$. In the FOC arrangement this comes naturally dispensing with the trick of letting the radius of the disc go to infinity and the angular speed to zero while the peripheral velocity is kept constant.

Before we leave this section, we write explicitly the expressions for c_+ and c_- in the full relativistic context:

$$c_+ = \frac{c}{1-\beta}, \tag{5.2.17}$$

$$c_- = \frac{c}{1+\beta}, \tag{5.2.18}$$

which follow from Eqs. (5.2.14) and (5.2.15) where the expressions for F_1 and F_2 as given in Eq. (5.2.11) have been substituted. Here we may point out that the genesis of SP relates to these equations since in the limit of infinite radius and zero angular velocity, the above results do not change indicating (as if) the violation of second relativity postulate (isotropy and constancy of light speed). As we have mentioned earlier, the above results although correct, are so counter-intuitive that the authors of Refs. [6, 7] in their initial reactions discarded the results altogether only to retract from their position later in a sort of a rejoinder [8].

5.3 CS Thesis and Absolute Synchrony

In the relativity theory distant simultaneity is conventional. In order to synchronize spatially separated clocks in a given inertial frame one should know the one-way speed (OWS) of the synchronizing signal, however to know OWS one needs pre-synchronized clocks. One therefore is caught in a logical circularity. In order to break the circularity one has to *assume*, as a convention, a value for the OWS of the light signal within certain bounds. The CS thesis, first discussed by Reichenbach and Grünbaum [20, 21],[4] is the assertion that the procedure for distant clock synchrony is conventional. Einstein therefore assumes as a convention that the OWS of light is isotropic and is equal to the two-way speed (TWS) c of the signal. Note that the latter is an empirically verifiable quantity since it does not depend on the convention regarding the synchronization of spatially separated clocks since the TWS can be measured by a single clock. The synchrony is commonly known as the Einstein synchrony or the standard synchrony. However since the clock synchronization procedure is conventional, conventions other than the standard one may equally be chosen [23–26]. Selleri [1, 2] has shown that the space-time transformation between a preferred inertial frame S_0 (where clocks are standard-synchronized so that OWS is isotropic in the frame) and any other frame S may generally be written as

$$\begin{aligned} x &= \gamma(x_0 - \beta c t_0) \\ y &= y_0 \\ t &= \gamma^{-1} t_0 + \epsilon(x_0 - \beta c t_0) \end{aligned} \tag{5.3.1}$$

which represents a set of theories *equivalent* to SR. The free parameter ϵ which can at most be a function of the relative velocity of S with respect to S_0, depends on the simultaneity criterion adopted in S. For the standard synchrony however,

$$\epsilon = -\frac{\beta\gamma}{c}. \tag{5.3.2}$$

For this value of ϵ equation (5.3.1) reduce to Lorentz transformation. The OWS' of light in S, c'_+ and c'_- along the negative and positive x-directions respectively may easily be obtained from the transformation (5.3.1) as

$$\frac{1}{c'_+} = \frac{1}{c} - \left[\frac{\beta}{c} + \epsilon\gamma^{-1}\right] \tag{5.3.3}$$

[4]For a comprehensive review of the thesis see a recent paper by Anderson, Vetharaniam and Stedman [22].

and

$$\frac{1}{c'_-} = \frac{1}{c} + \left[\frac{\beta}{c} + \epsilon\gamma^{-1}\right] \tag{5.3.4}$$

If S_0 is assumed to be the inertial frame of reference at rest with the axis of the rotating disc and S be an MCIF, c'_+ and c'_- would then mean the local speeds of light counter-rotating and co-rotating with the disc respectively as measured on board the rotating platform. From Eqs. (5.3.3) and (5.3.4) one may thus obtain the ratio for these local speeds of light ρ' in terms of the ϵ-parameter

$$\rho' = \frac{c'_+}{c'_-} = \frac{1+\beta+\epsilon c\gamma^{-1}}{1-\beta-\epsilon c\gamma^{-1}}, \tag{5.3.5}$$

which agrees with the ratio ρ given by Eq. (5.2.16) provided $\epsilon = 0$. But as mentioned in the last section, the equality of ρ and ρ' according to Selleri as if follows from the symmetry of the situation. Therefore, in the rotating disc context, $\epsilon = 0$ appears to be the only allowed convention according to which the speed of light is anisotropic. Note that for this value of ϵ only the local speeds of light as given by Eqs. (5.3.3) and (5.3.4) reduce to the expressions (5.2.17) and (5.2.18). The transformation (5.3.1) with $\epsilon = 0$ is known as the Tangherlini transformation(TT) [27]

$$\begin{aligned} x &= \gamma\left(x_0 - \beta c t_0\right), \\ y &= y_0, \\ t &= \gamma^{-1} t_0. \end{aligned} \tag{5.3.6}$$

The transformation represents the relativistic world with absolute synchrony [24, 25].[5]

We now have a ramification of the original paradox. The value of ρ (and hence ρ') represented by equation (5.2.16), which implies anisotropic propagation of light in the rotating frame, is obtained theoretically from the perspective of the

[5]Notice that in view of the absence of the spatial coordinate x in the above transformation for time, the simultaneity is independent of the frame of reference considered and is therefore absolute.

inertial frame S_0. The result also finds its empirical support in the Sagnac effect. It therefore appears that as if a particular (non-standard) synchrony is dictated both by theory and experiment. This is absurd since, if it were true it not only would reject the Lorentz transformation but also would contradict the basic tenet of the CS thesis that clock synchronization is conventional.

Before offering a resolution of the SP we ask ourselves if such a paradox could exist in the classical (Galilean) world too. The initial reaction would be to answer in the negative since nothing seems to be mysterious or enigmatic in this world and as is well-known, counter intuitive problems by contrast exist in the relativity theory probably because of its new philosophical imports. However we answer the question in the affirmative. One of the so-called new philosophical imports of SR is the notion of relativity of simultaneity. It can be shown that this notion can also be introduced in the Galilean world. Indeed in the next section it will be shown that by doing so the paradox can be artificially created even in this world where normally one would not expect it to exist.[6] The perspective of the paradox will hopefully provide deeper understanding of the problem and other related issues.

5.4 Selleri Paradox in the Galilean World

Let us consider a fiction that we live in the Galilean (classical) world and suppose light travels through ether stationary with respect to an inertial frame S_0. The space-time coordinates of an arbitrary inertial frame S moves with respect to S_0 are related to those in S_0 by the so-called Galilean transformation (GT):

$$x = x_0 - \beta t_0, \qquad y = y_0, \qquad t = t_0. \tag{5.4.1}$$

[6] Such an approach has been found fruitful elsewhere in understanding a recent paradox in relativity [28]. For a detail account see Chap. 4

In the Galilean world synchronization issue usually does not figure in, since in principle all the clocks in any given inertial frame can be synchronized by sending signals with arbitrarily large velocities. Note that there is no speed limit in this world. However the ingredients of the CS thesis can also be incorporated in this world. For example, one may employ the Einstein synchrony to describe the kinematics in this world. Suppose one sends out a light signal from the origin of S outwards along a line which makes an angle θ with the x-axis and the signal comes back to the origin along the same line after being reflected by a suitably placed mirror, the TWS can be obtained by measuring the time of flight of the round-trip by a clock placed at the origin. The expression for this TWS can be obtained from Eq. (5.4.1) and is given by [25]

$$\overleftrightarrow{c}(\theta) = \frac{c(1-\beta^2)}{(1-\beta\sin^2\theta)^{1/2}}. \tag{5.4.2}$$

Now in a somewhat playful spirit one may choose to synchronize arbitrarily located clocks with one placed at the origin by sending light by *stipulating* the OWS of light to be equal to the TWS (in fact none can prevent one in doing so), the relevant transformation that would honour such a stipulation would be given by

$$\begin{aligned} x &= x_0 - \beta c t_0 \\ t &= \gamma^2\left(t_0 - \tfrac{\beta x_0}{c}\right) \end{aligned} \tag{5.4.3}$$

which was originally obtained by E. Zahar in 1977 [29] and is now commonly known as the Zahar transformation(ZT). For a quick check one may readily verify that the TWS of light along the x-axis and y-axis in S,that follow from Eq. (5.4.3) are given by the well-known classical results, $c(1-\beta^2)$ and $c(1-\beta^2)^{1/2}$, respectively [23, 30].

In the context of the rotating disc, x and t denote the coordinate and time of an event in an MCIF at any point on the edge of the disc, while x_0 and t_0 refer to the same in the inertial frame S_0 which is stationary with the axis of rotation. Let us now write the inverse of ZT (Eq. (5.4.3)) for time in the differential form as

$$dt_0 = dt \pm \frac{\gamma^2 \beta \, dx}{c} \tag{5.4.4}$$

where dx refer to the length of the infinitesimal element of the disc which is covered by the light signal in time dt when the signal is co-rotating (+ sign) or counter-rotating (− sign) with the disc. Note that the phase term (space dependent term) in (5.4.4) was absent in the GT. Clearly the term is an artefact of the Einstein synchrony. For the complete revolution for the counter-rotating light signal, the round-trip time in the laboratory is thus obtained by integrating (5.4.4) as

$$\Delta t_{0+} = \oint dt - \oint \frac{\gamma^2 \beta}{c} \, dx$$

or,

$$\Delta t_{0+} = \oint dt - \frac{\gamma^2 \beta L_0}{c}, \tag{5.4.5}$$

and similarly for the co-rotating signal

$$\Delta t_{0-} = \oint dt + \frac{\gamma^2 \beta L_0}{c}. \tag{5.4.6}$$

Notice that $\oint dt$ in Eqs. (5.4.5) and (5.4.6) are the same because of the adopted synchrony which is given by

$$\oint dt = \frac{L_0}{c(1-\beta^2)}, \tag{5.4.7}$$

since (from Eq. (5.4.2)), for $\theta = 0$,

$$\overset{\leftrightarrow}{c}(0) = c(1-\beta^2) \tag{5.4.8}$$

which has been assumed to be the same as the OWS following the synchrony. That the Zahar transformation and hence Eqs. (5.4.5) and (5.4.6) are consistent with the classical world can be checked by calculating $c_{\pm}$ $(= L_0/\Delta t_{0\pm})$ from Eqs. (5.4.5) and (5.4.6) and by making use of Eq. (5.4.7). They are obtained as

$$c_{\pm} = c(1 \pm \beta) \tag{5.4.9}$$

which could have been obtained from elementary kinematics using GT. This agreement is expected since the global round-trip speeds are observables independent of the synchrony gauge. Further by taking the difference of Eqs. (5.4.5) and (5.4.6), by virtue of the cancellation of the $\oint dt$ terms one obtains the usual classical expression for the Sagnac delay quoted earlier

$$\Delta t_s = \frac{2L_0\beta}{c}\gamma^2. \tag{5.4.10}$$

From Eq. (5.4.9) it is evident that in the classical world too

$$\rho_{\text{classical}} = \frac{c_+}{c_-} = \frac{1+\beta}{1-\beta}. \tag{5.4.11}$$

Clearly we are confronted with the same apparent paradox that the ratio of the round-trip speeds of the two counter-propagating light signals differ from unity ($\rho \neq 1$) although locally the one-way speeds of light in opposite directions have been assumed to be the same ($\rho' = 1$). (This is manifested in the cancellation of $\oint dt$ terms while taking the difference of (5.4.5) and (5.4.6) in arriving at the classical Sagnac effect formula (5.4.10)).The rather tortuous way of deriving the Eqs.(5.4.9), (5.4.10) and (5.4.11) serves two things. It demonstrates how the Sagnac effect can be construed as an effect of "desynchronization" of clocks (due to the contribution of the phase terms(5.4.4)) on the rotating platform even in the classical world. This effect is usually regarded as a 'real' physical phenomenon in the context of the relativistic Sagnac effect [31]. But the present derivation demonstrates that the desynchronization cannot be an objective phenomenon since here we clearly see it as an artifact of standard synchrony which is nothing but a stipulation. The other utility of this scheme of the derivation is that it allows us to understand clearly that the two apparently contradictory results ($\rho = 1$ and $\rho \neq 1$) follow from the same transformation (5.4.3). The contradiction is therefore a logical one. It means that the trouble lies in the arguments (and not in the physical theory — in this case it is the classical kinematics) leading to the paradoxical conclusions.

Further, not only Zahar transformation, the Galilean world can also be represented by the following transformation [25]

$$\begin{aligned} x &= x_0 - \beta c t_0, \\ y &= y_0, \\ t &= t_0 + \epsilon \left(x_0 - \beta c t_0\right), \end{aligned} \tag{5.4.12}$$

where, as before, ϵ is a free parameter which depends on the choice of synchrony. GT and ZT are recovered for $\epsilon = 0$ and $\epsilon = -\gamma^2\beta/c$ respectively. Note that these are the classical analogues of Selleri's transformation (5.3.1). The OWS' of light that follow from (5.4.12) are given by

$$\frac{1}{c'_+} = \frac{1}{c(1-\beta)} + \epsilon, \tag{5.4.13}$$

$$\frac{1}{c'_-} = \frac{1}{c(1-\beta)} - \epsilon \tag{5.4.14}$$

and the corresponding ratio of these velocities is given by

$$\rho'_{\text{classical}} = \frac{c'_+}{c'_-} = \frac{1-\beta}{1+\beta} \cdot \frac{1-c\epsilon(1+\beta)}{1+c\epsilon(1-\beta)}. \tag{5.4.15}$$

As before, here also we see that $\rho'_{\text{classical}}$ corresponds to $\rho_{\text{classical}}$ (5.4.11) provided $\epsilon = 0$. For ZT $\left(\epsilon = -\gamma^2\beta/c\right)$, $\rho'_{\text{classical}} = 1$ which agrees with the stipulation of standard synchrony used to derive the transformation. But now $\rho'_{\text{classical}} \neq \rho_{\text{classical}}$, although the latter ratio also has been obtained using the same transformation *i.e.* ZT. We thus see that Selleri's arguments, if carried over into the classical world, also lead to the paradox.

As remarked earlier, in order to address the paradox one needs to look into the reasonings leading to it rather than expecting any flaw in the theories (relativistic or classical). One may ask why Selleri expects that ρ should be equal to ρ' (or equivalently why $\rho_{\text{classical}}$ should be equal to $\rho'_{\text{classical}}$)? The primed ratios are measured in the MCIF whereas the unprimed ratios are global, *i.e.* they are based on the measurements of the average speeds of light signals when they make complete round-trips. Selleri's argument goes somewhat like this: Since the stationary inertial reference frame at rest with the centre of the disc is isotropic in every sense, the isotropy of space should ensure that the instantaneous velocities of light are the same at all points on the rim of the disc and therefore the average velocities should coincide with the instantaneous ones.

It is interesting that there is nothing wrong even in Selleri's observation regarding the symmetry of the situation, however the conclusion that the two ratios (ρ and ρ') are equal does not necessarily follow from the symmetry arguments. Below we give an example and explain why and how the local speeds of light may differ from their global values in spite of the symmetry.

Consider the motion of a rigid rod AB of length $L_0/2$ with respect to the inertial frame S_0.[7] Suppose that the rod initially moves with uniform velocity βc towards the right parallel to the x-axis of S_0 (vide Fig. 5.2).

The left end A of the rod is assumed to coincide with the origin of S_0 at the laboratory time $t_0 = 0$, when an observer at A on board the rod who carries a clock C_A sends out a light pulse towards B where another observer sitting on the rod holds a mirror (M) facing A. As soon as the light pulse reaches the observer at B and is reflected back and starts to travel towards A, the rod is also made to

[7]This is a reconstruction of linear Sagnac effect described in Sec. 3.4 to suit the represention of the present problem.

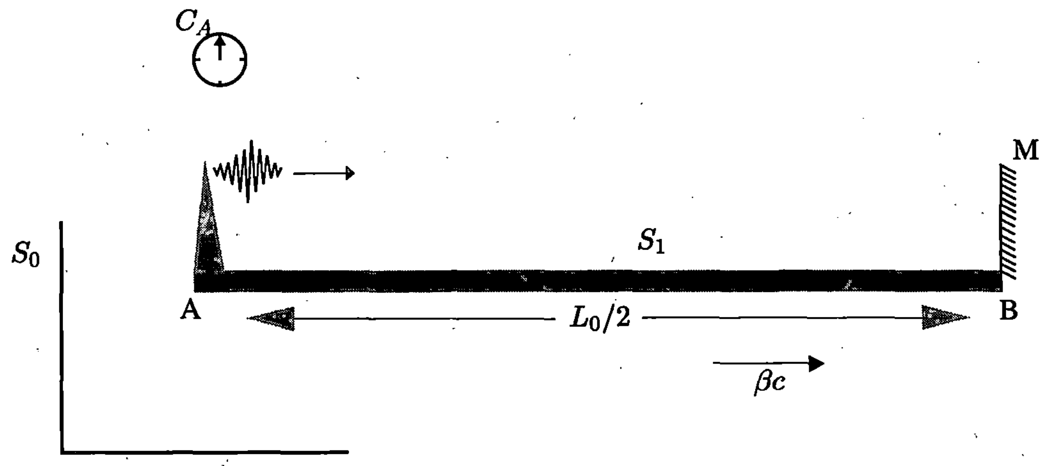

Figure 5.2: Rod moving towards the right

change its direction of motion and travel towards the left with the same uniform speed βc.[8] (vide Fig 5.3)

Suppose now that the observers in the laboratory record the times of the following three events:

Event 1: The light pulse sent out from A at the laboratory time $t_0 = t_{01} = 0$.

Event 2: The light pulse received at B at the laboratory time $t_0 = t_{02}$.

Event 3: The reflected light pulse received at A at the laboratory time $t_0 = t_{03}$.

From simple kinematics one obtains

$$t_{02} = \frac{L_0}{2c(1-\beta)} \quad \text{and} \quad t_{03} = \frac{L_0}{c(1-\beta)}. \tag{5.4.16}$$

If Galilean transformation is used for any event, there is no distinction between the laboratory times and the corresponding times measured by observers on board

[8]The present analysis of this thought experiment, which essentially corresponds to a linear Sagnac effect discussed elsewhere [15, 16, 32] by the present authors can be seen to fit well (with minor adjustment in the reasonings) with the FOC experiment [19] in the limit when the size of the wheels at the two ends tend to zero.

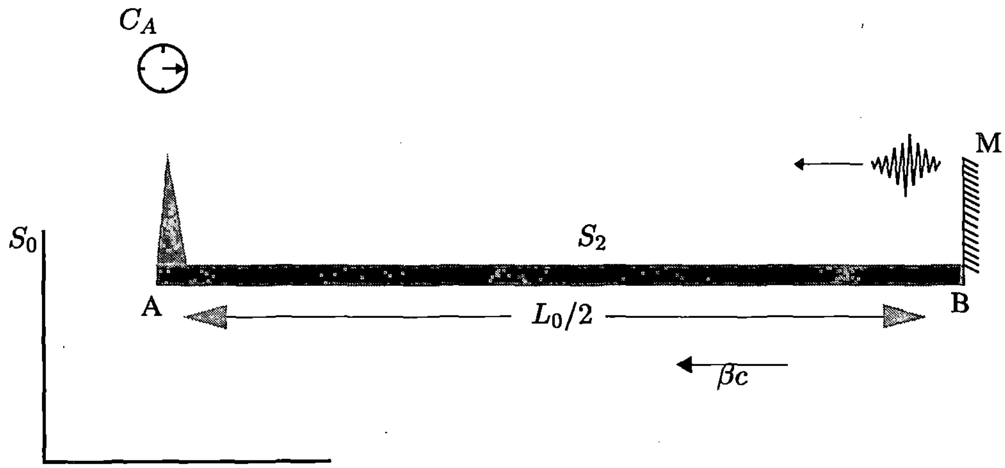

Figure 5.3: Rod moving towards the right

the rod.

However if the observers wish to adopt the Einstein synchrony (*i.e.* for light TWS= OWS) in the inertial frames of the moving rod (we label them S_1 for the rod moving towards the right and S_2 when it moves towards the left say), they may do it by correcting the times for the event 2 in the respective frames. Let us denote these corrected times by t_{12} for S_1 and t_{22} for S_2.[9] The corrected times will be given by

$$t_{12} = t_{01} + \frac{L_0}{2\overleftrightarrow{c}(0)} = \frac{L_0}{2c}\gamma^2 \qquad (5.4.17)$$

and

$$t_{22} = t_{03} - \frac{L_0}{2\overleftrightarrow{c}(0)} = \frac{L_0(1+2\beta)}{2c}\gamma^2, \qquad (5.4.18)$$

where we have made use of Eq. (5.4.16) and inserted Eq. (5.4.8)

Note that for the derivation of Eq. (5.4.17) and (5.4.18), it has been implicitly

[9]The symbol t_{ik} refers to the time of the k-th event according to an observer of the inertial frame S_i.

stipulated that the times recorded on rod-observer's clock, t_{11} and t_{23} (which are the times recorded on C_A) are the same as the laboratory times t_{01} and t_{03} respectively. In the classical situation this is possible because no rate-correction is necessary. In the relativistic situation this stipulation is also possible by making the rate correction to the moving clocks by an appropriate Lorentz factor.

For event 2 the total disagreement of times between observers in S_1 and S_2 is therefore given by

$$\delta t_{\text{gap}} = t_{22} - t_{12} = \frac{L_0 \beta}{c} \gamma^2. \tag{5.4.19}$$

Now in this example, physics is the same whether light propagates forward or backward with respect to S_0, but still the global speed $L_0 / (t_{03} - t_{01}) = c(1-\beta)$ is different from the local speeds

$$\frac{L_0/2}{(t_{12} - t_{01})} = \frac{L_0/2}{(t_{03} - t_{22})} = c\left(1 - \beta^2\right), \tag{5.4.20}$$

since the total discrepancy in synchrony given by Eq. (5.4.19) remains unaccounted for in such a comparison if Einstein synchrony is used. Thus we see that in spite of the symmetric situation the global speed of light ought to be different from its local counterpart in this synchrony.

It is interesting to note that in the rotating disc situation this discrepancy in synchronization between any two adjacent MCIFs can be evenly distributed throughout its circumference by honouring the symmetry of this situation. It is therefore evident that the global ratio ρ is in general not the same as the local ratio ρ'. In fact it should be amply clear by now that while the former is an empirically verifiable quantity (based on the measurements of times of flight of light by a *single* clock) the latter quantity depends only on one's own choice of synchrony (see Eq. (5.4.17) or (5.4.18) to understand how the times of the event 2 in S_1 and S_2 are required to be adjusted in order to synchronize the clocks in the Einstein way). Note that in this respect the classical kinematics is no different from its relativistic counterpart.

5.5 Desynchronization

From the above analysis it is evident that if in order to calculate the round-trip time for light in the (non-inertial) frame of the rod, one adds up the times of flight of the same in the inertial frames S_1 and S_2, where the Einstein synchrony has been employed, the result will be wrong by the amount δt_{gap}. This happens since $t_{22} \neq t_{12}$. It only means that S_1 and S_2 cannot be meshed together. However in seeking to dovetail these frames one may set $t_{22} = t_{12} = \frac{L_0}{2c}\gamma^2$. But in that case t_{23} has to be altered by the amount δt_{gap} to preserve the Einstein synchrony in S_2. However since according to our stipulation t_{23} is the time measured by C_A, any possibility of alteration in the value of t_{23} would mean C_A is desynchronized with itself.

In the literature this phenomenon is known as the "desynchronization" in the context of synchronization of clocks in a rotating platform. It is not difficult to show that the measure of this desynchronization in the case of a rotating disc, which is often termed as the "time lag" [12, 33] (for the corotating light signal) is the same as δt_{gap} obtained in the shuttling rod example above. Note that this δt_{gap} is just half of the classical Sagnac delay (see Eq. (5.2.7)). If the same effect is calculated for the counter propagating beam, the total time lag $\Delta\tau_{\text{lag}}$ comes out to be $2\delta t_{\text{gap}}$. As mentioned earlier, people tend to regard this desynchronization ($\Delta\tau_{\text{lag}}$) as the real cause of the Sagnac effect in the relativistic context [6, 7, 12, 33]. For example in Ref. [7], Tartaglia observes that the "simplest explanation for this effect attributes it to the time lag accumulated along any round trip ...". Earlier, Rizzi and Tartaglia [6] expressed a similar view in order to give the "true" relativistic explanation for the Sagnac time difference by ascribing it to the non-uniformity of time on the rotating platform and to the "time lag" arising in synchronizing clocks along the rim of the disc. Selleri also remarks (while not sharing this view) that "an "orthodox" approach to dealing with the rotating platform problem is to consider a position dependent desynchronization ... as an objective phenomenon."

The present analysis of the classical Sagnac effect using Einstein synchrony reveals that this desynchronization is only an artefact of the Einstein synchrony and hence is devoid of any empirical content. Since, if instead of ZT, one uses the Galilean transformation, there is no "desynchronization" but still there is Sagnac effect. Therefore "desynchronization" is conventional in nature and hence cannot be considered an "objective phenomenon". For future reference we call this desynchronization as desync1.

In a recent paper Rizzi and Serafini [12] acknowledges Selleri and Klauber (see footnote on page 4 of Ref. [12]) who have brought to their attention this fact that the much talked about "desynchronization" is merely a "theoretical artefact". However the present paper reveals this in a more convincing way by explicitly showing how this "desynchronization" can be manufactured in the classical world too.

The authors of Ref. [12] however somewhat supporting the orthodox view regarding the connection of the Sagnac effect and the "desynchronization", redefines the latter in the following way: Starting from any point Σ on the rim of a rotating disc if two synchronized clocks are slowly transported in opposite directions along the periphery and are brought back to the same position, they will be found to be out of synchrony by the amount which is equal to that obtained for desync1 *i.e.* $\Delta\tau_{\text{lag}}$. This desynchronization will hereafter be referred to as desync2.

The desynchronization, thus defined, is the result of the comparison of two clocks at the same space point and hence is independent of the distant synchrony convention. The authors therefore claim that they have revealed the "deep physical" and "non-conventional nature" of the time lag. However it is enough to point out the fallacy of this claim by mentioning that these two desynchronizations (desync1 and desync2) are two different things altogether, since if something is conventional, it can be changed or removed by altering the convention, but the "time lag" or time difference in the readings of the two slowly transported clocks after their round trips cannot be altered by redefining the synchrony on the rotating disc.

The equality of these time lags (*i.e.* desync1 and desync2), therefore, is itself conventional and is true accidentally (as opposed to logically) in the relativistic situation if the Einstein synchrony is used in the rotating frame. If instead, the absolute synchrony is used desync1 $= 0$ while desync2 still remains non-zero. In the classical case the situation is reversed, since in this case desync2 is always zero since there is no time dilation of clocks with respect to the laboratory frame however for the Einstein synchrony in the disc (which corresponds to ZT) desync1 $\neq 0$. These are however equal in the absolute synchrony (which corresponds to GT). Rizzi and Serafini also claim that desync2 brings to light the "dark physical root of the Sagnac effect". However this claim is also in error too. It is obvious that desync2 cannot be regarded as the physical cause of the Sagnac effect, since we observe that in the classical world desync2 is always zero but still the Sagnac effect exists. This reveals that desync2 and Sagnac effect are unconnected entities. The equality of these two different entities in the relativistic world is at best fortuitous.

5.6 Synchrony – A Value Judgement

One is now in a position to inquire if it is possible to consistently synchronize clocks on the rim of the turn-table so that no gap in synchrony arises. Let us call such a synchrony as "good synchrony". To answer this consider the following scheme for synchronization due to Cranor *et. al.* [34]. In this scheme before the disc is set into motion with respect to S_0 all observers on the rim of the disc and those in the laboratory set their clocks according to the Einstein synchrony. The disc is then set into rotation uniformly (here 'uniformly' means all the points of the rim are treated identically [34]) which after some time may be assumed to attain a constant angular velocity. Alternatively one may set all the clocks on the rim (as well as those adjacent to them in S_0) a common time (say $t = 0$) as soon as the observers on the rim receive a flash of light sent out from a light source at the center of the disc.

Clearly the symmetry of the problem demands that the observers in the laboratory as well as those on the rim of the disc should continue to agree on the question of simultaneity as the synchronization process "favours no particular observer" [34]. This symmetry argument is evidently true in the classical as well as in the relativistic world. Only in the latter case although the observers in the laboratory frame and in the rotating frame agree on simultaneity, the clock *rates* in these frames differ due to the time dilation effect of relativity.

It is evident that there will be no gap in the synchrony between two successive MCIFs (in the linear example between S_1 and S_2) if the observers in these frames agree on simultaneity with those in S_0. Again if there is no synchrony gap the global ratio ρ should be equal to the local ratio ρ'. The agreement on simultaneity between the frames in turn requires ϵ to be equal to zero in Eqs. (5.3.1) and (5.4.12). In the classical world this implies GT, on the other hand in the relativistic world this corresponds to TT (Eq. (5.3.6)).

It means if the clocks of the disc were synchronized according to the scheme discussed above when the latter was at rest with respect to S_0, nothing has to be done further to synchronize them in order to have consistent synchrony throughout the rim when the disc picks up its uniform angular speed. The synchrony is thus "automatic". Any other synchrony (which corresponds to $\epsilon \neq 0$) including the Einstein Synchrony is to be achieved through human intervention. Selleri [1] therefore singled out the absolute synchrony by calling it as "nature's choice".

One may however ask at this point if it is at all possible to synchronize the clocks on the rim in the absolute way (so that $\epsilon = 0$) without referring to the underlying inertial frame *i.e.* by means attached to the turn table itself. Indeed this can be done in practice. For instance an observer with a clock on the rim at a point Σ can start the process by sending a light pulse to an adjacent clock in the anticlockwise direction and synchronize the latter with his own clock first by assuming the OWS of light to be equal to c. In the same way the third clock adjacent to the second one in the same direction can be synchronized with the latter and the synchronization procedure may continue in this way until finally one arrives at the first clock. The observer then discovers that the clock at Σ is not synchronized with itself. The desynchronization, *i.e.* the defect in synchrony will again be different if checked clockwise rather than counter-clockwise. By trial however the observer will be able to discover that the defect in synchrony disappears if the one-way speeds in the two different directions correspond to two different numerical values c_1 and c_2 (say). With these obtained empirical values for the OWS of light, not only the clocks on the rim are synchronized in the absolute way but also the linear speed of the βc and hence the angular velocity $\omega = \beta c/R$ of the rotating disc are determined if c_1 and c_2 are substituted for c_+

and c_- in Eqs. (5.2.17) and (5.2.18) (or alternatively in Eq. (5.4.9) if one considers the Galilean world). All this however refers to the question of synchronization in the large and does not mean that in MCIFs it is mandatory to adopt the absolute (non-isotropic) synchronization.

One may now question our nomenclature "good synchrony" for the one for which light propagation is anisotropic (remember that for $\epsilon = 0$ light propagation is anisotropic in the classical as well as in the relativistic world). Let us clarify this: In the classical world people would be immediately happy to know that the demand for consistent synchronization in the large requires $\epsilon = 0$, which recovers GT. They would say, "After all we get back our old time tested transformation, the Einstein synchrony (leading to ZT) is a bad one, since it is not automatic and natural and it leads to inconsistent synchronization in the large." What should be our reaction who live in the relativistic world? If one carries on the same sort of arguments in the relativistic world, one may give a value judgment in favour of the absolute synchrony ($\epsilon = 0$) hence may call it the "good synchrony" by contrast, unless one seeks to indulge in double standard.

5.7 Conclusion

SP refers to a theoretical prediction regarding the OWS of light grazing the circumference of a rotating disc. The essential content of SP is that simple kinematics together with some appropriate symmetry arguments predict an anisotropy in the speed of light with respect to an "inertial observer". The claim apparently is substantiated by the Sagnac effect. (In the recent FOC experiment [19] the "inertial observer" is obtained automatically (see Sec 5.2 while in the original rotating disc context one needs to take the limit $R \to \infty$ and $\omega \to 0$ while preserving the linear speed of the rim of the disc so that any point on the rim can be thought of as an inertial observer.)

Some earlier responses to the issue are either incomplete or they suffer from certain drawbacks. Here we have shown that by adopting the Einstein synchrony SP can be recast in the Galilean world (see Sec. 5.4. This facilitates in understanding the weak point of the reasoning leading to the fallacy.

It has been argued that SP hinges on the assumption that the (global) ratio of the round-trip speeds of the light beams co-rotating and counter-rotating with the disc (as if) ought to be the same as the local ratio of the OWS in the MCIFs since no point on the rim is preferred. The present analysis in the classical world reveals how in spite of symmetry of the situation the two ratios can be different.

The issue of the "desynchronization of clocks" which is often regarded as the physical cause of the Sagnac effect has been put under the scanner. It is held that of the two types of desynchronization discussed here, desync1 is a theoretical artifact while desync2, although a convention-free entity, is also unable to qualify itself as the root cause of the effect. Finally, in spite of the lacunae in the reasonings leading to SP, the superiority of the absolute synchrony over the standard one for a rotating observer has been upheld.

Postscript: After the publication of the content of this chapter [13], Selleri has given an answer [35]. There the author has agreed with us in many ways. However, he has disagreed with us regarding our claim of consistency of SR in spite of his forceful paradox by the following words: "In conclusion the GRCS[10] way of dealing with the rotating platform problem introduces a useless complication." We consider that this is not strictly a refuting statement as such and indeed by the phrase "... *useless complication*" the author has supported our view in a way. We keep further discussion on it out of the present scope.

[10]Selleri referred our paper by this name.

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