# Chapter 1

# Introduction

## 1.1 Scope and Motivation

Since the time of Newton, physics on rotating frames remains a subject of fascination for the physicists: in addition to physical forces there appear some pseudo forces peculiar to rotating frames which shows, in classical context the absoluteness of rotation. The interest of physicists about rotation did not subside in the last century. With the development of newer physics, rotation stimulated further interests. The rotating disc problem, discussed by Paul Ehrenfest [1] in 1909 and now popularly known as Ehrenfest paradox apparently challenged the internal consistency of the theory of relativity. Einstein was interested in the effect of rotation on the spacetime geometry [2]. In recent past the desynchronization of clocks on a rotating frame became a subject of discussion.

In the early days of SR when it was not universally accepted by the scientists, the null result of Michelson-Morley experiment was not considered conclusive enough (along with the success of SR) to throw away the concept of all-pervading luminiferous ether. Georges Sagnac in 1913 very cleverly used rotation in his quest for the existence of ether. He considered his experiments conceptually similar to Michelson-Morley experiment and published his results in two papers (in french) [3] entitled *The existence of the luminiferous ether demonstrated by means of the effect of a relative ether wind in an uniformly rotating interferometer* and *On the proof of reality of the luminiferous ether with the experiment of the rotating interferometer*. In the Sagnac type experiments, one essentially sends out two coherent beams of light in opposite directions along the edge of a rotating disc.[1] The two beams are allowed to interfere at a point after they complete a full

[1]Sagnac's original experimental arrangement was different. This will be discussed in Chap. 2. By *the Sagnac type experiments* we refer to the set of experiments which use the basic principle of Sagnac's original experiment [4].

circle. When the disc is set into rotation, a fringe shift is observed which is found to depend on the angular velocity of the spinning disc. This is commonly referred to as the the Sagnac effect.

The Sagnac type experiments were repeated by several authors using photon (called optical Sagnac type experiment) and the accuracy is much improved by using laser and fibre optic interferometer. The effect has been observed in interferometers built for electrons, neutrons, atoms, superconducting Cooper pairs, radio wave and X-rays.

There are several applications of the Sagnac effect in recent years. Based on the Sagnac effect, ring laser and fibre optic gyros are being used as navigational tools. Importance of this effect also lies in connection with the question of time keeping clocks of clock-stations around the earth and Global Positioning System (GPS). Here the earth plays the role of rotating platform on which clocks between clock stations are synchronized by sending lights via satellites.

In spite of successful applications of the Sagnac effect in many fields, the conceptual challenges it put forward are no less interesting. Sagnac himself considered his experiment a proof of existence of luminiferous ether and thus explained it using classical kinematics. He was successful in his endeavour because his experimental result was of the first order in $v/c$. In a recent paper commenting on the early histories of theoretical studies in the Sagnac effect Selleri [3] remarks – "Surprisingly theoreticians were little interested in the Sagnac effect, as if it did not pose a conceptual challenge. As far as I know Einstein's publications never mentioned it, for example." Langevin [5] was the first to discuss its theoretical explanation. He was of the opinion that the Sagnac effect being a first order experiment cannot give judgement for or against any theory [3]. Langevin explained the empirical observations of the Sagnac experiment with Galilean kinematics which is "...slightly veiled in relativistic form by some words and symbols ..." [3]. In another publication in 1937 Langevin [6] tried to provide two relativistic explanations of the Sagnac effect. One of the explanations was based on the idea to adopt time of the centre of rotation (fixed in the laboratory) everywhere on the disc. Though for the standard relativity it looks queer, physicists acquainted with the CS thesis will recognize this for adopting absolute synchrony on the rotating frame. This will be made clear in the main text (Chap. 5).

Analysis of the Sagnac effect is usually done from the perspective of inertial frame and surprisingly there are several derivations for that. Hasselbach and Nicklaus [7] list twenty different derivations that exist in the literature and commented "This great variety (if not disparity) in the derivation of the Sagnac phase shift constitutes one of the several controversies ... that have been surrounding the Sagnac effect since the earliest days of studying interferences in rotating frames of reference." (This once again shows the great difficulty of explaining physics in rotating frame in SR.) Though so many derivations exists for the Sagnac formula, Selleri [8] claims that no calculation is available which is done truly from the perspective of the rotating frame. To provide one, he used inertial transformation (introduced by him) which is in conformity with the CS thesis to provide a calculation from the perspective of a rotating frame. He observes that the LT representing standard synchrony gives null result while the TT representing absolute synchrony gives the correct result for the Sagnac phase shift formula. (On the basis of this, Selleri termed absolute synchrony as the 'nature's choice' of synchronization.) The present author along with his collaborators has been fascinated by this very interesting observation of Selleri. The authors then decided to check the veracity of Selleri's observation that the

Sagnac effect has not been explained from the perspective of an observer on board the rotating platform. A brief literature survey brought attention to a very influential work by E. J. Post [9]. At the first sight it appears that Post has precisely done this. But a close scrutiny reveals some drawbacks of Post's considerations which has been explained in Chap. 6. There it has been explained how Post intuitively introduced a co-ordinate transformation from inertial to rotating frame (manifestly displaying absolute simultaneity – thereby contradicting *standard SR*) to use it in his metrical derivation of the Sagnac effect from the rotating frame perspective. Further, not being satisfied with the intuitive introduction of a coordinate transformation, Post 'derives' that TE from the LT under some kinematic condition due to rotation. The time transformation part of the TE is independent of space thus representing absolute synchrony. It is therefore surprising how, imposition of simple kinematical condition in the LT imply a TE which represent totally different synchrony!

There are other rich theoretical ramifications concerning the Sagnac effect. For example, we discovered that there exist two relativistic Sagnac phase shift formulae (one without a relativistic contraction factor and one with it) in the literature arising from the consideration (or lack of it) of length contraction of the periphery of the disc in rotation respectively. Present day experimental set up can measure upto the first order of precision in $v/c$ and thus is unable to give judgment in this dilemma. It has been shown [10, 11] that this problem is intimately connected with the Ehrenfest paradox [1]. A detailed study of this aspect of the phase-shift formula and the Ehrenfest paradox forms the text of Chap. 3.

There are many interesting issues related to the behaviour of clocks and their synchronization in a rotating frame. In any frame, if the clocks are synchronized in the method of standard SR, they become desynchronized if the frame is accelerated. Moreover, it can be shown that in rotating frames each clock gets desynchronized with itself. This desynchronization is regarded, by some authors, as the 'root cause of the Sagnac phaseshift'. Refuting this claim, it has been shown [12, 13] (Chap. 5) that even if the clocks are synchronized in an absolute way in conformity with the CS thesis of SR (discussed below), the Sagnac effect still exists.

A few year ago Selleri put forward a very interesting paradox [3, 14] concerning the Sagnac effect. The paradox concerns the theoretical prediction of an anisotropy in the speed of light in a reference frame comoving with the edge of rotating disc even in the limit of zero acceleration. The counter intuitive problem not only challenges the internal consistency of SR but also undermines the basic tenet of the CS thesis of relativity. In one of the chapters of the main text (Chap. 5 we have taken up the issue, where the CS thesis is used, as a tool, in a novel way to recast the paradox in the classical world facilitating the resolution of the issue. A value judgement is given in favour of absolute synchronization in rotating frame upholding Selleri's observation.

To prepare the stage for the discussion on Selleri paradox, another interesting paradox of SR, namely the Tippe-top paradox has been addressed (Chap. 4). A tippe top is a children's toy which, when spun on a flat base tips over after a few rotations and eventually stands spinning on its stem. The ability of the top to demonstrate this feat depends on its geometry *i.e.* all tops are not tippe tops. To a sufficiently fast moving observer the geometry of the top may get altered due to Lorentz contraction to such an extent that the top may not tip over! This is certainly paradoxical since a mere change of perspective cannot alter the fact that the top tips over on the base. Based on the CS thesis and different possible transformation equations in relativity (in classical world too) a novel method will be used to resolve the paradox by posing it in the classical world. This method indeed has been used to resolve Selleri paradox discussed in the earlier paragraph.

So far we have considered the Sagnac effect or issues involving rotation in flat spacetime. However in view of the fact that all the real experiments are performed in the curved spacetime of the gravitational field of earth, it will be interesting to study the effect of curvature (gravity) of the spacetime. In Chap. 7 we have taken up the issue in detail. We also ask what happen if the whole earth (or a rotating star) acts as the turn table. The Sagnac experiment may be suitably modified to be performed where the observers (light source) and the mirrors are carried by rockets orbiting round a gravitating source. The rockets may be replaced by satellites when they are moving in their natural (free falling) orbits. The interesting results of this investigation have been reported in the last chapter of the main text.

In most of the discussions we extensively make use of the CS thesis and possible different relativistic transformations. Therefore before we conclude, a brief introduction to the CS thesis may be in order. This we provide in the following section.

## 1.2 The CS Thesis: A Brief Introduction

The role of conventionality regarding synchronization of spatially distant clocks in a given reference are much discussed in the literature. In appendix A we review the Conventionality of simulataneity (CS) thesis for readers who are unfamiliar with this idea. In this section we briefly sketch the main philosophy behind the CS thesis.

The role of convention in the definition of the simultaneity of distant events is one of the most debated issues (problems) in special relativity. The source of this problem lies in the fact that in SR distant clocks in a *given* inertial frame are synchronized by light signals, the one-way speed of light (OWS) has to be known beforehand for the purpose. To know the OWS on the other hand one requires to have presynchronized clocks and the whole process of synchronization ends up in a logical circularity which forces us to introduce a degree of arbitrariness in assigning the value for the OWS of light. However, Einstein synchronized spatially distant clocks by assuming the equality of the velocity of light in two opposite directions. This is known in the literature as the *standard synchronization.* Einstein's procedure to synchronize clocks at different space points is but one of several possible alternative conventions (referred to in the literature as *non-standard synchronization*) and many of the results he obtained depended on his special choice of synchrony. As an example the question of the discordant judgments of simultaneity by two inertial observers moving with respect to each other is also matter of such a simultaneity convention.

Though Einstein identified the problem, the role of convention in the synchronization of clocks has been advocated especially by Reichenbach [15] in 1928 and later by Grünbaum [16]. They claimed that the relation of simultaneity *within* an inertial frame of reference contains an ineradicable element of convention and the conventionality lies in the assumption regarding the OWS of light. To clarify this point further recall that Einstein originally proposed that the criterion for the synchrony of distant clocks be that the time of arrival and reflection of a light ray as determined at one clock be precisely halfway between the time of its departure and its return upon reflection as determined at the other clock. This criterion clearly presupposes that light has the same speed in all directions. Indeed, since the specification of a value for the OWS of light enables directly a simple light-signal procedure for the synchronization of distant clocks, any assumption of the OWS values is equivalent to the assumption of a criterion for synchrony. It follows that the specifications of either distant simultaneity criterion or OWS of light will alike be referred to as synchrony conventions.

Einstein himself referred to the distant simultaneity criterion he proposed as a free stipulation of the empirical meaning of distant simultaneity [17], and the issue is whether other criteria leading to different distant simultaneity judgments and consequently different OWS might not have been chosen without compromising the empirical success of the theory. The conventionalist thesis holds that a range of choices are possible, all fully equivalent with respect to experimental outcome. According to the conventionalist thesis, any synchrony convention will be admissible so long as it is consistent with the round-trip principle, the principle which holds that the average speed of a light ray over any closed path has a constant value. In fact, one can restate the second relativity postulate by replacing *the velocity of light* by *the TWS of light.* A convention within the SR must be consistent with the round-trip principle since this principle is a consequence of the theory prior to the adoption of any criterion for distant simultaneity and may in principle be tested with a single clock. It is precisely this thesis that is known as the CS thesis. According the CS thesis the conventional ingredient of SR which logically cannot have any empirical content, gives rise to results that are often erroneously construed as the new philosophical imports of special relativity theory.

## 1.3 General Transformation for SR

There has now been a substantial amount of clarification of the CS thesis due to a number of authors (referred at suitable places in this dissertation). Possibility of using synchronization conventions other than that adopted by Einstein has also been much discussed. In appendix B we present a derivation of a transformation equations which is general enough to incorporate all the possible conventions of the OWS of light and thus, engulf all the possible synchronization procedures. We largely take a pedagogical approach with sufficient details in deriving these equations starting from a set of general transformation equations. Throughout the derivation matrix algebra is used since with matrix algebra it is easier to find the inverse transformation, composite transformation and velocity addition formulae. The derivation presented here closely follows the derivation of Sjödin [18].The equivalence (relation) of this general transformation with the transformation derived by Selleri [8] has also been discussed. At the end we discuss a set of transformation equations where acoustic signal is used synchronization agent and the TE is found out in a material subtratum. The transformation is called the Dolphin transformation (DT) [19]. In this very important transformation, derived by Ghosal, Mukhopadhyay and Chakraborty [19], two roles of speed of light – one as a synchronizing agent and the other as a physical constant – which is mingled up beyond recognition in standard SR are explicitly split up. That some important transformation equations in the relativistic as well as in the classical world can be obtained from the DT under suitable synchronization conditions is also discussed.

# 1.4 Topic-wise Summary

## 1.4.1 Relativistic Sagnac Effect and Ehrenfest Paradox

In Chap. 3 a long standing problem of rotating disc, known as Ehrenfest paradox [1] is discussed and a resolution showing its intimate relation with the dilemma as to the correct relativistic formula for Sagnac phase-shift formula is offered. This chapter will address the issue in the light of a novel, kinematically equivalent linear Sagnac-type thought experiment, which provides a vantage point from which the effect of rotation in the usual Sagnac effect can be analyzed. These thought experiment in its two versions will be discussed in Secs. 3.5 and 3.6. The relativistic formula for the Sagnac phase-shift seems to depend on the way the Ehrenfest paradox is resolved. Kinematic resolution of the Ehrenfest paradox proposed by some authors predicts the usually quoted formula for the Sagnac delay but the resolution itself is shown to be based upon some implicit assumptions regarding the behaviour of solid bodies under acceleration. In order to have a greater insight into the problem, a second version of the thought experiment involving linear motion of a "special type" of a nonrigid frame of reference (Sec. 3.6 is discussed. It is shown, in Sec. 3.7 and in Sec. 3.8, by analogy that the usually quoted special relativistic formula for the Sagnac delay follows, provided the material of the disc matches the "special type."

## 1.4.2 Conventionality of Simultaneity and Tippe Top Paradox

In this chapter we critically examine a recently posed paradox (tippe top paradox [20] in relativity) and its suggested resolution. A tippe top when spun on a table, tips over after a few rotations and eventually stands spinning on its stem. The ability of the top to demonstrate this charming feat depends on its geometry (all tops are not tippe tops). To a rocket-bound observer the top geometry should change because of the Lorentz contraction. This gives rise to the possibility that for a sufficiently fast observer the geometry of the top may get altered to such an extent that the top may not tip over! This is certainly paradoxical since a mere change of the observer cannot alter the fact that the top tips over on the table. In an effort to resolve the issue the authors of the paradox compare the equations of motion of the particles of the top from the perspective of the inertial frames of the rocket and the table and observe among other things that (1) the relativity of simultaneity plays an essential role in resolving the paradox and (2) the puzzle in some way is connected with one of the corollaries of special relativity that the notion of rigidity is inconsistent with the theory. We show here that the question of the incompatibility of the notion of rigidity with special relativity has nothing to do with the current paradox and the role of the lack of synchronization of clocks in the context of the paradox is grossly over-emphasized. The conventionality of simultaneity of special relativity and the notion of the standard (Einstein) synchrony in the Galilean world have been used to throw light on some subtle issues concerning the paradox

With a brief introduction to the content of the chapter, we shall briefly reproduce in Sec. 4.2 the basic arguments of Ref. [20] to clarify the paradox, in order to set the stage. The study will follow the CS approach to critically examine the work of Basu *et al.* Though a fairly comprehensive account of CS thesis at possible transformations alternative to LT is given in appendix A and appendix B, a brief introduction to this is given in Sec. 4.3 for ready reference and also to make the content of the chapter self-contained. The main arguments will be presented from Sec. 4.4 through Sec. 4.6. We summarize all this in Sec. 4.7. The table of comparison given at the end of the chapter gives the summary of our findings at glance.

### 1.4.3 On the Anisotropy of the Speed of Light on a Rotating Platform and Selleri Paradox

In this chapter(Chap. 5) we discuss a recently posed paradox in relativity concerning the speed of light as measured by an observer on board a rotating turn-table. The counter-intuitive problem put forward by F. Selleri [14] concerns the theoretical prediction of an anisotropy in the speed of light in a reference frame comoving with the edge of a rotating disc even in the limit of zero acceleration. The paradox not only challenges the internal consistency of the special relativity theory but also undermines the basic tenet of the conventionality of simultaneity thesis of relativity. The present paper resolves the issue in a novel way by recasting the original paradox in the Galilean world and thereby revealing, in a subtle way, the weak points of the reasonings leading to the fallacy. As a background the standard and the non-standard synchronies in the relativistic as well as in the Galilean world are discussed. In passing, this novel approach also clarifies (contrary to often made assertions in the literature) that the so-called "desynchronization" of clocks cannot be regarded as the root cause of the Sagnac effect. Finally in spite of the flaw in the reasonings leading to the paradox Selleri's observation regarding the superiority of the absolute synchrony over the standard one for a rotating observer has been upheld.

The chapter starts with a brief introduction to the Selleri paradox in Sec. 5.1. The paradox is discussed in Sec. 5.2. Selleri paradox is critically analysed from the view point of CS thesis and absolute synchrony in Sec. 5.3. Discussion of the paradox in the Galilean world can be found in Sec. 5.4. The phenomenon of desynchronization of clocks in rotating frame and its relation to Selleri paradox and Sagnac effect are critically examined in Sec. 5.5. A value judgement about different synchronization schemes applied to rotating frame will be given in Sec. 5.6 before the conclusions are summarized in Sec. 5.7.

### 1.4.4 Sagnac Formula from the Perspective of Rotating Platform and Absolute Synchrony

A recent claim by Selleri that the analysis of the Sagnac effect is usually done from the perspective of the laboratory frame and no derivation is available from the perspective of rotating frame is examined. Selleri further claims that a straight forward application of Lorentz transformation (LT) gives null result for the effect; however if instead of LT, Tangherlini tranformation (TT) representing absolute synchrony is used, then one can correctly predict the Sagnac effect from the perspective of a rotating observer. A calculation provided by E. J. Post in one of the most influential papers on the Sagnac effect might be construed as one done from the stand point of a rotating observer. The present paper adresses the issues raised by Selleri vis-a-vis Post's treatment. In Post's calculation a standard flat spacetime metric is transformed, by a proposed transformation representing the coordinates of a rotating frame. A critical examination reveals that Post's treatment has some inherent weaknesses and his intuitive transformation which gives the Sagnac result indeed leads to TT. This upholds Selleri's claim that in a rotating frame the absolute synchrony is the preferable one.

After a brief introduction on the calculation of Sagnac effect from the perspective of rotating frame we reviewed the calculation offered by Post. In the next section we critically examined Post's transformation to show that it predicts TT. In the last section some weaknesses of another 'derivation', given by Post in the appendix of his paper, of the proposed transformation are pointed out and it has been shown that this derivation predicts absolute synchrony (TT) too.

### 1.4.5 Sagnac effect in Curved Spacetime

The general relativistic correction to the Sagnac effect is obtained for a disc type experiment where the turntable is placed in an axisymmetric or spherically symmetric gravitational field. It will be shown that special cases of the present gedanken set up include a scenario where the beam splitter is placed on the surface of the earth which then acts as a turn table. Special cases where the observers move in geodetic or non-geodetic orbits have been discussed. The discussion of Sagnac experiment in the pre-horizon regime of the deep field of a neutron star or a black hole is done to gain an insight into the nature of such field in that region. The appearance of arbitrarily large Sagnac phase shift under certain conditions is noticed and these things have been discussed analytically and graphically in details.

After a brief introduction the Sagnac phaseshift formula in curved spacetime has been obtained in Schwarzschild field in Sec. 7.2. Sagnac effect for equatorial orbit is discussed in Sec. 7.3. Sagnac effect in Kerr-Newman field is discussed in Sec. 7.4. Experiment with satellites has been discussed in this case too. Some interesting results arising in the pre-horizon regime are discussed analytically and graphically.

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# 1.5 List of Publications

1. **Relativistic Sagnac Effect and Ehrenfest Paradox** – S. K. Ghosal, *Biplab Raychaudhuri*, Anjan Kumar Chowdhuri and Minakshi Sarker, *Found. Phys.* **33**(6), 981-1001 (2003).

2. **Rotating Disc Problem and Sagnac Phase-Shift formula** – S.K. Ghosal, *Biplab Raychaudhuri*, Anjan Kumar Chowdhuri and Minakshi Sarker **in** *Physical Interpretation of Relativity Theory VII, Late Papers*, Ed. M. C. Duffy, (PD Publications, Liverpool, 2000).

3. **Conventionality of Simultaneity and Tippe Top Paradox** – S. K. Ghosal, *Biplab Raychaudhuri*, Anjan Kumar Chowdhuri and Minakshi Sarker, *Found. Phys. Lett.* **16**(6), 549-563 (2003).

4. **On the Anisotropy of the Speed of Light on a Rotating Platform** – S. K. Ghosal, *Biplab Raychaudhuri* , Anjan Kumar Chowdhuri and Minakshi Sarker, *Found. Phys. Lett.*, **17**(5), 457–477, (2004).

5. **Synchronization and Desynchronization in rotating frames** – S.K. Ghosal, *Biplab Raychaudhuri*, Anjan Kumar Chowdhuri and Minakshi Sarker **in** *Physical Interpretation of Relativity Theory IX*, held at Imperial College, London: September 2004, Ed. M. C. Duffy (To be published).

6. **Sagnac Formula from the Rotating Frame Perspective and Absolute Synchrony** – *Biplab Raychaudhuri* and S. K. Ghosal, (*Ready for communication*).

7. **Sagnac Effect in Curved Spacetime** – *Biplab Raychaudhuri* , Anjan Kumar Choudhuri and S. K. Ghosal. (*Ready for communication*).

8. *Absolute synchrony in Microwave Background and Sagnac Effect* – S. K. Ghosal, Minakshi Sarker, *Biplab Raychaudhuri* and Anjan Kumar Chowdhuri *Proc. of International Conference on Gravitation and Cosmology (ICGC-2000)* held at IIT Kharagapur, 4-7 January, 2000 (Abstracted).

9. *Synchrony Gauge in Classical and Relativistic Sagnac Effect and related issues* – S. K. Ghosal, *Biplab Raychaudhuri*, Minakshi Sarker and Saroj Nepal, *Proc. of International Conference of Gravitation and Cosmology (ICGC-2004)* held at Kochi, 5-10 January, 2004 (Abstracted).