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The Sagnac effect in GPS, absolute simultaneity and the new meaning of time

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***Abstract* – The implementation of GPS systems has allowed the understanding of important facts about the true meaning of time and simultaneity. In fact GPS has became a fundamental source for the understanding of clock behaviour and synchronization, through the considerations of the relativistic effects affecting it. Among these, a very important role is played by the Sagnac effect, influencing the clocks readings. The correct consideration of such effect is fundamental in every synchronization process where the receiver is moving with respect to the source. In this paper we show how GPS system demonstrates that the explanation of Sagnac effect given by the commonly accepted version of Special Theory of Relativity is not correct and the use of an alternative formulation based on Inertial Transformations must be used. This implies the adoption of a new synchronization procedure, the renounce to the relativity of simultaneity and a novel meaning of physical time.**

I. INTRODUCTION

The realization of GPS systems has made it possible to develop many different technological facilities as, for example, satellite navigation system, cellular phone networks and so on [1]. Nevertheless, the use of such systems, beyond its technological usefulness, represents one of the most selective and hard tests of the Einstein's Theory of Relativity able to give valuable insights about the true meaning of physical time and validity of a given synchronization method.

On the other hand relativistic corrections themselves must be considered in order to make GPS system correctly working. As known, the GPS (Global Positioning System) is composed by 24 satellites orbiting around Earth on 6 different planes (inclined of 55° respect to equatorial plane) with a revolution period of about 12 hours. Every satellite describes a nearly circular orbit or radius $r = 4R$ (where R is the Earth radius) at about $3.9\,km/s$. Each satellite is equipped with four atomic clocks (two Cesium clocks and two Rubidium clocks) capable of a precision of about $10\,ns$. In addition to this spatial layer, there is the so – called "control layer" composed by a network of control stations at different points on the Earth surface (with "mother" station placed in Colorado). Every satellite emits omnidirectional signals at the two frequencies $f_1 = 1.5\,GHz$ (for usual purposes) and $f_2 = 1.2\,GHz$ (for military uses). In few words the system operates comparing the time of emission of every signals with the time of reception, this difference, multiplied by the velocity of signal propagation in the direction satellite – receiver, would give their mutual distance and then, by means of triangulation, the receiver position on Earth surface.

Obviously this method works only after the synchronization between the GPS clock and the clocks at Earth. This procedure is far from being obvious [2].

Another way by which GPS can give time is by sending a signal containing information about the time it has been sent as measured by the satellite clock; the receiver then compares the time given by its own clock with that received together with the signal of transmitter.

These synchronization procedures imply the introduction of different correction factors due to the propagation delays during propagation. One of the most important one is the relativistic correction, arising from the relative motion of the source and receiver and from the gravitational effects due to Earth and Sun. There are substantially three type of relativistic effects to be considered in GPS systems: a) the effect of source velocity (motion of the GPS satellites in their orbits) and receiver velocity upon clocks; b) the effect of gravitational potential upon satellite and receiver clocks; 3) the effect due to the receiver motion upon the signal reception time (Sagnac effect).

The first two effects can be explained within the Einstein's Special Theory of Relativity (STR), although the most part of these "official" explanations are flawed and must be seriously reconsidered [2]. But the Sagnac effect has been proved to be in conflict with the STR [2]. A lot of explanation has been proposed in order to "trace back" this effect to the commonly accepted framework of

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relativistic physics without success [2]. It has been shown that, in order to correctly explain this effect introducing the necessary correction to GPS, the postulate of isotropy of light velocity with respect the observer in every inertial frame must be abandoned and with it the assumption of absolute synchronization.

We have already shown in some previous papers [3] that a perfectly valid alternative to STR can be realized without using the postulate of isotropy of light velocity (that remains valid in a "preferred" inertial frame) considering the time and space Inertial Transformations (IT), deduce by Selleri [3]. This theory is able to simply explain the Sagnac effect (as well as all the other experimental evidences of STR) but it implies the concept of absolute simultaneity with respect a preferred isotropic inertial frame (and, consequently, the inapplicability of Einstein's synchronization procedure). We have also demonstrated [3] this implies a new understanding of time as numerical order of change of a system.

In this paper we'll show the GPS correction for Sagnac effect can be correctly interpreted only within this novel theoretical framework and that its inevitable presence further confirms the new vision of physical time previously proposed by us.

II. THE SAGNAC EFFECT IN GPS SYSTEM

In his original experiment [4] performed in 1913 Sagnac split a light beam into two parts each travelling along a circumference in opposite directions. The interference fringes effect has been then measured when the two light beams were bought back together (see fig. 1).

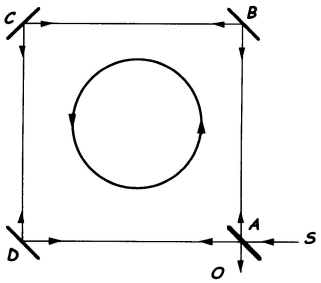

Fig.1. Schematic view of Sagnac experiment. Light from S is split in two parts: the first follows the path ABCDAO in the same direction of rotation, the second ADCBAO in the opposite direction, they interfere in O.

Sagnac observed the interference fringes at different positions and measured their displacement Δs overlapping the two figures. The value of Δs was a function of rotation velocity around the circumference or, equivalently, the light velocity relative to the rotating sensor depended of whether light beam travelled towards or opposite to the rotational velocity.

In particular, the displacement of fringes respectively occurred on the right or on the left when the rotational velocity was clockwise or anticlockwise and the entity of Δs was directly proportional to the value of rotational velocity and depended on light wavelength.

In the GPS system all the time calculations are performed assuming a non rotating Earth – centred frame or reference in which light speed is considered isotropic.

In this case the motion of receiver, due to the Earth rotation around its axis during the time the signal travels from the transmitter (satellite) to receiver (control stations or terminals), determines a shifting of the location of the GPS receiver during this time interval and must be carefully accounted for to ensure accurate navigation results. In fact the importance of the corresponding correction can reach even the value of hundreds of ns.

The interpretation of Sagnac effect is one of the most important facts in physics because of its deep consequences on its foundations. The key question is if it can be considered as a purely relativistic effect (so perfectly explainable within the Theory of Relativity) or if it indicates the presence of a new law of Nature.

So far all the attempts to explain the origin of this effect in the context of commonly accepted formulation of Theory of Relativity has failed for many reasons [2]. The problem is related to one of the most important postulate of STR namely the isotropy of light velocity (respect to the observer) in all the possible inertial frames and the consequent use of the Einstein's synchronization procedure.

In fact, it has been shown [2] that all the attempts to explain the effect by means of STR (as well as General Relativity) inevitably lead to the negation of the constant light velocity postulate and then are incompatible with STR itself.

One of the most common mistakes of the above attempts is to think that the anisotropy of light velocity in the Sagnac effect is actually due to rotation and to the presence of non inertial frame in which the STR is not applicable for definition. Nevertheless, as showed by Hatch [2] studying the GPS systems, rotation is only casually involved in the process and the motion of receiver during the signal transit time must be account for independently of the cause and trajectory of motion and the path followed by the receiver during the arrival time is irrelevant.

The solution to this dilemma, as we'll see can be obtained only by adopting a radically different point of view namely the reformulation of STR without using the postulate of isotropy of light velocity and assuming the existence of a preferred inertial frame in which absolute simultaneity holds. The origin of Sagnac effect is in fact due to non-isotropic propagation of light occurring every time an observer (or a measurement instrument) is moving with respect to the unique inertial frame in which light propagation is truly isotropic i.e the preferred one, defined, as we see in the following, by the IT.

On the other hand, in the GPS system this conception is actually already applied since the rate of the satellite and receivers clocks is adjusted not as a function of their relative velocity but considering their velocity with respect the quasi – inertial non – rotating frame centred to Earth that thus *de facto* acts as a preferred inertial frame.

III. THE INERTIAL TRANSORMATIONS AND THE REFORMULATION OF SPECIAL THEORY OF RELATIVITY

It has been shown that it is possible, considering only homogeneity of empty space and time and the Relativity Principle (RP), to build "alternative" versions of Special Theory of Relativity (STR), without assuming the invariance of light velocity in vacuum [3]. This result is also related to the non – measurability of the velocity of light, independently of conventions concerning the synchronization of distant clocks [3].

This synchronization is then substantially conventional and is not necessarily related to true properties of physical reality [3] as known to Einstein itself [3].

The Lorentz Transformations (LT) realize a complete equivalence between an inertial frame S_0, initially supposed to be stationary and in which the one - way velocity of light is assumed to be invariant, and all the other infinite possible inertial systems S in relative motion, in which LT leave the one way velocity of light equal to c in all directions ("Einstein synchronization").

The system S_0 then loses its "particularity" and becomes equivalent to any other inertial frame in the Universe. Nevertheless, the alternatives synchronization methods give rise to different space and time transformations, of which LT only represent a special case. Among these, the IT, founded by Selleri represent the best choice, since they are able to reproduce all the experimental evidences of STR [3].

If we consider two inertial frames S_0 and S, respectively specified by the space and time coordinates (x_0, y_0, z_0, t_0) and (x, y, z, t), in motion with relative velocity v along the $x_0 = x$ axis, the IT are defined by the following equations:

$$\begin{aligned} x &= \left(x_0 - \beta c t_0\right)\Big/\sqrt{1-\beta^2} \\ y &= y_0 \\ z &= z_0 \\ t &= \sqrt{1-\beta^2}\, t_0 \end{aligned} \qquad (1)$$

where $\beta = v/c$ and c is the invariant one – way velocity of light measured in S_0 [3].

The IT (1) implies [3]: the definition of absolute synchronization (namely two events taking place in different points of the system S but at the same time t are considered to be simultaneous also in the system S' and vice versa) and the existence of a "preferred" inertial frame S_0. The latter is called "preferred" because it is that in which the first synchronization of clocks is made according to the Einstein method, and where the speed of light is isotropic and equal to c, while, in the moving frame S it is given by

$$c'(\theta) = c\Big/\left(1 + \beta\cos\theta\right) \qquad (2)$$

where c' and θ respectively are the speed of light and the polar angle in the system S.

IV. THE EXPLANATION OF SAGNAC EFFECT AND THE NECESSITY OF NEW PICTURE OF TIME

In 1980 the CCDS (Comité Consultatif pour la Définition de la Seconde) has stated the rules, internationally accepted, to perform clocks synchronization between different Earth locations. There are two options: the first one is to initially adjust time when the clocks are at the same point and then transport one clock very slowly to the destination point; the second option is to use an electromagnetic signal to be transmitted between the two clock locations. In any case, before the comparison between the two time readings, the codified procedure prescribes, as above discussed, the application of three correction factors: a) the relativistic one proportional to $v^2/2c^2$ (where v is the speed of clock travel) as indicated by STR; b) the "gravitational" one generated by the Earth gravitational field as indicated by General Theory of Relativity (GTR) and proportional to $g(\alpha, h)/c^2$ (where $g(\alpha, h)$ is the total acceleration at latitude α and altitude h); the last one is a correction proportional to $2S\omega/c^2$, where S is the equatorial projection of the surface delimited by the clock / signal path and the segments connecting the two position considered (initial and final position of clocks) with the Earth centre.

The third correction, usually and incorrectly ascribed to earth rotation, cannot be derived, as discussed above, within the commonly accepted framework of Theory of Relativity and represent the consequence of Sagnac effect that, as we'll see, can be correctly interpreted through the IT, as the anisotropy of light velocity in the rotating Earth frame.

In the experiment of Saburi et al. [5] an electromagnetic signal is sent from a city A (east) to a city B (west) placed on the same parallel (see fig. 2). If the two clocks are synchronized by assuming an isotropic light velocity equal to c, we should write

$$t_A - t_B = \Delta t_{AB} = D_{AB}/c \qquad (3)$$

where t_A is the starting time, t_B the time of arrival and $D_{AB} = r\theta$ the geodetic distance between A and B.

Nevertheless, the experimental result obtained by Saburi didn't agree with (3), so he was forced to add a correction term "at hand" in order to give the correct result and whose form is the same of that proposed by CCDS. This expression can be simply explained in terms of IT.

According to IT, the one way velocity of light in the east – west direction is different from that in west – east direction and it is equal, by eq. (2) with $\theta = 0$, to

$$c_{EW} = c/(1+\beta) \tag{4}$$

with $\beta = \omega r/c$.

The correction $\Delta t'_{AB}$ to be applied to (3) is, by means of (4)

$$\Delta t'_{ab} = D_{AB}/c_{EW} \tag{5}$$

and the corrected interval time of arriving at B is

$$\begin{aligned} \Delta t_B &= \Delta t'_{AB} - \Delta t_{AB} = \\ &= D_{AB}/c_{EW} - D_{AN}/c = D_{AB}\beta/c \end{aligned} \tag{6}$$

that is positive, being $c > c_{EW}$. We can now write (6) as

$$\Delta t_B = r^2\omega\theta/c^2 = 2\omega A/c^2 \tag{7}$$

where $A = r^2\theta/2$ is the area of the triangle AOB in fig. 2.

The origin and the "mysterious" form of the correction required in GPS system to account for the Sagnac effect is then very simply explained considering the alternative version of STR based on IT.

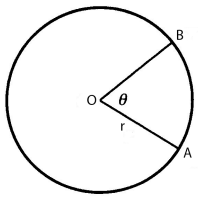

Fig.2. Electromagnetic signal from A to B

V. CONCLUSIONS

We have seen the occurrence of Sagnac effect, as confirmed by GPS, implies the light velocity respect to Earth is different as a function of the propagation direction, while it results isotropy only when referred to a privileged system as, for example, with a good approximations, a geocentric non – rotating frame. If an observer placed at Earth at a given point could contemporary send two light signals around the Earth the first to East and the second to West they would came back at different times.

In this case the effect cannot be determined by a invoking relative motion between source and receiver but only to a property of light that propagates with different velocity in the different directions. This phenomenon is obviously crucial in the synchronization procedures of the GPS control stations and it must be accounted for. Actually it is considered but only as a correction to a wrong calculation based on the isotropic light propagation. But it is conceptually and practically meaningless because it would be sufficient to consider, from the beginning, the difference in light velocity in order to automatically have a correct results, and this is just what the IT do. On the other hand a further confirmation of this fact is given by the GPS system itself because, after a first synchronization, they automatically "include" this correction giving the right time interval, since it light itself that transports this information. It is only when we try to calculate time through "standard" STR based on Lorentz transformations that the calculation result wrong, making it necessary to introduce "at hand" the Sagnac correction.

A first very important consequence of this reasoning is that a correct interpretation of light behaviour can be achieved only within a theory based on absolute simultaneity (i.e. that defined with respect a preferred inertial frame) in which, as occurs in the GPS, the clocks rates are adjusted not as a function of their relative velocity but of the velocity of each of them with respect the preferred (nearly) inertial Earth – centred non rotating inertial frame. The experimental results derived from GPS then give further experimental evidences of the correctness of IT and of the need for a new formulation of Theory of Relativity based on them. It has, as already shown [3], very deep consequences not only upon the definition of simultaneity but also on the meaning of time itself that must be considered as duration, namely as a mathematical parameter giving the numerical order of physical changes.

Within this picture, the correct synchronization of two clocks can be achieved only when they are synchronized in a resting "special" inertial frame and are subsequently used for the synchronization of all the other clocks located in the moving inertial frames in the instant when they meet the rest clocks. This method obviously leads to the inequality of different inertial frames among which the "preferred" one is that where the first synchronization of clocks takes place.

This conceptual framework could also be invoked to successfully explain another experimental fault of Einstein's Theory of Relativity related to GPS operation, that is the question known as "noon – midnight" problem, related to the absence in the difference between the rate of a clock, placed at a given position on Earth surface, at midday and midnight. The solution of this question, within the discussed model, will be considered in a forthcoming paper.

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