

Reinterpretation of the Michelson-Morley experiment based on the GPS Sagnac correction

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Abstract. – By examining the effects of rotational and orbital motions of the Earth on wave propagation in the global positioning system and an intercontinental microwave link, it is pointed out that the Earth's orbital motion has no influence on these earthbound wave propagations, while the Earth's rotation does contribute to the Sagnac effect. As the propagation mechanism in the Michelson-Morley experiment cannot be different from that in the aforementioned ones, it is concluded that due to the Earth's rotation, the shift in interference fringe in this famous experiment is not exactly zero. However, by virtue of the round-trip propagation path, this shift becomes second order and hence is too small to observe within the present precision.

Introduction. – Before the advent of Einstein's special relativity, it was generally believed that electromagnetic waves propagate by means of a universal medium called ether. Michelson and Morley attempted to measure the velocity of the Earth with respect to the supposed universal ether by using interferometry. As is well known, in 1887 the Michelson-Morley experiment came out with null result of zero (actually, an unexpectedly small) phase shift which indicates that the speed of the Earth with respect to the supposed ether is much lower than 30 km/s, the linear speed due to the Earth's orbital motion around the Sun [1, 2]. Meanwhile, it is generally believed that the Earth should not happen to be stationary with respect to the universal ether and hence the speed of the Earth with respect to the supposed universal ether should at least be this linear speed due to orbital motion. This reasoning together with the null result makes the existence of the universal ether unacceptable. After the introduction of the special relativity in 1905, the notion of ether eventually becomes obsolete and it is now widely accepted that both rotational and orbital motions of the Earth have no effect on wave propagation in the Michelson-Morley experiment.

Recently, an application that is heavily based on a highly accurate propagation model and has been put in everyday practice ubiquitously is the global positioning system (GPS) [3]. By virtue of its high precision, GPS provides a decisive evidence in determining the propagation mechanism of electromagnetic waves. It is expected that the propagation mechanism in the Michelson-Morley experiment cannot be different from that in GPS. Thereby, based on the propagation model actually adopted in GPS and other high-precision propagation experiments, we re-examine the Michelson-Morley experiment, particularly the effects of the Earth's rotational and orbital motions on wave propagation.

GPS propagation model and Sagnac correction. – It is well known that GPS provides a high accuracy in positioning. The NAVSTAR GPS employs about 24 half-synchronous satellites carrying highly precise and synchronized atomic clocks around six nearly circular orbits of radius of about 26600 km [3]. Each GPS satellite repeatedly broadcasts microwaves carrying a sequence of its own unique codes which can be used by a receiver to determine the propagation delay time from the satellite to the receiver and then the instant of signal emission.

The satellite position \mathbf{r}_s at the instant t' of signal emission can be easily determined from the instant t of signal reception, the propagation time $\tau (= t - t')$, and the satellite ephemeris constants. Then the position \mathbf{r}_e of a geostationary receiver at the instant of signal emission is related to the satellite position \mathbf{r}_s at this instant implicitly by the range formula

$$R = R_t + \mathbf{R}_t \cdot (\bar{\omega}_E \times \mathbf{r}_e)/c = R_t + 2\mathbf{S} \cdot \bar{\omega}_E/c, \quad (1)$$

where c is the speed of light, the propagation range $R = \tau c$, the propagation-path length $R_t = |\mathbf{R}_t|$, $\mathbf{R}_t (= \mathbf{r}_e - \mathbf{r}_s)$ denotes the directed separation distance from the transmitter to the receiver both referred at the instant of emission, the position vectors \mathbf{r}_e and \mathbf{r}_s are given with respect to the Earth's center, $\bar{\omega}_E$ is the directed Earth's rotation rate, and $\mathbf{S} (= \mathbf{r}_s \times \mathbf{r}_e/2)$ denotes the directed area of the triangle with vertices at the satellite, the receiver, and the Earth's center [4,5]. The term associated with the Earth's rotation rate is known as the GPS Sagnac correction. This range formula is practiced numerously everyday around the globe.

Recently, we have investigated the propagation of electromagnetic waves from a classical approach, by deliberately selecting a unique reference frame of propagation with respect to which the wave-propagation speed is isotropic [6–8]. According to the classical propagation model, the propagation time is given as $\tau = R/c$ and the propagation range R is the distance from the position \mathbf{r}_s of the transmitter at the instant t' of wave emission to the position \mathbf{r}_e of the receiver at the instant t of reception. That is, the propagation range is given as

$$R = |\mathbf{r}_e(t) - \mathbf{r}_s(t')| = |\mathbf{R}_t + \mathbf{r}_e(t) - \mathbf{r}_e(t')|, \quad (2)$$

where the position vectors \mathbf{r}_e and \mathbf{r}_s are referred to the unique propagation frame. It is of the essence to note that there is a significant discrepancy between the two closely related quantities R_t and R in their dependences on the reference frame. The propagation-path length R_t is associated with two positions at the *identical* instant and hence is invariant in different frames, whereas the propagation range R in general is different in different frames, since it is associated with two positions (or with the receiver position) at two *distinct* instants. Only when referred to the unique propagation frame is the propagation range related to the propagation time in the simple form of $\tau = R/c$. Otherwise, the propagation speed as well as the propagation range will change in a complicated way to make the propagation time remain invariant in a different frame. It can be convenient to express the propagation time in terms of the frame-independent path length. However, due to the movement of the receiver, the propagation time τ is not equal to R_t/c , although the difference is slight ordinarily. To keep this simple relation with a high accuracy, a treatment in the path length is needed. The difference between the propagation range R and the path length R_t is known as the Sagnac effect which is due to the movement of the receiver during wave propagation with respect to the unique propagation frame. For a receiver moving at a fixed velocity \mathbf{v}_e , the classical propagation-range formula given to the first-order normalized speed (with respect to c) is

$$R = R_t + \mathbf{R}_t \cdot \mathbf{v}_e/c, \quad (3)$$

where the receiver velocity \mathbf{v}_e is referred to the unique propagation frame [8].

For a geostationary receiver, its velocity is zero and $\bar{\omega}_E \times \mathbf{r}_e$ with respect to the ECEF (earth-centered earth-fixed) and an ECI (earth-centered inertial) frame, respectively, while, if the receiver velocity is referred to a heliocentric inertial frame or even to a frame beyond the solar system, the Earth's orbital motion should be taken into account in addition. Evidently, the classical propagation-range formula (3) is identical to the GPS range formula (1), if and only if $\mathbf{v}_e = \bar{\omega}_E \times \mathbf{r}_e$ for a geostationary receiver. Thereby, the wave propagation in GPS can be viewed in a classical way, if an ECI frame, rather than the ECEF or any other frame, is selected as the unique propagation frame. Thus the wave propagation in GPS depends on the Earth's rotation, but is entirely independent of the Earth's orbital motion. The actual value of the Sagnac range correction due to the Earth's rotation depends on the positions of satellites and receiver and a typical value is 30 m. The GPS provides an accuracy of about 10 m or better in positioning. Thus the precision of GPS will be degraded significantly, if the Sagnac correction due to the Earth's rotation is not taken into account. On the other hand, the orbital motion of the Earth around the Sun has a linear speed about 100 times that of the Earth's rotation. Thus the present high-precision GPS would be entirely impossible if the ignored correction due to orbital motion is really necessary. Thereby, it is concluded that the wave propagation in GPS is actually in accord with *the classical propagation in an ECI frame*.

GPS is not the only experiment in which the wave propagation is referred uniquely to an ECI frame. In an intercontinental microwave link between Japan and USA via a geostationary satellite as relay, the influence of the Earth's rotation is also demonstrated in a high-precision time comparison between the atomic clocks at two remote stations [9]. In this transpacific-link experiment, a synchronization error as large as about $0.3 \mu\text{s}$ was observed unexpectedly and then is attributed to the Sagnac effect due to the Earth's rotation after a detailed analysis, while no effects of the Earth's orbital motion are reported, although they would be easier to observe if they do exist. Moreover, Michelson and Gale have demonstrated the Sagnac effect due to the Earth's rotation by using a geostationary interferometer composed of a closed propagation path along which two coherent waves propagate in opposite directions. Although the propagation paths for these two counterpropagating waves are identical in structure, the propagation ranges tend to be different owing to the Sagnac effect associated with the movement of propagation paths with the Earth's rotation. Thereby, the phase difference between the two waves results in an interference fringe, as derived in a classical approach [8]. By constructing a loop interferometer enclosing an area as large as 0.2 km^2 , the Earth's rotation has been detected as early as in 1925 [10], while the following attempt to detect the Earth's orbital motion by using a similar terrestrial interferometer was unsuccessful.

However, not all the wave propagations are referred to an ECI frame. Consider the interplanetary radar, where a microwave signal is transmitted from the Earth to Venus, Mercury, Mars, or to a spacecraft, and then back to the Earth. It is of the essence to note that the measurement data in the high-precision interplanetary radar echo time show excellent agreement with those based on the classical propagation-range formula (2) in a heliocentric inertial frame [6, 11, 12]. Needless to say, a heliocentric frame is a convenient reference frame in dealing with the position vectors and the propagation path for the associated planets under the influence of the gravity due to the Sun. More importantly, a significant implication is that the wave propagation is referred uniquely to this heliocentric inertial frame. Accordingly, both the rotational and the orbital motions of the Earth and the orbital motion of the target planet contribute to this two-way Sagnac effect. Moreover, the deflection of a light beam passing near the Sun has also been derived based on a new classical model in a heliocentric inertial frame [7].

It may be puzzling to note that the interplanetary radar can be viewed as a microwave link via a planet or a spacecraft as relay, while its propagation frame is different from that in the

intercontinental link. The discrepancy in the unique propagation frame can be solved by the *local-ether model* of wave propagation recently presented [13]. In this new classical model, it is supposed that electromagnetic waves propagate via a medium like the ether. However, the ether is not universal. It is proposed that in the region under sufficient influence of the gravity due to the Earth, the Sun, or another celestial body forms a local ether which in turn moves with the gravitational potential of the respective body. Thereupon, each local ether together with the gravitational potential moves with the associated celestial body. Thus, as well as the Earth's gravitational potential, the Earth local ether is stationary in an ECI frame, while the Sun local ether for the interplanetary propagation is stationary in a heliocentric inertial frame.

Reinterpretation of Michelson-Morley experiment. – Then we proceed to consider the Michelson-Morley experiment of the interference between two light beams in two orthogonal propagation paths formed by beam splitter and mirror. In each of the two optical arms, light propagates from the beam splitter to a mirror and back. Thus, like that in monostatic radar, the propagation path is of round-trip nature. Based on the classical propagation model, the round-trip propagation time can be given from (2). To the second order of normalized speed, the round-trip propagation time τ is given as [6]

$$\tau = \frac{2R_t}{c} \left\{ 1 + \frac{v^2}{2c^2} (1 + \cos^2 \theta) \right\}, \quad (4)$$

where \mathbf{v} is the *velocity* of the propagation path, R_t is the path length between beam splitter and mirror in each optical arm, and θ is the angle between \mathbf{v} and \mathbf{R}_t . It is of the essence to note that the first-order Sagnac correction cancels out in this round-trip formula. The difference in the round-trip propagation time between the two paths corresponds to a phase difference which in turn can manifest itself as an interference fringe pattern by suitably arranging the arms. As the interferometer is rotating, the two values of angle θ and hence the two propagation times will vary. Consequently, a variation in the interference fringe can be observed, if the variation in the phase difference is large enough.

In the original proposal, the velocity \mathbf{v} was supposed to incorporate the Earth's orbital motion around the Sun. Thus, at least, $v \simeq 30$ km/s and $v^2/c^2 \simeq 10^{-8}$. Then the amplitude of the phase-difference variation could be as sufficiently large as $\pi/3$, as the wavelength $\lambda = 0.6 \mu\text{m}$ and the path length $R_t = 10$ m. It is well known that such a large variation in fringe pattern is never observed. Consequently, the effect of the Earth's orbital motion is ruled out. Although this null result surprised the physics community 100 odd years ago, it is simply in accord with the more recent experiments of GPS, intercontinental microwave link, and loop interferometer. Further, in the present common understanding, the null result is extrapolated without direct evidences to rule out the effect of the Earth's rotation on wave propagation, as in Einstein's original paper on special relativity where it is assumed that $\tau = 2R_t/c$ [14].

However, according to the local-ether model of wave propagation, the Earth's rotation does affect earthbound wave propagation, although the Earth's orbital motion does not. Anyway, the propagation mechanism in the Michelson-Morley experiment in no way can be different from that in GPS and earthbound microwave link, from the standpoint of any plausible propagation model. The null effect of the Earth's orbital motion in the Michelson-Morley experiment reflects no Sagnac correction due to this motion in GPS. On the other hand, the Sagnac effect due to the Earth's rotation in the high-precision GPS and intercontinental microwave link should reflect a nonnull effect of the Earth's rotation in the Michelson-Morley experiment.

The difficulty in the Michelson-Morley experiment is that, owing to the round-trip path, the effect becomes second order, while the Sagnac effect in the Michelson-Gale experiment with loop interferometer is of the first order. This round-trip Sagnac effect is as small as $v^2/c^2 \sim 10^{-12}$, as the linear speed due to the rotation is about 464 m/s at the Earth's equator. To observe such a predicted effect of the Earth's rotation, the precision of the Michelson-Morley experiment should be 10^4 times that designed to detect the orbital motion. According to the various measurements surveyed in [1], the interferometer precision has been increased by Joos to a few hundred times the minimum requirement for orbital motion. Thus, in order to test the effect of the Earth's rotation, the precision should be further improved more than tenfold. Thereby, based on the local-ether model or on the Sagnac effect in GPS and intercontinental microwave link, *the variations in the round-trip propagation times are not exactly zero, but are currently too small to cause a detectable shift in the interference fringe*, when the optical arms are changing their directions. This reinterpretation of the Michelson-Morley experiment is fundamentally different from that based on the special relativity, although the difference is quite small in magnitude.

Conclusion. – By examining the Sagnac effect in GPS and a transpacific microwave link, it is found that the Earth's orbital motion has no influence on these earthbound wave propagations. However, the Earth's rotation does contribute to the Sagnac effect. Thus the propagation mechanism in these microwave signals is actually in accord with the classical model with the unique propagation frame being an ECI frame. As the propagation mechanism in the terrestrial Michelson-Morley experiment in no way can be different from that in GPS and intercontinental microwave link, it is concluded that by virtue of the round-trip Sagnac effect due to the Earth's rotation, the shift in interference fringe in the Michelson-Morley experiment is not exactly zero, but is too small to detect. This reinterpretation is fundamentally different from that based on the special relativity, although the difference is quite small in magnitude. These earthbound experiments along with the interplanetary ones then provide a support for the local-ether model of wave propagation recently presented.

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