One-way Speed of Light Using Interplanetary Tracking Technology

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Abstract: The one-way speed of light is determined using the range equations employed in the tracking of planets and spacecrafts moving within our solar system. These equations are based on the observation that light travels in the sun-centered inertial frame at a constant speed *c* and have been extensively tested and rigorously verified. For light reflected from an object moving in space the light speed detected on the surface of the moving Earth is found to be $c+v$ and $c-v$ relative to the receiving antenna for the Earth moving at orbital speed *v* in directions toward and away from the reflector. This finding is consistent with results first presented by Wallace and later by Tolchel'nikova but is at variance with the postulate of light speed constancy.

Keywords: One-way speed of light; range equations; postulate of light speed constancy; solar barycentric frame, sun-centered frame.

Introduction

The idea that light travels at a constant speed in all inertial frames is central to modern physics and metrology [1, 2]. Over the years numerous experiments have been conducted to test this postulate [3]. The first among these was the Michelson-Morley experiment [4] that searched for ether drift based on light speed changes and interferometer fringe shifts. This experiment involved interfering light beams that traversed orthogonal paths on a movable apparatus. It was designed to reveal the speed of the Earth's orbital motion through the hypothesized ether based on the expected change in light speed arising from movement with or against the associated ether wind. The recorded fringe shift was significantly less than the value expected as a result of the revolving Earth and the essentially null result was interpreted as an indication of light speed constancy. Modern versions of this experiment use electromagnetic resonators in search of light speed anisotropy [5-9]. They compare the resonant frequencies of two orthogonal resonators and seek to detect light speed changes arising from orbital or rotational motion of the Earth. These experiments conducted in the frame of the rotating Earth have progressively lowered the limit on light speed anisotropy to a value of $\delta c / c < 10^{-17}$ where δc is the measured change in light speed. There are published cases of Michelson-Morley type experiments which produce positive results including experiments by Demjanov [10], Galeav [11], Winkell and Rodríguez [12] and Gift [13] but these have generally been ignored. Instead the preponderance of negative tests has encouraged the almost universal belief that the light speed constancy postulate has been confirmed.

Zhang [3] has shown that what the null Michelson-Morley type experiments have established is two-way light speed constancy and that one-way light speed constancy remains unconfirmed. Some experiments appearing to yield one-way light speed invariance have been conducted including those by Gagnon et.al. [14], Krisher et.al. [15] and Riis et.al. [16] but these are not true one-way tests because of the inability to obtain independently synchronized clocks [3]. Recently Spavieri [17] examined the issue of one-way light speed and suggested an indirect method for its determination.

Following the failure of the Michelson-Morley experiment to detect the orbital motion of the Earth, Michelson [18] suggested a test to detect the rotational motion of the Earth. Specifically he proposed that if the ether is not entrained by the rotating Earth then two rays of light circumnavigating the Earth in opposite directions would do so in measurably different times that are dependent on the rotational speed w of the Earth. This is because the ray travelling westward would do so at a speed $c + w$ while the ray travelling eastward would do so at a speed $c - w$. Michelson and Gale [19] confirmed the predicted fringe shift arising from the rotating Earth using a very large rectangular path fixed on the surface of the Earth. It was repeated with greater precision by Bilger et al. [20] using laser technology.

While the Michelson-Gale experiments give results consistent with the differences in light travel time predicted by Michelson for light travelling in opposite directions around the rotating Earth, they do not directly measure these time differences and therefore only indirectly indicate light speed variation. What is needed is a direct measurement of one-way light transmission time between two fixed points on the surface of the Earth such as attempted by Allen et al. [21]. The global positioning system (GPS) seems to possess the technology to implement this and thereby enable a true one-way light speed test on the surface of the Earth. It is a modern navigation system that employs accurate synchronized atomic clocks in its operation [22]. According to the IS-GPS-200E Interface Specification [23], GPS signals propagate in straight lines at the constant speed c (in vacuum) in an Earth-Centered Inertial (ECI) frame, a frame that moves with the Earth but does not share its rotation. This isotropy of the speed of light in the ECI frame is employed in the range equation of the GPS for the accurate determination of the instantaneous position of objects which are stationary or moving on the Earth. Based on the GPS Marmet [24] observed that time measurements using the synchronized clocks reveal that light signals take 28 nanoseconds longer travelling eastward from San Francisco to New York as compared with the signals traveling westward from New York to San Francisco. Also using GPS time measurements Kelley [25] pointed out that a light signal takes 414 nanoseconds longer to circumnavigate the Earth eastward at the equator than a light signal travelling westward around the same path. From these recorded differences in light travel times these researchers deduced light speeds $c-w$ eastward and $c+w$ westward relative to the surface of the earth where w is the speed of rotation of the Earth's surface at the particular latitude. Gift has directly confirmed and generalized this East-West light speed anisotropy $c \pm w$ resulting from the Earth's rotation using the CCIR clock synchronization algorithm [26] as well as the GPS range equation [27]. Thus while Michelson failed to detect light speed changes for the Earth's orbital motion in his celebrated experiment of 1887, his 1904 proposal [18] to detect light speed changes arising from rotational motion has now been indirectly and directly confirmed. This is an important scientific development that should be given due consideration by the scientific community.

In addition to the confirming evidence of light speed anisotropy in frames on or close to the surface of the Earth arising from its rotation, it turns out that there is also strong evidence of light speed variation resulting from the Earth's orbital motion for light travelling in space beyond the terrestrial frame where the unsuccessful Michelson-Morley experiments were conducted. In research done more than 40 years ago, Wallace [28] used published interplanetary data and presented evidence for the classical composition of light speed c in space and Earth's orbital speed v giving light speed $c+v$ relative to the moving Earth. The same result was obtained by Tolchel'nikova in 1991 [29]. Light speed variation involving orbital speed for light travelling through space was recently observed on Earth for light from planetary satellites in the Roemer experiment [30] and for light from stars on the ecliptic in the Doppler experiment [31]. Light speed anisotropy arising from the orbital motion of the Earth has also been reported in a laser diffraction experiment [32], for light propagation over cosmological distances [33] and in the Shtyrkov experiment involving the tracking of a geostationary satellite [34].

Following these many positive indications of light speed variation, we have further examined the phenomenon of speed variation for light travelling through space using another approach. Specifically equations used in tracking planets and spacecrafts are used to determine the one-way speed of light reflected from a planet or spacecraft and observed from the orbiting Earth moving in the solar barycentric frame.

One-way Light Speed in the Sun-Centered Inertial Frame

While position on the Earth can be precisely determined using the range equation of the GPS operating in the ECI frame, the orbital ephemerides of the planets and other bodies in the solar system are determined using a different set of range equations operating within the solar barycentric or sun-centered inertial (SCI) frame [35-37]. The SCI frame is a frame that moves with the Sun but does not rotate with it and provides a convenient reference frame for many astronomical events. The associated range equations are used to determine round-trip time of an electromagnetic signal that emanates from a transmitting antenna on Earth and is reflected by a spacecraft transponder or planetary body back to the same antenna on Earth. Time measurement is effected using atomic clocks based on Coordinated Universal Time (UTC) and the spatial coordinates are relative to the solar-system barycenter of the SCI frame.

The relevant range equations are given by [35-37]

$$c\tau_u = \left| r_B(t_R - \tau_d) - r_A(t_R - \tau_d - \tau_u) \right| \tag{2}$$

$$c\tau_d = \left| r_A(t_R) - r_B(t_R - \tau_d) \right| \tag{3}$$

where t_R is the time of reception of the signal, τ_u and τ_d are the up-leg and down-leg times respectively, r_A is the solar-system barycentric position of the receiving antenna on the Earth's surface, r_B is the solar-system barycentric position of the reflector which is either a responding spacecraft or the reflection point on the planet's surface and c is the speed of light in the SCI frame. These equations are based on the observation that light travels in the SCI frame at a constant speed and have been rigorously tested and verified. They are derived using data sets acquired over more than half a century of measurement. In order to obtain values for τ_u and τ_d, the two equations are solved iteratively. In practice time corrections must be made to τ_u and τ_d because of relativistic effects, the electron content of the solar corona and the Earth's troposphere [36, 37].

In determining one-way light speed using this system, consider a transmitting/receiving antenna A fixed on the surface of the Earth which is moving in the SCI frame at orbital speed v relative to the SCI frame and a reflecting spacecraft B stationary or moving relative to the SCI frame. On an axis fixed in the SCI frame along the line joining antenna A and spacecraft B at the instant of signal reflection with antenna A closer to the origin O than spacecraft B and taking positive values, let r_A be the coordinate along the axis of the position in the SCI frame of antenna A and r_B be the coordinate along the axis of the position of spacecraft B. At the time of reflection of the signal from B, let the distance between A and B be L given by

$$r_B(t_R - \tau_d) - r_A(t_R - \tau_d) = L \tag{4}$$

Antenna moving toward Reflector

At the instant of reflection of the electromagnetic signal at reflector B let antenna A move directly toward the reflector B at orbital speed v relative to the SCI frame. Then using the range equation (3),

$$c\tau_d = r_B(t_R - \tau_d) - r_A(t_R) \tag{5}$$

Since (for sufficiently small L) antenna A is moving uniformly toward reflector B at speed v relative to the SCI frame, it follows that the relation between the position $r_A(t_R)$ of antenna A at the time of reception of the signal and its position $r_A(t_R - \tau_d)$ at the time of reflection of the signal at reflector B is given by

$$r_A(t_R) = r_A(t_R - \tau_d) + \tau_d v \tag{6}$$

Substituting for $r_A(t_R)$ from (6) in (5) yields

$$c\tau_d = r_B(t_R - \tau_d) - r_A(t_R - \tau_d)) - \tau_d v \tag{7}$$

Using (4) this becomes

$$r_B(t_R - \tau_d) - r_A(t_R - \tau_d) = L = (c + v)\tau_d \tag{8}$$

Hence for an observer on Earth the range equation (3) yields the down-leg time as

$$\tau_d = \frac{L}{c + v} \tag{9}$$

Therefore the speed c_{BA} of the electromagnetic signal relative to antenna A traveling from the reflector B to the moving antenna A is given by the separation L at the time of reflection divided by the down-leg time τ_d which using (9) is

$$c_{BA} = \frac{L}{\tau_d} = \frac{L}{L/(c+v)} = c + v \tag{10}$$

This speed is different from the light speed c that is required by the postulate of light speed constancy.

Antenna moving away from Reflector

At the instant of reflection of the electromagnetic signal at reflector B let antenna A move directly away from the reflector B at orbital speed v relative to the SCI frame. Then using the range equation (3),

$$c\tau_d = r_B(t_R - \tau_d) - r_A(t_R) \tag{11}$$

Since antenna A is moving uniformly away from reflector B at speed v relative to the SCI frame, it follows that the relation between the position $r_A(t_R)$ of antenna A at the time of reception of the signal and its position $r_A(t_R - \tau_d)$ at the time of reflection of the signal at reflector B is given by

$$r_A(t_R) = r_A(t_R - \tau_d) - \tau_d v \tag{12}$$

Substituting for $r_A(t_R)$ from (12) in (11) yields

$$c\tau_d = r_B(t_R - \tau_d) - r_A(t_R - \tau_d)) + \tau_d v \tag{13}$$

Using (4) this becomes

$$r_B(t_R - \tau_d) - r_A(t_R - \tau_d) = L = (c - v)\tau_d \tag{14}$$

Hence for an observer on Earth the range equation yields the down-leg time as

$$\tau_d = \frac{L}{c - v} \tag{15}$$

Therefore the speed c_{BA} of the electromagnetic signal relative to antenna A traveling from the reflector B to the moving antenna A is given by the separation L at the time of reflection divided by the down-leg time τ_d which using (15) is

$$c_{BA} = \frac{L}{\tau_d} = \frac{L}{L/(c-v)} = c - v \tag{16}$$

Again this speed is different from the light speed c required by the postulate of light speed constancy.

Results

It follows from (10) and (16) that light travels from the reflector to the antenna on Earth at a speed $c+v$ relative to the antenna for the Earth moving toward the reflector at orbital speed v and light travels at speed $c-v$ relative to the antenna for the Earth moving away from the reflector at orbital speed v. This light speed variation for light traveling in the SCI frame confirms the findings of Wallace [28] and Tolchel'nikova [29] for light travel through space. It is consistent with the light speed changes observed on the orbiting Earth for light from planetary satellites in the Roemer experiment [30] and for light from stars on the ecliptic in the Doppler experiment [31].

In the case where the velocity of the reflecting spacecraft B is such that it is geostationary, then the receiving antenna and reflector are fixed relative to each other as well as to the surface of the moving Earth. In such a case the complete light speed measurement is conducted in the frame of the moving Earth, the same frame used in the vast majority of light speed experiments yielding *c*. These results in the SCI frame like the findings in the Shtyrkov geostationary experiment [34] indicate that the speed v of the uniformly moving Earth is readily detectable with apparatus in which the signal source and receiver are fixed relative to each other and to the moving Earth.

The observed light speed variation involving orbital motion within the SCI frame reported in this paper and elsewhere [28-31] and light speed anisotropy involving rotational motion within the ECI frame [24-27] where light travels at a speed *c* in the chosen frame suggest the existence of multiple preferred frames which are carried along by the Earth and the Sun respectively [38, 39]. Hatch however offers another interpretation in which the basic phenomenon is attributed to clock bias [40]. This phenomenon of light speed being influenced only by movement within a chosen frame calls for further investigation in order to understand the underlying mechanism. Whatever the explanation the detection of light speed variation is incontrovertible and therefore the light speed invariance postulate is inapplicable on the surface of the Earth and the immediate region beyond.

Conclusion

The main contribution of this paper is a demonstration of light speed variation using technology for tracking planets and cosmic bodies. The equations used to track planets, interplanetary space probes and other space vehicles involving UTC measurements and spatial coordinates relative to the solar-system barycentric frame were used to determine one-way light speed for light travelling to Earth from these bodies moving in our solar system. Based on the fact of the isotropy of the speed of light in the SCI frame, the speed of light reflected from a body and travelling to Earth was found to be $c \pm v$ where v is the orbital speed of the Earth toward or away from the reflecting surface at the time of reflection of the signal. The light speeds $c \pm v$ relative to the frame of the moving Earth computed using modern tracking technology are different from the results of the many light speed experiments [4-9] which appear unable to detect such variation [3]. These light speed changes are at variance with the postulate of light speed constancy which requires constant light speed c for light traveling between the reflector and Earth. Since the light speed invariance postulate directly yields the Lorentz Transformations [1, 2], in view of the failure of the postulate these transformations cannot represent the physical world.

Selleri [41] has derived the set of “equivalent transformations” which contains all possible space-time transformations that connect two inertial frames under a set of reasonable assumptions. The transformations are “equivalent” in the sense that they differ only by a clock synchronization parameter. Spavieri [17] discussed the two significant members of this “equivalent” set namely the Lorentz Transformations and the Inertial Transformations and proposed an approach to distinguishing between the two using a test of Faraday’s law for which the two transformations make different predictions. The two transformations can be separated by another method; they make different light speed predictions. The Lorentz Transformations predict (and are derived from) light speed constancy while the Inertial Transformations predict light speed variation $c \pm v$ for $v << c$ [17, 42]. This light speed variation predicted by the Inertial Transformations is precisely what has been demonstrated for rotational and orbital motion in this paper and the many papers cited. This is in accordance with the findings of Gift [43] and Selleri [41, 44] who identified the Inertial Transformations as the transformations that best accord with the physical world.

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