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Chapter 3

GPS and the One-Way Speed of Light

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Additional information is available at the end of the chapter

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1. Introduction

The constancy of the speed of light in a vacuum is a fundamental idea in modern physics and is the basis of the standard of length in metrology since 1983. Its genesis is in the theory of special relativity introduced 100 years ago by Albert Einstein who postulated that light travels at a constant speed in all inertial frames [1-3]. There have been numerous experiments [3] over the past century that test light speed constancy under a variety of conditions and they almost all yield a value c (in vacuum). The first experiment among these that was taken as indicating light speed constancy is the celebrated Michelson-Morley experiment of 1887 that searched for ether drift based on interferometer fringe shifts [4]. 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 using the expected change in light speed arising from movement with or against the associated ether wind. The observed fringe shift was significantly less than what was expected as a result of the revolving Earth. The null result was interpreted as an indication of light speed constancy. This basic experiment was repeated many times over the years with essentially the same results. In 1925 Miller did appear to achieve positive fringe shifts [5] but it was later argued that this resulted from diurnal and seasonal variations in equipment temperature [6].

In 1964 Jaseja et al. introduced a major enhancement of this basic experiment [7]. These researchers employed laser technology to realize a sensitivity increase of 25 times the original experiment but detected no change in the system's beat frequency within its measurement accuracy. A later improved version of the Jaseja experiment by Brillet and Hall [8] searched for light speed anisotropy in the form of changes in the resonant frequency of a cavity resonator. They claimed a 4000-fold improvement over the results of Jaseja et al. and again detected no change. The conclusion from these experiments was that light speed is constant.

Modern versions of the Michelson-Morley experiment operating along the lines of the approach by Brillet and Hall use electromagnetic resonators that examine light speed

isotropy. These systems compare the resonant frequencies of two orthogonal resonators and check for changes caused by orbital or rotational motion. Several experiments of this type have been conducted including experiments by Hermann et al.[9], Muller et al. [10] and Eisele et al. [11]. These experiments have progressively lowered the limit on light speed anisotropy with the most recent measurement being $\delta c / c < 10^{-17}$ where δc is the measured change in light speed. It should be noted however that Demjanov [12] and Galeav [13] have reported positive fringe shifts in recent Michelson-Morley type experiments but these have received little or no attention.

As a result of these many negative tests the almost universal belief among physicists is that the postulate of light speed constancy has been confirmed. However Zhang [3] has shown that what these experiments have established is two-way light speed constancy but that one-way light speed constancy remains unconfirmed. A few experiments testing one-way light speed have been conducted including those by Gagnon et.al. [14] and Krisher et.al. [15] but these too are not true one-way tests because of the apparent inability to independently synchronize the clocks involved [3].

The global positioning system (GPS) utilizes advanced time-measuring technology and appears to provide the means to accurately determine one-way light speed. It is a modern navigation system that employs synchronized atomic clocks in its operation [16]. This system of synchronized clocks enables the accurate determination of elapsed time in a wide range of applications including time-stamping of financial transactions, network synchronization and the timing of object travel. Based on the IS-GPS-200E Interface Specification [17], 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 utilized in the GPS range equation to accurately determine the instantaneous position of objects which are stationary or moving on the surface of the Earth.

Using the system, Marmet [18] observed that GPS measurements show that a light signal takes about 28 nanoseconds longer traveling eastward from San Francisco to New York as compared with the signal traveling westward from New York to San Francisco. Kelly [19] also noted that measurements using the GPS reveal that a light signal takes 414.8 nanoseconds longer to circumnavigate the Earth eastward at the equator than a light signal travelling westward around the same path. Marmet and Kelly both concluded that these observed travel time differences in the synchronized clock measurements in each direction occur because light travels at speed $c - v$ eastward and $c + v$ westward relative to the surface of the earth. Here v is the speed of rotation of the Earth's surface at the particular latitude. This research by Marmet and Kelley was the precursor to a series of papers by this author on the use of GPS technology in the unambiguous demonstration of one-way light speed anisotropy. In this chapter we bring this material together in one place so that the full impact of the technology on this important issue can be better appreciated and the significant results made available to a wider audience.

2. Clock synchronization

In light speed determination, synchronized clocks are required for the timing of a light pulse as it propagates between two separated points. In this regard, the IEEE 1588 Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems defines synchronized clocks as follows: "Two clocks are synchronized to a specified uncertainty if they have the same epoch and measurements of any time interval by both clocks differ by no more than the specified uncertainty. The timestamps generated by two synchronized clocks for the same event will differ by no more than the specified uncertainty." In other words clocks are synchronized if they indicate the same times for the same events and this is realised using a clock synchronization procedure. This is the logical and widely accepted meaning of synchronized clocks and is the one adopted in the chapter. Unfortunately some authors have created a degree of confusion by referring to other modes of clock operation as synchronized clocks, modes which result from what may be referred to as "clock synchronization schemes". Using such clocks, light speed measurement will show a dependence on these different clock synchronization schemes since differently synchronized clocks will measure different time intervals for the same light signal transmission. In fact virtually any value of speed can be obtained by suitably "synchronizing" the measuring clocks and according to Will [20], "a particularly perverse choice of synchronization can make the apparent speed…infinite"! These "apparent" speeds bear no relation to physical reality and are meaningless. A proper clock synchronization method is one that results in clock operation such that clocks indicate the same times for the same events and light speed can be reliably measured using such synchronized clocks.

The synchronization approach discussed by Einstein [1] involves the consideration of two clocks A and B at rest at different points in an inertial frame. Let a ray of light propagate from A directly to B and be reflected at B directly back to A. Let the start time at A as indicated on the clock at A be t_A and let the time of arrival of the light ray at B as indicated on the clock at B be t_B. Finally, let the time of arrival of the reflected ray back at clock A be t'_A. Then, Einstein declared [1] that the two clocks are synchronized if

$$t_B - t_A = t'_A - t_B \tag{1}$$

This synchronization technique demands that "the "time" required by light to travel from A to B equals the "time" it requires to travel from B to A" i.e. that light travels with the same speed in both directions which Einstein "established *by definition*". However it is precisely the light speed in the different directions that we wish to measure and therefore it would be circular logic to assume a priori that light speed in both directions is the same in order to synchronize the measuring clocks.

The GPS utilizes a clock-synchronization procedure that has been exhaustively tested and rigorously verified [16, 17] and now forms part of the specification for the GPS. This procedure for the synchronization of clock stations is also contained in standards published by the CCIR, a committee of the International Telecommunications Union in 1990 and 1997 [19]. Similar rules were established in 1980 by the Consultative Committee for the Definition

of the Second (now the Consultative Committee for Time and Frequency (CCTF)) [19]. In these synchronization procedures, the synchronization of two clocks fixed on the moving Earth is accomplished by transmitting an electromagnetic signal from one clock to the other assuming the postulate of the constancy of the speed of light c then applying a correction to the elapsed time that is said to arise because of the rotating Earth. This adjustment is called the "Sagnac correction" and is today automatically applied to all electromagnetic signals transmitted around the Earth in order to achieve clock synchronization.

This synchronization algorithm has been tested and confirmed in numerous experiments. While there is disagreement about the underlying theory, the procedure works. The resulting GPS clocks are synchronized according to the IEEE definition and enable the determination of one-way light speed relative to observers situated on the rotating Earth. The simple exercise is the transmission of a light or electromagnetic signal between separated GPS clocks fixed on the surface of the Earth and the division of the fixed distance between the clocks by the measured time interval between transmission and reception of the light signal. Since light was used to synchronize the clocks the objection to light speed measurement using these same clocks might be raised. This objection can however be answered by observing that the synchronized clocks have been rigorously and exhaustively tested and verified. In any event such a measurement will serve as a check on the requirement that the measured light speed be consistent with the assumed constant light speed c involved in the synchronization process that follows from the application of the postulate of light speed constancy.

3. One-way light speed test using the GPS clocks

In this section the synchronized clocks of the GPS are used in the one-way determination of the speed of light by timing the transmission of a light signal travelling between two fixed points on Earth. In order to exclude issues associated with the curvature of the Earth's surface and non-inertial frames, we consider a clock A located in a building in one city say Scarborough in the Republic of Trinidad and Tobago and another clock B located at the same latitude in the same building and a short distance l away from clock A. This is shown in figure 1.

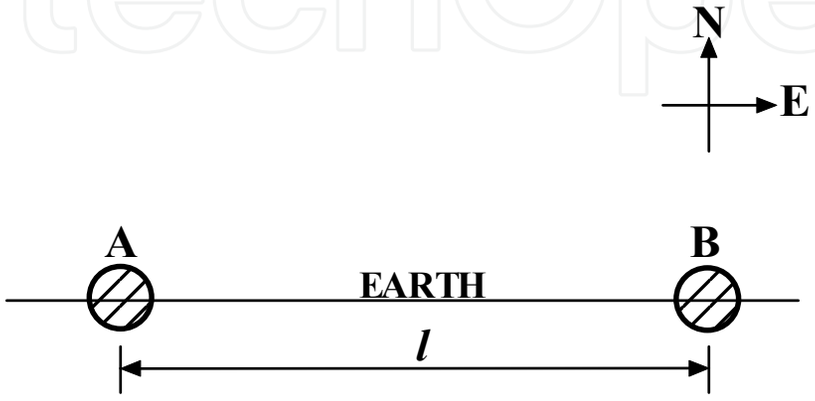

Figure 1. GPS Clocks A and B at fixed positions on Earth

Under such circumstances light travels between the two clocks in a straight line in an approximately inertial frame which is the same as that used in the performance of the many light speed measurements in which c is the reported value [7-11]. It is particularly noteworthy that the one-way experiment by Krisher et al. [15] which searched for light speed changes resulting from rotation of the Earth extended 21 km across the surface of the Earth and appears to violate the inertial requirement. Yet these authors who claimed $\delta c / c < 3.5 \times 10^{-7}$ gave no consideration to any non-inertial effects.

3.1. Eastward transmission

We establish synchronization of the GPS clocks by transmitting a light signal from clock A to clock B. Using the CCIR synchronization rules involving the assumed constancy of the speed of light c along with the so-called Sagnac adjustment, the total time Δt for light to travel the path from clock A to clock B is given by [16, 18]

$$\Delta t = \int_{path} \frac{d\sigma'}{c} + \frac{2\omega_E}{c^2} \int_{path} dA'_z \tag{2}$$

where $d\sigma'$ is infinitesimal distance in the moving frame, ω_E is the angular velocity of the rotating Earth and dA'_z is the infinitesimal area in the rotating coordinate system swept out by a vector from the rotation axis to the light pulse and projected onto a plane parallel to the equatorial plane. Carrying out the integration associated with (2) yields

$$\Delta t = \frac{l}{c} + 2A'_z \frac{\omega_E}{c^2} \tag{3}$$

where l is the distance between the two stations both moving at speed v the speed of the Earth's surface at that latitude. Let the circumference of the Earth at that latitude be l_C and let the corresponding radius be r . Then the area A'_z is given by

$$A'_z = \frac{l}{l_C} \pi r^2 \tag{4}$$

Since $\omega_E = v / r$ and $l_C = 2\pi r$, substituting equation (4) in (3) gives

$$\Delta t = \frac{l}{c} + \frac{lv}{c^2} \tag{5}$$

The first term in (5) corresponds to the light travel time under the assumption of constant light speed c and the second term is the so-called "Sagnac correction" that is said to be required because of the Earth's rotation. This total elapsed time must now be added to clock B such that if at the instant of light transmission the time on clock A is t_A , then at the instant of reception the time t_B on clock B is set to $t_B = t_A + \Delta t$. After this procedure Clocks A and B are synchronized.

Following the synchronization verification of the GPS clocks A and B, we use them to measure one-way light speed. Thus at a specified time, a light signal is transmitted eastward from clock A directly to clock B. Because the clocks have been synchronized using (5), the time interval $\Delta t = t_B - t_A$ between the transmission and reception of the signal is exactly that given in (5) as

$$\Delta t = t_B - t_A = \frac{l}{c} + \frac{lv}{c^2} \tag{6}$$

Equation (6) is like a law of nature as it indicates the time for light to travel eastward between two points at the same latitude fixed on the surface of the Earth. It means therefore that an actual clock measurement for the time of transmission is not required since clock behavior for eastward travel is fully represented by equation (6). This equation therefore makes available the full precision of the GPS clocks anywhere in the world without the need for actual clocks and is therefore a very useful result.

Using this elapsed time in speed determination, since the distance between the two clocks is l, it follows that the one-way speed of light c_{AB} traveling eastward between the two clocks is given by

$$c_{AB} = \frac{l}{\Delta t} = \frac{l}{\frac{l}{c} + \frac{lv}{c^2}} = c(1 + \frac{v}{c})^{-1} = c(1 - \frac{v}{c} + o(\frac{v}{c})) = c - v, v << c \tag{7}$$

Thus the synchronized clocks of the GPS give a one-way eastward light speed measurement of $c_{AB} = c - v$ relative to the surface of the Earth and not light speed $c_{AB} = c$ required by the postulate of the constancy of the speed of light.

3.2. Westward transmission

For westward transmission we again establish synchronization of the GPS clocks, using the rules of the CCIR, by transmitting a light signal from clock B to clock A. In this case the total time Δt for light to travel the path from clock A to clock B is given by [16, 18]

$$\Delta t = \frac{l}{c} - 2A'_z \frac{\omega_E}{c^2} \tag{8}$$

which reduces to

$$\Delta t = \frac{l}{c} - \frac{lv}{c^2} \tag{9}$$

Again, the first term in (9) is the elapsed time assuming constant light speed c and the second term is the so-called "Sagnac correction" said to be required because of the Earth's rotation. This total elapsed time must be added to clock A such that if at the instant of light

transmission the time on clock B is t_B, then at the instant of reception the time t_A on clock A is set to $t_A = t_B + \Delta t$. After this procedure clocks B and A are synchronized.

Using these clocks to conduct a one-way light speed test, at a specified time, an observer at clock B sends a light signal westward to an observer at clock A. Because the clocks are synchronized using (9), the time interval $\Delta t = t_A - t_B$ between the transmission and reception of the signal is given in (9) as

$$\Delta t = t_B - t_A = \frac{l}{c} - \frac{lv}{c^2} \tag{10}$$

Equation (10) is essentially a law of nature as it provides the time for light to travel westward between two points at the same latitude fixed on the surface of the Earth. It means therefore that an actual clock measurement for the westward time of transmission is not required since clock behavior is fully represented by equation (10). Equation (10) therefore brings the full precision of the GPS clocks to everyone anywhere in the world without the need for actual clocks! This constitutes another very useful result.

Using the time found in (10) for one-way light speed in the westward direction, since the distance between the two clocks is l, it follows that the one-way speed of light c_{BA} traveling westward between the two clocks is given by

$$c_{BA} = \frac{l}{\Delta t} = \frac{l}{\frac{l}{c} - \frac{lv}{c^2}} = c(1 - \frac{v}{c})^{-1} = c(1 + \frac{v}{c} + o(\frac{v}{c})) = c + v, v << c \tag{11}$$

Thus the synchronized clocks of the GPS give a one-way westward light speed measurement of $c_{BA} = c + v$ relative to the surface of the Earth and not light speed $c_{BA} = c$ required by the postulate of light speed constancy.

The results in equations (7) and (11) confirm the independent claims of Marmet and Kelley: Light travels faster westward than eastward relative to the surface of the Earth. Specifically the one-way measurement of light speed using GPS data in (6) clearly indicates that a signal sent eastward travels at speed c minus the rotational speed of the Earth v at that latitude giving $c - v$. The GPS data available in (10) also shows that a signal sent westward travels at speed c plus the rotational speed of the Earth v at that latitude giving $c + v$. These generalized results were first reported by Gift [21].

We are now better able to understand why the times Δt in (6) and (10) enable the synchronization of two clocks in GPS: Time interval (6) is the time for light to travel from clock A to clock B at the actual speed $c_{AB} = c - v$ relative to both clocks and time interval (10) is the time for light to travel from clock B to clock A at the actual speed $c_{BA} = c + v$ relative to both clocks. At the constant speed c required by the postulate of light speed constancy the associated time l/c for light to travel from one clock to the other when added to the receiving clock does not result in synchronization because this is not the true travel time. In

the CCIR synchronization rules the time l/c is adjusted by $\pm lv/c^2$ in order to compensate for the real changes in light speed $c \pm v$ that occur relative to the clocks. In view of these results, the interpretation that the time Δt is the time required for light to travel between clocks at constant speed c, with a correction added because of the rotating Earth is now known to be invalid.

4. Michelson-Morley experiment using the GPS clocks

With the availability of synchronized clocks, the Michelson-Morley experiment can be conducted with direct timing of the signals traversing the orthogonal arms of the apparatus. Such an approach was previously considered but never executed because of insufficient timing resolution. The approach proposed here does not encounter this problem since the novel feature of the method is that the light travel time is directly available from the GPS clock synchronization algorithm adopted by the CCIR. This renders actual signal timing with physical clocks completely unnecessary [22].

The basic configuration of the original Michelson-Morley experiment [4] is shown in figure 2 where the apparatus is moving with velocity v through the hypothesized ether in direction PM1. Light from a source S splits into two beams at beam-splitter P. One beam travels from P to mirror M1 and back and is reflected at P into the interferometer I. The second beam is reflected at P to mirror M2 and back and passes through P into the interferometer I where both beams form an interference pattern.

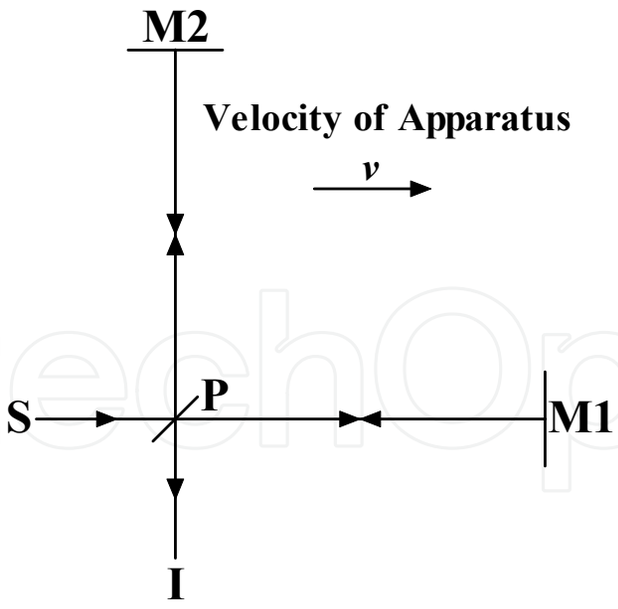

Figure 2. Michelson-Morley Experiment

In the frame of the moving apparatus as a result of ether drift, the resultant light speed between P and M1 would be $c - v$ toward M1 and $c + v$ toward P while the resultant light speed between P and M2 would be $(c^2 - v^2)^{1/2}$ in both directions. For optical path lengths $PM1 = l_1$ and $PM2 = l_2$ the time $t_1(a)$ for the light to travel from P to M1 is given by

$$t_1(a) = \frac{l_1}{c - v} \tag{12}$$

and the time $t_1(b)$ for the light to travel from M1 to P is given by

$$t_1(b) = \frac{l_1}{c + v} \tag{13}$$

Therefore the round-trip time along PM1 is given by

$$T_1 = t_1(a) + t_1(b) = \frac{2l_1}{c(1 - v^2 / c^2)} \tag{14}$$

The time $t_2(a)$ for the light to travel from P to M2 is given by

$$t_2(a) = \frac{l_2}{\sqrt{c^2 - v^2}} \tag{15}$$

and the time $t_2(b)$ for the light to travel from M2 to P is given by

$$t_2(b) = \frac{l_2}{\sqrt{c^2 - v^2}} \tag{16}$$

Therefore the round-trip time along PM2 is given by

$$T_2 = t_2(a) + t_2(b) = \frac{2l_2}{c(1 - v^2 / c^2)^{1/2}} \tag{17}$$

The time difference $\Delta T = T_1 - T_2$ is given by

$$\Delta T = T_1 - T_2 \approx \frac{2(l_1 - l_2)}{c} + \frac{2l_1 v^2}{c^3} - \frac{l_2 v^2}{c^3} \tag{18}$$

If the apparatus is turned through 90^o so that PM2 is in the direction of motion, the time difference becomes

$$\Delta T' = T_1' - T_2' \approx \frac{2(l_1 - l_2)}{c} + \frac{l_1 v^2}{c^3} - \frac{2l_2 v^2}{c^3} \tag{19}$$

The change in these time differences is

$$\Delta = \Delta T - \Delta T' = (l_1 + l_2)\frac{v^2}{c^3} \tag{20}$$

If $l_1 = l_2 = l$ then this reduces to

$$\Delta = \frac{2l}{c}\frac{v^2}{c^2} \tag{21}$$

A fringe shift proportional to this value (given by $\delta = \frac{c}{\lambda}\Delta$) is expected to appear in the interferometer. The time difference $\Delta = \frac{2l}{c}\frac{v^2}{c^2}$ is second-order and is significantly reduced by length contraction arising from motion through the ether [12]. This is why Michelson-Morley type experiments have been largely unsuccessful in detecting ether drift.

The accurate synchronized clocks in the GPS are now used to directly determine one-way light travel time. Thus in a modification of the original Michelson-Morley apparatus GPS clocks are placed at P, M1 and M2 in fig.2. Additionally the arm PM1 is oriented along a line of latitude and the arm PM2 is positioned along a line of longitude. As a result of the rotation of the Earth there is movement of the apparatus at velocity $v = w$ in the direction PM1 towards the East where w is the rotational speed of the surface of the Earth at the particular latitude.

4.1. Time measurement along PM1

The time $t_1(a)_{GPS}$ measured by the GPS clocks at P and M1 for the light to travel from P to M1 is [16, 18, 21]

$$t_1(a)_{GPS} = \frac{l_1}{c} + \frac{l_1 w}{c^2} \tag{22}$$

while from equation (12) of ether theory

$$t_1(a) = \frac{l_1}{c-w} \approx \frac{l_1}{c} + \frac{l_1 w}{c^2}, w << c \tag{23}$$

Hence $t_1(a)_{GPS} = t_1(a)$ and ether drift arising from the rotation of the Earth is detected. The time $t_1(b)_{GPS}$ measured by the GPS clocks for the light to travel from M1 to P is [16, 18, 21]

$$t_1(b)_{GPS} = \frac{l_1}{c} - \frac{l_1 w}{c^2} \tag{24}$$

while from equation (13) of ether theory

$$t_1(b) = \frac{l_1}{c+w} \approx \frac{l_1}{c} - \frac{l_1 w}{c^2}, w << c \tag{25}$$

Hence $t_1(b)_{GPS} = t_1(b)$ and ether drift arising from the rotation of the Earth is again detected. From ether theory as well as clock measurement, the difference in the out and back times along PM1 is given by

$$\Delta t_1 = t_1(a) - t_1(b) = \frac{2l_1}{c}\frac{w}{c} \tag{26}$$

Result (26) is first-order and therefore not affected by second-order length contraction as is the second-order result (21) in the conventional Michelson-Morley type experiments. Equation (26) has been extensively verified in GPS operation.

4.2. Time measurement along PM2

The time $t_2(a)_{GPS}$ for the light to travel from P to M2 measured by the GPS clocks at P and M2 is [16, 18]

$$t_2(a)_{GPS} = \frac{l_2}{c} \tag{27}$$

while from equation (15) of ether theory

$$t_2(a) = \frac{l_2}{\sqrt{c^2 - w^2}} \approx \frac{l_2}{c}, w << c \tag{28}$$

Hence $t_2(a)_{GPS} = t_2(a)$ and ether theory is confirmed by GPS measurement. The time $t_2(b)_{GPS}$ for the light to travel from M2 to P measured by the GPS clocks is [16, 18]

$$t_2(b)_{GPS} = \frac{l_2}{c} \tag{29}$$

while from equation (16) of ether theory

$$t_2(b) = \frac{l_2}{\sqrt{c^2 - w^2}} \approx \frac{l_2}{c}, w << c \tag{30}$$

Hence $t_2(b)_{GPS} = t_2(b)$ and ether theory is again confirmed by GPS measurement. From ether theory as well as GPS clock measurement, the difference in the out and back times along PM2 is given by

$$\Delta t_2 = t_2(a) - t_2(b) = 0 \tag{31}$$

This has been confirmed by actual GPS measurements which have shown that unlike East-West travel, there is no time difference between light travelling North and light travelling South.

The modified Michelson-Morley experiment using synchronized GPS clocks to measure light travel times out and back along the arms of the apparatus has detected ether drift resulting from the rotation of the Earth. The clocks have directly confirmed the light travel times for changed light speeds $c \pm w$ in the East-West direction arising from the drift of the ether as the apparatus moves through the medium at speed w corresponding to the speed

of rotation of the Earth's surface at the particular latitude. The experiment is operated within the dimensions of the original Michelson-Morley apparatus where the frame is considered to be approximately inertial and where special relativity has been universally applied [2]. This negates any objections about rotating coordinates and non-inertial frames which are never raised in the original Michelson-Morley experiment or in any of the several modern versions of the experiment [7-11].

5. One-way light speed using the range equation

In section 3 in the determination of one-way light speed, the CCIR algorithm was used to determine flight time for light transmission between two fixed points on the same latitude. In this section the range equation used in the GPS to evaluate distance and determine position is employed in the determination of flight time. Specifically by substituting known spatial positions in the range equation, light travel times can be determined without the direct use of the GPS clocks. These times are then used to determine one-way light speed in the East-West direction.

The range equation is central to the operation of the GPS. It holds in an ECI frame which is a frame that moves with the Earth as it revolves around the Sun but does not share its rotation. It is given by [16]

$$\left|\overline{r}_r(t_r) - \overline{r}_s(t_s)\right| = c(t_r - t_s) \tag{32}$$

where t_s is the time of transmission of an electromagnetic signal from a source, t_r is the time of reception of the electromagnetic signal by a receiver, $\overline{r}_s(t_s)$ is the position of the source at the time of transmission of the signal and $\overline{r}_r(t_r)$ is the position of the receiver at the time of reception of the signal. Using elapsed time measurements determined by the GPS clocks and the light speed value c in this equation, position on the surface of the Earth can be accurately determined. It has been exhaustively tested and rigorously verified and has resulted in the worldwide proliferation of the GPS.

Wang [23] has used the range equation operating in the ECI frame to show that the speed of light is dependent on the observer's uniform motion relative to the ECI frame. He did this by using the range equation to determine elapsed time and concluded that the successful application of the range measurement equation in GPS operation is inconsistent with the principle of the constancy of the speed of light. Instead of using the synchronized clocks of the GPS, we use the range equation (32) of the GPS to determine elapsed time for light traveling between two known adjacent points at the same latitude fixed on the surface of the rotating Earth. We then use this time and the known distance between the two fixed points to calculate the one-way speed of light.

Consider figure 3 in which two adjacent GPS stations A and B are at the same latitude and fixed on the surface of the Earth a distance l apart with B East of A. Since the Earth is rotating, the stations are moving eastward at speed v the Earth's surface speed at that latitude. Let l be sufficiently small by for example having stations A and B in the same

building such that the stations are moving uniformly in the same direction at speed v relative to the ECI frame. In such circumstances stations A and B constitute an approximately inertial frame moving at speed v relative to the ECI frame, again similar to the many light speed experiments conducted to verify light speed constancy.

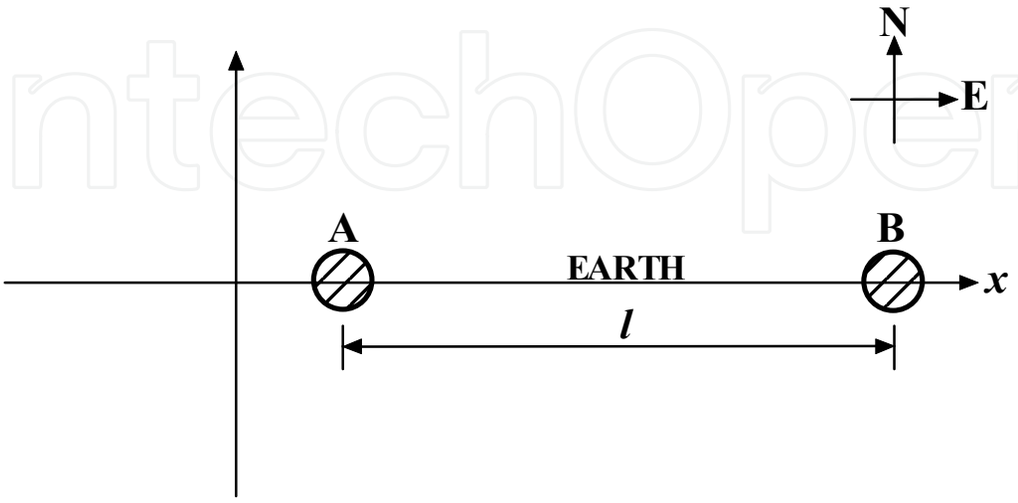

Figure 3. GPS Stations A and B at fixed positions on Earth

5.1. Eastward transmission

Let station A transmit a signal eastward at time t_I to station B which receives it at time t_F. On an axis fixed in the ECI frame along the line joining the two stations with the origin west of station A, let $x_A(t)$ be the position of station A at time t and $x_B(t)$ be the position of station B at time t. Then from the range equation (32),

$$x_B(t_F) - x_A(t_I) = c(t_F - t_I) \tag{33}$$

where $x_B(t_F)$ is the position of station B at time t_F and $x_A(t_I)$ is the position of station A at time t_I. Since the stations are moving uniformly in the same direction at speed v relative to the ECI frame, it follows that the relation between the position $x_B(t_F)$ of station B at the time of reception of the signal and its position $x_B(t_I)$ at the time of emission of the signal is given by

$$x_B(t_F) = x_B(t_I) + v(t_F - t_I) \tag{34}$$

Substituting for $x_B(t_F)$ from (34) in (33) yields

$$x_B(t_I) - x_A(t_I) + v(t_F - t_I) = c(t_F - t_I) \tag{35}$$

This gives the elapsed time as

$$(t_F - t_I) = \frac{l}{c - v} \tag{36}$$

Therefore the speed c_{AB} of the light traveling from station A to station B is given by separation l divided by elapsed time $(t_F - t_I)$ which using (36) is

$$c_{AB} = \frac{l}{(t_F - t_I)} = \frac{l}{l/(c-v)} = c - v \tag{37}$$

5.2. Westward transmission

Let station B transmit a signal westward at time t_I to station A which receives it at time t_F. Then using the range equation (32) and noting that $x_B(t_I) > x_A(t_F)$,

$$x_B(t_I) - x_A(t_F) = c(t_F - t_I) \tag{38}$$

where $x_B(t_I)$ is the position of station B at time t_I and $x_A(t_F)$ is the position of station A at time t_F. Since the stations are moving uniformly in the same direction at speed v relative to the ECI frame, the relation between the position $x_A(t_F)$ of station A at the time of reception of the signal and its position $x_A(t_I)$ at the time of emission of the signal is given by

$$x_A(t_F) = x_A(t_I) + v(t_F - t_I) \tag{39}$$

Substituting for $x_A(t_F)$ from (39) in (38) yields

$$x_B(t_I) - x_A(t_I) - v(t_F - t_I) = c(t_F - t_I) \tag{40}$$

This yields the elapsed time as

$$(t_F - t_I) = \frac{l}{c+v} \tag{41}$$

Therefore the speed c_{BA} of the light traveling from station B to station A is given by separation l divided by elapsed time $(t_F - t_I)$ which using (41) is

$$c_{BA} = \frac{l}{(t_F - t_I)} = \frac{l}{l/(c+v)} = c + v \tag{42}$$

The results in equations (37) and (42) first reported in [24] indicate that light travels faster westward than eastward relative to the surface of the Earth. In particular the one-way determination of light speed using the range equation of the GPS establishes in (37) that a signal sent eastward travels at speed c minus the rotational speed of the Earth v at that latitude giving $c - v$. The range equation data also shows in (42) that a signal sent westward travels at speed c plus the rotational speed of the Earth v at that latitude giving $c + v$. This is true for the short-distance travel in the approximately inertial frame considered here as well as long-distance circumnavigation of the Earth [19] and fully corroborates the light speed determined in section 3 using the synchronized GPS clocks [21].

6. Test of the light speed invariance postulate using the range equation

The direct one-way tests above reveal that light travels faster West than East and does so for short-distance travel which approximates an inertial frame or large-distance travel such as circumnavigating the Earth. This finding contradicts the light speed invariance postulate of special relativity according to which the speed of light is constant in all inertial frames [1-3]. A particularly interesting interpretation of this postulate was presented by Tolman in 1910 [25]. Referring to a similar figure 4 he said the following:

> "A simple example will make the extraordinary nature of the second postulate evident. *S* is a source of light and *A* and *B* two moving systems. *A* is moving towards the source *S,* and *B* away from it. Observers on the systems mark off equal distances *aa′* and *bb′* along the path of the light and determine the time taken for light to pass from *a* to *a′* and *b* to *b′* respectively. Contrary to what seem the simple conclusions of common sense, the second postulate requires that the time taken for the light to pass from *a* to *a′* shall measure the same as the time for the light to go from *b* to *b′*."

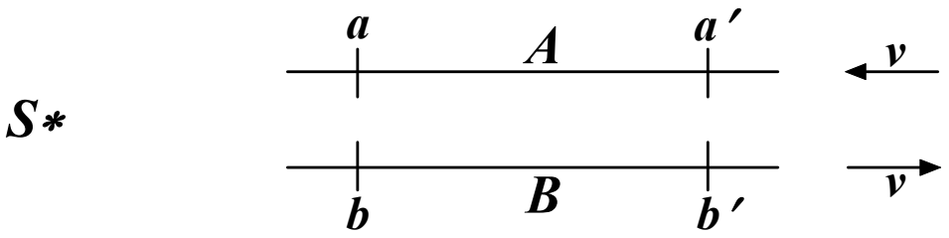

Figure 4. Test of Light Speed Invariance

The range equation of the GPS now makes it possible to test this prediction of the light speed invariance postulate of special relativity [26].

In figure 4 consider a light source S fixed in the ECI frame and two systems A and B moving uniformly in the ECI frame. A is moving towards the source at a constant speed v relative to the ECI frame and B is moving away from the source at a constant speed v relative to the ECI frame. Observers on the two systems mark off equal distances *aa′* and *bb′* equal to *D* along the light path and determine the time taken for the light to pass from *a* to *a′* and *b* to *b′* respectively. As Tolman has observed, "the second postulate [of special relativity] requires that the time taken for the light to pass from *a* to *a′* shall measure the same as the time for the light to go from *b* to *b′*." According to the second postulate this measured time must be D/c on both systems. This prediction will now be tested using the range equation of the GPS.

6.1. Analysis on system A

Let GPS stations be placed at a and a' respectively. On an axis fixed in the ECI frame along the line *aa′* joining the two stations with station *a* closer to the origin O than station *a′* and taking positive values, let $x_a(t)$ be the position of station *a* at time *t* and $x_{a'}(t)$ be the position

of station a' at time t. Let light from S arrive at station a at time t_I and later at station a' at time t_F . Then using the range equation (32) and noting that $x_{a'}(t_F) > x_a(t_I)$,

$$x_{a'}(t_F) - x_a(t_I) = c(t_F - t_I) \tag{43}$$

Since both stations are moving uniformly toward S at speed v relative to the ECI frame, it follows that the relation between the position $x_{a'}(t_F)$ of station a' at the time of its reception of the signal and its earlier position $x_{a'}(t_I)$ is given by

$$x_{a'}(t_F) = x_{a'}(t_I) - v(t_F - t_I) \tag{44}$$

Substituting $x_{a'}(t_F)$ from (44) in (43) yields

$$x_{a'}(t_I) - x_a(t_I) - v(t_F - t_I) = c(t_F - t_I) \tag{45}$$

Since $x_{a'}(t_I) - x_a(t_I) = D$ then (45) becomes

$$x_{a'}(t_I) - x_a(t_I) = D = (c + v)(t_F - t_I) \tag{46}$$

Hence for an observer on system A the range equation gives the time for light to travel between a and a' as

$$t_F - t_I = \frac{D}{c + v} \tag{47}$$

Thus the light travel time measured by an observer on A is $D/(c+v)$ and not D/c as required by the light speed invariance postulate. Therefore the light speed $c_{aa'}$ detected on system A for the light traveling from station a to station a' is given by the fixed length D divided by elapsed time $(t_F - t_I)$ which using (47) is given by

$$c_{aa'} = \frac{D}{(t_F - t_I)} = \frac{D}{D/(c+v)} = c + v \tag{48}$$

6.2. Analysis on system B

Let GPS stations be placed at b and b' respectively. On an axis fixed in the ECI frame along the line bb′ joining the two stations with station b closer to the origin O than station b′ and taking positive values, let $x_b(t)$ be the position of station b at time t and $x_{b'}(t)$ be the position of station b′ at time t. Let light from S arrive at station b at time t_I and later at station b′ at time t_F . Then using the range equation (32),

$$x_{b'}(t_F) - x_b(t_I) = c(t_F - t_I) \tag{49}$$

Since both stations are moving uniformly away from S at speed v relative to the ECI frame, it follows that the relation between the position $x_{b'}(t_F)$ of station b′ at the time of its reception of the signal and its earlier position $x_{b'}(t_I)$ is given by

$$x_{b'}(t_F) = x_{b'}(t_I) + v(t_F - t_I) \tag{50}$$

Substituting $x_{b'}(t_F)$ from (50) in (49) yields

$$x_{b'}(t_I) - x_b(t_I) + v(t_F - t_I) = c(t_F - t_I) \tag{51}$$

Since $x_{b'}(t_I) - x_b(t_I) = D$ then (51) becomes

$$x_{b'}(t_I) - x_b(t_I) = D = (c - v)(t_F - t_I) \tag{52}$$

Hence for an observer on system B the range equation gives the time for light to travel between b and b' as

$$t_F - t_I = \frac{D}{c - v} \tag{53}$$

Thus the light travel time measured by an observer on B is $D/(c-v)$ and not D/c as required by the light speed invariance postulate. Therefore the light speed $c_{bb'}$ observed on system B for the light traveling from station b to station b' is given by the fixed length D divided by elapsed time $(t_F - t_I)$ which using (53) is given by

$$c_{bb'} = \frac{D}{(t_F - t_I)} = \frac{D}{D/(c-v)} = c - v \tag{54}$$

Equations (47) and (53) indicate that the light travel times over the distance D on systems A and B are $D/(c+v)$ and $D/(c-v)$ respectively and not the value D/c required by the second postulate of special relativity. This is because the light speeds observed on systems A and B in equations (48) and (54) are $c+v$ and $c-v$ respectively and are different from the value c required by the second postulate. The light speed variation demonstrated here in the ECI is exactly what is observed using the synchronized clocks of the GPS in section 3 and the range equation of the GPS in section 5 in the frame of the surface of the rotating Earth.

7. One-way light speed in the sun-centered inertial frame

The demonstration of light speed anisotropy has thus far been confined to a space on or close to the surface of the Earth. It is possible to broaden the scope of the discussion beyond the terrestrial frame to the region encompassed by the solar system. In this regard Wallace [27] used published interplanetary data to present evidence of light speed $c+v$ relative to the moving Earth where v is the Earth's orbital speed. This light speed variation for light travelling through space is exactly what has been observed on the orbiting Earth for light from planetary satellites in the Roemer experiment [28] and for light from stars on the ecliptic in the Doppler experiment [29]. Light speed anisotropy arising from the orbital motion of the Earth has also been reported for light propagation over cosmological distances [30] and in the Shtyrkov experiment involving the tracking of a geostationary satellite [31].

This phenomenon of light speed anisotropy arising from light transmission through space has recently been investigated by this author using planet and spacecraft tracking technology [32]. Specifically range equations operating in the solar system barycentric or sun-centered inertial (SCI) frame used in tracking planets and spacecrafts were 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. Time measurement was effected using atomic clocks based on Coordinated Universal Time (UTC) and the spatial coordinates were taken relative to the SCI frame. The equations are given by [33]

$$c\tau_u = \left| r_B(t_R - \tau_d) - r_A(t_R - \tau_d - \tau_u) \right| \tag{55}$$

$$c\tau_d = \left| r_A(t_R) - r_B(t_R - \tau_d) \right| \tag{56}$$

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. In practice in order to obtain values for τ_u and τ_d, the two equations must be solved iteratively.

Using these equations in a novel approach it was found [32] that light travels from the reflector to Earth at a speed $c+v$ relative to the Earth for the Earth moving toward the reflector at orbital speed v and light travels at speed $c-v$ relative to the Earth 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 earlier finding of Wallace [27] for light travel through space and is consistent with light speed changes observed on the orbiting Earth for light from planetary satellites in the Roemer experiment [28] and for light from stars on the ecliptic in the Doppler experiment [29].

8. Conclusion

Measuring the speed of light has for many years been a major activity in science. Following the introduction of special relativity theory in 1905 in which light speed invariance was postulated, light speed tests assumed even greater significance. Numerous experiments have been conducted over the past century the vast majority of which appear to confirm the postulate. A careful examination by Zhang [3] however revealed that while two-way light speed constancy has been confirmed, one-way light speed constancy has not. Indeed these experiments by their very nature seem unable to detect one-way light speed variation and therefore cannot be used to fully test the postulate. The main contribution of this chapter is the use of GPS technology in testing one-way light speed and the demonstration that light speed does in fact vary contrary to the postulate of light speed invariance. This technology includes the synchronized clocks of the GPS, the range equation of the GPS and the UTC clocks and range equations used in tracking of planets and space missions.

The light speeds $c \pm v$ in the East-West direction determined using both the GPS clocks and range equation in the frame of the surface of the Earth are different from the results of the many light speed experiments [7-11, 14, 15] conducted in the same frame which all give c. These non-constant light speed values $c \pm v$ induced by the rotation of the Earth contradict the postulate of light speed constancy since the postulate requires constant light speed c for light traveling eastward or westward between the two clocks. In his consideration of light travel between San Francisco and New York, Marmet [18] has remarked that "Unless we accept the absurd solution that the distance between [New York] to [San Francisco] is smaller than the distance between [San Francisco] and [New York], we have to accept that in a moving frame, the velocity of light is different in each direction" a difference that "is even programmed in the GPS computer in order to get the correct Global Positioning." Wang [23] has also argued that the successful application of the range equation in GPS operation is inconsistent with the postulate of the constancy of the speed of light.

Apart from this demonstration of the postulate's inapplicability in the frame of the rotating Earth, the range equation was used to directly test this postulate in a form expressed by Tolman and again showed that the postulate of light speed constancy is not valid even in the ECI frame. Light speed changes were also observed for light travelling through space. Based on range equations employing UTC measurements and spatial coordinates relative to the solar-system barycentric frame, the speed of light reflected from a body such as a planet or a space vehicle 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.

It is clear therefore that GPS technology very easily demonstrates that light speed is not constant and hence that the light speed invariance postulate which leads to the Lorentz Transformation and special relativity is invalid. This significant finding has profound implications for modern physics and metrology where light speed constancy is a foundation tenet. Moreover this light speed variability indicates the existence of a preferred frame, the search for which interestingly was the original objective of the Michelson-Morley experiment.

In order to confirm this preferred frame detection, the GPS clocks were utilized in a modified Michelson-Morley experiment where the clocks replaced the interferometer. The clocks measured light travel times along the arms of the apparatus and revealed ether drift arising from the Earth's rotation. This direct determination of the light travel times rendered the measurement essentially immune to the second-order length contraction phenomenon which negates the fringe shift in the conventional Michelson-Morley experiments. The GPS technique did not require actual time measurement but utilized light travel time that is directly available from the CCIR clock synchronization algorithm. The modified experiment succeeded in detecting ether drift for rotational motion while the majority of other Michelson-Morley-type experiments are considered to have produced null results. In the approximately inertial frame of the experiment, special relativity is directly applicable and predicts a zero time-of-flight difference between equal orthogonal arms and hence a null result [2].

Contrary to this prediction of special relativity, the modified Michelson-Morley experiment detects non-zero time-of-flight differences corresponding to ether drift and thereby reveals a preferred frame as previously reported by Gift [34] and Shtyrkov[31] and also by Demjanov [12] and Galaev [13]. This is consistent with the preferred frame associated with the set of "equivalent" transformations identified by Selleri [35]. This set contains all possible transformations that connect two inertial frames under a set of reasonable assumptions and which differ only by a clock synchronization parameter. This includes the Lorentz Transformation of special relativity and the Inertial Transformation which yields a modern ether theory [35, 36]. Using this "equivalent" set Selleri [36] and Gift [37] have identified the Inertial Transformation and the associated modern ether theory as the space-time theory that best accords with the physical world. Light speed variation, so easily demonstrated by GPS technology and which invalidates the Lorentz Transformation, decidedly confirms the Inertial Transformation that predicts it.

Thus the modern ether theory based on the inertial transformation is a robust replacement for special relativity [35, 36] and the transition to this new theory is facilitated by the similarity of the structure of the members of the set of "equivalent" transformations. Such a transition can usher in a period of renewed scientific discovery as areas that are now prohibited can legitimately be explored. A good example of this is the case where Lorentz covariance imposed by relativistic considerations was relaxed as a result of which a new quantum theory of magnetism emerged that for the first time provided convincing explanations for the chemical reactivity of free radicals, the covalent bonds underpinning organic chemistry and the celebrated Pauli Exclusion Principle [38].

In view of the incontrovertible demonstrations of light speed variation using GPS technology presented in this chapter, investigation into the properties of the Inertial Transformation and the nature of the associated Modern Ether Theory should be the main focus of space-time research in the twenty-first century.

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9. References

[1] Einstein, A., On the Electrodynamics of Moving Bodies, p 37-65 in The Principle of Relativity edited by H.A. Lorentz et al., Dover Publications, New York, 1952.
[2] Rindler, W., Relativity Special, General and Cosmological, 2nd edition, Oxford University Press, New York, 2006.
[3] Zhang, Y.Z., Special Relativity and its Experimental Foundations, World Scientific, Singapore, 1997.

[4] Michelson, A.A. and E.W. Morley, The relative motion of the Earth and the luminiferous aether, American Journal of Science, ser.3, v.34, 333-345, 1887.
[5] Miller, D. C., The ether-drift experiment and the determination of the absolute motion of the earth, Review of Modern Physics, *5*, 203, 1933.
[6] Shankland, R. S., Mc Cuskey, S. W., Leone, F. C., & Kuerti, G., New analysis of the interferometer observations of Dayton C. Miller, Review of Modern Physics, 27, 167, 1955.
[7] Jaseja, T.S., A. Javan, J. Murray and C.H. Townes, Test of Special Relativity or of the Isotropy of Space by Use of Infrared Masers, Physical Review 133, A1221-A1225, March 1964.
[8] Brillet, A. and J.L. Hall, Improved Laser Test of the Isotropy of Space, Physical Review Letters, 42, 549-552, February 1979.
[9] Hermann, S., A. Senger, E. Kovalchuk, H. Müller and A. Peters, Test of the Isotropy of the Speed of Light Using a Continuously Rotating Optical Resonator, Physical Review Letters, 95, 150401, 2005.
[10] Müller, H., P.L. Stanwix, M.E. Tobar, E. Ivanov, P. Wolf, S. Herrmann, A. Senger, E. Kovalchuk and A. Peters, "Relativity tests by complementary rotating Michelson-Morley experiments". Physical Review Letters 99 (5): 050401, 2007.
[11] Eisele, C, A. Nevsky and S. Schiller, Laboratory Test of the Isotropy of Light Propagation at the 10^{-17} Level, Physical Review Letters, 103, 090401, 2009.
[12] Demjanov, V.V., Physical interpretation of the fringe shift measured on Michelson interferometer in optical media, Physics Letters A 374, 1110-1112, 2010.
[13] Galaev, Y.M., The Measuring of Ether-Drift Velocity and Kinematic Ether Viscosity Within Optical Wavebands, Spacetime & Substance 3 (5,15) (2002) p207-224
[14] Gagnon, D.R., Torr, D.G., Kolen, P.T. and Chang, T., Guided-Wave Measurement of the one-way Speed of Light, Physical Review A, 38, 1767, 1988.
[15] Krisher, T.P., Maleki, L., Lutes, G.F., Primas, L.E., Logan, R.T., Anderson, J.D. and Will, C.M., Test of the Isotropy of the One-way Speed of Light Using Hydrogen-Maser Frequency Standards, Phys. Rev. D 42, 731, 1990.
[16] Ashby, N., Relativity in the Global Positioning System, Living Reviews in Relativity, 6, 1, 2003.
[17] IS-GPS-200E 8 June 2010, http://www.gps.gov/technical/icwg/IS-GPS-200E.pdf accessed August 21, 2011.
[18] Marmet, P., The GPS and the Constant Velocity of Light, Acta Scientiarum, 22, 1269, 2000.
[19] Kelly, A., Challenging Modern Physics, BrownWalker Press, Florida, 2005.
[20] Will, C.M., Clock synchronization and isotropy of the one-way speed of light, Physical Review D, 45, 403, 1992.
[21] Gift, S.J.G., One-Way Light Speed Measurement Using the Synchronized Clocks of the Global Positioning System (GPS), Physics Essays, Vol.23, No2, pp 271-275, June 2010.
[22] Gift, S.J.G., Successful Search for Ether Drift in a Modified Michelson-Morley Experiment Using the GPS, Applied Physics Research, Vol. 4, No. 1, pp 185-192, February 2012.

[23] Wang, R., Successful GPS Operations Contradict the Two Principles of Special Relativity and Imply a New Way for Inertial Navigation-Measuring Speed Directly, Proceedings of the IAN World Congress in Association with the U.S. ION Annual Meeting, 26-28 June 2000, San Diego, CA.
[24] Gift, S.J.G., One-Way Light Speed Determination Using the Range Measurement Equation of the GPS, Applied Physics Research, 3, 110, 2011.
[25] Tolman, R., The Second Postulate of Relativity, Physical Review, 31, 26, 1910.
[26] S.J.G. Gift, Another Test of the Light Speed Invariance Postulate, Modern Applied Science, 5, 152, 2011.
[27] Wallace, B. G., Radar Testing of the Relative Velocity of Light in Space, Spectroscopy Letters 2, 361, 1969.
[28] Gift, S.J.G., Light Speed Invariance is a Remarkable Illusion, Physics Essays, 23, 1, 2010.
[29] Gift, S.J.G., Doppler Shift Reveals Light Speed Variation, Apeiron, 17, 13, 2010.
[30] Nodland, B. and Ralston, J. P., Indication of Anisotropy in Electromagnetic Propagation over Cosmological Distances, Physical Review Letters, 78, 3043, 1997.
[31] Shtyrkov, E.I., Observation of Ether Drift in Experiments with Geostationary Satellites, Proceedings of the Natural Philosophy Alliance, pp201-205, 12th Annual Conference, Storrs CT, 23-27, May 2005.
[32] Gift, S.J.G., One-way Speed of Light Using Interplanetary Tracking Technology, submitted for publication.
[33] Myles Standish, E. and Williams, J. G., Orbital Ephemerides of the Sun, Moon and Planets, p16, http://iau-comm4.jpl.nasa.gov/XSChap8.pdf accessed May 17, 2012.
[34] Gift, S.J.G., The Relative Motion of the Earth and the Ether Detected, Journal of Scientific Exploration, 20, 201, 2006.
[35] Selleri, F., Recovering the Lorentz Ether, Apeiron, 11, 246, 2004.
[36] Selleri, F., La Relativita Debole, Edizioni Melquiades, Milano, 2011.
[37] Gift, S.J.G., Separating Equivalent Space-Time Theories, Apeiron, 16, 408, 2009.
[38] Gift, S.J.G., A Quantum Theory of Magnetism, Progress in Physics, 1, 12, 2009.