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An Experiment to Measure the One-Way Velocity of Propagation of Electromagnetic Radiation[1]

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In this paper we describe a propagation experiment to measure the one-way velocity of electromagnetic radiation. The experiment utilizes the rotation of the earth to interchange the positions of two rubidium vapor frequency standards over 12 h, thereby canceling initial clock phase differences. It is demonstrated that although the drift characteristics of modern rubidium atomic clocks may be large for long-term absolute timing requirements, the short-term random fluctuations are small. It is found that over a 24-h period, the long-term drift can be accurately parametrized in retrospect and removed, thereby permitting the detection of temporal variations less than 1 nsec in magnitude. With coherent summing techniques this value may be significantly reduced, and it becomes realistic to consider an experiment where the clocks are separated by distances of the order of several hundreds of meters in order to detect velocities of the order of that of the solar system with respect to the center of the galaxy ($\sim 10^5\, m\, sec^{-1}$), thus ensuring that the rotational motion of the earth has a negligible effect in altering the relative inertial characteristics of the reference frames of each clock. It is demonstrated that under such conditions the measurement of the one-way speed of propagation of electromagnetic radiation is not only meaningful, but can be simply implemented with commercially available instrumentation.

1. INTRODUCTION

Recently several nonrelativistic theories have appeared in the literature in competition with the special theory of relativity (see, for example,

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Giannoni[3]). Winnie[11] has established rigorously three synchrony-free principles which embody the empirical evidence that forms the factual basis for special relativity. Any theory, therefore, that does not violate Winnies' three principles will account equally well for the available observational evidence. In addition, Torr and Kolen[9] have recently established, contrary to popular belief, that the classical etheric Lorentz[5] theory also satisfies the essence of Winnies' synchrony-free principles as modified by Giannoni.[3] This fact was apparently known to Lorentz[5] and Poincaré[8] (see also the review by Whittaker[10]), but has been overlooked in recent years due to confusion between the meaning of proper length in special relativity and the Lorentz theory. Podlaha also reclarified this question in 1976.[7] However, the value of his work was lost because he subsequently fell prey to the common error, also made by Poincaré[8] and Lorentz,[5] that because of various cancellation effects, motion with respect to absolute space cannot be detected, even in principle. Hence both relativity and the Lorentz theory argue that a one-way measurement of the velocity of light is meaningless. The rationale behind this argument proceeds as follows. In order to make the measurement by timing the one-way flight of a light pulse it is necessary to synchronize two clocks separated by some distance d. To do this it is apparently necessary to make some assumptions about the propagation speed in one or both directions. This requirement introduces a circular argument which renders the concept of the experiment meaningless.

It has been argued that the experiment becomes meaningful if the two clocks are synchronized at one location and then separated by slow clock transport.[2] However, since the Lorentz theory predicts a null result for this kind of one-way experiment,[1,9] it is not clear how a positive result should be interpreted. Our purpose is to identify an experiment which could be used to distinguish between special relativity and the Lorentz theory. Such an experiment requires a nonsymmetric arrangement for transmission of signals, while retaining near-identical environments for the clocks. In this paper we consider an alternative to slow clock transport, which requires that the position of the clocks be interchanged by motion that does not violate the conditions discussed above. Clearly this kind of motion can be provided by the rotation of the earth on its axis. However, in this case it is necessary to make d small enough to ensure that the clocks remain in near-identical inertial environments over a diurnal cycle of measurements. In principle d could be made very small, if sufficiently stable and accurate clocks were available to obtain a meaningful measurement of the times of flight. In this paper we determine the smallest value for d that could be used with commerically available clocks to detect velocities with respect to absolute space of the order of $10^5\ \mathrm{m\ sec^{-1}}$, i.e., of the order of the velocity of the solar system with respect to the center of the galaxy.

Before proceeding with the analysis of the technical details, we outline briefly the theory behind the experiment.

2. THEORY BEHIND THE EXPERIMENT

Two rubidium frequency standards of known stability are placed a distance d apart. No attempt is made to synchronize the clocks. However, for purposes of discussion we assume that the frequency of the clocks is perfectly stable, so that no drift in their relative phase occurs. Under these conditions the clock signals at any given instant in time may be out of phase by some residual value θ, where

$$\theta = \frac{2\pi \Delta t}{T} \tag{1}$$

where T is the period of the clocks and Δt is the time difference measured between wave maxima for $d = 0$.

Consider the experimental arrangement shown in Fig. 1, where clock A and clock B are separated by a distance d. The clocks generate a 5-MHz, 1-V rms sine wave. The signal from clock A is used to trigger the start input of an interval counter located at clock A. The signal from clock B is fed to the stop input of the counter. If we ignore the technical details of the experiment for the moment and concentrate on the concept, it is clear that the time interval recorded by the counter will be given by

$$\Delta t_{A1} = \Delta t + d/c^{-} \tag{2}$$

where c^{-} represent the velocity of propagation of the electromagnetic radiation from clock B to the stop input of the interval counter. If the interval counter is moved to the location of clock B, the interval recorded there is given by

$$\Delta t_{B1} = \Delta t - d/c^{+} \tag{3}$$

where c^{+} represents the velocity of propagation from A to B. Clearly this experiment yields no information on c^{+} or c^{-}, since the difference between Δt_{A1} and Δt_{B1} provides the round-trip time, and $\Delta t_{A1} + \Delta t_{B1}$ includes the unknown quantity Δt. Torr and Kolen[9] have shown that both special relativity and the Lorentz theory yield exactly the value c for the round-trip velocity if d is accurately known. Hence the clock positions must be interchanged if the Δt term is to cancel, i.e., 12 h later

$$\Delta t_{A2} = \Delta t + d/c^{+} \tag{4}$$

and

$$\delta t = \Delta t_{A1} - \Delta t_{A2} = d/c^- - d/c^+ \tag{5}$$

According to the Lorentz theory,

$$c^- = c - v \tag{6}$$

and

$$c^+ = c + v \tag{7}$$

and

$$\delta t = 2\,dv/(c^2 - v^2) \tag{8}$$

which Torr and Kolen[9] have shown reduces exactly to

$$\delta t = (2d_0/c)\,v/c \tag{9}$$

$$= t_0 v/c \tag{10}$$

where d_0 is the value of d in a frame for which $v = 0$, and t_0 is the round-trip time under the same conditions. Therefore

$$v = \delta t\, c/t_0 \tag{11}$$

A measurement of d in any inertial frame according to the Lorentz theory yields the numerical values $d = d_0$. Hence $t = t_0$. Therefore, a measurement of the round-trip time of flight provides an accurate value for d_0 in (9) and hence t_0 in (10) and (11). Naturally if relativity is correct, $\delta t = 0$ for all orientations of the experiment.

3. EVALUATION OF ERRORS OF MEASUREMENT USING COMMERCIALLY AVAILABLE INSTRUMENTATION

For purpose of analysis we consider the 5065A Rubidium Vapor Frequency Standard and the 5370A Universal Time Interval Counter manufactured by the Hewlett Packard Company. Factors which will affect the proposed measurement are the stability, temporal resolution, and settability of the clocks, i.e., the limit in the accuracy to which the clocks can be synchronized. The net effect to these parameters on the measurement of an interval of time is given by the equation[4]

$$\Delta t_e = aT^2 + bT + \Delta t_0 \tag{12}$$

where Δt_0 is associated with some initial dc offset in phase between clocks; bT represents a drift due to the settability; and the term aT^2 represents the combined effects of a steady drift and instability of the clocks on the measurement. We discuss the question of temporal resolution later.

Although Eq. (12) represent the behavior of a single rubidium clock with respect to a "perfect" standard, the equation for the relative variation between two rubidium clocks is of the same form. In a measurement of the type proposed here, the predictable variations are not serious. This is discussed further below. The primary source of error which limits the measurement capability arises due to random fluctuations in the clock periods.

In order to gain first-hand knowledge of the behavior patterns of the HP 5065A rubidium standards, we have monitored the behavior of two clocks using the experimental configuration shown in Fig. 1 with d negligibly small. The 5370A HP Interval Counter was used. Figure 2 illustrates the measurements made of the relative phase variation between clocks expressed as a time interval in units of 200 nsec, the clock period. Since the clocks were available for only 7 days, the data shown cover the same period. Each point plotted represents an average sample size of 10^5.

It is clear from Fig. 2 that over the 7-day period the phase underwent a nonlinear variation. However, 1 24-h segment can be fairly accurately represented by a linear fit. Figure 3 shows a shorter period of data at higher temporal resolution. In this case measurements were taken continuously. Each point represents the average of 100,000 samples. Figure 4 shows one diurnal cycle with the linear drift component removed. From these data it is evident that nonlinear variations over this particular diurnal period did not exceed 1 nsec. The behavior pattern in Fig. 2 shows that for the conditions under which we operated the clocks, i.e., normal office air-conditioned shirt-sleeve environment, the drift remained nearly linear over most diurnal segments. Departures from linearity occurred as a sudden change in slope, which then remained constant for periods of the order of a day.

We now interpret these measurements in terms of the specifications supplied by the company in the instrument handbook. The short-term

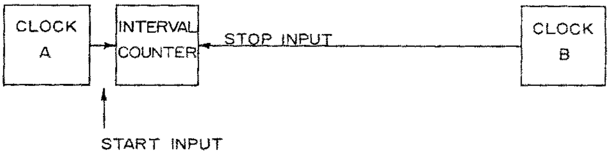

Fig. 1. A schematic illustration of the experimental arrangement.

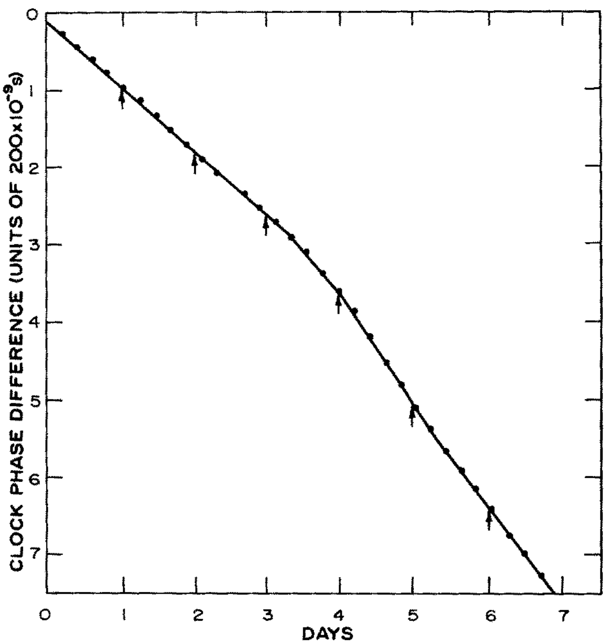

Fig. 2. The relative phase difference between clocks as a function of time, in units of the clock period.

stability is guaranteed to better than 1×10^{-12} sec per sec for averaging over 10–1000 sec. The settability is given as $b = \pm 2 \times 10^{-12}$ and the drift coefficient $a = 1 \times 10^{-11}$ per month. Now the effect that we are proposing to measure will vary diurnally in a sinusoidal manner, i.e., the one-way velocity of light c^* will attain maximum and minimum values of $c + v$ and $c - v$,

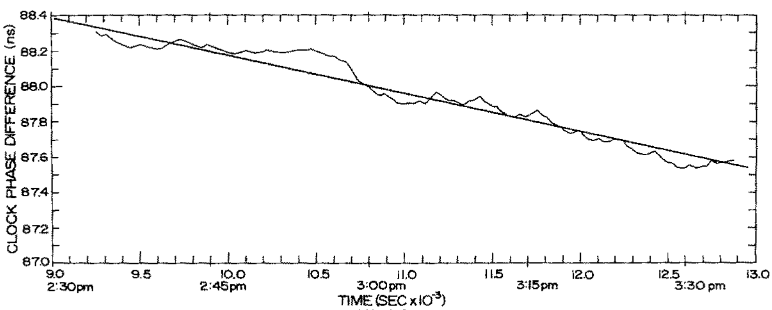

Fig. 3. The relative phase difference between clocks as a function of time. This figure illustrates short-term random fluctuations in clock periods. Each point represents the mean of 100,000 samples taken continuously.

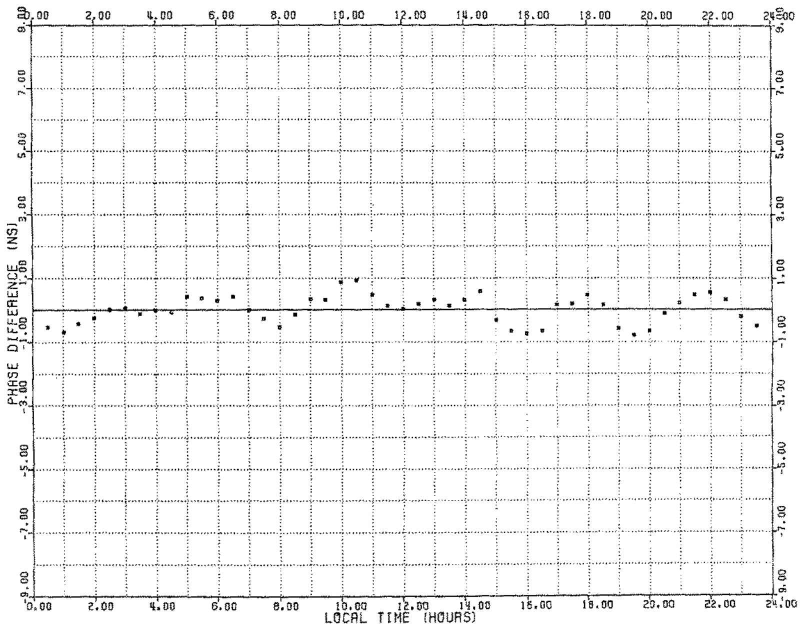

Fig. 4. The same as Fig. 3 but for one diurnal period.

respectively, with a corresponding modulation of the phase of the signal if the Lorentz theory is correct. It is clear from Eq. (12) that the linear component of the drift can be removed simply by least squares fitting a straight line through the data and subtracting out this variation, and Fig. 4 shows the effect of doing this for a diurnal section of the data where the relative drift appeared to be linear. As mentioned above, the results show that for this section of the data the amplitude of the nonlinear component did not exceed 1 nsec, indicating that the a coefficients for each clock are similar.

If we compute the predicted nonlinear drift component per day using the company-supplied value for the coefficient a, we obtain a value of $\sim$30 nsec per day. Over the 7 days we operated the clocks the mean value of the amplitude of the nonlinear component amounted to $\sim$47 nsec per day. However, it is especially important to note that these nonlinear variations occurred as a result of very large sudden changes in slope which could be clearly identified even in the presence of a small sinusoidal diurnal variation of the order of 2 nsec amplitude. This aspect of the clock behavior therefore also clearly represents a characterizable trend which can be functionally removed in retrospect. As far as our requirements are concerned, the short-term stability, i.e., random fluctuations about the characterizable trends, amount to ~1 nsec, which implies a short-term effective stability nearly two orders of magnitude better than that specified for absolute time-keeping purposes. The measurement precision therefore amounts to approximately one part in 5×10^{13} over a diurnal cycle. It should be noted that Torr and Kolen[9] showed that the conventional Mössbauer experiments were subjects to Lorentz cancellation effects, and that a configuration similar to that described here would have to be used to provide a valid test of the Lorentz theory (See note added in proof).

4. SUGGESTED DATA ANALYSIS PROCEDURE

Superimposed on the clock variations discussed in the previous section will be the sinusoidal phase shift predicted by the Lorentz theory. In order to separate this signal from variations produced by the clocks, it is necessary to first remove the characterizable trends in the data as discussed above. The information contained in the diurnal sinusoidal character of the predicted phase shift can then be utilized. Measurements can be made at fixed times throughout the diurnal cycle, and the data taken on successive days coherently summed at these times. The ether component would therefore be maximized, and short-term random variations in clock behavior would be reduced. If we assume that the clock error is reduced to truly random variations by this technique, the signal-to-noise ratio as a function of the number of days used in the integration is given by

$$\mathrm{SNR} = \frac{\delta t \sqrt{n}}{\delta t_e} \tag{13}$$

where δt_e represents the rms random clock error for the number of samples taken per temporal bin per day. Here n represents the number of diurnal cycles used in the summation, and δt is the mean ether-induced phase shift at a given time of observation in the diurnal cycle. Therefore from (9)

$$\mathrm{SNR} = \frac{2 d_0 v \sqrt{n}}{c^2 \delta t_e} \tag{14}$$

and

$$d_0 = \mathrm{SNR} \frac{c^2}{2\sqrt{n}} \frac{\delta t_e}{v} \tag{15}$$

If SNR = 5 and $v = 10^5\,\text{m sec}^{-1}$, then

$$d_0 = \frac{220}{\sqrt{n}} \times 10^{10} \delta t_e \text{ meters} \tag{16}$$

We measured δt_e for the 7-day sample of data and found $\delta t_e = 0.35$ nsec. Hence for the 7-day measurement

$$d_0 \simeq 291 \text{ m} \tag{17}$$

which ensures that the two clocks are in the same inertial environment to a high degree of approximation.

The question now arises as to whether we will have the temporal resolution needed to make the measurement. We therefore evaluate δt from (9) using (17),

$$\delta t = 2 \times 291 \times 10^5/9 \times 10^{16} = 0.64 \text{ nsec} \tag{18}$$

To evaluate the temporal resolution of the interval counter, we use the 5-MHz output of one clock to trigger the interval counter time base, and measured the period of the second clock (note that the period of the same clock could have been measured, but the absolute stability of the periods is better than 2×10^{-19} sec). The value measured remained constant at 200 nsec $\pm$ 50 psec; i.e., the temporal resolution is $\sim$50 psec, which is significantly less than the 64 nsec of (18).

All the experiments discussed in this paper were conducted in a normal office, shirt-sleeve air-conditioned environment. According to discussions with Hewlett Packard personnel, it is possible to reduce the temporal resolution of the counter to less than 10 psec if environmental conditions are strictly controlled if such temporal resolution is required. The company claims to have achieved consistent ± 5 psec accuracy under controlled environmental conditions.

It is our conviction that the minimum length deduced for d_0 lies significantly below the safe threshold needed to ensure that the clock environments are the same, and that d_0 could be greatly increased, thereby offering the opportunity to detect values for v significantly lower than 10^5 m sec^{-1}. For example, for a signal-to-noise ratio of 3, with $d_0 = 2000$ m, a threshold value of $\sim 10^4$ m sec^{-1} for v is attainable in principle, which would allow detection of the orbital motion of the earth for confirmation of the experimental procedure. Although this value is large in comparison to the claims made by other methods, in an accompanying paper Torr and Kolen[9] have shown that with the exception of Marinov's[6] experiment, all experiments conducted to date were subject to Lorentz cancellation effects, which yield null results. Hence the possibility should not be overlooked that v is greater than 10^5 m $\sec^{-1}$ (See note added in proof).

To achieve the optimum environmental stability, it would be necessary to use high-quality evacuated coaxial cable buried in the earth at a depth of about 3–4 ft. This will eliminate thermal changes in d_0. As a control procedure d_0 should be measured at regular intervals in a round-trip time-of-flight configuration. The clocks and counter should be housed in environments controlled to $\sim 1\%$ in temperature and humidity. It is also advisable to isolate the counter from external electrical interference.

5. CONCLUSION

In this paper we describe an experiment involving commercially available instrumentation to measure the velocity of the earth with respect to absolute space. The experiment involves the measurement of the one-way propagation velocity of electromagnetic radiation down a high-quality coaxial cable. We demonstrate that the experiment is both physically meaningful and exceedingly simple in concept and in implementation. It is demonstrated that with currently available commercial equipment one might expect to detect a threshold value for the component of velocity of the earth's motion with respect to absolute space in the equatorial plane of approximately 10 km $\sec^{-1}$, which greatly exceeds the velocity resolution required to the detect motion of the solar system with respect to the center of the galaxy.

It is our intention to perform this experiment if adequate funding becomes available to lease the required instrumentation for a suitable period of time, and to construct the facilities needed for the strict environmental control. Although the opportunity was available to us to carry out this experiment within limited time under uncontrolled conditions, the temptation to do so was resisted so that no unnecessary ambiguities would prematurely be introduced into the literature.

NOTE ADDED IN PROOF

Since this paper was submitted for publication in December, 1980, several new developments have occurred in the field. In a paper to be submitted for publication in Physical Review Letters, D. G. Torr and D. Fraser show that the Mossbauer experiment analyzed by Torr and Kolen[9] represents an unusual case of cancellation by symmetry of the experimental arrangement. They predict that variations in the Mossbauer absorption signal should exceed 5 % in most other experimental configurations. The signal is predicted to vary as $\sin(2\omega t)$ (ω = angular velocity) whereas past experimenters curve fitted their data with a $\cos(\omega t)$ function derived from classical doppler theory which yields a null result incorrectly. Torr and Fraser also identify new cancellation terms for the clock experiment proposed in this paper. They point out that a 5 % positive result from the Mossbauer experiment coupled with the smaller values they predict for the clock experiment would uniquely prove the Lorent theory to be correct. The clock experiment is nevertheless suitable for the detection of variations in the one-way velocity of light within the context of other theories such as the ε-generalized relativity of Winnie[11].

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