Guided-wave measurement of the one-way speed of light

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A new experiment has been performed as a step toward settling an unresolved issue in the testing of the special theory of relativity. The experiment is a test for velocity or direction-dependent variation of the one-way speed of light due to particular motion of a light source and an observer. The apparatus consists of a novel type of radio-frequency bridge, in the configuration of a Mach-Zender interferometer, one arm of which is a waveguide operated near its lowest cutoff frequency (at 40 GHz) to give a very large phase velocity. Clock-transport effects have been avoided by employing only one clock that effectively remains at rest in the laboratory. Our results have not yielded a measurable direction-dependent variation of the one-way speed of light. A clear null result is obtained for a hypothesis in which anisotropy of the cosmic background radiation is used to define a preferred reference frame.

I. INTRODUCTION

It has been argued that, since the speed of light is the limiting speed of any signal available for synchronizing clocks, a measurement of the speed of light on a one-way path is not possible. This argument, of course, presumes the Einstein synchronization by light signals. Although the use of light or electrical signals is certainly not the only possible method for synchronizing separated timers, a true one-way measurement of the speed of light has thus far been elusive. The one-way measurement also remains the definitive point of experimental distinction between the special theory of relativity and a semiclassical absolute space theory such as the Lorentz ether theory.[1] In fact, a few methods have been proposed to detect variation of the one-way speed of light. Notable among these are the Mössbauer-effect experiments of Champeney and Moon[2] and of Turner and Hill.[3] For an experiment of this type, the rates of moving clocks are compared without the need for synchronization. However, as Sama[4] has pointed out, this experiment cannot be used to distinguish between the relativistic Doppler effect and classical Doppler effect.

Also notable is the "one-way" speed of light measurement of Vessot and Levine.[5] This experiment employed two stable clocks, one of which was carried by a rocket, the other fixed on the Earth. The frequencies of the two clocks were continuously compared by use of a one-way radio link. Vessot and Levine interpret their results to set an upper bound of about 10^{-8} for fractional variation in the one-way speed of light. It can be shown, however, that transport of the space-borne clock produces an effect that cancels any possible direction-dependent variation of the measured speed of light. Vargas[6] has rigorously analyzed this experiment in the framework of a generalized theory, showing that it cannot reveal anisotropy in the propagation of the radio wave. As discussed by Maciel and Tiomno,[1] other historical tests are generally incapable of revealing effects which might violate special relativity due to cancellation by effects which were not anticipated in the design of the experiments.

Our experiment is motivated, in part, by measured anisotropy in the cosmic microwave background radiation. Smoot, Gorenstein, and Muller[7] have interpreted their measurements of a dipole anisotropy as being attributable to a Doppler shift produced by motion of the solar system with respect to the primordial matter which emitted the radiation. If this interpretation is correct, it implies the existence of a unique reference frame in which the background radiation is isotropic. This makes a reasonable case for the existence, in some sense, of an absolute reference frame. According to Smoot, Gorenstein, and Muller, their data can be interpreted to give a value of 390 km s^{-1} for the peculiar velocity of the solar system. We shall examine the specific implications for the present experiment when this value is assumed for the absolute velocity of the laboratory reference frame.

To form our hypothesis, we consider a theory which postulates the existence of a preferred or absolute frame of reference in which light propagates isotropically at a fixed speed. In all other reference frames the one-way speed of light depends on the state of motion of an observer with respect to the preferred reference frame. The mathematical description of this alternative theory shall be referred to here as the generalized Galilean transformation (GGT). The theory is in predictive agreement with special relativity to a high degree of precision for nearly every type of measurable effect. When the Einstein convention of synchronization by light signals is imposed upon the GGT, the usual Lorentz transformations of special relativity are obtained[8] and possible measurement of variation of the speed of light is automatically precluded. In order to experimentally distinguish between these two theoretical alternatives, it is therefore necessary to measure the one-way speed of light without recourse to the Einstein synchronization. Nor can the measurement depend on the length of a "standard" rod or the transport of clocks, because the effects of length contraction and time dilation produce the same result as the Einstein synchronization. The guided-wave interference experiment, described here, is expected to meet the special requirements for a true one-way measurement since it measures interference between unidirectional continuous waves which are excited by a single radio-frequency "clock."

For the simple case of motion along the x direction, the generalized Galilean transformation is given by the following expressions:

$$x=\gamma(x_0-vt_0),\quad t=\gamma^{-1}t_0,\quad y=y_0,\quad z=z_0 , \qquad (1)$$

where the zero-subscript coordinates are the coordinates of space and time in the so-called absolute reference frame. The unsubscripted coordinates are the coordinates in a reference frame which is moving with velocity v with respect to the absolute frame. The quantity γ is the usual length-contraction, time-dilation factor which appears in special relativity, i.e.,

$$\gamma=(1-v^2/c^2)^{-1/2} . \qquad (2)$$

Here c is the constant of the velocity of light in the absolute reference frame. The inverse transformations of the GGT are also represented here, obtained by ordinary algebraic inversion of these equations. This is a result of the fact that length contraction and time dilation are taken to be real physical effects rather than the artifacts of measurements which are made according to the conventions of special relativity.

The GGT has many of the properties of the Lorentz transformation. For instance, the four-dimensional line element

$$dS^2=(dr_0)^2-c^2(dt_0)^2 \qquad (3)$$

is invariant under the generalized Galilean transformation. An invariant four-momentum is thus obtained which yields the usual relation between energy and momentum in any inertial frame. Unlike the Lorentz transformation, however, the GGT allows for the possibility of absolute simultaneity. Events which are simultaneous in the absolute frame are simultaneous for all reference frames. From Eq. (1),

$$\Delta t=\gamma^{-1}\Delta t_0 . \qquad (4)$$

This condition implies the existence of spatially separated clocks which read the same coordinate time. In order to circumvent the problems involved with instantaneous synchronization, i.e., faster-than-light signaling, it is sufficient to avoid considering any experiment which requires the synchronization of timekeeping clocks. While this is a rather restrictive condition, it does apply to many important experiments such as that of Michelson and Morley. The remaining problem is to find an experimental arrangement which is not a round-trip measurement like the Michelson-Morley experiment. Toward this end, we shall examine the way that Maxwell's equations transform under the GGT.

One of us (T.C.) has employed the four-dimensional tensor form of the generalized Galilean transformation to obtain the formulation of Maxwell's equation in a vacuum,[9] in a reference frame moving with absolute velocity v. The vacuum wave equation which is obtained from this formulation of Maxwell's equations is given by

$$\nabla^2 E+2\left[\frac{\mathbf{v}}{c}\cdot\nabla\right]\frac{1}{c}\frac{\partial E}{\partial t}-\left[1-\frac{v^2}{c^2}\right]\frac{1}{c^2}\frac{\partial^2 E}{\partial t^2}=0 , \qquad (5)$$

where E is a component of the electric field in the moving laboratory frame. Substituting the usual solution for a plane wave traveling in the z direction, i.e., $E(z)=E\exp(ikz-i\omega t)$, and solving for k, we find that the wave number corresponds to a wave with phase velocity $c+v$, to the first order of approximation. The classical velocity addition is thus obtained for electromagnetic waves in a moving reference frame.

II. HYPOTHESIS

For the development of the experimental hypothesis, we shall analyze the propagation of a transverse electric (TE) mode in the waveguide via Eq. (5). For a waveguide lying along the z direction of the laboratory-coordinate system, the field in the waveguide is required to have the following form:

$$E(x,y,z)=E(x,y)\exp(ikz-i\omega t) . \qquad (6)$$

The boundary conditions on the waveguide assume perfectly conducting walls and require the tangential component of the electric field in the laboratory frame to vanish at the waveguide walls. For a rectangular waveguide, the following expression is obtained for the guide wave number in the reference frame of the laboratory:

$$k_g=-\frac{\omega}{c}\frac{v_z}{c}+\frac{1}{c}\left[\omega^2\left[1-\frac{v_x^2}{c^2}\right]-\omega_c^2\left[1-\frac{v_x^2}{c^2}-\frac{v_z^2}{c^2}\right]\right]^{1/2} . \qquad (7)$$

Here ω_c is the cutoff frequency, in the laboratory frame, for a given waveguide mode, and the absolute velocity is expressed in terms of its components in the laboratory-coordinate system. Notice that for $v=0$, the conventional results for waveguide propagation are obtained. For a rectangular waveguide, the cutoff frequency is given by

$$\omega_c = \omega_{mn}\left[1-\frac{v_x^2}{c^2}-\frac{v_z^2}{c^2}\right]^{-1/2} , \tag{8}$$

where ω_{mn} is the usual value for the cutoff freqeuency of the mn mode of the waveguide[10] which, in this case, corresponds to the value of the cutoff frequency in the absolute frame. Equation (8) defines the particular frequency at which the wave number is zero valued. This condition implies that, in the limit as the cutoff frequency is approached from above, the guide wavelength becomes infinite and there is no longitudinal position dependence for the electrical phase of the wave along the waveguide. This familiar result is, of course, highly idealized and cannot be applied to the case of a real waveguide. However, it does suggest some interesting possibilities for at least a conceptual experiment. For instance, if the phase of the wave on an ideal waveguide at cutoff is compared with the phase of a plane wave in free space, it is found that the phase difference is linearly dependent on the absolute velocity of the experimental reference frame.

While infinite guide wavelength is not physically realizable, phase velocities which are much greater than the speed of light can certainly be achieved. With this fact in mind, let us now proceed to develop a realistic experiment. The basic apparatus consists of two waveguides of the same length, with widely different cutoff wavelengths, which are driven at the same frequency by a common driving oscillator. One of the waveguides is operated very close to the cutoff frequency of its fundamental mode and the other is well above cutoff. The two waveguides are parallel and propagate waves in the same direction. At the terminating end of the two waveguides is a phase detector which measures the relative phase of the waveguide outputs. Let waveguide 1, with cutoff frequency ω_1, be operated close to its cutoff frequency so that the common driving frequency is $\omega_1+\delta$ with small δ. If the cutoff frequency of waveguide 2 is much lower than the cutoff frequency of waveguide 1, then the following approximation can be made for the phase difference between the two waveguides:

$$\Delta\phi=\phi_0+\frac{\omega_1 L}{2c}\left[\frac{\omega_1}{2\delta}\right]^{1/2}\frac{v^2}{c^2}\sin^2\theta . \tag{9}$$

Here, ϕ_0 is a constant phase difference for a given inertial reference frame and θ is the angle between the absolute velocity vector and the waveguide. The quantity L is the length of the waveguide pair. We see from this expression that, for a nonzero separation of the driving frequency from the cutoff frequency, a second-order effect is obtained which depends on the pointing angle of the waveguide.

In order to predict the magnitude of actual measurable effects we must consider the constraints which are imposed on the experiment by nonideal waveguides and by instrumentation. For instance, it is well known that as the cutoff wavelength is approached, attenuation in the waveguide increases sharply, limiting the length of the experimental base line. Also, the precision to which the waveguide can be manufactured determines how close to cutoff the waveguide can be driven. A frequency at the low end of the so-called millimeter wave bands was chosen as a reasonable trade-off between sensitivity and ease of fabrication, since at higher frequency the waveguide precision becomes increasingly critical. Although this experiment was designed for the radio-frequency regime, the same basic considerations would be applied to design an optical version of the experiment.

III. EXPERIMENTAL APPARATUS

The basic experimental apparatus is depicted schematically in Fig. 1. The arrangement consists of a standard WR-28 rectangular waveguide and a specially prepared waveguide which is driven near the cutoff frequency of the TE_{10} mode. The two waveguides, each about 8 ft in length, are fed in common by a klystron oscillator operating at 40.160 GHz. At this frequency, the near-cutoff waveguide is driven only 50 MHz above the cutoff frequency, producing a phase velocity of about 20 times the speed of light for the guided wave. The WR-28 waveguide is driven well above cutoff, giving a phase velocity of about 1.2 times the speed of light. Isolators are placed at various points to reduce standing waves in the waveguides.

A 10-dB coupler is used to couple power to the WR-28 waveguide, acting in a role analogous to the beam splitter on the input end of an optical Mach-Zender interferometer. Signals from the two waveguides are recombined in a balanced mixer which gives a dc output proportional to their phase difference when the waveguide outputs are set near phase quadrature. Because the two diodes in the balanced mixer are not perfectly matched, the mixer produces a power-dependent offset voltage which is sensitive to amplitude fluctuations from the klystron oscillator. In order to minimize AM noise effects, a variable attenuator is used to "bias" the mixer at a minimum on the offset voltage curve. With 300 mW of power available from the klystron, the instrument yielded a phase sensitivity of approximately 1 mV per milliradian of phase shift, measured at the output of the balanced mixer phase detector. The output of the phase detector is amplified by a voltage gain factor of 10^5 and the amplified signal is integrated in a low-pass filter with cutoff at 1 Hz.

A small part of the output from the klystron oscillator is down-converted at a mixer which is located close to the klystron, and the intermediate frequency signal is sent to a phase-locking frequency counter. The frequency counter and a stable crystal reference oscillator are held in an equipment rack which remains stationary in the laboratory. An error voltage from the frequency counter is applied to the klystron reflector terminal via the klystron power supply to form a phase-lock loop. For an arrangement of this kind, the closed-loop output of the klystron oscillator is held to the fractional stability of the reference oscillator, averaged over a period of 1 ms or greater.[11] With a short-term frequency stability of one part in 10^{10} for the oven-controlled crystal reference oscillator, the time-averaged bandwidth of the phase-locked klystron is less than 100 Hz. Since it is phase locked to a

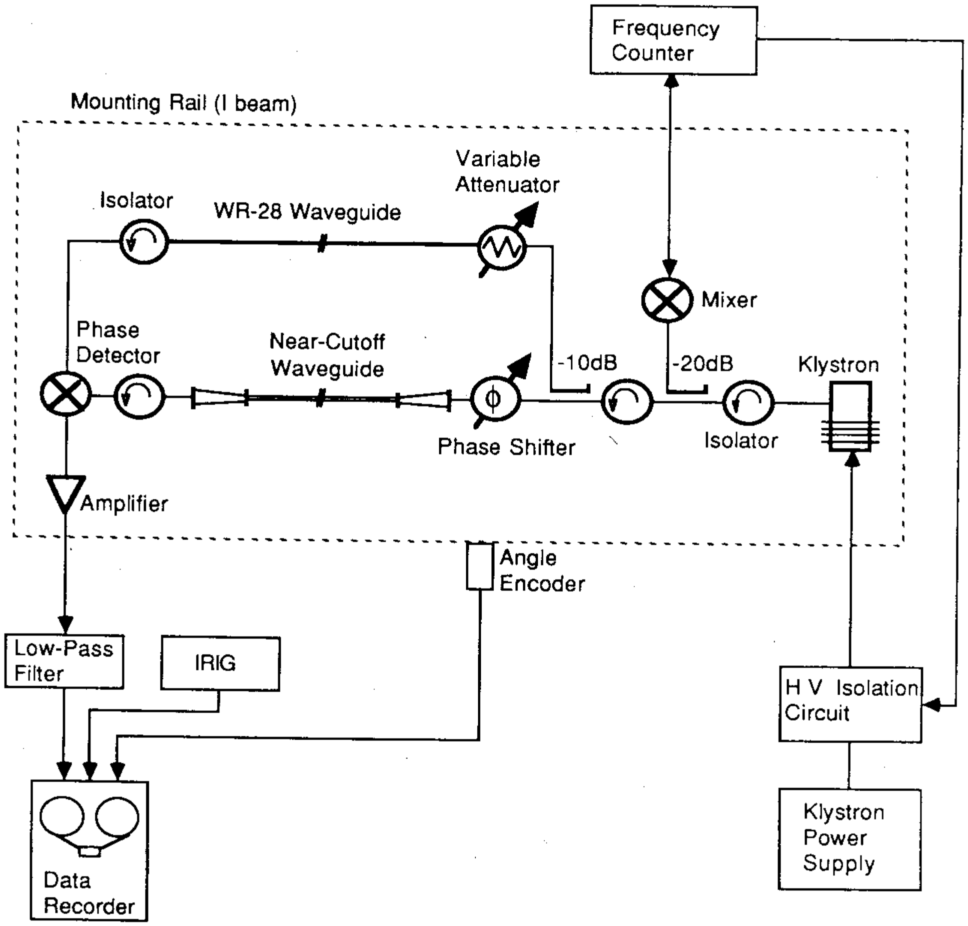


FIG. 1. Schematic diagram of the experimental apparatus.

reference oscillator which is at rest in the laboratory, the output frequency of the klystron is unaffected by rotation of the apparatus. Note that because the phase-lock loop forms a closed signal path, it is subject to round-trip invariance.

The entire waveguide apparatus, including the klystron, was mounted on an aluminum I beam to provide rigid support. The mounting rail was suspended by steel cables which allowed the beam to swing in a horizontal plane in the manner of a torsion pendulum. Data was acquired as the arrangement was allowed to swing freely through just over 180° of travel with a rotation period of about 30 s. The angular position of the apparatus was read from a potentiometer attached to the mounting rail. The 0° laboratory angle was aligned due east. Lacking any sort of electromechanical drive, the rotation of the apparatus was sustained by a gentle push, applied manually, at the extreme ends of travel of the mounting rail where it was nearly motionless.

A fundamental limitation to the sensitivity of this experiment is imposed by the requirement for uniformity of the waveguide cross-sectional dimensions over a long length of waveguide. For the case at hand, a variation of 50 μ in. in the broadwall dimension of a rectangular waveguide with 40 GHz cutoff frequency would result in a 14-MHz variation of the cutoff frequency from one section to another. If 50 μ in. represents a limiting value on the precision available for a waveguide produced by conventional manufacturing techniques, then the waveguide must be driven at a frequency at least 14 MHz above the nominal cutoff frequency so that no section of significant length will be below cutoff. Imperfections in the waveguide which are small with respect to a wavelength do not pose a significant problem, since they act like reactive element constants on the waveguide transmission line and slightly impact the attenuation in the waveguide. The precision-drawn waveguide used in the near-cutoff arm of the instrument was specially manufactured using conventional processes which were refined to give the greatest possible uniformity. The waveguide was made with a 0.148-in. square bore to give minimum attenuation for the TE_{10} mode. The nominal cutoff frequency of the finished 8 ft. length of waveguide was determined by measuring the change of the waveguide electrical length with a small change in driving frequency over a range of frequencies close to cutoff. An uncertainty of about ± 8 MHz was obtained for the cutoff frequency by this measurement.

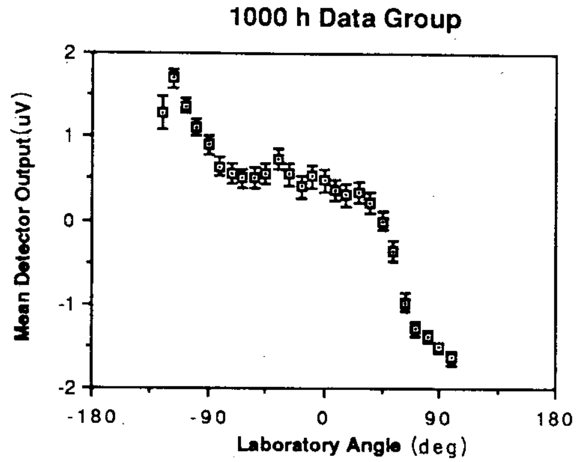
Temperature fluctuations acting on the near-cutoff waveguide were found to be a significant source of noise because of the extreme sensitivity of cutoff frequency to small expansion or contraction of the waveguide. As a result, the waveguide was driven at a frequency somewhat higher than the limit imposed by manufacturing precision. A driving frequency 50 MHz above cutoff was found to limit the noise to an acceptable level without comprising the sensitivity of the experiment. In an attempt to reduce temperature fluctuations, the near-cutoff waveguide was enclosed in an oil-filled sleeve, although this achieved only a slight improvement. The signal which provided the phase-shift data was subject to a slow monotonic drift, apparently caused by ohmic heating and gradual expansion of the near-cutoff waveguide as power from the klystron was absorbed in the waveguide.

IV. DATA AND ANALYSIS

Phase-shift and angular-position data were recorded on magnetic tape using frequency-modulating input channels of multitrack analog tape recorder. Local time was continuously recorded on another track from a signal provided by an International Range Instrumentation Group (IRIG) time code generator. Data was recorded in runs of approximately 10 min each in separate groups which were centered at 1000 and 1600 h, local time. An approximate total of 7 h of data was accumulated over a two-week period in July of 1987. The 6 h separation between data sets was designed to provide a means of detecting direction-dependent effects by directly comparing data, averaged at pointing angles fixed in the laboratory, from each data set. Hypothesized effects, which vary with respect to direction fixed in the distant stars, could thereby be distinguished from purely systematic effects caused by rotation of the apparatus in the laboratory.

The analog data was converted to numerical form by playback of the data tape into a system employing analog-to-digital converters under computer control. The playback signal from the tape was sampled once for every half second of record time. Instrument drift was removed by performing a least-squares linear regression on data from each run. In each of the two separate data groups, residual data was then coherently averaged in angular sectors with a width of 9° each.

The averaged value of the phase-detector output was plotted versus the pointing angle of the apparatus in the laboratory. Results from the data taken at 1000 h and 1600 h local time are displayed in Figs. 2(a) and 2(b), respectively. The two plots are identical to within the value of one standard error at every data point. The larger error bars in the 1600-h data group reflect the fact that, overall, slightly less data were taken in the afternoon. Note that, over more than 120°, both plots are essentially flat and that both display positive and negative peaks in the same positions. The locations of the peaks coincide with the angular positions at which a gentle push was applied to sustain the motion of the rotating apparatus. These features are apparently due to a slight bending of the waveguide as the apparatus was being pushed. According to the data, with a measured phase sensitivity of 60 μV per degree, the phase shift attributable to reorientation of the apparatus by a 6-h rotation of the Earth does not exceed 8×10^{-3} degrees.



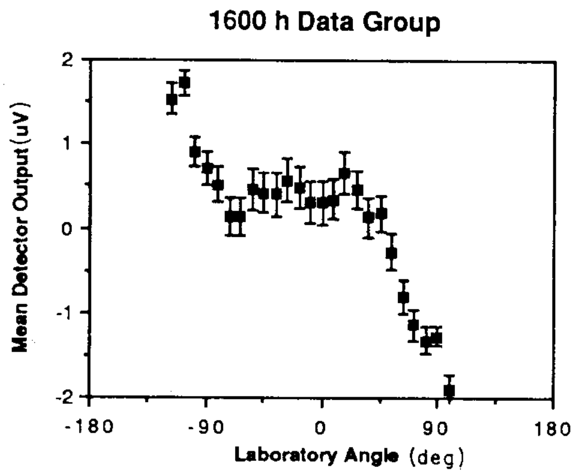


FIG. 2. Plots of averaged output of the phase detector. The abscissa is the pointing angle of the apparatus in the laboratory, with 0° due east. (a) Data from runs clustered about 1000 h, local time. (b) Data from runs at 1600 h, local time.

The measured phase shift predicted from Eq. (9) is determined by the direction of the Earth's hypothetical absolute velocity. However, regardless of the direction of the absolute velocity, the predicted phase shift will be a sine-squared function of the laboratory angle and, unless the absolute velocity is aligned with the Earth's axis of rotation, a 6-h time change will produce a 90° shift in the angular dependence. Measurements of the cosmic microwave background radiation[7] imply a speed of about 400 km s^{-1} in the nominal direction of 11 h right ascension, +6° declination for the peculiar motion of the Earth. Using these figures, a peak-to-peak phase shift of at least 19° is predicted as the apparatus turns in the laboratory (at 36° N latitude).

Insofar as our experiment is a true one-way speed of light measurement, we conclude that motion of the solar system, to which the anisotropy of the cosmic background radiation is attributed, does not constitute an "absolute velocity" in the context of the semiclassical theory which we have examined. Our results are consistent with the special theory of relativity and do not tend to support the semiclassical theory or the existence of a preferred frame of reference.

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