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Test of the isotropy of the one-way speed of light using hydrogen-maser frequency standards

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A new test of the isotropy of the one-way velocity of light has been performed using NASA's Deep Space Network (DSN). During five rotations of the Earth, we compared the phases of two hydrogen-maser frequency standards separated by 21 km using an ultrastable fiber optics link. Because of the unique design of the experiment, it is possible to derive independent limits on anisotropies that are linear and quadratic in the velocity of the Earth with respect to a preferred frame. Assuming that the anisotropies have not been partially canceled by systematic environmental effects on the instrumentation, the best limits that can be inferred from the data are $\Delta c/c < 3.5\times 10^{-7}$ and $\Delta c/c < 2\times 10^{-8}$ for linear and quadratic dependencies, respectively, on the velocity of the Earth with respect to the cosmic microwave background. The theoretical interpretation of the experiment is discussed.

The constancy or isotropy of the velocity of light for inertial reference frames, first tested in the classic experiments of Michelson and Morley,[1] is a fundamental postulate of the theory of special relativity. Because of the success of relativity, there is little reason to doubt the validity of this postulate. Nevertheless, in most previous tests of isotropy, light was propagated in a closed path instead of one way.[2] Consequently, round-trip propagation would be sensitive to an anisotropy which is of second order in the velocity of the reference frame of the experiment with respect to a hypothetical universal rest frame, but would be insensitive to an anisotropy which is of first order in this velocity. Because of technological limitations, the high speed of light has necessitated round-trip experiments in order to achieve meaningful results. The exceptions to this are the Mössbauer-rotor experiments of Turner and Hill and of Champeney, Isaak, and Khan[3] which yield a one-way limit of $\Delta c/c < 2\times 10^{-10}$, and a recent experiment using fast-beam laser spectroscopy.[4] The latter, amounting to a test of the isotropy of the first-order Doppler shift of light emitted by the atomic beam (and indirectly thereby a test of the speed of light) yielded a limit of $\Delta c/c < 3\times 10^{-9}$ in an anisotropy of the one-way velocity of light. Vessot *et al.*[5] have inferred a similar limit for a possible difference in c between the uplink and the downlink signals used in the NASA GP-A rocket experiment to test the gravitational redshift effect. These experiments were all similar in that the basic approach involved a frequency measurement. While frequency comparisons can be performed extremely precisely, the use of this technique to constrain a variation in c is nevertheless possibly limited because the propagation delay (or its variation) was not directly measured.

As a result of the ongoing technological development in the National Aeronautics and Space Administration Deep Space Network (DSN), we have been able to perform a new, direct test of the isotropy of the one-way velocity of light. We have compared two *stationary* clocks using one-way propagation in order to test a possible anisotropy which is dependent upon the orientation of the Earth in space. Furthermore, the clocks used in our experiment were separated by over 21 km, which extends the domain of this type of experiment to space-time separations not accessible in the laboratory. The experiment was made possible by the use of highly stable frequency standards and a highly stable fiber optics link which minimized unwanted propagation delays between the standards.

Experimental results. A description of the experiment and of preliminary data has been presented elsewhere.[6] Two hydrogen-maser oscillators separated by a baseline of 21 km were compared at the DSN Deep Space Communications Complex in the Mojave desert at Goldstone, California. The masers have permanent locations at Deep Space Stations (DSS) 13 and 14, respectively. Each maser provides a stable 100-MHz output frequency. This signal was split, with one signal being fed directly into one channel of a Hewlett-Packard 8753A Network Analyzer. The other signal was used to modulate a laser carrier signal propagated along a 29-km-long ultrastable fiber optics link that is buried five feet underground between the stations. This signal was fed into the second channel of the other Network Analyzer at the distant site. The configuration is completely symmetrical, with each analyzer being used to measure the relative phases of the masers. These phase comparisons were performed simultaneously in both directions along the *same* optical fiber to provide the capability later both to difference and to add the phase comparison data recorded at one site with the data recorded at the other site. IBM personal computers were used at each location to control the Network Analyzers and to automate the storage of the phase measurements onto micro disks. Beginning on 12 November 1988 at 20:00:00 (UTC) phase measurements were made every ten seconds until the experiment was ended on 17 November 1988 at 17:30:14 (UTC).

This unique capability either to difference or to add the relative maser phase recorded at each site permits us to set separate limits on two possible variations in the one-way velocity of light. In some theories, the observed variation could have the form $\delta c/c_0 = c_1\cos\theta + c_2\cos^2\theta$, where c_0 is a fiducial value of the speed of light, whose value will be chosen to be unity for simplicity, and where θ is the angle between the light propagation path and the direction of motion of the Earth with respect to a universal reference frame. We will consider this motion to be in the direction of the observed dipole anisotropy of the cosmic microwave background.[7] The observable quantity is the variation in relative phase, related to the variation in c through the equation (or definition) $\phi = 2\pi\nu L/c$, where ν is the maser frequency and L is the propagation path length. Then $\delta\phi/\phi_0 = \phi_1\cos\theta + \phi_2\cos^2\theta$, where $\phi_1 = -c_1$, $\phi_2 = c_1^2 - c_2$. For propagation in the reverse direction, $\theta \rightarrow \theta + \pi$; therefore, summing and differencing the dual phase records for the forward and backward propagation directions provide a way to limit ϕ_1 and ϕ_2 separately:

$$(\delta\phi/\phi_0)_+ - (\delta\phi/\phi_0)_- = 2\phi_1\cos\theta\,, \quad (1)$$

$$(\delta\phi/\phi_0)_+ + (\delta\phi/\phi_0)_- = 2\phi_2\cos^2\theta\,. \quad (2)$$

Because we are interested only in phase variations having a 24- or 12-h period, we have sampled the phase records at 1000-sec intervals in order to filter unwanted higher-frequency variations and to reduce the amount of data to a more manageable level for analysis. The two data sets were then differenced and added, respectively. After fitting a bias and a linear trend, each of these records was then low-pass filtered using a fast Fourier transform. The resulting filtered phase records are shown in Fig. 1(a). The differenced data is sensitive to possible diurnal variations in the relative frequencies of the masers, caused by environmental effects such as temperature and barometric pressure variations. The amplitude shown in Fig. 1 is consistent with diurnal fractional frequency variations of order 10^{-13}, which have been seen, for example, in hydrogen masers placed side by side.[8] This maser variation cancels out when the phase records are added instead of differenced; the added data [Fig. 1(b)] are sensitive to a small diurnal temperature effect on the fiber optics link.

In order to determine the limits which these phase records set on the signatures predicted by Eqs. (1) and (2), we have evaluated these equations in an inertial reference frame centered on the Earth which was taken to have a uniform velocity in the direction of the dipole anisotropy of the cosmic microwave background[7] ($\alpha = 11.2$ h, $\delta = -6.1°$). The propagation path was taken to be along a straight line between the two masers, whose geodetic longitude and latitude are given by (243° 12′21.″37, 35° 14′51.″82), and (243° 06′40.″65, 35° 25′33.″37). From Fig. 1, it can be seen that the phase variations in the differenced data have an amplitude of less than 25°, while the amplitude of the cosine variation in the differenced phase [Eq. (1)], because of the projection effect, is 0.75. Equation (1) yields $2|\phi_1|\phi_0(0.75) < 25°$, where $\phi_0 = 2\pi\nu nL/c_0 = (3.7\times10^6)°$, where $n = 1.43$ is the index of refraction of the fiber optics link. Thus we obtain the crude bound $|\phi_1| = |c_1| < 4.5\times10^{-6}$. For the added data, the observed amplitude of variations of less than 1.5° leads to a limit $|\phi_2| \approx |c_2| < 3.6\times10^{-7}$.

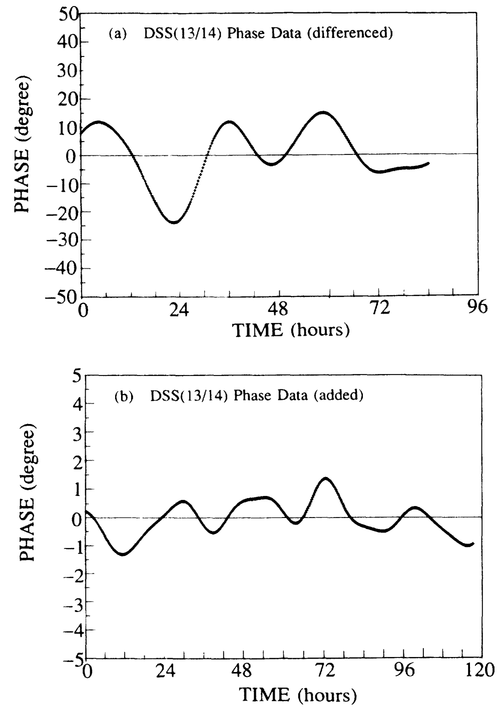

FIG. 1. (a) Differenced and (b) added phase records after low-pass filtering. The differenced data was truncated after 72 h because of an anomalously large phase excursion, which cancels out when the phase records are added.

Because the signatures of Fig. 1 are not perfectly correlated with the predicted phase variations, better limits can be derived by fitting the data by a least-squares method. We take as our limits on c_1 and c_2 their fitted values resulting from the least-squares estimation. A simple fit to the differenced data of the predicted cosine variation yields $|c_1| < 3.5\times10^{-7}$, while a fit to the added data of the predicted cosine-squared variation results in $|c_2| < 1.5\times10^{-7}$. If in the latter fit we also include a 24 h cosine of arbitrary amplitude and phase to model a diurnal variation in the link delay, there results $|c_2| < 2\times10^{-8}$ with an improvement in the fit. A similar fit to the differenced data to model a maser diurnal variation is not meaningful because of the high degree of correlation with the predicted cosine variation.

The validity of these limits rests upon the assumption that the predicted phase variations were not partially canceled by systematic errors. A Smithsonian Astrophysical Observatory (SAO) maser was used at DSS 14 which has a temperature and barometric pressure sensitivity of $8\times10^{-15}/°C$ and $5\times10^{-15}/(\text{in. Hg})$ in fractional frequency variation, respectively. This maser is kept in a stable environment where the ambient temperature varies less than 0.2 °C per day. An older model JPL maser was used at DSS 13 which has sensitivities of $9\times10^{-14}/°C$ and $4.3\times10^{-14}/(\text{in. Hg})$. While the physics unit of this maser is kept in a stable environment, the electronics package is separate and susceptible to temperature variations of as much as 3 °C per day. Barometric pressure variations of a few tenths inches Hg can also occur. With the above sensitivities, there could have occurred a larger phase variation due to the masers than was apparent in the differenced data. Thus we cannot exclude the possibility that a relative maser diurnal variation could have canceled a larger predicted anisotropy than was fit to the differenced data.

A firmer limit is implied by the added data, however, because systematic errors larger than the 1.5° observed phase variation were not expected. The temperature coefficient of delay (TCD) of the optical fiber used is $7\times10^{-6}/°C$ in terms of fractional length variations. For 29 km of fiber, a 1.5° phase variation would have required a temperature variation of 31 °mC. A larger temperature variation along the link was not expected because of the insulation provided by burying the link five feet underground.

The instrumentation and procedures which were used in the experiment did not exceed operational DSN requirements. In the future we plan to make special improvements which will reduce the level of systematic error, especially in the differenced data. We have the capability to replace the maser in DSS 13 with one which is less sensitive to environmental conditions. In addition, a greater degree of environmental isolation can be used for the masers and other instrumentation. Simultaneous measurements of environmental conditions can also be carefully made for the purpose of calibrating any remaining associated systematic error. A longer data span would also improve the spectral resolution at low frequencies.

Theoretical interpretation. Whether the resulting limits on c_1 and c_2 are of interest depends on the particular theory in question. In special relativity (SR) their values should be exactly zero, independently of the type of experiment. Their observed values for a possible violation of SR can be determined precisely only by applying the theory in question to a detailed analysis of the experiment. For the present, we adopt the "test theory" of special relativity developed by Mansouri and Sexl,[9] which has been used conventionally to categorize and compare the results of tests of SR. This formalism provides a kinematic model for violations of Lorentz invariance[10] in which the transformation between a preferred universal reference frame $\Sigma:(T,\mathbf{X})$ and a moving inertial frame $S:(t,\mathbf{x})$ is given by

$$T=a^{-1}(t-\boldsymbol{\varepsilon}\cdot\mathbf{x})\,, \tag{3}$$

$$\mathbf{X}=d^{-1}\mathbf{x}-(d^{-1}-b^{-1})\mathbf{w}\cdot\mathbf{x}\mathbf{w}/w^2+\mathbf{w}T\,, \tag{4}$$

where $\mathbf{w}$ is the velocity of the moving frame, a, b, and d are functions of w^2, and $\boldsymbol{\varepsilon}$ is a vector determined by the procedure adopted for the global synchronization of clocks in S. In special relativity, with either Einstein (round-trip light signals) or clock-transport synchronization, $a^{-1}=b=\gamma\equiv(1-w^2)^{-1/2}$, $d=1$, $\boldsymbol{\varepsilon}=-\mathbf{w}$. We consider the following simplified model for the experiment described above. In a moving frame S, three clocks are at rest at the vertices A, B, C of a triangle, with the lengths $AB=AC=L$, and with the angle CAB equal to θ (L and θ are measured in S). The point A is at the origin of S and the line AB lies parallel to $\mathbf{w}$. The three clocks have been synchronized by some procedure that establishes the vector $\boldsymbol{\varepsilon}$. Clock A represents one of the experimental clocks, while clocks B and C are auxiliary clocks, used only to establish the time in S. A simple kinematic argument using Eqs. (3) and (4) gives, for the time of arrival at either B ($\theta=0$) or C of a signal emitted from A at time t_e,

$$t_{\rm arr}=t_e+ab^{-1}\gamma^2L[(\cos^2\theta+b^2d^{-2}\gamma^{-2}\sin^2\theta)^{1/2}+w\cos\theta]+L(\varepsilon_x\cos\theta+\varepsilon_y\sin\theta)\,. \tag{5}$$

At $T=t_e=0$, a light signal is sent from A to B, and received at B at a time $t_{\rm arr}(B)$.[11] The light signal carries its emitted phase, $\phi=0$, while the phase of the clock at B is $2\pi\nu t_{\rm arr}(B)$. At the moment of reception of this signal, a traveling clock T (the second experimental clock) located at B is synchronized with clock B; the measured phase difference between it and the light signal from A is therefore $2\pi\nu t_{\rm arr}(B)$. Clock T then travels slowly (speed $\ll w$) until it reaches C. In our experiment, this transport is effected by the rotation of the Earth.[12] The time elapsed on T during the transport can be calculated using Eqs. (3) and (4), but employing the net velocity of T relative to Σ derived from the appropriate formula for addition of velocities. One can then show that, at the moment of arrival of T at C, its reading is related to that on clock C by

$$t_T=t_C+2\alpha ab^{-1}wL(\cos\theta-1)-L[\varepsilon_x(\cos\theta-1)+\varepsilon_y\sin\theta]\,, \tag{6}$$

where α is defined by $\alpha w\equiv(1/2a)\partial a/\partial w$. At this very moment, a second signal from the clock at A arrives, emitted at a time t_e when its phase had increased by $2\pi k$ (k is an integer) since the emission of the initial light signal. The measured difference between the phase of T, $2\pi\nu t_T$ and of the signal $2\pi k$ can be obtained from Eqs. (5) and (6). The observable quantity is the *variation* in the phase differences as θ changes, or equivalently the difference in phase differences measured by T between locations B and C. The result is[13]

$$\delta\phi=ab^{-1}\gamma^2\phi_0w[1+2\alpha\gamma^{-2}](\cos\theta-1)+ab^{-1}\gamma^2\phi_0[(\cos^2\theta+b^2d^{-2}\gamma^{-2}\sin^2\theta)^{1/2}-1]\,, \tag{7}$$

where $\phi_0=2\pi\nu L$. Notice that the result is independent of the synchronization procedure embodied in the vector $\boldsymbol{\varepsilon}$.[14] In SR, the w-dependent terms vanish identically.

In the limit $w^2\ll1$, we expand $a\approx1+\alpha w^2+\cdots$, $b\approx1+\beta w^2+\cdots$, and $d\approx1+\delta w^2+\cdots$ (in SR, $\alpha=-\frac{1}{2}$, $\beta=\frac{1}{2}$, $\delta=0$) and obtain (modulo constants)

$$\delta\phi/\phi_0=w(1+2\alpha)\cos\theta+w^2(\tfrac{1}{2}+\delta-\beta)\cos^2\theta\,. \tag{8}$$

With $w\approx10^{-3}$ (300 km/sec),[7] the experimental constraints give $|\alpha+\frac{1}{2}|<1.8\times10^{-4}$ and $|\frac{1}{2}+\delta-\beta|<2\times10^{-2}$. By comparison, the Mössbauer-rotor experiments provide the limit $|\alpha+\frac{1}{2}|<10^{-7}$ [see Mansouri and Sexl, paper II (Ref. 9)], while the experiment of Riis *et al.* yields $|\alpha+\frac{1}{2}|<1.5\times10^{-6}$. A limit on the $\cos^2\theta$ variation has not been reported in these experiments, however (a theoretical analysis suggests that the Riis *et al.* experiment is not in fact sensitive to such a variation[13]). This term is expected to enter at higher order, producing a fractional frequency shift of order $w^2 u$, where **u** is the relative velocity of the source and receiver. Thus our $\cos^2\theta$ limit may be of interest because it does not depend upon this velocity.[15]

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[10]Haugan and Will (Ref. 1) have emphasized the importance of using a dynamical framework for Lorentz-invariance violations, since such violations lead to altered dynamics for the rods and clocks on which the transformations between inertial frames are based. For example, different clocks can suffer different time dilation. Because we are looking for an anisotropy in an otherwise stationary situation, the structure of the atomic clocks should not play an important role, so we have adopted a kinematic approach.

[11]In ignoring the fact that the light propagates along an optical fiber, we are assuming that the effective index of refraction of the material is not dependent on the orientation of the fiber relative to **w**, so that the effective velocity of light is $c'(\theta) = c(\theta)/n$. Here, in order to understand fully the effect of propagation along the fiber, one would have to use a dynamical approach to Lorentz noninvariance.

[12]Because both clocks are located on the surface of the rotating Earth, we should also transport a clock from A to its new location. However, this complication of the model does not change the final answer.

[13]C. M. Will (unpublished).

[14]This had to be the case, since the experiment contains only two clocks. Because we look only for a variation in the relative phase with angle, the relative synchronization of the two clocks at an initial time is completely arbitrary.

[15]Gagnon *et al.* have inferred a weak limit on a $\cos^2\theta$ variation in the one-way velocity of light by comparing the phases of dual waveguides having different cutoff wavelengths. They limit the measured phase variations to less than 8×10^{-3} degrees, which for a predicted variation of 19° implies $\Delta c/c < 4.2\times10^{-4}$. See D. R. Gagnon, D. G. Torr, P. T. Kolen, and T. Chang, Phys. Rev. A **38**, 1767 (1988).