Improved Laser Test of the Isotropy of Space

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Extremely sensitive readout of a stable "etalon of length" is achieved with laser frequency-locking techniques. Rotation of the entire electro-optical system maps any cosmic directional anisotropy of space into a corresponding frequency variation. We found a fractional length change $\Delta l/l = (1.5 \pm 2.5) \times 10^{-15}$, with the expected $P_2(\cos\theta)$ signature. This null result represents a 4000-fold improvement on the best previous measurement of Jaseja *et al*.

Our conventional postulate that space is isotropic represents an idealization of the null experiments of Michelson and Morley[1] and the later improved experiments of Joos.[2] Lorentz[3] and FitzGerald[3] showed that a specific longitudinal contraction could account for the null result. In his study of the axiomatic basis of the special theory of relativity, Robertson[4] has shown how this result may be combined with similarly idealized experimental results from the Kennedy-Thorndike[5] and Ives-Stilwell[6] experiments to lead unambiguously to the special theory of relativity, assuming the constancy of the speed of light. He shows that—between two inertial frames moving along x—the metric transforms as

$$ds^2 = dt^2 - c^{-2}(dx^2 + dy^2 + dz^2),$$

$$ds'^2 = (g_0 dt')^2 - c^{-2}[(g_1 dx')^2 + g_2^2(dy'^2 + dz'^2)]. \tag{1}$$

The special theory of relativity corresponds to $g_0 = g_1 = g_2 = 1$. A recent Letter summarizes the excellent agreement obtained in a wide variety of precision experiments with the predictions of special relativity.[7] Still, major advances in the three fundamental experiments are clearly of strong scientific interest, since in general we have only finite experimental limits for the velocity or absolute orientational dependences of the g_i. For example, the Joos version[2] of the Michelson-Morley experiment shows that $g_2/g_1 - 1 = (0 \pm 3) \times 10^{-11}$.

The sensitivity advantage of laser frequency metrology for length measurements was first pointed out by Javan and Townes, and with co-workers they were the first to apply laser techniques to a Michelson-Morley–type measurement.[8] Unfortunately their length etalons were in fact lasers, and a serious systematic frequency shift (275 kHz) was observed as the apparatus rotated. Thus, although their excellent intrinsic laser stability (~ 30 Hz) gave a glimpse of future metro-

logical possibilities, the large spurious systematic effect limited their test for cosmic anisotropy to $g_2/g_1 - 1 = \pm 2 \times 10^{-11}$. This value is about 10^{-3} of the "predicted ether drift," based on Earth's orbital velocity $[(v/c)^2 \simeq 10^{-8}]$ and represents only a small improvement over the Joos result. The present paper extends the null result by a factor 4000 below the value of Jaseja *et al*.,[8] to a frequency shift limit of $\pm 2.5 \times 10^{-15}$, corresponding to $\pm 5 \times 10^{-15}$ in $g_2/g_1 - 1$.

Our experiment has been designed to be clear in its interpretation and free of spurious effects. Its principle may be understood by reference to Fig. 1. A He-Ne laser ($\lambda = 3.39$ μm) wavelength is servostabilized so that its radiation satisfies optical standing-wave boundary conditions in a highly stable, isolated Fabry-Perot interferometer. Because of the servo, length variations of this cavity—whether accidental or cosmic—appear as variations of the laser wavelength. They can be read out with extreme sensitivity as a frequency shift by optically heterodyning a portion of the laser power with another highly stable laser, provided in our case by a CH_4-stabilized[9] laser. To separate a potential cosmic cavity-length variation from simple drift, we arranged to rotate the direction of the cavity length by mounting the length etalon, its laser and optical accessories, onto a 95-cm × 40-cm × 12-cm granite slab which, along with servo and power-supply electronics, may be continuously rotated. (The frequency readout beam comes from a beam splitter up along the rotation axis and is directed over to the CH_4-stabilized laser. Electrical power comes to the rotating table through Hg-filled channels and a contactor pin assembly below the table.) The table rotation angle is sensed via 25 holes pierced in a metal band under the table. A single, separate hole provides absolute resynchronization each turn. The laser beat frequency is counted for 0.2 sec under minicomputer con-
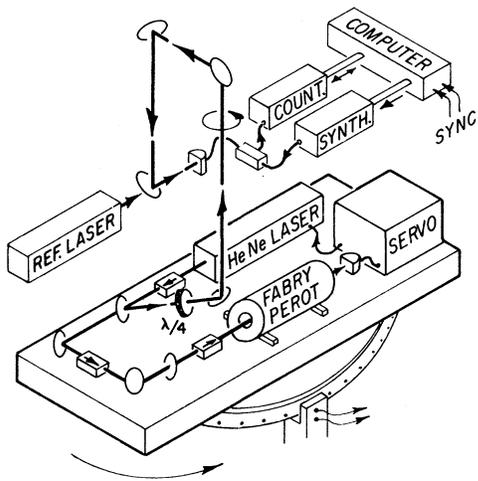
FIG. 1. Schematic of isotropy-of-space experiment. A He-Ne laser (3.39 μm) is servostabilized to a transmission fringe of an isolated and highly stable Fabry-Perot resonator, with provision being made to rotate this whole system. A small portion of the laser beam is diverted up along the table rotation axis to read out the cavity length via optical heterodyne with an "isolation laser" which is stabilized relative to a CH_4-stabilized reference laser. The beat frequency is shifted and counted under minicomputer control, these frequency measurements being synchronized and stored relative to the table's angular position. After 30 minutes of signal averaging the data are Fourier transformed and printed out, and the experiment is reinitialized.

trol after each synchronizing pulse, scaled and transfered to storage and display. A genuine spatial anisotropy would be manifest as a beat-frequency variation $\propto P_2(\cos\theta)$. The associated laser-frequency shift may be conveniently expressed as a vector amplitude at twice the table rotation frequency, f, of 1 per ~10 sec. Furthermore, its component in the plane perpendicular to Earth's spin axis should precess 360° in 12 h.

Our fundamental etalon of length is an interferometer which employs fused-silica mirrors "optically contacted" onto a low-expansion glass-ceramic[10] tube of 6-cm o.d. ×1-cm wall×30.5-cm length. The choice of 50-cm mirror radii provides a well-isolated TEM_∞ mode. Dielectric coatings at the mirrors' centers provide an interferometric efficiency of 25% and a fringe width ≃4.5 MHz. The interferometer mounts inside a massive, thermally isolated Al vacuum envelope. The environmental temperature is stable to 0.2 °C.

Fringe distortion due to optical feedback is prevented by a cascade of three yttrium-iron-garnet

Faraday isolators, each having a return loss ≥26 dB. The laser is frequency modulated ≃2.5 MHz peak to peak at 45 kHz. Both first-harmonic and third-harmonic locking were tried, the unused one being a useful diagnostic for adjustment of the Faraday isolators. Based on the 200-μW available fringe signal, the frequency noise of the cavity-stabilized laser is expected (and observed) to be about 20 Hz for a 1-sec measurement, using a first-harmonic lock.

Our CH_4-stabilized "telescope-laser" frequency reference system achieves a comparable stability.[9] The random noise of the beat signal in a typical 20-min data block is observed to be ~3 Hz, compared with the laser frequency of almost 10^{14} Hz. To ensure absolute isolation of the cavity-stabilized and CH_4-stabilized lasers, the latter actually is used to phase lock a "local-oscillator" laser offset by 120 MHz. The ~35-MHz beat of this isolation laser with the cavity-stabilized laser is the measured quantity.

The *useful* sensitivity of our experiment is limited mainly by two factors: drift of the interferometer (~−50 Hz/sec) and a spurious nearly sinusoidal frequency shift at the table rotation rate f. This latter "sine-wave" signal was typically about 200 Hz peak to peak, and arises from a varying gravitational stretching of the interferometer, if the rotation axis is not perfectly vertical. The centrifugal stretching due to rotation is −10 kHz at $f = (1$ turn$)/(13$ sec$)$ and implies a compliance ~10 times that of the bulk spacer material.

We find that taking data in blocks of N table rotations ($N \simeq 8-50$) is helpful in minimizing the cross coupling of these noise sources into the interesting Fourier bin at 2 cycles per table revolution (actually at $2N$ cycles per N table revolutions). Typically 10–20 blocks of N revolutions were averaged together in the minicomputer before calculating the amplitude and phase of the signal at the second harmonic of the table rotation frequency. The average result is an amplitude of $\cos 2\theta$ of ≃17 Hz (2×10^{-13}) with an approximately constant phase in the laboratory frame. A number of such $\frac{1}{2}$-h averages spanning a 24-h period are illustrated in Fig. 2 as radius vectors from the origin to the open circles. The noise level of each such average was estimated by computing the noise at the nearby Fourier bins of $2N$ ± 1 cycles per N table revolutions. For a $\frac{1}{2}$-h average ($N = 10$, averaged 10 times) the typical noise amplitude was 2 Hz with a random phase.

To discriminate between this persistent spuri-
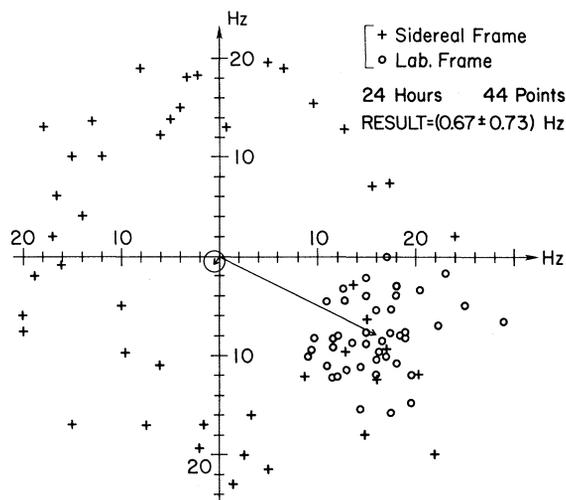
FIG. 2. Second Fourier amplitude from one day's data. The vector Fourier component at twice the table rotation rate is plotted as the radius vector from the origin to the open circles. After precessing these vectors by their appropriate sidereal angles they are plotted as the (+). For the 24-h block of data the average "ether drift" term is 0.67 ± 0.73 Hz, corresponding to $\Delta\nu/\nu = (0.76 \pm 0.83) \times 10^{-14}$.

FIG. 3. Averaged data of isotropy-of-space experiment. Data such as those in Fig. 2, were averaged in blocks of 12 h (thinner bars) or 24 h (thicker bars). For completeness this figure includes data from diagnostic experiments before day 225. The data after day 238 represent near-ideal automatic operation of the present apparatus. A 1-Hz amplitude represents $\sim 1.1 \times 10^{-14}$ fractional frequency shift. The reference axis for the projection is the direction identified by Smoot et al. [11.0-h R.A. (right ascension), 6° dec. (declination)], Ref. 12.

ous signal (17-Hz amplitude at $2f$) and any genuine "ether" effect, we made measurements for 12 or 24 sidereal hours. We must rotate each vector to obtain its phase relative to a fixed sidereal axis prior to further averaging. Averaging after this rotation leads, as shown in Fig. 2, to a typical 1-day result below 1 ± 1 Hz. Averages for 24 h were sometimes quieter than 12-h averages, an effect which may be related to the observed 24-h period of the floor tilt ($\approx \mu$rad). A number of 12- and/or 24-h averages are shown in Fig. 3. These data include most of the points taken during various diagnostic experiments. The data taken after day 238 correspond to approximately "ideal" automated operation of the present apparatus. The lack of any significant signal or day dependence allows us to perform an overall average. This final result of our experiment is a null "ether drift" of 0.13 ± 0.22 Hz, which represents a fractional frequency shift of $(1.5 \pm 2.5) \times 10^{-15}$. From Eq. (1) we have $\Delta\nu(2\theta)/\nu = \frac{1}{2}[(g_2/g_1) - 1]$, so that our experimental result[11] can be written in the form $g_2/g_1 - 1 = (3 \pm 5) \times 10^{-15}$. We may conservatively use Earth's velocity around the sun to calculate the "expected" shift $\frac{1}{2}(v^2/c^2) \simeq \frac{1}{2}(10^{-8})$, which gives a null result[11] some 5×10^{-7} smaller than the classical prediction. This limit represents a 4000-fold improve-

ment over the most sensitive previous experiment. This advance is due to smaller spurious signals in our experiment (2×10^{-13} instead of 10^{-9}), to superior data-processing techniques, and to superior long-term stability of the length etalon and reference laser.

The present sensitivity limit arises from two sources: the finite averaging time and some mechanical problems. To improve our result another decade by simple averaging would require 15 yr. The same decade improvement should be possible in several months' averaging, with improved mechanical design (rotation speed stable to 10^{-4} and the rotation axis actively stabilized to $\pm 1''$) and better vacuum stability inside the interferometer (to reduce the drift).

The recent discovery of a pure $P_1(\cos\theta)$ anisotropy in the cosmic blackbody radiation was interpreted as a Doppler shift produced by our motion (~ 400 km/sec) relative to a "privileged" inertial frame in which the blackbody radiation is isotropic.[12] If this velocity is considered to be the relevant one, our sensitivity[11] is $\sim 3 \times 10^{-9}$ and constitutes the most precise test yet of the Lorentz transformation. It will be especially interesting in the near future to develop techniques to

look even more sensitively for some extremely small residual "preferred frame" or general-relativistic effects.[13]

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[10]CER-VIT is a registered trademark of Owens Illinois Inc., Toledo, Ohio.

[11]For comparison with earlier work we also omit a 0.43× sensitivity reduction factor associated with our 40° latitude and the assumed $P_2(\cos(\vec{v}, \vec{l}))$ dependence.

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