LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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Can we use the LIGO interferometers to test the isotropy of space?

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Can we use the LIGO Interferometers to test the isotropy of space?

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The Michelson-Morley experiment [1], carried out in 1887, was the first search for an anisotropic propagation of light. Robertson [2] shows that, assuming the constancy of the speed of light, the metric between two inertial frames moving along the x-axis transforms from

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

to

$$ds'^2 = c^2(g_0 dt')^2 - [(g_1 dx)^2 + g_2^2(dy'^2 + dz'^2)]$$

Special relativity demands, of course, $g_0 = g_1 = g_2 = 1$. We have only finite experimental limits for the dependence of the g_i on relative velocity and orientation. For instance in Joos' version [3] of the M-M experiment $g_2/g_1 - 1 = (0 \pm 3) \times 10^{-11}$. In the Brillet-Hall [4] experiment , $g_2/g_1 - 1 < 5 \times 10^{-15}$. For experiments in the Michelson configuration, the ratio of the metric coefficients corresponds to a relative velocity

$$(v/c) \sim (g_2/g_1 - 1)^{1/2}.$$

We examine whether using the data from the current S5 run we can set better limits on the anisotropy of space. The LIGO interferometers are not fixed length instruments. For H1 both the frequency of the carrier and the arm length are adjusted to keep the interferometer in lock and on a dark fringe. Some of these adjustments are major and are pre-programmed (feed forward) to compensate for the tidal deformation of the arm lengths [5]. We can therefore consider the interferometer as maintaining fixed arm lengths with respect to the instantaneous carrier frequency. In addition to the carrier, the upper and lower sidebands (separated by one free spectral range, fsr,) circulate in the interferometer. We argue that an interference between the sidebands returning from the two arms is a measure of any anisotropic propagation of light. Note that while the signal at the carrier is subject to continuous feedback, no feedback is applied at the sideband frequencies.

Because of the earth's rotation the interferometer rotates with respect to a solar or galactic frame. Anisotropic effects will manifest as a twice diurnal modulation of the dark port signal at the fsr frequency. The difficulty arises in recognizing the instrumental contribution to such a modulation. Nevertheless one can set upper limits on a possible anisotropy by referring to the observed modulation [6]. One finds a twice daily, a daily and a semi-annual modulation of the signal corresponding to

$$\Delta l/l \sim 10^{-23}$$

This is an improvement by seven orders of magnitude over the best existing limit [4].

At this sensitivity we should be dominated by the red shift induced by the gravitational field of the sun (the analogue of the Pound-Rebka effect). For an arm length of 4 km along the sun's direction the frequency of the light shifts by $\Delta f/f = 2.5 \times 10^{-16}$, while there is no shift in the perpendicular arm. This would cause a diurnal variation in the differential signal much larger than the observed value given in the previous paragraph.

To detect the modulation due to the earth's rotation we integrate the psd (power spectral density) of the H1 interferometer over a narrow frequency band ($\Delta f \sim 180$ Hz) around the fsr. The instrumental issues that are associated with these measurements are discussed in ref. [6]. The first remark is that the level of integrated power (we refer to it as the signal) remains constant over the 18 months of the S5 run, except for the twice annual modulation. This is a remarkable result and it is encouraging when one wishes to examine long term trends. The daily and twice daily modulation are completely unambiguous and consistent over the entire data set.

The observed modulation can be due, principally, to two effects: (a) A phase shift in the optical fields returning to the AS port from the arms, at the fsr frequency, or (b) A modulation of the amplitude of the optical fields. The amplitude of the optical fields depends on the power stored in the arms and in the recycling cavity. Since the tidal servo (for H1) changes the carrier frequency, and thus the tune of the recycling cavity this may be a cause for the observed modulation of the signal. As pointed out in [6] the modulation at the fsr is at least five times larger than that observed in the AS-Q channel. This could be due to the active feedback at the AS-Q (absent from the fsr) which would tend to suppress any modulation.

In conclusion, we have discussed the possibility of using one of the LIGO interferometers to test the isotropy of space. The present configuration for compensating for the earth tides and for maintaining lock may not be optimal for such investigations. However by analyzing the control signals one may be able to recover any variations in the wavelength of the light propagating in the two orthogonal arms. Fixing the carrier frequency in a brief dedicated future run is another option. If the experiment is carried out properly the result should be dominated by the general relativity effects due to the gravitational field of the sun.

References

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