Measurement of Optical Path Fluctuations due to Residual Gas in the LIGO 40 Meter Interferometer

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ABSTRACT

Statistical fluctuations in the column density of residual gas in the beams of a laser interferometer gravitational wave detector induce noise in the measured optical path. Resulting limits on the permissible gas pressure for a given strain sensitivity strongly influence the LIGO vacuum system's configuration and cost. Until recently these limits were based entirely on a theoretical model. The displacement noise spectral density of the LIGO 40 meter interferometer was monitored as samples of carbon dioxide, nitrogen, and xenon gases were admitted to its vacuum system. Measurements confirm the model's predicted dependencies on frequency, molecular polarizability and mass, and pressure. Independent calibration of the interferometer verifies that the model also accurately predicts the effect's observed magnitude, within the 10% calibration accuracy.

1. Introduction

Provision of evacuated, multikilometer laser beam paths is a major challenge in building the large scale interferometric gravitational wave detectors now planned[1, 2] and under construction[3]. Fluctuation in the effective refractive index of residual gas, due to statistical variation in the column density of gas particles, can mask or imitate the expected signals if high vacuum is not maintained. The large volume and surface area and low conductance characteristic of these vacuum systems (of order 10^7 l, 10^5 m^2, and 100 l/s, respectively) have motivated development of novel methods to economically limit outgassing through preparation of raw materials and specialized fabrication techniques.

Optical path length noise caused by residual gas has been modeled by calculating the impulsive disturbance to the laser field's phase as a gas molecule moves through the beam (a function of its polarizability, radius of closest approach, and velocity), and integrating the effect of such impulses over the distributions of molecular speed and trajectory[4, 5]. The calculation is simplified by assuming molecules do not typically collide within distances comparable to the beam diameter, a condition readily satisfied in the intended application. The detailed model result is compared with our data below. Briefly, we expect the power spectrum of the optical path noise $S_L(f)$ to be approximately white for measurement intervals much longer than the duration of a typical molecule's passage through the beam, i.e. for spectral frequencies f such that $2\pi f \ll v_0/w$ where $v_0 = (2k_BT/m)^{1/2}$ is the molecule's most probable speed, m is its mass and w is the beam radius. We also expect the noise to scale as $S_L \propto \alpha^2 m^{1/2} P$ for molecules of polarizability α and weight m present at partial pressure P (proportional to their number density ρ).

2. Experimental Tests

The LIGO 40–meter interferometer[6] was used in a direct test of this model. This interferometer, a scientific testbed and prototype for LIGO gravitational wave detectors, comprises two 40–meter optical cavities at right angles in an evacuated enclosure. The mirrors of each cavity are suspended from isolated platforms to limit the influence of external forces. Active control systems maintain alignment and resonance of each cavity with the laser beam. The difference in optical path between the two arms is detected and Fourier–analyzed. The spectrum is calibrated by applying test current to fixed coils near small permanent magnets on one of the suspended mirrors; the force constant is derived by comparison with the laser wavelength. In this way the interferometer readout spectrum may be interpreted as absolute differential displacement, to an accuracy of approximately ±10%.

The interferometer's vacuum vessel was pumped by a combination of turbomolecular and cryogenic pumps, and in normal operation attained a pressure of approximately 3×10^{-6} Torr. A wide-range capacitance manometer vacuum gauge[7] allowed pressure readout to a precision of ±0.5 mT or less independent of gas species. For each test the interferometer background noise level was measured at low pressure ($< 10^{-5}$ T), the pumps were sealed off and a fixed sample of pure xenon, carbon dioxide or nitrogen was admitted; after equilibration, the new noise level was recorded. The background was then rechecked after opening the pumps and removing the test gas.

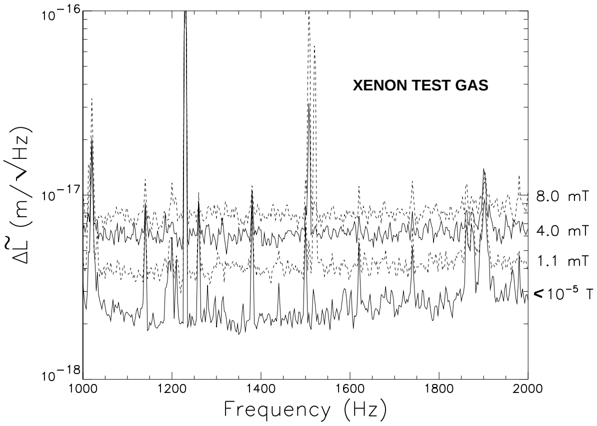

Figure 1. Amplitude spectral density of apparent differential arm lengths in the 40 meter interferometer as a function of xenon test gas pressure. The peak at 1230 Hz is for calibration; other peaks arise from mechanical resonances and interference.

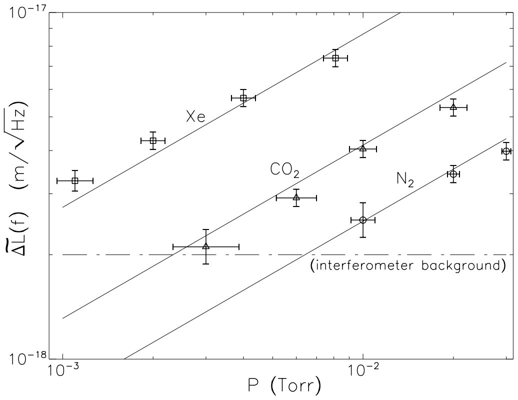

Figure 2. Amplitude spectral density near 1500 Hz for three gases as a function of pressure (points). The background noise (dot-dashed line) was subtracted in quadrature from each raw measurement. Solid lines are model predictions of Eq. (1) for each gas.

Noise spectral densities measured with xenon at several pressures are shown in Figure 1. Note that the noise added by the gas is approximately independent of frequency from approximately 800 to 2000 Hz (where gas noise exceeds the background). This was expected, since $v_0/2\pi w \gtrsim 8\ \mathrm{kHz}$ for our beam radius $w \approx 2\ \mathrm{mm}$ with all the gases tested. Narrow peaks in the spectra are due to mechanical resonances of the apparatus or powerline interference. At the highest pressures (above about 10 mT) some new peaks appeared as well; these may be caused by acoustic transmission through the sample gas. At the lower test pressures, the observed noise was only slightly higher than the background.

This constant background level was subtracted in quadrature from each measurement to give the contribution due to the gas alone, plotted in Figure 2. Here each point shows the measured noise in the region near 1.5 kHz. Magnitude error bars reflect calibration, measurement and background subtraction contributions; pressure errors are derived from the gauge specifications.

3. Conclusions

Our model predicts the power spectral density of the optical path length L to be

$$S_L(f) = \frac{4\rho(2\pi\alpha)^2}{v_0} \int_0^{L_0} \frac{\exp\left[-2\pi f\, w(z)/v_0\right]}{w(z)}\, dz \tag{1}$$

where L_0 is the actual length of the beam path and $w(z)$ is the beam's Gaussian radius parameter. The apparent difference in the lengths of the interferometer's two arms will have amplitude spectral density $\Delta\tilde{L}(f) \equiv \sqrt{S_{\Delta L}(f)} = \sqrt{2S_L(f)}$. This model prediction is overplotted on Figure 2 for each type of gas, using the interferometer's known L_0 and $w(z)$ and handbook values of the gas properties. The data appear to confirm the model within experimental errors, verifying the expected dependencies with respect to pressure, molecular polarizability and molecular mass.

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References

1. C. Bradaschia et al. *Nucl. Instrm. & Methods Phys. Res.,* **A289**:518, 1990.
2. J. Hough et al. Proposal for a joint German-British interferometric gravitational-wave detector. Technical report, Max–Planck Institute of Technology (Technical Report MPQ 147) and Rutherford Appleton Laboratory (GWD/137/JH), September 1989.
3. A. Abramovici et al. LIGO: the laser interferometer gravitational wave observatory. *Science*, **256**:325–333, 1992.
4. S. E. Whitcomb. Optical pathlength fluctuations in an interferometer due to residual gas. Technical report, California Institute of Technology, October 1984.
5. R. Weiss. Scattering by residual gas. Technical report, Massachusetts Institute of Technology, February 1989.
6. M. E. Zucker. The LIGO 40m prototype laser interferometer gravitational-wave detector. In H. Sato and T. Nakamura, editors, *Proceedings of the Sixth Marcel Grossmann Meeting on General Relativity, Kyoto, Japan,* pages 224–226. World Scientific, Singapore, June 1991.
7. *M.K.S. Model 107B Baratron.* M.K.S. Instruments, Inc., Andover, MA.