Five-year frequency stability of a Zeeman stabilized laser

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A five-year record of the lockpoint frequency of a Zeeman stabilized laser shows an observed drift rate of 0.3 ± 0.5 MHz/yr following an initial drift of 5.7 ± 2.2 MHz/yr in the first eighteen months of intermittent operation. A second Zeeman laser drifted at a rate of −0.8 ± 1.0 MHz/yr over the last 2.5 yr; the frequency drift was −0.2 ± 0.6 MHz/yr over the last 3.3 yr. Empirical temperature corrections to laser frequency measurements produce a slight variance reduction in the data but no effective bias in the drift estimates.

A Zeeman stabilized laser uses a magnetic field to induce Zeeman splitting of the atomic energy levels of the gain medium. The laser output is split into two modes whose frequency separation depends partially on their position in the gain profile. A minimum in their beat frequency occurs at the atomic line center. The laser cavity length can be servoed to minimize the intermode beat frequency and thus lock the laser to a well-defined frequency reference.

Two Zeeman lasers were constructed along these lines for use in an absolute gravity meter and to monitor the wavelengths of other stabilized lasers used in monitoring crustal deformation. The field environment requires a portable, stable, and rugged laser system.

The Zeeman laser output was heterodyned with an iodine stabilized laser to determine its absolute frequency and its dependence on its thermal environment. Measurements were made of the temperature of the laser plasma tube surface and the ambient temperature. A relationship between the Zeeman laser frequency, tube surface temperature $T_z$, and ambient temperature $T_a$ was determined. The data can be fit by an empirical formula with the form

$$f(T_z, T_a) = f_0 + (\alpha - \beta T_z)(T_z - 40^\circ C),$$

where the parameters $\alpha$, $f_0$, and $\beta$ are unique to our laser Zeeman S/N 1 and have the values of

$$f_0 = 473,612,233.0 \text{ MHz}, \quad \alpha = 0.612 \text{ MHz}^\circ C^{-1}, \quad \beta = 0.00496 \text{ MHz}^\circ C^{-2}.$$  

Equation (1) predicts the laser frequency with an accuracy of ±2 MHz for the temperature ranges of $19^\circ C < T_a < 30^\circ C$ and $30^\circ C < T_z < 55^\circ C$.

A second Zeeman laser (S/N 2) was built and its absolute frequency was measured as a function of tube temperature at a single ambient temperature around 20°C. At this ambient temperature, the frequency varies in a linear fashion with tube temperature and can be fit as

$$f(T_z = 20^\circ C, T_a) = f_0' + A(T_z - 40^\circ C),$$

where

$$f_0' = 473,612,209.8 \text{ MHz}, \quad A = 0.59 \pm 0.02 \text{ MHz}^\circ C.$$

Zeeman S/N 1 has accumulated <1500 h of operating time in five years (~8 h of operation every two weeks). Frequency comparisons of the laser with an iodine stabilized laser were made at approximately three-month intervals. Frequency measurements of Zeeman S/N 2 were made much less often, for a total of only five measurements over three years. Table I lists the observed frequencies, the temperature conditions of the measurement, and the temperature corrected frequencies.

The 4-MHz error bars in the first eighteen months of data are due to the uncertainty in the frequency corrections and the use of a spectrum analyzer's graphic display in determining the frequency difference. The 2-MHz error bars in the later measurements reflect the use of a more accurate averaging frequency counter whenever possible as well as the temperature correction uncertainty. Also, the first thirteen measurements of S/N 1, which predate 1984.8 (denoted by open circles in Fig. 1), were taken before the frequency dependence on temperature was recognized. We have applied a crude estimate of 26°C for the ambient temperature $T_a$ and 50°C for the tube temperature $T_z$. Subsequent measurements were made in a different laboratory which maintained a cooler ambient temperature. Because the frequency controlling servo relies on thermal expansion of the laser
tube, the available temperature range of the lasers is restricted during frequency comparisons.

For measurements made after 1984.8, the laser frequency of S/N 1 increased (drifted blue) at a linear rate of $0.33 \pm 0.51$ MHz/yr. During the first eighteen months of operation, from 1983.2 to 1984.8, the frequency drift was much greater, at a rate of $5.7 \pm 2.2$ MHz/yr. The initial eighteen-month period accounts for $<500$ h of laser operation.

Zeeman S/N 2 showed an effective drift rate over the last 2.5 yr of $-0.8 \pm 1.0$ MHz/yr. The frequency drift computed for the last 3.3 yr is $-0.2 \pm 0.6$ MHz/yr. The data set for S/N 2 is not sufficiently dense to detect a change in the drift rate over this period.

The temperature corrected data show an insignificant variance reduction when compared with the uncorrected data (<2%). This is expected, since most of the measurements were made in the same conditions. The temperature effects account for less than a 4-MHz correction in any case, of the same order as the error bars, and numerical tests show the corrections do not strongly bias the estimates for frequency drift.

The drift rate for S/N 1 corresponds to a frequency stability of better than $1 \times 10^{-9}$ per year in the period ranging from twenty months to five years after construction.

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References


5. Frequency values plotted in Ref. 3 differ from those given here due to a lack of temperature corrections in the former.

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**Error sources in the determination of the refractive index of air**

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Sources of error in the determination of the refractive index of air using optical techniques have been identified.

In high accuracy distance measurement in the free atmosphere, using optical techniques, the precise determination of the refractive index of air is of great importance. For a number of years the highest accuracy values have been obtained by calculation from the Edlen equation or by direct measurement using interference refractometers. Comparisons of the calculated and measured values have shown significant differences often at the level of a few parts in $10^{-7}$.

Several error sources associated with such determinations have been identified at the NPL and are discussed in this Letter.

Air refractivity values measured directly at $\lambda = 633$ nm with the NPL refractometer using specimens of standard dry air were compared with values calculated from Edlen's equation. The calculated values were derived from direct measurements of atmospheric pressure, air temperature, and the relative humidity of the air using sensors calibrated against primary standards at the NPL.

The comparisons, which were made over pressure and temperature ranges of 20–115 kPa and 10–30°C, respectively, showed that all the differences between the measured and calculated air refractivities were within the $\pm 3 \times 10^{-8}$ measurement uncertainty.

However, when comparisons of air refractivities were made using moist standard air specimens, there was a systematic difference between the measured and calculated values. This difference, where the measured value was always higher than that calculated, was seen to progressively increase with the relative humidity of the air. The comparison, therefore, implies an error in the water vapor term of Edlen's equation and a modification to the equation has been introduced. The error, which was found to be $\sim 13 \times 10^{-8}$ for fully saturated air at 20°C, may be attributable to water vapor adsorption effects in the apparatus used by Barrell and Seams. Edlen used the results from this apparatus as the basis of his water vapor term. Further measurements made at the NPL and at other geographical locations have confirmed that the modified Edlen equation gives more accurate results.

The above study also enabled water vapor absorption and adsorption effects to be observed in a variety of gas cell configurations used in the refractometer. These effects are due to water vapor being removed by the metallic surfaces of