Characteristics of a Ring Laser for Geodesy

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Abstract

Large Ring lasers are not yet used for geophysical applications. C-II is a prototype for such a device and has a square optical path with side 1 m. One difference with the earlier C-I laser testbed - and similarity to an aircraft gyro - is its monolithic construction. It is housed 30 m underground in a New Zealand military bunker. The measured ringdown time of 0.20 ms corresponds to a quality factor 6×10^{11} and a finesse 9.4×10^4. for the observed exit beam power of 10 pW, this gives an angular rotation sensitivity 4×10^{-9} rad/s/sqrt(Hz). C-II performance limits therefore rival those of Sagnac matter- wave gyroscopes (2×10^{-8} rad/s/sqrt(Hz), Gustavson et. al., Phys. Rev. Lett. 78, 2046-9 (1997)). This also corresponds to a quantum noise line width of 220 microhertz, consistent with that observed (172 microhertz) in the direct spectrum and with the coefficient of inverse time in the Allan variance plot.

Keywords: Ring laser gyroscope, Sagnac effect, earth rotation

1. INTRODUCTION

Ring lasers are known mostly from their application in inertial aircraft navigation, where they are used due to their many advantages over mechanical gyroscopes employing spinning masses. The relationship between the imposed rate of rotation and a splitting of the frequency of two counter-rotating laser beams enclosing a given area **A** is given by the Sagnac equation (1) for active cavities:

$$\delta f = \frac{4\mathbf{A} \cdot \mathbf{\Omega}_e}{\lambda L} \tag{1}$$

where L is the perimeter of the ring and $\lambda = 633$ nm the wavelength of the HeNe laser, while $\mathbf{\Omega}_e$ is the rate of earth rotation. Under ideal conditions this defines the unbiased operation of ring laser gyroscopes.

The C-II ring laser project involves a multinational and multi- institutional collaboration (as detailed in the acknowledgements). Its planning was reported at the Stuttgart Symposium Gyro Technology 1996 [1]. C-II was installed in January 1997 and we report here some of the results obtained so far.

2. THE C-II EXPERIMENT

Details of the rationale and design of C-II and the mathematical formulae needed to analyse these results in the manner done below have been published elsewhere [1, 2] and we summarise here only a few key points. C-II has a square beam path, with side 1.000 m, mirror mountings machined and polished to an accuracy of 10 arc sec, and two flat mirrors diagonally opposed, with two curved mirrors of radius 6.0 m on the other diagonal (figure 1). The supermirrors have total losses including transmission of each mirror of 1.2 ppm when new. The path is bored out of a solid piece of Zerodur, $1.2 \times 1.2 \times 0.18$ m, except that in two cut-out sections the path and laser gas are bounded by tubes, one of which functions as a gain tube (under r.f. excitation) and the other of which is available to access beams for research purposes.

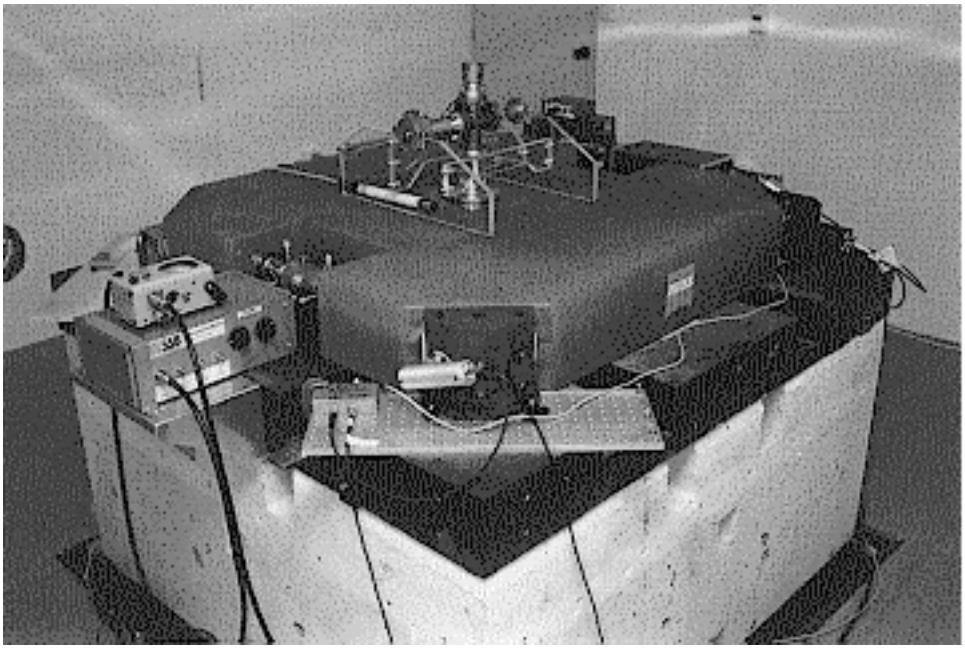

Figure 1: *Photograph of the C-II ring laser at its site in the cashmere cavern in Christchurch, New Zealand*

The d.c. component from a single beam is used to monitor the emergent optical beam power, and to servo the radio frequency amplitude for driving the plasma in order to keep the beam ampitude at a predetermined level. For monomode operation with this servoing system the required plasma power is typically 0.8 W, the plasma length 10 mm, and the exit beam power (measured for the quantum noise calculation to follow) 10 pW. Any higher power level leads to appreciable excitation of adjacent longitudinal modes. The Earth Sagnac rate nominally 79.4 Hz, was obtained with a measure of pushing and pulling associated with ambient pressure and believed to result from mirror backscatter, details have been published elsewhere [3]. The Sagnac frequency was stable, showing no variation to a precision of 1 mHz when the gain tube was used to vignette the beam, driving the servoed r.f. power to 1.2 W. With a 4 mm gain tube, the laser operated consistently in TEM(0,0). Transverse modes were absent under virtually all conditions.

The ringdown time was determined to be 0.20 ms as shown in figure 2. This translates into a quality factor of 6.0×10^{11}, and a cavity finesse of 9.4×10^4. We believe this to be a record for the passive quality factor of an optical resonator.

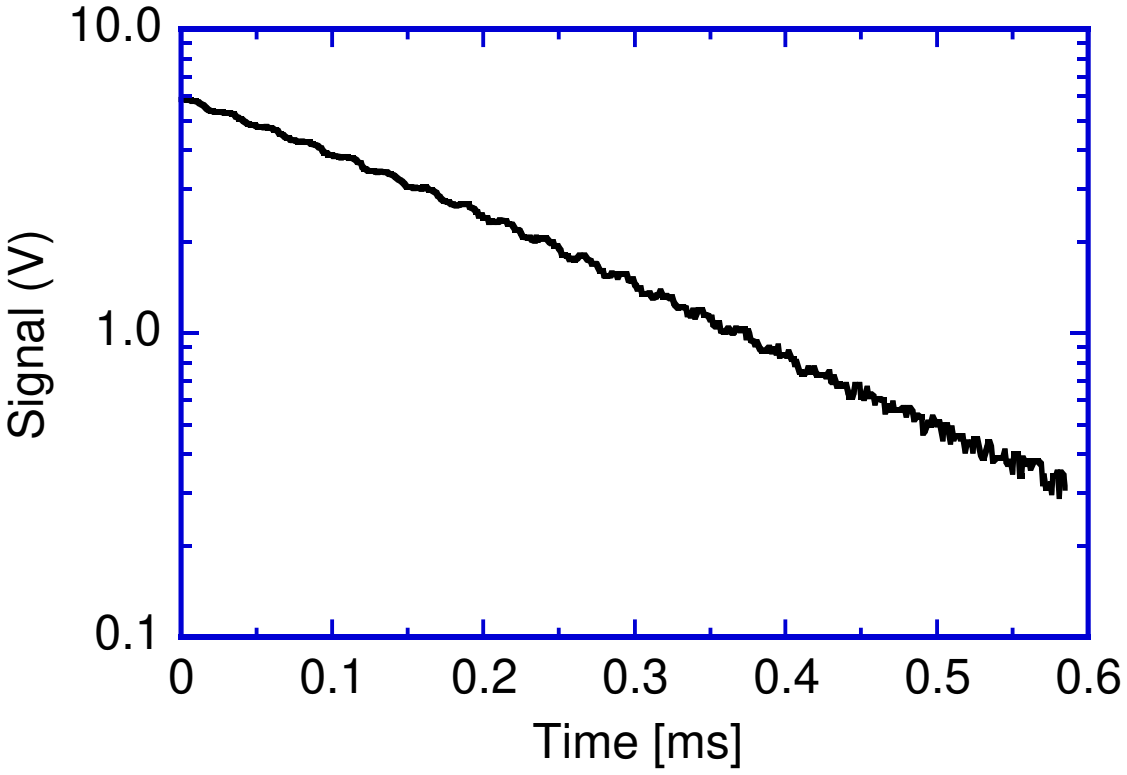

Figure 2: *Ringdown time measurement on the C-II ring laser. The 1/e- value is reached 0.2 ms after the driving power was cut off.*

One of the major requirements for a longterm stable ring laser operation is a constant ambient temperature. Therefore the ring has been located in an underground cavern at Cashmere, New Zealand, which was originally built in World War II for defence purposes

and has no use otherwise. The mechanical and temperature stability are greatly superior to those of alternative sites, for example, the typical temperature excursion of the C-II pier is less than 10 mK over a few hours, and microseismic background effects may be monitored. This project therefore serves as another illustration of the increasing use of gyros for peaceful and purely scientific purposes [2].

This cavern environment has unusually good thermal and mechanical stability, and its availability has helped to meet the ultimate performance limits of such a device. When combined with the observed output power (10 pW) and mirror transmission of 0.24 ppm, this implies a circulating energy of 1.1 pJ and, with the observed ringdwon time, a total power loss (mainly from scatter and transmission) of 5.6 nW. Together, these results imply a quantum noise induced full width half maximum of 220 microhertz. This is in good agreement with the observed value of 172 microhertz of the measurement shown in figure 3. It also agrees well (to within a factor of 2) with an Allan variance study of the output frequency in such runs (figure 4). At the right side of the Allan variance plot of two sample runs the instrumental drifts from scaling factor variations caused by atmospheric pressure changes are the dominating error sources.

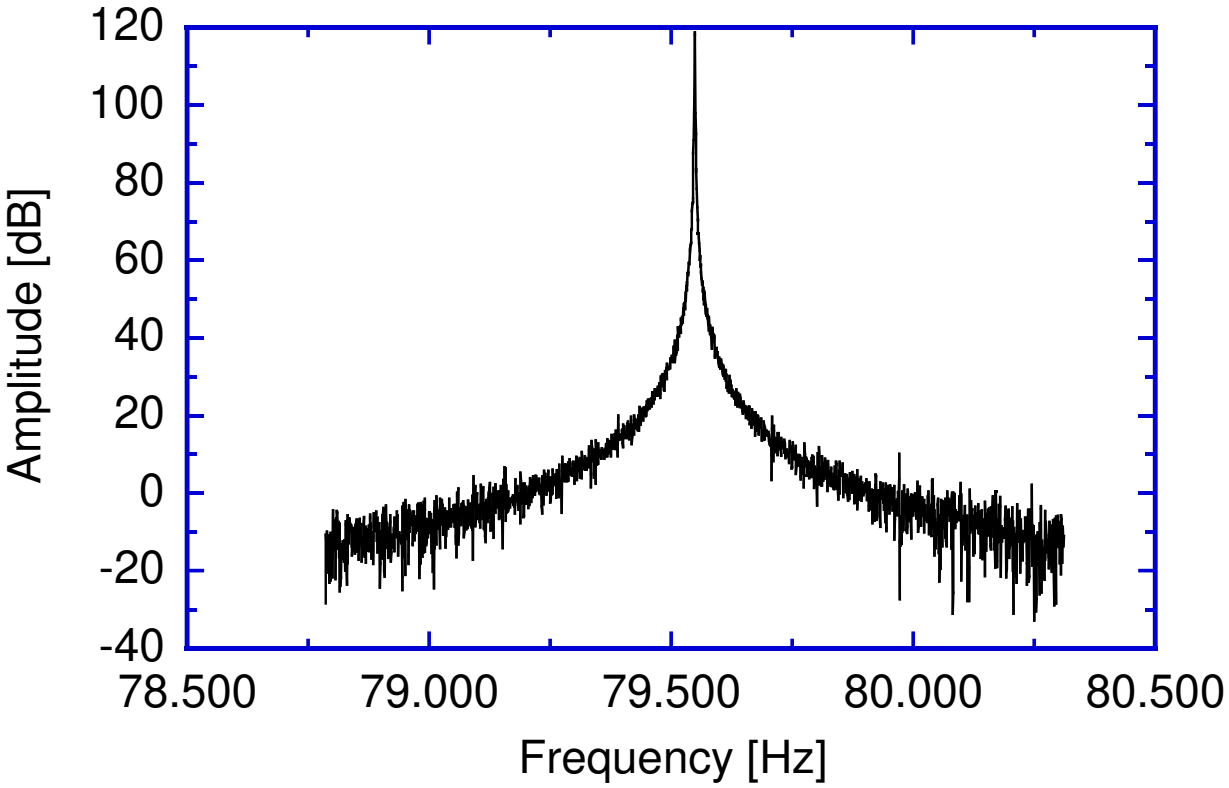

Figure 3: *A sample spectrum from the C-II ring laser. The full width at half maximum was determind to be 172 microhertz.*

The defining relationship [4] is that the Allan variance times sample time is half the one-sided power spectral density, itself (within a quantum noise picture) the above-mentioned

full width at half maximum power divided by pi. This argument renders C-II of sensitivity $4 \times 10^{-9} rad/s/sqrt(Hz)$, somewhat greater than that of atomic gyros (Gustavson et al. (1997) who obtained $2 \times 10^{-8} rad/s/sqrt(Hz)$, Lenef et al. (1997) who obtained $3 \times 10^{-7} rad/s/sqrt(Hz)$).

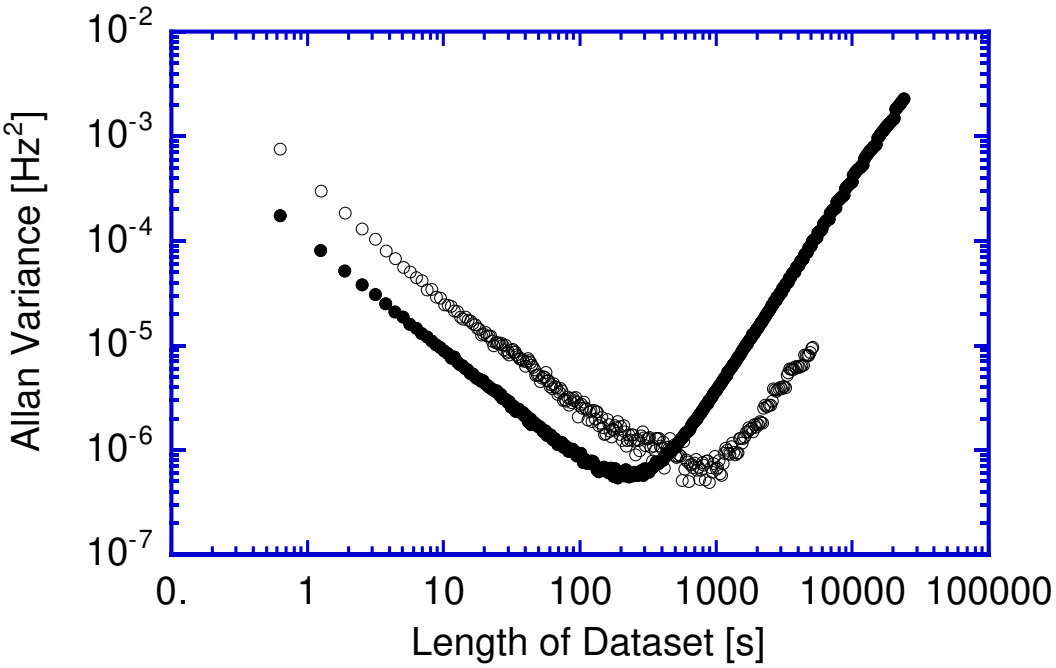

Figure 4: *Allan variance plots for two sample runs. C-II currently produces the lowest scatter for a dataset length of 300 to 1000 s. For runs longer than that scaling factor variations introduced by changes in the atmospheric pressure are the dominant error source.*

A scanning Fabry-Perot, a Newport SR-130 supercavity, is used for monitoring the absolute frequency of the C-II beam relative to that of an external Winters iodine- stabilised HeNe reference laser. The resultant frequency information is used to servo a piezo on one supermirror, stabilising the perimeter, and this has significantly reduced the drift in the Sagnac frequency. The residual drift now has an rms variation typically of a few millihertz as shown in figure 5.

An online display is available at:

`http://www.phys.canterbury.ac.nz/research/ring_laser/latest.html`

This drift itself is significantly reduced by continuing development, including the implementation of pressure compensation and numerical correction methods, which is now well in progress. Figure 5 shows the difference between the raw data and the current simple correction model.

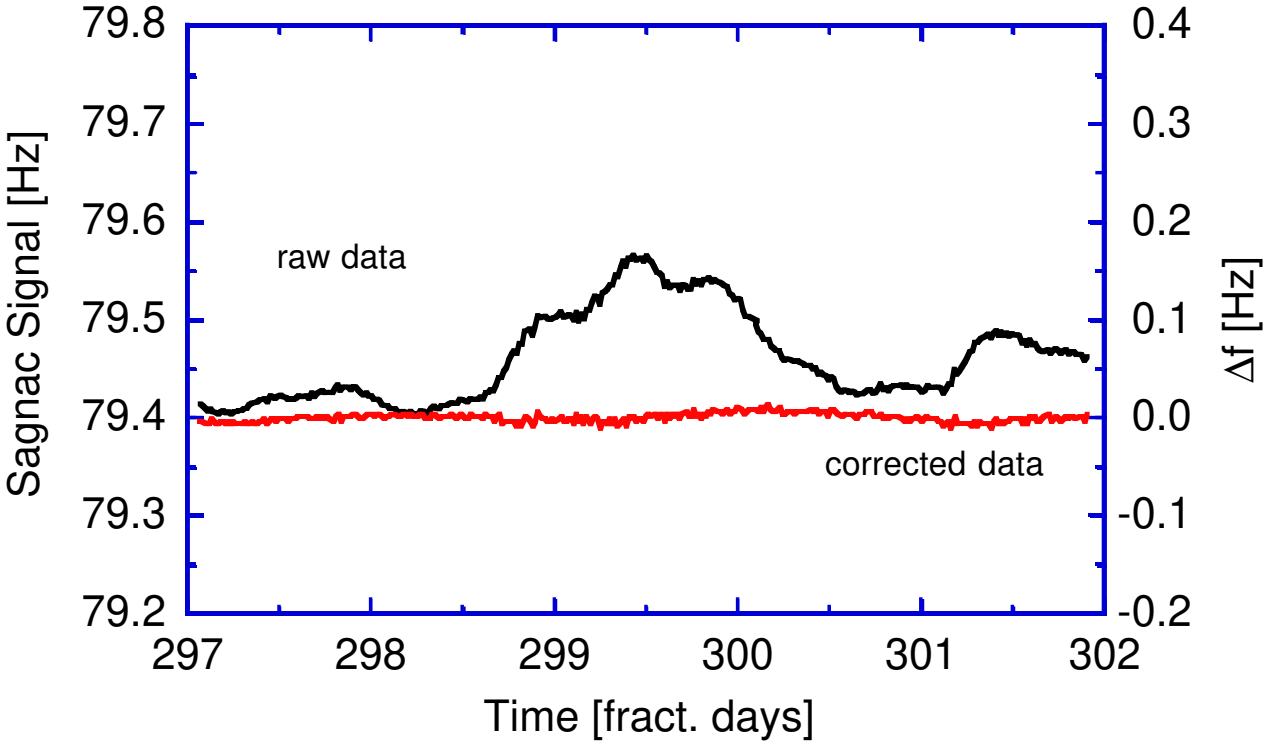

Figure 5: *A sample plot of the Sagnac frequency over time. The raw data shows excursions which are caused by the atmospheric pressure variations. A correction model which takes fluctuations of the scaling factor into account smoothes the timeseries of the Sagnac frequency substantially.*

3. SUMMARY

These results, and in particular the reduction of drift to a few millihertz, are reassuringly close to the original projections, and augur well for the eventual performance of C-II reaching the parts-per-million level (of the Sagnac frequency) precision as proposed in its original conception. This indicates that the C-II laser system is fulfilling its intended purpose of acting as a prototype and testbed for the much larger ($4m \times 4m$) laser G, itself under construction for the detection of short-terms fluctuations in Earth rotation [1, 2].

4. ACKNOWLEDGEMENTS

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