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INITIAL EVALUATION OF THE NPL CAESIUM FOUNTAIN FREQUENCY STANDARD

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Abstract - **An initial performance evaluation of the caesium fountain primary frequency standard at the NPL is reported. Improved magnetic shielding has resulted in the inhomogeneity of the C-field being below 1 nT and has enabled the observation of full-contrast Ramsey fringes. A direct evaluation of the fountain's stability in comparison to a hydrogen maser is shown to agree with the short-term stability inferred from the signal-to-noise ratio. The stability is consistent with the limit set by the local oscillator. The measurement of the frequency bias due to cold collisions is described, together with the associated uncertainty.**

***Keywords* - primary standard, caesium fountain.**

I. INTRODUCTION

Caesium fountain primary frequency standards have been developed by a number of national standards institutes to the point that they are now realising the SI second and contributing to TAI. Fountains [1] use lasers to cool the caesium atoms and launch them vertically. The atoms fall back, allowing a simple microwave cavity to replace the Ramsey cavity used in beam devices.

II. THE NPL CAESIUM FOUNTAIN

The design of the NPL fountain is shown in Fig. 1. The central part is the cooling region (1) with the flight tube (C-field region, 2) above and detection region (3) below.

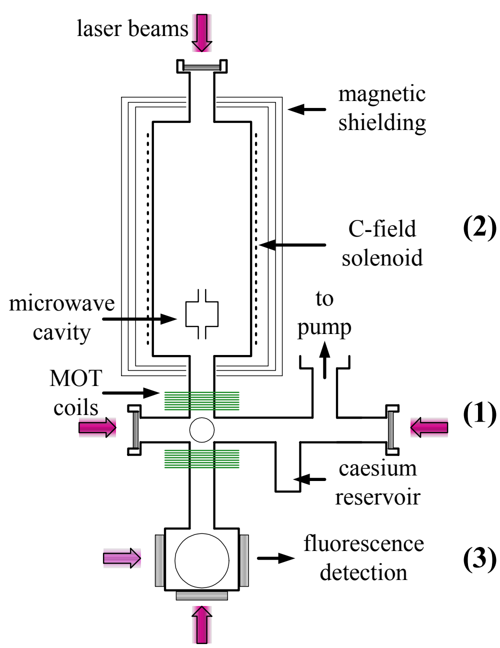

Fig. 1. The design of the NPL fountain.

Three pairs of circularly-polarized beams (one vertical and two horizontal), together with anti-Helmholtz coils create a magneto-optical trap, which is loaded for 500 ms, collecting about 5×10^7 atoms. The magnetic field is extinguished to form an optical molasses, then the atoms are launched upwards by changing the frequencies of the upward- and downward-going vertical beams by +4.3 MHz and –4.3 MHz, respectively. During the last 2 ms of this moving molasses phase the laser is decreased in intensity and detuned to the red, reducing the velocity in the cloud to v_{rms}=1.2 cm/s, equivalent to a temperature of 2.5 μK.

The atoms are prepared and launched in F=4 with all magnetic sub-levels occupied. A microwave pulse of millisecond duration transfers a controlled proportion of the atoms in F=4,m_f=0 to F=3,m_f=0. The remaining F=4 atoms are removed by an optical "pushing" pulse. The fraction is computer controlled and can be used to stabilize the atom number. Care is taken ensure that the ac Stark shift due to the presence of these microwaves is insignificant.

The atoms are launched up to 85 cm above the cooling region. The peak of the atomic trajectory is 31 cm above the microwave cavity. The atoms travel in a magnetic field (the C-field), of 100-150 nT, produced by a 72 cm long and 21 cm diameter solenoid.

The atoms experience a $\pi/2$ pulse each time they traverse the microwave cavity. Their final state is detected by measuring fluorescence induced by two laser beams (8 mm in vertical extent, separated by 20 mm). The upper beam is used to detect the number (P_4) of atoms in F=4, which are then removed by radiation pressure. The atoms in F=3 reach the lower beam, are optically pumped to F=4, and the number (P_3) detected. The detection signal is time resolved, allowing the temperature of the atomic cloud to be measured by the time-of-flight technique in addition to measuring the number of atoms in each of the atomic states.

The fountain cycle is repeated every 1.5 seconds. Successive microwave interactions utilize a frequency that is detuned from the peak of the central Ramsey fringe by plus or minus ¼ of the fringe period. A frequency error can be calculated from pairs of values of $P_3/(P_3+P_4)$. The error is used to track the central fringe.

Our fountain has three layers of mu-metal shielding, each 2 mm thick and with a diameter ratio of 1.7 between each shield. We have a shielding factor of greater than 10,000 in the Ramsey interaction region. A solenoid field of 123.3 nT was applied for the data presented here.

III. STABILITY

The $P_3/(P_3+P_4)$ data have, in general, noise contributions from the detection process (technical noise), local oscillator phase noise and quantum projection noise. Our S/N ratio of the detection technical noise is more than 500. However the S/N measured on the slope of a fringe is typically limited to 200. This is due the local oscillator phase noise. The contribution of the quantum projection noise is negligible with the 5×10^5 atoms detected.

The Allan deviation, $\sigma_y(\tau)$, of the Cs fountain frequency can be expressed as

$$\sigma_y(\tau) = \frac{2}{\pi}\frac{\Delta\nu}{\nu_{Cs}}\frac{N}{S}\sqrt{\frac{T_c}{\tau}} \qquad (1)$$

For a S/N ratio of 200, $\sigma_y(1s) = 4.3\times10^{-13}$ is obtained.

NPL F1 uses a Datum MHM 2010 hydrogen maser as a reference for its microwave local oscillator. The Allan deviation, calculated from pairs of values of $P_3/(P_3+P_4)$, is 4.6×10^{-13} at 1s (Fig. 2). With this value of $\sigma_y(1s)$, a frequency stability of 2×10^{-15} can be reached in less than one day.

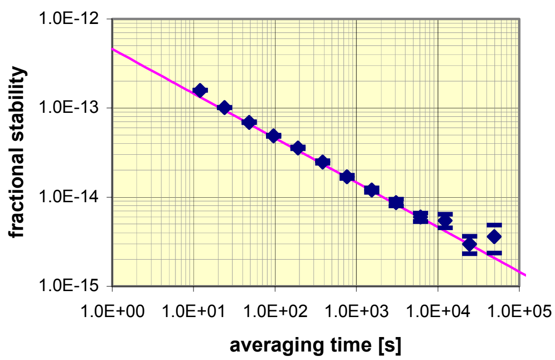

Fig. 2. Short-term stability of the NPL F1 primary frequency standard.

IV. Frequency Biases

NPL F1 must be corrected for three frequency biases, the second order Zeeman shift, the ac Stark shift due to black body radiation (BBR) and the shift due to collisions.

A. *Quadratic Zeeman Shift*

A transition with linear dependence on B, such as $F=4, m_f=1$ to $F=3, m_f=1$, is used to map the B-field. Fig. 3 shows the frequency of this fringe over 60,000 seconds, a measure of the temporal stability of the field. The calculated change in the "clock transition" due to the temporal instabilities of the C-field over this range is 5×10^{-17} Hz.

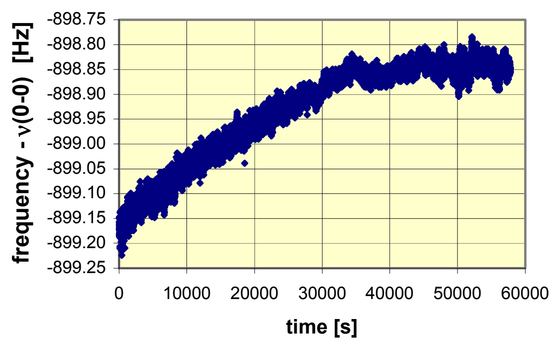

Fig. 3. Temporal stability of the fringe frequency.

We launch the atoms to different heights and observe the position of the central fringe. This provides a direct measure of the time average of B, <B>, for different heights. Fig. 4 shows the magnitude of <B> as a function of height above the cavity. We use the Breit-Rabi formula to estimate the second order Zeeman shift in the "clock transition", from the linear shift data. The bias, so introduced, is the variance:

$$\langle B^2\rangle - \langle B\rangle^2 = \sigma_B^2 \qquad (2)$$

The variance of the data in Fig. 4 is an approximation of the inhomogeneity of the C-field. This approximation introduces a negligible bias in fractional frequency (10^{-19}) to the correction of 7.07×10^{-14}.

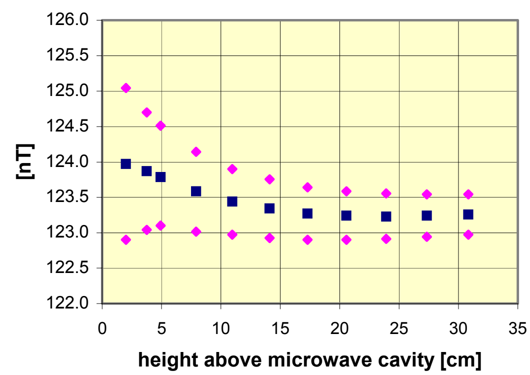

Fig. 4. Magnitude of <B> as a function of height above the cavity for central fringe and immediate neighbours.

B. *AC Stark Shift*

F1 is housed in a temperature controlled room at 295 K (usually within 1 K). F1 has a long time constant for temperature changes (several days) and has no additional temperature control. The resonant frequency of the microwave cavity is known as a function of temperature and can be used, together with records of measurements of the outside of the C-field vessel, to estimate temperature and temperature uniformity. We calculate the shift for 295K and estimate the uncertainty as due to a ±2 K variation, equating to $\pm4\times10^{-16}$.

C. *Shift due to Collisions*

For atoms at microkelvin temperatures, this shift depends linearly on atom density. The change in frequency of NPL F1 has been measured for a change in atom density of a factor of two (from *n* to *n/2*). An estimate of the collisional shift, when operating at the *n/2* density, is taken as the change in frequency between that found at *n* and at *n/2*. This change is found to be 2×10^{-15}.

The stability of our fountain is such that it is not practicable to make this determination by using a single hydrogen maser reference, due to the long averaging times required. Instead, pairs of frequency measurements using the two atom densities are made every 6 seconds, two cycles at *n*, two cycles at *n/2*, two cycles at *n* etc. We use the microwave state preparation pulse to select the proportion of atoms required at each cycle. Fig. 5 shows the Allan deviation of the detected atom number. One can see that it is possible to stabilize the atom number so, that the average over about 200 s (130 fountain cycles) is stable to 1%. Thus the uncertainty of the shift will be dominated by inaccuracy of the *n*:*n/2* density ratio, likely to be about 20% in our method. This gives the limiting uncertainty of the shift to be: $0.2\cdot2\times10^{-15} = 4\times10^{-16}$.

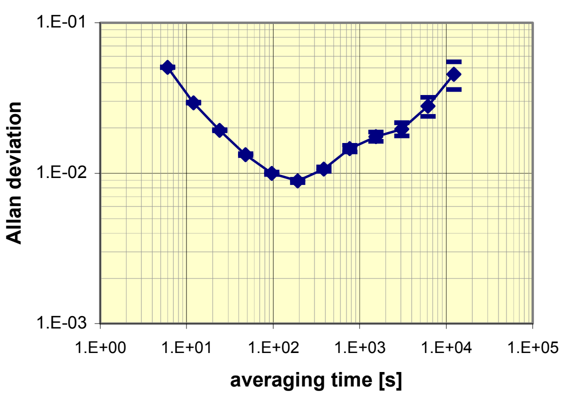

Fig. 5. The Allan deviation of the detected atom number.

V. Conclusion

A preliminary evaluation of the NPL primary frequency standard has been reported. The type B (systematic) uncertainty is shown to be dominated by the shift due to collisions, of 2×10^{-15}.

It has been shown that the apparatus has adequate stability to enable the uncertainty due to collisions to be reduced to 4×10^{-16}. The uncertainty will then be dominated by that due to the gravitational red shift, currently 8×10^{-16}. A summary of biases and their type B uncertainties is given in the table.

TABLE I
SUMMARY OF BIASES AND THEIR TYPE B (SYSTEMATIC) UNCERTAINTIES

Effect	Bias ($\times10^{-15}$)	Uncertainty ($\times10^{-15}$)
2^{nd} order Zeeman	70.9	0.1
ac Stark(BBR)	-16.2	0.4
Collisions	-2.0	2.0 (0.4)[a)]
Other	-	0.8
Total (1σ)		2.2 (<1)[a)]

[a)] numbers in brackets are target values

ACKNOWLEDGMENT

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