

# Towards A Caesium Fountain Frequency Standard At The NPL

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## 1. Abstract

We report on progress made at the NPL towards a caesium fountain primary frequency standard. We present an evaluation of the short-term and long-term stability of our experimental device. The short-term stability (Allan deviation) is  $5 \cdot 10^{-13} \tau^{-1/2}$ . The long-term stability is compromised by an effect similar to Ramsey pulling due to insufficient magnetic screening.

## 2. Introduction

In an atomic fountain a cloud of cooled atoms is launched up and then falls back under gravity. The atoms pass twice through a single microwave ( $\mu$ W) cavity, once on their way up and again on their way down. Such an implementation of Ramsey's method of *separated oscillatory fields* was first suggested in the 1950s, but the successful realisation was only achieved in the early 1990s, once the technique of *laser cooling* and trapping had been demonstrated [1].

In the fountain the time interval between the  $\mu$ W interactions can be of the order of a second, which gives a width for the central *Ramsey fringe* of 1 Hz or less. (The quality factor of the atomic resonance is  $Q_{\text{at}} \sim 10^{10}$ .)

Fountain frequency standards usually operate in a pulsed mode<sup>\*)</sup>. A single pulse (or cycle) consists of three phases:

1) cooling and launching – thermal Cs atoms are collected from a vapour by a *magneto-optical trap* (MOT) or *optical molasses* and cooled down to a few  $\mu$ K ( $v_{\text{rms}} = 1\text{--}2$  cm/s). Next the frequencies of the cooling beams are shifted and the atoms are accelerated (launched) upwards. After the launch the atoms are cooled further in the *moving molasses*. The cooling process prepares the atoms in one of the two ground state hyperfine sublevels ( $F=4$ ).

2) ballistic flight & interaction with  $\mu$ W field – the upward-moving atomic cloud is falling freely under gravity. The atoms have a chance to be transferred to  $F=3$  by interaction with the  $\mu$ W field either on their way up or down. Those two 'paths' from  $F=4$  to  $F=3$  interfere giving rise to observation of the so-called Ramsey fringes.

3) detection is done by laser-induced fluorescence. Atomic populations in  $F=4$  and  $F=3$  are detected separately and usually a normalized ratio of the two populations  $P_3/(P_3+P_4)$  is given as the 'fountain signal'.

## 3. The NPL Experimental Fountain

The design of the NPL fountain has been shown previously [2]. The cooling region forms a central part of the vacuum system with the flight tube (the C-field region) above and detection region below.

Three pairs of laser beams (one vertical and two horizontal) create an optical molasses, which is loaded for 500 ms, collecting about  $10^6$  atoms (we do not use the MOT). The atoms are launched upwards by changing the frequencies of the upward- and downward-going vertical beams by +4 MHz and –4 MHz, respectively. During the last 2 ms of the *moving molasses* phase the laser is decreased in intensity and detuned to the red, reducing the cloud's temperature to 2  $\mu$ K ( $v_{\text{rms}} = 1$  cm/s).

The atoms are launched up to 60 cm above the cooling region. The peak of the atomic trajectory is about 30 cm above the microwave cavity. The atoms travel in a weak (100–200 nT) magnetic field (C-field) produced by an 80 cm long and 15 cm diameter solenoid. This field should be uniform and stable. Hence the flight tube is screened by three layers of  $\mu$ -metal shields.

The atoms experience a *p/2 pulse* each time they traverse the microwave cavity. Their final state is detected by measuring fluorescence induced by two laser beams ( $6 \times 12 \text{ mm}^2$  cross-section, separated vertically by an 8 mm gap). The upper beam is used to detect the 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 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.

## 4. Short-Term Stability

A requirement for any fountain performance evaluation is its capability to produce Ramsey fringes with a good signal-to-noise ratio. Fig. 1. shows an example of the Ramsey fringes obtained in our fountain for typical parameters:

Fountain height: 31 cm,  
Atomic temperature:  $< 2 \mu\text{K}$  ( $v_{\text{rms}} = 1$  cm/s),

<sup>\*)</sup> A continuous fountain has also been demonstrated and is being developed by the group in the Observatoire de Neuchâtel.

Number of atoms detected:  $7 \times 10^5$ ,  
Number contributing to  
the 'clock' transition:  $5 \times 10^4$ .  
(no pre-selection of the (4,0) state)  
Note that the fringe contrast at the centre is less than  
the potential maximum by about 20%.

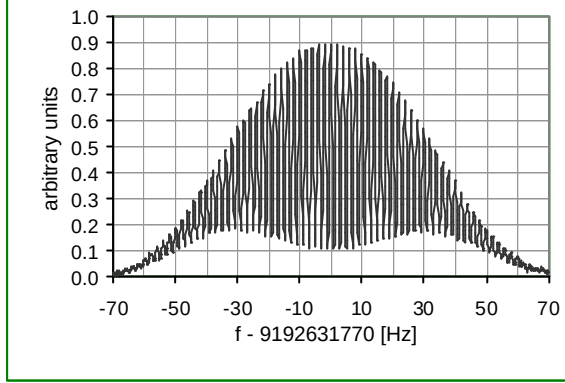


**Figure 1.** A Ramsey fringe record. Shown is a normalized ratio of populations  $P_3/(P_3+P_4)$ . Data were taken with no averaging.

The narrow central Ramsey fringe is used to lock the local oscillator (LO) to the Cs resonant frequency. Every fountain cycle the LO frequency is toggled between  $f+\Delta\nu/2$  and  $f-\Delta\nu/2$  (where  $\Delta\nu$  is the full width at half maximum of the fringe). The fountain signal is measured and the difference between the LO frequency and the Cs frequency is calculated every two cycles. This frequency correction is then fed back to the LO. (This approach is called fringe 'tracking'.) The correction values for a measurement session are recorded, enabling statistical analysis. We measured the time constant of the servo loop locking the LO to the frequency of the Cs hyperfine transition. This was done by setting the starting value for  $f$  to 0.5 Hz offset from the Cs resonant frequency. This is the maximum offset we could use, resulting in an excitation frequency on one side of the central fringe being near to the fringe minimum. Beyond three pairs of cycles, the corrections were distributed symmetrically about the caesium resonance, giving a time constant of about 10 s. The LO frequency was updated with 1 mHz resolution.

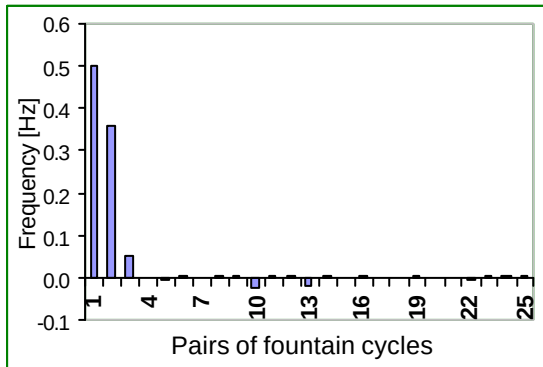


**Figure 2.** The frequency correction applied to  $f$ , starting with an offset of 0.5 Hz.

The frequency of the Cs resonance can only be determined with a finite resolution due to the noise processes in the measurement. The main contributions to the noise are:

- 1) detection (technical) noise (S/N);
- 2) local oscillator noise ( $\gamma$ );
- 3) quantum projection and partition noise ( $\propto \sqrt{N_{at}}$ ).

The Allan deviation of the measured Cs frequency  $\sigma_y(\tau)$  can be expressed as [3]:

$$s_y(t) = \frac{\Delta n}{p \cdot n_{Cs}} \sqrt{\frac{T_c}{t}} \left( \left( \frac{N}{S} \right)^2 + g + \frac{1}{N_{at}} \right)^{1/2}$$

or

$$s_y^2(t) = (s_y^{(1)}(t))^2 + (s_y^{(2)}(t))^2 + (s_y^{(3)}(t))^2$$

For our fountain we found:

$$s_y^{(1)}(t) = 2.6 \times 10^{-13} t^{-1/2} \quad (\text{for } S/N=150),$$

$$s_y^{(2)}(t) = 2 \times 10^{-13} t^{-1/2} \quad (\text{for LO stability } 4 \times 10^{-13} \text{ at } 1 \text{ s [4]}),$$

$$s_y^{(3)}(t) = 1.8 \times 10^{-13} t^{-1/2} \quad (\text{for } 5 \times 10^4 \text{ atoms contributing to the 'clock' signal}),$$

Hence the expected value of the Allan deviation is:

$$s_y^{TH}(t) = 4 \times 10^{-13} t^{-1/2},$$

which can be compared with the measured value of

$$s_y^{EXP}(t) = 5 \times 10^{-13} t^{-1/2} \quad (\text{see below}).$$

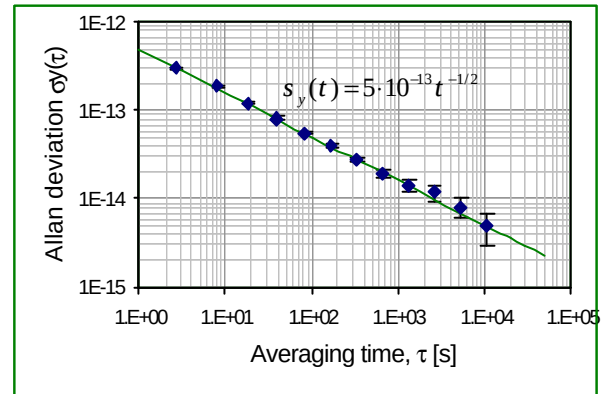


**Figure 3.** The frequency stability of the fountain relative to an H-maser.

## 5. Long-Term Stability – Frequency Offsets

### 5.1. Reduced fringe contrast

The reduced contrast of the Ramsey fringes suggests that magnetic sublevels  $F=3$ ,  $m_F \neq 0$  are populated during the Ramsey interaction. To confirm this, we selected the atoms in  $m_F=0$  and transferred them to  $F=3$  during the first passage through the microwave cavity. (We removed those remaining in  $F=4$  by radiation pressure.) During the second passage

through the cavity we probed all the sublevels of the  $F=3$  state by changing the microwave frequency so as to be resonant with the other transitions. A normalized signal of  $F=4$  atoms was measured ( $P_4/(P_3+P_4)$ ) (see fig. 4). A single peak at the “clock” frequency ( $m_F=0 \leftrightarrow m_F'=0$ ) should be observed if there is no population transfer between Zeeman sublevels. However, in our case we see other peaks spaced by the Larmor frequency. The spectra depend strongly on the applied static magnetic field. For certain values of the C-field, a small change of the field results in a strong suppression of the  $m_F=0$  and an increase of  $m_F \neq 0$  populations. (Compare the grey and black lines in fig. 4.)

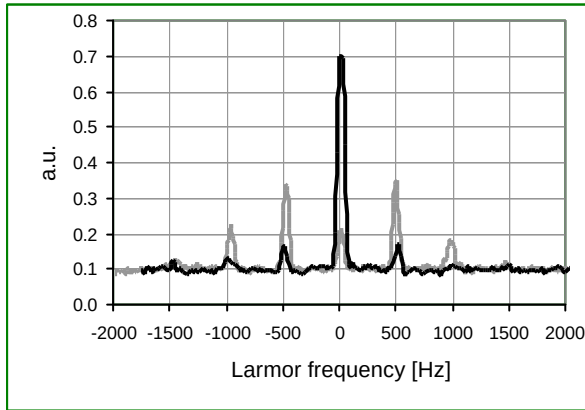


**Figure 4.** The population of the magnetic sublevels during the second  $\mu\text{W}$  interaction. (The first interaction selects the  $m_F=0$  atoms.) The grey and the black lines correspond to data taken for 37 and 40 nT respectively.

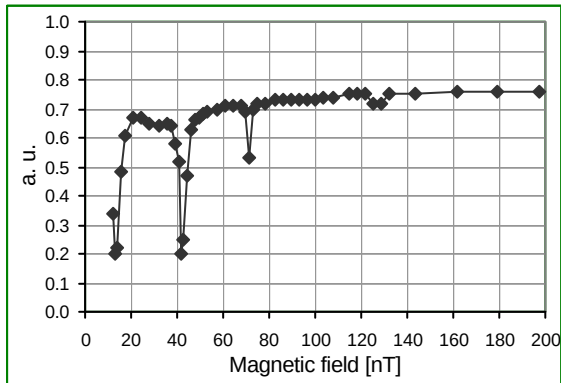


**Figure 5.** The height of the central peak ( $m_F=0$  population) as a function of the C-field. The sharp dips correspond to Larmor frequencies of 50, 150, 250,...Hz.

## 5.2. Shielding factor

We believe that the populating of the  $m_F \neq 0$  states is due to an AC field in the C-field region. As shown in fig. 6, the shielding factor,  $S$ , of our magnetic screens is better than 1000 only between 10 cm and 38 cm above the  $\mu\text{W}$  cavity. At the cavity level the

shielding factor has dropped to 170. We measured the shielding factor by applying a known magnetic field with alternating polarity and using atoms as a probe. We launched the atoms to different heights and applied a microwave pulse of 100 ms duration at the top of their trajectory. The  $\mu\text{W}$  frequency was scanned over the magnetic field-sensitive resonance ( $3,+1 \leftrightarrow 4,+1$ ) and the Larmor frequency was measured. The uniformity of the applied C-field was mapped in the same way (fig. 7).

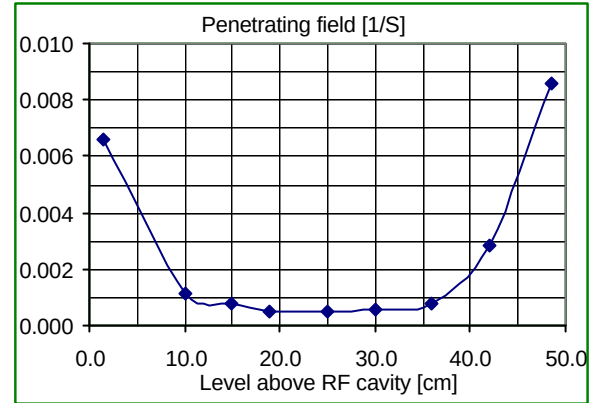


**Figure 6.** A map of the magnetic field “leaking” into the C-field region, expressed as a reciprocal of the shielding factor.

## 5.3. C-field map

The spectral and spatial accuracy of the pulsed microwave method was sufficient to determine the quadratic Zeeman shift of the ( $3,0 \leftrightarrow 4,0$ ) transition with uncertainties of better than 2 parts in  $10^{-15}$  for a C-field in the range of 100-200 nT. An example of a C-field map (DC component) is shown in fig.7. The DC component of the “leaking” field can be compensated for by trim coils. The AC component, however, cannot be readily eliminated.

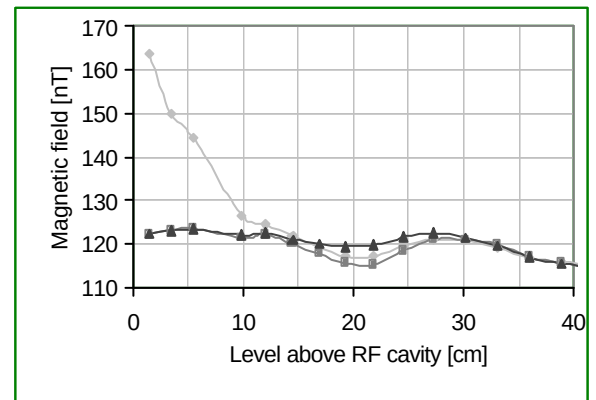


**Figure 7.** A map of the static magnetic field in the C-field region. To improve the uniformity two trim coils were used, at the cavity level (1) and one 20 cm above (2). Light grey line - no correction applied, dark grey - coil (1) only, black - both coils (1) and (2) used.

## 5.4 Ramsey pulling

The excitation of the  $\Delta m_F=1$  ( $\Delta F=0$ ) transitions during the Ramsey interaction may lead to a large error in the measured frequency of the hyperfine transition. The cause is similar to that of the Ramsey pulling effect [5]. The frequency shift will appear only if there is an asymmetry in the probability of  $m_F=-1$  and  $m_F=+1$  excitation. An asymmetry of a few percent may result in a relative frequency shift of the order of  $10^{-12}$ . As the level of asymmetry may vary in the long term, so may the measured frequency of the Cs resonance.

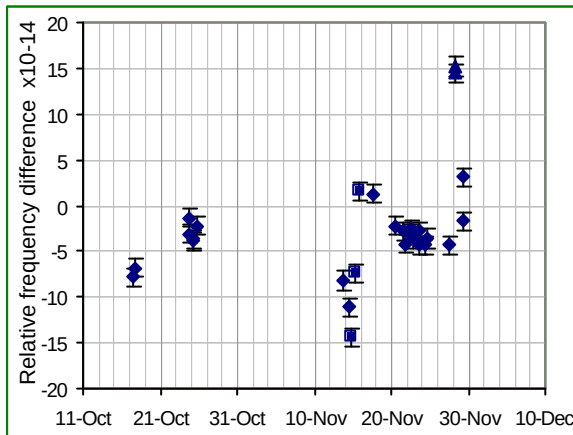


**Figure 8.** The caesium hyperfine frequency measured against an H-maser, stable to  $3 \times 10^{-15}$  over the period.

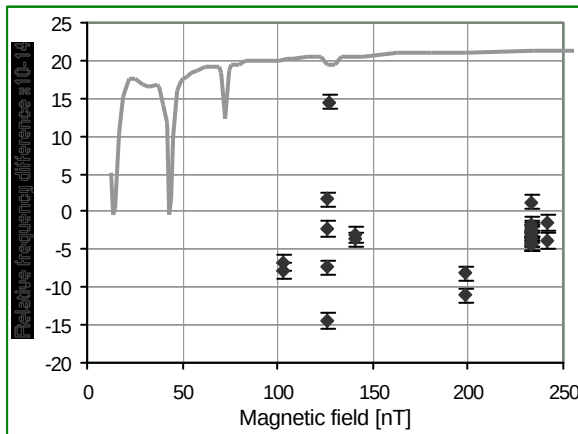


**Figure 9.** The same data as in fig. 8, plotted as a function of the applied C-field. Fringe contrast data from fig. 5 are also shown as a reference. Note the excessive scatter of the frequency data for the C-field of 129 nT, corresponding to Larmor frequency of  $9 \times 50$  Hz.

We measured frequency offsets ranging from  $1.5 \times 10^{-13}$  to  $+1.5 \times 10^{-13}$  over a period of two weeks by comparing the fountain with a stable H-maser (see fig. 8). The fountain was run in sessions lasting from 5 to 15 hours. The statistical uncertainty of the frequency measurement in each session was

less than  $10^{-14}$ . The measured frequencies were corrected for the quadratic Zeeman shift and the black body radiation shift. The cold-collisional-shift is negligible on the  $10^{-14}$  scale for the atomic densities we used. Similarly, other known systematic frequency shifts were estimated to be negligible.

## 6. Conclusions

We have demonstrated an experimental caesium fountain frequency standard with a short-term stability (Allan deviation) of  $5 \times 10^{-13} \tau^{-1/2}$ .

We have also found a variable frequency offset, or instability, of parts in  $10^{13}$  due to an effect similar to Ramsey pulling. We have established that the frequency offset is due to inadequate magnetic shielding.

A second fountain (F2) is under construction with improved magnetic shielding. F2 will use an MOT, and the larger number of atoms, together with a BVA-based local oscillator, is expected to improve both the short-term and the long-term stability.

## 7. References

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This work is supported by the UK National Measurement System in the Foundation Programme.

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