NPL Cs fountain frequency standards and the quest for the ultimate accuracy

K Szymaniec\textsuperscript{1}, S N Lea\textsuperscript{1}, K Gibble\textsuperscript{2}, S E Park\textsuperscript{3}, K Liu\textsuperscript{4} and P Glowacki\textsuperscript{5}

\textsuperscript{1}National Physical Laboratory, Teddington, UK
\textsuperscript{2}The Pennsylvania State University, University Park, USA
\textsuperscript{3}Korea Research Institute of Standards and Science, Daejeon, Korea
\textsuperscript{4}National Institute of Metrology, Beijing, China
\textsuperscript{5}Poznań University of Technology, Poznań, Poland

E-mail: ks1@npl.co.uk

Abstract. NPL operates a system of two primary caesium fountain clocks consisting of a fully characterised standard NPL-CsF2 together with a new standard NPL-CsF3, which has recently become operational. Both fountains feature a single-stage vapour-loaded magneto-optical trap as the source of cold atoms and an approximate cancellation of the potentially large cold collision frequency shift. As a result, the collision-shift type-B uncertainty is less than 10\textsuperscript{-16}. Subsequently, more subtle systematic effects, including the frequency shifts from distributed cavity phase, microwave lensing and collisions with background gas have also been evaluated at the level of 10\textsuperscript{-16} or below. Now, as several systematic effects contribute to the fountains’ uncertainty budgets similarly, further significant improvement of their accuracies is expected to be even more difficult. The short-term stability of these standards is also a significant factor limiting the overall precision as many days or even weeks of averaging is required for the type-A statistical uncertainty to approach the declared type-B systematic uncertainty. Going forward, further improvements in the reliability and robustness of operation of fountain standards is one of our priorities.

1. Introduction

Operation of atomic fountain frequency standards has been one of the first and most successful examples of applications of the laser cooling technology. A prototype atomic fountain was first demonstrated in 1989 [1] and, by 1995, a metrological fountain made the first contribution to TAI [2]. A number of time and frequency laboratories have further developed and improved the design and operation of fountain standards. Inaccuracies of fountains primary frequency standards (PFS) have improved by more than an order of magnitude, approaching an uncertainty of $\delta v/v$ of 10\textsuperscript{-16}. Today, the calibration of TAI rests almost entirely on the evaluations performed by about a dozen PFS run by several National Measurement Institutes around the world. With the operation of fountains becoming more reliable, a number of labs have also been using them to discipline clocks, forming local timescales [3]. The availability of fountain standards is instrumental for the development of optical clocks, the anticipated next generation of primary frequency standards. Here, they provide the most accurate frequency to measure the frequency of an optical clock transition, but they also provide a practical, highly stable and accurate reference for numerous test measurements. Frequency measurements of spectrally narrow transitions in microwave fountain and optical standards have placed the tightest constraints on the time variation of fundamental constants [4].
Most Cs fountain PFS share the key aspects of the design of various subsystems [5]. At the same time, different and sometimes complementary approaches have been adopted to address particular issues like cold collisions, blackbody radiation, or microwave cavity design. This is a healthy situation increasing the confidence and the robustness of the realization of the SI definition. In this paper we give an overview of the Cs fountain development at NPL over the last decade. In the following section we describe the main specific features of the NPL approach to the physics package design and to the operation protocol. In section 3 we report on recent enhancements of the short-term stability and, in section 4, we discuss the accuracy of our PFS and comment on a long-term behaviour of one of our fountains. Finally, we give an outlook for the future operation and planned improvements.

2. NPL Cs fountains – main features

NPL currently operates two Cs fountain PFS, NPL-CsF2 and NPL-CsF3, which share major design features. A prototype system, NPL-CsF1, operated from 2004 until 2007 and was later decommissioned and parts of its physics package and optical bench were reused to construct NPL-CsF3. A key feature of the NPL Cs fountains is a single-stage vapour-loaded magneto-optical trap (MOT) as source of cold atoms. Because early studies of cold collisions in Cs had reported large density dependent frequency shifts [6], MOT’s have often been avoided in PFS designs to reduce the atomic density during the interrogation time. Instead, atoms are often collected and launched with optical molasses (e.g. loaded from another cold atom source, such as a two-dimensional MOT). The desire for high short-term stability requires many atoms, which in turn requires accurate density ratios to determine and correct relatively large collisional shifts. Along this line, an elegant approach is to accurately select half of the atoms with an adiabatically chirped pulse [7]. Alternatively, we have shown that the collisional frequency shift can be cancelled by launching a small cloud from a MOT [8]. This requires the clock state populations to produce frequency shifts with opposite signs [9], which occurs for Cs atoms at nanokelvin temperatures [10]. Although such temperatures are not achieved by the polarisation gradient cooling in fountains, the collision energies in an expanding small cloud become very low during the fountain trajectory as correlations between position and velocity develop. The collisional shift is precisely cancelled for the proper clock state population ratio after the first Ramsey interaction (see figure1).

![Figure 1](image.png)

**Figure 1.** Collisional frequency shifts from measured frequency differences at high and low atomic density in NPL-CsF3, as a function of the |F=4, m_F=0⟩ population fraction (ρ_40) after the first Ramsey interaction. Full (open) squares correspond to a launched cloud size of 0.9 mm (1.0 mm).

To achieve a better short-term stability, one may attempt to increase the detection signal-to-noise ratio by loading more atoms in the MOT. This, however, may eventually lead to an increase of the initial cloud size and increase the effective collision energy. An alternative is to optically pump atoms distributed throughout all m_F states into m_F = 0. This technique has been demonstrated for thermal beam
clocks, but has not been widely implemented for normal operation. In principle, one can expect a 9-fold increase of the $m_F=0$ population from 9 $m_F$ states. In practice, our enhancement is about a factor of 5, due to photon scattering during the optical pumping pulse and a subsequent heating and accelerated expansion of the atomic cloud, which is truncated by apertures in the fountain [11].

A major novelty introduced in NPL-CsF3 is a non-cylindrical microwave cavity. Its shape was designed to minimize the distributed cavity phase (DCP) frequency shift [12], especially longitudinal phase gradients (related to the $m=0$ component of the azimuthal expansion of the cavity field) and their dependence on microwave amplitude [13]. A further reduction of the shift is achieved by feeding the cavity by four rectangular waveguides with coupling holes placed symmetrically about the mid-plane. This also significantly reduces the $m=1$ contributions to the DCP shift. Care was taken to assure homogeneity of the detection (probing) beam across the active area, which, together with orienting the beam direction at 45˚ with respect to the cavity feeds, makes the $m=2$ DCP shift negligible. The new design also allows for a larger opening in the cavity endcaps, approximately doubling the number of atoms passing through the cavity on the descent. Preliminary measurements of the $m=0$ and $m=1$ DCP shifts as a function of the field amplitude show good agreement with model predictions (figure 2).

![Figure 2](image-url)

**Figure 2.** Calculated (solid line) and measured (full symbols) perturbations to the clock transition probability $dP$ due to DCP for the new cavity installed in NPL-CsF3. Also shown are the much larger calculated shifts for the cylindrical cavity of NPL-CsF2 (dotted lines). The microwave field amplitude is $b$, with $b$ approximately equal to 1 for $\pi/2$ pulse areas. The left plot is the $m=0$ DCP component and the right is the $m=1$, increased by feeding fully asymmetrically and tilting the fountain by 1 mrad.

In both NPL fountains, the temperature of the flight tube (and thus of the microwave cavity) is set and stabilised by a water jacket installed around the tube. This helps to accurately determine the blackbody radiation frequency shift as well as to tune the Ramsey cavity to resonance. The cavities are constructed so that their resonant frequencies are at temperatures within a few degrees of the lab temperature.

3. **Short-term stability**

By launching atoms from the MOT, and including the optical pumping, several millions of atoms in the clock state arrive in the detection region after the Ramsey interrogation. A signal-to-noise ratio of around 2500, limited by the quantum projection noise, was observed when exciting the atoms with $\pi/4$ pulses on resonance so the excitation is insensitive to the local oscillator (LO) phase noise. This sets a limit for the attainable short-term stability in the range of low $10^{-14}$ at 1 s. However, under normal operating conditions, when using a room temperature quartz-based LO, the stability is poorer, about $1.5 \times 10^{-13}$ (1 s), owing to the Dick effect. Recently, an interrogation signal synthesized from an ultra-stable laser via a femtosecond optical frequency comb has been used, demonstrating four times lower instability of $3.7 \times 10^{-14}$ (1 s) (figure 3). Based on the highest atom number observed in detection, an even lower instability of $2.5 \times 10^{-14}$ (1 s) can be expected.
Figure 3. Short-term stability of NPL-CsF3 using an LO based on an ultra-stable laser. The LO was free running and drifted at a rate of approximately $10^{-16}$ s$^{-1}$. The solid line represents the demonstrated stability of $3.7 \times 10^{-14}$ at 1 s.

The collisional frequency shift may vary significantly in the vicinity of the cancellation point (figure 1) and therefore a residual shift is measured and corrected during the normal operation of the fountain as frequency standard. The number of atoms is alternated by varying a microwave field amplitude in the state selection cavity, instead of changing the MOT loading, to preserve the cloud parameters (initial size and temperature). From the measurements for the high and low atom numbers (i.e. high and low density), we extract a zero-density frequency $F_{\text{ext}} = (kF_L - F_H)/(k-1)$; $F_H/F_L$ is the frequency measured for the high (low) density of the atomic cloud and $k$ is the high-to-low density ratio. An uncertainty $\sigma_{\text{ext}}$ of $F_{\text{ext}}$ can be expressed as [14]:

$$\sigma_{\text{ext}}^2(t) = \left(\frac{k}{k-1}\right)^2 \sigma_L^2(t_L) + \left(\frac{1}{k-1}\right)^2 \sigma_H^2(t_H) + \left(\frac{F_L - F_H}{(k-1)^2}\right)^2 \sigma_r^2;$$

where $\sigma_L(\sigma_H)$ and $\tau_L(\tau_H)$ are the short-term stability and averaging time for operation at low (high) atom number; $\sigma_r$ is an estimated fractional deviation of the density ratio from the measured atom number ratio. The last term is a type B uncertainty and, close to the cancellation point, can be made small compared to other type B contributions (see table 1 below). The first two terms are included in the type A (statistical) uncertainty, increasing the effective short-term instability. If the detection noise is dominated by QPN, $\sigma_{\text{ext}}$ is minimized for $k = 4$ at $\sigma_{\text{ext}} = 3\sigma_H$. This yields $2.5 \times 10^{-16}$ after 1 day of averaging for the lowest expected $\sigma_H = 2.5 \times 10^{-14}/\sqrt{t}.$

4. Accuracy evaluations and long term operation

NPL-CsF2 was first operational in 2009 and its total type B uncertainty was initially $u_B = 4.1 \times 10^{-16}$ [15]. Over the following years the systematic effects with large uncertainties were re-evaluated, leading to a reduction of $u_B$ by a factor of two, as in 2013 [16, 17]. The optical pumping stage was introduced during this time, but no modifications to the physic package were made.

The major reduction of $u_B$ came from a reassessment of the distributed cavity phase frequency shift based on the model of [13] and a series of measurements verifying its predictions for the microwave cavity used in NPL-CsF2. Similarly, the mechanical effect of the microwave photons on the atomic wave functions, microwave lensing, was evaluated, extending the treatment in [18]. Finally, the uncertainty related to frequency shifts due to collisions with room temperature background gas was lowered, following [19], which showed that a limit on the frequency shift can be set by measuring the atom loss rates in the cloud due to background gas collisions during the Ramsey interaction time. Loss rates in NPL-CsF2 were measured by increasing the background gas pressure and extrapolating to the normal operating conditions [17].
The new PFS setup NPL-CsF3 became operational in 2014 and is currently undergoing an accuracy evaluation. Preliminary values for the major uncertainties are listed in Table 1 and the total uncertainty is expected to be noticeably below $2 \times 10^{-16}$. The most significant reduction is expected to result from implementing the novel microwave cavity and reducing the total DCP uncertainty.

| Systematic effect / uncertainty $(10^{-16}$ | NPL-CsF2 (2009) | NPL-CsF2$^\dagger$ (2013) | NPL-CsF3 (2015) |
|---------------------------------------------|-----------------|-----------------------|-----------------|
| $2^{nd}$ order Zeeman                        | 0.8             | 0.8                   | 0.5             |
| Blackbody radiation                         | 1.1             | 1.0                   | 0.6             |
| Cold collisions                             | 1.0             | 0.4                   | 0.4             |
| Background gas                              | 1.0             | 0.3                   | 0.3             |
| Microwave leakage                           | 1.0             | 0.6                   | 0.5             |
| Distributed cavity phase                    | 3.0             | 1.1                   | 0.5             |
| Microwave lensing                           | 1.5             | 0.3                   | 0.3             |
| Gravity                                     | 0.5             | 0.5                   | 0.5             |
| Other                                        | 0.4             | 0.3                   | 0.3             |
| **Total $u_B$**                              | **4.1**         | **2.0**               | **1.4**         |

Table 1. Successive improvements of accuracy of the NPL caesium fountain standards following re-evaluations of NPL-CsF2 and construction of NPL-CsF3. Underlined are uncertainties that were reduced the most. In italic are preliminary or expected values for NPL-CsF3, subject to verification. $^\dagger$ The re-evaluation of NPL-CsF2 involved new analyses and measurements of systematic effects, but no modifications to the physics package; a marginal reduction of the uncertainty due to the blackbody radiation follows from using coefficients published in [20] for the calculation of the frequency offset.

The declared type B uncertainty should be consistent with long-term frequency comparisons with other PFS. We have analysed the data contributed to BIPM by NPL-CsF2 over more than 5 years and covering over 1300 days of measurement. We have compared the standard rate realized by NPL-CsF2 and that of the time scale TT (calculated by BIPM based on relevant contributions by all PFS) for all the periods when the NPL-CsF2 data were available. The average difference is $1.1 \times 10^{-16}$, within the $u_B$ (1 $\sigma$) of NPL-CsF2.

5. Conclusions and outlook
We have developed and now operate a system of highly accurate and stable caesium fountain primary frequency standards. NPL-CsF2 has been contributing regularly to the TAI evaluations for several years and NPL-CsF3, which has been constructed more recently, is currently undergoing a full performance characterisation. Both devices feature a relatively simple physics package with a vapour loaded MOT as the cold atom source and operate with nearly zero collisional frequency shift. Boosting the detected signal by optical pumping and using an optical frequency-comb based microwave source, which derives its stability from an ultra-narrow laser, has reduced the short-term stability to few parts in $10^{14}$ at 1 s. Improved accuracy evaluations for NPL-CsF2 significantly reduced the type B uncertainty to $2 \times 10^{-16}$, among the lowest values reported. These reductions followed analyses based on new models of frequency shifts due to distributed cavity phase, microwave lensing, and background gas collisions, combined with supporting measurements, without modifying the physics package.

The novel microwave cavity realized in NPL-CsF3 and other minor modifications, compared to NPL-CsF2, promise further accuracy improvements. However, we appreciate that bringing the total $u_B$ significantly below $10^{-16}$ may be difficult because several systematic effects contribute to the uncertainty budget at a similar level. Anticipated future efforts are likely to improve the reliability and robustness.
of operation. Although a routine use of the optically based local oscillator would shorten the averaging time required for \( u_A \) to match the level of \( u_B \) to 3 days from the currently needed 3 weeks for NPL-CsF2, the effective statistical resolution of Cs fountain clocks remains a practical limitation to their performance.

We plan to enhance the generation of the timescale UTC(NPL) by regularly disciplining an existing maser ensemble to the local PFS’s. Running at least two independent PFS’s provides a minimum operational redundancy. It would also be useful to compare, as often as possible, the NPL fountains to similar devices at other NMIs for verification and to avoid operational errors. This is anticipated, for example, using the growing network of optical fibre links between European time and frequency labs.

We acknowledge financial support from National Measurement System (UK) and National Science Foundation (US).

References

[1] Kasevich M, Riis E, Chu S and De Voe R 1989 Phys. Rev. Lett. 63 612
[2] Clairon A, Laurent P, Santarelli G, Ghezali S, Lea S N and Bahoura M 1995 IEEE Trans. Meas. Instrum. 44 128
[3] Bauch A, Weyers S, Piester D, Staliumiene E and Yang W 2012 Metrologia 49 180
[4] Godun R M, Nisbet-Jones P B R, Jones J M, King S A, Johnson L A M, Margolis H S, Szymaniec K, Lea S N, Bongs K and Gill P 2014 Phys. Rev. Lett. 113 210801
[5] Wynands R and Weyers S 2005 Metrologia 42 S64
[6] Gibble K and Chu S 1993 Phys. Rev. Lett. 70 1771
[7] Pereira Dos Santos F, Marion H, Bize S, Sortais Y, Clairon A and Salomon C 2002 Phys. Rev. Lett. 89 233004
[8] Szymaniec K, Chalupczak W, Tiesinga E, Williams C J, Weyers S and Wynands R 2007 Phys. Rev. Lett. 98 153002
[9] Gibble K and Verhaar B J 1995 Phys. Rev. A 52 3370
[10] Leo P J, Julienne P S, Mies F H and Williams C J 2001 Phys. Rev. Lett. 86 3743
[11] Szymaniec K, Noh H R, Park S E and Takamizawa A 2013 Appl. Phys. B 111 527
[12] Gibble K, Lea S N and Szymaniec K 2012 Proc. Conference on Precision Electromagnetic Measurement (Washington DC, USA) 700
[13] Li R and Gibble K 2010 Metrologia 47 534
[14] Szymaniec K, Park S E 2011 IEEE Trans. Meas. Instrum. 60 2475
[15] Szymaniec K, Park S E, Marra G and Chalupczak W 2010 Metrologia 47 363
[16] Li R, Gibble K and Szymaniec K 2011 Metrologia 48 283
[17] Szymaniec K, Lea S N and Liu K 2014 IEEE Trans. UFFC 61 203
[18] Gibble K 2006 Phys. Rev. Lett. 97 073002
[19] Gibble K 2013 Phys. Rev. Lett. 110 180802
[20] Rosenbusch P, Zhang S and Clairon A 2007 Proc. IEEE International Frequency Control Symposium and 21st European Frequency and Time Forum (Geneva, Switzerland) 1060.