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Robust Cs fountain clocks, novel evaluation tools and flexible operational configurations

Richard J. Hendricks*, Kathryn Burrows, and Krzysztof Szymaniec
National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, UK
e-mail: rich.hendricks@npl.co.uk

Maintaining a robust and largely autonomous timescale is a task not only for national measurement institutes, but also for timing labs at large scientific facilities, military and security agencies or telecom and financial service providers. The most stable local timescales consist of a flywheel clock (usually a hydrogen maser) that is frequently steered using corrections provided by an atomic fountain frequency standard whose local oscillator is weakly locked to that clock.

We have refined the NPL Cs fountain design and assembled several systems for different metrology laboratories. We will describe the main design features of these new systems and show that they achieve state-of-the-art accuracy and stability. In addition we will present a new technique for determination of the atomic trajectories in fountains that enables simplified determination of a leading systematic effect – the distributed cavity phase frequency shift. Finally we will show results of a new operational configuration where, without loss of short-term stability, the referencing maser is not co-located with the fountain but is connected by an optical fibre link.

The new fountain design is based on the approach used in NPL-CsF2 and NPL-CsF3 with a single-stage vapour loaded magneto-optical trap as the cold atom source and an additional optical pumping stage to increase the detected atom number. Despite operating with high atom densities, the frequency shift due to cold collisions is minimized by tuning the collision energies and hence is controlled to parts in 10^{17}. With signal-to-noise ratios above 3500 the fountains are capable of reaching a short-term stability better than 3E-14 (at 1s), when using a sufficiently low noise local oscillator. The new compact optical system for cooling and detection allows for many weeks of uninterrupted operation. The physics package was reduced in size for transportability, and three such systems have already been delivered to customers after being transported thousands of kilometres by land or air. Full accuracy evaluations are currently being carried out by the users and we expect total type-B uncertainties in the low 10^{-16} range, similar to the fountains operated at NPL.

One of the leading systematic effects in atomic fountains is the distributed cavity phase frequency shift. It is sufficient to consider the lowest terms of the azimuthal expansion of the microwave field in an interrogation cavity containing travelling wave components. The shifts due to terms with m=1 and m=2 can be determined more precisely if the crossing positions through the cavity are known for the centre of mass of the atomic ensemble that is eventually detected in the fountain. We have devised a convenient experimental method for establishing these crossing points and the verticality of launch without requiring the long frequency measurements with alternating microwave feeding that are commonly used. It expands on earlier work [Metrologia 49, 468 (2012)] showing that a displacement of the atoms from the axis of the fountain at the cavity level leads to a measurable asymmetry of normally inhibited hyperfine sigma transitions. By applying a small transverse magnetic field we were able to enhance this asymmetry, and by introducing a controlled tilt of the fountain and simulating the trajectories of the atoms we were able to establish the displacement of the atomic ensemble to within a fraction of a millimetre.

Operation of fountain standards still requires considerable specialized effort. In some cases it might be desirable to run a fountain in a suitable location some distance from the institution operating the maser that it is intended to discipline and that provides the fountain's local oscillator reference signal. In such a situation the frequency transfer link between the two labs must not compromise the long- and short-term stability of the fountain standard. We have demonstrated such remote referencing with a 50 km spooled fibre using both a quartz-based microwave source and an ultrastable optically-derived one. Further field tests were performed on links of nearly 400 km of buried fibre using a commercial stabilisation system (ELSTAB) based on precisely matched electronic delay lines. We found that with optimal servo locking of the local oscillator to the maser reference the short-term stability of the fountain could be preserved in all of these configurations.