# Robust Design and Performance of NPL Cs Fountain Clocks

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Atomic fountain clocks have become ubiquitous in maintaining the most stable national time scales within nanoseconds of UTC in the short- and long-term. After three decades of development their design has reached a level of maturity offering accuracy of about 1 part in $10^{16}$. Recent efforts have been aiming towards increased reliability and a robust commercial design.

At NPL we have pursued a distinctive design approach offering the highest short-term stability and accuracy, yet with relatively simple construction and operation. The physics package is based on a single-stage vapour-loaded magneto-optical trap as the source of cold atoms, an easy to align (0,0,1) optical configuration, and efficient time-of-flight detection with large solid angle of fluorescence collection. The cold atom signal is further boosted by accumulation of the $m_F = 0$ clock state sublevel population via optical pumping. High detection signal-to-noise ratio and short-term stability below $3 \times 10^{-14}$ (1 s) have been achieved for a sufficiently low-noise local oscillator [1]. Despite the high atom number and density, a leading systematic effect, the cold collision frequency shift, can be controlled at parts in $10^{17}$ thanks to a cancellation mechanism and manipulation of the atom cloud parameters [2]. To limit the uncertainty of another potentially dominant systematic, the distributed cavity phase effect, to the $10^{-17}$ level, we have elaborated on a technique to precisely determine the position of the cloud of atoms in the microwave cavity [3].

The complete system consists of a physics package, which can be transported assembled by road or air, and just two full height 19-inch racks for control electronics, microwave generation and optics. The optical package is entirely mounted in one of the racks. Incorporating a distributed Bragg reflector (DBR) type diode laser for cooling and detection enables months of operation without any unintentional stoppages.

The system has been designed in compliance with the latest engineering standards and delivered to customers under the rigour of commercial contracts. Our customer base includes national measurement institutes, as well as large scientific facilities and providers of telecommunication and financial services. In order to support flexibility of timing infrastructure design and its resilience we have demonstrated operation of the fountain with a reference maser installed in a lab several hundred kilometres away. The maser was linked by an optical fibre connection and no deterioration of the fountain's short-term stability was observed [4].

Despite rapid progress in the development of other ultra-precise frequency standards, atomic fountains are likely to remain widely used in time scales as well as in experiments on the stability of fundamental constants and symmetries. Our current efforts are concentrated on developing a miniaturised version of the fountain with only a modest sacrifice of performance. We are building a prototype physics package 20 times smaller in volume and an all-in-fibre optics module that is also significantly reduced in size. From a different perspective, the nearly continuous uptime may enable the operation of time scales without the necessity of using a hydrogen maser as flywheel.

## References

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