The Caesium Fountain:
Progress Towards The New Primary Frequency Standard At NPL

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Introduction

The international time scale, UTC (Coordinated Universal Time), is generated using data from more than 200 atomic clocks around the world. Among these are a few primary caesium beam clocks, located in national standards laboratories, which provide the long term accuracy of the time scale by directly realising the definition of the second. Since 1967 this has been specified by assigning an exact value of 9 192 631 770 Hz to the frequency of the transition between the two hyperfine energy levels in the ground state of the caesium atom. The requirement for better long term stability of the time scale therefore necessitates improved primary caesium standards which can realise this definition with greater accuracy.

In a caesium beam clock, a beam of caesium atoms is emitted from an oven at around 100 °C. Atoms in one of the two ground state energy levels pass through the two arms of a U-shaped microwave cavity (called a Ramsey cavity) and interact with the radiation inside at close to the resonance frequency of about 9.192 GHz. Those which undergo a transition to the other energy state are then detected and their number maximised by adjusting the microwave frequency precisely onto resonance. The linewidth resulting from this Ramsey double interaction method is proportional to the time interval between the two interactions of the atoms with the microwaves, and is typically around 100 Hz.

These devices have been refined over many years, and the best laboratory standards attain an accuracy of around 1 part in 10^{14}. Further improvements in their performance are now constrained by several fundamental limitations of their design. The three largest causes of uncertainty in their accuracy are:
- cavity phase shift, arising from asymmetry between the two arms of the cavity and the finite conductivity of its walls;
- second order Doppler shift, a relativistic effect dependent on the atomic velocity;
- magnetic field effects, arising from inhomogeneity in the magnetic field (applied to separate the field-dependent energy sub-levels) and imprecise knowledge of its value.

Using Cold Atoms

The caesium fountain frequency standard promises an improvement in accuracy of perhaps two orders of magnitude by reducing or eliminating all of these causes of uncertainty. This new standard is based on techniques developed over the past few years for cooling and manipulating atoms using lasers.

The most basic mechanism by which atom cooling occurs is the transfer of momentum from photons of laser light to atoms within a particular range of velocities. When the laser frequency is de-tuned slightly below (to the red of) an atomic resonance frequency, an atom

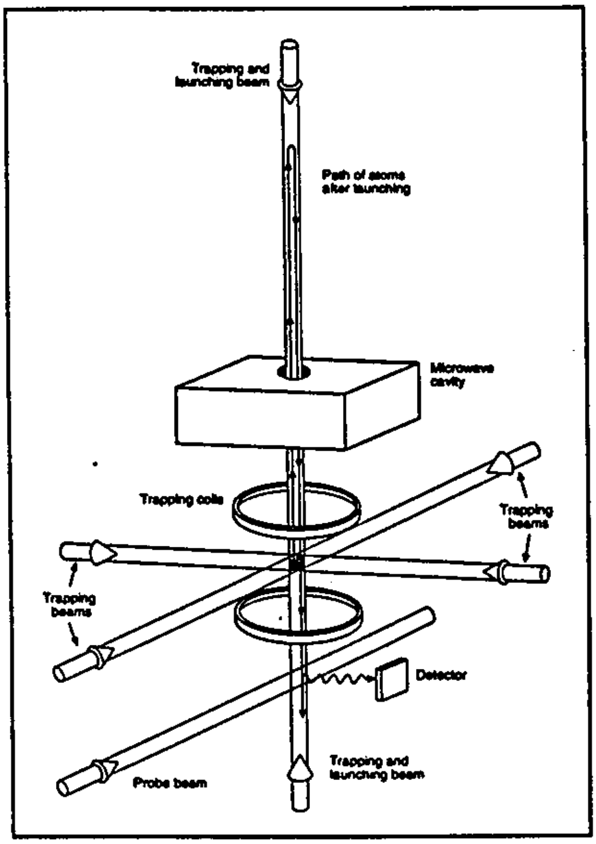

Figure 1. Schematic illustration of the laser beams and atomic trajectory within the fountain standard.

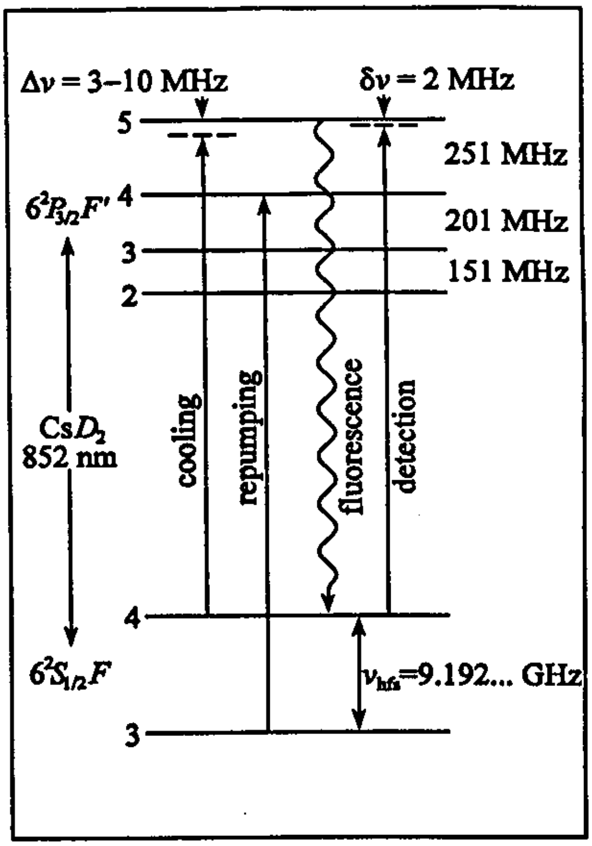

Figure 2. Energy level scheme for the caesium D2 line, showing the hyperfine structure of each level and the transitions used in laser cooling and detection.

moving into the beam will be Doppler-shifted into resonance. It therefore absorbs photons from the beam, reducing its velocity, while other atoms with different initial velocities are unaffected. With three orthogonal pairs of counter-propagating laser beams (figure 1), an atom within the region of intersection experiences a retarding force whichever direction it is moving - hence the term "optical molasses" used for this configuration. A magnetic field gradient, formed for instance by a pair of coils carrying opposed currents (anti-Helmholtz configuration), can generate a restoring force and transforms the molasses into a magneto-optical trap.

The fountain standard makes use of an optical molasses as its source of atoms. A cloud of caesium atoms, cooled to around 3 μK, is launched upwards by shifting the frequencies of the vertical laser beams. The atoms pass up through a tuned cavity, interacting with the microwave radiation inside at about 9.192 GHz, and continue upwards for some way before falling back under gravity along the same path. The second pass through the cavity occurs about 1 second after the first, giving a resonance linewidth of approximately 1 Hz. The atoms then fall through a probe beam which stimulates fluorescence to reveal the proportion which have undergone the state transition.

The combination of cold atoms and a single microwave cavity significantly reduces the main factors which limit the accuracy of a beam standard:

- the cavity phase shift is reduced by the use of a simple cylindrical cavity through which the atoms pass twice;
- the lower thermal velocity of the cooled atoms gives a smaller second order Doppler shift;
- because the cooled atoms spend longer within the microwave cavity, a smaller background magnetic field can be used and the effects of any inhomogeneities are reduced.

Realising The Caesium Fountain

A prototype caesium fountain standard is under construction at the NPL, in collaboration with a group at the Clarendon Laboratory, University of Oxford, and with several European laboratories which form an EC-funded network on caesium primary standards. Work to date has concentrated on developing the hardware required to realise the fountain, and various aspects of this work are described in more detail here.

Lasers.

Cooling and launching the caesium atoms, and probing their energy state after interaction with

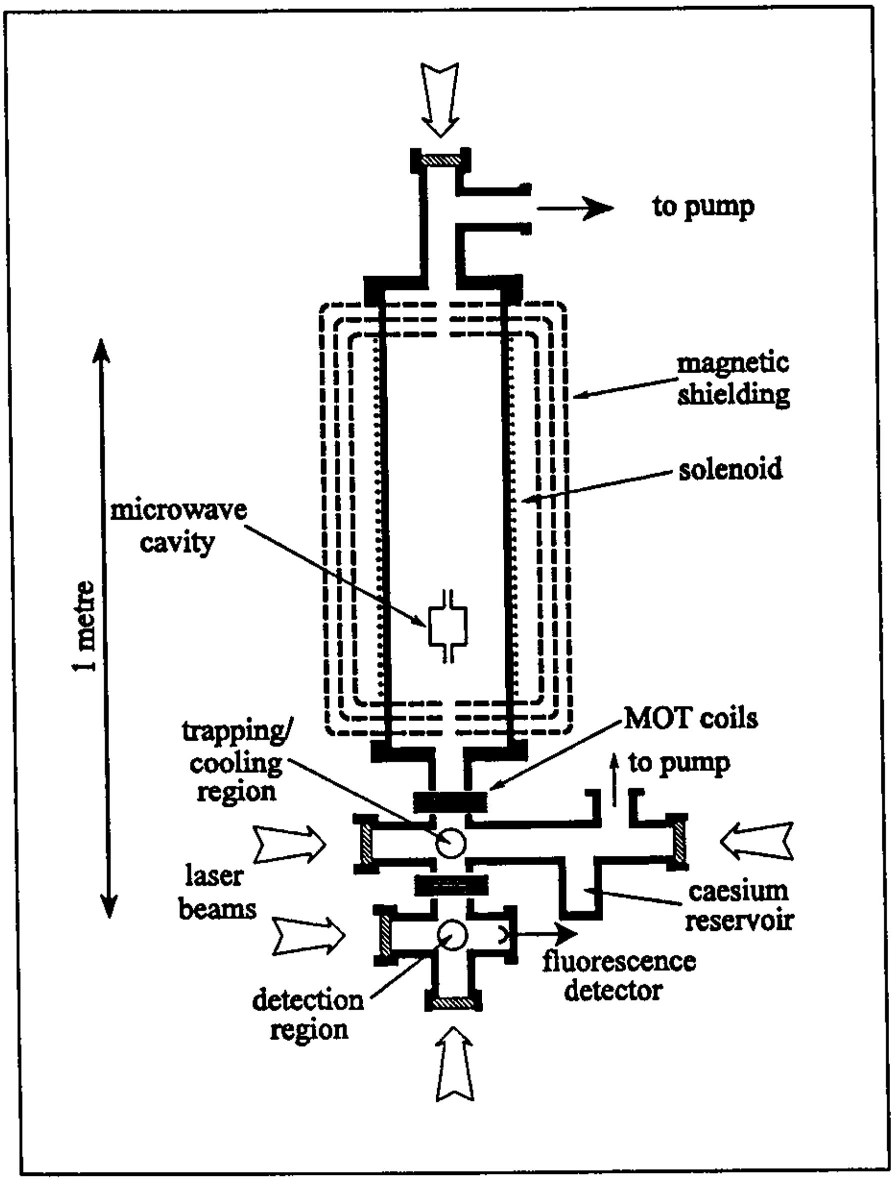

Figure 3. Vertical cross-section through the caesium fountain standard.

the microwave radiation, requires three laser diodes operating at 852 nm, the wavelength of the caesium D2 line (shown in figure 2). The master laser is mounted in an external cavity using a reflection grating to give strong optical feedback. This method reduces the laser linewidth to a few 100 kHz and allows tuning over several MHz by varying the grating angle. The laser frequency is stabilised at just below the F=4-F'=5 transition. This is done by locking to the caesium resonance line observed by saturated absorption spectroscopy, and passing the beam through acousto-optic modulators to generate the frequency offset. This laser provides the probe beam and also injection-locks the slave laser. The output from the slave is split six ways to form the cooling beams. A third laser, the repumper, is mounted in an external grating cavity similarly to the master, but is stabilised onto the frequency of the F=3-F'=4 transition. Its light is superimposed onto the horizontal cooling beams to prevent the caesium atoms accumulating in the F=3 state during cooling.

Microwave cavity.
The microwave enclosure is a cylindrical TE011 cavity with the trajectory of the cooled atoms along its axis. This gives the minimum phase variation across the 10 mm diameter beam apertures. Tubes attached to these apertures act as waveguides beyond cut-off to minimise microwave leakage from the cavity.

Fountain enclosure.
The vacuum enclosure is constructed from UHV components to achieve an ultimate pressure of the order of 10^{-11} mbar. It consists of three distinct chambers, as shown in figure 3. The trapping chamber in the centre is in the form of a six-way cross to admit the cooling beams as well as mount a cooled caesium reservoir and ion pump. Above is the interaction chamber containing the microwave cavity, which is made from titanium to give a minimal magnetisation. A solenoid wound onto this chamber provides the uniform longitudinal field which separates out the magnetic field-dependent ground state sub-levels, and three concentric mu-metal shields screen the external fields. Temperature stabilisation of this chamber to a uniformity of 0.1 K is required to keep the black-body frequency shift within acceptable limits. The third chamber mounts a photodiode which measures the fluorescence stimulated by the probe laser beam, in order to determine the proportion of atoms which have undergone a transition within the cavity.

Once the caesium fountain is complete an extensive series of measurements will be carried out to investigate and quantify the various causes of frequency shifts and their uncertainties. It is expected that this prototype frequency standard will achieve an accuracy of a few parts in 10^{15} with a stability of around 10^{-13} $Hz^{-1/2}$.

References

1. K. Gibble & S. Chu, "Future slow-atom frequency standards", Metrologia 29, 1992, 201-212.

2. A. Michaud, M. Chowdhury, K. P. Zetie, C. J. Cooper, G. Hillenbrand, V. Lorent, A. Steane & C. J. Foot, "Realisation of a frequency standard using an atomic fountain", 7th European Frequency and Time Forum, Neuchâtel, 1993, 525-530.

3. A. Clairon, P. Laurent, G. Santarelli, S. Ghezali, S. N. Lea & M. Bahoura, "A caesium fountain frequency standard: preliminary results", IEEE Transactions on Instrumentation and Measurement, 44 (2), 1995, 128-131.