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Continuous beams of cold atoms for space applications

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ABSTRACT The precision of atomic state measurements should ideally be limited by irreducible fluctuations associated with the number of atoms available, e.g. shot noise or quantum projection noise. In practice, other noise sources can limit the precision achievable; a well-known effect is the intermodulation effect, or Dick effect, which degrades the stability of atomic fountain clocks using pulsed sources. One way to beat this source of instability consists of interrogating the atoms with a microwave signal derived from exceptionally stable local oscillators, such as cryogenic oscillators, which are however bulky and not ideally suited to the constraints of space. Another way of reaching atomic-noise limited instability is to use continuous sources of cold atoms. Experimental results obtained both on a fountain standard and on an experimental Cs fountain illustrate the potential of continuous cold atomic beams for improving signal-to-noise ratio and precision of measurement. Current developments towards higher atomic beam flux are also described.

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1 Short time stability and reduction of intermodulation effects

The short term (in)stability of passively operated atomic frequency standards, characterized by the Allan deviation $\sigma_y(\tau)$, generally follows a $\tau^{-1/2}$ behaviour according to the relation $\sigma_y(\tau) = \kappa(Q\mathrm{S/N})^{-1}\tau^{-1/2}$, where κ is a number close to 1, dependent on the modulation/demodulation details of the interrogation scheme, Q is the quality factor of the atomic resonance, S/N is the signal-to-noise ratio of the resonator output signal at resonance, and τ is the sampling time. Ideally, the noise spectral density N should be dominated by the statistical noise associated with the limited number of atoms available for the measurement.

However, in passive standards, the correction signal obtained from the resonator to steer the local oscillator is obtained by a modulation–demodulation process, carried out at the modulation frequency f_M. The non-linearity of this process leads to the generation of an additional, spurious contribution to N, which arises from the down-conversion to low Fourier frequencies of local oscillator phase noise at frequencies equal to even multiples of the modulation frequency f_M [1–3]. The case of Ramsey resonators is of particular interest. Results for the intermodulation noise have been obtained in this case

a) in the pulsed operation case, using the concept of the sensitivity function [3]

b) in the continuous operation case, by a generalization of the concept of the sensitivity function [4]

c) using a different approach [5, 6], based on an analytical calculation of the noise spectrum associated with the error signal in the locked frequency servo-loop. This approach covers any time dependence of the atomic flux, in particular the usual, pulsed case, and the continuous case discussed in this paper.

The theoretical results of [6] can be summarized as follows:

1. The spurious noise contributions of the local oscillator can be cancelled only if the even harmonics ($2kf_\mathrm{M}$) of the modulation frequency coincide with zeros, if any, of the transfer function of the atomic resonator. A Ramsey resonator compares the atomic frequency and the local oscillator frequency during a square time window of length approximately equal to T. It therefore effectively filters out noise components at frequencies equal to m/T, which would otherwise be down-converted by the modulation–demodulation process (k and m are integers). $f_\mathrm{M} = 1/2T$ is the slowest modulation frequency that allows this filtering to occur. This condition can not, however, be met in pulsed fountains: because of the presence of dead times, the cycle time $T_\mathrm{c} = 1/(2f_\mathrm{M})$ is necessarily longer than the free evolution time T.
2. The effectiveness of the reduction noise cancellation is reduced in the case of a wide velocity distribution (since $T = T(v)$, f_M can not match $1/2T$ for all velocity classes), and if the duration of atomic transients in the microwave cavity can not be neglected.
3. The effectiveness is improved by using a square-wave phase modulation scheme, rather than the more usual square-wave frequency modulation scheme.

Three approaches have been proposed to reduce the intermodulation noise and the associated degradation of the short-term frequency stability [7]:

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a) Very low noise local oscillators, such as cryogenic dielectric resonator oscillators. This solution can be very effective [8]. However, cryogenic oscillators in their present form are not suited for space applications, and the compromise between stability and accuracy in Cs fountains (collisional shift) is not relaxed.

b) Juggling, or multi-ball fountains, which provide an intermediate solution between pulsed and continuous fountains, both from the point of view of intermodulation effects and collisional effects [7].

c) The continuous fountain [9–11] which allows one to reduce simultaneously intermodulation effects and collisional shifts by more than two orders of magnitude. This relaxes, by the same margin, the compromise faced in most pulsed fountains between high stability (but high collisional shift and uncertainty), and high accuracy (but moderate frequency stability), without resorting to a better oscillator than state-of-the-art, space qualified, quartz oscillators.

2 The continuous cold Cs fountain FOCS-1

The cold atom fountain clock FOCS-1 developed at ON with METAS (presently operating at METAS) differs from all presently operating cold fountain clocks in one important respect: instead of being pulsed, the atomic beam is continuous. A schematic of the fountain is presented in Fig. 1, together with its main operating characteristics.

FOCS-1, key parameters:

- Mean transit time: $T = 0.51$ s; $Q = 10^{10}$
- Longitudinal temperature (after transverse cooling): 75 μK
- Transverse temperature: 7 μK
- atomic flux of $F = 4$, $m = 0$ atoms at detection: 200 000 atoms/s
- signal is shot-noise limited with quartz local oscillator
- Short-term stability: $2.5 \times 10^{-13}\tau^{-1/2}$ (Fig. 2a, shot-noise limited Fig. 2b)
- Collisional shift : $< 1 \times 10^{-16}$
- Light-shift without light-trap: 1×10^{-12} (measured)
- Light-shift with light-trap: $< 1 \times 10^{-16}$ (deduced from measured attenuation of light trap)

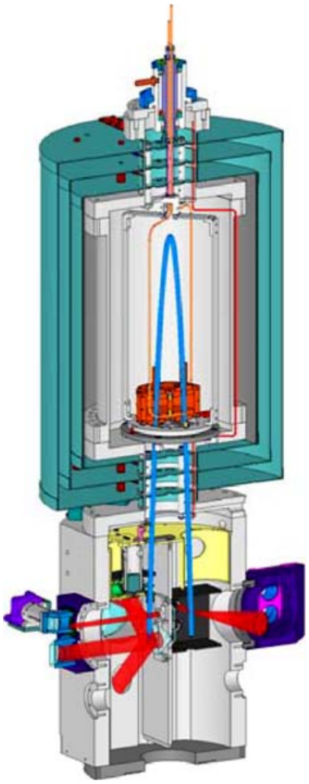

FIGURE 1 Schematic view of FOCS-1, showing the continuous beam of cold atoms, the source chamber (*lower left*) contains a vapour loaded 3-D moving molasses, a 2-D collimating molasses and the rotating light trap

As described in detail in [9–11], the continuous beam is produced from a 3D molasses with three pairs of counter-propagating beams, orthogonal to each other, one horizontal and two at 45° to the vertical. About 10^8 Cs atoms/s are launched vertically. The necessary compromise between capture efficiency from the thermal vapour and temperature of the resulting beam results in a temperature of 60 μK at the exit of the 3D molasses. The width of the transverse velocity distribution is then reduced by a 2D molasses with laser beams detuned by 25Γ ($\Gamma = 2\pi\, 5.3$ MHz) to the red of the $44'$–$55'$ transition of the Cs D2 line, resulting in a transverse temperature of 7 μK, and a longitudinal temperature of 75 μK. Atoms are then pumped to the $F = 3$ level before entering a rotating light trap, which acts as a velocity selector. The rotation speed of the glass blades is adjusted to allow 90% of the atomic flux to be transmitted while blocking ($> 10^4$) or deflecting the light

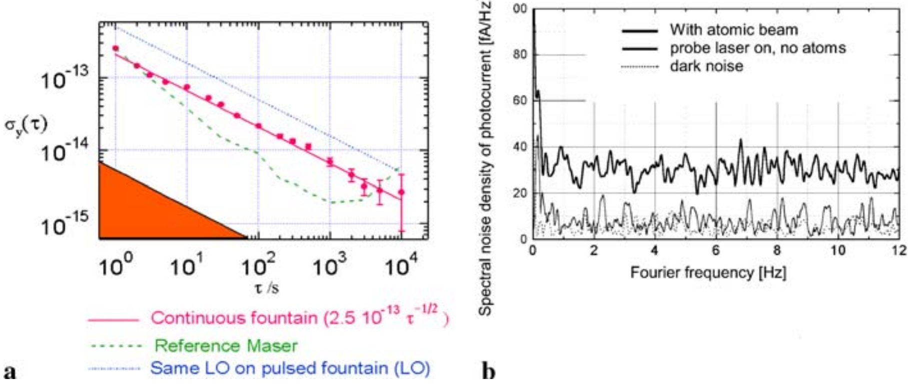

FIGURE 2 (**a**) Allan deviation of FOCS-1. (**b**) Noise spectral density of the probe detector photocurrent, fountain operating at clock resonance (180 000 at/s, as determined from resonator S/N ratio). *Dots*: dark noise; grey: probe beam on, no atomic beam; black: atomic beam on

scattered by the 3D molasses out of the atomic beam. The light shift that atoms would otherwise suffer in the microwave interaction region is thus reduced to negligible values. The Ramsey interrogation takes place in a coaxial cavity which provides a microwave magnetic field distribution nearly identical to the usual TE011 cavities used in vertical, pulsed fountains. A single probe beam detects atoms in the $F = 4$ level.

The two important advantages of the continuous fountain are

1. The reduction, by two orders of magnitude [5, 11], of the collisional shift, due to the reduced atomic density compared to that of a pulsed fountain with the same average atomic flux, and short-term stability. This allows in principle operation of the fountain with a much higher flux than a pulsed fountain before the collisional shift becomes a limiting factor for the accuracy. This is especially valuable in Cs fountains where the collisional shift contributes substantially to the inaccuracy budget [7]
2. The removal of the intermodulation noise discussed in the preceding section.

However, the continuous operation of the fountain exposes atoms in the microwave interrogation region to the light scattered by atoms in the cold atom source, which induces an unacceptable light-shift of the clock transition, unless steps are taken to prevent scattered light from reaching the upper part of the fountain. This can be very efficiently implemented by means of a rotating light-trap [11]. The light intensity measured in the cavity is attenuated by more than a factor of 10^4 while the cold atomic beam attenuation is calculated to be about 10% [5].

The instability measured so far on the continuous fountain is $2.5 \times 10^{-13}\tau^{-1/2}$ (Fig. 2a, red circles and fit). We have calculated the short term stability provided by a hypothetical fountain using a pulsed, rather than continuous, atomic beam with the same average flux, together with the same local oscillator (Fig. 2a, dotted line). It is interesting to note that even at the relatively low flux generated so far by our continuous fountain, the stability is not limited by local oscillator noise. The noise spectral density of the atomic resonator signal is flat, (un-modulated microwave at resonance) (Fig. 2b), strongly indicating that technical noise does not play any significant role although no normalization is applied to remove its effects. Atomic shot noise is most probably the major contribution to the measured S/N ratio.

The question arises, how much improvement of the Allan deviation can be expected by increasing the atomic flux? A calculation of the residual contribution of inter-modulation noise, due to the velocity distribution in the atomic beam (longitudinal temperature 75 μK), indicates that a stability as low as 7×10^{-15} at 1 s could be reached before being limited by the local oscillator noise (shaded zone).

3 Towards higher flux in a continuous fountain

The potential for significantly improving the short term stability without affecting the accuracy is the main motivation for efforts to substantially increase the continuous atomic flux.

Two types of improvements can be made in order to reach this goal (Fig. 3):

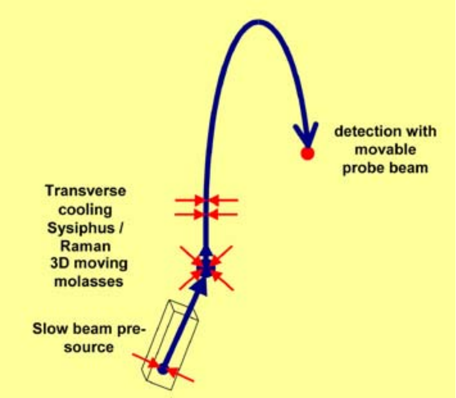

FIGURE 3 Schematics of the experimental continuous fountain

1. Presently the moving 3D molasses which produces the continuous beam is loaded from a thermal Cs vapour. It is well known ([12] and references therein) that a beam of slow atoms from a Zeeman slower or any variant of a 2D magneto-optical trap (MOT), can load substantially more atoms into a 3D molasses than the slow velocity tail of the Maxwell–Boltzmann distribution. We have designed a novel, simplified 2D MOT which, instead of polarizing beam-splitter cubes and quarter-wave plates [12], uses simple gold-coated 90° roof-prisms to direct the laser beams and reverse their helicity. This optical structure provides acceptable intensity balance between counter-propagating – retro-reflected – beams, as required for Doppler cooling, while saving laser power. With the slow-atom source in its present configuration, we have already obtained a twenty-fold increase of the useful fountain flux [17].
   Another advantage of the slow beam source is the strong reduction of vapour density in the main source chamber, reduced Cs consumption and more localized, and therefore controllable, Cs deposition on optical surfaces.
2. While the longitudinal temperature is by no means a disadvantage (it further reduces the collisional shift at a given density, and it allows one to obtain essential information on the residual inhomogeneity of the static magnetic field), the transverse temperature results in a sizeable divergence of the fountain beam: about 1% only of the fountain flux emitted by the source reaches the detection region.
   A first improvement was obtained by replacing the two independent, retro-reflected beams of the 2D transverse cooling stage by a phase-stable, power recycling, folded 2D optical lattice [13]. In the simplest scheme, namely Sisyphus cooling, a factor of two has been gained in transverse temperature, and useful flux.
   More elaborate schemes based on degenerate-sideband Raman cooling promise greater gains but are harder to implement and optimise. We have already obtained 1.6 μK using the Zeeman-tuned variant [14] but have yet to implement pre-cooling, so as to collimate most of the atoms and not just the 10% trapped in the 20 μK deep lattice, followed by adiabatic population transfer [15] to populate the $F = 3$ $m = 0$ clock state rather than the $m = 3$ stretched state.
   An equally promising scheme is Stark-tuned degenerate-sideband Raman cooling [16], which populates the clock state directly and is compatible with in-lattice pre-cooling.

Combining the two approaches, it seems possible to improve the flux by a factor of more than 100, resulting (provided that possible technical noise can be controlled to the required level) in at least a factor 10 improvement of the short term stability, to about 2×10^{-14} at 1 s.

4 A cold, continuous-beam space clock

The atomic quality factor of an atomic beam resonator scales as the transit time T between the two microwave interactions. On earth, the transit time in a fountain scales as $(H/g)^{1/2}$, where H is the fountain height above the microwave cavity and g is the acceleration of gravity. In microgravity, however, T can be increased by at least an order of magnitude by reverting to the original geometry of Cs beam clocks, namely that of a straight beam. The cold atom clock PHARAO, developed by SYRTE-CNES in the frame of the ACES mission [18], is indeed planned as a demonstration of the potential gain in both stability and accuracy brought about by operating a cold-atom clock in micro-gravity. Here again, the concept of a continuous beam clock would bring interesting features:

- The short term stability scales as $1/(Q\Phi^{1/2})$, where Q is the quality factor and Φ is the average atomic flux ($\sim$ density $n \times$ velocity v). The average atomic velocity in a straight beam of cold atoms must be typically one order of magnitude lower than in a ground fountain to obtain a ten-fold improvement of the quality factor. However, in order not to decrease the average flux, the atomic density must be increased by the same order of magnitude. The compromise between stability and accuracy (insofar the latter is limited by density-related shifts) is more stringent in a space-clock than in a ground fountain. In a continuous beam configuration, this compromise is relaxed by more than two orders of magnitude; this features becomes even more attractive in a space clock than in a ground clock.
- The rejection of intermodulation noise in a continuous beam makes it possible to reach the highest stability with a quartz oscillator rather than with a bulkier high stability local oscillator noise.
- The light trap is not expected to be a major issue in a space version of the continuous beam: the rotating light trap of FOCS-1 weighs a mere 40 g, with much room for reduction. Also, the reduced atomic velocity would require a correspondingly lower speed of rotation. It would also open up alternative trap designs not even involving any friction.

5 Conclusion

Continuous beams of cold atoms can be produced with high stability: 2×10^5 clock signal atoms per second with no detectable technical noise.

They provide a mode of operation – for ground fountains, or straight beams in microgravity – which is intrinsically free of intermodulation noise ("Dick effect") when interrogated by the Ramsey method with a modulation frequency f_M equal to the fringe width.

We have shown that it is possible to replace an intense, pulsed beam resonator interrogated by a cryogenic oscillator by a continuous beam interrogated by a good quartz oscillator to obtain the same stability while reducing the collisional shift.

We suggest that continuous beams of slow atoms are to be considered for future precision experiments and their applications in space: microwave clocks, optical clocks, and possibly atom interferometry applications.

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