Cesium fountains and micro-gravity clocks

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Abstract

Recent progress in laser cooling and trapping of neutral atoms is paving the way for the development of more accurate caesium atomic clocks. Producing micro-Kelvin atoms having an r.m.s. velocity of 1 cm/s requires no more than two diode lasers and a small glass cell.

This paper surveys the progress of ground-based fountain clocks, reporting the most recent results obtained with the prototype clock operating at LPTF. The narrowest Ramsey fringe is 0.7 Hz wide and the Allan variance of the fountain clock versus a H maser displays a stability of $2\ 10^{-13}\ \tau^{-/2}$ down to $2\ 10^{-15}$ for an integration time of 10 000 seconds.

Satellite-based clocks, by taking advantage of a reduced-gravity environment, should enable the full potential of laser cooling to be realized, opening the fascinating possibility to achieve performances superior to those of their ground-based counterparts. The expected relative stability of fountain and satellite clocks is about $3\ 10^{-14}$ at one second or $\sim 10^{-16}$ per day with an accuracy in the 10^{-16} range. The intercomparison of clocks with these performances raises interesting challenges in the time and frequency transfer domain and should also allow a new generation of tests of general relativity.

1 Introduction

Today the most stable clocks are atomic clocks, the Hydrogen Maser, trapped ion clocks and the cesium clock. The unit of time, the second, is defined using a hyperfine transition in atomic cesium. Cesium clocks have the best long term stability ($\sim 10^{-14}$ from 1000 s to several years [1]) and accuracy while H masers present the best short term stability ($\sim 10^{-15}$ from 1000 to 10000 s). These clocks are currently used on Earth in a variety of science areas ranging from fundamental tests of physics laws to Very Large Baseline Interferometry (VLBI), the timing of millisecond pulsars and the positioning of mobiles on Earth (GPS) or in deep space. A Hydrogen maser has flown in space for two hours in 1976 in the NASA Gravity Probe experiment (GPA) [2]. Several tens of cesium clocks (as well as less precise Rubidium clocks) are now in continuous operation in GPS satellites orbiting at 20 000 kms above the Earth.

Recent progress in the field of cooling and trapping of neutral atoms or ions is having considerable impact on time and frequency standards. Ions can be trapped with magnetic or radio frequency electric fields for days and weeks leading to very long coherent interogation times (500 seconds) [3]. Commercial systems with stability approaching that of H masers exist and space versions are beeing actively developped. The field of laser cooling of neutral atoms is less than ten year old and the application to the realization of better time and frequency standards is actively pursued since 1989 [4, 5].

2 The Benefits of Cooling

Commercial cesium clocks use a 400 Kelvin atomic beam of cesium atoms. By contrast, cesium clocks using laser cooled atoms operate with atoms at temperatures in the 1 μK range allowing a 100-fold improvement in the observation time. Nowadays, one can very easily produce a dense gas of cold cesium atoms at a temperature of $2.5\mu K$ corresponding to atoms with an r.m.s velocity of 12mm/s [6]. These small velocities allow interaction times between atoms and electromagnetic fields approaching one second on Earth when using an atomic fountain geometry. As the atomic resonance linewidth in cesium clocks is inversely proportional to this interaction time, an improvement of two orders of magnitude in the clock performances over conventional devices running at a temperature of 400 K is expected. It is predicted that microgravity conditions should enable a further factor of ten improvement in the interaction time with a simple and compact device [7].

Furthermore, new laser cooling techniques enabling to reach temperatures below the temperature set by the single photon recoil are presently being developped in several laboratories [8, 9, 10, 11, 12, 13]. Atoms have been cooled in one and two dimensions to much less than the recoil velocity, down to the nanoKelvin range.

2.1 Atomic Fountain

On Earth, the gravity limits the available interaction time and it was Zacharias' idea in 1953 to use an atomic fountain to obtain interrogation time in the one second range when using Ramsey's method of separated oscillatory fields. Efforts to build such an atomic fountain in that period were unsuccessful because of collisions near the oven exit. Laser cooling and the very slow velocities in optical molasses have enabled this idea to be brought-up to date[4, 5]. Fountain clock prototypes are being built in more than a dozen laboratories around the world and two of them (at Stanford [15] and LPTF [16]) are now running as frequency standards. In the LPTF fountain, Ramsey fringes as narrow as 0.7 Hz have been obtained with a signal to noise ratio of 300 at one second integration time (Fig. 1). The short term frequency stability, measured against an H-maser is $2\ 10^{-13}\ \tau^{-1/2}$ (Fig.2). While this stability is five times better than in any conventional cesium device, it is still limited by the local oscillator frequency noise (ultra-stable BVA quartz crystal) and not by the cesium fountain noise. The long term relative stability (Allan variance) as compared to a Hydrogen maser reaches $2\ 10^{-15}$ at 10 000 seconds, a value which is most probably limited by the H maser itself.

The accuracy of the fountain clock also benefits greatly from the reduction of the velocity as compared to the thermal beam machines. Most systematic frequency shifts contribute much less than 10^{-15} to the accuracy of the fountain clock except the shift due to collisions between the cold atoms in the fountain [15]. This shift is presently the most serious limitation to the accuracy and it sets a limit to the density of the atomic fountain. Our measurements of collisional shifts are $-5.9\ 10^{-22}\ <n>$ for $5\mu K$ atoms entering the microwave cavity evenly distributed among Zeeman substates of $F = 3$ (a value in very good agreement with [15]) and $-1.0\ 10^{-21}\ <n>$ for atoms evenly distributed among $F = 4$ substates. $<n>$ is the average atomic density in the fountain and its absolute determination presents a relative uncertainty of 60%. In normal operation of our fountain, atoms are loaded from optical molasses and the density is low, $<n>= 3\ 10^6$ At/cm^3,

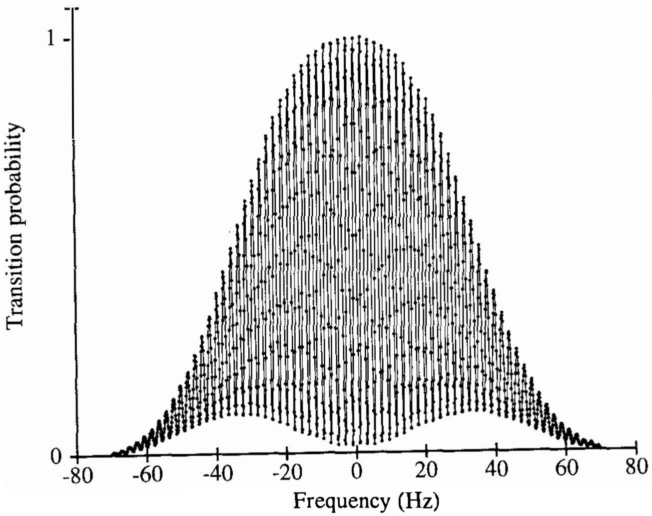

Fig.1 Ramsey fringes of the LPTF fountain clock for a 0.5 second flight time of the atoms above the microwave cavity [16]. The fringes are 1 Hz wide and signal to noise is 300 per point. The frequency detuning is scanned around the cesium hyperfine transition frequency at 9 192 631 770 Hz.

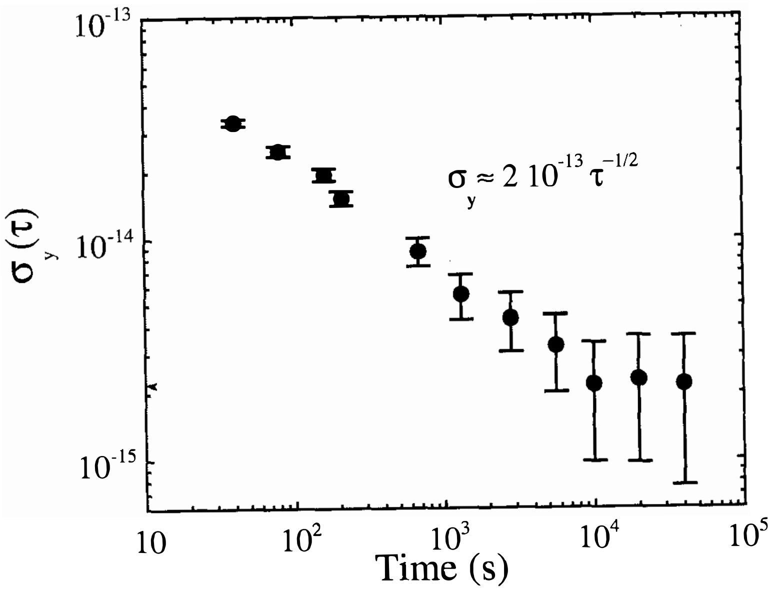

Fig.2 Frequency stability of the fountain clock measured against a Hydrogen Maser: Allan variance versus the number of fountain cycles [16]. Each cycle lasts 1.1 second. The stability reaches that of the H maser at about 10^4 seconds and is probably limited by the maser stability for longer measurement times.

the shift is $\sim 3\ 10^{-15}$ and the uncertainty on this shift is presently $\pm 2\ 10^{-15}$ limited by the stability of our H maser. A factor ten improvement in the evaluation of this shift and keeping the density constant to $\pm 5\%$ will reduce the uncertainty in the 10^{-16} range. Several ways have been proposed to reduce this shift further [15, 18] and microgravity is one of them.

2.2 Microgravity Clock

Gravity imposes an obvious limit on the resolution which can be obtained in a fountain clock: the resolution increases only as the time T spent by the atoms above the cavity i.e. as the square root of the fountain height. Going much beyond a 1 s fountain time would require an expensive and bulky apparatus and would probably be to the detriment of the accuracy. A promising alternative is to build a clock in a reduced gravity environment. Measurement time of several seconds can be envisaged using a smaller and simpler apparatus, leading to a factor of 10 increase in T i.e. in resolution. If we assume that we keep a short term stability equal to that of the Earth fountain, it is easy to show that the collisional shift scales as $T^{-1/2}$. In addition, because of the constant velocity of the atoms in a microgravity clock it is much easier than on Earth to increase the duty cycle of the fountain by preparing successive clouds of atoms filling the space between the cold atom source and the microwave cavity. This enables one to either increase the signal to noise ratio by working with more atoms in a clock cycle time T_c (atom collection+ launching +free flight to the microwave cavity + microwave interrogation + free flight to detection zone + detection) or to reduce strongly the collisional shift. We believe that about 20% of T_c can be used to be compared with 1% in our present fountain.

First experiments on laser cooling of atoms in microgravity were recently performed by our group in Paris using jet plane parabolic flights and very simple experimental techniques [7]. Efforts now concentrate on building a clock prototype designed for microgravity conditions. Such a system is an extension of the work developped for fountain clocks on Earth described in detail in [15, 5, 16, 17, 18]. A prototype of a micro-gravity clock is schematically described in [18] and is under study at CNES (PHARAO project). It includes a laser diode system and optics for atom manipulation and cooling, a high stability 9.2 GHz microwave source and a vacuum tank containing a cooling region, a microwave interrogation region and a detection zone. The clock is operated fully automatically using a micro-computer.

3 Expected Performances of a Space Clock

A first scientific objective of a clock experiment in space could be the demonstration of a clock running with laser cooled atoms in micro-gravity conditions and the determination of its performances. These performances are expected to be better than $10^{-13}\ \tau^{-1/2}$ where τ is the integration time in seconds. For one day of operation, the stability will be $3\ 10^{-16}$, corresponding to an absolute time fluctuation of 30 picoseconds. This stability would be two orders of magnitude better than present Cs clocks. Such a demonstration would open a new era of space missions using ultra-stable clocks as space VLBI, high precision measurement of the sun gravitational potential to second order and of the Shapiro delay as proposed in the SORT mission (Solar Orbit Relativity Test) [14].

Since no other clock is known to give yet such performance for a one day measurement time, it will be necessary either to fly two identical systems in order to make frequency comparisons on board the spacecraft or to use high performance two-way time and frequency transfer systems with Earth-based clocks of similar performances. These frequency links could be in the microwave or optical domains using either X or K-band microwave signals or pulsed lasers as in the lunar ranging experiment. The required timing precision is on the order of a few ps at 10^3 s or, as said above, 30 ps at one day.

If microgravity cold atom clocks become eventually more stable than their Earth-based counterparts, two or more similar clocks on board the spacecraft are required in order to assess their performances using frequency intercomparison techniques.

4 Possible Applications

With clocks having a stability of 10^{-16} in one day, it should be possible to measure with a potential 100-fold improvement over the 1976 GPA experiment the gravitational red-shift (Einstein effect). This general relativity effect was determined at the 10^{-4} level using H masers having a stability slightly better than 10^{-15} over the 2 hour mission duration [2]. The precision on such a measurement depends directly upon the excentricity of the orbit. A satellite with a large excentricity (e=0.6, major axis 20 000 kms and a 12 Hour period) would be an ideal choice.

A second application belongs to the field of time and frequency dissemination. A geostationnary satellite is an ideal tool for dissemination toward the Earth of ultra-stable timing signals and for frequency comparisons between various Earth stations. The very low drift of the space clock might also allow frequency comparisons between Earth-based clocks without the constraint of common view of the satellite. Positioning of mobiles on the surface of the Earth as in the GPS system could also benefit from satellite clocks with improved stability.

More ambitious space applications deal with measuring the relativistic Shapiro delay in the Sun gravitational potential with four orders of magnitude improvement in precision over current values [14]. A measurement of the second order Sun gravitational potential is also possible using these highly stable clocks.

4.1 Time and Frequency Transfer

When a stable clock is orbiting around the Eath, a crucial factor appears to be the quality of the frequency comparison between the satellite clock and one or several clocks on Earth. The picosecond time stability over a few minutes required for assessing properly the stability of the satellite clock demands that the frequency comparison be at least two-way. Since the GPA experiment, the Harvard group has performed detailed studies of several possibilities for achieving frequency comparisons below the 10^{-15} range [19]. Today, two major directions emerge, a microwave two-way link and an optical link using picosecond laser pulses [14]. By contrast to the optical link, the microwave link has the advantage of being independent of wheather conditions. It is clear that both methods are very different in their approach of the time transfer. A comparison of the performances of the two methods is highly desirable and would certainly be an important issue. The synchronized two-way frequency transfers (Earth-spacecraft- Earth) and (spacecraft-Earth-spacecraft) allow complete cancellation of isolated tropospheric or ionospheric noise as well as of the first order Doppler effect [19]. Measurements of the relativistic effects (second order Doppler and redshift) requires a very good knowledge of the satellite orbit and velocity.

5 Summary

The possibility to install high stability clocks in space is very attractive from the viewpoint of testing new concepts of clocks using cold atoms and for potential applications. The development of time and frequency transfer with a few picosecond accuracy is required in order to read these ultra-stable clocks in orbit. This would open the way for more ambitious physics missions such as space VLBI or tests of general relativity in solar orbit with unprecedented precision.

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