PHARAO: A SPACE CLOCK WITH COLD CESIUM ATOMS

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Abstract

We describe a cold atom clock designed for operating in microgravity, the PHARAO project. Preliminary results have already been obtained on earth and the prototype will be tested in the reduced gravity of aircraft parabolic flights in the beginning of 1997. The PHARAO prototype is an extension of the work done at the BNM-LPTF on a cesium atomic fountain, which presents a resonance linewidth of 700 millihertz, a frequency stability of $1.5\cdot 10^{-13}\tau^{-1/2}$ where τ is the integration time in seconds. The accuracy of the fountain clock is presently $2\cdot 10^{-15}$, more than three times better than previously achieved with uncooled conventional devices. The expected relative stability of the PHARAO cesium clock in space is about $3\cdot 10^{-14}$ at one second or 10^{-16} per day. Because the reduced gravity environment allows a mode of operation of the clock different from earth fountains, the accuracy of PHARAO should surpass that of fountains and be in the 10^{-17} range. The PHARAO frequency standard could be a key element in future space missions in fundamental physics such as SORT (Solar Orbit Relativity Test), detection of gravitational waves, or for the realization of a global time scale and a new generation of positioning system.

1 INTRODUCTION

Today, the most stable frequency standards are cesium clocks, hydrogen masers, and trapped ion clocks. The unit of time, the second, is defined using the hyperfine transition F=3 to F=4 of atomic cesium. In a cesium clock, the atoms pass through a microwave cavity where they undergo the hyperfine transition. The microwave frequency, generated by a local oscillator, is frequency-locked on the atomic resonance. Cesium clocks have the best long-term frequency stability.[1] ($\sim 10^{-14}$ from 1,000 s to several years) and accuracy ($\sim 10^{-14}$), while hydrogen masers present the best short-term stability ($\sim 10^{-15}$ from 1,000 to 10,000 s).[2] A hydrogen maser has flown in space for two hours in 1976 in the NASA Gravity Probe experiment (GPA) and current plans exist to fly hydrogen masers again on board the Mir space station before the end of this century.[2,3] Several tens of cesium clocks (as well as less precise rubidium clocks) are now in continuous operation in GPS satellites orbiting at 20,000 km above the earth.

The conventional cesium clocks use a ~400 Kelvin thermal atomic beam of cesium atoms (beam velocity ~100 m/s and velocity distribution width ~50 m/s). Nowadays, laser cooling techniques can very easily produce a dense gas of cold cesium atoms at a temperature of 2.5 μK corresponding to atoms with an rms velocity of 12 mm/s.[4] These small velocities allow interaction times between the atoms and the electromagnetic field approaching one second on earth as compared to a few milliseconds when using a conventional cesium clock.[5,6,7,8] As the atomic resonance linewidth in cesium clocks is inversely proportional to the interaction time, an improvement of two orders of magnitude in the frequency stability and accuracy over conventional devices is expected. A first frequency standard using cold atoms in a fountain configuration has been constructed at the BNM-LPTF. The interaction time in this atomic fountain can reach 700 ms, leading to a 0.7 Hz resonance linewidth. The frequency stability is $1.5 \cdot 10^{-13} \tau^{-1/2}$ and reaches $1.5 \cdot 10^{-15}$ at $\tau = 10^4$ s. For longer integration times, the stability is limited by the hydrogen maser used as a reference oscillator. The accuracy of the fountain clock has been recently improved over the value reported in [5] to $2 \cdot 10^{-15}$. These are the best results ever obtained with cesium frequency standards. We are at present constructing a second cesium fountain in order to measure the stability over one day. The expected accuracy is in the 10^{-16} range.

It is predicted that microgravity conditions should enable a further factor of 10 improvement in the interaction time with a simple and compact device.[9] The objective of the PHARAO project is to develop a space clock using cold cesium atoms. Such a frequency standard opens the way to a new generation of experiments.

2 PHARAO PROJECT

In 1994, the French space agency (CNES) decided to support a preliminary research program on a space frequency standard using cold atoms. Three laboratories, the BNM-LPTF, the ENS-LKB, and the LHA, have cooperated to construct a prototype that will be tested in aircraft parabolic flights. Simultaneously, studies on local oscillators, frequency synthesis chains, microwave cavity modeling, and time-frequency transfer are being performed.

The Microgravity Clock Prototype

The main progress in laser cooling were achieved in the last few years. Although well understood and quite easily reproduced in laboratories with the recent development of diode lasers, these experiments are far from being compatible with space requirements. The weight of the BNM-LPTF atomic fountain is about 2 tons, with some hundreds of optical components. The device has to operate in a quiet environment.

The main point of the PHARAO project is the construction of a much smaller, reliable, and automatic prototype which will be tested in aircraft parabolic flights in the beginning of 1997. We want to record the microwave resonance fringes ($\nu \sim 9.2$ GHz) during the reduced gravity of the parabolic flights to prove the reliability of the prototype in a hostile environment. This device is also designed to be transformed later into a high performance transportable fountain frequency standard.

The experimental setup is shown in Fig. 1. As in the atomic fountain[5], the prototype operates in a pulsed mode driven by a computer. In a vacuum tube, the cesium atoms are cooled and launched, experience a microwave interaction in a cylindrical TE013 cavity, and are finally optically detected. Due to the absence of gravity, only a single pass in the cavity is possible. With a low velocity of 5 cm/s, the resonance linewidth can be as low as 0.1 Hz, a factor of 10 narrower than on earth. All the laser beams are generated on a separate optical bench and connected to the tube chamber by optical fibers. A frequency chain synthesizes the 9.19... GHz microwave field from a 10 MHz BVA quartz oscillator.

Optical Bench

The optical setup generates the laser beams (~852 nm) for cooling and detecting the atoms. A narrow linewidth diode laser, frequency locked on the F=4-F'=5 transition of the cesium D2 line, provides the two detection beams. Two different diode lasers will be tested in the aircraft: an extended cavity diode laser and a DBR diode laser spectrally narrowed with a weak optical feedback and a fast electronic servo-lock. Both have a linewidth in the 100 kHz range, a value much lower than the cesium D2 natural linewidth (5.3 MHz). A narrow laser linewidth is required for the atom detection in order not to add noise to the fluorescence signal.[10] After double-pass through an acousto-optic modulator (AOM) which sets the molasses detuning, the beam of this laser is also used to inject two slave diode lasers which provide the cooling beams. The two slave lasers deliver each 200 mW of optical power. Each beam is divided in three and coupled into polarizing optical fibers after a double pass in an AOM. The laser intensity (a few mW per beam) is controlled in each fiber by means of variable retarder plates. The AOM detunes the laser to launch the atoms and allows quick turning off of the laser light. To avoid any parasitic excitation of the atoms during the microwave interaction, mechanical shutters insure a complete extinction of the laser beams. An additional DBR diode laser pumps the atoms in the upper hyperfine state (F=4) during the cooling process and at the detection of the atoms in F=3. The linewidth is 3 MHz, and the frequency is locked to the F=3-F'=4 of the cesium D2 line. The whole optical bench, designed with standard optical components, has the following dimensions: 65×65×15 cm. Eight optical fibers link the optical bench to the vacuum tube: six for cooling, two for detection.

Vacuum Tube

The cooling region contains a low pressure cesium vapor (10^{-6} Pa). The 10 mW output of each of the six optical fibers are expanded to a 1 cm waist and are distributed in three orthogonal pairs of counterpropagating beams. Each beam is tilted from the vertical direction. With this geometry, the cold atoms are launched in the (1,1,1) direction with the moving molasses technique.[7] The launch velocity can be adjusted up to 8 m/s. The pressure in the interaction and detection regions is $\sim 10^{-8}$ Pa to avoid collisions and parasitic background fluorescence in the detection region. The chamber is pumped by a 20 l/s ion pump and a graphite tube cesium getter.

The microwave cavity is a 20-cm-long TE_{013} cavity which has a loaded quality factor of several thousands. The duty cycle (interaction time over cycle time) is around 0.5. A highly homogeneous static magnetic field (2 mG) is produced with a long solenoid and a mu-metal magnetic shield around the cavity. Two compensation coils and three additional magnetic shields ensure the direction homogeneity of the magnetic field along the experiment. The axial shielding factor is larger than 10^5 over the cavity lengths. In addition, an external active compensation system will improve this figure by another factor of 10.

After the atoms pass through the cavity, the populations of both hyperfine levels are independently measured by fluorescence in the detection region. The atoms in the F=4 level are first detected with a standing wave tuned 2 MHz below the F=4-F'=5 transition of the D2 line. They are then pushed away by the radiation pressure of a traveling wave tuned at the same frequency. The remaining atoms in the F=3 level are optically pumped to F=4 by the repumping beam and detected with the same procedure. Condenser lenses collect about 3% of the fluorescence emitted by the atoms.

Frequency Chain

The output of a 10 MHz reference oscillator is frequency multiplied to 100 MHz. The 100 MHz signal is bandpass filtered and then routed to a $\times 92$ multiplier. The output power is 10 dBm. The 9.2 GHz and the 7.3 MHz of a RF synthesizer are mixed in a single sideband mixer with better than about 25 dB image and carrier rejection. The resulting signal at the interrogation frequency is then level controlled by an active microwave attenuator.

The acceleration variations in the plane are 2 g. This sets strong constraints on the accelerometric sensitivity of the reference oscillator. The projected atomic resonance linewidth is in the hertz range. To scan this resonance without introducing errors greater than a few percent, the frequency retrace from one parabola to the other must be a few 10^{-12}. The duration of a parabola (20 s) forbids long measurement averaging. The short-term stability of the frequency chain must, therefore, be a few 10^{-13} at one second. The typical static g-sensitivity of a high performance commercial quartz is a few 10^{-11}, with a frequency stability of $3\text{-}6 \cdot 10^{-13}$ between 1 and 10 seconds. The LCEP at Besançon has provided a quartz oscillator with an acceleration sensitivity of $\sim 4 \cdot 10^{-12}$/g.

The performances of the aircraft clock prototype will also be evaluated on earth and compared to the atomic fountain. The long-term stability measurement of the fountain being now limited by the H-maser, this comparison will test both the fountain and the prototype. A relative stability of 10^{-16} per day is expected. The accuracy of the prototype will also be evaluated.

3 PRELIMINARY RESULTS

The prototype is being tested on earth in the scope of the future parabolic flights. The atoms are launched vertically with a velocity of 4 m/s in order to reach the detection region. In preliminary experiments we recently obtained a microwave resonance with a central fringe having a width of 10 Hz (Fig. 2). The signal-to-noise ratio is presently 350 for a one second cycle time. We expect large improvements of the S/N in the near future. During 1997 we will compare the PHARAO prototype to the atomic fountain. An accuracy and stability evaluation of PHARAO as a high performances compact and transportable frequency standard will then be carried out.

4 INTEREST OF MICROGRAVITY ENVIRONMENT

Operating in space with longer interaction times should lead to an improvement, in terms of accuracy and long-term stability. Indeed, most of the systematic effects are reduced with the atomic velocity.

The short-term stability depends on both the atomic interrogation scheme and the local oscillator. If we assume a perfect local oscillator, the fractional frequency stability is given by:[5]

$$\sigma_{at}(\tau) \cong \frac{\Delta\nu}{\pi\nu}\frac{1}{\sqrt{N_{at}}}\sqrt{\frac{T_c}{\tau}} \tag{1}$$

where ν is the frequency of the clock transition, T_c is the cycle duration, about twice the interaction time T_i, and $\Delta\nu$ is the resonance linewidth varying as $1/T_i$. N_{at} is the number of detected atoms per cycle.

One way to improve the short-term stability is to increase N_{at}. Yet, for an accuracy in the 10^{-16} range, the density, averaged over the flight time, cannot exceed 10^6 atoms/cm^3. As a matter of fact, the dominant uncertainty is that of a shift proportional to the atomic density, which is due to collisions between the cold atoms.[8,11] In the BNM-LPTF fountain, this shift is typically $1 \cdot 10^{-15}$ with a $0.5 \cdot 10^{-15}$ uncertainty. It is presently a serious limitation to the performances of cold atom clocks on earth and it also dominates the design of the microgravity clock. In space, as the launching velocity is much smaller, several clouds of cold atoms can be prepared before the first one enters the cavity. This allows the increase of the number of detected atoms with the same average density. This improves the short-term stability without increasing the cold collision shift.

The radius of the cold atom cloud expands as $((V_{rms}\, T_i)^2 + r_0^2)^{1/2}$, where V_{rms} is the transverse velocity of the atoms and r_0 the initial cloud radius. To optimize the stability for a given initial number of cold atoms, the interaction time must be equal to r_0/V_{rms}. With the typical parameters (a rms velocity of 1 cm/s and an r_0 of 1 cm), the optimum T_i is around 1 s. Thus, in the PHARAO prototype with one cm diameter holes in the cylindrical microwave cavity, a transverse temperature of 1 μK, an interrogation time of 0.5 second and a cycle time T_c of 1 second, we detect $4 \cdot 10^5$ atoms in mF=0 per cycle for a stability of $3 \cdot 10^{-14}\tau^{-1/2}$ or 10^{-16} per day. Using three successive clouds of cold atoms loaded in ~300 ms, the collisional shift is $3 \cdot 10^{-16}$. Assuming 5-10% fluctuation in the average atomic density will lead to a stability floor of $1.5\text{-}3 \cdot 10^{-17}$. A second interesting case is to assume transverse cooling or transverse selection of the atoms to a temperature so low that all the atoms entering in the microwave cavity do contribute to the signal after an interaction time of 10 seconds. With sub-recoil laser cooling techniques[12,13,14], the atomic transverse velocity can be reduced below 1 mm/s. This corresponds to an optimum T_i of 10 s, which would lead on earth to a fountain height of 100 m. In space this is realizable with a compact device. Assuming an ideal local oscillator, the Ramsey fringe width is 0.05 Hz and the short-term stability is $10^{-14}\tau^{-1/2}$ with the same collisional shift of $2\text{-}3 \cdot 10^{-16}$. The stability floor of $1\text{-}2 \cdot 10^{-17}$ will then be reached after about 3 days of integration time. As pointed out by K. Gibble, it might well turn out that rubidium atoms would ultimately lead to still better performances if the cold collision shift is smaller than that of cesium.

However, the short-term stability performances also depends on the local oscillator: for a pulsed operation, an aliasing phenomenon downconverts the local oscillator noise at all the harmonics of the sampling frequency. This can bring a strong limitation to the short-term stability of the frequency standard. Over a time around T_c, if the flicker frequency noise dominates (for instance with a quartz crystal oscillator), the stability of the frequency standard is expressed by:[15,16]

$$\sigma^2(\tau) \approx 0.25\ \sigma_{LO}^2 \frac{T_c}{\tau} + \sigma_{at}^2(\tau) \tag{2}$$

where σ_{LO} is the flicker floor stability of the local oscillator. For the present BNM-LPTF atomic fountain, $\sigma_{at}(\tau) = 7 \cdot 10^{-14}\tau^{-1/2}$, $\sigma_{LO} = 2\text{-}3 \cdot 10^{-13}$ at one second and the measured stability is

$1.5{\cdot}10^{-13}\tau^{-1/2}$. Development is being carried out to improve the stability of the quartz oscillator. As long as the short-term stability is limited by the flicker noise floor of the local oscillator, the degradation of the stability increases with the interaction time. With present state-of-the-art quartz oscillator technology, a local oscillator stability of $7{\cdot}10^{-14}$ at 1 s is available. Thus, the PHARAO clock in space can readily reach the fractional frequency stability of $3{\cdot}10^{-14}\tau^{-1/2}$ with 1 s interaction time. For a 10-second interaction time, an H-maser or a cryogenic oscillator are good candidates as local oscillator.

Depending on the requirements of each use of the clock (stability over a few hours or accuracy), a compromise between the different parameters discussed above will be determined: the choice of the local oscillator, the interaction time, the atom number, and velocity.

5 SPACE APPLICATIONS

Time and Frequency Metrology

A space cold atom clock would be a primary frequency standard accessible from anywhere. It opens the way to frequency comparisons, to dissemination of an international time and to a next generation of navigation and positioning systems. The very low drift of the space clock would also allow frequency comparisons between clocks without the constraint of common view of the satellite.

A Tool for Tests of Fundamental Physics

With clocks having a stability of 10^{-16} over one day, it should be possible to measure with a potential 100-fold improvement over the 1976 GPA experiment[2] the gravitational redshift (Einstein effect). This general relativity effect was determined at the 10^{-4} level using H-masers having a stability around 10^{-15} over the 2-hour mission duration. With a measurement in the 10^{-6} level, the validity of theory could be assessed up to the second order.

A new measurement of the Shapiro effect is proposed: the SORT project.[17] It intends to measure the gravitational delay on the travel time of light pulses sent from the earth and differentially detected on two satellites orbiting in the solar system. The signature of the gravitational delay is extracted from the comparison between the arrival times of the light pulses to the satellites. This measurement will lead to a better determination of the post-Newtonian parameter γ which is equal to 1 in general relativity. Yet, a more general class of theories predicts a slightly different value of γ.[18] The best experimental evaluations so far show no deviation from 1 at the 10^{-3} level.[19] With the SORT project, we could estimate γ with an accuracy of about 10^{-7}.

Various other tests and measurements can be thought of: direct detection of gravitational waves[20], isotropy of light velocity.[21]

First Mission

A first objective of a space experiment is the demonstration of a clock running with laser-cooled atoms and the determination of its performance. In space, we expect in a first stage a stability better than $10^{-13}\tau^{-1/2}$ and an accuracy of about 10^{-16}. The evaluation of these performances would be made either on board or from the earth. On board, the comparison oscillator could be either another cold atom clock, or a frequency standard with a better short-term stability (10^{-15} from 1 hour to 1 day). These include space versions of a hydrogen maser, ion trap, or cryogenic dielectric resonator. The international space station (ISSA) could be the platform of this first experiment (ACES proposal).

A crucial factor in the use of a space frequency standard is the quality of the frequency comparison between the onboard clock and frequency standards on earth. In order to transfer this space clock performance, a 10^{-16} accuracy is required. Today, the GPS is in the 10^{-14}-10^{-15} range and two-way links are in the 10^{-15} range.[22,2] We need at least a one order of magnitude improvement. An optical link using picosecond laser pulses is being developed by the Observatoire de la Côte d'Azur (OCA)[23], with an expected accuracy of 10^{-16}. However, by contrast to the optical link, the microwave link has the advantage of being independent of weather conditions and can allow a continuous link with the space clock.

The PHARAO project aims at developing a new generation of space clocks. In the beginning of 1997, a prototype will be tested in the reduced gravity of aircraft parabolic flights. It will be the first step toward the construction of a satellite cold atom clock with a stability and an accuracy in the 10^{-17} range. This performance, as well as future time and frequency transfer methods, can be validated on board the international space station. This ambitious program seems realistic with an international cooperation.

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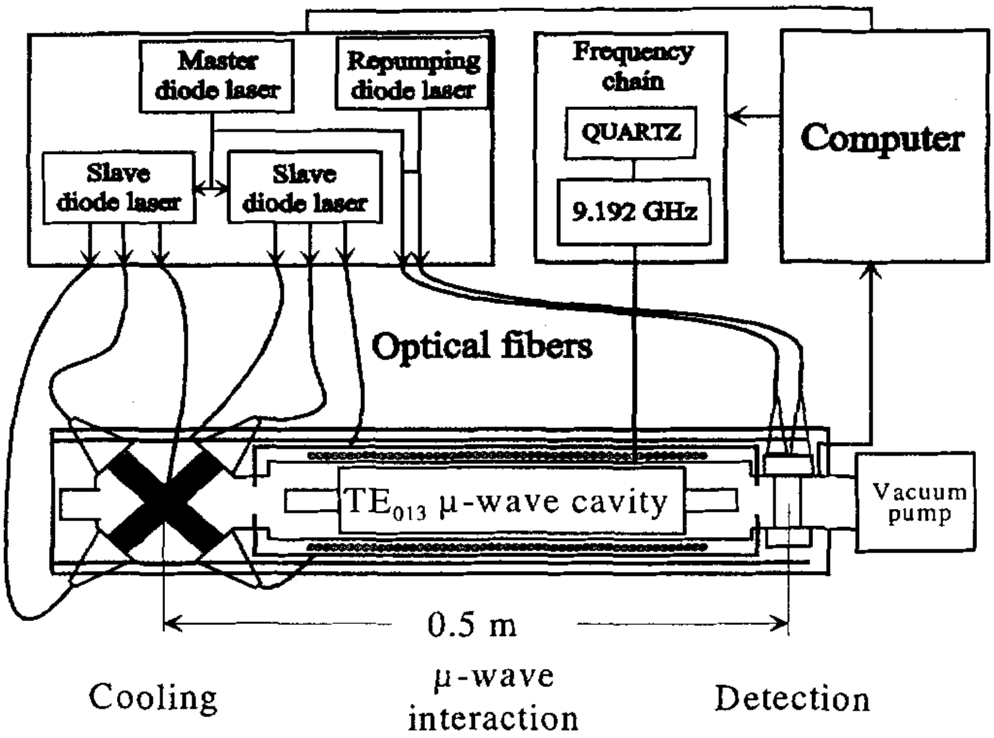

Fig. 1. Scheme of the aircraft clock prototype. The length between the cooling and the detection region is about 50 cm.

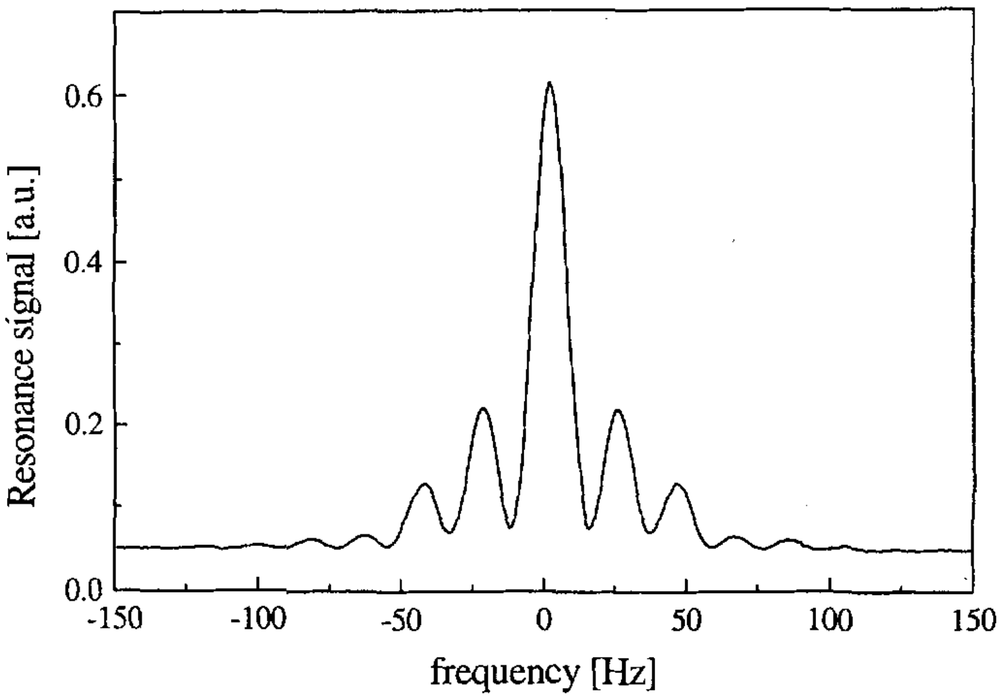

Fig. 2. Experimental microwave resonance fringes in the TE_{013} cavity. Single scan recorded with a 1 Hz frequency step.