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Characterization of the Frequency Pulling by Magnetic Field Oscillations of the Brazilian ^{133}Cs Atomic-Frequency Standard.

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Abstract

In this work, we present a progress report made on the Brazilian scientific time and frequency program. In the last evaluation comparing our frequency standard with a HP 5061-B we have obtained the Allan standard deviation $\sigma_y(\tau)=(1.62\pm0.08)x10^{-11}\tau^{-0.5}$. We have applied the method described by Makdissi et al and Shirley et al to determine the major frequency shifts like, the second-order Zeeman shift, magnetic field inhomogeneity along the rf-cavity, Rabi and Cavity Pulling, in order to characterize our standard.

1 Introduction

Time and frequency metrology is well known as strategic domain, important for industry, commerce and other branches of the modern society. A scientific program to develop this area in Brazil was started some years ago. This program is composed of several parts. The first one, concerns the construction and characterization of an atomic beam clock as a frequency standard. The second part is devoted to the construction of an atomic fountain. This paper is related to the first part of our program and complements our last report [1], where we have evaluated the stability and some major shifts.

The aim of this paper is to describe the cesium beam clock used as a frequency standard, as well as, to relate the methods used to measure its short-term stability and to determine the main frequency biases. The paper is organized as follows: section 2 is dedicated to a brief description of the clock. The optical set-up is shown in section 3. The new evaluation of the frequency stability and the measurement of the main shifts not included in the previous work are reported in section 4 and section 5, respectively.

2 Description of the frequency standard device

The ^{133}Cs atomic beam frequency standard is a conventional optically pumped frequency standard [2]. The vacuum chamber is made of stainless steel, it is 60 cm long and 20 cm diameter. The background pressure in the chamber is lower than 1.3 x 10^{-5} Pa and it is maintained with an ionic pump. An effusive oven heated to about 363 K produce the ^{133}Cs atomic beam. An array of stainless steel and graphite disks, collimate the beam to less than 2 x 10^{-4} sr. Four coils placed on the bottom of the chamber produce the C-field, which is perpendicular to the beam and has magnitude of about 20μT. Before getting in the microwave-cavity, the atoms are optically prepared in the $6^2S_{1/2}(F = 3)$ level. After passing through both microwave-zones we observe the fluorescence of the atoms that interact with a laser beam resonant with the transition $6^2S_{1/2}$ (F = 4) $\rightarrow$ $6^2P_{3/2}$(F'= 5). The optical pumping and the detection beams are produced by a commercial diode laser (SDL 5410C), 850nm and single mode, stabilized in an extended cavity configuration. The linewidth of our laser is estimated to be less than 500kHz. The saturated absorption spectroscopy technique is used to lock the laser in the $6^2S_{1/2}$ (F = 4)$\rightarrow$$6^2P_{3/2}$ (F'= 5) transition. The optical pumping beam comes from an acoustic-optical modulator operating at 251 MHz, where the first diffracted order is resonant with the $6^2S_{1/2}$(F=4)$\rightarrow$$6^2P_{3/2}$ (F'=4) transition, and the zeroth order is used for detection, at the $6^2S_{1/2}(F = 4)$ $\rightarrow$ $6^2P_{3/2}$ (F'= 5) transition.

The interrogation cavity has a conventional U shape. It is made by copper and the distance between the interrogation zones is 10 cm and the Q of the cavity is about 500. The microwave-synthesizer, which has three quartz oscillators at 5 MHz, 100 MHz and 10.7 MHz, was built by F. Walls (NIST – Boulder - USA). The optimum microwave-power is about

7.17 dBm. The modulation of the 9.192 GHz signal is introduced into the 10.7 MHz oscillator by an external function generator (Stanford DS 345). A LabVIEW computer interface program implemented by our group performs the control of the clock. The evaluation of the Cesium beam frequency standard performance was made by a GPS receiver (Model 9390 - 6000 - Datum) and a commercial standard (HP 5061-B). The same reference system was used to investigate the several frequency shifts that take part of this paper.

3 Frequency shifts

3.1 Quadratic Zeeman effect

In an atomic frequency standard, which is based on the transition between two hyperfine levels, it becomes important to work with a finite dc magnetic field. This field lifts the degeneracy from the levels and therefore, the atomic transition line shape depends on the amplitude of the C-field.

As described in [2], we have minimized the field inhomogeneity and improved the C-field control. After these improvements, it is important to determine the second-order Zeeman shift and time variation of this shift. For this, we have applied the method described by Makdissi et al [3], where a periodic measure of the Zeeman frequency between a pair of transitions with the same absolute value of magnetic quantum number was made. We have chosen the $6^2S_{1/2}$(F = 3, m_F = 1) → $6^2S_{1/2}$(F = 4, m_F = 1) and $6^2S_{1/2}$(F = 3, m_F = -1) →$6^2S_{1/2}$(F = 4, m_F = -1) transition. The transition frequency between these two levels of the ground-state with $\Delta m_F = 0$ is given by:

$$\nu_m = \nu_0\sqrt{1 + (m/2)x + x^2}$$

where x ≈3.0496B_0, and B_0 is the magnitude of the C-field, 20μT. The resonance frequency transition for which $m_F \neq 0$ is:

$$\nu_m = \nu_0[1 + (m/4)\langle x\rangle + (1/2)\left(1 - m^2/16\right)\langle x^2\rangle$$

where $\langle\rangle$ represents the average over the free of oscilatory field region, L. The value of $\langle x\rangle$ is measured from the resonance frequency of ν_1 and ν_{-1}, so we obtain

$$\langle x\rangle = (4/\nu_0)\left(\nu_1 - \nu_{-1}\right)/2 = 4f_z/\nu_0$$

where the quantity f_z is the Zeeman frequency. Because the field has almost constant amplitude B_0

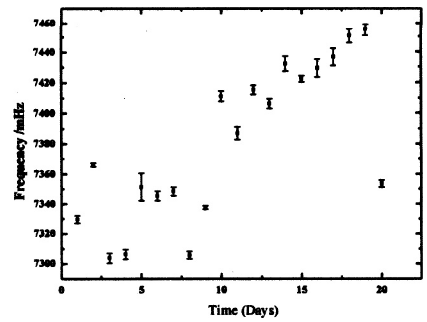

Figure 1: Time variation of the quadratic-Zeeman shift.

along the atoms trajectory, we can make the approximation $\langle x^2\rangle = \langle x\rangle^2$, so that we could express the second order Zeeman shift as:

$$\nu_Z = 8f_z/\nu_0$$

In our atomic frequency standard we have f_z = 9,2 kHz and the second order Zeeman shift its about 7,3 Hz.

A periodic measurement of this Zeeman frequency is necessary to observe its temporal dependence. We have measured it during twenty days, five times per day, to study the way it changes in normal operating condition of our laboratory. The figure 1 shows the variations of the quadratic Zeeman shift. We can see that from the tenth to the nineteenth day the Zeeman frequency increased abruptly. That happens because during those days the trap coils from the fountain clock which is in the same room, was turned on. In the last days, we have turned of the coils and have seen that the Zeeman frequency returned back to its normal value. We obtained the relative uncertainty in the quadratic Zeeman shift of $\Delta\nu/\nu_0 = 5,43x10^{-13}$.

3.2 Inhomogeneity of the magnetic field along the microwave-cavity

The superimposed of a narrow spectral feature (Ramsey fringe) on a broader resonance (Rabi pedestal) make the resonance line shape of a thermal beam frequency standard. The Rabi pedestal is due to the probability that the transition occurs in the first excitation region and not in the second, plus the probability that the transition occurs in the second excitation region and not in the first one. In ideal conditions the Ramsey fringe is centered with the Rabi pedestal. If there is any inhomogeneity in the magnetic field along

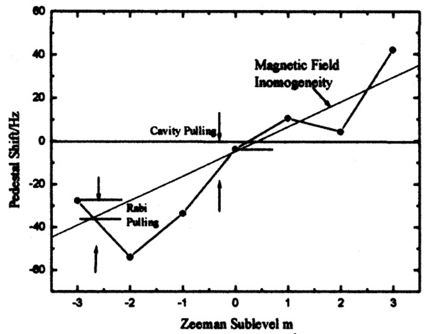

Figure 2: Difference of frequency $\Delta(m)$, between the center of the Ramsey fringe and the Rabi pedestal, as a function of the Zeeman sublevels number m_F. The points deviate from the straight line because of the Rabi pulling effect.

the atom trajectory through the microwave cavity a frequency shift in the resonance line is observed and the Ramsey fringe is not anymore centered of the Rabi pedestal [4].

The center of Rabi line and Ramsey line were measured for each of the neighbour transition (Δm_F =0) and for the clock transition and we computed the difference between them [4], which can be written as:

$$D(m) = \nu^{Ram}(m) - \nu^{Rabi}(m) = \nu_0 (m/8)(\epsilon_1 + \epsilon_2)$$

where ϵ_1 and ϵ_2 are fluctuations in the mean static field in the first and second interaction regions respectively. The slope in the linear curve of m and $D(m)$ determines the value $(\epsilon_1 + \epsilon_2)$.

The modulation of the 9.192 GHz signal, introduced in the 10.7 MHz oscillator of the microwave synthesizer, had been driven by a computer program . That made possible to choose the modulation amplitude and lock our system to the center of the Ramsey line or to the center of the Rabi line hat for each neighbor transition and for the clock transition. We have compared the output signal of the 5 MHz oscillator with the output signal from the 5 MHz of either the GPS receiver or the commercial Cs standard and a computer program collected these oscillation data during fifty minutes per line. Figure 2 shows the effects.

The estimated linear slope from the experimental curve $D(m)$ is (11,35±0,05) and it yields $(\epsilon_1 + \epsilon_2)$=-$(0,99 \pm 0,05) \times 10^{-8}$. For the operating condition of the standard, the frequency error due to the field inhomogeneity is ν_Z=$(1,92 \pm 0,01) \times 10^{-6} Hz$.

The other Zeeman transitions are also shifted by the same effect and it is necessary to count them. As the velocity distribution is the same for all transition, we have used the same procedure to study the effect of the magnetic inhomogeneity for the $m_F \neq 0$ transition. For our standard the Zeeman frequency is shifted by an amount $f_z = 6Hz$.

3.3 Rabi Pulling

The Rabi Pulling is the result of the overlaping of the wings of adjacent transitions in the Zeeman spectrum. In figure 2, we observe that the points deviate from the straight line and the difference is stronger for the outlying m_F = 2 and m_F = 3 transition. It holds for both, the Ramsey fringe and the Rabi pedestal. The Rabi pulling for the Rabi pedestal is larger than for the Ramsey fringe because the pedestal slope is smaller and the modulation amplitude is larger . It decreases with the C-field.

To measure the Rabi pulling we have used the same procedure to obtain the field inhomogeneity. The C-field current was adjusted to produce $B_0 = 20\mu$T and for $B_0 = 30\mu$T. The results are depicted in figures 2 and 3.

Comparing the Figure 2 and 3, it is possible to observe that the m_F = -2 transition deviate less from the linear slope. For the m_F = -2 transition we have a shift of about 33 Hz and 2,46Hz to B_0=20μT and B_0=30μT, respectively. The same result is possible to observe for the m_F = 2 transition, where the shifts are 14.31Hz and 6.15 Hz for B_0 = 20μT and B_0 = 30μT, respectively. Because the wing is curved, the Rabi pulling shift of the Ramsey fringe is smaller by a quantity of $(l/2L)^2$, where l is the interrogation cavity length, than that of the Rabi pedestal, which is 2.5 x 10^{-3} for our standard [2].

3.4 Cavity Pulling

The cavity pulling arises from the variation of the microwave amplitude with the frequency when the cavity is mistunned. It is nearly independent of m_F, but it has a strong dependence on the microwave power and on the modulation amplitude. Our procedure to measure the cavity pulling was similar to that described by Shirley et al [5] and it is again the same used to measure the magnetic field inhomogeneity. Since the cavity pulling is nearly independent of m_F and the Rabi pulling for the clock transition is small [5, 6], the pedestal shift shown in figure 3 corresponds to the cavity pulling. The measured pedestal shift is (3.76 ± 0.1) Hz for a measurement time of 1000 s.

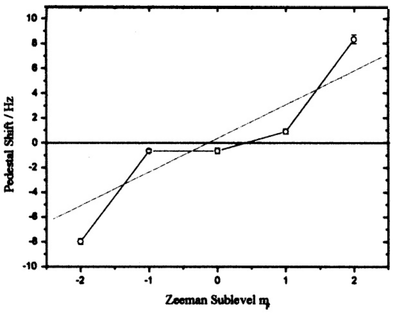

Figure 3: Difference of frequency $\Delta(m)$, between the center of the Ramsey fringe and the Rabi pedestal, as a function of the Zeeman sublevels number m_F, for a higher magnetic field compared to figure 2. The points are much closer to the straight line because the Rabi pulling is less important.

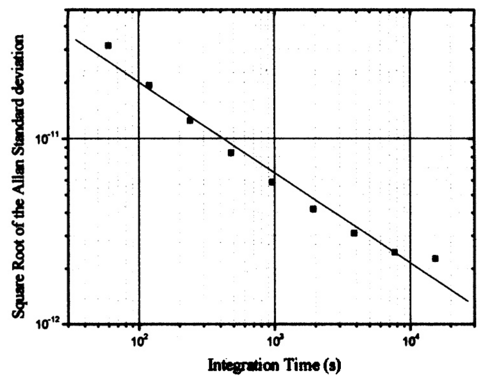

Figure 4: Allan standard deviation of CsSC-1 versus the 5071-A. The fitted shot-term stability is $\sigma_y(\tau) = (1.62 \pm\ 0.08)x10^{-10}\tau^{-0.50}$,where τ is the averaging time.

4 Evaluation of the standard

The short-term stability of our clock has been measured using a complete comparison system, comprising a GPS receiver (Model 9390-6000 - Datum), a commercial Cs standard (HP5061 B), a counter (SR620 - Stanford) and a computer to store the data reading, which allow us to make a constant evaluation. The 5 MHz output was compared to a reference. We have made several important improvements to increase the previous stability. Setting the optimum microwave power injected in the resonant cavity was important in order to increase the stability of our clock. The microwave power was set 2.5 dBm below the optimum. Afterwards, some adjusts and demagnetisation cycles we made a new evaluation, and the short-term stability is $\sigma_y(\tau) = (1.62 \pm\ 0.08)x10^{-10}\tau^{-0.50}$. Figure 4 shows the Allan standard deviation. We are about two order above the limited stability imposed by the geometry of the interrogation cavity, $\sigma_y(\tau) = 4x10^{-12}$.

5 Conclusions

To evaluate some shifts and the Rabi frequency we used a method proposed by Makdissi and de Clercq [3]. The evaluation of the frequency shifts is made directly from the experimental data. We analyze the frequency-standard Ramsey pattern to obtain the Rabi frequency and shifts due to end-to-end cavity phase difference and second-order Doppler effect as functions of the modulation frequency.

This last year was devoted to finalize the accuracy evaluation of our beam frequency standard. We have measured the magnetic field homogeneity during 20 days, under two regimes of operation. We have noted that when the atomic fountain is in operation it causes a bias on the C-field of the beam frequency standard. There are also some influence from the laboratory surroundings. We have investigated the optimal microwave power to inject into the cavity. The cavity pulling due to the oscillating field was also evaluated when the injected power was 2.5dBm lower than the optimal value. The Rabi pulling was also measured, and the obtained shift is (14.31 $\pm$ 0,30) Hz. We have varied the C-field magnitude in order to assure that some inhomogeneity on the Ramsey fringes were due to these pullings. We noted that in the normal operation conditions there is a certain asymmetry in the most external fringes ($m_{+3}\_m_{+3}$ or $m_{-3}\_m_{-3}$). We suppose that it is due to Rabi and Ramsey pulling. Some improvements are being implemented in the detection system, specially concerning the electronic parts, in order to reduce the noise and reach the stability limit.

Acknowledgements

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