Brazilian Microwave Standards of Time and Frequency

Renato Ferracini Alves, Stella Torres Müller, Aida Bebeachibuli, Diego Lencione, Vanderlei Salvador Bagnato
Departamento de Física e Ciência dos Materiais
Instituto de Física de São Carlos, USP
São Carlos, São Paulo, Brazil

Daniel Varela Magalhães
Departamento de Engenharia Mecânica
Escola de Engenharia de São Carlos, USP
São Carlos, São Paulo, Brazil
daniel@sc.usp.br

***Abstract*—Time and Frequency scientific metrology is a necessary component of many important scientific and technological applications. A few years ago we have started an effort to establish a Brazilian Laboratory for the development of atomic clocks. In this communication a progress report of our activities is described, providing present status and future perspectives. The original goal is the construction and characterization of a Fountain as well as alternative frequency references based on cold atoms. Along the past years such goals were achieved with a Cs Fountain operation, which improvement and characterization is presently under progress. In another experiment, interrogation of a cold atomic cloud in free expansion was demonstrated and the implementation of a new chamber overcoming some limitations is now in course. Finally, a system based on a composition of commercial clocks and a hydrogen maser is being assembled to define a local timescale and to provide a link for future contributions to TAI.**

I. INTRODUCTION

The development of scientific Time and Frequency metrology has importance in many aspects. It creates the ability for precision measurement and reference systems, which is essential for the commerce and industrial activity. Also, defense applications to keep the integrity of a nation demands more adequate domain of time and frequency metrology, and finally, the scientific progress relays more and more on the ability of high precision measurement of time and frequency, and therefore the domain of the "state-of-the-art" in this subject brings capability for scientific research [1,2]. Being so strategically important the efforts towards the establishment of laboratories on scientific Time and Frequency are not a choice, but an obligation for a country like Brazil. The growing investment in science and technology must have together the investment in improving scientific metrology.

II. THE BRAZILIAN ^{133}CS ATOMIC FOUNTAIN

One of the main goals of our frequency standards laboratory would be the development of an operational atomic fountain [3], planned to work as a primary frequency standard and efforts have been made on the last few years to accomplish that [4,5]. Several changes were performed in the experimental set-up to fix some technical problems in its structure and some new parts were implemented in order to launch the atoms to higher altitudes and obtain even better Ramsey fringes. After these changes, we were able to launch the atoms of 80 cm above the capture region and still measure a TOF signal with better SNR.

The cycling process of the atomic fountain is started with about 10^9 cesium atoms being captured in a magneto-optical trap (MOT). The next step is launching the atomic cloud to the interrogation cavity through the moving molasses technique and the atoms pass once through the microwave cavity, continue to the summit of their trajectory, then fall again through the same cavity, completing the Ramsey separated-field interaction. The radiation pressure that launches the atoms heats them and a second cooling process is important. The frequency of the trapping beams are then detuned adiabatically far from the resonance and the laser intensity is decreased during 4 ms, performing a sub-Doppler cooling of the cloud. The cloud temperature just after this phase is 4 μK.

Along the interrogation cavity, the atoms feel a static magnetic field which defines the atomic quantization axis with respect the oscillatory magnetic field. Finally, after the parabolic flight, the cloud reaches the detection region, where the population in each hyperfine level of the fundamental state is measured through the time of flight signal (TOF). Recently we got the first results with our set up. When the launching velocity is about 3.09 $m.s^{-1}$, the atoms reach the apogee about 49 cm above the capture region and the population difference between the two fundamental levels is measured through the Ramsey fringe with a linewidth of 2 Hz and a stability given by the Allan variance of $5.18x10^{-12}\ \tau^{-1/2}$ as shown in the graphics of figure 1 and 2.

Some frequency shifts that perturb the transition probability were determined based on the characteristics of the fountain experimental set up. These shifts are listed as well as the associated uncertainties are shown in table 1.

The obtained stability is $5.18x10^{-12}\tau^{-1/2}$ and improvements are in course in order to achieve the short term stability of one order bellow. The first step concern the improvement of the

FAPESP, CNPq and CAPES support this work

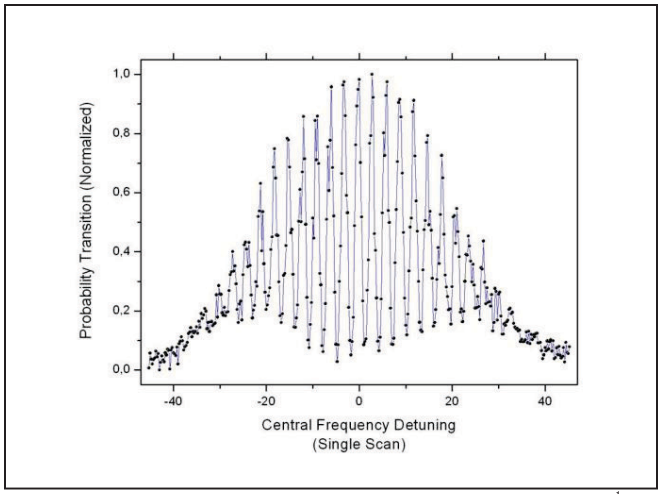

Figure 1. Central Ramsey Fringe when the launching velocity is 3.09 $m.s^{-1}$ and the atoms spend 17.27 ms in the interaction region and 220.38 ms in the free flight region.

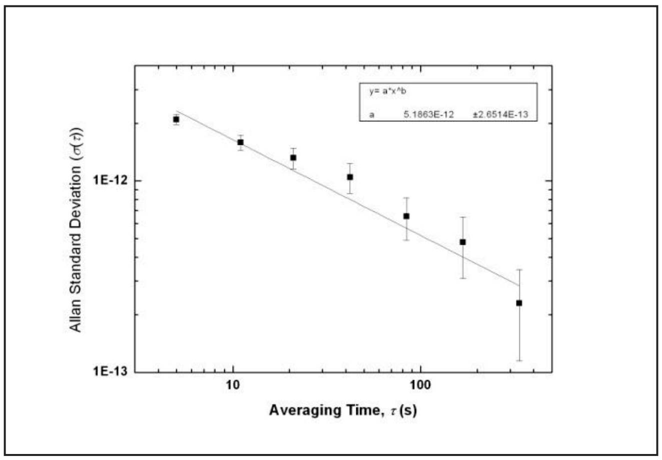

Figure 2. Allan Standard Deviation as a function of the integration time. The fit gives a stability of $5.18x10^{-12}\tau^{-1/2}$.

TABLE I. LIST OF SOME FREQUENCY SHIFTS FOR THE ATOMIC FOUNTAIN EXPERIMENT

Physical effect	Correction ($x10^{-12}$)	Uncertainty ($x10^{-12}$)
Red shift	$-1.0x10^{-2}$	$-1.0x10^{-3}$
2nd order Doppler effect	$-2.08x10^{-3}$	——
2nd order Zeeman effect	2.97	0.41
Black body radiation shift	$-2.05x10^{-2}$	$-2.636x10^{-5}$
Global budget	2.97	0.41

SNR of the detected signal with the implementation of a state selection process before the atoms enter in the Ramsey cavity.

Besides the state selection others implementations are being done on our present system. This concerns the reduction of the detection laser noise and a better controlling system.

A noise-eater was implemented in the detection beam laser to minimize amplitude noise (AM noise) that induces fluctuations in the number of detected atoms in each hyperfine level. As we reduce the optical noise on the detection system, the SNR of the Ramsey fringe increases.

After these changes, it is natural that we continue with a complete characterization of our atomic fountain and study each of the physical effects that shift the clock transition. This procedure is essential to use it as a primary standard.

III. FREQUENCY STANDARD BASED ON A FREE EXPANSION OF A COLD ATOMIC CLOUD OF CS

Our laboratory on scientific time and frequency has also made efforts to develop an alternative frequency reference. The new system developed combines cold atoms in a simplified configuration and is based in the interrogation of a free expanding atomic cloud of Cs, where all the process of capture, cooling and interrogation takes place inside a microwave cavity, resonant with the clock transition. The use of cold atoms, prepared and interrogated in same place, reduce the size and leads to a smaller clock [6].

In the first experiment Cs atoms were trapped in a magneto optical trap within the limits of a small Pyrex cell and interrogated by an antenna during the free expansion of the cloud of atoms. This antenna was used to apply one or two microwave pulses resonant with the clock transition in 9.192 GHz . After the interrogation phase, the number of atoms in the $F = 4$, $m_f = 0$ state were detected by fluorescence. Results with a single interrogation pulse of 12 ms (Rabi method) were very good, with a linewidth of 39 Hz and evaluated stability of $9x10^{-11}\tau^{-1/2}$ [7,8]. With two oscillatory fields interrogation method the Ramsey fringes were observed with poor contrast, as shown in Fig. 3. A theoretical model was constructed to explain this poor Ramsey fringes contrast and the simulation took into account the microwave pattern emitted by the antenna and the free expansion of the atoms. With this it was possible to explain the poor contrast due to the microwave amplitude and phase distributions between the two interrogation stages [9].

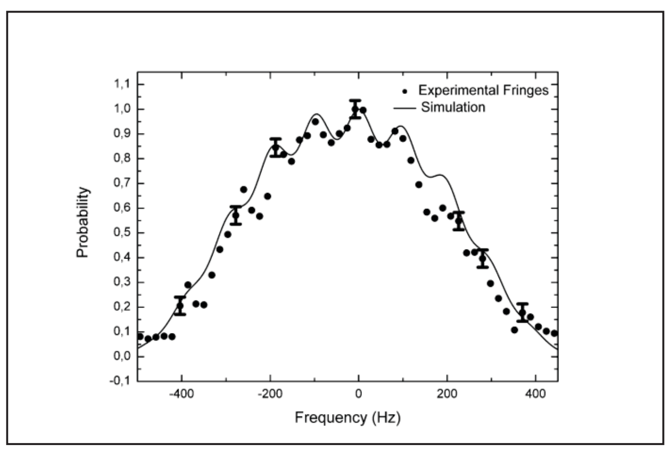

Figure 3. Comparison between the simulation (solid line) and the experimental Ramsey fringes (dots).

Continuing the development of this new frequency standard, a new vacuum chamber with the internal dimensions of a microwave cavity was constructed and replaced the glass cell. This microwave cavity was developed to couple the TE011 mode and thus the atoms, trapped in the center of the cavity, do not feel the phase and amplitude variation. The quality factor measured for the cavity is 2500, that is an excellent value if take into account that the cavity was constructed using stainless steel (316L). We succeed in trapping and cooling about 10^8 atoms inside the microwave cavity and now the search for the clock transition resonance is taking place.

IV. Time and Frequency Comparisons and the Dissemination of the Reference Signal

For the evaluation of the stability of the atomic frequency standard developed in our laboratories, a local oscillator (LO) provides the interrogation signal to probe the atoms. A Hydrogen Maser (KVARZ CH-75) serves a central reference, once we slave the LO to it through a PLL (Phase locked loop).

The maser is also compared to others commercial Cs standard (two 5071A standards and one 5061A standard), which allows continuous evaluation of the stability of the several commercial systems. One of the Cs commercial standards is used as local reference for the time transfer system (Allen Osborne TTR-6). The acquired data are used to slave the local commercial standard with time coordinate diffused through the GPS navigation system.

This system serves as a starting point for a local time scale and will be used to compare our commercial and laboratory standards to the GPS time scale. The first step in this direction has started with the complete characterization of our commercial standards with respect of the GPS scale. For a collection of data, the phase fluctuations between a pair of oscillators were carried out, with some tools to automate the acquisition process and the evaluation of the data collected in the computer being developed in our laboratory. The phase data between GPS time and the CH1-75 Maser signal were acquired as function of time and it was possible to observe the frequency offset of 4.8×10^{-13} Hz. The same procedure was followed for the commercial ^{133}Cs standard and the frequency offset in this case is 9.8×10^{-14} Hz.

The output of the H Maser is also used to phase lock the frequency synthesizer chain used in the fountain, for example. This link, added to the link between the maser and the GPS time will enable a future contribution of our fountain system to the atomic time scale (TAI).

V. Conclusion

We have been establishing a scientific time and frequency standard program in our laboratory, developing different experimental set-ups to reproduce the second definition: an atomic fountain and a compact clock based on an expanding cold atom cloud.

Concerning the atomic fountain a lot of changes have been done to improve the SNR of the detected signal so that the Ramsey fringe was measures with a linewidth of about 2 Hz and stability of $5.18 \times 10^{-12} \tau^{-0.5}$, given by the Allan standard deviation. The actual stage is the implementation of the state selection process before the atoms enters in the Ramsey cavity so reducing the background signal and the collisional shift. Other improvement concerns the implementation of a noise eater to the detection beam laser. With the maser system installed, it will be possible to have a better reference in long term comparisons and, consequently better evaluations.

Efforts have also been done to develop alternative ways of atomic interrogation. In this sense, an atomic standard based in the interrogation of a free expanding atomic cloud of Cs was realized. In this system, all the process of capture, cooling and interrogation takes place inside a microwave cavity resonant with the clock transition. Trapping and cooling atoms inside this microwave cavity was succeeded and now the searching of the clock transition resonance is taking place.

A central reference system was also implemented to provide a local time scale to compare the several experimental set up to UTC (Universal Coordinate Time) through satellite receivers. New equipments are being purchased to make possible the generation of a local time scale based on simultaneous comparison between all standards available in the laboratory. A geodesic receptor is in course of acquisition in order to better contribute for TAI.

References

[1] BIZE, S. et al. *Cold atom clocks and applications*. Journal of Physics B: Atomic, Molecular and Optical Physics, **38**, S449–S468, 2005.

[2] Ahmed, M.; Magalhães, D.V.; Bebeachibuli, A.; Müller, S.T.; Alves, R.F; Ortega, T.A.; Weiner, J.; and Bagnato, V.S.. *The Brazilian time and frequency standards program*. Annals of the Brazilian Academy of Sciences, **80**(2), p.1-36, 2008.

[3] Wynands, R.; Weyers, S.. *Atomic fountain clocks*. Metrologia, **42**, p. S64–S79, 2005.

[4] Magalhães, D.V.; Santos, M.S.; Bebeachibuli, A.; Müller, S.T.; Bagnato, V.S.. *Progress towards a ^{133}Cs fountain as frequency standard in Brazil*. Laser Physics, **14**, 1, p 1-4, 2004.

[5] Bebeachibuli, A.; Alves, R.F.; Müller, S.T.; Bagnato, V.S.; Magalhães, D.V.. *The Brazilian Atomic Fountain Primary Frequency Standard*. Proceedings of the IEEE International Frequency Control Symposium, 2006.

[6] Esnault, F.X; Perrin, S.; Holleville, D.; Guerandel, S.; Dimarcq, N.; Delporte, J.. *Reaching a few 10^{-13} $\tau^{1/2}$ stability level with the compact cold atom clock HORACE*. Proceedings of the IEEE International Frequency Control Symposium, 2008.

[7] Müller, S.T.; Magalhães, D.V.; Bebeachibuli, A.; Santos, M.S.; Bagnato, V.S.. *Demonstration and Observation of a Frequency Standard based on na Expanding Cold Atom Cloud of Cesium*. Proceedings of the IEEE International Frequency Control Symposium, 2005.

[8] Magalhães, D.V.; Müller, S.T.; Bebeachibuli, A; Alves, R.F.; Bagnato, V.S.. *Comparative Short-term stability for Cs beam and an Expanding Cold Atomic Cloud of Cs used as Atomic Frequency Standard*. Laser Physics, **16**, 8, p. 1268-1271 2006.

[9] Müller, S. T.; Magalhães, D. V.; Bebeachibuli, A.; Ortega, T. A.; Ahmed, M.; Bagnato, V. S.. *Free expanding cloud of cold atoms as an atomic standard: Ramsey fringes contrast*. Journal of the Optical Society of America. B, Optical physics, **25**, p. 909 (2008).