CCTF/04-23

CONTRIBUTION TO THE 16th CCTF

BNM-SYRTE
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Introduction.

The laboratoire de l’Horloge Atomique (LHA) and BNM-LPTF belong now to the same structure: the BNM-SYRTE (SYRTE: SYstèmes de Réference Temps Espace), UMR 8630.
All the scientific themes mentioned in the previous CCTF have been developed: The accuracies of Cs and Rb atomic fountains reach $8*10^{-16}$ and 6*10-16 respectively; the ACES/PHARAO space project is in the C/D phase and the engineering model of the experiment will be delivered by the end of the year 2004. The development of compact clocks using cold Cs atoms is pursued in two directions: Laser cooling of atoms in a microwave cavity (HORACE project) or Coherent Population Trapping in a cell.

Activities in the field of optical frequencies have been reoriented towards two main directions: Realization of an optical frequency standard using the strongly forbidden $^1S_0$ -$^3P_0$ line of ^{87}Sr atoms and improvement of the link between microwave and optical frequencies by using femto-second lasers. In 2002, we measured, with a 20kHz uncertainty, the frequency of the $^1S_0$ -$^3P_0$ transition in a laser cooled ^{87}Sr cloud. We are presently installing the 813nm dipole trap. The femtosecond laser setup allows frequency comparisons between optical and microwave clocks with a frequency noise level of $7*10^{-14}\tau^{-1/2}$.
During the past two years GPS P3 and TWSTFT time transfer techniques have been implemented at BNM-SYRTE and are now routinely used.

Realization of the second

The BNM-SYRTE operates 4 laboratory primary frequency standards:

JPO(an optically pumped atomic beam which is operated nearly continuously) and three atomic fountains.

FO1(The first atomic fountain of the laboratory has been refurbished in 2003 and is now being reevaluated. The cold atom source is a pure optical molasses loaded from a laser slowed atomic beam. This atomic beam will be replaced by a 2D MOT to improve the reliability of the clock. When operated with a cryogenic oscillator as local oscillator its frequency stability reaches $3*10^{-14\tau-1/2}$ for $2*10^6$ atoms detected).

FOM (This one is derived from the zero g prototype developed for the PHARAO/ACES project. Recent experiments performed with this clock showed a sensivity to clock tilts much larger than expected and in disagreement with 3D simulations taking into account the microwave phase distribution in the interrogation cavity. We are now making improvements to FOM; the optical setup has been completely rebuilt and the physical package will be modified during the next months).

FO2 (The dual Rb Cs fountain will be soon modified to allow simultaneous operation with both atoms, a 2D MOT will be used to load Rb molasses in place of the present laser slowed atomic beam. The magnetic field stability in the clock has been improved and reaches 10^{-12}T over one day. We have also implemented in FO2 an automatic measurement of the magnetic field. The best frequency stability obtained up to now with FO2 is $1.5*10^{-14}\tau^{-1/2}$ for~ 10^7 Cs atoms detected. This setup has been used to remeasure, in 2002, the ^{87}Rb hyperfine frequency).

Both FO1 and FO2 (and FOM after modification) use a new method of transfer of population by adiabatic passage to evaluate the collisional frequency shift. This method allows one to prepare cold atomic samples with a well-defined ratio (1/2) of atomic density and atom number. Experimental and theoretical evaluations show that the accuracy of this method is better than 1% of the collisional shift (Recent experiments and improvements on FO2 show that the accuracy of this method can be improved up to the .1% level. In the ourse of these experiments, when looking at the contribution of of the residual $|F=3, m_F\neq o>$ populations to the collisional frequency shift, we discovered Feschbach resonances for magnetic fields as low as 5 mG). To measure the cold collisional shift and the cavity pulling effect in a differential way one alternate sequences of measurements with high and low density (every ~50 clock cycles). Presently the collisional frequency shift of both clocks FO1 and FO2 is continuously measured and the resolution on the collisional frequency shift is of the order of 10^{-16}. When comparing this new method to measure the collisional shift to standard ones we find a difference of about 10% .

Before dismounting FO1 in 2003 we performed a preliminary direct measurement of the blackbody radiation shift. A thermally isolated graphite radiator was placed above the microwave cavity. The temperature of the radiator was varied from 300K to 480K. Four platinum thermistors and the microwave cavity resonance frequency are used to determine the radiation temperature at various places in the fountain and to calculate the effective radiation temperature experienced by the atoms taking into account the geometry of the fountain. The result of this experiment is shown in Fig.1. The fit to the measurements gives:

$$\Delta\nu_{BB}/\nu = -1.7*10^{-14}*(T/300)^4[1+.014*(T/300)^2]$$

This result is in very good agreement with the value deduced from DC Stark shift measurements ($-1.71*10^{-14}$). The total estimated uncertainty of this measurement is 5% . This result is in disagreement with the value recently reported by IEN.

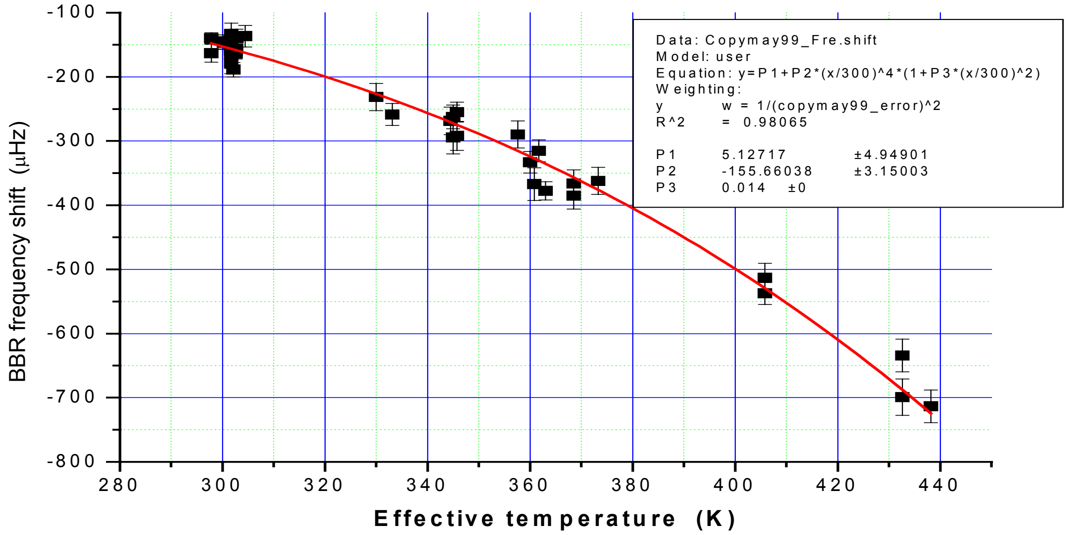

Fig. 1: Blackbody frequency shift as a function of the effective temperature.

We performed two comparisons between CSF1 of PTB and FOM, FO2. For the first one FOM was moved to PTB and a GPS link was used to compare CSF1 and FO2. A frequency difference of $4*10^{-14}$ between CSF1 and FOM was observed. This frequency difference, larger than cumulated uncertainties of both clocks, remains unexplained. In july 2003 we performed a second comparison during 15 days between CSF1, FOM and FO2 by using simultaneously GPS P3 and TWSTFT time transfer techniques. During this period we found a well resolved frequency difference of $\sim 2*10^{-15}$ between FO2 and FOM. As schown in Fig. 2 frequencies deduced from GPS P3 and TWSTFT time measurements differed by $\sim 2*10^{-15}$.

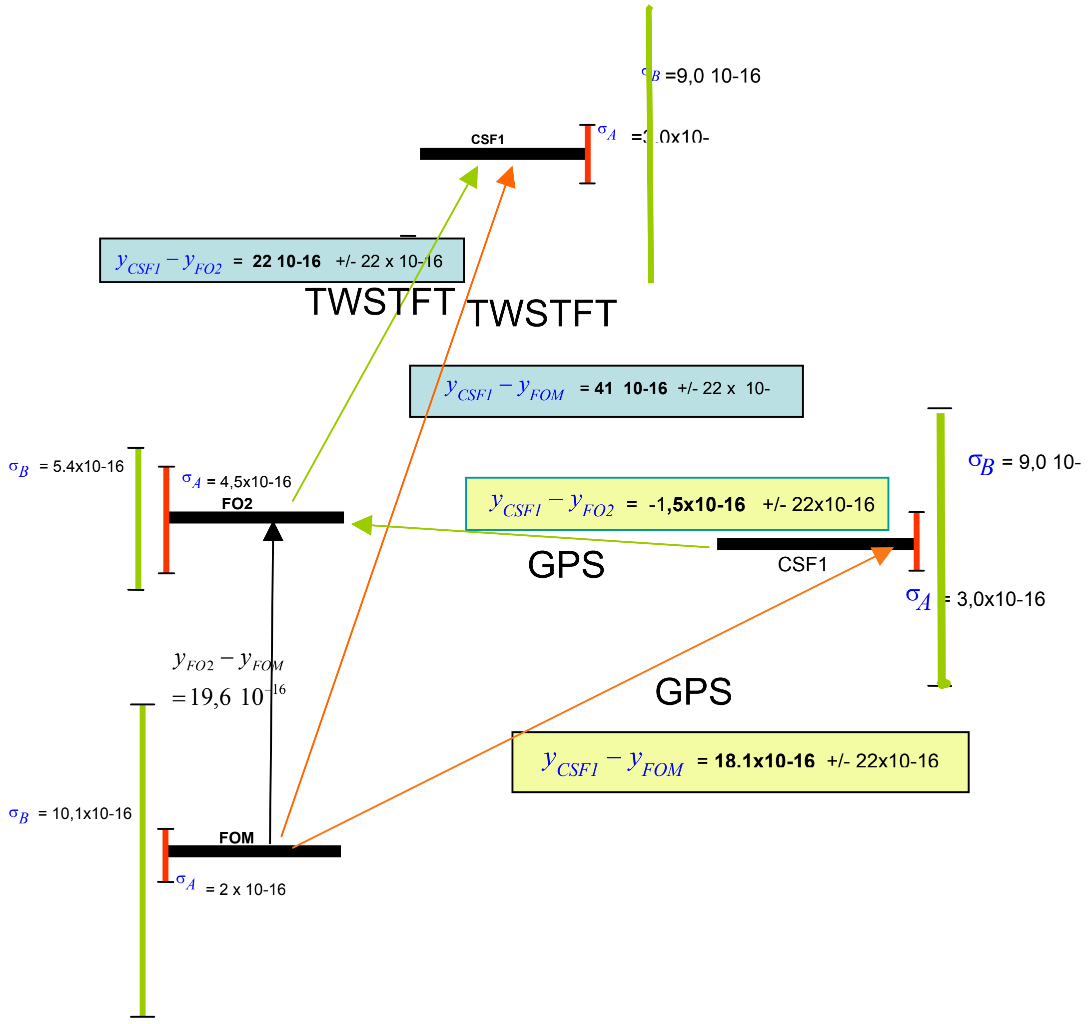

Fig2: Comparisons of CSF1, FO2, FOM by using GPS P3 and TWSTFT

Compact cesium clocks

In parallel to the development of high performance frequency standards, BNM-SYRTE is carrying out experiments on new cold atom atomic clocks combining compactness and high frequency performance. Thanks to the low atomic velocities, these clocks could exhibit a frequency stability better than $5.\ 10^{-13}\ \tau^{-1/2}$ with an accuracy much better than 10^{-14}.

The first compact clock project, called HORACE, is the simplest cold atom clock where the cesium atoms are successively cooled, interrogated and detected at the same place, inside an optically polished microwave cavity. An original cooling configuration, which operates without collimated laser beams, has been demonstrated to lead to noticeable cold atom numbers (a few 10^8) with very low temperatures (a few μK). As all interactions take place in the microwave cavity, it is possible to use almost the same cold atoms at each operation cycle. For an operation on Earth, the operation cycle is limited by the free fall under gravity of the atoms inside the cavity. Cycle periods as fast as 50 ms with an interrogation time limited to a few 10 ms can be obtained, at least ten times larger than those reached in commercial Cs beam clocks. Ramsey fringes have been observed and clock signal linewidths as low as 25 Hz have been measured.

The second clock project aims at utilizing Coherent Population Trapping (CPT) techniques in a cold atom clock. In a CPT clock, the microwave interrogation is replaced by optical interactions with copropagating laser beams which induce Raman resonant transitions. Atomic clocks based on CPT are interesting because of the narrow linewidths achievable with simple and compact design. The linewidth of a CPT resonance mainly depends on the following effects : transit time across the laser beams, coherence relaxation, first order Doppler effect and saturation of the optical transitions. A preliminary CPT experiment has been done on the D1 line of cesium atoms in a vapour cell filled with N_2 as buffer gas. Clock signal linewidths of 50 Hz have been obtained. Nevertheless, the important collisional shift due to the buffer gas is detrimental for the long term stability and accuracy. This limitation should be eliminated in the CPT clock using cold atoms which is under construction in BNM-SYRTE.

TIME AND FREQUENCY INTERCOMPARISONS

Following a call for participation by the BIPM in 2001, the BNM-SYRTE has implemented the GPS P3 time transfer technique in Observatoire de Paris (OP) in 2002. It is based on multi-channel geodetic GPS receivers, and it uses the software developed by P. Defraigne (ORB) to compute the ionosphere free multi-channel GPS P-Code common-views. The OP multi-channel receiver has been differentially calibrated at the nanosecond level against the BIPM absolutely calibrated receiver. The link between OP and PTB was more specifically scrutinized, because H-Masers were used for more than one year in both sides as frequency references. It does not seem that the 10^{-15} level of stability could be reached before an averaging period of 4 days on that link.

With the support of CNES (French Space Agency), an Earth station of the European satellite navigation system EGNOS (European Geostationary Navigation Overlay Service) has been implemented in 2003 in the BNM-SYRTE at OP. UTC (OP) is the input reference of this specific station. It is going to be used for a link between the EGNOS Network Time, the internal time scale of EGNOS, and UTC through the link between UTC (OP) and UTC. EGNOS is scheduled to be declared operational at the end of 2004.

In 2001, BNM-SYRTE launched the TWSTFT project. Two years later, an Intelsat approved TWSTFT station in Ku-band (Vertex antenna, Miteq RF equipment, SATRE modem, 100 % automated system) was installed and made operational within the TWSTFT working group sessions in the frame of the Europe-Europe links and Europe-USA links. In 2003, a direct comparison between TWSTFT and GPS P3 was made on the link OP-PTB by comparing the same clocks in both sides. The results show a consistency of 1,3 ns RMS over two months.

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