CONTRIBUTION TO THE 17th CCTF, September 2006

LNE-SYRTE

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On 1 January 2005 the name of the laboratory changed from BNM-SYRTE to LNE-SYRTE, as a consequence of the reorganisation of French metrology which saw the *Laboratoire National de Métrologie et d'Essais* (LNE) become the new National Metrology Institute for France, in replacement of the *Bureau National de Métrologie* (BNM).
This report describes the activities pursued since the last meeting of the CCTF, in 2004.

1. PRIMARY CLOCKS

Optically pumped Cs beam

LNE-SYRTE operates an optically pumped cesium beam clock (JPO) which presents an accuracy of 6.6×10^{-15} and contributes regularly to TAI.

Fountain clocks

By the end of 2004 the cesium fountain FO1 had resumed operation for a few months, before its vacuum chamber was opened for installation of the micro-wave cavity of the PHARAO space clock for testing. During this period FO1 reached an accuracy of 7.5×10^{-16}, while the double fountain FO2 was at 6.6×10^{-16} (for cesium). The Allan variance of a comparison between these two clocks carried out at that time is shown in Figure 1; the relative stability is $5\times10^{-14}\,\tau^{-1/2}$, reaching 2×10^{-16} after 50000s. This measurement includes all type B corrections, particularly the cold collisions frequency shift and Zeeman shift, measured continuously during the comparison. The frequency difference observed between the clocks was 4×10^{-16}, well within their combined uncertainty.
Recently FO1 has been reopened and a new cold atom source, using a 2D MOT to load the molasses, has been mounted. A new optical bench for FO1 has also been installed during 2005-2006 and the clock is now under re-evaluation. FO2 has recently been modified to allow simultaneous operation with Rb and Cs. A 2D MOT is also used for optical Rb molasses loading.
The mobile fountain FOM has been modified to allow higher launching of the atoms and the use of the adiabatic passage method for cold collisions shift evaluation. This clock will soon be moved to the CNES (Toulouse) to be used for the evaluation of the PHARAO space clock Engineering Model.
On both FO1 and FO2 the uncertainty of the evaluation of the black-body shift has been reduced to 6×10^{-17} by operating the clock at the stabilized and continuously monitored room temperature, allowing a reduction of the temperature gradient to less than 0.2 K along the vacuum tube. Recent highly accurate theoretical evaluations (by Flanbaum *et al* and Derevianko *et al*) corroborate our 1998 Stark coefficient measurement and our direct black-body measurement reported in the CCTF 2004 documents.

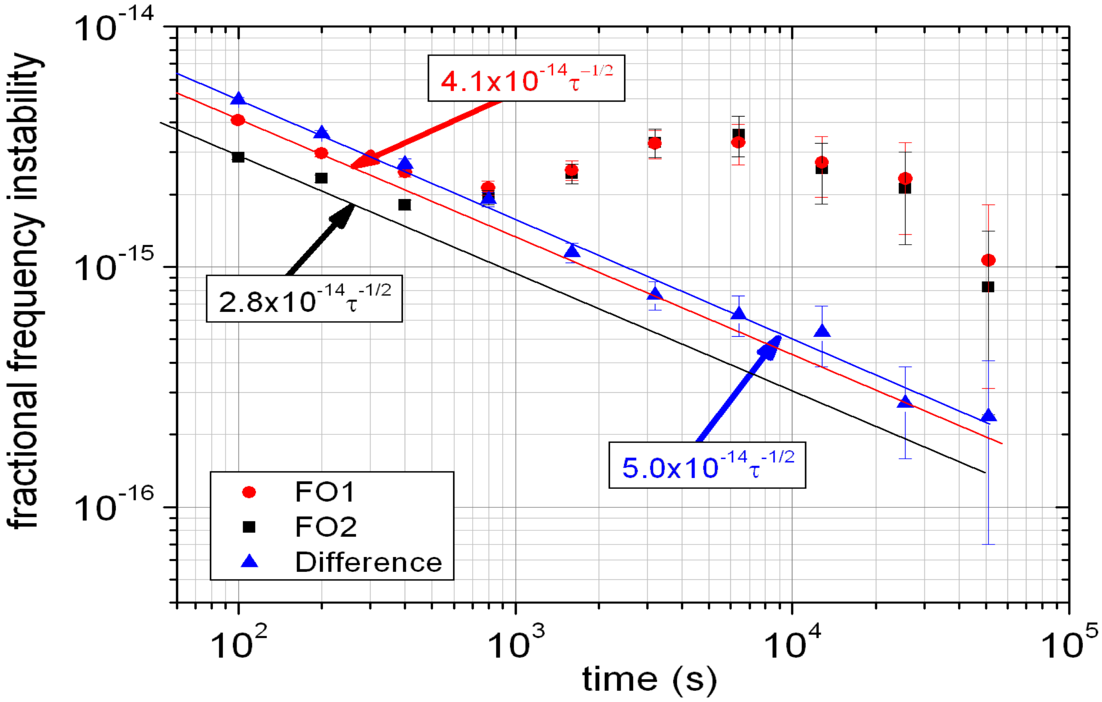

Figure 1. Frequency stabilities of FO1 and FO2 measured against the cryogenic oscillator stabilized in the long term on a H maser. In blue is shown the Allan deviation between the two fountains.

On both FO1 and FO2 the stability of the magnetic field has been considerably improved, reaching $\sim 10^{-12}$ T over a few hours. Furthermore, during TAI contributions, the magnetic field is automatically measured every hour.

A phase measurement system with micro-radian resolution at micro-wave frequency has been developed to study possible synchronous phase perturbations on the interrogation signal of the fountains. This system has been used to develop and evaluate phase transient-free microwave switches (≤2µrd) on a time scale of few ms. Theses switches are now used to evaluate unambiguously or to eliminate the frequency shift due to micro-wave leakage in fountains. Using this system we found on FO2 a 2×10^{-16} frequency shift due to this effect in standard operating conditions (π/2 pulses).

We have also recently studied the distributed phase shift in the cylindrical fountain cavity of FO2 by tilting the clock with respect to the vertical direction and by measuring for various microwave powers the frequency differences between asymmetric and symmetric cavity feeds. We hope to be able to deduce from these measurements the phase gradient in the cavity when the clock is operated in normal conditions.

An international maser and fountain clock comparison involving five laboratories took place during two weeks in autumn 2004 using various time and frequency transfer techniques. Three fountains contributed to this experiment: frequency differences of 3.7×10^{-15} for IEN-OP and 3.4×10^{-16} for OP-NPL were found.

In 2005, FO2 was used to study the spectroscopy of transitions which depend linearly on the static magnetic field, showing that any incidence of such states on the evaluation of the 2nd order Zeeman effect is very much smaller than 10^{-16}. Interpreted as a test of Lorentz invariance, this study provided strong new limits on several parameters of the extended standard model of particle physics.

The PHARAO/ACES experiment

All elements of the Engineering Model (EM) of the PHARAO space clock have been manufactured and delivered to CNES (Toulouse) at the beginning of 2006. Initial results are very promising: a few $\times 10^7$ atoms are cooled to 2.5µK and when launched at 3.4 m/s, 10^7 atoms are detected with an excellent signal to noise ratio in the detection area. Ramsey fringes with a 5 Hz width (as expected in the presence of gravity) and a signal to noise ratio of a few hundred have also been observed. Tests will now be performed in a thermal-vacuum environment representative of the spatial environment. Some critical parts of the PHARAO clock, the µ-wave cavity Flight Model and the µ-wave source EM, were tested by the LNE-SYRTE using the FO1 and FO2 fountains.

The Frequency Comparison and Distribution Package (FCDP) of the ACES (an ESA mission) payload, which is used to phase lock the PHARAO microwave synthesizer to the 100 MHz output signal of the Space Hydrogen Maser (SHM), was tested successfully in August 2006 in Toulouse. The FCDP is also used to distribute the 100 MHz signal to the ACES time transfer micro-wave link (MWL).

(Note that LNE-SYRTE provides scientific leadership and expertise and test facilities to the PHARAO/ACES project, it does not manufacture space instruments.)

2. MINIATURE CLOCKS

The development of compact clocks continues. The HORACE prototype (laser cooling of Cs atoms directly in the µ-wave cavity) has produced Ramsey fringes as narrow as 20 Hz when atoms are detected using a time of flight signal. A new configuration has been designed to allow detection of the atomic resonance by optical absorption in the µ-wave cavity. This method may allow a better clock stability. A clock using coherent population trapping on Cs has reached a frequency stability of $3.5 \times 10^{-12}\ \tau^{-1/2}$. This experiment uses linear orthogonal polarization, leading to an increased CPT resonance contrast, and pulsed operation to avoid power broadening of the CPT resonances.

3. TIME SCALES

UTC(OP)

UTC(OP) has been maintained at less than 50 ns from UTC over the years 2004-2005. During this period 13 frequency corrections, ranging between -1×10^{-14} and $+1.5 \times 10^{-14}$, were applied using a micro-phase stepper. The introduction of a leap second at the end of 2005 presented no particular problem.

The project of a new realisation of UTC(OP), using a H maser steered in the long term by a local ensemble of commercial Cs clocks, is in progress. A time scale algorithm has been developed and tested, displaying a stability of 3×10^{-15} at 30 d using historical clock data. Further modules (input/output clocks data process, automatic detection of phase steps and/or missing clocks data, etc) are being developed.

TA(F)

Since 2004, further corrections to the frequency of TA(F) have been applied in order to cancel the long-term frequency drift. The corrections applied were between -1×10^{-16}/d and $+1.658 \times 10^{-16}$/d. In 2005, the frequency stability of TA(F) reached 3.7×10^{-15} at 80 d.

Since December 2005, TA(F) has been frequency steered using data from the primary standards of the laboratory. During this period, the monthly mean frequency of TA(F) has stayed within 1.2×10^{-14} of SI, and is typically much closer.

Contribution of primary standards to TAI

The LNE-SYRTE primary standards JPO and FO2 have contributed to TAI many times since the last CCTF. From January 2005 to June 2006, FO2 contributed four times and JPO twelve times.

We are currently studying the possibility of realizing a new time scale using our ensemble of four H masers, in order to reduce the noise induced by dead time in fountain operation during TAI contributions. This time scale will also be very useful during the ACES mission. Figure 2 shows the Allan deviation measured between FO2 and maser 890, which is now used as the reference for TAI contributions. Even when operated alone this maser allows an accurate evaluation of the effect of dead time.

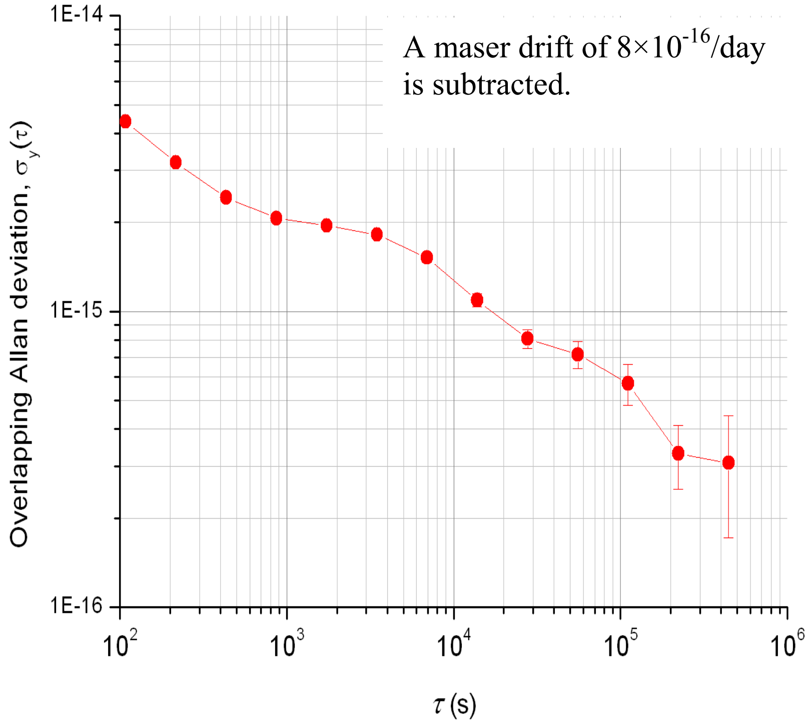

Figure 2. Allan deviation of the KVARZ hydrogen Maser 890 against the fountain FO2.

4. TIME AND FREQUENCY TRANSFER

GNSS for time and frequency transfer and contribution to European projects

GPS P3: the calibrated link OP-PTB is used by the BIPM as a back-up for the French contribution to TAI. This technique will be used to establish a link to the mobile fountain FOM, while it is situated at the CNES (Toulouse) for the purposes of PHARAO/ACES.

One of our dual-frequency GPS receivers is registered as a permanent IGS operational station.

EGNOS: our operational activity associated with the EGNOS ground segment has started. In its navigation message, EGNOS provides an estimate of the offset of its internal time scale, EGNOS Network Time (ENT), from UTC. Currently UTC(OP) serves as the realisation of UTC for the purposes of this estimate, through an EGNOS ground station installed on the site of Paris Observatory, under the responsibility of the CNES.

GALILEO: LNE-SYRTE is a core member of the Fidelity consortium, coordinated by Helios Technologies, which was awarded a contract by the Galileo Joint Undertaking in June 2005 for the provision of the prototype Galileo Time Service Provider (GTSP) for the In Orbit Validation phase of Galileo. The GTSP will provide a link to TAI/UTC for the Galileo core system, as well as steering information for Galileo System Time (GST). LNE-SYRTE tasks in Fidelity include GNSS time transfer and calibration activities, provision of clock and transfer (GPS, TWSTFT) data, recommendations on the use of Galileo in time metrology.

Two-Way Satellite Time and Frequency Transfer

The LNE-SYRTE station is driven by an active hydrogen maser. The link to UTC(OP) is realized by interpolation of measurements which are done every hour. In 2005, the link OP-PTB by two-way became the official link for the French contribution to TAI, improving the accuracy of the time transfer measurement by six times in comparison with GPS C/A. During 2005 many changes were operated: satellite orbital position, microwave frequencies for European and transatlantic links, adjustment of the satellite translation frequency, link calibration, intensified measurement schedule, additional participating stations, etc, and additional equipment was installed: EIRP measurement device, satellite simulator prototype, electromechanical switches, …

A satellite simulator has been developed and installed. The first measurement results show a time stability of the system below 50 ps over an averaging period from 0.3 d to 3 d. The next steps will be the characterisation of the system using a vector network analyzer, a long term stability study and the use of the system for the time difference delay measurement.

The LNE-SYRTE has also started collaborations in view of establishing two-way links with NTSC, NICT and TL. The implementation of a 2nd VSAT station is in progress on the site of the Observatoire de Paris. Experimental tests are expected for the beginning of 2007.

Comparison between GPS and TWSTFT

In 2004, IEN, NIST, NPL, PTB and LNE-SYRTE participated in a frequency comparison campaign between remote masers used as reference frequencies for atomic fountains. Both TWSTFT (12 measurement sessions per day over 25 days) and dual-frequency GPS receivers were used. Two-way data were processed by participating stations, GPS P3 data by BIPM and GPS carrier phase data by AIUB. This comparison permitted the characterization of the noise of the different links as well as the determination of the time when the noise floors of the masers were reached. It was shown that a frequency stability of 1×10^{-15} is achievable at 1 d (~3 d for GPS P3), and a noise level of 2×10^{-16} can be reached over only 5 d averaging time, using the TWSTFT and GPS carrier phase techniques.

Optical Fibre link

In collaboration with the Laser Physics Laboratory (LPL, CNRS and Université Paris 13), we are developing optical fibre links for time and frequency transfer. The current system is based on a 1 GHz amplitude modulation of the 1.55 μ optical carrier. Over an 86 km length of fibre installed “in the field” (a return trip between LNE-SYRTE and LPL), this system has a stability of 5×10^{-15} at 1 s, reaching 2×10^{-18} at 1 d. Over a 186 km length of fibre, of which 100 km is in the laboratory, including 2 amplifiers, the system has a stability of $1\text{-}2\times10^{-14}$ at 1 s and better than 10^{-17} at 1 d.

5. OPTICAL CLOCKS

The Sr clock

Sr atoms from an atomic beam are laser cooled to a temperature of ~1 mK using the $^1S_0$-$^1P_1$ transition at 461 nm. Atoms are then loaded into an optical lattice and further cooled to the motional ground state of the lattice using the narrow $^1S_0$-$^3P_1$ intercombination transition. Once this preparation stage is completed, the clock transition is probed with a low frequency noise laser which is pre-stabilized to an ultra-stable cavity. The transition probability to the $^3P_0$ state is finally measured by laser induced fluorescence. The present linewidth of the resonance is about 50 Hz, which corresponds to an atomic quality factor of 8×10^{12}, more than two orders of magnitude higher than in atomic fountains. To operate the clock, the sides of the resonance are probed alternatively, the difference between two successive transition probability measurements being the error signal used to lock the frequency of the probe laser to that of the atomic transition. With this signal, we have experimentally demonstrated that the first order light-shift of the clock transition is cancelled to better than 10^{-6} of the shift of both clock states and that higher-order light-shifts induced by the lattice will not constitute a limitation to the future clock accuracy down to the 10^{-18} level [Brusch et al 2006].

The blackbody radiation shift due to the surrounding vacuum chamber at room temperature is expected to be at the level of 6×10^{-15} for Sr atoms. This is a factor of 3 "only" reduction as compared to a Cs fountain and will probably be the ultimate limitation to the clock accuracy.

We have performed a measurement of the $^1S_0$ - $^3P_0$ transition frequency of ^{87}Sr in an optical lattice clock. The clock frequency was measured relative to the Cs atomic fountain FO2 using a self-referenced optical frequency comb. The fractional frequency stability of this comparison was $6\times10^{-14}\,\tau^{-1/2}$ with τ the averaging time in seconds, so that individual measurements with 1 Hz (2×10^{-15}) statistical uncertainty were performed within about 15 minutes.

The measured frequency of the transition is **429 228 004 229 879 (5) Hz**. In fractional units the uncertainty is 1.2×10^{-14}. The details of the experiments performed for this evaluation are given elsewhere. This value is in excellent agreement with that reported by the JILA group, which is 10 Hz lower with an error bar of 19 Hz.

It should be stressed that there are significant differences between the two experimental setups (LNE-SYRTE and JILA) which reinforce their mutual independence: The spectral widths of the atomic resonances differ by a factor of 4 (50 Hz vs 200 Hz). In our measurement the probe laser was locked to the atomic resonance while the JILA measurement was based on fits of atomic resonances. The depth of the lattice in our experiment is up to one order of magnitude larger than used in JILA. The time sequences of operation of the clocks differ significantly. In both experiments an important contributor to the final error is the uncertainty of the first order Zeeman effect. The evaluation of this effect was performed differently in the two cases: JILA explored the effect of an intentional additional magnetic field, while we studied the dependence of the clock frequency on the probe laser polarization and on the width of the frequency modulation used to lock the probe laser to the atoms.

The group at Tokyo University initially published a measurement of this transition frequency which was incompatible with those of LNE-SYRTE and JILA, but has recently reported a new measurement which is in agreement: 3 Hz lower than the LNE-SYRTE value with an error bar of 5 Hz.

Development of an optical lattice clock based on mercury

Another interesting candidate for an optical lattice clock is neutral mercury. Hg has an alkaline-earth like electronic structure with a $^1S_0$-$^3P_0$ intercombination transition which is totally forbidden for bosonic natural isotopes and weakly allowed by hyperfine mixing for fermions. The wavelength of this transition is 265.6 nm. The natural linewidth of the transition has been calculated and measured to be in the 100 mHz range for fermions. As for other proposed neutral atoms (Ca, Sr, Yb), bosonic isotopes can also be used for an optical clock provided a quenching scheme is used. One possible foreseeable limitation of the accuracy of an optical lattice clock, when accuracy below 10^{-17} is targeted, is the black body radiation shift. In this respect, Hg is an interesting candidate with an estimated black body radiation shift of 2×10^{-16}, between 10 and 100 times smaller than other alkaline-earth atoms. Hg also possesses 6 abundant isotopes (2 fermions and 4 bosons, natural abundance >6%) and 1 relatively rare, although probably usable, bosonic isotope (^{196}Hg) with a 0.15% natural abundance. All isotopes have no more than F=3/2 (^{201}Hg) total spin in the ground state.

Two other important considerations making Hg a reasonable candidate are the feasibility of laser cooling and of a non-perturbing lattice trap. Unlike other alkaline-earth candidates, the strongly allowed $^1S_0$-$^1P_1$ transition is not practical (185 nm) and has a very high Doppler cooling temperature. On the other hand, the $^1S_0$-$^3P_1$ transition at 254 nm with a natural linewidth of 1.2 MHz should lead to efficient magneto-optical trapping together with a low Doppler cooling temperature of 30 μK. Unlike the 185 nm radiation, the 254 nm wavelength can be accessed with sufficient power using available technologies. Similarly, it has been shown that Hg possesses at least one useable “magic wavelength” for the non-perturbing dipole trap, at 342 nm.

To conclude, Hg is an interesting candidate for an optical lattice clock. One interesting metrological feature is the smallness of the blackbody radiation shift. Also, Hg would have a high sensitivity to variations of the fine structure constant α. One of the challenging aspects of using Hg for an optical clock is the necessity to generate and use UV laser light with relatively high power.

Based on the above considerations, LNE-SYRTE has started developing an optical lattice clock based on Hg. This project started in 2005 with financial support principally from the LNE. Initial developments concerning the vacuum system and the clock laser at 265.6 nm have been completed in 2005-2006. Resonant frequency doubling of an alpha-DFB diode laser at 1062.4 nm using a PPKTP crystal leads to more than 100mW at 531.2 nm, which should provide sufficient power at 265.6 nm for all experiments. Design studies for all main sub-systems have also been completed. In 2006, we have started developing the source for laser cooling, based on a commercial frequency doubled disk laser at 1014.9 nm delivering ~3 W at 507 nm. More than 700mW has been observed at 254 nm after resonant frequency doubling with a BBO crystal. Saturated absorption spectroscopy of Hg vapour has been performed in order to stabilise this laser source. These results clearly demonstrate the feasibility of a laser source for cooling of Hg. Construction of the vacuum chamber and of the ultra stable reference laser at 1062.4 nm are now under way. We are targeting to observe laser cooling by the beginning of 2007 and to probe the clock transition for the first time in 2007. 2007 will also be devoted to the development of the optical lattice trap (laser sources, build-up cavity, and modified vacuum chamber).

6. WORK OF OTHER FRENCH LABORATORIES COORDINATED BY THE LNE

The LNE-INM (Conservatoire National des Arts et Métiers) is developing an optical frequency standard based on a transition of atomic silver near 907 THz, which can be excited by two photons of 661 nm wavelength (453.3 THz). This line has a natural width of less than 1 Hz and the use of two-photon spectroscopy has the advantage of eliminating the first order Doppler effect, but the high clock laser power required means that light-shift effects will have to be very well controlled. The 661 nm clock transition was observed for the first time by the LNE-INM in 2004, using a thermal beam. Current work is focused on developing a magneto-optical trap for silver in order to construct a cold-atom frequency standard.

The LNE-FEMTO-ST (CNRS and Université de Franche-Comté) works in particular on the development of cryogenic sapphire oscillators. A prototype resonator has shown a stability of a few $\times 10^{-15}$ at 1 s, rising to only 2×10^{-14} at 1 d. Current work is centred on the exploitation of a maser effect in cryogenic iron-doped sapphire crystals, discovered by LNE-FEMTO-ST.

The LNE-Observatoire de Besançon (CNRS and Université de Franche-Comté) has over a number of years developed a compact system "SYREF", based on a commercial miniature GPS receiver, which provides a continuous link to UTC(OP) for their clients. In 2005, the latest version of this system showed a stability of 8×10^{-14} at 1 d for transfers between Besançon and Paris, a distance of 320 km.

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