Report to the 18th CCTF, June 2009

LNE-SYRTE

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This report describes activities pursued since the last meeting of the CCTF, in 2006.

1. PRIMARY FREQUENCY STANDARDS

LNE-SYRTE operates 4 primary cesium clocks which contribute regularly to TAI. JPO is an optically pumped cesium beam clock, FO1 is a cesium fountain, FOM is a transportable cesium fountain and FO2 is a cesium and rubidium fountain. JPO and FO1 have contributed calibrations to TAI since 1995, FOM and FO2 since 2002.
In addition LNE-SYRTE is leading the development of a cold atom space primary standard, PHARAO, a project of the French space agency CNES. This clock is a major component of the payload of the *Atomic Clock Ensemble in Space* (ACES) mission of the European space agency ESA. The mission launch is scheduled in 2013.

Optically Pumped Cs Beam JPO

JPO is operating continuously. The relative frequency accuracy of this clock is 6.3×10^{-15} and the current relative frequency stability is $8\times10^{-13}\ t^{-1/2}$. The frequency instability is slowly increasing with time due to a decline of the cesium flux.

Fountain clocks

Since 2006 the 3 fountains have been profoundly refurbished to both improve reliability and performance. In addition, the dual fountain FO2 can now operate simultaneously with cesium and rubidium atoms. The systematic effects of all 3 fountains have been reevaluated and their uncertainties minimized.
Among these effects the blackbody frequency shift has been revisited due to a discrepancy of about 10^{-15} compared with the value published by two other groups. Using FO1, both the scalar and tensor polarizabilities have been measured again, with a lower electric field than the one we used in 1997. The new value of the polarizability coefficient is in agreement with our 1997 measurement. Furthermore, other groups have renewed the theoretical calculations on the cesium polarizability using a full quantum treatment, in particular taking into account the continuum states. Their results are in agreement with our value. Consequently the coefficient of the blackbody frequency shift remains unchanged.
The current fountain frequency accuracies and stabilities are as follows:

fountain	accuracy	stability
FO1	4.4×10^{-16}	$3 \times 10^{-14}\ t^{-1/2}$
FO2 (cesium)	4.5×10^{-16}	$3 \times 10^{-14}\ t^{-1/2}$
FOM	7×10^{-16}	$8 \times 10^{-14}\ t^{-1/2}$

The frequency uncertainty of FO2 with rubidium due to systematic effects is 4.6×10^{-16}.
A series of frequency comparisons of the fountains is shown in Figure 1. As can be seen, they are in good agreement within the error bars. Nevertheless the FO1 and FO2 frequencies appear to have a systematic offset of the order of $5\text{-}6\times10^{-16}$. We are investigating this and suspect phase instabilities in the comparison link.

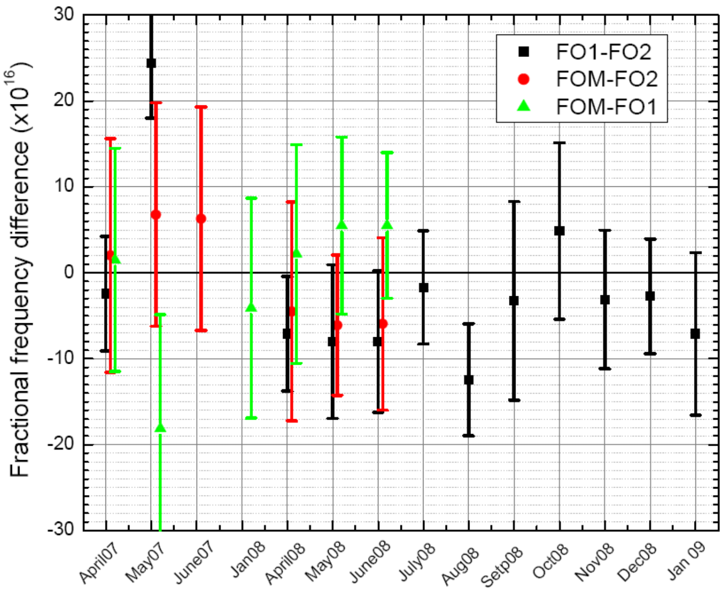

Figure 1: Fractional frequency differences between the 3 LNE-SYRTE fountains over several months.

We have recently remeasured the rubidium hyperfine frequency, obtaining the improved value of 6 834 682 610.904 314 (4.4) Hz. The 10-year history of our frequency comparisons between the cesium and rubidium hyperfine lines (FO1-FO2Rb, FOM-FO2Rb, FO2Cs-FO2Rb) is shown in Figure 2. A linear fit to test for evidence of fundamental constant change shows a drift of 2.1×10^{-16}/year which is not statistically significant.

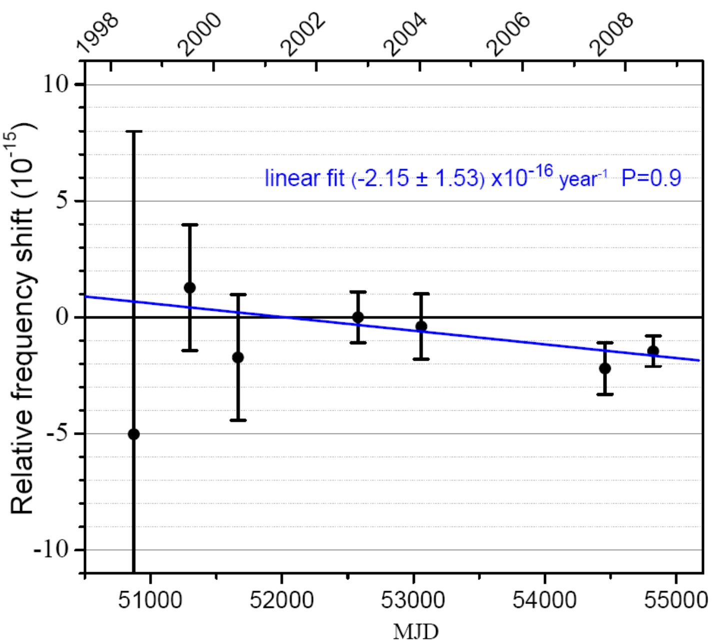

Figure 2: Fractional frequency difference between cesium and rubidium hyperfine levels over 10 years.

In 2007 we took the transportable fountain FOM to the Quantum Optics and Spectroscopy laboratory of Innsbruck University, Austria, to participate in an absolute frequency measurement of the $^{40}Ca^{+}$ $4s^2S_{1/2}$–$3d^2D_{5/2}$ electric-quadrupole transition. The measured value of this new optical frequency is 411 042 129 776 393.2 (1.0) Hz. Since June 2008 the FOM has been operating at CNES, Toulouse, for testing of the PHARAO space clock.

Contribution of primary standards to TAI

The LNE-SYRTE primary standards JPO, FO1, FO2 and FOM have regularly carried out calibrations of TAI. From January 2006 to December 2008 they contributed 35, 11, 19 and 15 times respectively.

The PHARAO/ACES space mission

The PHARAO/ACES mission is now fully funded and the launch is scheduled in 2013. The Engineering Model (EM) of the PHARAO space clock is currently under test at CNES, Toulouse. The frequency stability is as expected while the accuracy will be evaluated during 2009. The fabrication of the flight model (FM) started in January 2009.
The EM of the two-way microwave link MWL has been tested and has demonstrated phase noise at the 0.3 ps level, compatible with the scientific objectives of the ACES mission.
Tests of the ACES payload EM will commence in July 2009. The physical package includes the PHARAO EM, an H-maser, the Frequency Comparison and Distribution Package (FCDP) EM and the MWL EM.
(Note that LNE-SYRTE provides scientific leadership and expertise and test facilities to the PHARAO/ACES program, it does not manufacture space instruments itself.)

The Microwave Oscillator OPUS

In order to provide an ultra low noise microwave frequency source we have developed an optical oscillator based on a 1064 nm laser frequency-locked to an ultra stable Fabry-Perot cavity. The frequency down conversion is done through a femtosecond comb laser locked to the optical oscillator. This development started in 2006 and has reached its objective with the demonstration of microwave signal generation with a short term frequency stability below 3×10^{-15} from 1 to 10s. This signal has been used to drive directly the microwave frequency of the fountain FO2 without degrading its stability.

2. COMPACT CLOCKS

LNE-SYRTE has continued the development of the two compact clocks HORACE and CPT. HORACE is based on the laser cooling of cesium atoms directly in the microwave cavity. Its frequency stability has now reached $2.2\times10^{-13}\ t^{-1/2}$ with a floor at 4×10^{-15}. CPT is based on coherent population trapping of cesium. Its short term frequency stability is now 7×10^{-13} @1s. Further work will concentrate on the buffer gas and integrated optics.
In 2006 LNE-SYRTE started work on a new concept of an integrated clock, based on magnetically trapped cold rubidium atoms on a micro-circuit (Trapped Atom Clock on a Chip – TACC). An important objective is to compare the clock characteristics obtained using thermal (cold) atoms and using a Bose Einstein condensate (BEC). Using a BEC the collisional shift can be made to vanish. In 2008 a BEC was obtained and the Ramsey microwave resonance observed. The next steps will deal with clock operation and evaluation.

3. TIME SCALES

UTC(OP)

UTC(OP) has been maintained at less than 60 ns from UTC over the years 2006-2008. During this period 11 frequency corrections, ranging between -2×10^{-14} and $+1\times10^{-14}$, were applied using a micro-phase stepper. The introduction of a leap second at the end of 2008 presented no particular problem.

Development of a new system to generate UTC(OP) from a physical signal delivered by an active H-maser has continued, including the development of a time scale algorithm based on NIST AT1 with various integrated modules, in particular concerning the automatic detection of phase steps and/or missing data, the automatic suppression of clocks, weightings based on Allan variance, steering, etc. This development work will be completed by the end of 2009.

TA(F)

Over the period 2006-2008, 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 $-2{,}683\times10^{-16}$/d and $+3{,}083\times10^{-16}$/d. In 2008, the frequency stability of TA(F) reached 9×10^{-16} at 80 d. The steering was done using data from the primary frequency standards of the laboratory. The frequency of TA(F) with respect to the SI second since 2007 is shown in figure 3. This figure also shows the frequency of TAI as published monthly by the BIPM in the Circular T.

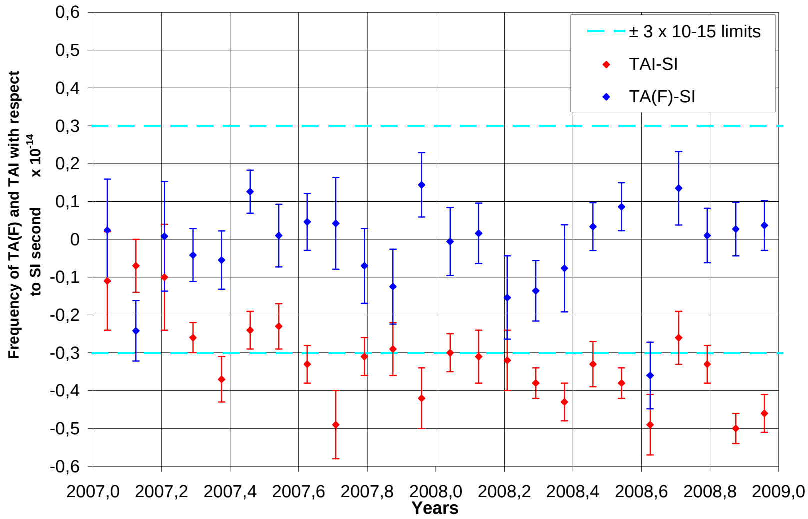

Figure 3: Frequency of TA(F) and TAI with respect to the SI second.

Local frequency reference

We have started the development of 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. For this purpose, the four H-masers are compared continuously using a high performance (high resolution and low noise) phase comparator.

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. Transfer data are provided daily to BIPM for the PPP calculation. One of our dual-frequency GPS receivers is registered as a permanent IGS operational station.

EGNOS: the French space agency CNES has validated the broadcast value for ENT-UTC which is obtained through UTC(OP). These data have been declared compliant to the specification, with a combined uncertainty better than 10 ns on ENT-UTC(OP).

GALILEO: LNE-SYRTE has actively contributed to the different tasks within the Fidelity consortium: design and validation of the prototype Galileo time service provider; coordination and preparation of publications; organization and realization of the relative calibration campaign of GPS receivers among NMIs involved in Fidelity (INRiM, NPL, PTB and LNE-SYRTE); participation in the calibration campaign of TWSTFT links using a portable station and the daily provision of clock and transfer data.

Two-Way Satellite Time and Frequency Transfer

LNE-SYRTE now has two fully operational TWSTFT stations (OP01 – equipped with a satellite simulator developed in our laboratory – and OP02). Since 2005, OP01 operates on the Europe-Europe and the Europe-USA networks. The OP to USA links are calibrated by the BIPM since August 2008. In order to accommodate the change of satellite operated by Intelsat in February 2008 and to use new microwave frequencies, OP01 is now equipped with a 4-port feed antenna. Recently, OP02 has successfully completed the Up-Access-Test to Intelsat (with only 4.6° elevation) and started operation on the Europe-Asia network. OP01 and OP02 are judiciously installed permitting to do two-way measurement in collocation: the common clock deviation obtained is better than 200 ps over more than one day. The installation of new, independent signal distribution equipment for the stations and related devices has allowed us to use our best H-maser (HM890) to drive the stations since February 2009. Figure 4 illustrates the new performance obtained on the different networks. Note that on the OP-NIST link the frequency stability reaches 8×10^{-16} at one day.

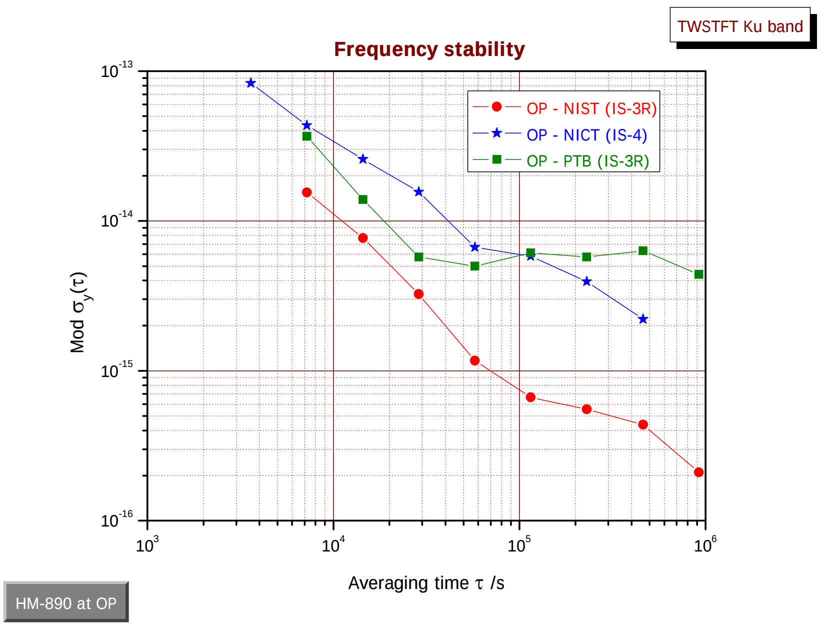

Figure 4: Recent TWSTFT performance on three links.

Optical Fibre link

In collaboration with the Laboratoire de Physique des Lasers (LPL, CNRS and Université Paris 13), we are developing optical fibre links for time and frequency transfer. As opposed to a previous version of the link where transfer was performed by RF amplitude modulation of a telecommunications laser, the transmitted signal is now the frequency of this laser, which can be referenced to any atomic clock via a femtosecond frequency comb. By sending back the transmitted signal to the emitter we are able to measure and compensate for the fluctuations induced by perturbations on the optical fibre. Over a distance of 86 km, the Allan deviation of the compensated link is 2.10^{-16} after one second of averaging time, down to a few 10^{-19} after a few hours. These results were obtained using a dedicated dark fiber connecting LPL and LNE-SYRTE. Very recently, we demonstrated that such a system could be operated by using one frequency channel on an operational telecom data network, sharing the fiber with internet traffic. We observed no degradation of the frequency transfer characteristics. This opens the way to the development of a high performance frequency comparison and distribution network at the continental scale.

5. OPTICAL CLOCKS

Two optical clocks using neutral atoms confined in an optical lattice are under development at LNE-SYRTE. The first uses Sr atoms and presently exhibits an accuracy close to 10^{-15}. The second is based on Hg and is at a preliminary stage of development: mercury atoms have been laser cooled in a MOT and the 1S0-3P0 clock transition observed on cold atoms.

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. The 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 10 Hz, which corresponds to an atomic quality factor higher than 10^{13}. 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 demonstrated experimentally that the first order light-shift of the clock transition is canceled 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.
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 reduction of "only" a factor of 3 compared with 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 the 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 **429 228 004 229 873.6 (1.1) Hz**. In fractional units the uncertainty is 2.6×10^{-15}. The details of the experiments performed for this

evaluation are given elsewhere. This value is in excellent agreement with those reported by JILA and Tokyo university.
It should be stressed that there are significant differences between the three experimental setups at LNE-SYRTE, JILA and Tokyo, which reinforce their mutual independence: the spectral widths of the atomic resonances differ by a large factor; the depth of the lattice in our experiment is up to one order of magnitude larger than used at JILA and Tokyo; the time sequences of operation of the clocks also differ significantly.

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 as a clock transition. The wavelength of this transition is 265.6 nm. Its natural linewidth has been calculated and measured to be in the 100 mHz range for the fermionic isotopes of Hg. As with other proposed neutral atoms (Ca, Sr, Yb), bosonic isotopes of Hg 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, with natural abundances greater than 6%, and another relatively rare although probably usable bosonic isotope (^{196}Hg) with a natural abundance of 0.15%. All isotopes have no more than F=3/2 (^{201}Hg) total spin in the ground state.
Two other important considerations making Hg an interesting candidate are the feasibilities 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 leads to efficient magneto-optical trapping together with a low Doppler cooling temperature of 30 µK. The 254 nm wavelength can be accessed with sufficient power using available technologies. Similarly, it has been shown that Hg possesses at least one usable “magic wavelength” for the non-perturbing dipole trap, at around 350 nm.
Based on the above considerations, LNE-SYRTE has started developing an optical lattice clock using Hg. This project started in 2005. Initial developments concerning the vacuum system and the clock laser at 265.6 nm were 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 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. Laser cooling of Hg was performed using a 2D-3D MOT scheme. The MOT has been operated with all the isotopes of interest for a lattice clock. The typical number of cold atoms is in the 10^6 range and the typical temperature close to 30 µK. The clock transition was observed on cold atoms using the fermionic isotopes 201Hg and 199Hg. Finally, a preliminary measurement of the transition frequency was performed with an accuracy of about 4 10^{-12}.