TAI/12-13
CCTF/12-18

Report to the 19th CCTF, September 2012

LNE-SYRTE

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This report describes activities pursued since the last meeting of the CCTF, in 2009.

1. PRIMARY FREQUENCY STANDARDS

LNE-SYRTE currently operates 3 primary cold cesium clocks which regularly contribute to TAI: FO1 is a cesium fountain (TAI since 1995), FOM is a transportable cesium fountain (TAI since 2002) and FO2 is a double fountain operating with cesium (TAI since 2002) and rubidium (since 2012 published in circular T as secondary frequency standard).
We can also note that our first primary frequency standard called JPO based on a thermal beam, has been definitively stopped on 2010 after 20 years of operation.
LNE-SYRTE is also leading the scientific development of a cold atom primary standard for space, called PHARAO. The development of this program is managed by the French space agency CNES. The PHARAO clock is a major component of the payload of the *Atomic Clock Ensemble in Space* (ACES) mission of the European space agency ESA. The PHARAO flight model delivery is scheduled on 2013.

Fountain clocks

The first order Doppler frequency shift was the dominant uncertainty in the accuracy budget of the fountains. A detailed theoretical analysis in conjunction with a complete experimental study has been performed with the FO2 fountain in collaboration with Kurt Gibble (Pennstate University, USA). This work, published in *Phys.Rev.Lett. 106, 130801 (2011): "Evaluation of Doppler Shifts to Improve the Accuracy of Primary Atomic Fountain Clocks"*, led to a reduction of the Doppler shift uncertainty for our fountains. The calculation of the microwave lensing shift (recoil effect) has also been refined in collaboration with K. Gibble, and its uncertainty reduced by a factor 2. The resulting new accuracy budgets of our fountains, discussed in *Trans. on UFFC, vol. 59, n°3, 391-410 (2012), "Progress in Atomic Fountains at LNE-SYRTE"*, are given in the following table:

	FO1	**FO2-Cs**	**FOM**	**FO2-Rb**
Quadratic Zeeman shift	−1274.5 ± 0.4	−1915.9 ± 0.3	−305.6 ± 1.2	−3465.5 ± 0.7
Blackbody radiation	172.6 ± 0.6	168.0 ± 0.6	165.6 ± 0.6	122.8 ± 1.3
Collisions and cavity pulling	70.5 ± 1.4	112.0 ± 1.2	28.6 ± 5.0	2.0 ± 2.5
Distributed cavity phase shift	−1.0 ± 2.7	−0.9 ± 0.9	−0.7 ± 1.6	0.4 ± 1.0
Spectral purity and leakage	<1.0	<0.1	<0.1	<0.1
Microwave lensing	−0.7 ± 0.7	−0.7 ± 0.7	−0.9 ± 0.9	−0.7 ± 0.7
Second-order Doppler shift	<0.1	<0.1	<0.1	<0.1
Background collisions	<0.3	<1.0	<1.0	<1.0
Total	**−1033.1 ± 3.5**	**−1637.5 ± 2.1**	**−113.0 ± 6.9**	**−3341.0 ± 3.3**

Table 1: Systematic fractional frequency corrections and uncertainties for FO1, FO2-Cs, FOM and FO2-Rb, in units of 10^{-16}.

Frequency comparisons between FO2 and FOM show a mean fractional frequency difference of $3x10^{-16}$ over the last four years. However, the other frequency comparisons with the FO1 fountain show some long-term (month) instability, up to a level of 10^{-15}. This anomaly detected a few years ago, has not yet found a clear origin although the main systematic frequency shifts including the spectral purity, the phase instabilities and the leakage of the microwave synthesizers have been carefully measured, analyzed and controlled in all the fountains.

New absolute frequency measurements, referenced to our fountains, have been performed on our two strontium optical clocks and our mercury clock.

The fountain FO2 has a reliable operation using simultaneously Rb and Cs atoms since 2009. The frequency stability on the Rb reaches routinely $3.8\times10^{-14}\tau^{-1/2}$. The Rb/Cs frequency comparisons, initiated in 1998, span now over 14 years with large amount of data cumulated over the recent years. They have provided new constraints on the variation of the fundamental constants in time and position, and on their couplings to gravity (*J. Guéna et al., Phys. Rev. Lett. 109, 080801, 2012: "Improved Tests of Local Position Invariance Using ^{87}Rb and ^{133}Cs Fountains"*). To date our most accurate absolute determination of the ^{87}Rb ground state hyperfine frequency, which is based on the Rb/Cs comparisons over the February 2012 to August 2012 period, is 683468261.904312 (3) Hz. We remind the recognized value of the Rb secondary representation is 683468261.904324 (21) Hz (CCTF 2004 recommendation).

FOM remains the unique transportable primary frequency standard since more than 10 years. On 2009 FOM moved to CNES, Toulouse, for PHARAO evaluation. On 2010 FOM moved to Max Planck Institute for Quantum Optics in Garching, Germany, for a new absolute measurement of the 1s-2s transition frequency of hydrogen with an accuracy of $4.2x10^{-15}$. At last, before coming back to SYRTE, FOM was used at Observatoire de la Côte d'Azur, Grasse, for a study of the T2L2 satellite time transfer by laser link. During these tours FOM has continued doing TAI calibrations through GPS phase data comparisons.

Contribution of primary standards to TAI

The LNE-SYRTE primary standards, FO1, FO2-Cs and FOM have regularly carried out calibrations of TAI. From January 2009 to July 2012 they contributed 27, 37 and 19 times respectively. FOM also contributed while operating in a distant laboratory (4 at CNES, 1 at MPQ, 3 at OCA).

JPO, stopped on September 2010, has performed 22 calibrations.

The LNE-SYRTE secondary standard FO2-Rb was for the first time also compared to TAI: 17 Rb evaluations have been transmitted to BIPM .

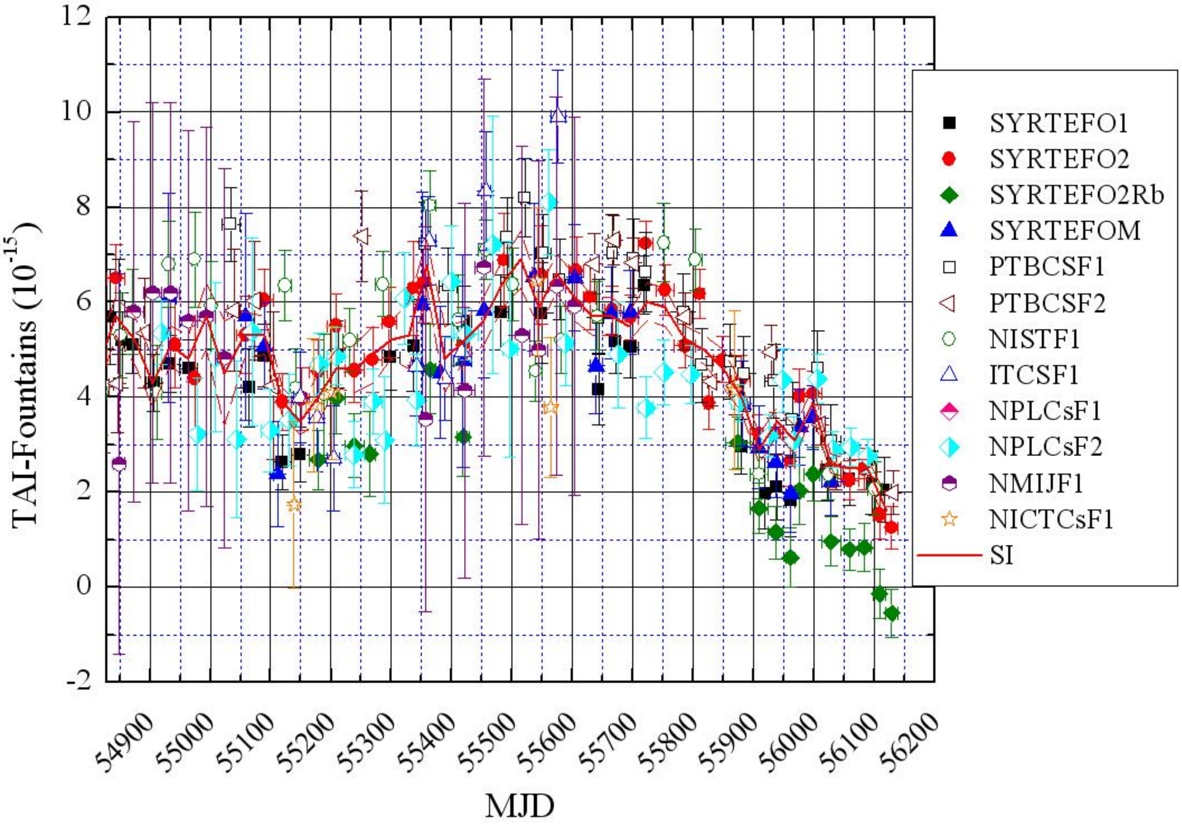

Figure 1: Contributions to TAI from all PFS over January 2009 – July 2012, including the first evaluations from the Rb secondary representation (see text below).

Using a secondary representation in TAI

Last January, eight evaluations of FO2-Rb spanning over the years 2010-2011 were submitted to BIPM for possible use in TAI, together with a statistical analysis of our Rb/Cs comparisons spanning from 1998 to December 2011 showing that the long-term data are well consistent: the probability of the fit by a constant value of the Rb/Cs frequency ratio is Q=0.92 and Birge ratio 0.67. The fitted mean value is shifted from the recognized value of the Rb secondary representation by about -1.4x10^{-15}, a shift that is well within the recommended relative uncertainty of 3x10^{-15} (CCTF 2004). The submission was reviewed by the WGPFS which recommends that the FO2-Rb reports be published in Circular T, but not yet used in the steering of TAI until the definition of the Rb secondary representation is revised. In total, 17 Rb evaluations are now published.

Regarding revising the Rb definition, we suggest using our most precise absolute determination (data from February 2012 to August 2012) given above 6 834 682 610.904 312 Hz, with an uncertainty enlarged by a factor 3 (i.e. 9 µHz) since this determination comes from a single laboratory. This means a relative change of -1.73×10^{-15} of the Rb definition, again well within the current recommended relative uncertainty of 3×10^{-15}, and a new relative uncertainty of $\sim1.3\times10^{-15}$. Possibly, inputs from all PFS worldwide through TAI/TT could be incorporated to determine the best possible value to recommend.

The PHARAO/ACES space mission

LNE-SYRTE participates to the space mission PHARAO/ACES. It is the Principal investigator in the development of the first primary frequency standard (PHARAO) for space operation, and it is developing the software for the scientific analysis of the data comparisons between ground and space clocks. In addition LNE-SYRTE will be a major ground station to fulfill the scientific objectives of the ACES mission.
The engineering model of the PHARAO clock has been fully and successfully tested. Final tests for the other instruments are under completion. The flight models of all instruments are under development. The performance tests on ground of the PHARAO flight model will start on 2013. The schedule of the launch will be fixed when the flight models of all instruments will be delivered (expected 2013).

2. OTHER MICROWAVE CLOCKS

Trapped Atom Clock on a Chip

In 2006 LNE-SYRTE started work on a new concept of an integrated clock, based on magnetically trapped atoms on a micro-circuit (Trapped Atom Clock on a Chip – TACC). The trap increases the density by four orders of magnitude and thereby amplifies atom-atom interactions. In addition, it allows evaporative cooling such that ultra-cold temperatures can be reached. Under these novel conditions, we have discovered a new spin synchronisation mechanism based on the quantum statistics of the interactions. The new mechanism leads to extraordinarily long coherence times of 58s [PRL **105**, 020401 (2010)], such that, in principle, a clock linewidth of 10 mHz can be reached. The current set-up runs at a short-term stability of 6×10^{-13} at 1s. It is limited by the small duty cycle (T_{Ramsey}=5s, T_{cycle}=15s). Small changes to the vacuum systems should allow to increase the duty cycle and consequently to improve the frequency stability. The current long-term stability is 6×10^{-15} at 300 000 s. Drifts of external parameters, such as the magnetic field, are currently under investigation. Future improvements will make use of entanglement between atoms in order to surpass the standard quantum limit.

Compact clocks

LNE-SYRTE has continued the development of the two compact clocks HORACE and CPT.
The HORACE project is a cold atom clock with better stability by about one order of magnitude than today commercial atomic clocks. In the years 2009-2012, the mainline activity was the metrological characterization and optimisation of the clock frequency performances. The short-term stability was measured at $2.2\times10^{-13}\ \tau^{-1/2}$, which is at the same level than any atomic fountain not referenced to a cryogenic sapphire oscillator, and which is obtained in a physics package about 50 times less than a fountain. The long-term stability is limited at 3.2×10^{-15} (@20000s) mainly dominated by the effects of cavity pulling and atomic collisions.

The CPT clock is a compact clock project based on the original and innovative architecture designed several years ago at SYRTE, using a pulsed Coherent Population Trapping (CPT) interrogation technique. The main achievements in the years 2009-2012 are:

- Collisional shifts measurements for the neutral gas Ne, N2, Ar;
- Production and characterization of cells with compensated collisional shifts;

- Light shifts measurements and models;
- Clock frequency stability improvement: 6×10^{-13} (@1s) and 2.5×10^{-14} (@3000s);
- Dual frequency laser prototype developed with French academic and industrial partners (LCFIO, LPN, TRT).

3. TIME SCALES

UTC(OP)

UTC(OP) has been maintained at less than 80 ns from UTC over the years 2009-2012. During this period 38 frequency corrections, ranging between $\pm 2\times10^{-14}$, were applied using a micro-phase stepper. The introduction of a leap second in UTC(OP) in late June 2012 has not generated particular technical problem.

We have pursued the development of a new system to generate UTC(OP) from a physical signal delivered by an active H-maser steered using the calibrations of the LNE-SYRTE primary frequency standards. For that purpose, we have developed a low noise micro-phase stepper operating at 100 MHz. This device will also allow delivering an accurate and stable frequency reference to the other experiments of the laboratory (fountains, optical clocks, compact clocks, time transfer links). This reference will also be very useful during the ACES mission.

TA(F)

Over the period 2009-2012, 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 -2×10^{-16} / d and $+3\times10^{-16}$ / d. The frequency stability of TA(F) reached 1×10^{-15} at 60 d and 7×10^{-16} at 180 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 2. This figure also shows the frequency of TAI as published monthly by the BIPM in the Circular T.

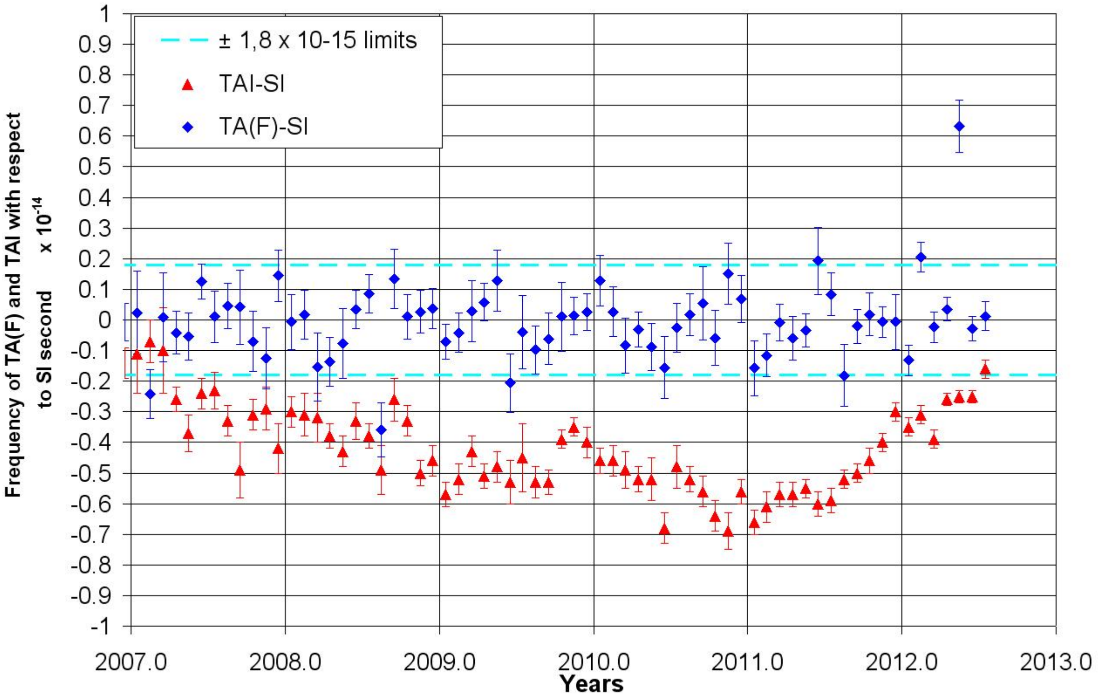

Figure 2: Frequency of TA(F) and TAI with respect to the SI second

It is to be noticed that the outlier point at 6×10^{-15} given in Figure 2 is due to an error in the processing of the steering of EAL by the LNE-SYRTE primary frequency standards: a "bad" maser was considered, and the difference between TA(F) and SI at this point reflects the difference between masers.

4. TIME AND FREQUENCY TRANSFER

GNSS for time and frequency transfer and contribution to European projects

GNSS

LNE-SYRTE provides daily to BIPM the required GPS data for the PPP processing part of the TAI/UTC generation and for the computation of UTC – UTC(USNO)_GPS data. LNE-SYRTE is also participating to BIPM UTCr Pilot Project. The uncertainties on the OP-PTB link are validated with respect to TWSTFT over a period of a few years despite the occurrence of many changes having affected both techniques (Figure 3). LNE-SYRTE provides support to BIPM GNSS travelling receiver campaigns, including regular provision of GLONASS receiver data. One of our dual-frequency GPS receivers is registered as a permanent IGS operational station called OPMT, which is also part of the French Réseau GPS Permanent (RGP) established by the Institut Géographique National (IGN). The NRCan PPP processing has been implemented in LNE-SYRTE for scientific purposes.

EGNOS

The French Space Agency CNES validates in a quarterly report the broadcast value for UTC - ENT (EGNOS Network Time) which is obtained through UTC(OP). Since the start of such CNES reports in 2008, these data have always been compliant with the requirements: as broadcast to the users, UTC – ENT stayed between – 25 ns to + 5 ns limits, within a expanded uncertainty of 10 ns (k = 3) on UTC(OP) - ENT.

Galileo

LNE-SYRTE has actively contributed to the development of the Galileo project. Over the period 2009-2012, this includes the last part of the Fidelity activities, the participation to the Galileo FOC Timing Interface Working Group (GFTIWG, "FOC" for Full Operational Capability) of the European Commission (EC) from 2010 to 2012, and since 2011 the provision of required data to the Timing Validation Facility (TVF) operated by INRiM, and the relative characterization of the delays of the GPS receivers implemented in one of the Precise Timing Facilities (PTF). LNE-SYRTE is also engaged on short term contracts with different industrial teams involved in Galileo.

Two-Way Satellite Time and Frequency Transfer

LNE-SYRTE has two fully operational TWSTFT stations (OP01 – equipped with a satellite simulator developed in the laboratory – and OP02). OP01 operates within the two networks: Paris to Europe and Paris to USA. The major links with OP01 are calibrated by the BIPM. In February 2010, OP02 interrupted two-way links within the Europe to Asia network due to the unavailability of a geostationary satellite covering Paris area. OP01 and OP02 are judiciously installed permitting to do measurements in the frame of research and development in the field (collocation configuration, satellite simulator technique, SAW-filters issues, two-way carrier phase experience, optimization of the technical parameters). The most important realization and event are reported below:

- Characterization of the OP01's differential delay using a satellite simulator within 400 ps combined uncertainty;
- Reduction to 36 % of the bandwidth satellite following the raise of the costs by the operator of satellite;
- Considerable improvement of the short-term noise (down to 1 ns) on the two-way links with OP by the introduction of offsets into the transmitted frequencies;
- Implementation of the carrier phase technique: frequency stability of 1x10^{-12} at 1 s and 3x10^{-14} at 100 s are obtained with OP01 and OP02 in collocation; however, a degradation on the stability is observed at 300 s. Further investigations are in progress;
- The use of a quiet transponder with appropriate configuration of stations improves considerably the main characteristics of a 1 MChips two-way network: an excellent stability of 40 ps at 1 d is obtained on the OP-PTB link (the diurnal effect and noise were reduced).

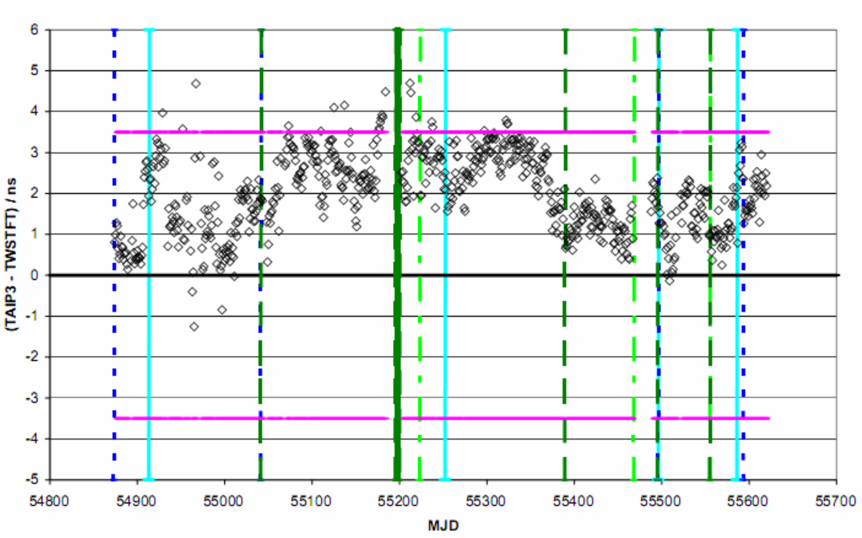

Figure 3: Direct comparison between UTC(OP) – UTC(PTB) obtained by GPS TAIP3 CV and by TWSTFT: red horizontal lines materialize the combined uncertainties, blue and green vertical lines materialize changes or incidents (like satellite transponder, UTC(k) reference clock, GPS equipment, power outages, weather issues, …) having affected either the equipment locally or the links in OP (blue) or PTB (green)

Time Transfer with Laser Link T2L2 experience

An international campaign was conducted in 2010: six laboratories (including OCA-Observatoire de la Côte d'Azur and OP-Paris Observatory) were participated using laser ranging stations in common view mode. In parallel, OCA and OP have used GPS receivers and TWSTFT stations, as well. About 1100 T2L2 passes were recorded. For the T2L2 data processing, one ground to space time transfer is computed for each pass, resulting from the adjustment of a polynomial among the elementary G/S time transfer and the calculation of one value in the middle of the pass. The OCA-OP preliminary results of the 1st time comparison involving T2L2, GPS carrier phase and TWSTFT techniques are given in Figure 4 and shown that the three time transfer techniques are consistent within 2 ns over two months measurement period (33 T2L2 common view passes). Further investigations are needed to improve the data processing and to extend T2L2 versus microwave links comparison to more links.

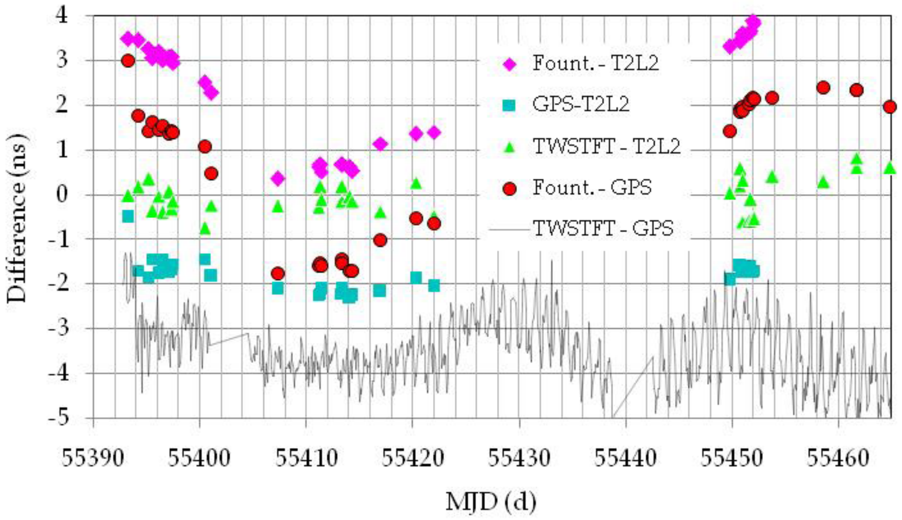

Figure 4: Residual noise fluctuations of the differences between the three different techniques on the OCA-OP link. Voluntary jumps were applied to facilitate the reading of curves. Atomic fountains not working continuously throughout the period, a significant increase in noise in the medium term is observed on comparisons with masers

Optical Fiber links

These activities are described in Section 6-OPTICAL FREQUENCY METROLOGY.

5. OPTICAL CLOCKS

LNE-SYRTE is developing two optical lattice clocks based on strontium and one optical lattice clock based on mercury. Below we summarize the main achievements on these lattice clocks since the 18th CCTF report.

Sr lattice clocks

- A second Sr lattice clock has been constructed and is fully operational since 2010.
- We replaced the titanium:sapphire laser used for the lattice trap with semiconductor lasers. Thanks to this change, the continuous (and unattended) operation of our Sr clocks has been extended to more than 12 hours. Measurements for this type of duration are now done routinely.
- We performed in-depth studies of systematic shifts and notably, the lattice induced frequency shifts (vector and tensor shifts, effects of electric quadrupole and magnetic dipole terms, hyperpolarizability). We performed an accurate determination of the magic wavelength for the Sr clock: 368 554 718 (5) MHz (here, the magic wavelength is defined as the wavelength for which the scalar light shift of the clock transition is zero).
- The current accuracy of both Sr lattice clocks is 1.3 parts in 10^{16}.
- The stability achieved in both clocks is $2.2\text{x}10^{-15}$ at 1 second, $3.2\text{x}10^{-15}$ for the comparison between the 2 clocks. Clocks are typically operated with a Rabi probe time of 100 ms leading to an atomic quality factor of $5\text{x}10^{13}$. Quality factors up to $1.3\text{x}10^{14}$ are obtained corresponding to 3.2 Hz, with contrast higher than 80%.
- We performed comparisons between the two Sr lattice clocks down to statistical uncertainties of $2\text{x}10^{-17}$. Our best measurement of that type to date gives agreement between the 2 clocks: $(1.2\pm1.4)\text{x}10^{-16}$. This was achieved after chasing and tackling a

number of technical, initially unanticipated shifts (DC stark shift due to stray electric fields, spectrum of the lattice light out of tapered semiconductor amplifiers, etc).

- We performed a series of absolute frequency measurements against LNE-SYRTE Cs fountains, giving an absolute frequency of the Sr clock transition of 429 228 004 229 873.18 ± 0.08 (stat) ±0.16 (sys) Hz down to a systematic uncertainty of $4x10^{-16}$, limited by fountains.
- We performed measurements of the ratio between the Sr lattice clock frequency and the Rb hyperfine frequency, realized by the FO2-Rb fountain. The statistical uncertainty of this measurement is $1.1x10^{-15}$.
- We demonstrated a classically non-destructive detection scheme of trapped Sr atoms that could, in the future, be used to optimize the duty cycle of the clock to minimize the impact of the probe laser frequency noise and thereby improve the stability. 10^4 atoms can be detected at the quantum projection noise limit while keeping 95% of the atoms in the lattice trap.

Hg lattice clock

- We developed a laser source and a dipole lattice trap that can operate near the predicted magic wavelength. We trapped a few thousands of atoms in this dipole lattice trap of only 22 recoil energy (due to the technical difficulty of the wavelength). Based on a cooled electron multiplied CCD camera, we can detect trapped atoms with shot to shot noise equivalent to 40 atoms. Lattice trapping was observed for several isotopes.
- We performed Lamb-Dicke spectroscopy of the clock transition in lattice bound ^{199}Hg. The narrowest observed linewidth so far is 11 Hz at 265 nm, which corresponds to an atomic quality factor of 10^{14}. This was obtained with a contrast limited to ~30%, which we attribute to the modest lattice depth and the absence of in-lattice cooling.
- We performed the first experimental determination of the magic wavelength in ^{199}Hg. Our best measurement of the magic wavelength so far gives: 362.5697±0.0011 nm.
- We performed preliminary investigation of the main systematic shifts down to an uncertainty of $5.7x10^{-15}$. In our system, no collision shift was observed at the level 10^{-15} at estimated average densities of $2x10^{8}$ cm^{-3}. 1st order Zeeman splitting was observed as expected. No quadratic dependence was observed at our ~10^{-15} resolution and for the range of magnetic field that was used (~40 µT). This is expected given the calculated value of the 2nd order Zeeman effect.
- We performed a series of absolute frequency measurements against the FO2-Cs fountain: 30 measurements sessions accumulated over a total time span of 90 days have an overall statistical uncertainty of 3 parts in 10^{16}. We measured the absolute frequency of the ^{199}Hg clock transition with an uncertainty of 5.7 parts in 10^{15} limited by the Hg clock. We found that the absolute frequency of the Hg clock transition is: 1 128 575 290 808 162.0±6.4(syst)±0.3(stat) Hz.
- We obtained short term frequency instability of 5.4 parts in 10^{15} at one second.

6. OPTICAL FREQUENCY METROLOGY

Ultra-stable lasers

Main achievements on ultra-stable lasers since the 18th CCTF report:

- For optical lattice clocks and for other applications (see next), we have developed a number of ultra-stable lasers at 1542 nm, 1062.5 nm and 698 nm. These lasers are based on 10 cm long ULE spacers. The 1062.5 nm and 698 nm systems are using fused silica mirrors for low thermal noise limit. From the beat note between two similar 1062.5 nm systems (10 cm, fused silica mirrors), we estimated that one laser has a flicker floor of $4x10^{-16}$ at 1 second. The same laser has a typical drift rate of $-6x10^{-17}$ per second (-16.9 mHz/s). With this linear drift removed, the stability against LNE-SYRTE ultra-stable microwave reference (cryogenic oscillator locked to a H-maser) is below $2x10^{-15}$ at 1000 seconds. The 698 nm laser measured either the Sr clock transition or against the 1062.5 nm laser through an optical frequency comb has a flicker floor of $7x10^{-16}$.
- We developed other types of stable lasers for applications. This includes lasers stabilized to fiber delay lines that can be comparatively simple, robust and cost effective for a number of demanding applications: ultra-low noise microwave generation, signal regeneration for coherent optical fiber link, ultra-stable agile laser for satellite Doppler tracking in the optical domain, etc. We also developed, with industrial partner, elegant breadboard level, ultra-stable cavity aimed at space applications. A transportable, 10 cm long prototype of this cavity, that can stand several g of acceleration, has shown stability of $\sim 6x10^{-16}$ at 1 second. Finally, we are developing compact, high performance stabilized lasers based on in-cavity Doppler-free spectroscopy of iodine.

Optical frequency combs

Main achievements on optical frequency combs since the 18th CCTF report:

- We investigated and developed a number of methods to generate extreme low noise microwave signals with Erbium fiber based optical frequency combs. This includes tests of high bandwidth actuator for combs (collaboration with industrial partner) together with the carrier-enveloped “mix-out” method. We also developed cascaded fiber delay lines for pulse rate multiplication and performed detailed studies of noise conversion processes in the detection of femtosecond pulses. Combining all these methods, we demonstrated optical-to-microwave conversion at the level of $1.1x10^{-16}$ at 1 second and $2x10^{-19}$ at 1000 s.
- We performed accuracy test of a Ti:Sa and a fiber based combs by measuring independently (2 separate rooms) but simultaneously the frequency of same 1062.5 nm light against LNE-SYRTE ultra-stable microwave reference (cryogenic oscillator lock to a H-maser). Measurements were found to be in agreement at the $<10^{-17}$ level.
- Optical frequency combs were used for many absolute frequency measurements of 1542 nm, 1062.5 nm and 698 nm light against Cs fountains and measurements against FO2-Rb fountain.

Coherent optical links

Main achievements coherent optical links (fiber and free space) since the 18th CCTF report:

Fiber links

This work is done in collaboration with LPL-Laboratoire de Physique des Lasers (CNRS and Université Paris 13.

We investigated frequency dissemination of an ultra-stable 1.5 µm optical carrier through the fiber network RENATER, using the so-called "dark channel approach", sharing fibers with internet data traffic. We implemented a cascaded optical link of 2x150 km that comprises all the elements for future large scale deployment. This notably includes OADM bidirectional amplifiers for the chosen channel, an optical carrier signal regeneration station and 200 km of fiber shared with internet data. Stabilities of $4x10^{-15}$ at one second and $<10^{-19}$ at one day are measured for this link (measurement bandwidth 10 Hz). We have extended this test bed to 500 km.

We initiated regional and national (REFIMEVE) scale projects and are participating to European scale project that aim at connecting key laboratories with such coherent optical fiber links.

Links in free space

This work is done in collaboration with OCA-Observatoire de la Côte d'Azur.

We investigated the possibility of ground-to-space, and space-to-space transmission of a coherent ultra-stable carrier. In a first experiment, we implemented a horizontal, 5 km transmission of a 1064 nm optical carrier through the atmosphere in order to have a representative characterization of the phase noise introduced by turbulence. Next, we developed and characterized an agile ultra-stable laser system based on fiber spool delay line. This system will use to test the coherent transmission from ground to a corner cube reflector located on Low Earth Orbit satellites and back. The agile ultra-stable agile laser system will allow compensating for the Doppler shift due to the satellite motion, which on the order of ±10 GHz.