Report to the 21st CCTF, June 2017

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This report describes activities in Time and Frequency Metrology pursued since the last meeting of the CCTF in 2015.

Content

1- Primary frequency standards

LNE-SYRTE operates 2 cold atom fountains which regularly contribute to TAI: FO1 is a cesium fountain (PFS since 1995) and FO2 is a double fountain operating simultaneously with cesium as PFS (since 2002) and with rubidium as SFS also included in the steering of TAI (since 2013).

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.

▪ Fountain clocks

In nominal operation, the fountains use the same reference signal provided by a cryogenic sapphire oscillator (CSO) phase locked to a hydrogen maser allowing to reach the quantum projection noise limit. Typical relative frequency instabilities are typically $\sigma_y(\tau) \sim 8\times10^{-14}\,\tau^{-1/2}$ for FO1 and FO2-Cs and $6\times10^{-14}\,\tau^{-1/2}$ FO2-Rb. These instabilities result from the combination of low and high atomic density operations required for the real time extrapolation of the cold collisions frequency shift and correspond to the quantum projection noise. The magnetic field and the temperature around the interrogation zone are measured every ~1 hour in order to estimate the corresponding frequency shifts of the clock transition. The distributed cavity phase shift is verified from time to time with differential measurements alternating the cavity feedings. Absence of phase transients synchronous with the fountain cycle or induced by the switching of the microwave interrogation signal is also regularly tested.

Frequency calibrations of the reference hydrogen maser updated every one hour with an uncertainty of 10^{-15}, or below, are used on a daily basis to steer the frequency of the reference hydrogen maser which is the clock at the basis of the French timescale UTC(OP) (Sect. 2).

New absolute frequency measurements, referenced to our fountains, have been carried out locally with our two strontium optical clocks and our mercury clock (Sect. 4).

The large amount of Rb/Cs data provided by the dual fountain FO2 over the last six years have been exploited to search for cosmological dark matter. The results improve over results from similar searches with Dy by more than one order of magnitude. This work is reported in Phys. Rev. Lett. 117, 061301 (2016).

The following table gives typical accuracy budgets of the LNE-SYRTE fountains:

	FO1	**FO2-Cs**	**FO2-Rb**
Quadratic Zeeman Shift	-1224.3± 0.2	-1920.1 ± 0.3	-3471.4 ± 0.7
BlackBody Radiation	171.4 ± 0.6	169.1 ± 0.6	124.9 ± 1.4
Collisions and Cavity Pulling	43.4 ± 1.7	68.8 ± 1.6	7.3 ± 1.4
Distributed Cavity Phase Shift	-1.0 ± 2.7	-0.9 ± 0.9	-0.4 ± 1.0
Spectral Purity and Leakage	<1.0	<0.5	<0.5
Ramsey & Rabi pulling	<1.0	<0.1	<0.1
Microwave Lensing	-0.7 ± 0.7	-0.7 ± 0.7	-0.7 ± 0.7
Second-Order Doppler Shift	<0.1	<0.1	<0.1
Background Collisions	<0.3	<1.0	<1.0
Total without Red Shift	1011.2 ± 3.6	-1683.8± 2.4	-3340.3 ± 2.7
Red Shift	-69.3 ± 1.0	-65.5 ± 1.0	-65.4 ± 1.0
Total with Red Shift	-1080.5 ± 3.8	-1749.3±2.6	-3405.7 ± 2.9

Table 1: Systematic fractional frequency corrections and uncertainties for FO1, FO2-Cs and FO2-Rb, in units of 10^{-16} (see calibration reports to BIPM of April 2017 for FO2-Cs/Rb, and of June 2015 for FO1).

Contributions to TAI with the primary and secondary frequency standards (PSFS)

From January 2015 to April 2017 (MJDs 57019-57869, 28 months), the LNE-SYRTE PSFS, FO1, FO2-Cs and FO2-Rb provided 2, 27 and 29 calibrations reports to the BIPM, respectively, to contribute to the steering of TAI (see Figure 1). They represent almost 40% of the total number of calibration reports from the fountains worldwide. Note that a fractional change (about $3x10^{-16}$) in the definition of the ^{87}Rb secondary representation of the second has been applied starting March 2016 following the recommendation of the last CCTF.

Besides, we have performed the first international comparison of distant fountains PSFSs via an optical link. Our 3 fountains PSFSs were compared to the 2 PFSs of PTB (Braunschweig), CSF1 and CSF2, using the same link as the one implemented for the comparison of the optical clocks from our two institutes. The results of the comparisons fully support the stated LNE-SYRTE and PTB PFSs' uncertainties. In addition, the comparisons of FO2-Rb (SFS) to the four Cs fountains provide a new absolute frequency determination of the ^{87}Rb ground state hyperfine splitting with an uncertainty of $3.1\text{x}10^{-16}$. This work is reported in Metrologia 54 (2017) 348–354.

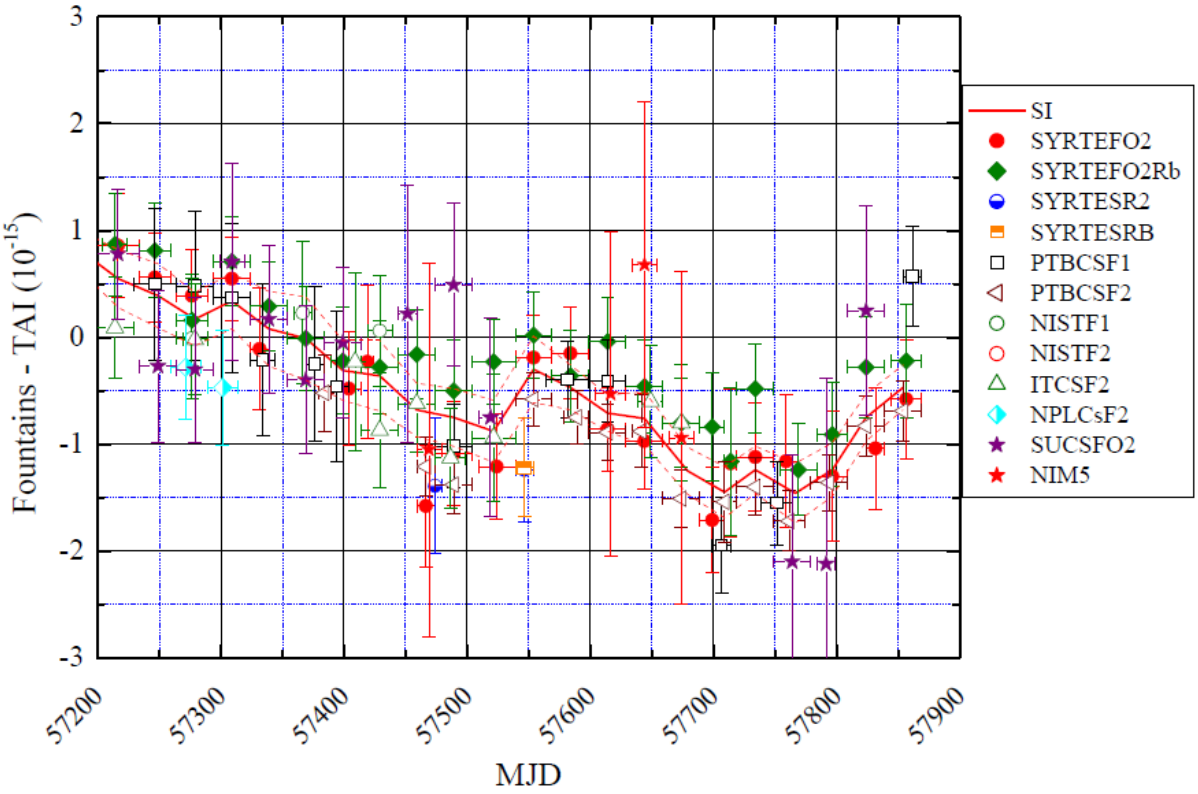

Figure 1: Contributions to TAI from all PFSs worldwide over January 2015 – April 2017, including the evaluations from the SFS FO2-Rb.

Some mention concerning FO1. By end of 2015, the fountain was opened to remove its internal electric plates previously used for measurements of the Stark shift involved in the evaluation of the blackbody radiation shift. A complete refurbishment including the change of the 2D-MOT Cs atom presource and improvement of the fountain environmental conditions, was undergone during 2016. Since several months now, FO1 is operating reliably. The uncertainty budget is under evaluation and FO1 contribution to TAI should soon restart.

▪ The PHARAO/ACES space mission

In the framework of the ACES space mission of ESA, LNE-SYRTE is the principal investigator in the development of the first primary frequency standard for space operation: the laser cooled atomic clock PHARAO developed by CNES. LNE-SYRTE is also developing the software for the scientific analysis of the data comparisons between ground and space clocks. During the mission LNE-SYRTE will be a major ground station to fulfill the scientific objectives of the ACES mission.

The flight model of PHARAO, delivered to ESA in July 2014, has been retested on site in autumn 2016, with the ACES payload partially integrated. The performances of PHARAO have not evolved during the >2 years of storage. During this campaign, the control loops between the two clocks on board, PHARAO and the SHM (space hydrogen maser), have also been tested. At the next campaign planned in autumn 2017, the ACES should be completely assembled.

The installation of the infrastructure required to accommodate the microwave ground station at Observatoire de Paris is ready, including the distribution of the reference signals which are currently under characterization.

2- Time scales

▪ UTC(OP)

UTC(OP) is realized using a microphase stepper fed by the reference H-maser of the laboratory. A frequency correction is updated every day to compensate for the maser frequency variations and to maintain UTC(OP) close to UTC. This correction is the sum of two terms. The main term corresponds to the current frequency of the maser as calibrated daily by LNE-SYRTE's atomic fountains. The second term is a fine steering to maintain UTC(OP) close to UTC, compensating for the frequency and the phase offset between UTC(OP) and UTC. It is updated monthly at the BIPM *Circular T* publication. The steering correction is usually of the order of 10^{-15} or below.

The UTC(OP) generation and distribution hardware has been completely renewed in 2015. Two low noise 100 MHz frequency offset generators fed by two different masers have been implemented in order to generate two independent timescales for redundancy. The new system includes a switch allowing the commutation between these nominal and backup timescales with negligible impact on the amplitude and on the phase of the distributed signals. The equipment of the laboratory was progressively transferred from the previous UTC(OP) generation chain to the new one between June and November 2015, while preserving the phase continuity of the measurements.

Figure 2 below shows the comparison of three UTC(k) to UTC as published in *Circular T* since beginning of 2015. Over the reported period, UTC(OP) is one of the three best real-time realizations of UTC. The departure between UTC(OP) and UTC remains well below 10 ns, with an rms value of less than 3 ns, which approaches the uncertainty of the time transfer calibrations. The time step on UTC(OP) at the end of the period is due to the application of a new calibration result for the TWSTFT at MJD 57842.

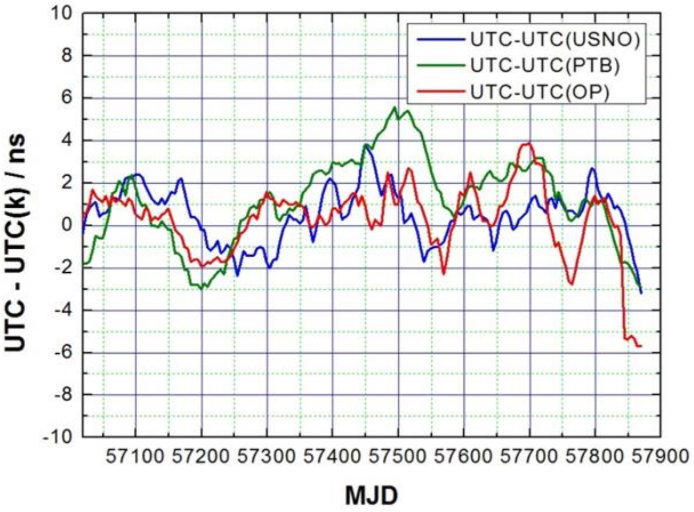

Figure 2: Comparison of UTC(OP), UTC(PTB) and UTC(USNO) with UTC from data published in *Circular T*.

- ## TA(F)

LNE-SYRTE also maintains the French time scale TA(F), which is based on a weighted average of about 20 to 25 commercial caesium beam clocks located in some 10 French laboratories that are compared daily to UTC(OP) using GPS TAIP3. This time scale is calculated monthly before sending clock data to the BIPM to contribute to EAL computation. The time scale algorithm uses the ARIMA method for the weighted averaging of the clock data. The resulting time scale is also frequency steered using the LNE-SYRTE fountain calibrations. With this method, the monthly average frequency of TA(F) is in agreement with that of the SI second within a few 10^{-15} as can be seen from the data published in the BIPM *Circular T*.

3- Time and frequency transfer

- ## GNSS for time and frequency transfer

Time and frequency transfer

LNE-SYRTE provides daily to BIPM the required GPS RINEX data for the PPP processing part of the TAI/UTC generation and for UTCr generation. In addition, GPS and GLONASS CGGTTS data are forwarded to BIPM too, including data for the computation of UTC – UTC(USNO)_GPS. One of LNE-SYRTE 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 OPMT IGS station main unit is directly connected to the UTC(OP) signal. Since the end of 2016, two new independent GNSS receiving chains were implemented in OP. RINEX data from these two additional OP chains are ready to be delivered daily to BIPM.

Calibration

The continuous monitoring carried out in LNE-SYRTE of the differences between GPS TAIP3 CV and TWSTFT on the OP-PTB link shows an average drift of about 1 ns/year during the last six years. As G1 laboratory, LNE-SYRTE receiving chains were calibrated twice by BIPM in 2015 (#1001-2014) and in 2016 (#1001-2016), the latest including the two recently added chains. Calibrated results have been implemented for each GNSS receiver in due time following BIPM request. In 2016, LNE-SYRTE performed G1/G2 calibration campaigns for the French Space Agency (CNES), INRIM, SP and ROB. The LNE-SYRTE formal calibration reports are built today to fit as close as possible the BIPM Guidelines for GNSS calibrations.

- ## Contribution to European GNSS projects

EGNOS

The broadcast value for UTC – ENT (EGNOS Network Time) is obtained through UTC(OP) via a ground station located in OP. The improvement in the UTC(OP) time scale since 2012 has led naturally to an improved access to UTC for EGNOS users.

Galileo

Together with other European NMIs, LNE-SYRTE is contributing to Galileo activities at system level by providing daily GPS CV and TWSTFT data collected against UTC(OP), to be used for the generation of a prediction of UTC aiming at Galileo System Time steering. In addition LNE-SYRTE is in charge of the characterization of GPS receiver delays, for receivers located in the participating NMIs and in the Galileo Precise Time Facilities (PTF). Since the start of the current contract, all requirements have been fulfilled on these aspects.

▪ Two-Way Satellite Time and Frequency Transfer

LNE-SYRTE operates two fully independent Ku-band VSAT stations, that have been connected since the end of September 2015 directly to UTC(OP), by removing any intermediate clock. The station named OP01, calibrated at the nanosecond level, is equipped with a satellite simulator developed in the laboratory.

OP01 is linked to the European and Transatlantic two-way networks, for which the recorded measurement data are processed and provided in a specific ITU format, for:

1) The computation by the BIPM of UTC - UTC(OP) using the primary two-way link OP-PTB. Over the past two years, a combined uncertainty of 1.2 ns to 1.8 ns on UTC - UTC(OP) was obtained, as calculated and published by the BIPM. The OP-PTB calibration values deviation between the two last TWSTFT calibration campaigns remains below 100 ps.
2) The contribution to Galileo activities at system level as described above in this report.

The second station named OP02, dedicated to research and development activities, has been re-characterized and upgraded during the past year. In the frame of the BIPM pilot study on SDR, LNE-SYRTE implemented in 2016 an SDR receiver using a software developed by TL. LNE-SYRTE established SDR receiver-based two-way links with some European stations and the NIST. SDR receiver data are recorded continuously and provided to the BIPM on a daily-basis.

4- 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 20th CCTF report.

Sr lattice clocks

- The best reported total fractional frequency uncertainty for our lattice clocks is 4.1×10^{-17} (see Lodewyck et al., Metrologia 53, 1123(2016)).
- We have performed several absolute frequency measurements of the Sr optical lattice clock, reaching a total fractional frequency uncertainty of 2.8×10^{-16} (see Metrologia 53, 1123 (2016)). We have also measured the ratio between Sr and the 87Rb hyperfine frequency with an uncertainty of 3.3×10^{-16}. Measurements are consistent with previous measurements of the same quantity.
- We have measured the ratio between Sr and the Hg optical lattice clock (see next).
- We published the result of the comparison between Sr optical lattice clocks at LNE-SYRTE and at PTB via coherent optical fiber link. See C. Lisdat et al., Nature Communications 7, 12443 (2016). The result of the comparison is $\mathrm{Sr(PTB)/Sr(SYRTE)} - 1 = (4.7 \pm 5.0) \times 10^{-17}$.

- We improved the reliability and operability of our Sr clocks. As a result, measurement time above 80% is obtained over several weeks.
- We performed a series (five) of calibrations of the frequency of one of our H-maser using our Sr optical lattice clock as a secondary representation of the second. Calibrations were made in the format necessary for TAI calibrations (in particular following the conventional 5 day grid and including the necessary relativistic correction). These calibrations were submitted to the BIPM time section which processed these calibration as for TAI. LNE-SYRTE proposed that such calibrations be used for TAI. The proposal was considered by the working group on primary and secondary frequency standards. The working group approved the use of such calibration for TAI. This set of calibrations is published in Circular T350. These are the first calibrations of TAI based on an optical frequency standard. The working group approved that such calibrations be used for steering TAI, after the revision of the recommended value of the 87Sr optical clock transition by the CCL-CCTF frequency standards working group at the 2017 CCTF.
- We have developed, on one of our Sr lattice clock (SrB), a highly sensitive non-destructive atomic detection. The detection is based on measuring the dispersive effect (index of refraction) of the atomic sample on light at 461 nm. The sensitivity is enhanced with a Fabry-perot with a finesse of 16000 and a noise-immune measurement scheme (see G. Vallet et al., arXiv:1703.04609, accepted in New Journal of Physics). The detection as a sensitivity equivalent to 3.7 atoms for 38 scattered photons. As such, it is highly non-destructive in the classical sense. It can be further optimized to reach the regime of quantum non-destructivity. Such detection will be used in tailored probing sequence that can mitigate laser noise to improve the clock stability. Further, it can be used to generate and manipulate entangled atomic states or spin-squeezed states that can even further improve stability beyond the quantum projection noise limit.
- We are conducting a number of improvements, in particular the implementation of a vacuum system with an improved (room temperature) blackbody environment, compatible with uncertainties near 10^{-18}.

Hg lattice clock

- Our ^{199}Hg optical lattice clock reached a total fractional frequency uncertainty of 1.7×10^{-16}.
- We published an absolute frequency measurement of the Hg optical lattice clock frequency with a fractional frequency uncertainty of 3.7×10^{-16}. We also measured the frequency ratio between Hg and the 87Rb hyperfine frequency, with a fractional uncertainty of 3.8×10^{-16}.We published an optical-to-optical frequency comparison between the Hg optical lattice clock and Sr lattice clock. See Tyumenev et al., New Journal Phys. 18, 2016, 113002. The Hg/Sr ratio is determined with an uncertainty of 1.8×10^{-16}. It is in agreement with the other measurement reported in Yamanaka et al. Phys. Rev. Lett.114, 230801 (2015).
- Several improvements of the Hg optical lattice clock are close to completion:
    - Replacement of the titanium:sapphire laser use for the lattice trap, which gives access to lattice trap depth higher than 100 recoil energy.
    - Frequency measurement and stabilization of the lattice laser frequency with an optical frequency comb.
    - Use of a fiber amplifier in replacement of an injection-locked semi-conductor laser to amplify the ultra-stable clock light at 1062.5 nm.
    - Implementation of an additional laser source at the cooling wavelength of 254 nm to allow the operation of 2 dimensional magneto-optical trap to increase the number of atoms.
    - Implementation of a normalized detection
- Altogether, we expect that these improvements will enable stability in the mid 10^{-16} at 1 s or less, with our existing ultra-stable laser, and better with new generation ultra-stable lasers. This shall in turn enable total uncertainty for the clock in the low 10^{-17} in the existing setup.

5- Optical frequency metrology

Ultra-Stable Lasers

Laser stabilization based on spectral hole burning:

We developed an experimental device aimed at realizing ultra-stable lasers locked onto narrow spectral features photo-imprinted in a rare-earth-doped crystal at cryogenic temperature (4K). This new technology has the potential to reach short term stabilities in the 10^{-17} or lower, due to the extremely low impact of thermal-agitation on the spectral features at cryogenic temperatures. We have demonstrated imprinting of spectral features narrower than 3 kHz (FWHM) and generation of an error signal suitable to servo a laser on them. We are developing agile and low noise detection methods to take full advantage of the observed narrow spectral holes. We have improved and are still improving the environment of the crystal in the cryostat to minimize perturbations (temperature, vibration, etc.).

Other ultra-stable lasers:

We are maintaining and using ultra-stable lasers based on 10 cm long Fabry-Perot cavities at wavelengths of 1062.5 nm, 1542 nm and 698 nm with flicker noise floor ranging between 4×10^{-16} and 2×10^{-15}.

We are developing an ultra-stable laser based on ~40 cm long Fabry-Perot cavity at the wavelength of 1542 nm.

Optical frequency combs

The activities on optical frequency combs are two-fold: operational activities to measure clock frequencies ratios (internal measurements at SYRTE or comparison to European clocks during international fiber links campaigns) or search of extreme spectral purity in the generation of microwave at 12 GHz by division of a 1542 nm optical carrier by frequency combs.

The output range of the operational frequency chain has been extended, and the comb is now able to measure frequencies at 698, 813, 1062, 1160, 1450, 1542 and 1544 nm. All optical measurements are now routinely performed in order to measure the frequency ratios between the SYRTE clocks (Sr and Hg) with a resolution in the low 10^{-17}, or to reference these clocks to the 1542 nm carrier of the international optical fiber link, therefore allowing remote and low noise comparisons to other European optical clocks (stability at the $1\text{x}10^{-15}$ level at 1 s). Frequent comparisons to SYRTE microwave standards have led to refined absolute frequency values and monitoring of the long term reproducibility of the connection of optical standards to SYRTE primary (Cs) and secondary (Rb) microwave clocks. During the measurement campaigns, the uptime of the chain is larger than 95 %.

We also investigated and developed a number of methods to generate extreme low noise microwave signals with Erbium fiber based optical frequency combs. This includes, in collaboration with industrial partners, the setup and characterization of new fiber-comb technologies with reduced intensity noise, use and characterization of new very high power handling and linearity photodetectors and repetition rate interleavers, and realization of phase noise measurement device with very low amplitude noise sensitivity. In our latest publication (Nature Photonics 11, 44 (2017), we demonstrate microwave signals with exquisitely low phase noise floor of -173dBc/Hz for a 12 GHz carrier, which corresponds to a timing noise floor of 41 $\text{zs.Hz}^{-1/2}$.

6- Coherent optical links

Fiber links

This work is done in collaboration with LPL-Laboratoire de Physique des Lasers (CNRS and Université Paris 13) and RENATER, the French National Research and Education Network. We investigate 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. Regional and national (REFIMEVE) scale projects are under development and we are participating to European scale project that aim at connecting key laboratories with such coherent optical fiber links.

We implemented a cascaded optical link of 1420 km connecting SYRTE to University of Strasbourg through the RENATER network with parallel data traffic. This long haul fiber link comprises all the elements for future large scale deployment. This notably includes OADM for the chosen channel, bi-directional amplifiers, and four optical carrier signal regeneration stations. Relative frequency stabilities of $4x10^{-16}$ in 1-Hz bandwidth at one second and $<10^{-19}$ at one day integration are measured with this link. The accuracy of the link is evaluated to be $<1x10^{-19}$.

We are operating two international coherent fiber links. The first one connects SYRTE and PTB (Physikalisch-Technische Bundesanstalt, Braunschweig, Germany), with interconnection at the university of Strasbourg with the link PTB-Strasbourg. The second one connects SYRTE and NPL (National Physical Laboratory, United Kingdom), with interconnection at LPL. These two international links enable optical frequency comparison by fiber links between the three metrology institutes. SYRTE is the only laboratory in the world to be connected by two international links.

By operating SYRTE-PTB links, we carried out the first international optical frequency comparison between distant optical Sr lattice clocks. The relative frequency stability of the comparison is about $2x10^{-15}$ at one second in 1 Hz bandwidth, and reaches a statistical uncertainty $< 4x10^{-17}$ in less than one day of operation. We were able to use the same link to carry out the first international fountain clocks comparison, without any limitation arising from the mean of comparison. We found perfect agreement inside the statistical errors bars between all the pairs formed by the 5 fountains set (3 at SYRTE, 2 at PTB)

We operate the SYRTE-NPL link for clock comparison in June 2016. By combining the data with the one obtained with PTB, we were able to carry a test of Lorentz invariance using the clock comparison data that outperform previous experimental limits based on accelerated ions.

Links in free space

Initial work focused on experimental studies for ground-to-space, transmission of a coherent ultra-stable carrier (Djerroud et al., Opt. Lett, 35, 1479, (2010); Chiodo et al. Applied Opt., 52, 7342 (2013)). Whilst horizontal short distance (5 km) links showed very promising results, ground to satellite links remained unsuccessful due to extremely low return signal power in the presence of atmospheric turbulence. In the past 2 years we have focused on extensive numerical simulations of laser propagation in the turbulent atmosphere, specifically applied to optical clock comparisons (Robert et al., Phys. Rev. A93, 033860, (2016)). We have shown that in spite of uplink vs downlink asymmetries two-way compensation of phase noise in the turbulent atmosphere is very efficient and allows frequency stabilities as low as 10^{-17} after only a few seconds averaging time. However, a minimum of adaptive optics (tip-tilt correction) is mandatory to maintain an acceptable signal level.

Present work is focusing on preliminary design for an intermediate distance (few 100 km) clock comparisons system, consisting of two ground telescopes and a relay mirror onboard a high altitude platform (stratospheric balloon or similar). One of the first applications of such a system would be chronometric geodesy with one of the clocks transported in the field in order to map out a high resolution geoid as studied e.g. in (Lion et al. J. Geod (2017) 91: 597).