ONGOING IMPROVEMENTS OF THE TIME AND FREQUENCY REFERENCES AT LNE-SYRTE

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ABSTRACT

We present the current developments performed at LNE-SYRTE, to produce a new time reference, called UTC(OP)_Maser. This time reference aims at taking benefits of our clock ensemble: the short term stability of a hydrogen maser, the mid term stability of our ensemble of industrial cesium clocks, and the accuracy of our three cold atom fountains. This paper describes an algorithm that produces a timescale optimised in terms of stability over averaging periods of 1-2 months, with a weighted average of the cesium clocks data. We also present the steering processes, involving the fountain calibrations, to drive the timescale towards UTC, and to control the hydrogen maser. The simulations, based on past data, show an improvement of a factor of 5, in terms of time accuracy, compared to the current UTC(OP). The first experimental results demonstrate a gain of more than one order of magnitude on the short term stability.

INTRODUCTION

The time reference UTC(OP) is the real time realization of the Coordinated Universal Time (UTC) for France, produced at Observatoire de Paris. It is currently based on the manual steering towards UTC of the output signal of a single industrial cesium beam clock, according to the departures monthly published by the BIPM (Bureau International des Poids et Mesures) in the Circular T. With this system, we maintained the difference |UTC - UTC(OP)| below 80 ns over the past 10 years. UTC(OP) is also the pivot for the time comparisons with our other industrial clocks (seven cesium beams and four hydrogen masers), and the time reference for the time transfer links by GPS and TWSTFT, that allows distant comparisons to other laboratories and the connexion to the BIPM. On the other hand, we use the output signal of a free running hydrogen maser as a stable frequency reference for the time transfer links. This frequency reference is also distributed to our four Primary Frequency Standards, the thermal beam JPO, and the three cold atom fountains FO1, FO2 and FOM, and to the other experiments under development in the laboratory (optical clocks, miniature clocks …).

In this paper, we describe the current status of the development we have undertaken a few years ago [1] to improve the performances of UTC(OP). We have developed a new timescale UTC(OP)_Maser, based on the steering of the output signal of a hydrogen maser by a weighted average of the industrial cesium clocks data, to take benefits of the short term stability of the maser and of the long term stability of the clock ensemble. The free running timescale is then steered towards UTC using its calibration against the Primary Frequency Standards, and using the frequency departures of TAI from the SI second, as published in the Circular T by the BIPM. The stability algorithm, inspired from AT1 developed by National Institute of Standards and Technology (NIST) [2, 3], is described in section 1. We present the steering processes in section 2 and the first experimental results in section 3, before to conclude.

STABILITY ALGORITHM

We have developed a robust algorithm based on a weighted average of the industrial clocks data to produce a free running timescale, called EAL(F), optimised in terms of stability for averaging times of 1-2 months. This period corresponds to the delay before the availability of new calibration data from the Primary Frequency Standards and from the Circular T, for the steering of the timescale towards UTC.

The stability algorithm is based on the AT1 method developed at NIST years ago [2, 3]. This was chosen at the beginning of the study because of the simplicity and the reliability of the algorithm that demonstrates good performances. The method is based on the phase and the frequency predictions of the clocks with respect to the ensemble, determined at each step of the calculation. The clock model also includes a possible frequency drift. The weight attributed to each clock is calculated from the phase error between the predictions and the measurements. In order to smooth the clock fluctuations, the algorithm also includes exponential filters on the frequencies, the frequency drifts and the prediction errors.

We have implemented and optimised this algorithm using our cesium clocks data accumulated over the past 5 years. These data stem from daily comparisons between the clocks and UTC(OP), measured by time interval counters. To face events such as missing data, phase and frequency steps, or the failure of a clock, unavoidable over long periods on a real time operational timescale, we have implemented in the algorithm a default detection module that automatically excludes the defective clock from the ensemble. For that purpose at each step of the algorithm, we calculate phase predictions of the clocks, and compare them to the measurements. The clock is eliminated if the difference is higher than a threshold of 20 ns. To ensure the phase continuity during the rejection, we compute one step back the timescale for two times, with and without the defective clock. The phase continuity corrections to be applied to the remaining clocks for the next step are then the differences between the phase predictions obtained in both calculations. On the other hand, if the failure of the clock disappears, or if a new clock is available, the algorithm automatically introduces the clock in the ensemble. This is performed after an observation period of 10 or 180 days of the clock against the timescale, for the initialization of its parameters.

We tried to optimise the stability of the EAL(F) with other weighting methods, such as the Allan standard deviation at 30 days. Indeed, once the timescale computation is performed, one can calculate the Allan deviation over a given averaging period for each clock against the ensemble. We estimated that 180 days was long enough to estimate the Allan deviations at 30 days with a sufficiently low statistical uncertainty. This induces that a longer observation period is necessary for the introduction of a new clock, compared to the weighting with prediction error (10 days). This could affect the robustness of the algorithm in case of a low number of clocks in the ensemble. We tested a third weighting method based on a simple average of the prediction errors and the Allan standard deviations. The initial idea was to affect a stronger weight to the clocks the most stable both on the short term (daily prediction error) and on the long term (Allan standard deviation).
We also try to reduce the timescale long term frequency fluctuations, which depends on the clock frequencies. The more the weight of a clock is growing, the more the frequency of EAL(F) depends on this clock. In our early computations, the initial frequency of a clock was just an evaluation against the timescale. One could expect to reduce the fluctuations of the timescale, if we compensate the initial clock frequencies. This has been tested with two methods: the correction corresponds to the frequency of the clock either at the beginning of the observation period or at the end of the observation period, when the weight is allowed to grow.

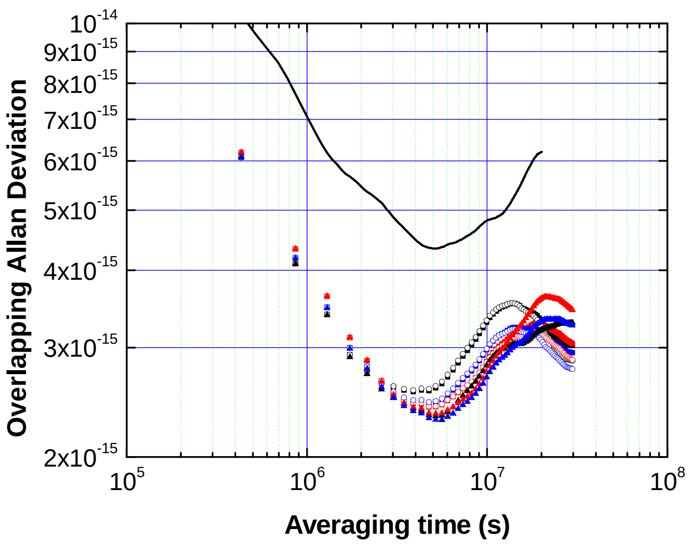

Fig. 1: Overlapping Allan deviation of the free running timescale compared to UTC, after removing a quadratic fit on the phase comparison. The timescale is computed for the different combinations of the three different weighting processes (Black: prediction error; Red: Allan standard deviation, Blue: the average of both), associated with the three methods to correct the frequency of the clocks when introduced in the ensemble (■: no correction; ○: correction at the beginning of the observation period; ▲: correction at the end of this period). Black line: typical stability of a single cesium beam clock.

In Fig. 1, we present Allan deviations of the difference between UTC and EAL(F), computed with the clock data of the past ~5 years, after removing a quadratic fit on the phase comparisons. The nine dot curves correspond to the different combinations of the three weighting processes, and the three initial clock frequency correction methods when introduced in the ensemble. We observe that the short term stabilities are almost the same for averaging times lower than 30 days. There are small variations between 1 and 2 months, which is our integration period of interest. If we compare the first two initial clock frequency correction methods (no correction or at the beginning of the observation period), we observe no significant differences, for a given weighting method. If we look at these 6 curves, as a function of the weighting process, we deduce that using the Allan standard deviation improves the stability. The best results are obtained with the third clock initial frequency correction method (determined at the end of the observation period). The stability is less sensitive to the weighting process in these cases. We reach a stability better than 3 x 10^{-15}. This is a gain of a factor of ~2 compared to a single cesium clock (black line in Fig. 1). This is consistent with what could be expected, if we consider the number of weighted clocks in the timescale (between 4 and 6, over the computation period).

STEERING PROCESSES OF AN HYDROGEN MASER TOWARDS UTC

The role of EAL(F) is to produce a stable reference keeping the memory of UTC between two publications of the Circular T. At this step of the discussion, the free running timescale has arbitrary phase and frequency offsets against UTC. Thus, before to steer the hydrogen maser, we calculate an intermediate calibrated timescale called TA(OP). For that purpose, we have taken benefit of the three atomic fountains currently in operation at LNE-SYRTE: FO1, FO2 and the mobile fountain FOM. The accuracies are ~ 4 x 10^{-16} for the first two fountains and ~ 7 x 10^{-16} for the third one [4,5]. The operation of the Primary Frequency Standards is almost continuous since a few years, and data are regularly transmitted to the BIPM to participate to the monthly steering of Temps Atomique International (TAI) and to the computation of the SI second. These data are also used internally for the frequency correction of the other French timescale TA(F) [6, 7]. The steering method of EAL(F) is somehow similar to the one applied to TA(F). We estimate monthly a frequency correction from the average frequency difference between EAL(F) and the fountains. But contrary to TA(F), which is a post processed timescale, we use this correction as a prediction of EAL(F) frequency for the following month. In addition, a second correction is necessary to compensate the small departure between the frequencies of UTC and the SI second. The value of this difference is given by the parameter d = TAI - SI published in the Circular T. Fig. 2-a gives the resulting phase differences TA(OP) - UTC over the past 540 days. We observe that TA(OP) is affected by a residual phase drift probably due to the delay of 1 month for the calibration of EAL(F) against the fountains. The corresponding average frequency of TA(OP) with respect to UTC is of the order of 8 x 10^{-16}. We have plotted in Fig. 2-b, the overlapping Allan deviations of EAL(F) - UTC and TA(OP) - UTC. The graphs show that the steering has no major effect on the stability for averaging periods lower than 10 days. But it produces a ~ 3 x 10^{-15} bump around 30 days, as expected. For longer periods, the frequency drift of the free running timescale is well compensated and the stability of TA(OP) - UTC reaches 10^{-15} at 60 days.

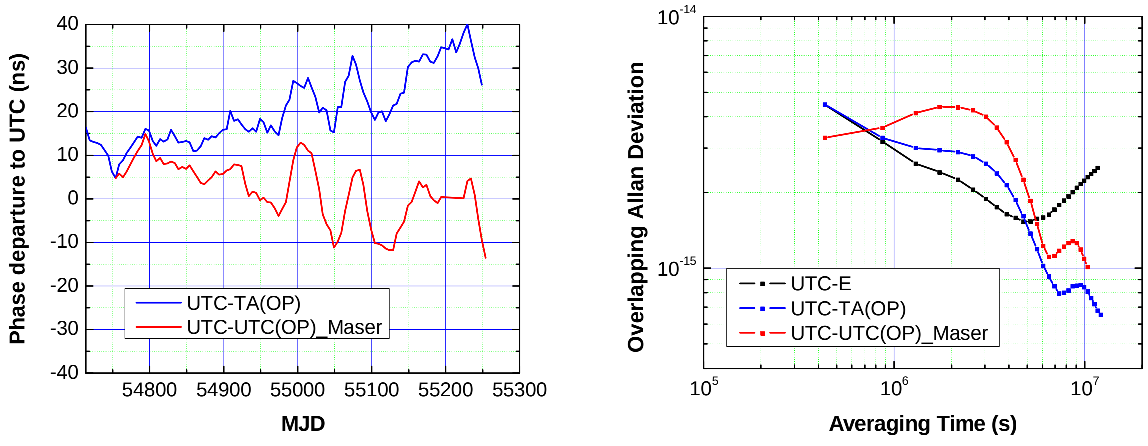

Fig. 2: (a) Phase comparison of TA(OP) and UTC(OP)_MASER to UTC; (b) Overlapping Allan deviation of EAL(F) - UTC, TA(OP) - UTC and UTC(OP)_MASER - UTC

The main difficulty in the steering of a hydrogen maser towards UTC using TA(OP), is to find the best trade-off that preserves the short term stability of the maser and the long term stability of TA(OP). We have thus chosen to use adjacent averages of the comparisons between the maser and the steered timescale, in order to smooth the short term fluctuations of TA(OP). The steering is applied daily and consists in the sum of three corrections: first, a frequency correction based on the average evaluated over the past 10-20 days; second, a frequency drift correction determined over the last 30-40 days; and third, a frequency correction based on an initial evaluation of the frequency difference between UTC and TA(OP). The value of this manual frequency correction is 7.8 x 10^{-16}. The averaging periods depend on the maser behaviour and are determined experimentally. The best results are currently obtained with the maser H890, which is the most predictable. It has also the lowest frequency drift. The overlapping Allan deviation of UTC(OP)_MASER - UTC is plotted in Fig. 2-b. The bump on the stability at 30 days increases to 4 x 10^{-15}, compared to TA(OP), because of the additional corrections. The deviation is also slightly degraded for longer averaging periods. We observe an improvement at an averaging period of 5 days. This is due to the fact that the stabilities of the maser and of UTC are both better than the one of TA(OP) for this integration time. This indicates that the steering process does not dramatically affect the short term stability of the maser. The phase difference UTC(OP)_MASER-UTC for the last ~540 days is plotted in Fig. 2-a. We observe that the departures remain below 15 ns, which is a very good result. We are nevertheless aware that the difference could increase in the future. Indeed, a residual slope is clearly visible on UTC(OP)_MASER – UTC. It corresponds to a frequency of ~ - 4 x 10^{-16}. Hence, to compensate from slow evolutions of the timescale or the hydrogen maser, we will probably have to change the manual correction in the future. This correction might be updated by considering the past ~ 6 months.

FIRST EXPERIMENTAL RESULTS ON UTC(OP)_MASER

The automatic daily calculations of EAL(F) and TA(OP) have been implemented since the middle of 2009. At the beginning of 2010, we have also started to produce a physical signal of UTC(OP)_MASER. For that purpose, we use the backup micro-phase stepper of UTC(OP) to steer the output of the maser. To characterize the long term performances of the new timescale, we have installed an additional time interval counter, operated with 1 PPS signals, to measure the phase differences UTC(OP) - UTC(OP)_MASER. The comparison to UTC will be performed by using the differences UTC - UTC(OP) published in the Circular T. The number of accumulated data is nevertheless not sufficient for the moment to access the time accuracy with respect to UTC of the new timescale. To evaluate the short term performances, we used our 100 MHz mutli-channel phase comparator. This device is in fact already used to monitor continuously our four hydrogen masers. We have added the measurements of the 5 MHz output signals of UTC(OP) and UTC(OP)_MASER, after frequency multiplications by a factor of 20.
Fig. 3 gives the Allan deviations we obtain, after almost 2 months of continuous measurements. The lowest deviation corresponds to the comparison between H889 and H890. The stability of the comparison decreases from 10^{-13} at an averaging period of 1 s to 10^{-15} above 3000 s. The stability reaches then a flicker floor, before to be degraded because of the masers drift. The blue curve is the deviation of the comparison between the free running H890 and UTC(OP), dominated by the noise of the time reference. The stability is characterised by a white noise of 8 x 10^{-12} x $\tau^{-1/2}$ over any averaging period, except before $\tau = 4$ s, where we probably see the lock of the internal quartz oscillator on the cesium atoms resonance. On the red curve, we have the deviation of H890 - UTC(OP)_MASER. For integration times lower than 10^4 s, the stability is degraded by the micro-phase stepper. Indeed, this device is more adapted to the performances of a cesium clock. We had tested earlier the operation of this actuator, and we found out that the device operates with phase steps of several ps, with a repetition rate depending on the applied frequency correction. The dot curve shows the deviation obtained for a frequency correction of 5 x 10^{-13}, which is a factor of 2-3 higher than the current steering of H890 in the new timescale. This stability is comparable to the red curve. The slight difference is probably due to changes in the measurement conditions. The red curve shows also that the noise due to the micro-phase stepper reaches the maser floor above an averaging period of 10^4 s. For integration times of about 1 day, we begin to see the frequency steering. These results show that the short term stability of the new timescale UTC(OP)_MASER is dominated by the noise added by the steering actuator. This is nevertheless an improvement of more than 1 order of magnitude compared to the current UTC(OP).

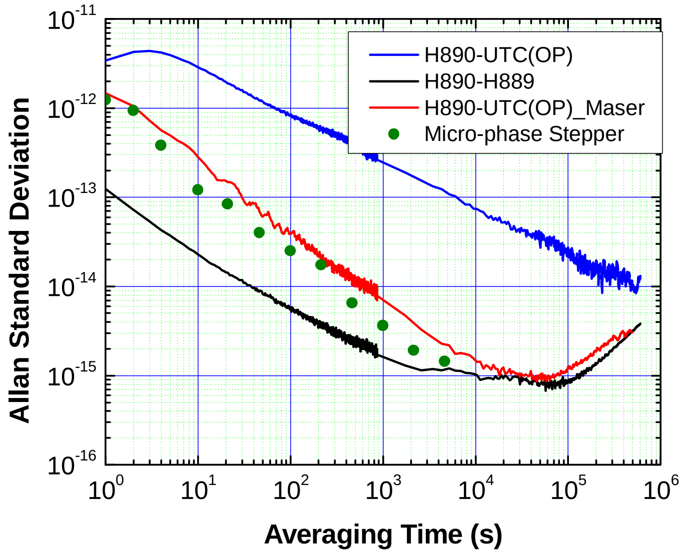

Fig. 3: Allan standard deviation of H890 - H889, H890 - UTC(OP)_MASER and H890 - UTC(OP). The first part of each plot is made from a set of rough data measured with a sample time of 1 s. The second part is made from data averaged over 1/100 day. The circles correspond to an earlier characterization of the micro-phase stepper.

CONCLUSION

We presented in this paper the development and the current status of the new timescale UTC(OP)_MASER. This time reference aims to combine the good short term stability of a hydrogen maser, the mid-term deviation of our ensemble of industrial cesium beam clocks and the accuracy of our three cold atom fountains. In a first step we have developed a robust and reliable algorithm, based on NIST AT1, that computes a weighted average of the cesium clock data. This algorithm produces the free running timescale EAL(F), optimised in terms of stability over 1-2 months. The time reference is then steered towards UTC to produce TA(OP), by using the frequency calibrations against the atomic fountains. We apply an additional frequency correction based on the departure between the frequencies of TAI and of the SI second, as calculated and monthly published by the BIPM. We finally steer the hydrogen maser towards this calibrated timescale, by compensating the frequency and the frequency drift of the maser against TA(OP). The determination of these corrections is performed while using adjacent averaging of the past data to smooth the short term fluctuations of TA(OP). We also apply also a manual correction based on an initial evaluation of the frequency difference between TA(OP) and UTC. The simulation of UTC(OP)_MASER, performed with the last 540 daily measurements, presents a departure to UTC between +/- 15 ns. We nevertheless anticipate possible higher fluctuations in the future. We hope that with updates of the manual frequency correction, evaluated over periods of ~6 months, it will be possible to maintain the timescale within +/- 30 ns with respect to UTC. We have implemented a complete setup for the new timescale. We use the backup of UTC(OP) micro-phase stepper to control the output of the maser H890 and to produce a physical signal. The characterisation of the short term stability of the time scale shows an improvement of more than a factor of 10 compared to the current UTC(OP). We observe nevertheless a degradation due to the micro-phase stepper. We are currently evaluating the long term performances of UTC(OP)_MASER against UTC. This validation will last until the beginning of next year before to replace the current UTC(OP).

According to the good short term stability of the masers, the accuracy of the fountains and their almost unattended operation for 1 or 2 years, we are planning to produce, in the future, the time reference with the ensemble of masers. For that purpose, we have started to adapt the algorithms described here to the behaviour of the masers. The objective is, in a first step, to produce a more stable and accurate frequency reference that will be distributed in the laboratory to the time transfer links, to the primary frequency standards and to the optical clocks. The delivery of a new maser this year should help for the robustness of the new reference.

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