Mixing UTCr and Cesium Fountain Measurements for the Generation of UTC(IT)

V. Formichella, G. Signorile, T. T. Thai,
M. Gozzelino, I. Sesia and F. Levi
Quantum Metrology and Nano Technologies Division
INRiM
Turin, Italy

G. A. Costanzo
Department of Electronics and Telecommunications
Politecnico di Torino
Turin, Italy

***Summary*—After two years of automated generation of the Italian time scale UTC(IT) based on UTCr as steering reference, and after switching to the steering algorithm based on the Italian cesium fountain ITCsF2, INRiM Time Laboratory is ready for the next upgrade: mixing UTCr and ITCsF2 measurements to improve stability, accuracy and robustness of UTC(IT).**

Keywords*—*time scale; steering; atomic clock; cesium fountain; UTCr; UTC(IT)

I. Introduction

The Italian time scale UTC(IT) is generated at the Time Laboratory of the Italian National Institute of Metrological Research (INRiM), by the new automated system described in [1]. From the 13th of January 2020 to the 6th of February 2022, UTCr has been the steering reference for the generation of UTC(IT). The 95th percentile of the phase offset of UTC(IT) with respect to UTC, over such a 2-year period, has been of about 4 ns. During 2021, a test time scale has been generated by using the Italian cesium fountain ITCsF2 as the steering reference [2, 3], showing improved performances with respect to UTC(IT) when the fountain was regularly available. Then, starting from the 7th of February 2022, the fountain steering algorithm replaced the one based on UTCr for the generation of UTC(IT). Over the first two months of operations, the 95th percentile of the phase offset with respect to UTC has been of about 2 ns, as expected.

The next step, aimed to further improve robustness, stability and accuracy of UTC(IT), is to mix the steering corrections computed with UTCr and ITCsF2, according to the so called 'fountain/backup solution' discussed in [1]. This work presents the basic theory of such a 'mixer', its implementation within the automated system for time scales generation, and the first results obtained during an on-line test started on the 7th of February 2022 and currently on-going.

II. The Mixer

The mixer is at the core of the post-processing module of the software architecture presented in [1], corresponding to the block highlighted in Fig. 1 by the dashed line. It takes in input the steering corrections computed by all the available steering algorithms and gives in output a unique steering correction to be applied to the master clock generating UTC(IT). The mixer

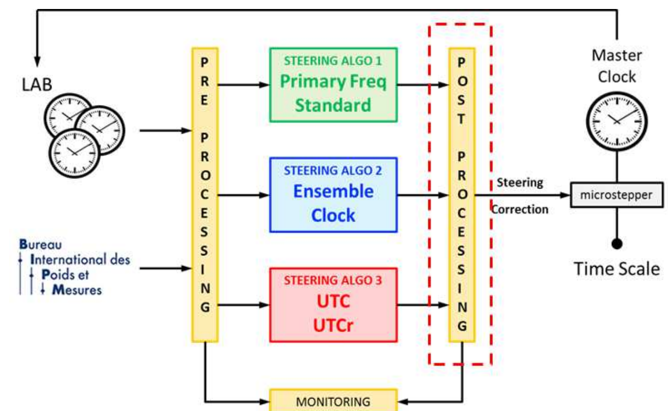

Fig. 1. Scheme of the time scale algorithm used at INRiM for the generation of UTC(IT). The mixer is implemented in the post-processing module, highlighted by the red dashed line.

operates in a mode that is selected by configuration file among the following ones: use a single steering reference among the available ones (one mode for each of the available references); mix the steering corrections from a subset of the available steering references (one mode for each possible subset); mix the steering corrections from all the available references. In this work we consider the second mode, where the subset is made of ITCsF2 and UTCr.

The applied frequency steering correction is actually the sum of two components, $\Delta f = \Delta f_0 + \Delta f_2$, where Δf_0 corrects the frequency offset of the master clock and Δf_2 corrects the residual time offset of the generated time scale with respect to UTC or UTCr. The Δf_0 component is the output of the mixer and, in the case considered in this work, it is computed as a weighted average of the steering corrections based on ITCsF2 and UTCr:

$$\Delta f_0 = W_F\, \Delta f_{0,F} + (1 - W_F)\, \Delta f_{0,UTCr} \qquad (1)$$

where $\Delta f_{0,F}$ is the output of the fountain steering algorithm, $\Delta f_{0,UTCr}$ is the output of the UTCr steering algorithm, and W_F is the weight of the fountain computed by the mixer itself. When both the steering references are available, the mixer algorithm gives weight 1 to the fountain whereas, in case ITCsF2 is unavailable, $\Delta f_{0,F}$ is extrapolated from the old data and W_F

decreases linearly in time, eventually reaching zero after a configurable time constant, θ_0. This approach improves the time scale performances in terms of stability and accuracy by taking full advantage of the fresh and accurate fountain data when they are available, and by using UTCr data to mitigate the degradation of the fountain steering correction when the fountain is unavailable. Analogously, using UTCr as a backup steering reference guarantees robustness and reliability to the time scale, in any case of unavailability of the fountain.

Finally, the output of the mixer is summed to the Δf_2 component of the steering correction, which is the output of a dedicated module. In particular, $\Delta f_2 = \Delta x / N_{acc}$ where Δx is the most recently measured time offset of the time scale with respect to UTC or UTCr, whereas N_{acc} is the number of days after which Δx has to be compensated. For the test discussed in this work, as well as for the generation of UTC(IT) since January 2020, UTCr is used for the computation of Δf_2.

III. Testing the Mixer

The objective of the on-line test is to generate a real-time time scale by using the mixer and to compare its performances with those of UTC(IT). To perform a meaningful comparison, the master clock generating the test time scale must be the same used for the generation of UTC(IT), and this is possible thanks to the hardware setup available at the INRiM Time Laboratory, where two test time scales can be independently generated from the same Active Hydrogen Masers (AHM) used for UTC(IT) and its hot backup [4].

The test started on the 7th of February 2022 and, while it is still on-going, the results collected up to the 3rd of April 2022 are shown in this work. After two weeks from the beginning of the test, the new (daily) measurements from ITCsF2 have been deliberately removed from the input data sets, only for the test time scale, as to simulate a fountain unavailability. The fountain data are made available again after a gap of 23 days. In order to highlight the effect of the mixer during a gap of such length, the θ_0 parameter has been set to 30 days, which is probably smaller than the ideal value based on the fountain data quality and on the master AHM predictability.

Finally, note that no Δf_2 has been applied to the test time scale generated during the above mentioned test period.

IV. Test Results

The results are shown in terms of time offset with respect to UTC. The test time scale performances are compared with those of UTC(IT) as disseminated through the Circular T, and also as obtained in post-processing by subtracting the effect of the Δf_2 component of the steering correction.

First of all, Fig. 2 shows the time evolution of the fountain weight during the test period (black curve with dots), where the gray shaded area indicates the fountain data gap. As it is clear from the figure, the fountain weight decreases linearly in time during the gap, then it immediately comes back to 1 as soon as the fountain data become available again. Note that, in case of longer gaps with duration exceeding the length of the batch of past data used for the computation of $\Delta f_{0,F}$, an additional delay would be necessary before the weight can be

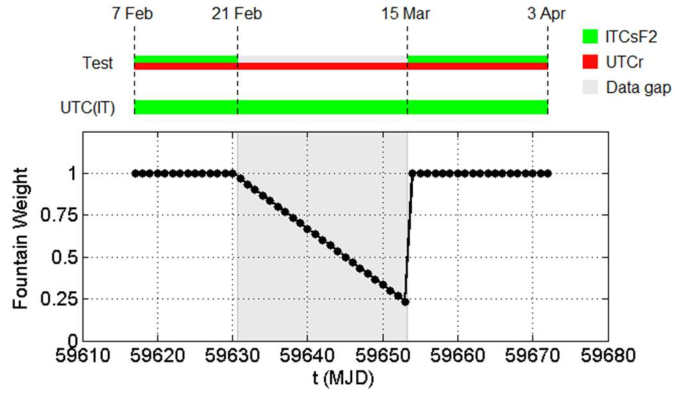

Fig. 2. Top: data availability during the test and steering references used for UTC(IT) and the test time scale. Bottom: time evolution of the fountain weight during the test, fountain data gap indicated by the gray shaded region.

set to 1, in order to accumulate a minimum number of fountain measurements necessary to update $\Delta f_{0,F}$ (see [1] for further details on the fountain steering algorithm). The colored bars in the upper part of the figure summarize the data availability during the test and the steering references used for generating UTC(IT) and the test time scale: in particular, UTC(IT) has been generated by the fountain steering algorithm with almost 100% ITCsF2 availability, whereas the test time scale has been generated by the mixer fountain/UTCr steering algorithm with a 23-day ITCsF2 unavailability indicated by a gray bar.

The test results are shown in Fig. 3, where four curves are plotted: the blue curve with dots is UTC(IT) as reported in the Circular T; the cyan curve with circles is UTC(IT) as obtained in post-processing by subtracting the effect of Δf_2, to make it directly comparable with the test time scale; the purple curve with squares is the on-line test time scale; finally, the green curve with squares is an off-line version of the test time scale, representing the time scale that would have been obtained if only the fountain was used as a steering reference, despite the presence of the 23-day fountain data gap. First of all, it can be observed that the blue curve, UTC(IT), is slightly different from the others as it is the only one implementing the time accuracy correction, Δf_2, driving the time offset of the time scale towards zero. Therefore, the discussion of the results will be focused on the remaining curves, which should be kept flat by the Δf_0 component of the steering correction.

The purple curve and the green one (test time scale with and without mixer, respectively) are almost equal: this can happen, it is expected for short fountain data gaps and highly predictable masers, and shows that UTCr is a good backup reference for the primary frequency standard, not degrading too much the performances with respect to the use of a good prediction of the fountain-AHM frequency offset. However, in general, the purple curve should be better than the green one as this is the whole purpose of using the mixer, and this is especially true for longer gaps and/or less predictable masers, as shown in Fig. 4. Such figure shows the results of an off-line test performed on experimental data collected during the years 2016 and 2017, with a 6-month unavailability of ITCsF2 (shaded region on the left side of the plot) and an AHM master clock less stable than the one used for the on-line test. Further

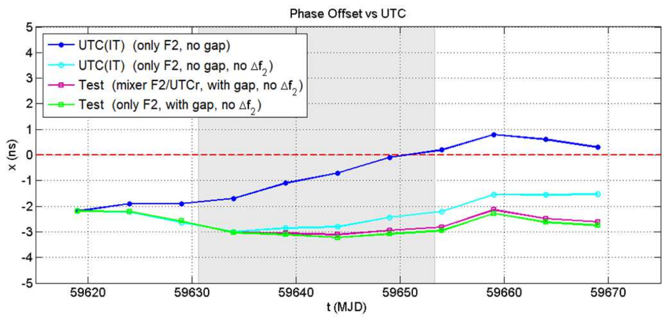

Fig. 3. On-line test results in terms of time offset versus UTC. The 23-day fountain data gap is indicated by the shaded region. The blue curve with dots is UTC(IT) as from the Circular T; the cyan curve with circles is UTC(IT) as obtained in post-processing by subtracting the effect of the time accuracy correction; the purple curve with squares is the on-line test time scale; the green curve with squares is an off-line version of the test time scale obtained by using only the fountain as a steering reference, despite the presence of the fountain data gap.

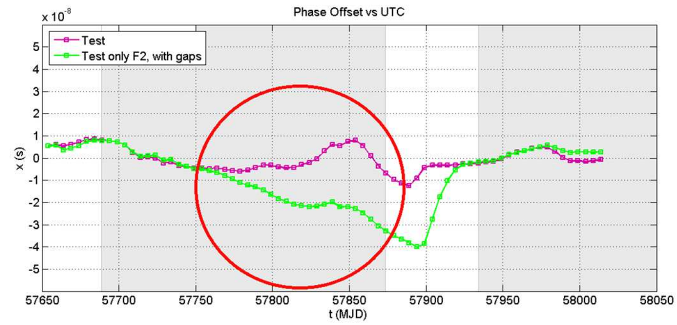

Fig. 4. Off-line test results in terms of time offset versus UTC, with experimental data from 2016-2017. A 6-month fountain data gap is indicated by the shaded region on the left. The purple curve with squares is the test time scale obtained with the ITCsF2/UTCr mixer algorithm; the green curve with squares is the test time scale obtained by using only the fountain as a steering reference, despite the presence of the fountain data gap.

details on the off-line test can be found in [1], here it is worth mentioning that the Δf_2 component of the steering correction was applied, and that the value of the θ_0 parameter was set to 90 days. The color code is the same used for Fig. 3 and, as expected in this particular case with a larger data gap and a less predictable maser, it can be easily observed how the use of the mixer improves the time scale performances, preventing the time offset to diverge during the fountain data gap (i.e. the behavior of the green curve within the region indicated by the red circle).

Coming back to Fig. 3, it can be observed that the green curve is better than the cyan one, despite the fact that the fountain data gap only affects the time scale represented by the green curve. This can happen even if, in general, the opposite result is expected (i.e., a higher fountain availability should lead to a better fountain-steered time scale). In order to explain such a result, note that the fountain measurements could have been noisier than usual during the period indicated by the shaded region, so that the prediction of the fountain-AHM frequency offset could have been better than the actual measurements, which is possible when dealing with a highly-predictable AHM.

V. Conclusions

A “mixer” has been successfully implemented in the post-processing module of the time scale algorithm, in the frame of the automated system for time scales generation at the INRiM Time Laboratory. The aim of such a mixer is to improve the robustness, stability and accuracy of the generated time scales, including UTC(IT), by using multiple steering references.

In particular, the ITCsF2/UTCr mixer algorithm has been successfully tested on-line with a dedicated test time scale, whose performances have been illustrated in this work. As expected, the performances improvement with respect to the fountain steering algorithm is especially evident in case of long fountain data gaps. However, the improvement is also evident for short fountain data gaps if the master clock suffers from possible non-stationarities or, more in general, when its stability and predictability are degraded for any other reason.

After these positive results, our aim at the INRiM Time Laboratory is to start generating UTC(IT) and its hot backup with the ITCsF2/UTCr mixer algorithm by the end of 2022. Meanwhile, we are proceeding with the design and test of the algorithms for other possible operating modes of the mixer. Currently, the supported operating modes are:

- Use UTCr as a single steering reference
- Use ITCsF2 as a single steering reference
- Mix the steering corrections from ITCsF2 and UTCr

The third one, presented in this work, is the best performing mode among those currently supported. The modes still under development include, for example:

- Use the optical clock IT-Yb1 [5] as a single steering reference (see [6] for a discussion on the generation of time scales with optical clocks)
- Mix the steering corrections from IT-Yb1, ITCsF2 and UTCr
- Mix the steering corrections from all the available references, including an ensemble time scale made of all the cesium beam clocks and AHMs available in the Time Laboratory

References

[1] L. Galleani, G. Signorile, V. Formichella and I. Sesia, “Generating a real-time time scale making full use of the available frequency standards,” Metrologia 57, 2020, 065015, doi: 10.1088/1681-7575/ab8d7d.

[2] V. Formichella, G. Signorile, T. T. Thai, L. Galleani, M. Gozzelino, G. A. Costanzo, I. Sesia and F. Levi, “On-Line Tests of Real-Time Time Scale Generation Algorithms Based on a Primary Frequency Standard and a Clock Ensemble,” 2021 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium, 2021, doi: 10.1109/EFTF/IFCS52194.2021.9604266.

[3] F. Levi, D. Calonico, C. E. Calosso, A. Godone, S. Micalizio and G. A. Costanzo, “Accuracy evaluation of ITCsF2: a nitrogen cooled caesium fountain,” Metrologia 51, 2014, 270, doi: 10.1088/0026-1394/51/3/270.

[4] A. Perucca, T. T. Thai, F. Fiasca, G. Signorile, V. Formichella, I. Sesia and F. Levi, “Network and Software Architecture Improvements for a Highly Automated, Robust and Efficient Realization of the Italian National Time Scale,” 2021 Joint Conference of the European Frequency and Time Forum and IEEE International Frequency Control Symposium, 2021, doi: 10.1109/EFTF/IFCS52194.2021.9604318.

[5] M. Pizzocaro, F. Bregolin, P. Barbieri, B. Rauf, F. Levi and D. Calonico, “Absolute frequency measurement of the $^1S_0$–$^3P_0$ transition of ^{171}Yb with a link to international atomic time,” Metrologia 57, 2020, 035007, doi: 10.1088/1681-7575/ab50e8.

[6] V. Formichella, L. Galleani, G. Signorile and I. Sesia, “Robustness tests for an optical time scale,” Metrologia 59, 2022, 015002, doi: 10.1088/1681-7575/ac3801.