# Generating a Real-Time Time Scale With an Ensemble Clock and a Primary Frequency Standard

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***Abstract*—The robustness and reliability of a reference time scale is becoming more and more crucial in many applications, particularly in global navigation satellite systems (GNSS) and in critical infrastructures with time synchronization needs. This paper proposes two steering algorithms aimed at generating a real-time time scale, the first based on a primary frequency standard (PFS), and the second on an ensemble of clocks. Extensive tests on real data from the Italian National Metrology Institute (INRIM) cesium fountain ITCsF2 and atomic clocks have been carried out. The results show that the PFS algorithm has higher performances, but it requires a cesium fountain, a prototype standard currently available in a few timing laboratories only, whereas the ensemble clock algorithm uses commercially available clocks. A special emphasis is put on the system robustness: data pre-processing and possible combinations of the proposed algorithms have been tested in order to cope with outage periods, while maintaining good performances in terms of stability and accuracy of the resulting time scale. Such algorithms can be used in several applications where a stable time reference is needed, such as for the generation of a local real-time realization of UTC, as well as for any GNSS reference time.**

***Keywords—time scale; steering algorithm; cesium fountain; primary frequency standard; commercial frequency standard; clock ensemble; real data; atomic clocks; UTC; UTCrapid; GNSS reference time; robustness; reliability.***

## I. Introduction

Robust and reliable time scale references play a crucial role in a variety of applications, such as global navigation satellite systems (GNSS) and critical infrastructures with synchronization needs. In the past few years, the Italian national metrological institute (INRIM) started the design and testing activities of steering algorithms for the generation of real-time time scales. The goal of these activities is to realize stable, accurate, reliable, and robust time scales for continuous and automatic operations. This paper presents two algorithms for the generation of a time scale, the first based on a primary frequency standard (PFS), and the second on an ensemble of clocks.

## II. Fountain Steering

When a PFS is used to generate a time scale [1]-[3], it is used to measure the frequency of the hydrogen (H) maser, whose frequency offset is corrected to generate the time scale. The proposed algorithm, based on the INRIM cesium fountain data, computes a frequency correction $\Delta f_0$ to be applied to a master clock, in order to correct its frequency offset. This correction is obtained through a linear fit over a batch of past frequency measures, up to the current day. If the latest frequency measures are not available, the frequency correction is extrapolated by using the last performed linear fit, thus maximizing the use of the available information. If the time scale is used to generate a realization of a UTC(k) time reference, then the total frequency correction applied to the H maser is $\Delta f = \Delta f_0 + \Delta f_2$, where $\Delta f_2$ is computed based on the latest available phase offset with respect to UTCrapid (UTCr) reference products, namely, UTCr-UTC(k), as periodically published by BIPM.

A test on real data based on the cesium fountain ITCsF2 available at the INRIM laboratories has been carried out. Almost one year of data, from March 2015 to February 2016, have been used in the test. The results are shown in Fig. 1, where the grey curve represents the real UTC(IT), whereas the green curve shows how UTC(IT) would have performed with the proposed fountain steering. Note that, despite the fact that the frequency measures are not continuously available (a data gap of 90 days has been tested), the fountain-steered UTC(IT) remains well within ±5 ns from UTC for the whole period, outperforming the real UTC(IT).

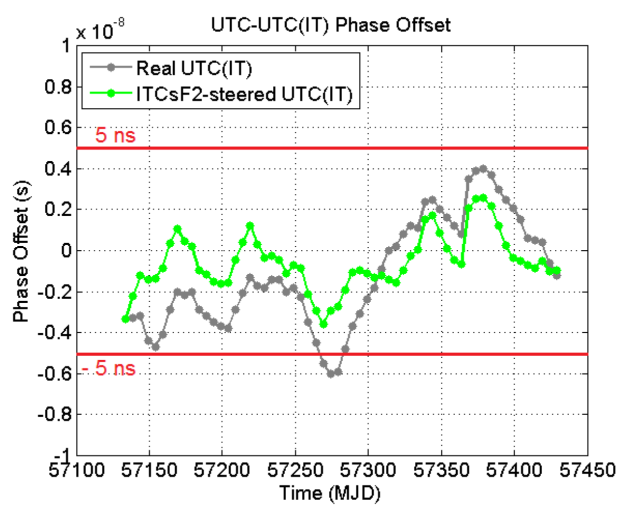


Fig. 1. Phase offset of UTC with respect to the real UTC(IT) (grey curve), and with respect to UTC(IT) if the fountain steering would have been used (green curve).

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## III. ENSEMBLE STEERING

The steering algorithm based on the clock ensemble approach optimizes the use of all the available atomic clock data. The aim is in fact to take advantage of the different features of the available oscillators, so that the resulting time scale has higher performances than any of the individual clocks. By relying on multiple clocks, the effect of possible anomalies is reduced and more detectable, making the real-time time scale more robust. For such reason, the ensemble clock approach is effective also for the generation of a reference time scale for a GNSS.

The proposed algorithm is based on the assumption that the considered clocks are continuously measured with respect to a stable reference, hence the clock-to-clock phase offsets can be easily obtained. By using these data, an ensemble time scale is computed with an averaging algorithm. The clocks used are cesium standards and H masers, which are among the most used commercial oscillators for time-keeping activities. The cesium clocks are averaged according to their long-term stability. The resulting ensemble time scale is then steered to align its frequency to that of UTCr, obtaining the so called TAst time scale.

Subsequently, TAst is used as a reference to steer an H maser, thus generating a UTC(k) realization. The total frequency correction $\Delta f$ applied to the H maser is computed exactly as for the cesium fountain steering, except for the fact that $\Delta f_0$ is computed from the frequency measures TAst-H maser, instead of cesium fountain-H maser.

We performed a test on INRIM real data by using 6 cesium clocks in the period March 2014-July 2015. Figure 2 compares the obtained results to the actual behavior of the Italian time scale. The grey curve represents the real UTC(IT), whereas the green curve is UTC(IT) as it would have been with the ensemble steering. Note that the ensemble-steered UTC(IT) remains well within ±10 ns from UTC for the whole period. This result is very promising because the ensemble clock algorithm requires commercial clocks, whereas the higher performance PFS algorithm requires a cesium fountain, a prototype standard currently available in a few timing laboratories only.

## IV. CONCLUSIONS

We have discussed two steering algorithms, the first based on the data of a PFS, and the second on an ensemble clock approach. The results obtained by applying the proposed algorithms to the UTC(IT) case, on almost one year of real data, are reported. The algorithm based on the cesium fountain keeps the time scale well within ±5 ns from UTC, despite the fact that the fountain is not always available. The obtained performances with the ensemble steering show that the resulting time scale is kept within ±10 ns from UTC by using 6 cesium clocks.

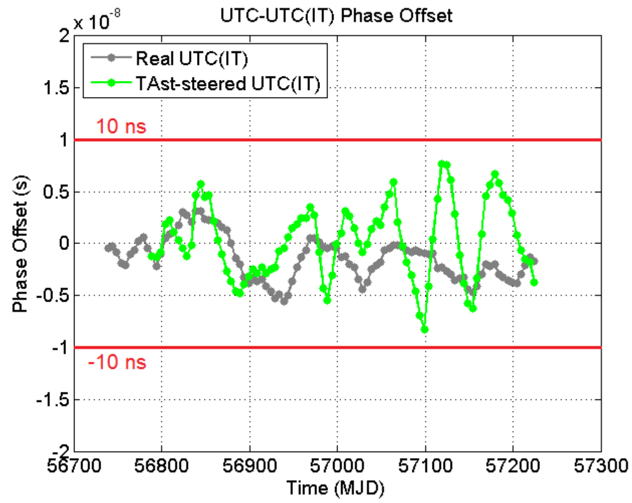


Fig. 1. Phase offset between UTC and the real UTC(IT) (grey curve) or UTC(IT) as it would have been with the cesium ensemble steering (green curve).

The PFS algorithm achieves higher performances but requires a cesium fountain, a prototype standard available in few timing laboratories worldwide. The ensemble clock algorithm has lower (although good) performances, but it can be implemented with commercially available clocks.

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