Preliminary step for a UTC(IT) steering algorithm based on the ITCsF2 primary frequency standard measurements

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G. Signorile*, P. Tavella*, D. Calonico*, F.Levi*, G. Costanzo*+, G.Cerretto*, R. Costa*, E. Cantoni*, I. Sesia*
*Physics Metrology Division, INRIM, Turin, Italy
+ Electronics Department, Politecnico di Torino, Turin, Italy

Abstract— **A preliminary test to base the generation of the Italian standard time UTC(IT) also on a primary Cesium fountain has been carried out and the results are reported also in comparison to a steering strategy based only on UTC or rapid UTC data. In addition, the results of the first months of a hardware implementation of the fountain steering algorithm currently in operation in INRIM is also reported. This work represents the first step towards the realization of UTC(IT) with a complete set of primary and commercial frequency standards.**

Keywords—Time scale, steering algorithm, primary frequency standard, Cesium fountain;

I. INTRODUCTION

The generation of the Italian reference time scale UTC(IT) is currently based on the signal of a Hydrogen maser which is continuously monitored versus commercial Cesium frequency standards and other Hydrogen masers [1]. Our plan is to base the realization of UTC(IT) on a larger set of frequency standards with a triple generation chain, also based on the frequency measures referenced to a Cesium fountain primary frequency standard, to improve the stability, accuracy, and reliability of the UTC(IT) time scale.

As a first step we have developed, implemented, and tested a new steering algorithm based on the measurements of the ITCsF2 Cesium Fountain developed and operated in INRIM [2,3].

The algorithm implementation is described and the results obtained with almost one year of experimental data are reported and compared with similar results that could have been obtained by steering the same H maser by using only BIPM products, namely UTC and rapid UTC.

In addition, since January 2015, an experimental time scale, named *Exp TA(IT),* is physically realized by applying the fountain steering to a H maser. The results of the steered time scale are reported and compared with the previous estimates.

The performances on the test period are finally analyzed and discussed and the benefits of using fountain measures in the steering algorithm are pointed out.

II. THE NEW STEERING ALGORITHMS

The current UTC(IT) generation is based on a 5 MHz signal provided by an Active Hydrogen Maser fed to a phase micro stepper (named AOG), that compensate the H maser frequency offset and drift. The steering parameters are obtained from the BIPM evaluation of UTC and rapid UTC and automatically provided to the AOG [1].

In order to improve robustness, reliability, accuracy, and stability of the Italian Time Scale, a new time scale generation system is under development.

The realization will always be based on steered H masers (one master plus a redundant one), but the steering values will be evaluated by three parallel independent steering chains. The first one is based on BIPM rapid UTC data, the second one will be based on an ensemble time scale using INRIM six commercial Cesium standards and four Hydrogen masers, while the third one will use the measures of INRIM Cesium fountain ITCsF2. The ITCsF2 also contributes to the TAI realization by the BIPM.

All input measurement data will be automatically provided. The first step in the analysis will be a pre-processing [4] stage aimed at detecting and filtering possible anomalies on the measurements. Then the steering parameters of the same H maser will be evaluated in parallel by the 3 chains.

Finally, the outputs consistency will be checked by the post-processing block and then a combiner will determine the frequency correction to be provided to the AOGs, to steer the frequency of the Hydrogen Masers and, hence, to generate the future time scale UTC(IT).

The concept of the new steering algorithms is illustrated in the Fig 1.

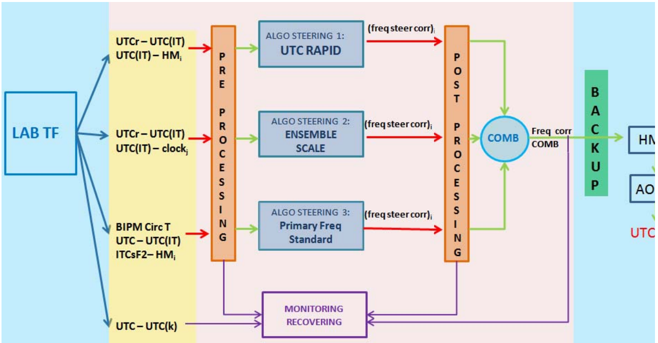

Fig. 1. Scheme of the new UTC(IT) steering algorithms

III. EXPERIMENTAL DATA WITH ITCSF2 FOUNTAIN

ITCsF2 is the new INRIM Nitrogen cooled Cs Fountain primary frequency standard, that is fully operative since 2013. Its Type B uncertainty is 1.7×10^{-16}, while its short term stability in the high density regime is $2\times10^{-13}\,\tau^{-1/2}$ [2]

ITCsF2 has been used to calibrate TAI providing during 2014 nine frequency evaluations for a total measurement time of 165 days. ITCsF2, together with its twin system NIST-F2, also operating at cryogenic temperature, were used to measure the Black body radiation shift, comparing their frequency with that of the room temperature PFS NIST-F1 [3].

ITCsF2 has operatively measured the frequency of a H maser, namely HM3, for a period of almost one year, from mid February 2014 to March 2015. These primary measures are used in this test to evaluated which could have been the steering of the H maser compared with the steering that could have been obtained basing on UTC or rapid UTC data.

Since HM3 is the H maser currently realizing UTC(IT), the results of the real UTC(IT), based on the current steering strategy, are also compared.

The frequency rates of the HM3 reported in Fig 2 have been measured with respect to 3 different references:

- ITFCsF2 measurements (blue)
- UTC (red)
- rapid UTC (green)

The plot represents also the BIPM estimated rates (yellow) as reported in the BIPM web page

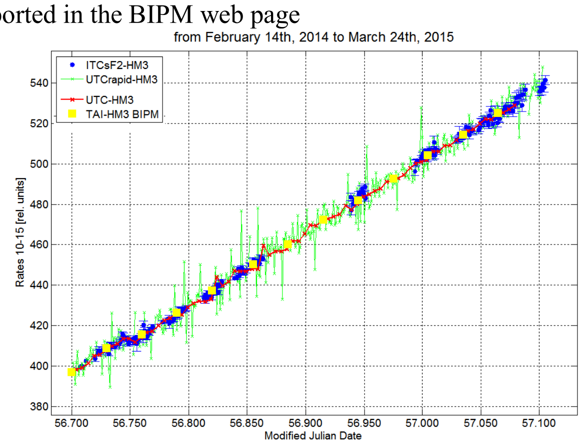

Fig. 2. The measures used for the steering test

IV. THE FREQUENCY STEERING EVAUATIONS

The steering algorithm based on ITCsF2 data uses every day a certain number of past daily measurements, typically 30 and compute a frequency correction to be applied to the HM3 through the estimation of a linear fit based on the weighted least squares method.

In case there are few available measures or when the last update is not available, the steering estimation is not updated and the previous frequency steering is maintained, only updated for the effect of the frequency drift previously estimated. This is the reason why in case of missing ITCsF2 measures, the frequency steering could not be optimal. With the final triple chain, in those cases, the steering would be evaluated by another chain, but here we concentrate on the steering evaluated only by a single method.

In Fig 3 the frequency steering corrections computed through ITCsF2 measurements are compared with the correction computed for the same HM3 in the same period (February 2014 – March 2015) with the current steering strategy applied to generate the official UTC(IT) scale.

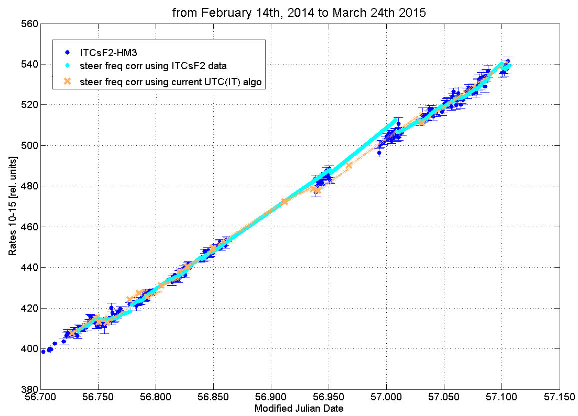

Fig. 3. Steering corrections estimated from the ITCsF2 measures and the correction estimated by the current UTC(IT) algorithm

To analyze the performances of the new algorithm based on the ITCsF2 measures, we compare such steering results with the ones that we could have obtained by steering the same HM3 using BIPM data. In particular we evaluated the possible steering estimates based only on monthly UTC or weekly rapid UTC measures.

The approach is the same used for the steering through the fountain: every day a frequency correction is estimated by a linear fit on a certain number of previous data.

To this aim the following measures have been obtained and used in the fit computation:

$$\text{UTC-HM3} = (\text{UTC-UTC(IT)})_{\text{BIPM}} + (\text{UTC(IT)-HM3})$$

$$\text{UTCr-HM 3} = (\text{UTCr-UTC(IT)})_{\text{BIPM}} + (\text{UTC(IT)-HM3})$$

where $(\text{UTC-UTC(IT)})_{\text{BIPM}}$ comes from the BIPM publications and UTC(IT)-HM3 is measured inside the INRIM lab.

In such cases the data latency plays a crucial role as it is one month for UTC or one week for rapid UTC. Consequently we estimated the new steering parameters once a month and once a week respectively, but considering also that monthly data are available on the 10th of successive month, while weekly data are available on successive Wednesdays.

Fig 4 represents the steering estimates in this case. The steering estimated with UTC monthly data (red) are updated every month, on the 10th of successive month, and they are kept constant (in frequency and drift, therefore giving a straight line) for one month. The steering correction based on rapid UTC are updated every week (green), while the correction estimated with ITCsF2 are updated daily (pale blue), unless measures are not available. It appears that the use of "old" data does not allow to quickly follow possible changes in the clock linear trend, but on the whole all the steering methods are following the trend of the HM3.

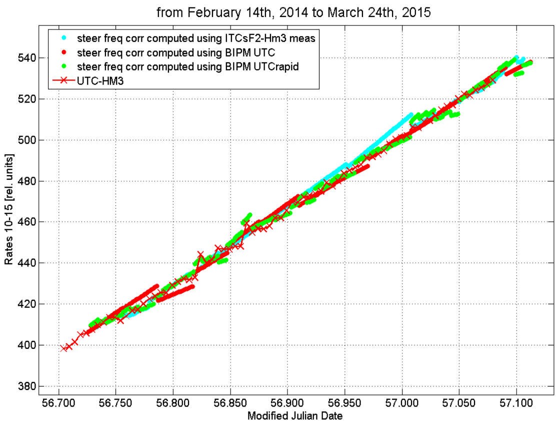

Fig. 4. Steering corrections estimated from the ITCsF2, UTC, and rapid UTC measures, together with the measures of the rate of the H maser versus UTC

To evaluate the effect of such a steering, we estimate the steered rate that could have been obtained by subtracting the steering correction from the H maser rate. The results is a sort of residual rate and it is represented in Fig 5.

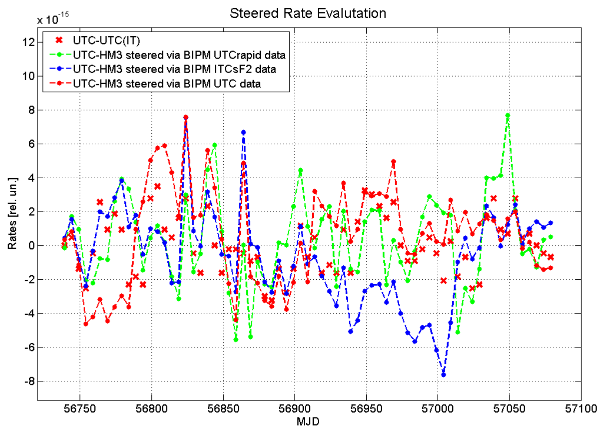

Fig. 5. Estimation of the residuals of the steered rate in case the steering is obtained with ITCsF2 , UTC, or rapid UTC, together with the measures of the rate of the official UTC(IT) versus UTC for comparison purposes

From the residual rate we can easily infer by integration what would be the residual time offset gained by such a steered time scale and this is represented in Fig 6 reporting the time scale that would have been obtained by steering the HM3 using ITCsF2 (blue), UTC (red), or rapid UTC (green) steering techniques.

It appears that the steering obtained with ITCsF2 is very accurate in the first period, but then it degrades when the measured are not available (from MJD 56850 till 57000) and the steering is based on old measures. When fresh measures are available starting from MJD57000, the steering is immediately effective. Similarly the steering based on UTC (red points) suffers from being based on old measures not promptly following the HM3 behavior. The steering based on rapid UTC is not the most stable as it suffers important variations from week to week, but on the whole the time accuracy is very good.

For comparison we report in the same plot the behavior of UTC-UTC(IT) (red crosses), official time scale data.

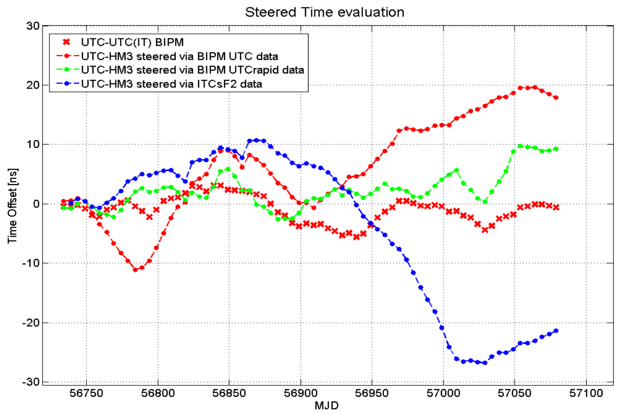

Fig. 6. Evaluation of the steered time scakles that could have been obtained steerinmg the HM3 with 3 diffenent steering strategies, together with the official UTC(IT) time scale.

The obtained results give us a good confidence on the steering strategies and their implementation with an automatic software and they show that the planned triple chain would help by using other techniques when the primary steering based on ITCsF2 is not available.

V. EXPERIMENTAL TA(IT)

Since mid January 2015, the steering algorithm based on ITCsF2 measures has been automatically applied to the signal of HM3 to generate a physical steered time scale named TA(IT). The experimental set up for the generation of the official UTC(IT), the experimental TA(IT), and a back up UTC(IT) is represented in the following block diagram, Fig 7, while the devices realizing the time scales are reported in Fig 8.

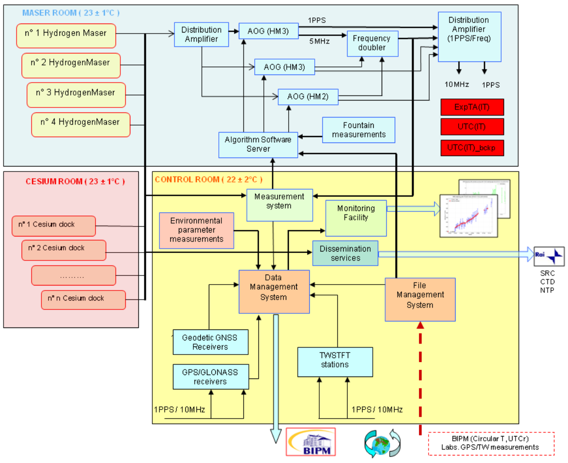

Fig. 7. Block diagram of the experimetal set up for the realization of the INRIM time scales

Fig. 8. Picture of the devices realizing the UTC(IT), Exp TA(IT), and UTC(IT) back up time scales steering algorithms

The behavior of the experimental TA(IT) with respect to UTC(IT), as measured through a Time Interval Counter in the laboratory, and versus rapid UTC and UTC is reported in Fig 10. The apparent “jumps” in the estimate versus rapid UTC visible on MJD 57054 and 57089 are due to the monthly update of rapid UTC. This is in fact visible also in Fig 11 where the differences UTCr-UTC(k) for some time scales are reported and the apparent jumps appear on the same date for all the labs.

We can now check the behavior of the experimental TA(IT) with respect to the evaluation presented before, for the common period of Jan-March 2015. Results are in Fig 10. The blue line represented the time scale that we estimated could have been obtained by steering the HM3 with the ITCsF2. The blue dots in the last period represents was has been experimentally obtained with the Exp TA(IT) physically realizing a steered time scale based on ITCsF2. For comparison purposes this last results are also reported with the addition of an arbitrary constant to show the excellent agreement with the theoretically evaluation we explained before.

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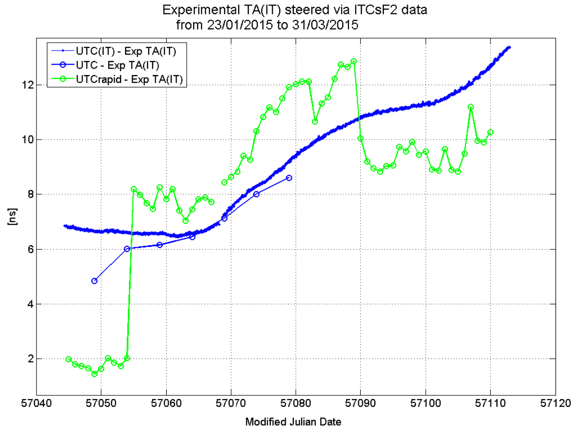

Fig. 9. The behaviour of the experimental TA(IT) versus UTC(IT) (blue), UTC (blue with dots), and rapid UTC (green)

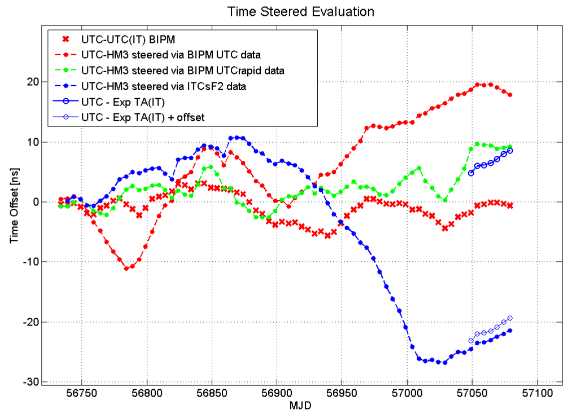

Fig. 10. Steered time scales together with the Exp TA(IT) (true measures in blue dots, and with the additional of an arbitrary constant in white blue dots)

a.

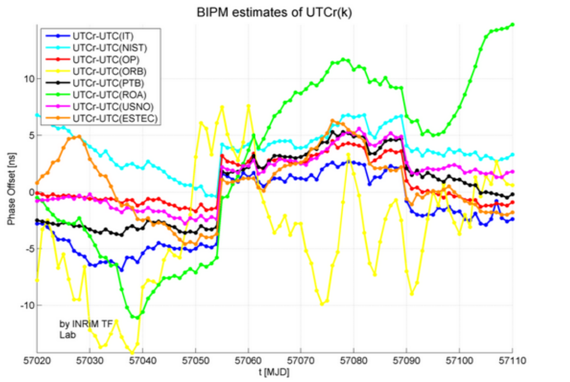

Fig. 11. UTCr-UTC(k) showig that in same cases the monthly update of rapid UTC may result is an apparent jumps of a few ns.

VI. CONCLUSION

We have discussed and reported experimental tests on the possibility to steer a H maser based on measures obtained with reference to ITCsF2, UTC, and rapid UTC. These results are a sort of offline evaluation of what could be the time scale behavior if the estimated steering were applied.

In the last months we have also set up a physical realization of an experimental time scale based on a H maser steered by the measures on the Cesium fountain ITCsF2 and we could confirm that the offline estimation are sound as in excellent agreement with what can be experimentally obtained.

Moreover the positive rate of UTC-TA(IT) of about1*10^{-15} observed in February 2015 is in agreement with the rate of IT-CsF2 versus TAI (opposite sign) appearing in Circular T n 326 as

IT-CsF2 57029 57054 d= -1.11(0.5) x10-15
IT-CsF2 57054 57074 d= -0.76(0.72) x10-15

This residual rate will be compensated for in the steering algorithm.

We are therefore quite confident on the algorithms and on the software implementation of the steering strategy based on ITCsF2 and we will continue the work to set up a complete redundant steering evaluation chain to realize the national time scale UTC(IT) with a more robust and accurate steering strategy using all the frequency standard available in INRIM.

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