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INXE and LRTE: Progress on Frequency Standards and Timescales

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Abstract. In this work, we overview some progresses of the Brazilian scientific program for time and frequency metrology. The results involve the development of an atomic fountain of Cs 133, a compact frequency standard with cold atoms and two new timescales contributing to TAI and UTC. These are different running experiments in two locations in Brazil and consists on a joint effort to develop infrastructure in the area.

1. Introduction

The Brazilian NMI, INMETRO (Instituto Nacional de Metrologia e Qualidade Industrial), and the University of São Paulo, through the São Carlos Institute of Physics and the São Carlos School of Engineering (USP-SC) develop a joint program on Scientific Time and Frequency Metrology. In their laboratories several metrological systems are being developed. They are an atomic cesium fountain and a compact standard with cold Cs 133 atoms. We have also implemented a timescale in both locations (distant by 480 km), in order to contribute with TAI (International Atomic Time) formation, so serve as traceable frequency and time sources for several scientific or technological users [1][2][3].

2. Primary Systems under development

2.1. Atomic Fountain

The first atomic fountain experiment was carried out with systematic characterizations, regarding magnetic field and temperature stability in order to evaluate for Zeeman and blackbody radiation effects. Despite all this, the vacuum chamber and its attached optics showed to be compromising for the operational use of the fountain apparatus in long term. Considering its intended use as a national frequency standard, the group decided to develop a second generation system. It deals now with a trap vacuum chamber built with borosilicate glass. The first results for the cooling of atoms using Cs dispensers as the source of atoms [4] are shown in Figure 1. Here, we did several loading essays, with different current values for the dispensers.

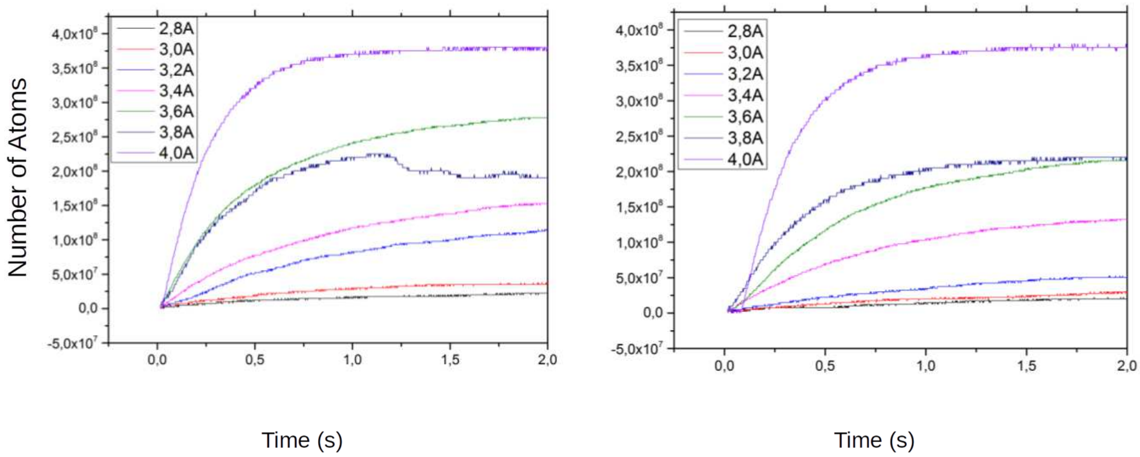

Figure 1. Trap loading curves for different dispensers currents using the repumping light (right) or the MOT coils current (left) to start the loading process.

2.2. *Compact System with Cold Atoms*

Another system in our laboratories is a frequency standard that uses cold atoms in a more compact enclosure. We have been devoted to the development of subsystems that should lead to a reliable setup, providing the reduction of volume and mass of the different components and parts [2].

One of the most important parts are the light sources. We have been developed new extended-cavity diode lasers and reached a very lightweight laser box. We built it with additive manufacturing (3D printing) and the actual design can be seen in Figure 2.

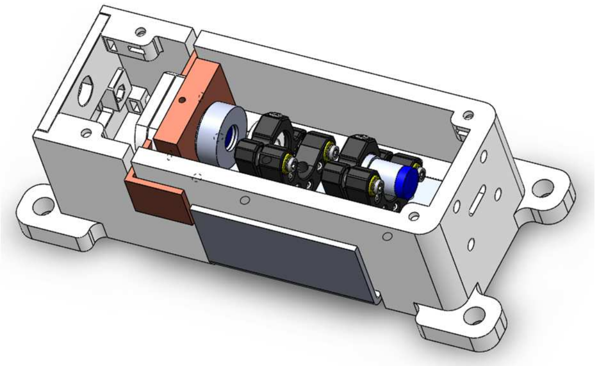

Figure 2. Renderized image of the lightweight laser prototype to be used in the compact clock.

The estimated thermal expansion coefficient of ABS plastic ($110x10^{-6}$) is about 4 times that for aluminum ($24x10^{-6}$). This could compromise the stability of the system due to changes in cavity length with temperature. On the other hand, due to the lower thermal conductivity of ABS (0.2 W/m-K), the overall effect showed to be reduced, and a similar performance is observed between two material versions of the system. The general control topology and electronic drivers for the compact standard are still evolving [2], with the test of different credit card sized computers. We are also dedicating efforts to reduce the optomechanical package for the experiment.

3. Timescales

To provide time links with TAI and UTC, our groups established two timescales: The first, named UTC(INXE), operates since 2012, contributing regularly to BIPM and reported in Circular T. It is located in the Brazilian NMI Campus at Xerém-RJ and provides traceability for different metrological laboratories involved in several technology areas.

The second timescale is located on the Campus of the University of São Paulo in São Carlos. This timescale contributes formally to TAI and UTC since december 2018 and received the name of UTC(LRTE). It is intended to provide traceability for scientific experiments being realized in the Campus. Furthermore, it is intended to be able to receive contributions from several primary frequency standards, like the cesium atomic fountain under development, as well as the compact system operating with a cloud of cooled atoms.

For this work, we show the data for the comparisons of UTC(INXE) and UTC(LRTE) with respect to UTC, using a remote comparison procedure using P3 codes of the individual RINEX files [3].

3.1. Performance indicators for timescales comparison

We used some performance indicators to compare the reliability of three timescales, INXE, LRTE and GPS with respect to UTC. The selected indicators were availability, accuracy, and stability and they were defined as the accessibility or dependability of the timescale system, confidence level or degree of equivalence of the timescale results and the frequency stability of the timescale operation by using Allan variance, respectively.

3.2. Availability of timescale system

The availability was evaluated by computing the ratio between the actual operation time and the total time of evaluation, for instance, the GPS system during these 140 days of operation was accessible during all 140 days and the availability is 100%. For the timescale at Inmetro campus, local coordinated universal time UTC(INXE) was available for 135 days, and this indicator should be 96.4% due to an energy failure during February 14th to 16th. This indicator is also 96.4% for timescale at USP campus, UTC(LRTE) due to an energy failure during April 4th to 6th. In Figure 3 the energy failures were highlighted with square boxes, red for LRTE and grey for INXE.

The operation of the two timescales as a consortium would avoid this kind of event, and both timescales operating concurrently would give a 100% of availability because the probability for energy failure at the same period in both campuses is minimal.

3.3. Accuracy of timescale results

In order to ensure the validity of the results of the timescales, the P3 technique was employed in this work to compare the accuracy of three timescales, INXE, LRTE and GPS. These timescales collect data every 30 s and send these data to BIPM every day. The timescales comparison is performed at BIPM by using satellite constellations, for instance, the GPS constellation. The communication between the satellite transponder and receiver antenna uses two radio frequencies L1 (f_1 = 1575.42 MHz) and L2 (f_2 = 1227.60 MHz) and the difference of phase between the timing signal for satellite clock and ground station clock is measured by P1 and P2 pseudo range values. The technique used by BIPM performs a combination of P1 and P2 to reduce the ionospheric delay by creating ionosphere free P3 code as shown in Equation 1.

$$P_3 = \frac{f_1^2 P_1 - f_2^2 P_2}{f_1^2 - f_2^2} \tag{1}$$

With the P3 technique, BIPM computes the reference value for the key comparison and it is named UTC- Coordinated universal time by using all contributing clocks around the world to perform an average of them. All three timescales in this work can be compared to this reference value and in Figure

3 this reference value corresponds to zero in the ordinate axis. The abscissa is ordered by taking a 5-day average for every data collected.

During this evaluation, the uncertainties for each timescale are computed and for instance, the GPS system connected to USNO time scale has a type A uncertainty due to statistical dispersion of 0.3 ns and a type B uncertainty due to the satellite-receiver link calibration of 1.5 ns. The combined uncertainty is expanded to level of confidence 95% by using a coverage factor of 2 and the expanded uncertainty is 3 ns. For INXE and LRTE systems the values are 0.4 ns and 20 ns because both receivers were not calibrated yet, giving an expanded uncertainty for these measurements of 40 ns.

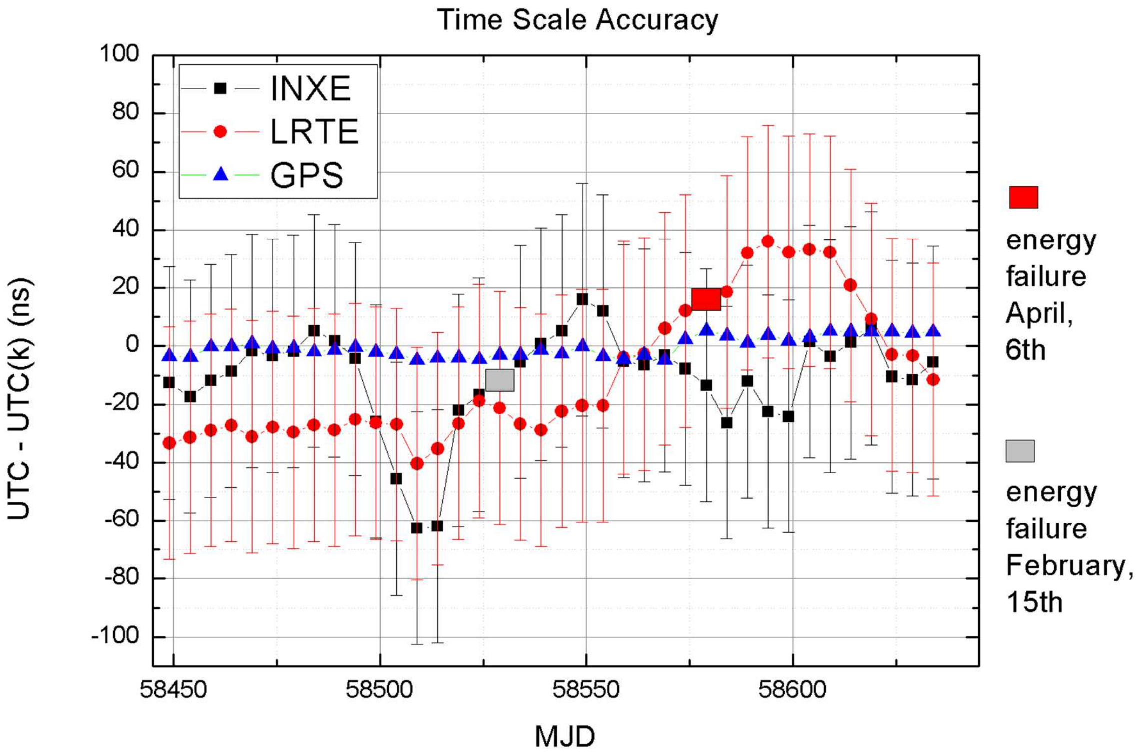

Figure 3. Comparison between UTC and the three timescales (GPS, INXE, LRTE).

In Figure 3, one can see that the GPS values are near the UTC for every point of comparison and has the best accuracy in 3ns uncertainty range. Both timescales are steered when they are near the limits of -40ns or +40 ns, to avoid reaching these limits by using a frequency offset correction that should be evaluated from the satellite results. For this key comparison, in the uncertainty range of 40 ns, the results for INXE and LRTE are similar except in three events, that can be better visualized by using the normalized error predictor as shown in Figure 4 by using the Equation 2.

$$E_n = \frac{V_{lab} - V_{GPS}}{\sqrt{U_{lab}^2 + U_{GPS}^2}} \quad (2)$$

Where V_{lab} is the time difference between UTC and UTC(INXE) or UTC(LRTE), V_{GPS} is the time difference between UTC and UTC(GPS) and U_{lab} and U_{GPS} are the expanded uncertainties for UTC(INXE), UTC(LRTE) and UTC(GPS).

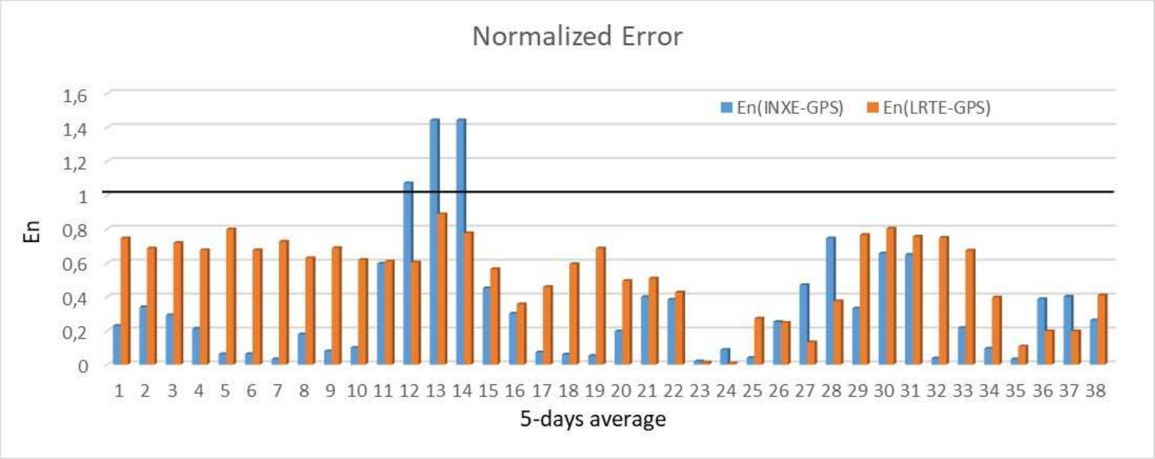

Figure 4. Normalized error for the three scales comparison to GPS time.

One can observe in Figure 4 that during 15 days the INXE timescale had a normalized error greater than 1, this was due to a mistakenly proposed frequency offset correction with wrong sign and instead of avoiding the limit of -40 ns, it accentuated the difference. After 5 days the proposed correction with the right sign was enough to keep the difference steady but not bringing it to the right range and a new correction was inserted to bring the scale to the right range between -40ns and +40ns.

3.4. *Stability evaluation by using Allan variance analysis*

When performing the Allan variance statistical treatment for the three timescale results we can obtain histograms for all the measurement data. In Figure 5 we can measure that the collection time and frequency measurements have a relative uncertainty of $0.4\text{x}10^{-15} \pm 4.6\text{x}10^{-15}$ for GPS system and for the laboratories we have $0.1\text{x}10^{-14} \pm 2.8\text{x}10^{-14}$ for INXE and $0.1\text{x}10^{-14} \pm 2.0\text{x}10^{-14}$ for LRTE results.

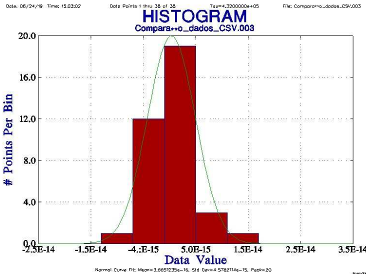

Figure 5a. Histogram for GPS time difference

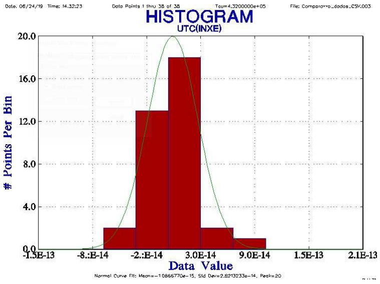

Figure 5b. Histogram for INXE time difference

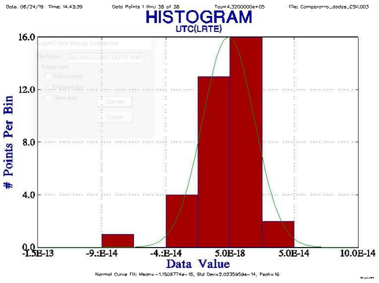

Figure 5c. Histogram for LRTE time difference

Usually Allan variance results are plotted as di-log graphs, as can be seen in Figures 6 and 7.

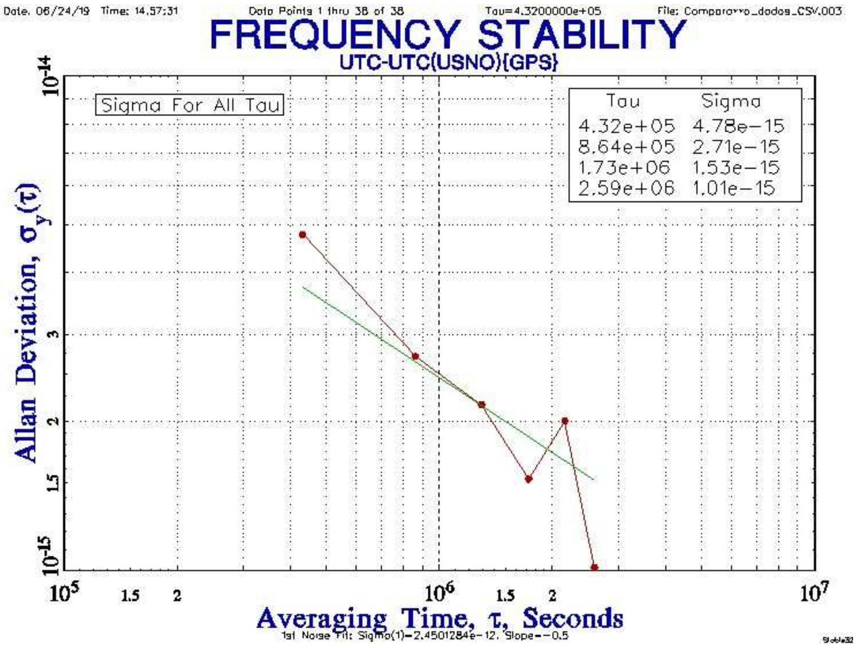

Figure 6. Frequency stability for GPS results and white noise identification.

The GPS results demonstrate that satellites timescale has an Allan deviation of $4.78\text{x}10^{-15}$ for 5-days averaging time and $1.01\text{x}10^{-15}$ for 30-days averaging time and the characteristic noise is $2.45\text{x}10^{-12}\ t^{-1/2}$.

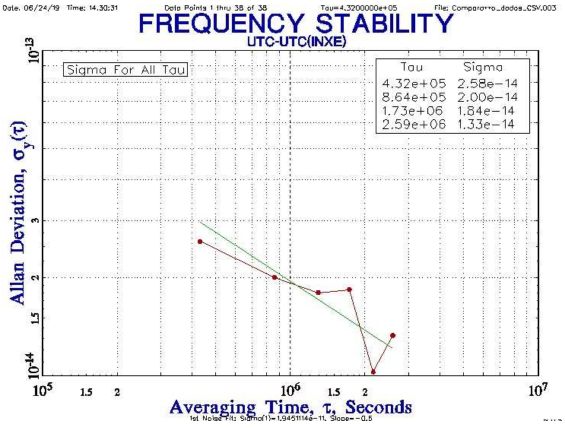

Figure 7a. Frequency stability for INXE results and white noise identification.

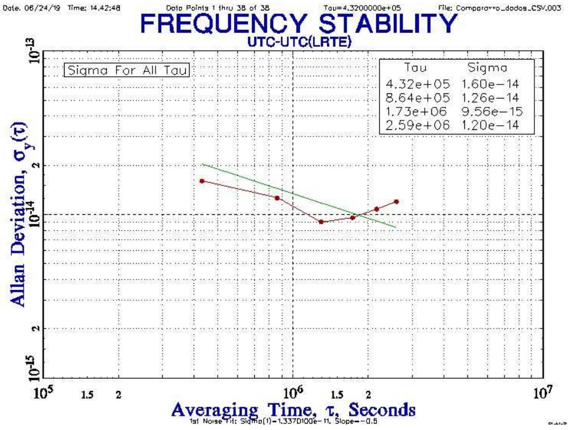

Figure 7b. Frequency stability for LRTE results and white noise identification.

The results for the labs demonstrate that they have compatible Allan deviations for 30-days averaging time. For INXE the Allan deviation is $2.58\text{x}10^{-14}$ for 5-days averaging time and $1.33\text{x}10^{-14}$ for 30-days averaging time, while for LRTE it is $1.60\ \text{x}10^{-14}$ for 5-days averaging time and $1.20\text{x}10^{-14}$ for 30-days averaging time.

For INXE and LRTE time scales the characteristic noises are $1.95\text{x}10^{-11}\ t^{-1/2}$ and $1.33\text{x}10^{-11}\ t^{-1/2}$, respectively. These preliminary results demonstrate that the LRTE timescale is slightly more stable than the INXE timescale, although the Allan deviation for LRTE results demonstrate that the white noise is a good fit for INXE results but the LRTE results for longer averaging times (> 15-days) seems to present a floor region or beginning to enter a region of increasing divergence. This result also can indicate the longer experience of the INXE team in time scale steering [5] compared to the much newer implementation of LRTE time scale.

4. Conclusions

This work reports different systems our groups are working on, in order to provide the state of the art in our laboratories, related to scientific time and frequency metrology. We decided recently about a new strategy for the atomic fountain system and partial results were shown. The compact system with cold atoms has seen further development and a new laser system was developed and is under tests. Concerning time scales, we implemented UTC(INXE) and UTC(LRTE), to provide references for both campi, INMETRO and USP-SC. The evaluation of three performance indicators demonstrate that the timescales are equivalent and can be used in joint or separate operation with a good degree of confidence.

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