Fifteen years of development of the Time and Frequency area in UTE Laboratory

L. Trigo[1]**, A. Garcia**[1]**, D. Slomovitz**[2] **and R. Sandler**[1]

[1] UTE Laboratory, Montevideo, Uruguay
[2] University of the Republic, Faculty of Engineer, Montevideo, Uruguay

ltrigo@ute.com.uy

Abstract. This paper presents the last developments carried out by UTE Laboratory, relative to Time and Frequency standards in the last 15 years. Therefore, the technologies were very diverse, from quartz clocks to cesium atomic clocks, which relative stabilities cover several orders of magnitude, from 10^{-7} Hz/Hz to 10^{-13} Hz/Hz. The last achievement was the incorporation in the UTC system, which demonstrates the progress in the development of the Time and Frequency Area.

Keywords: Frequency standard, time, rubidium clock, cesium clock, mixer, UTC.

1. Introduction

Since the 1960s, UTE (Electric Power Plants and Transmissions) Laboratory (LABUTE) has maintained Time standards, beginning with pendulum clocks [1]. After that technology, Time and Frequency standards were maintained with electronic quartz crystal oscillators, and since the last fifteen years, with atomic clocks. Calibrations systems were developed with different degrees of precision. There are several types of atomic clocks that are fundamentally differentiated by the chemical element they use as a frequency reference. The cheapest are rubidium-based, followed by cesium, but there are attempts to use other elements.

All these developments are described in detail in the following sections.

2. Quartz oscillator clocks

First electronic standards in LABUTE were based on a crystal oscillators. It is an electronic oscillator circuit that uses a piezoelectric crystal as a frequency-selective element. It relies on the slight change in shape of a quartz crystal under an electric field, and the generation of a small voltage due to its mechanical oscillation. As a result, it behaves like an RLC circuit, but with a much higher Q factor and stability. The biggest problem with these oscillators is the influence of temperature on the frequency. Therefore, some form of compensation to minimize the influence of temperature is often implemented in a single package with the crystal oscillator circuit. This standard was used for different type of calibrations of quartz oscillator clock based, in particular for function generator, universal counter, tachometer and stopwatches.

2.1 Stopwatch Calibration

A stopwatch calibration system was developed in LABUTE, based on capturing the LCD display refresh rate [2]. This frequency is proportional to the frequency of the stopwatch's internal oscillator, generally 32678 Hz (2^{15} Hz). Therefore, the fractional deviation of that frequency is the same than the main oscillator. Figure I shows its block diagram and Figure II a photo of the system. It comprises the frequency detection system, a universal counter an oscilloscope and the computer.

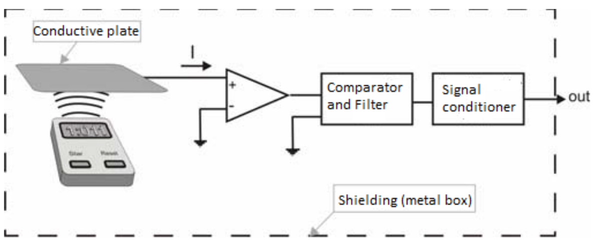

Fig I. Block diagram for signal acquisition by induction method.

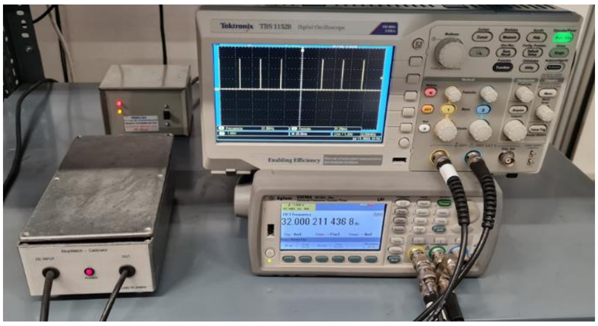

Fig II. Calibration system for stopwatches.

The software was developed in LabWindows CVI, programmed in C language. It records the counter measurements and calculates the fractional frequency deviation and time deviation. A conventional calibration takes at least 24 h, while with this automatic system the time is reduced at 1 h. Figure III shows a typical result.

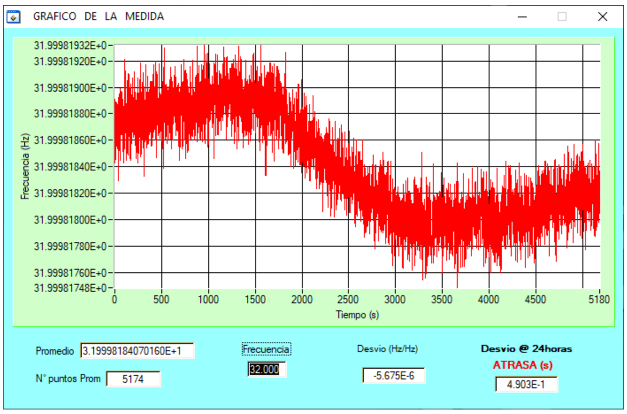

Fig III. Screen software of a stopwatch calibration.

3. Rubidium Clocks

Although rubidium-based clocks mainly depend on atomic transitions, they have drift that is typically on the order of 1.5×10^{-12} (Hz per day), four orders better than that of quartz clocks. The main cause is due to the variation of the ratio between the rubidium gas and the buffer gas. This last gas is used to decrease the dispersion in the frequency. Both gases are slowly absorbed or released through the walls of the container, which alters the composition and affects the value of the frequency.

3.1 Drift-Compensated Rubidium Clocks

To eliminate long-term drift, another type called a GPSDO (GPS Disciplined Oscillator) uses a GPS connection to control its frequency. The GPS system, in addition to providing global positioning services, also transmits standard frequencies of 1 PPS, 5 MHz and 10 MHz. GPS frequencies have not long-term drift, however, they have high noise levels in short-term measurements. On the other hand, rubidium clocks exhibit low short-term internal noise. Combining both systems, very high stability and low noise standards can be achieved.

UTE Laboratory has developed multiple standards based on this technology [3-7]. The configuration involves utilizing a Spectratime GPS receiver with frequency output (model GPSource), a Spectratime rubidium atomic clock (model RMO), an electronic control circuit, and an HP universal counter (model 53132A). All system operations are computer-controlled. Figure IVa shows the block diagram and Figure IVb, a photograph of the system.

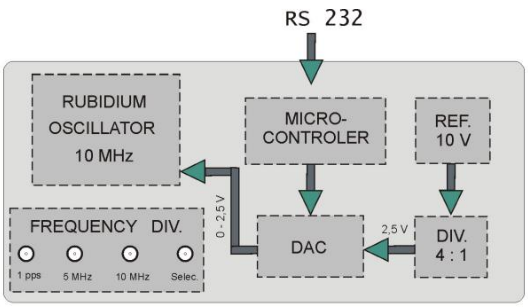

Figure IVa

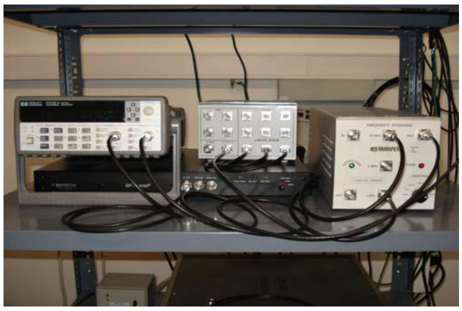

Figure IVb

Block diagram and photograph of a rubidium-clock GPS controlled, developed in LABUTE.

3.2 Intercomparisons

A facility of the SIM (Inter-American Metrology System) was used to calculate the difference between this standard and those corresponding to the National Metrological Institutes: NIST (United States), CENAM (Mexico) and NRC (Canada). Figure V shows the results between 2009 and 2011.

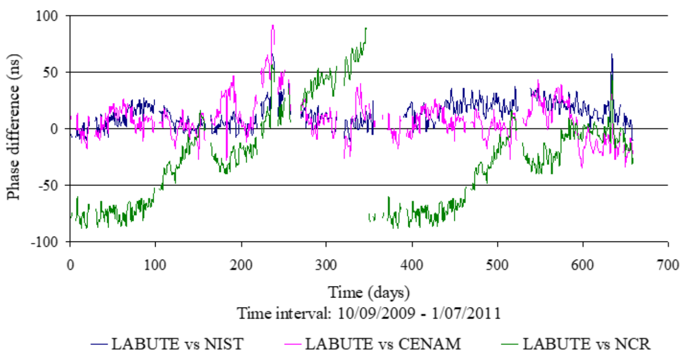

Figure V. Phase differences between LABUTE and NIST, NRC, CENAM clock standards.

Phase differences between LABUTE and NIST, and LABUTE and CENAM were below ±30 ns for most of the period; while the phase difference between LABUTE and NRC varied within ±100 ns.

4. Cesium Clocks

Cesium atomic oscillators are primary standards, as they reproduce the International System (SI) definition of the unit of time [8]. Its frequency doesn't change with time or by the influence of environmental conditions. They use the cesium Cs133 hyperfine transition frequency 9.192 631 770 GHz (see Figure VI). There are 16 magnetic states, but only one is useful for a primary standard of frequency, since that transition is basically insensitive to magnetic fields. This hyperfine transition is the one used to define the SI second.

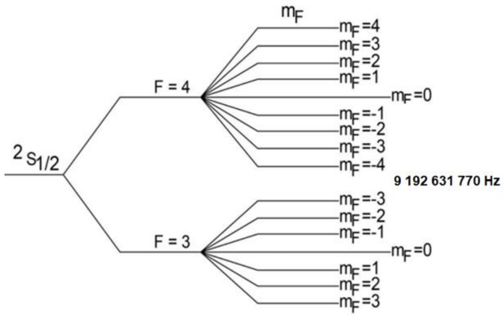

Figure VI. Cs133 hyperfine transition frequencies.

A block diagram and a photograph of the LABUTE cesium clock is shown in Figure VII [9]. On the left side, an oven heats cesium atoms until they reach a gaseous state. A beam of atoms emerges from the oven heat at a temperature close to 100 °C and passes through a magnetic field (magnet A), where it splits into two beams of atoms with different magnetic states. One of the beams is absorbed and of no interest, but the other beam is diverted into the microwave interrogation cavity, known as the Ramsey cavity. Inside it, the cesium beam is exposed to a microwave frequency generated by a frequency synthesizer based on a quartz oscillator. If this frequency is precisely matched to the resonant frequency of cesium, some of the atoms will change state. After leaving the Ramsey cavity, the atoms pass through a second magnetic field (magnet B). This magnet directs only the atoms that have changed state towards the detector. In essence, the magnets located on either side of the Ramsey cavity function as a gate, allowing only those atoms undergoing the desired energy transition to pass through the detector.

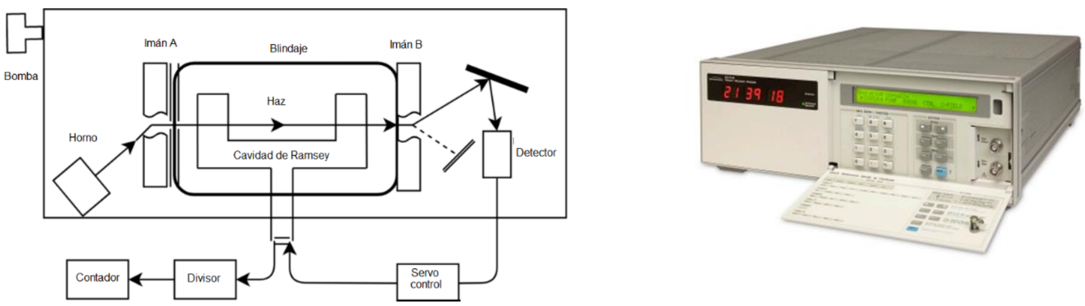

Figure VII. Block diagram and photograph of the LABUTE cesium clock [8].

The detector sends a feedback signal to a servo circuit that continually adjusts the quartz oscillator so that the maximum number of atoms reach the detector. In this way, the quartz oscillator generates a frequency equal to the resonance of cesium. By means of frequency dividers the typical outputs of 1 PPS, 5 MHz and 10 MHz are obtained. At the moment, our cesium clocks are capable of generating frequencies with a stability of the order of 5×10^{-13} Hz/Hz.

Some laboratories (NIST, PTB, NPL and others) have developed higher precision systems, called Cesium Atomic Fountain [10]. These use a different system. Cesium atoms are cooled with a laser to temperatures very close to absolute zero, decreasing their velocities and therefore their frequency dispersion. These cesium beams are shot up like a water fountain and pass through a Ramsey cavity twice, once going up and once going down. Improvements made to the latest clocks allow an accuracy of 1.5×10^{-16} Hz/Hz.

5. Atomic Clocks Comparison

5.1 Direct comparison

The very high precision performance of cesium atomic clocks does not allow measuring their frequency output directly with a universal counter, because this type of meter does not have the required precision.

LABUTE has developed a specific measurement system based on two mixers [12]. Each mixer [11] has two inputs and one output proportional to the multiplication of the inputs. In the frequency domain, two new frequencies are generated, the add and the subtraction of the two input frequencies. The output is connected to a low-pass filter, to get the subtraction. However, it is not convenient to directly measurement this frequency, because the frequencies of the reference (Standard) and the clock to be calibrated (UUT) are very close, in the order of a few micro-hertz. To solve this, an auxiliary generator (function generator) is added (see Figure VIII), adjusted to a frequency close to that of the clocks (e.g. 9.9995 MHz for 10 MHz). Subtracting this frequency from the Standard and UUT frequencies, we get a resulting frequency of the order of 500 Hz, much easier to measure. The outputs of the mixers are connected to the input of a universal counter, which is set as a time-interval counter. In its output, the signal has a time difference Δt which varies with time because of the frequency difference of the counter inputs.

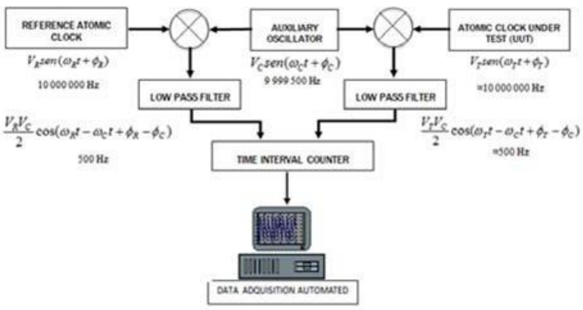

Figure VIII. Measuring system diagram.

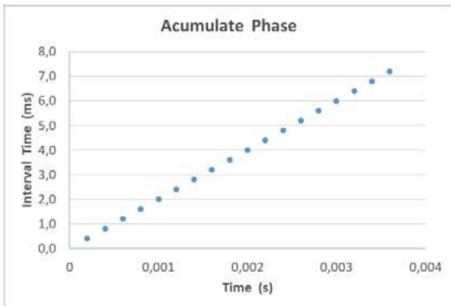

Figure IX. Accumulate phase difference.

Figure IX shows the phase change (ms) as a function of time (s). With a fixed frequency difference, the variation follows a straight line. To get low uncertainties, it is necessary to calculate the accumulated phase change during several hours. This measurement system works well for fractional frequency differences between 1×10^{-11} Hz/Hz and 1×10^{-15} Hz/Hz.

5.2 Remote Comparison

When the comparison must be made between physically distant places, the problem becomes more complex. This is necessary for distributing time signals, calibrate standards remotely and validate National Standards from different countries. Unlike other quantities, such a remote comparison is possible in the frequency quantity. In the Americas, a remote inter-comparison system was developed between National Metrology Institutes (NMI), of which LABUTE participates. It was developed by SIM and allows to monitor standards of this magnitude online. This system (SIM Common View Time and Frequency Measurement System) [13] makes it possible to compare clocks from NMI of the American countries. It is based on the common view of the satellites of the GPS system. From each laboratory, the time difference between its standard and the satellite clocks is measured. These differences are reported and subtracted to remove the clock-satellite variable. The process has certain corrections for atmospheric effects and other variables, and results in the time difference between the two laboratories, independent of the satellite clock error. This is done for all satellites that have a common view between that pair of labs. Every ten minutes, the values of the time difference between all the countries included in this system (today, 26 countries) are published. A matrix with these differences and their historical values is shown on the SIM website (see Table I). Additionally, it shows graphs of these values, mean values and Allan deviations. The system calculates a time scale called SIMT (SIM Time Scale) [14] from the data of all the countries that have cesium clocks, averaged according to the weight of the uncertainty of each one. As an example, Figure X shows the comparison between the UTE and NIST clocks. The countries to be compared and the period are selected on the SIMT system website. In this case, the information shown corresponds to the dates between February and April, 2023. The graph shows the behavior between both clocks, as well as the average differences in time (17 ns) and frequency (-2.45×10^{-15} Hz/Hz).

SIM Time Network

(real-time measurement results for the 10-minute period ending on 05-09-2023 at 1220 UTC)

SIM	United States SIMT(NIST)	Mexico SIMT(CNM)	Canada SIMT(NRC)	Panama SIMT(CNMP)	Brazil SIMT(ONRJ)	Costa Rica SIMT(ICE)	Colombia SIMT(INM)	Argentina SIMT(INTI)	Guatemala SIMT(CNME)	Jamaica SIMT(BSJ)	Uruguay SIMT(UTE)
United States SIMT(NIST)		-2.0	-8.1	-3.0	9.0	-18.5	-86.2	-213.9	58.9	-153.7	-39.0
Mexico SIMT(CNM)	2.0		-6.8	0.7	15.9	-15.6	-85.4	-208.6	57.3	-154.7	-30.1
Canada SIMT(NRC)	8.1	6.8		4.5	17.9	-11.0	-78.7	-200.4	69.7	-145.1	-25.5
Panama SIMT(CNMP)	3.0	-0.7	-4.5		10.2	-16.9	-87.8	-213.2	60.3	-155.7	-34.2
Brazil SIMT(ONRJ)	-9.0	-15.9	-17.9	-10.2		-27.9	-102.5	-224.1	46.1	-169.4	-45.7
Costa Rica SIMT(ICE)	18.5	15.6	11.0	16.9	27.9		-71.0	-195.1	75.7	-138.2	-16.1
Colombia SIMT(INM)	86.2	85.4	78.7	87.8	102.5	71.0		-118.8	146.6	-70.1	58.8
Argentina SIMT(INTI)	213.9	208.6	200.4	213.2	224.1	195.1	118.8		263.6	51.9	175.3
Guatemala SIMT(CNME)	-58.9	-57.3	-69.7	-60.3	-46.1	-75.7	-146.6	-263.6		-214.8	-85.2
Jamaica SIMT(BSJ)	153.7	154.7	145.1	155.7	169.4	138.2	70.1	-51.9	214.8		127.6
Uruguay SIMT(UTE)	39.0	30.1	25.5	34.2	45.7	16.1	-58.8	-175.3	85.2	-127.6	

Table I. Comparison between standard clocks of American countries in nanoseconds (partial) [16].

Mean Time Offset (ns)	Range (ns)	Frequency Offset
16.73	215.91	-2.45×10^{-15}

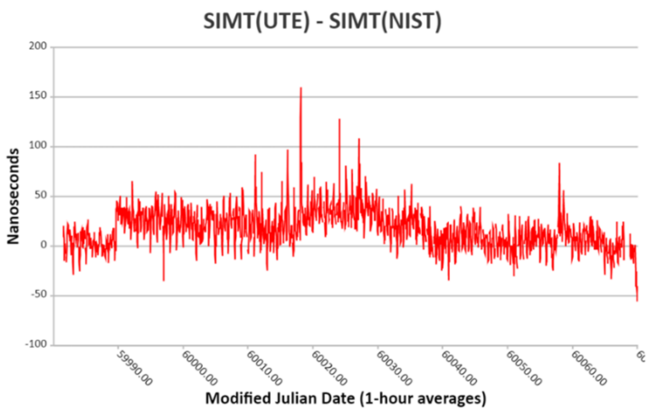

Figure X. Comparison between SIM(UTE) and SIM(NIST) between February and April 2023.

6. UTC System

One of LABUTE's latest great achievements in the area of Time and Frequency is the participation in the UTC (Coordinated Universal Time) [15] as UTC(UTE), starting in March 2023. UTC is the main standard for time by which the world regulates clocks. Engagement was achieved with the primary cesium standard, accessory devices and a common satellite view system (NIST Tai-1), shown in Figure XI. This set is responsible for the measurement and generation of the daily report that is then sent to the servers of the International Bureau of Weights and Measures (BIPM) for processing and comparison with other laboratories. To be admitted into this system, high stability over a long time had to be demonstrated. It is also necessary to follow the recommendation that UTC(UTE) be within ±100 ns time interval of UTC, so made corrections to our cesium primary standards to stay within this interval. The BIPM periodically issues a report of all contributing laboratories (around 86), called Circular T [16-17]. The weight of each one is determined by its uncertainty, with laboratories with less uncertainty having a greater influence.

Table II partially shows some of the participating laboratories and their results, and Figure XII, the time differences between UTC and UTC(UTE) during the months of March to June, 2023.

1 - Difference between UTC and its local realizations UTC(k) and corresponding uncertainties.
From 2017 January 1, 0h UTC, TAI-UTC = 37 s.

Date 2023 0h UTC	FEB 24	MAR 1	MAR 6	MAR 11	MAR 16	MAR 21	MAR 26	MAR 31	Uncertainty/ns			Notes
MJD	59999	60004	60009	60014	60019	60024	60029	60034	uA	uB	u	
Laboratory k	[UTC-UTC(k)]/ns											
NRC (Ottawa)	-7.8	-8.7	-8.9	-8.8	-9.1	-9.6	-8.9	-8.6	0.3	3.5	3.6	
NRL (Washington DC)	-0.4	0.4	0.8	2.4	4.6	5.7	2.6	-0.3	0.3	20.0	20.0	
NSAI (Dublin)	8.7	6.4	10.7	15.8	13.8	14.3	-	-	0.3	7.3	7.3	
NTSC (Lintong)	0.3	-0.6	-0.4	-0.4	-0.3	0.0	-0.5	-0.5	0.5	3.1	3.1	
ONBA (Buenos Aires)	2586.7	2605.2	2612.1	2616.5	2651.9	2664.5	2684.7	2689.2	2.0	11.2	11.4	
ONRJ (Rio de Janeiro)	1.4	1.3	-5.0	-2.2	1.5	1.0	0.2	2.1	0.7	3.0	3.1	
OP (Paris)	0.9	1.2	0.9	0.9	0.6	0.6	1.0	0.9	0.3	1.7	1.7	
ORB (Bruxelles)	2.3	1.8	1.1	2.1	1.8	2.0	2.0	1.6	0.3	3.1	3.1	
PL (Warszawa)	-1.4	-2.1	-2.2	-1.4	-1.2	-0.2	0.3	0.7	0.3	2.9	2.9	
PTB (Braunschweig)	0.4	0.4	0.5	0.3	0.1	0.1	-0.1	-0.1	0.1	1.0	1.0	
ROA (San Fernando)	-2.3	-2.9	-2.3	-2.5	-2.9	-2.9	-3.1	-2.6	0.3	1.8	1.8	
SASO (Riyadh)	-417.1	-431.8	-445.6	-480.2	-513.8	-542.0	-566.9	-585.5	0.3	3.5	3.5	
SCL (Hong Kong)	50.1	49.9	52.1	48.4	51.6	52.7	49.5	50.9	0.3	3.5	3.5	
SG (Singapore)	6.8	-4.9	-14.6	-8.1	3.4	18.6	15.0	-2.9	0.3	3.3	3.3	
SIQ (Ljubljana)	-6.1	-8.9	-4.3	-0.8	-6.6	-0.4	-11.7	-6.8	0.3	3.9	3.9	
SL (Colombo)	-	-	-	-	-	-	-	-				
SMD (Bruxelles)	1.7	1.4	1.1	1.1	0.6	0.5	0.5	0.5	0.3	3.6	3.6	
SMU (Bratislava)	-	264.4	255.0	-	-	-	-	-	1.5	12.2	12.3	
SP (Boras)	-0.3	-0.3	-1.1	-2.0	-2.8	-3.5	-3.6	-3.2	0.3	1.9	1.9	
SU (Moskva)	-0.6	-0.7	-0.9	-1.1	-1.0	-1.3	-1.1	-1.1	0.3	1.8	1.8	
TL (Chung-Li)	-0.5	-0.7	-1.2	-2.0	-2.4	-2.7	-1.6	-0.7	0.3	2.1	2.2	
TP (Praha)	25.7	17.0	10.5	11.5	10.7	7.5	0.9	3.5	0.3	2.9	2.9	
UA (Kharkiv)	4.0	-13.1	9.8	8.5	-2.4	-7.1	-11.8	-14.6	1.5	7.4	7.5	
UAE (Abu Dhabi)	24.0	38.7	28.3	35.6	41.1	25.4	7.1	18.4	7.5	4.6	8.8	
UME (Gebze-Kocaeli)	1.0	0.3	1.2	1.2	0.4	-2.2	-0.2	-1.2	0.3	3.7	3.7	
USNO (Washington DC)	0.2	0.2	0.1	0.4	-0.1	-0.7	-0.8	-0.8	0.3	1.8	1.8	
UTE (Montevideo)	-	-12.6	-16.2	3.4	-13.9	-22.0	-28.2	-10.2	3.0	7.7	8.2	

Table II. Participating laboratories in the UTC (partially).

Figure XI.- LABUTE equipment for measuring and sending reports to UTC

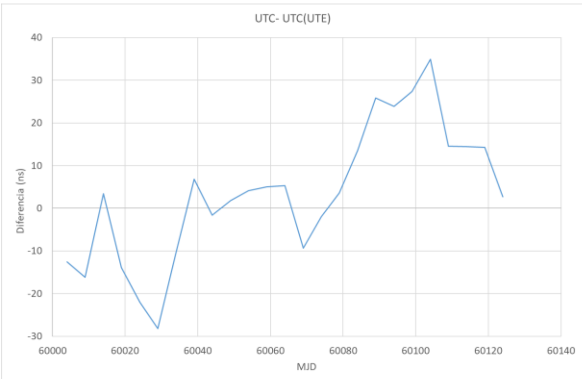

Figure XII.- Time difference between UTC and UTC(UTE)

7. Conclusions

Over approximately 15 years, LABUTE has developed standards and calibration systems of Time and Frequency, based from quartz crystal oscillators to rubidium and cesium atomic clocks. Calibration accuracy levels have been improved, from 10^{-7} Hz/Hz to 10^{-11} Hz/Hz for quartz crystal clocks, and up to 10^{-14} Hz/Hz for rubidium and cesium clocks, in daily averages, As a result, LABUTE was admitted to participate directly in UTC (Coordinated Universal Time) as UTC(UTE), and its results appear in the periodic reports of the BIPM (International Bureau of Weights and Measures), Circular-T.

The last developed standard system allows direct traceability of the local Time of Uruguay through UTC(UTE), and the calibrations of other high accuracy standard clocks.

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