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Double Mixer Measurement System for Atomic Clock Calibration

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Abstract

Atomic clocks have very high precision, so it is not possible to directly measure the output frequency with a universal counter because this instrument do not have enough precision. This paper shows an atomic clock calibration system based on a double mixer, a universal frequency counter, a control and a frequency-fractional-deviation calculation software.

1. Introduction

UTE Laboratory is a designated laboratory by LATU (National Metrology Institute of Uruguay) for maintenance of National Standard in the Electrical and Time-Frequency fields. Our laboratory offers calibration services for our own and customers' equipment. New technologies require the implementation of new calibration methods, for example, rubidium, cesium or hydrogen maser atomic clocks.

In order to provide calibration services, it was necessary to acquire different types of atomic clocks. Therefore, we currently have three rubidium atomic clocks [1], a drift-compensated rubidium atomic clock [2] and a cesium atomic clock [3] and the purchase of another is planned for 2024, the clock being cesium atomic the National Standard of Time and Frequency of Uruguay.

The very high precision of atomic clocks does not allow their frequency output to be directly measured with a universal counter, because this equipment does not have the required precision. This is why it was necessary to develop a specific high-precision measurement system. Previous research, on the state of the art [4, 5], showed that the system could be based on a double mixer, a universal frequency counter, a control system and a fractional frequency deviation calculation software. The following chapters detail the development of the measurement system and the results obtained.

2. Measurement System

Our measurement system is based on a measurement system that uses two mixers. The mixer we use is the MC1496B integrated circuit [6], low cost and easy to implement, it only requires a few components to work correctly. Each mixer has two inputs and one output, being the output a signal proportional to the multiplication of the inputs, in the domain time, as shown in Fig. 1.

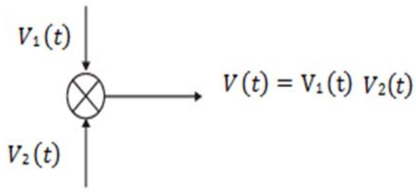

Fig. 1. Mixer operation.

$$V_1(t) = A_1\ sen(\omega_1 t + \emptyset_1) \quad (1)$$

$$V_2(t) = A_2\ sen(\omega_2 t + \emptyset_2) \quad (2)$$

$$V\ (t) = A_1\ sen(\omega_1 t + \emptyset_1)\ A_2\ sen(\omega_2 t + \emptyset_2) \quad (3)$$

Developing (3), we obtain

$$V(t) = \frac{A_1 A_2}{2}[cos(\omega_1 t + \omega_2 t + \emptyset_1 + \emptyset_2) - cos(\omega_1 t - \omega_2 t + \emptyset_1 - \emptyset_2)] \quad (4)$$

$$V(t) = \frac{A_1 A_2}{2}[cos(2\Pi(f_1 + f_2)t + \emptyset_1 + \emptyset_2) - cos(2\Pi(f_1 - f_2)t + \emptyset_1 - \emptyset_2)] \quad (5)$$

After passing through a low-pass filter, the first term of (5) is eliminated, resulting

$$V(t) = \frac{A_1 A_2}{2}[cos(2\Pi(f_1 - f_2)t + \emptyset_1 - \emptyset_2)] \quad (6)$$

The use of the mixer and low-pass filter allows obtaining a signal with a frequency equal to the subtraction of the two input frequencies. In principle, the reference frequency (Standard) and the frequency of the atomic clock to be calibrated (DUT) are similar, so by connecting them directly to the mixer we obtain a frequency difference of a few microhertz, which is very difficult to measure.

To solve this, an auxiliary generator (function generator) is added (see Fig. 2), adjusted to a frequency close to the clocks (9.9995 MHz for 10 MHz clocks). Subtracting this frequency from the Standard and DUT frequencies, we get a resulting frequency of the order of 500 Hz, much easier to measure. The outputs of both mixers are connected to the input of a universal counter, which is configured as a time interval counter. The time difference Δt between output signals varies with time due to the difference between both frequencies.

The measured time interval is:

$$\Delta t = \frac{f_R - f_T}{500} t + \emptyset \tag{7}$$

Then, the fractional frequency difference is

$$\frac{f_R - f_T}{f_R} = \frac{\Delta t}{t}(5 \times 10^{-5}) \tag{8}$$

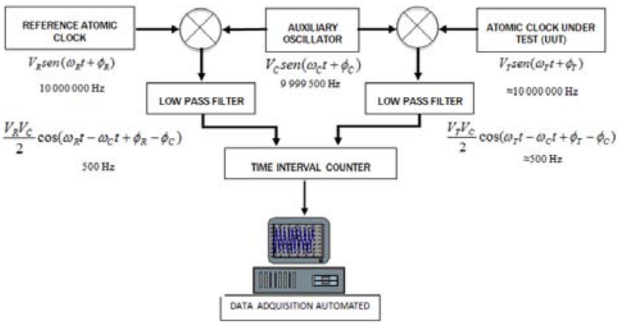

Fig. 2. Measuring system diagram.

The phase shift (in ms) as a function of time at the counter output (see Fig. 3).

Theoretically, for a fixed frequency difference, the variation follows a straight line. The phase difference increases or decreases with time depending on which frequency is higher. To obtain low uncertainties, it is necessary to calculate the cumulative phase change over several hours. The software adds the partial intervals (see Fig. 4), attaching a timestamp. This is a critical point in software development, since a good correspondence between partial sectors is required. A poor fit between sectors generates errors in measurement. This measurement system works well for fractional frequency differences less than 1×10^{-10} Hz/Hz. For frequency differences equal to or greater than 1×10^{-10} Hz/Hz, it is advisable to measure the frequency directly with the universal counter.

Fig. 5 shows the arrangement of the instrumentation. It includes a self-developed double mixer (left at the bottom), the universal counter [7], above, and the auxiliary function generator [8], on the right.

To obtain a very high precision measurement system, it is very important to link the time base of the auxiliary function generator and the universal counter to the output of the 10 MHz reference atomic clock. The reason for this option is to have a better base of metrological quality times, which improves the precision of measurements. This external time base controls the function generator since it has DDS (Direct Digital Synthesis) technologies to generate the signals, based on its time base. The universal counter also bases its frequency dividers, internal counters and PLL (Phase Locked Loop), on the external time base. The measurement of the time interval is based on the external time base.

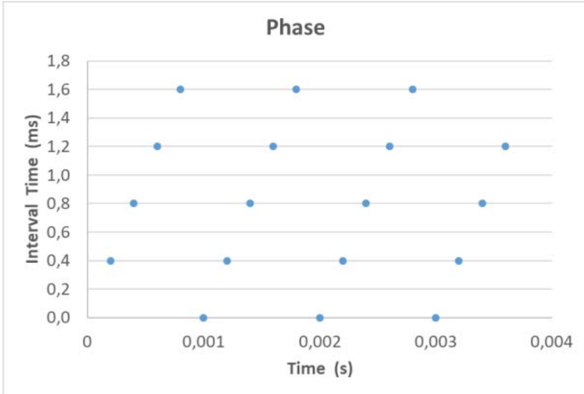

Fig. 3. Phase measurement.

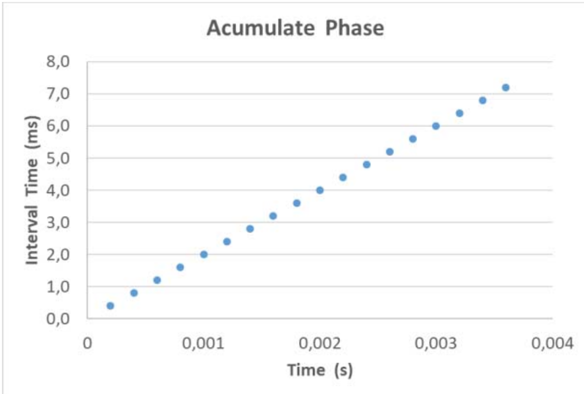

Fig. 4. Accumulate phase difference.

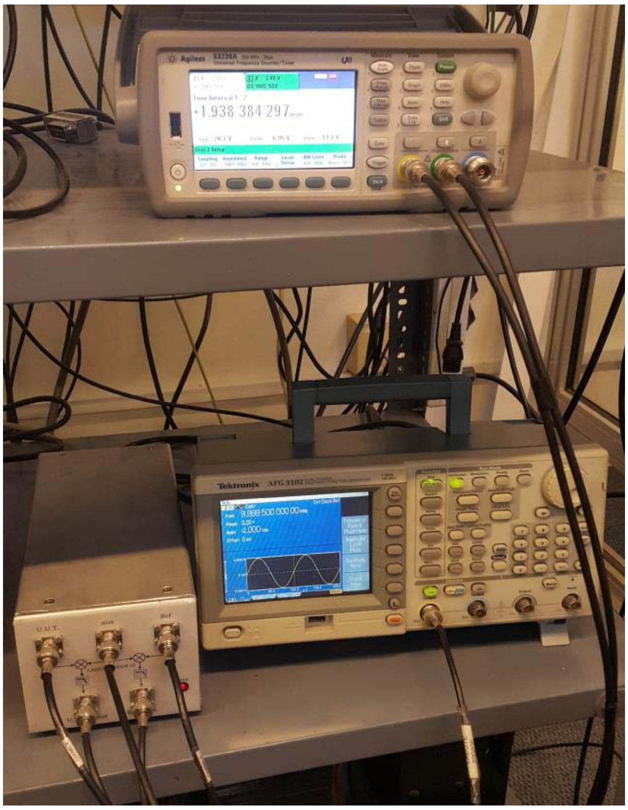

Fig. 5. Measuring system

3. Uncertainty

In atomic clock calibrations, the associated noise is of type f^{-1}, f^{-2} or more. This implies that the noise changes with the observation time of the phenomenon. Type A uncertainty calculations are performed using the Allan variance [9]. Uncertainty values are reported as a function of measurement time, in seconds, usually in multiples of 2. Our measurement system software calculates and reports the Allan deviation during calibration, this is important to evaluate the correct evolution of measurements during calibration.

The type B uncertainty is obtained from the technical specifications of the Cesium Atomic Clock Standard.

Type A and type B uncertainty values are reported as a function of measurement time, in seconds. The expanded uncertainty is calculated using the classical formula and is also expressed as a function of the measurement time.

4. Software

The measurement system software was written in C language, in the Labwindows/CVI programming environment [10]. This software configures the counter and acquires the time interval measurements every 1 s. The software also communicates with an NI USB-TC01 [11] thermometer (manufactured by National Instrument) to record temperature during calibration. A timestamp is added to each universal counter and temperature measurement. All data is saved to a file on the computer.

The time interval and temperature measurements are graphed (see Fig. 6 and Fig. 7). The accumulated phase and its slope are calculated and graphed. The slope is proportional to the deviation of UUT (see equation 8 and Fig. 8). The Allan's deviations are calculated and represented (see Fig. 9), the Allan's deviations at times multiple of two (2^n) are also shown. Each time a set of measurements is acquired (time interval and temperature) the calculations are updated and graphics.

The software can load a file, make all the calculations, and display all the graphs described above.

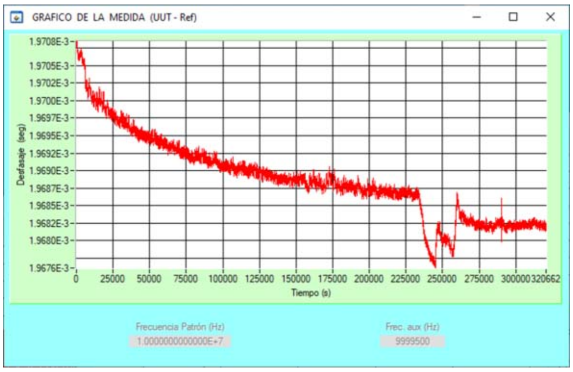

Fig. 6. Interval Time Measuring (time interval(s) vs time (s))

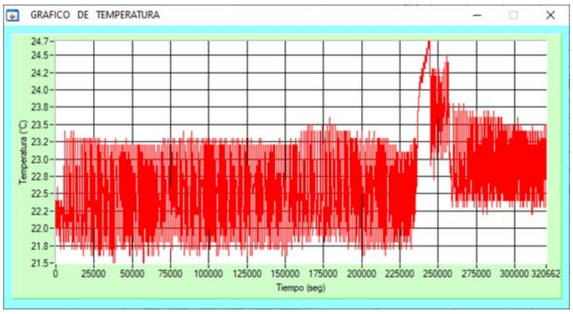

Fig. 7. Temperature Measuring (temperature (°C) vs time (s))

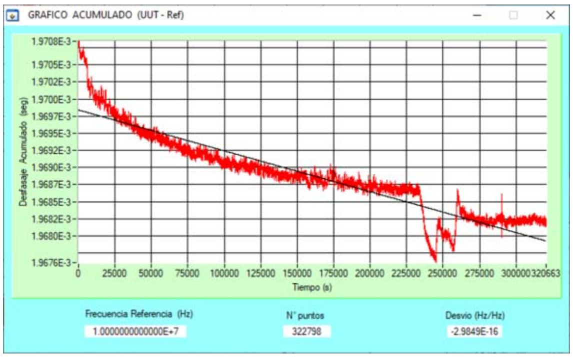

Fig. 8 Accumulated phase, slope and frequency-fractional-deviation value (2.98×10^{-16} HZ/Hz)

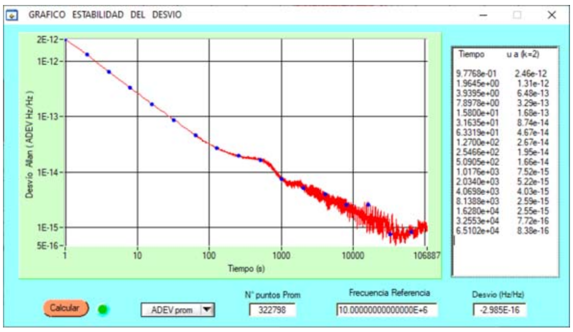

Fig. 9 Allan's deviations

5. Results

To evaluate the precision of our measurement system, the self-calibration test is carried out. This technique consists on putting the same signal into both inputs of the mixer (UUT and REF). Theoretically, by putting the same signal into both inputs of the mixer, the frequency-fractional-deviation should be 0 Hz/Hz. Obviously, due to the equipment precision and the noise of the system of measurement, its will always have a value other than 0 Hz/Hz.

An example of self-calibration is shown in the figures in the previous chapter. We connect the 10 MHz signal of the Cesium atomic clock to both inputs of the mixer (UUT and REF). We set the auxiliary generator to generate a 1Vpeak-peak and 9.9995 MHz signal. The software ran for just over 3 days.

In figures 6 and 7, we see the time interval and temperature records. The fig 8 showed accumulated phase, slope and frequency-fractional-deviation value. In this case, the frequency-fractional-deviation is around -3.0×10^{-16} Hz/Hz. Fig. 9 shows the evolution of the Allan's deviations as a function of time and the values of the Allan's deviations (k=2) for time multiples of two, Allan's deviation (tau=2^{16}s) = 8.3×10^{-16} (k=2). The frequency-fractional-deviation and Allan's deviations values demonstrate the very high precision of the developed measurement system. Similar values of frequency-fractional-deviation and Allan's deviations were obtained for the 1 MHz and 5 MHz frequencies.

6. Conclusions

A very high precision measurement system was developed for the calibration of atomic clocks. A self-calibration test showed excellent performance for frequencies of 1 MHz, 5 MHz and 10 MHz, with a frequency-fractional-deviation of the order of 1×10^{-16} Hz/Hz and an Allan's deviation of the order of 1×10^{-15} Hz/Hz (average one day, k=2). The type A uncertainty is mainly due to the noise of the clock to be calibrated and our cesium atomic clock. The type B uncertainty is mainly obtained from the technical specifications of the Cesium Atomic Clock Standard.
Our system is based on two low-cost and easy-to-implement mixer integrated circuits to achieve very good performance, making it a viable alternative for Laboratories with fewer economic resources. Furthermore, since it is an analog circuit we only need to connect the signals of the atomic clocks (REF and UUT) and the signal of the auxiliary generator and obtain the output signals to be measured by the universal counter.

References

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7. Next Work

Based on this very high precision calibration system, other Time and Frequency calibration methods and the values reported by the BIPM Circular T, we are ready to publish CMC this year. We had a successful peer review, last year. At the QSTF meeting in March, we will present the necessary documentation.
Therefore, during this year our CMC proposal will be circulating in the different RMO.
We hope to have the CMC approved and published this year.