Positioning performance of Chip-Scale Atomic Clock GNSS augmentation systems

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***Abstract*—Current GNSS (Global Navigation Satellite System) receivers include an internal quartz oscillator, such as TCXO (Temperature Compensated Crystal Oscillator) or similar, limited by its frequency stability and a poor accuracy, being one of the main sources of uncertainty in the navigation solution (also multipath and ionosphere effects are an important error sources.) Replacing the internal TCXO clock of GNSS receivers by a higher frequency stability clock such a CSAC (Chip Scale Atomic Clock) can improve the navigation solution in terms of availability, positioning accuracy, tracking recovery, multipath and jamming mitigation and spoofing attacks detection. For achieving these benefits, the deterministic errors from the CSAC need to be modelled, by determining and predicting the clock frequency stability in the positioning estimation process. The procedure of calculating a position without the need of estimating continually the clock error parameter is also known as clock coasting. The presented research shows the potential of the clock coasting method in order to be able to obtain position with only three satellites, improve the vertical positioning accuracy and increase the navigation solution availability.**

Keywords—GNSS; Atomic clocks; Clock coasting; CSAC; Navigation;

I. INTRODUCTION

Clocks are one of the fundamental components of GNSS receivers. GNSS solution is based on pseudo-ranges derived from the propagation time of a signal between the satellites and the GNSS receiver [1]. Due to the fact that these measurements are the key point for estimating the positioning solution, the transmitter and the receiver clocks must be synchronized as accurately as possible [2]. Since satellite clocks are of the highest quality, such synchronization accuracy mainly depends on the GNSS receiver clock accuracy and stability [3].

Current GNSS receiver clocks, typically quartz oscillators, exhibit a noisy short-term stability and a poor long-term stability. To overcome this problem, GNSS receivers estimate periodically, epoch by epoch, the receiver clock errors (bias and drift) in order to improve the measured pseudo-ranges quality. The clock calibration adjustment is achieved by considering the time as an unknown when solving the positioning solution.

New generation of atomic clocks, like CSAC [4], are now commercially available. Their price, size and power consumption have been reduced considerably in the past years. This tendency is driving GNSS providers to incorporate one of these clocks into their high-end products [5]. When using a higher stable clock reference such as a CSAC it is possible to get rid of the receiver clock errors unknowns. However, in order to get rid of them, it is necessary to calibrate the CSAC output frequency and it is mandatory to synchronize the CSAC with the GPS time.

In order to calibrate the CSAC a rigorous procedure needs to be implemented [6]. The calibration starts with an estimation of the delays introduced by the system, due to cables and electronic components, in order to remove systematic errors. In addition, a clock calibration procedure needs to be implemented. It consists on estimating the drift and the bias of the clock by a steering process. The calibration values are strongly correlated with the ambient temperature so this calibration process is repeated for a range of temperatures by using a climate chamber [7]. Moreover, due to the CSAC aging, after some time, typically few months, the CSAC calibration needs to be reiterated.

Once the CSAC is properly calibrated the GNSS receiver can benefit of its accuracy. Firstly, there will be an improvement in the correlator's synchronism, this yield to the reduction of the PLL bandwidth and thus, it helps to the improvement in the tracking recovery time (holdover) and the signal to noise ratio (SNR) [6].

In addition, by adding a precise clock into a GNSS receiver, it is possible to obtain position without the need of estimating the receiver clock errors for a long time period by using the clock coasting estimation method [8]. This technique allows the determination of a positioning solution with only three satellites while classical methods require at least four satellites. This method also contributes to the GNSS navigation benefits such as improving the navigation solution in terms of availability, vertical positioning accuracy [9], multipath [10], jamming mitigation and spoofing attacks detection [11].

The research presented in this paper is focused on the analysis of the improvement of the GNSS solution availability and horizontal accuracy by applying the clock coasting method with a CSAC.

II. THEORY BASIS

A. Clock modelling

Oscillators produce a hovering signal. Far away from oscillating at a constant frequency, always occur small deviations with respect to their nominal frequency. The performance of a clock is normally expressed in its stability to maintain a nominal frequency output. Depending on the oscillator's stability, clocks can be classified in different categories. In the GNSS context, consider the next clock classification from high to low performance:

- Satellites – Rubidium/Cesium clocks.
- CSAC – Cesium clock.
- GNSS receiver – TCXO clock.

The on-board satellites oscillators, such as the Rubidium/Cesium clocks are the classical atomic clocks. This high-grade clocks behave a stability performance in the order of $10^{-13}$to 10^{-15} (TAU = 1sec) [12]. The new chip scale atomic clocks stability is around 10^{-10} (TAU = 1sec) in cold start and can reach up to 10^{-12} (TAU = 1sec) when calibrated [4]. Finally, the TCXO quartz clock present a poor stability of about 10^{-9} (TAU = 1sec) [13].

Therefore, all oscillators suffer from systematic errors, in one order of magnitude or another, coming from environmental effects such as vibrations, shock, radiation, humidity, temperature and aging [11]. In order to take as much benefit as possible of any clock, its errors must be properly characterized. This need of characterization yields to a rigorous clock modelling. Generally, oscillators can be approximated by a three-state clock model: an offset or range bias plus a drift or range bias rate and a Gauss-Markov (GM) process representing the range bias error ([14] and [15]).

The Allan variance (AVAR) [3], also known as two-sample variance, is a common technique used to measure oscillator's stability. In eq.1, it is represented the mathematical equation of the AVAR in the frequency domain. Using this method, it is possible to estimate the frequency noise characteristics of oscillators.

$$S_y(f) = \frac{h_{-2}}{f^2} + \frac{h_{-1}}{f} + h_0 + h_1 f + h_2 f^2 \qquad (1)$$

Where, f is the sampling frequency and $S_y(f)$ is the clock's AVAR power spectrum. Typically only h_0 (White noise), h_{-1} (Flicker noise), and h_{-2} (Random walk noise) are used to model the three state clock model. The theoretical noise values of the CSAC have been obtained from manufacturer's technical notes [16]. Hence the following Fig. 1 shows the Allan deviations of different kind of clocks and TABLE I. shows the TCXO and the CSAC clock model characterization.

TABLE I. CLOCK ERROR MODELLING

Clock model	h_0	h_{-1}	h_{-2}
TCXO	9.4E-20	1.8E-19	3.8E-21
CSAC	7.2E-21	2.6E-23	2.7E-27

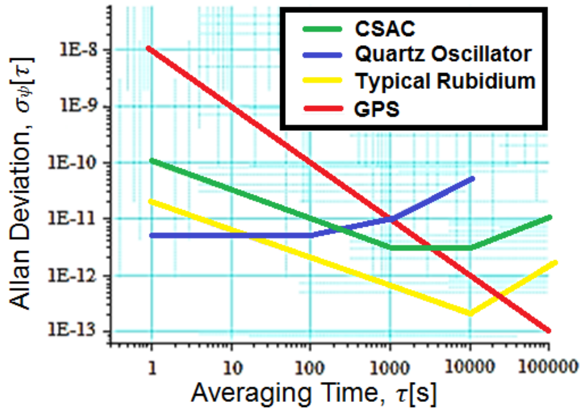

Fig. 1: Allan deviation of CSAC, TCXO, Rubidium and GPS

B. CSAC calibration

For the sake of completeness, this section is focused on the main concepts related to clock calibration. For more detailed information refer to [6] and [7].

In order to calibrate an oscillator, a typical methodology used is the clock disciplining procedure [17]. This methodology consists on constantly monitor the clock frequency and compare it with a reference oscillator by measuring the phase difference (offset time value) between both clocks. The clock is then re-adjusted, in other words steered, to increase its stability performance and to synchronize with the reference oscillator. Typical disciplining methods track the clock drift rate using an average filter in order to avoid errors due to jitter noise.

The CSAC steering process is based on using the clock of a GNSS receiver – which has a better long-term stability but a worse short-term stability – as a reference input. Note that the long-term stability of the GNSS receiver clock considered is enhanced by the corrections obtained from the satellite clocks. This is the reason why the GNSS receiver clock has a better long-term stability than the CSAC oscillator. For that, the PPS signal from a GNSS receiver is used as an input to discipline the CSAC.

The parameters defining the differences between the two aforementioned clocks in the disciplining environment are obtained by means of the steering algorithm. A value defining the time average filter is necessary to adjust such algorithm. This value is obtained from the AVAR charts provided by CSAC's manufacturers, as the one shown in figure 1. For instance, this figure shows that the GNSS and CSAC curves cross at approximately $\tau = 3000$ seconds. But, other publications from the manufacturers specifies that is it better to set $\tau = 5000$ seconds. This means that the stability of the CSAC is better than GNSS for averaging times below 3000 to 5000 seconds and its worse for times greater than 5000 seconds [16]. Therefore, to discipline the CSAC using the GNSS, the value for the time average filter should be greater than 3000, since is within this range of values that the GNSS clock is better than the CSAC. An accurately adjusted CSAC needs to be disciplined at least from two to three times the disciplining filter window. Therefore, usually this process requires some hours (e.g. with a filter window of 5000 seconds, the process will take from 3 to 4 hours.)

The disciplining process is concluded with a steering adjustment value. Afterwards, this time steering parameter is set to the CSAC in the initialization stage as a calibration value. However it is observed that the steering adjustment value is temperature dependent so the disciplining process needs to be implemented in a more sophisticated way.

In order to model the temperature coefficient into the CSAC calibration, it is necessary to steer the CSAC inside a climate chamber, where the ambient temperature is controlled. The clock disciplining process is repeated at different temperatures, therefore in the end is obtained a table that relates the temperature with the steering adjustment value coefficient.

In addition, the CSAC calibration values are not constant in time due to CSAC degradation. The calibration process must be repeated with some time periodicity, typically few months, but it depends on the required frequency accuracy. The aging effect of a CSAC is approximately about $9 \cdot 10^{-9}$/ month [18].

C. GNSS positioning estimation

Again for the sake of completeness, a brief review of the code-based positioning estimation algorithm is presented in this section. One of the methods that GNSS receivers implements to estimate the position is through the pseudoranges measurements, this is, the distance between the satellites and the receiver. In order to measure these pseudoranges the receiver computes the time that takes to the signal to travel from the satellite to the receiver. By using the speed of light factor it is possible to obtain the distance between the GNSS receiver and the satellite. Finally, knowing the satellites positions, the receiver localization is obtained by means of triangulation. Since the clock receiver is not perfectly synchronized with the satellite's clocks, the error in measuring travel times is directly translated in a systematic error in pseudoranges. This error can be up to several meters, leading to a fully incorrect position estimation.

Thus, GNSS receivers usually require at least four pseudoranges to solve the receiver's position. The system needs to determine four unknowns being three for determining the position and the last for determining the receiver's clock error. For each satellite and each available frequency, the following equations must be accomplished:

$$\begin{aligned} &P^k + v^k = \left\| X - X^k \right\| + c*(b + f*\Delta t) + K^k \\ &X' = 0 + w; \sigma = \sigma_d \\ &b' = f + w; \sigma = 10^{-9} \\ &f' = 0 + w; \sigma = 10^{-10} \end{aligned} \tag{2}$$

Where P^k_i is the measured pseudorange, X^k is the known satellite position, K^k are the modelled or provided atmospheric and instrumental corrections, X and *(b,f)* are the unknown receiver position and receiver clock corrections (bias and drift [19]). v^k is the residual error. The receiver position is considered as a random walk process with a process noise directly related to the vehicle dynamics, while the clock error is considered as a stochastic process controlled by b and f with a bias process noise of around 10^{-9} and a drift process noise of around 10^{-10}. Please note, that for less than four pseudoranges this system is not observable.

D. Clock coasting

By using a stable oscillator, such as the CSAC (with a known clock model error), it is possible to estimate the position with only three satellites. This is due to the short term stability performance of the CSAC, once it is synchronized with the GPS time, for some time period, it can be considered as a reference clock value whose residual error is below 10^{-12} sec, or equivalently below the millimeter. Thus, we can assume that the system will be able to determine a solution within specifications only with three satellites. For each satellite and each available frequency, the following equations must be accomplished:

$$\begin{aligned} &P^k + v^k = \left\| X - X^k \right\| + c*dt \ + K^k \\ &X' = 0; \sigma = \sigma_d \\ &dt' = 0; \sigma = 10^{-12} \end{aligned} \tag{3}$$

Where P^k_i is the measured pseudorange, X^k is the known satellite position, K^k are the modelled or provided atmospheric and instrumental corrections, dt is the receiver clock correction, X are the unknown receiver position and c is the constant of light velocity. v^k is the residual error. In the new model, the receiver position is once more considered as a random walk process with a process noise directly related to the vehicle dynamics, while the clock error is considered as a random walk process with a process noise of around 10^{-12}.

E. Expected impact of improving receiver clock in positioning solution

The use of atomic clocks as CSAC allows not only working with fewer observations (satellites) but should have also an impact on solution performance. With this equipment, the modelling of clock parameter is simpler and more reliable, leading to a more accurate estimation. This improvement on accuracy will have an impact on the accuracy of the other parameters; this is, on position unknowns. There are several studies [20] that demonstrate that this improvement is not equivalent in all parameters. The height component is the one that takes more benefits from this new system configuration. This is due to the fact that this component is the one with a stronger correlation with the parameter clock. Misra [21] explains this phenomenon conceptually by the fact that, the impact on the pseudorange measurements of the clock bias is like moving the antenna along the vertical axis. A clock bias adds or subtracts almost the same amount from each pseudorange, while moving the antenna vertically changes each pseudorange in the same direction although not equally.

III. Tests and Results

A. Tests equipments

In order to evaluate the clock coasting method, two Novatel OEM-V geodetic GNSS receivers, a single CSAC, a dual-frequency (L1/ L2) GNSS geodetic antenna and an acquisition computer are used.

Fig. 2 shows a schematic diagram that includes all the systems involved and the configuration applied. The first GNSS receiver uses the internal TCXO oscillator while the second GNSS receiver uses the CSAC as an external oscillator. Both GNSS receivers receive the same signals coming from the satellites by using a splitter between the antenna and the GNSS receivers. They are connected with cables of the same length.

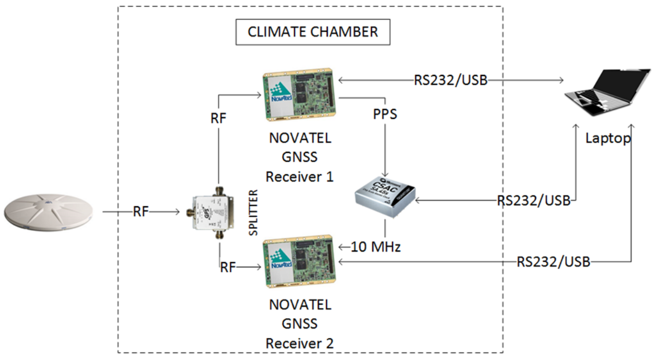

Fig. 2: System diagram

B. Tests procedures

To evaluate the clock coasting method, it is necessary to acquire the GNSS receiver's raw data. As mentioned before one GNSS receiver uses the internal TCXO oscillator while the second uses the external CSAC oscillator. The output navigation solution is estimated in an off-line real time process by using a custom algorithm with the clock coasting method integrated.

The tests performed are divided in two main groups: static tests and dynamic tests.

In relation to the statics tests, all the systems (except the GNSS antenna) have been installed inside a climate chamber with the temperature under control. It is important to mention that some satellites measurements have been intentionally removed. It has been taking into account their elevation mask, to simulate an environment with periods where only three satellites are visible.

The dynamic tests have been performed with a van using a stop/start dynamics with a medium velocity of around 20 km/h. The GNSS receivers, the CSAC and the acquisition computer were mounted inside a van and the GNSS antenna was mounted on the roof of the van. In this scenario the environmental temperature is not controlled, so a temperature compensation mechanism has been applied to the CSAC. Analogously to the static tests, to evaluate the capability of the SW to estimate solution with three satellites, the excess satellites were removed manually of the recorded data. The presented data set involve observations from six satellites and was collected in an open space not affected by multipath.

C. Static tests results

In the following plots the main outputs regarding the static acquisition collection campaigns are presented. In Fig. 3 the number of satellites involved in the process are presented. It can be seen that there is a slot of one thousand seconds where the number of satellites has been manually set to three. During all the other epochs, the number of satellites involved in the process is the maximum one.

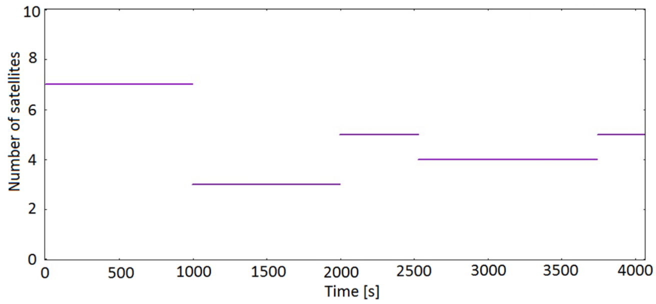

Fig. 3: Number of satellites used for static test

Clock error estimation

Fig. 4 presents both the error-estimated correction for the TCXO error (purple) and the error-estimated correction for the CSAC error (green). As it can be seen both the magnitude and the shape of both errors are quite different. In the three satellites period, it is observed a gap in the TCXO clock estimation due to the insufficient number of satellites, while the CSAC clock maintains the clock observation. As it can be seen the variability of the TCXO correction is some orders of magnitude higher than the one of CSAC. From this fact, it can be deduced that the impact in the solution of an incorrectly estimated TCXO error will be higher than in the case of CSAC.

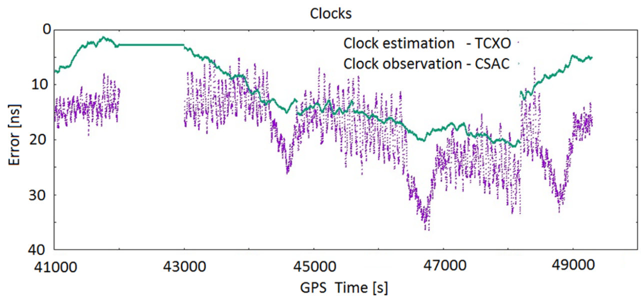

Fig. 4: TCXO clock correction estimation and CSAC clock correction observation

Availability of positioning solution

Fig. 5 shows the output of the navigation algorithm for the equipment working with TCXO and the equipment working with CSAC. As long as there are enough available satellites both solutions are quite similar. However, when the number of satellites decreases to three, the system using the CSAC clock is still able to provide a solution within the GNSS specifications, while the equipment with TCXO can not.

Table II presents the mean of the standard deviation of all static tests using each of the available equipment. From these results, it can not be deduced any relevant improvement in terms of planimetric positioning.

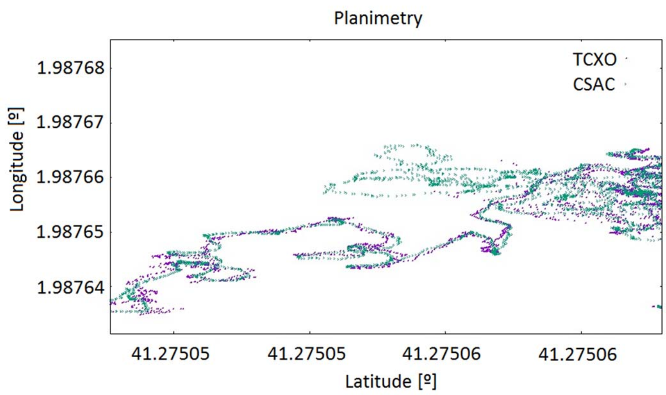

Fig. 5: Available positions for static test

TABLE II. STATIC TESTS - PLANIMETRIC ERROR STANDARD DEVIATION

	Standard deviation
TCXO	40.0 cm
CSAC	38.5 cm

Vertical accuracy results

In Fig. 6, a small window of the height estimation is presented. The purple samples represent the estimated solution of the equipment using TCXO while the green samples represent the solution including the CSAC clock. In Table III the mean of a windowed standard deviation is presented. These values do represent a significant improvement in the height precision determination, in concrete the CSAC standard deviation is reduced by a factor of 2.

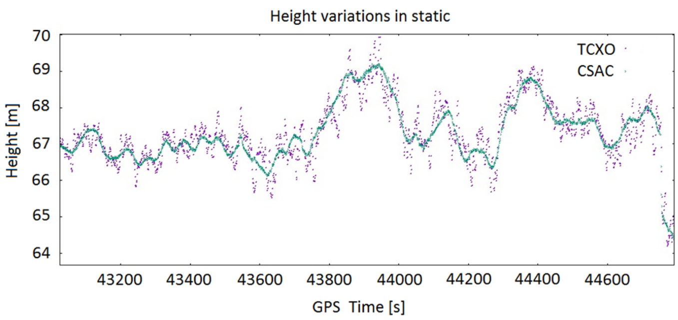

Fig. 6: Height estimation for static test

TABLE III. STATIC TESTS - HEIGHT ERROR STANDARD DEVIATION

	Standard deviation
TCXO	50.0 cm
CSAC	25.5 cm

D. Dynamic tests results

The main outputs regarding the dynamic acquisition collection campaigns are presented hereafter. In Fig. 7 the number of satellites involved in the process are presented. In the presented scenario, the number of satellites has been manually set to three in a slot of 30 seconds. During all the other epochs, the number of satellites involved in the process is the maximum one.

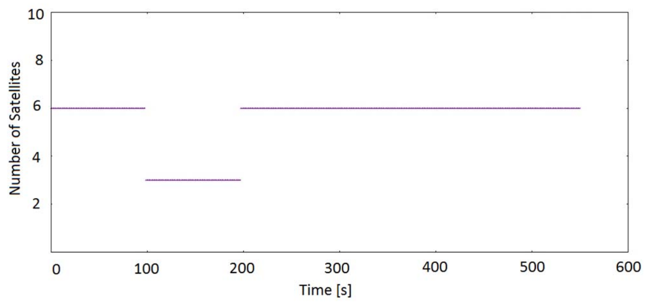

Fig. 7: Number of satellites used for dynamic test

For each test, a code-base processing with all the available satellites has been performed using the data collected by the CSAC augmented system. In Fig. 8, a plot of one of those reference trajectories is presented.

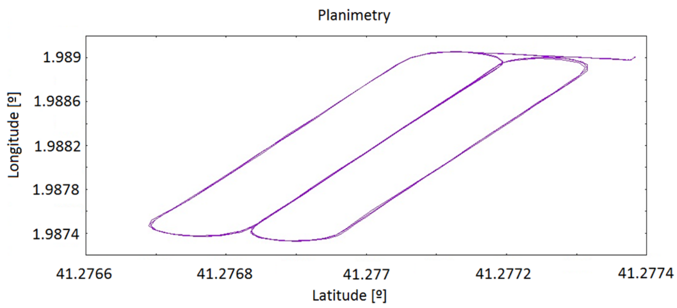

Fig. 8: Reference trajectory for the dynamic test

Clock error estimation

Fig. 9 presents both the error estimated correction for the TCXO error (purple) and the error estimated correction for the CSAC error (green). As it is observed the stability of both clocks is quite different. Once again, at analyzing the figure it can be deduced that the impact of an incorrectly estimated TCXO error in the final positioning solution will be higher than in the case of CSAC.

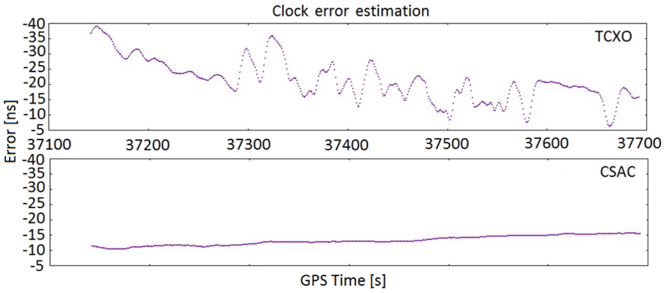

Fig. 9: TCXO clock correction estimation and CSAC clock correction observation

Availability of positioning solution

Analogously to the Fig. 5, Fig. 10 shows the comparison of the reference trajectory and the output of the navigation algorithm for the equipment working with TCXO and the equipment working with CSAC. Once more, it can be seen that when there are enough available satellites both solutions are quite similar. However, when the number of satellites decreases to three, the system using the CSAC clock is still able to provide a solution within specifications, while the equipment with TCXO can not.

Table IV presents the mean of the standard deviation of the difference between reference trajectories and target trajectories. Please note that the slots with three satellites have not been taken into account. Then, the reference trajectory is coincident with the CSAC trajectory. From this result, a relevant improvement in planimetric positioning can not be deduced.

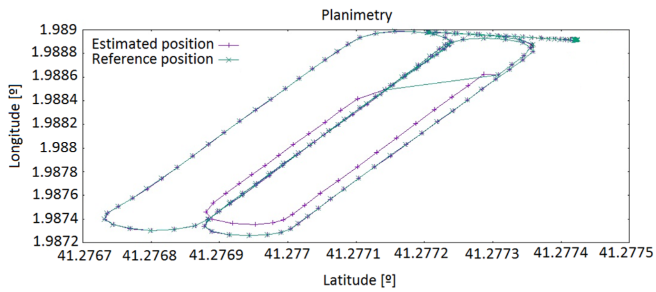

Fig. 10: Available positions for dynamic test

TABLE IV. DYNAMIC TESTS - PLANIMETRIC ERROR STANDARD DEVIATION

	Standard deviation
TCXO	0.1 cm
CSAC	0.0 cm

Vertical accuracy results

Figure 11 presents a zoom of one of the slots of the height estimation. Again, the purple samples represent the estimated solution of the equipment using TCXO while the green samples represent the solution including the CSAC clock. In Table V the mean of a windowed standard deviation is presented. As in the static tests, these values do represent a significant improvement in height precision determination.

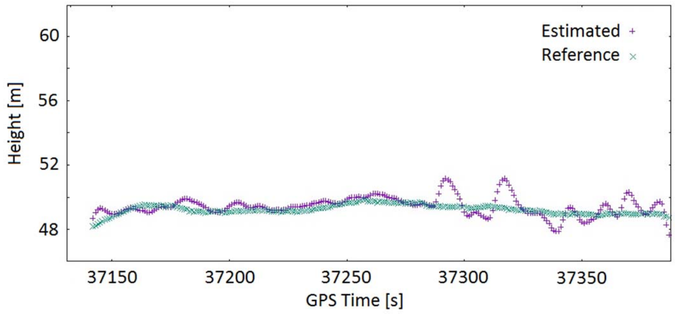

Fig. 11: Height estimation for dynamic test

TABLE V. DYNAMIC TESTS- HEIGHT ERROR STANDARD DEVIATION

	Standard deviation
TCXO	55.0 cm
CSAC	24.3 cm

IV. CONCLUSIONS & OUTLOOK

After the evaluation of the results obtained from this research, some of the conclusions can be derived. Firstly, it has been proved that CSAC clock allows estimating position within specifications even when only three satellites are available. It has been also observed that the impact of reducing and simplifying the clock unknown has almost no impact in planimetry performance neither for static or dynamic trajectories. However, the results demonstrate that having access to these precise clocks has a relevant impact on the performance of height estimations in both scenarios.

In the next future, the working team plans to keep on with this research focusing firstly on the evaluation of the positioning performance in dynamic platforms in non-friendly environments (multipath, spoofing and jamming.) The team intends also to consolidate the presented results using other CSAC units, to check that the behavior of this type of system is not dependent of a particular unit. Finally, it is planned to use a GNSS signal simulator to be able to test them intensively in a repeatable GNSS configuration.

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