Phase error reduction method for free-run QZSS clock

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***Abstract*— A method for limiting the phase error of the remote time keeping system, RTKS, clock for the Japanese Quasi-Zenith Satellite System (QZSS), is presented. To provide a proper positioning signal, QZSS satellites need stable on-board time references. Instead of using atomic references, the recently proposed RTKS employs a remote synchronization scheme that provides an opportune synchronization/correction signal able to keep a master time reference, located on the ground, and the QZSS satellite on-board time reference constantly in lock step. One of the critic issues regarding this architecture is the loss of synchronization due to satellite communication interruption. The proposed method consists of a learning algorithm that monitors the on-board clock behavior during its regular functioning. Consequently, when synchronization becomes unavailable the QZSS onboard clock phase/frequency drift is kept contained by using a consecutive estimation of the clock phase error. The proposed system is particularly suitable for the RTKS for QZSS and is characterized by a low hardware requirement profile, particularly suitable for the RTKS satellite payload.**

I. Introduction

In satellite positioning systems (i.e GPS or GLONASS), satellites continuously broadcast a positioning signal which is related to stable time references, all synchronized to one another, located on board the satellites. Generally, such time references are Rubidium Clocks and Cesium Clocks. Atomic references of each GPS satellite are monitored by several ground stations and when necessary, the GPS navigation message clock drift information is uploaded to the satellites.

In the 2003, Iwata et. al., [1], presented a novel time keeping method which would not require a space-born atomic reference for a particular kind of positioning system, specifically, the Japanese Quasi-Zenith Satellite System (QZSS). This novel system bases its theoretical feasibility on the QZSS orbit design and on the high satellite visibility, [2]. Such peculiar features make it possible to reconsider the GPS classic TKS structure as a remote TKS where the main time reference (atomic reference) is located on the ground in the control station and a correction/synchronization infrastructure keeps the on-board time reference continuously synchronized. The first concrete implementation to realize this synchronization technology for QZSS was proposed under the name of RESSOX in [3]. The idea is based on the compensation of the ground station satellite delays through satellite position prediction. A double feedback is used to measure the overall phase error and compensate for it. In early 2006 an alternative schematic, named Remote Time Keeping System, RTKS, and based on the Two Way Time Transfer Method (TWTTM) was presented in [4]. Additional details of both system can be found in [5], [6], [7].

The RTKS scheme as well as the RESSOX scheme represent a way to synchronize two clocks distant from one an other. Both systems, relying on a master/slave clock synchronization architecture, which can guarantee a certain time synchronization quality as long as the master clock and the slave clock are able to communicate. The main drawback of this technology is the inability to guarantee the desired accuracy when the satellite becomes unavailable to the ground station. In fact, during these periods, the satellite on-board clock cannot be actively controlled due to the absence of feedback [6], and therefore the global accuracy ends up depending solely on the quality of the satellite on-board clock. It has to be mentioned that QZSS satellite communication interruptions are unavoidable and the condition of having the QZSS satellite operating on its own happens twice a day, when the satellite crosses the equatorial region. Such a condition is necessary for guaranteeing the absence of communication interference with geostationary telecommunication satellites.

In the following sections we present a method to reduce the phase error of the QZSS on-board time reference when, because of the satellite communication unavailability, the remote synchronization network RTKS cannot perform the synchronization. The proposed method is based on a learning algorithm which monitors the behavior of the on-board clock and takes actively control of it, steering its output until the ground correction signal becomes available again.

II. Optimum clock prediction

Any two independent clocks will walk away from one another without bound, and the difference between them will exceed any limit given enough time [12]. Because of the backward correlation of the precise-clock noise, we can estimate the future reading of a precise-clock at some precision, which is better than that obtained only from statistical information,

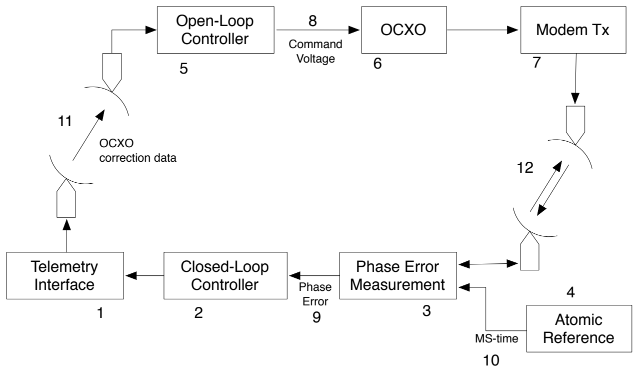

Fig. 1. Simplified representation of the remote time keeping system, RTKS, presented in [4] for the remote synchronization of QZSS clocks.

[9].

For metrology purposes, several algorithms,[10], [11], [8], have been developed to characterize atomic standards and to weight clocks to profitably offset them before combining, in order to have an optimum clock ensemble, [13].

In the field of the disciplined clock, e.g. ground station CDMA network, work has been carried out to improve the performance of the slave clock located on the ground [14], [20], [16], [17]. In principle, an adaptive oscillator model is employed to correct the slave oscillator when the external timing reference is unavailable, [18], [19]. These models differ from the previous because in that they consider prediction over time periods in the order of months and years. An accurate method, based on a double Kalman filter algorithm focused on accurate prediction over the relatively short holdover periods of 8 and 24 hours, was presented in [20].

The RTKS synchronization scheme for which this method is proposed has some peculiar characteristics. The PLL feedback interruption period length is unknown but generally not longer then 20 minutes, therefore the OCXO phase error reduction has to be maximized for short periods (t<20 min at worst). Furthermore the slave clock, Fig. 1 (6), is located on board the QZSS satellite together with a payload computer with limited computational power. On-board memory size and computation power is limited. Furthermore, because of the RTKS structure, the compensation of the phase error has to occur during a free run period which comes after a period of nominal functioning where the phase error is virtually zero. Therefore the phase error reduction algorithm cannot be trained with past samples of phase error.

The algorithm proposed here takes advantage of the slave clock statistical knowledge as well as its systematic behavior. Unlike many other methods, it works on the real-time processing of the slave clock command, which is related to phase error measurements. The proposed algorithm analyzes the dynamics of the slave clock in real time, and uses this to produce the best prediction when the slave clock is in free run.

III. Clock Synchronization Network

The synchronization scheme for QZSS presented in [3] and the remote time keeping system, RTKS, presented in [4] are fundamentally different. However, both suffer the same basic synchronization problem: proper synchronization during lack of satellite communication. From hereafter, we will refer to the RTKS scheme. More details can be found in [4]. Fig. 1 shows a simplified representation of the RTKS scheme. It consists of a PLL synchronization loop where the actual phase error measurement is provided by a two-way time transfer, TWTT, device. Some interesting details on the TWTT for QZSS can be found in [22].

Referring to Fig. 1, the two clocks, (4) and (6) are located in two different location, (4) is in at the ground station and (6) is on board the QZSS satellite. The clock (4) is considered as reference and its output cannot be changed. The clock (6) is an accurate steerable clock, i.e. a oven-controlled crystal oscillator (OCXO). Blocks (1), (7) and (11) constitute the communication infrastructure for this system. Blocks (12) (3) are responsible for the measurement of the phase error between clock (4) and clock (6). Block (2) is the closed-loop controller and it is responsible for the correct synchronization of the OCXO when the satellite is capable of communicating with the ground station. The block (5) is the open-loop controller, its task is to control the OCXO when the satellite is unable to communicate with the ground station (PLL in open-loop condition).

In the following sections the structure of some of the main blocks of the RTKS architecture are addressed.

A. Atomic Reference

During the study of this synchronization method, the atomic reference (4) of Fig. 1, was simulated accordingly to the behavior (Allan standard deviation) of the Hydrogen Maser, available in AIST laboratories, the Anritsu Hydrogen Maser RH401A. For the study of this specific control method the Atomic Reference represent by the block (4) will be considered an ideal time reference.

TABLE I
SPECIFICATION OF THE OSCILLOQUARTZ OCXO 6607-BM EMPLOYED FOR OUR EXPERIMENTS.

Model	OCXO 8607-BM
Manufacturer	Oscilloquartz
Nominal frequency	5 MHz
Power Consumption	3 W (10 W max)
Freq. Stability, Allan std. dev. 1s to 30s	2.5×10^{-13}
Aging over 1 day	2×10^{-11}
Aging per one month	5×10^{-12}
Aging per year	4×10^{-9}
Mass (weight)	$<$ 900 g
Dimensions	138 mm X 63 mm X 88 mm
Price	$\sim$ US$ 10,000

B. Telemetry Interface, Modem Transmitter and Communication Blocks

Referring to Fig. 1, the Telemetry Interface block (1), the Modem Transmitter block (7) are blocks responsible for the communication between the two locations where the two clocks are located (11) and (12), they will be considered ideal and no noise or whatever contribution will be therefore considered for them.

C. Closed-Loop OCXO Controller

The closed-loop controller is a PLL controller which uses the output (9) to directly control (6). Several methods have been studied and implemented to improve the performance of the Closed-Loop OCXO Controller. [14], [17] are examples of patents dealing with novel methods to improve close-loop controller performances for SS-TDMA satellite networks, where in fact a similar problematic appears.
For our purposes, the Closed-Loop OCXO Controller has been developed as a PI (proportional integral) controller, coupled with a running average block suitable for getting rid of the large white noise that affects the input of the Closed-Loop OCXO Controller (2).
It is assumed that during closed-loop periods the functioning of the PLL and the Closed-Loop OCXO Controller satisfy the requirements. Some details of this controller can be found in [21].

D. Oven-Controlled Crystal Oscillator (OCXO)

For our experiments, the Swiss Oscilloquartz (Swatch Group) 8607-BM has been employed, its frequency deviation due to the input voltage is:

$$\frac{\Delta f_{ocxo}}{f_0} = 6.0 \times 10^{-9} \times \Delta V_{ocxo} \qquad V_0 = 5.47V$$

The characteristics of the OCXO employed in the actually satellite payload might have slightly different characteristics. That does not however constitute a problem, in fact, the proposed control creates the optimum control voltage monitoring both OCXO voltage as well as phase error using an iterative calculation process which continuously updates its inner OCXO model. Any OCXO with similar characteristics can therefore be employed. Table I lists the characteristics of the OCXO employed for our experiments.

IV. Proposed System

The Least Square Method (LSM) gives a prediction of the status of the system, based on past measurements. The Kalman filter used as predictive filter takes it one step further, taking advantage of the knowledge (differential equation) of the dynamic of the system, the OCXO clock, to better predict the status of output, in this case the OCXO phase error. Because of the nature of RTKS, neither of them are directly available, however an indirect measurement through the command voltage, of the phase error is possible.
The proposed method consists of an algorithm which collects samples of phase error, (9) Fig. 1, and samples of control voltage, (8) Fig. 1, during the normal functioning of the PLL scheme, in other words, when the PLL feedback is available and synchronization is achieved ($0 < t < t_c$). As soon as a new sample is available the oldest sample is dumped as in a stack structure.
A secondary algorithm recursively uses the collected OCXO voltage samples to construct a series of approximation curves over the intervals: t_c, $t_c/2$, $t_c/4$, $t_c/8$, ...
There curves are approximations of the behavior of the OCXO and they store the dynamics of the OCXO. As soon as the satellite becomes unavailable to the ground station and synchronization is not achievable anymore through the PLL-like scheme, a warning flag is given and the satellite on-board computer will calculate the appropriate OCXO voltage based on the collected data.
At this stage, these curves are represented by first order straight lines and the approximation method to generate them is the least square method (LSM). Other types of approximation curves could be employed, we believe however that specifically for RTKS no particular improvement would be achieved otherwise.
The creation of the approximation curves could be done every epoch, e.g. every second, or every given epochs. The latter is preferred because less computationally power consuming. Fig. 2 show a graphical representation of the generation of the curves. During the period t_c samples of OCXO control voltage, $V_{ocxo}(n)$, are collected. After t_c the PLL feedback becomes

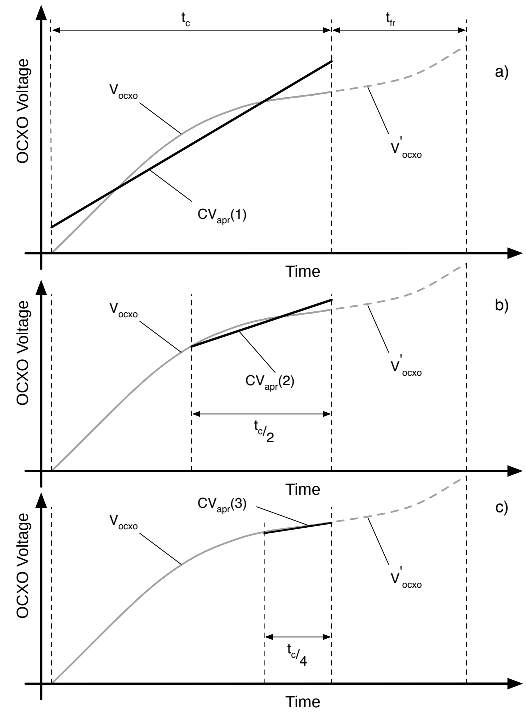

Fig. 2. Method to generate the the approximation curves $CV_{apr}(n)$. Out of the t_c available samples, a sub-series of them is used to produce approximation curves with the least square method.

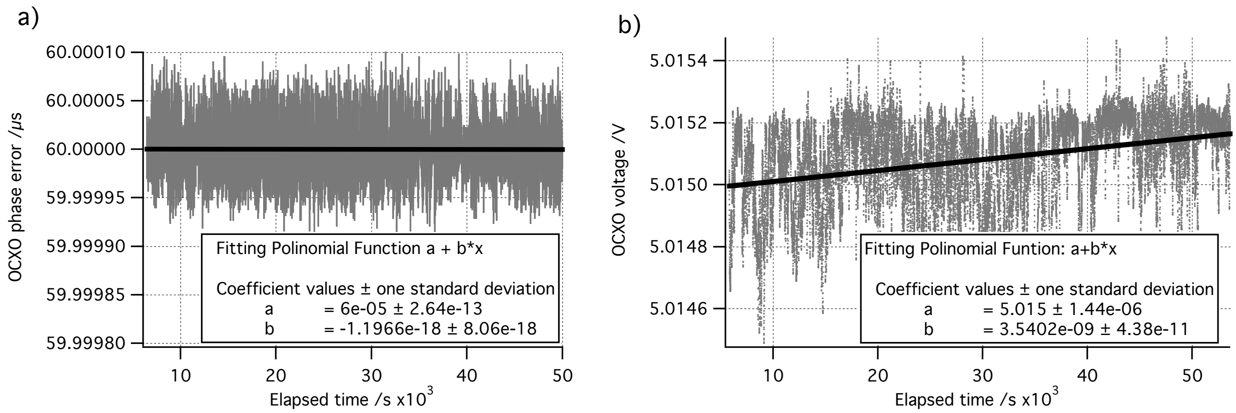

Fig. 3. OCXO phase error and OCXO voltage during a closed-loop controlling period of about 50,000 s.

unavailable and this condition lasts for t_{fr}. The value of V'_{ocxo} is the value of voltage that the closed-loop controller should ideally apply. Approximation curves are calculated over the interval t_c, $t_c/2$, $t_c/4$, $t_c/8$, ... where $t_c/8$ is the most recent interval of OCXO voltage samples. The whole series is stored in the matrix $CV_{apr}(n)$.

The construction of the voltage command $V'_{apr}(t)$ during t_{fr} for $n = 10$ is given by the following scheme:

$$\begin{array}{ll} 0 < t < h & \Rightarrow V'_{apr}(t) = CV_{str} + \times C_{apr}(10) \times t \\ h < t < 2*h & \Rightarrow V'_{apr}(t) = V'_{apr}(h) + CV_{apr}(9) \times t \\ 2*h < t < 4*h & \Rightarrow V'_{apr}(t) = V'_{apr}(2*h) + CV_{apr}(8) \times t \\ 4*h < t < 8*h & \Rightarrow V'_{apr}(t) = V'_{apr}(4*h) + CV_{apr}(7) \times t \\ .... & \end{array}$$

Where $CV_{apr}(n)$ is the angular coefficient of the n^{th} approximation curve and CV_{str} is the mean value of the most recent h samples at $t = t_c$. h is the number of points used to generate the curve $CV_{apr}(10)$. During out test $h = 60$.

The method, as presented, tends to preserve the dynamic of OCXO, learned from past OCXO behavior, and analyzes the phase noise contribution from the short-term components, $CV_{apr}(10)$, to the long-term components, $CV_{apr}(1)$. The size of h fixes how sensitive the algorithm is towards the OCXO or the TWTT apparatus short-term noise.

More information is actually extractable from the behavior of the OCXO, e.g. white noise sigma, random walk sigma, and such information could be used to implement a more clever algorithm to generate the OCXO voltage during free run, (e.g. covariance matrix analysis, residuals analysis). More research work will be undertaken to understand how convenient a more sophisticate approach would be.

V. OCXO PHASE COMPENSATION, PRELIMINARY RESULTS

A set of preliminary tests have been performed to evaluate the ability of the proposed algorithm to reduce the phase error during free run. A hardware simulator based on a simplified version of the RTKS schematic of Fig. 1 has been implemented. The TWTT apparatus was replaced by a time interval counter. The white noise introduced by the Telemetry and communication components have been neglected.

Closed-loop synchronization has been successfully achieved. Fig. 3 a) shown the phase error between the OCXO and the atomic reference (10) over a period of about 13 hours. Fig. 3 b) shows the OCXO control voltage during the whole 13 hours. At this stage, the effectiveness of the method presented here has been tested through a post-processing method, and the generation of the approximation curves was based on a realistic estimation of past OCXO voltage samples employing the Swiss Oscilloquartz 8607-BM, table I.

A. Closed-loop case

As long as the phase error measured by the block (3), Fig. 1, is fed into the OCXO controller, block (5), with an acceptable noise level, the proper synchronization, phase error <1ns, has been successfully achieved with a large margin. Fig. 3 a) shows the OCXO phase shift error over a simulation period of 13 hours. The collected OCXO control voltage samples are shown in Fig. 1 b). The high level of white noise, visible in the plot, is attributable to the time interval counter which substitutes the TWTT block (3). The superimposed curve in Fig. 3 b) represents the approximation straight line, that shows the aging of the OCXO during the 13 hour period.

B. Open-loop case

After a long enough period ($t > 20,000$ s) of successful synchronization, the PLL open-loop condition was simulated and the OCXO was left in free run. Three possible scenarios were considered:

- No OCXO phase error reduction algorithm.
- Linear OCXO phase error reduction using one element of the series $CV_{apr}(n)$.
- Composite OCXO phase error reduction using some elements of the series $CV_{apr}(n)$.

During free run, the OCXO phase was compared with a highly accurate hydrogen maser, the Anritsu Hydrogen Maser RH401A. Fig. 4 shows the performance of the OCXO under test for the three scenarios.

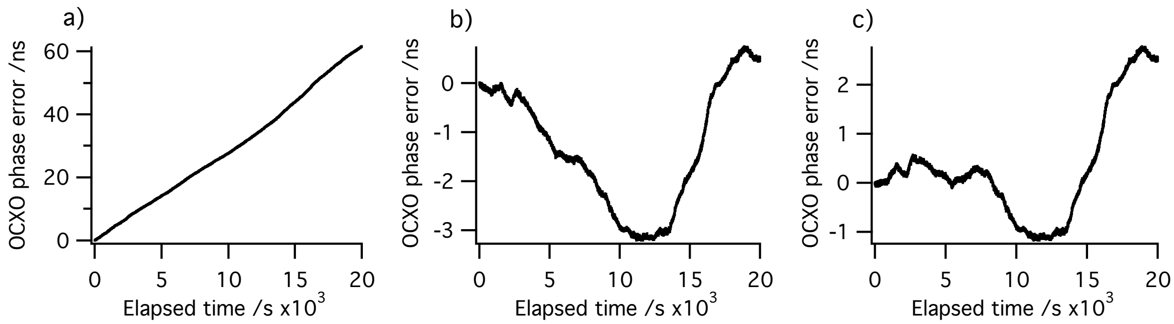

Fig. 4. Results of a 20,000 s experiment using the Oscilloquartz OCXO 8607-BM with no PLL feedback control. a) is the OCXO phase error when no controlling method is applied. b) is the OCXO phase error when the proposed algorithm is applied using the simples approximation function $CV_{apr}(1)$. c) is the OCXO phase error when the proposed method is set to combine a limited series of $CV_{apr}(n)$ with $n < 3$.

Without any compensation, the aging of the OCXO together with the uncertainty of the true Hydrogen Maser central frequency, causes the OCXO phase to drastically drift away very quickly. If the simplest version of proposed method is applied, Fig. 4 b), the OCXO phase could be contained within about 3 ns over 10,000 s. In this case the main cause of drift is the noise of the OCXO. Furthermore, applying the proposed method with a limited set of approximation curves $CV_{apr}(n)$ with $n < 3$ the OCXO phase error could be significantly contained within about 1 ns over the first 10,000 s.

C. On-board computer requirements

The approximation curve series $CV_{apr}(n)$ can be calculated once every epoch, intensive calculation mode, or once every a given samples, i.e. every 50 epochs. The frequency by which $CV_{apr}(n)$ is calculated certainly has an optimum which, through our experiments, does not seem to lead to any computation power problem. During our tests, 20,000 samples of OCXO command voltage haven been continuously collected and the required on-board computer memory size for the vector $CV_{apr}(n)$ was 40 Bytes (32bit X 10 samples) where a single precision floating point 32 bit processing system was used. The memory needed to store the 20,000 samples is located in the ground station computer and therefore does not constitute a problem. The vector $CV_{apr}(n)$ holds a good approximation of the history of the OCXO requiring a very limited amount of memory. This is definitely one of the strengths of this method. However, the creation and the updating of its elements require quite a bit of computational power. furthermore, when the computational power turns out to be a critic issue, the content of the vector $CV_{apr}(n)$ can be resized.

VI. Conclusion

A method to reduce the phase error of the RTKS/QZSS on-board time reference during synchronization interruptions as been presented. Advantages of the proposed method can be summarized as follow:

- OCXO aging can be totally compensated and its effects are negligible even for synchronization interruptions of the order of one day.
- Phase errors due to period events can be detected and compensated.
- The approximation curve database is a suitable method to roughly estimate the performance of the on-board time reference.
- The proposed method can be used to detect environmental causes that can alter the output of a time reference. Possible causes could be thermal variation, electromagnetic radiation, gravity changes, etc.
- The proposed method shows a quite low hardware requirement profile which is suitable as component for the payload or RTKS for QZSS.

Preliminary results show that the OCXO employed during out lab tests can be controlled such that the maximum phase error over a period of 10,000 s, can be kept lower that about 1 ns. Studies on how convenient it would be to store more OCXO history are now undergoing.

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