SBAS with ground based atomic reference station

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GNSS augmentation system with a ground-based atomic reference

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Abstract

To provide the proper positioning signal, global navigation satellite systems (GNSSs), need very accurate satellite on-board time references. For GPS, GLONAS and GALILEO, such time references are space-born atomic clocks. The augmentation/positioning system QZSS (Quasi-Zenith Satellite System) would need the same kind of accuracy. However, due to the high QZSS satellite visibility, a completely new kind of time reference method, where no on-board atomic references are needed, could be adopted. If an opportune ground location is chosen, QZSS satellites are fully visible for the whole orbital period. Therefore, a main time reference (atomic clock), located on the ground, could be kept synchronized to a inexpensive and compact time reference (VCXO) on board each QZSS satellite. In the following article, a new practical implementation of such a remote synchronization method is proposed and some of its problematic are discussed.

1. Introduction

The Japanese Quasi-Zenith Satellite System (QZSS) is a positioning system that will offer a complementary/augmentation service for the present GNSSs [1]. The integration of the QZSS with present GNSSs will improve accuracy, availability and positioning capability over Japan, Australia and the whole East Asia. Fig. 1 shows the orbital ground track of QZSS and the spacial distribution of the three QZSS satellites.

Like for classic GNSSs, i.e GPS and GLONAS, QZSS satellites need very stable on-board time references, by which the positioning signal is derived from. In order to achieve high time reference accuracy, GNSS satellites adopt very stable atomic clocks. On board GNSS satellites, the Time Keeping System (TKS), is responsible for the synchronization of the on-board atomic clock with the on-board Voltage Controlled Crystal Oscillator (VCXO). Due to the good long-term frequency stability of on-board Rubidium and/or Cesium atomic clocks, GNSS satellites end up being fairly independent from master ground station time-drift corrections. However the lifetime, cost, weight and power consumption of the on-board time reference are certainly important issues. Just to have an idea of how expensive is to launch one kg is space, consider that modern rocketry gives prices that are on the order of thousands of US$ per kg for transfer to low earth orbit, and roughly twenty thousand US$ per kg for transfer to geosynchronous orbit. Each GALILEO satellite will carry two Rubidium Atomic Frequency Standards (RAFS) and two Passive Hydrogen Masers (PHM) for a total weight of about 36 Kg (3.3 Kg for each RAFS and 18 kg for each PHM) [2].

Throughout a collaborative research program, the University of NSW, Australia and the Space Technology group of AIST, Japan, are studying the feasibility of a revolutionary remote synchronization scheme for implementing a QZSS with no on-board atomic clocks. The novelty of our research is based on the QZSS orbit design and on the fact that if an opportune ground location is chosen, each QZSS satellite is fully visible by one unique ground control station for the whole orbital period. For instance, Fig. 1 shows that if the American Marshal Islands are chosen as location for the master station, visibility of QZSS satellites with an elevation angle greater that 20 deg, at all time, is in fact guaranteed [3].

Such a peculiar feature makes possible to reconsider the classic on-board TKS as a remote TKS (RTKS) where the main time reference (atomic clock) is located on the ground, in the master control station, and a correction signal keeps the on-board time reference (VCXO) continuously synchronized with it. This novel concept has been extensively studied in the last three years and two basic schemes have been presented as practical implementation of it [3,4]. To prove the feasibility of such a remote synchronization method and to discern its requirements both in terms hardware implementation and from the system design point of view, extensive positioning accuracy studies have been carried out.

RTKS: the basic idea

The feasibility of a synchronization method where one clock is in the ground and the other is flying in space is certainly a non trivial task. [3,4,5,6] are some of the articles that report results of the undergoing research of this novel concept. Theoretically, the difficulties in synchronizing the two clocks lies in knowing what the phase shift between the two clocks is and in knowing how to proper steer the remote on-board clock.

The most common way to measure accurately the phase between to clocks located away from each other is the Two-Way Time Transfer Method (TWTTM). The Japanese National Institute of Information and Communications Technology (NICT) and the Japanese Aerospace Exploration Agency (JAXA) are now working on the development of a Two-Way Satellite Time a Frequency Transfer, TWSTFT, scheme that will be employed on board QZSS satellite to gain some fundamental knowledge of satellite atomic standard behavior in space [7]. Throughout the TWSTFT method, the phase shift between QZSS on-board clocks and the local ground station time reference can be accurately measured with an uncertainty lower than 1 ns at all time [7]. AIST and UNSW plans to use the QZSS-TWSTFT equipment for investigating the RTKS synchronization architecture. Fig. 2 presents a simplified representation of RTKS. The phase shift available at the ground station, throughout the TXTFT apparatus, is used to remotely control the on-board clock that, in this case, consists of an ultra stable VCXO. The QZSS positioning signal is then built over the VCXO output, so no atomic clocks are therefore needed. Conceived specifically for QZSS, RTKS takes full advantage of the TWSTFT scheme and requires very little additional equipment: the remote VCXO controller and a satellite communication channel used to broadcast the voltage information to the QZSS satellite. The RTKS method does not need any feedback and/or feed forward because it totally relies on the TWSTFT apparatus. Moreover, because of the TWSTFT structure, delays that can affect the communication signals between ground station and satellite do not represent any problem.

5. QZSS RTKS Positioning Accuracy Study

If the phase shift between the on-board clock and the ground station clock can be estimated within an appropriate accuracy (i.e 3 ns), the synchronization system should be able to remotely correct the on-board time reference as long as satellite-ground station communication capability is available [8].

One of the big issues regarding the RTKS architecture is to understand what could happen when the synchronization is temporary lost. For instance, when QZSS satellites cross the equatorial region, ground-satellite communications have to be turned off, leaving the satellite on its own for at least 10 minutes, twice a day. During such period the VCXO tends to drift much faster than an atomic reference. Considering 5 ft or 5 ns as the acceptable limit for the maximum buildup error caused by the on-board clock [8], the satellite must be resynchronized at least every 2000 s (33 minutes). If such requirement is not respected the VCXO drift will negatively influence the overall accuracy.

By means of a dedicated RTKS software simulator, we evaluated the positioning performance of the combined system GPS/QZSS when RTKS is adopted for the clock synchronization. Specifically we wanted to analyze how bad positioning would gets when one QZSS satellite on-board clock is left to free run for a given interval of time. This was an attempt to understand what would happen during the unavoidable equatorial region interruption. Results could be also used to understand how stable the on-board VCXO has to be if the RTKS scheme is adopted. The high mask angle (40 deg) chosen for this experiments, represents the conditions where the Japanese QZSS is meant to provide the greatest positioning improvement.

For this experimental a scenario of 26 GPS satellites were combined with 3 QZSS satellites. The RTKS network was employed to keep the QZSS satellite clocks synchronized for a certain period of time (10 minutes). The sigma Northings, sigma Eastings, the RMS positioning error and the 2DRMS positioning error were calculated using the last 10 minutes worth of data for each point. In this way we could represent the evolution of positioning accuracy over time. After about 10 minutes, the clock on the QZSS satellite at the Zenith (the most visible QZSS satellite) was left in free running after about 10 minutes. As before the Northing error sigma, the Easting error sigma, the RMS positioning error and the 2DRMS positioning error was computed every 10 minutes for the whole simulation period. Fig. 3 show the results over 3 hours. As clearly noticeable, for the first 10 minutes (all clocks synchronized) accuracy was quite good (beginning of the curve). After that, the VCXO started drifting bringing an almost linear error during the whole duration of the experiment. The red area represents what the 2DRMS would be if all QZSS satellites were carrying ideal atomic references. Therefore it represents our ideal case. The overall 2DRMS positioning error shows an error of about 1.5 m after about 3 hours of free running. It is interesting to notice that the drift of the VCXO in free running create a positioning error that starts to be relevant only after about 100 minutes. It is important to point out that this study-case takes into account only one uncontrolled QZSS satellite clock, the one which would cross the equatorial region.

6.2. VCXO control Algorithm

One of the key points for the realization of RTKS for QZSS is the implementation of a controller for the on-board VCXO that can combine the good short-term stability of the VCXO with the good long-term stability of the ground station atomic standard. When the synchronization information is up-loadable, such controller should be able to keep the VCXO looked to the ground station clock within acceptable limits. However when the syntonization is not possible (communication interruption) the VCXO controller has to work in the free-run condition (open-loop condition) and therefore use the knowledge relative to the behavior of the VCXO to opportunely compensate its natural drift.

7. Conclusions

The proposed methods, RTKS, is a practical implementation of the remote synchronization concept specifically made for QZSS. Its functioning strongly rely on the Two-Way SAtellite Time and Frequency Transfer (TWSTFT) apparatus that will be developed by JAXA. RTKS is characterized by its simplicity as well as by the a ground-based VCXO controller. In fact, future improvements of the VCXO controller do not require on-board satellite software upload. The idea of a GNSS with no on-board atomic clocks would offer several advantages in term of satellite cost, life expectancy and satellite power consumption. The RTKS concept could be quite advantageously applicable to Low Earth Orbit, LEO, positioning systems or, theoretically, for a Lunar satellite positioning system, where satellite weight is clearly a critical issue.

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PICTURES

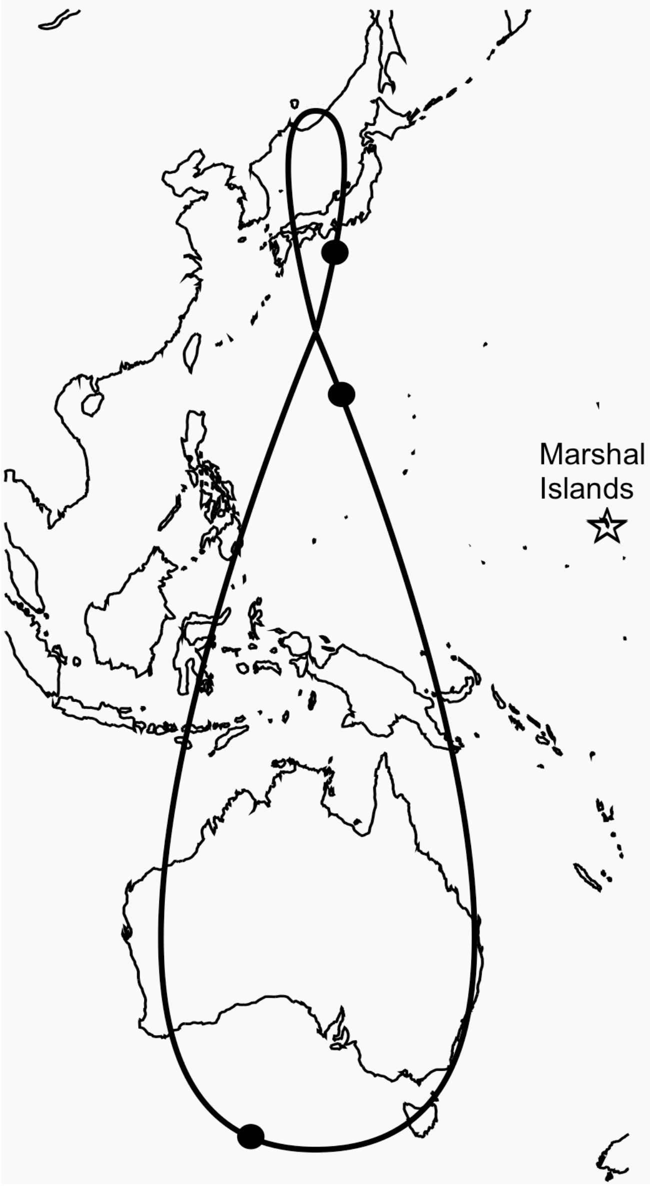

Figure 1. Orbital ground track of the Quasi-Zenith Satellite System (QZSS).

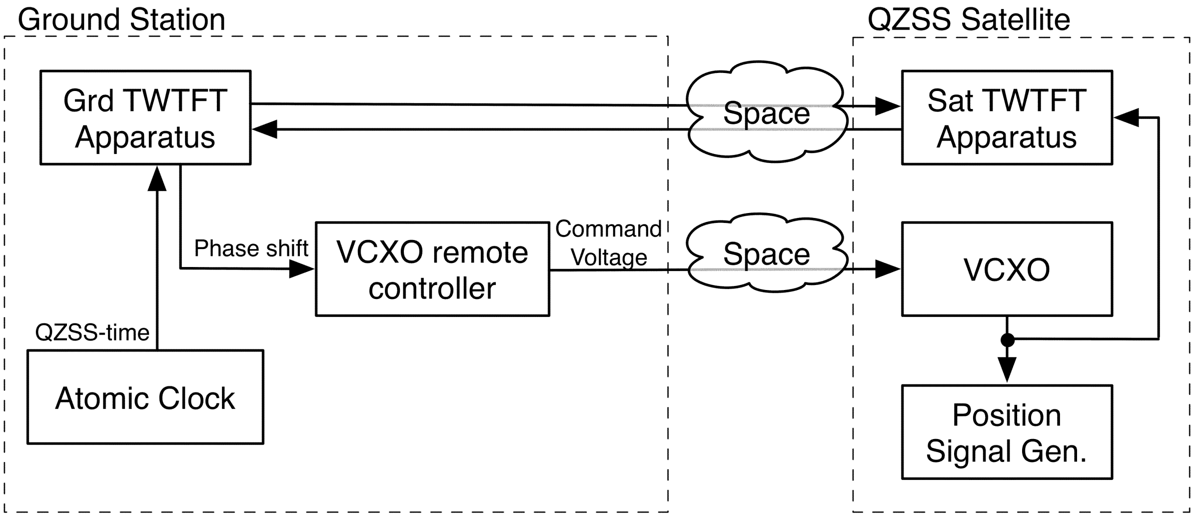

Figure 2. Schematic of the RTKS synchronization apparatus. The Grd TWTFT block and the Sat TWTFT block represent the whole TWTFT apparatus used to measure the phase shift between the two clocks.

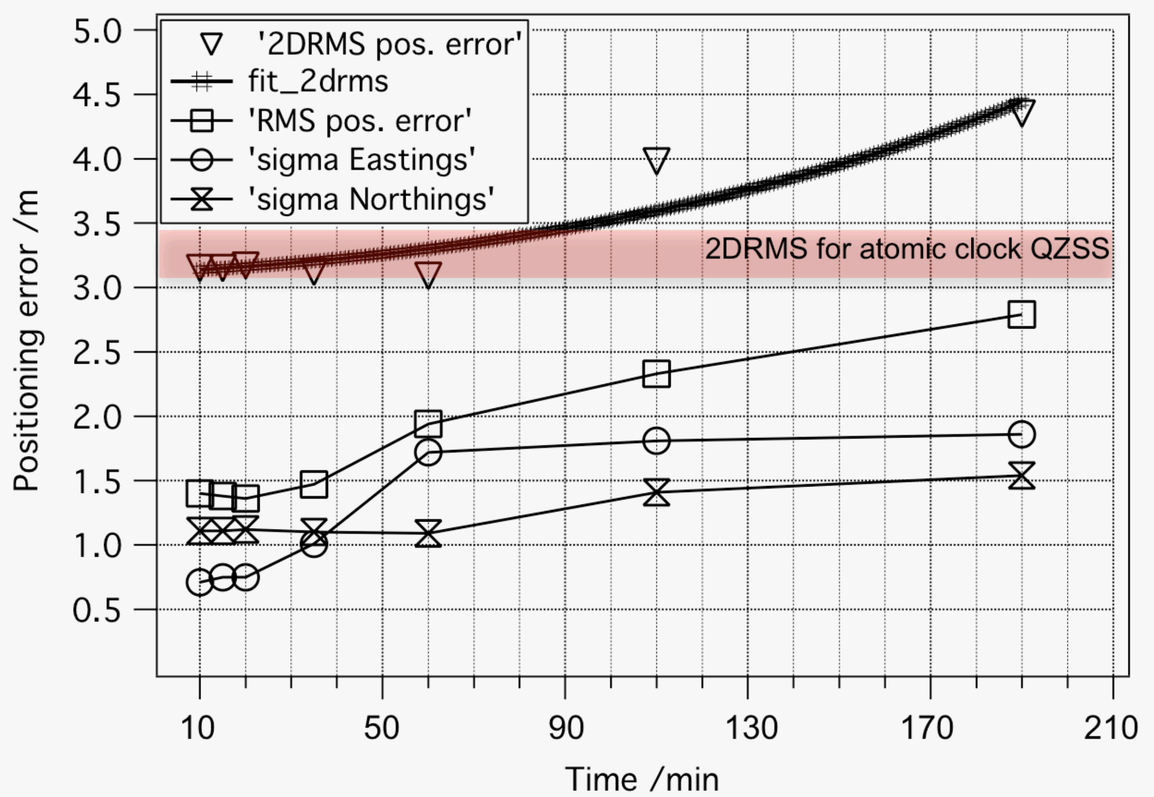

Figure 3. Positioning error, expressed as 2SRMS, RMS, Sigma Eastings and Sigma Northings, of the combined system GPS&QZSS when one of the QZSS clocks (VCXO) crosses the equatorial region and therefore is left in free running. The red area represents what the 2DRMS would be if all QZSS satellites were carrying ideal atomic references.