SBAS with Ground Based Atomic Reference Station

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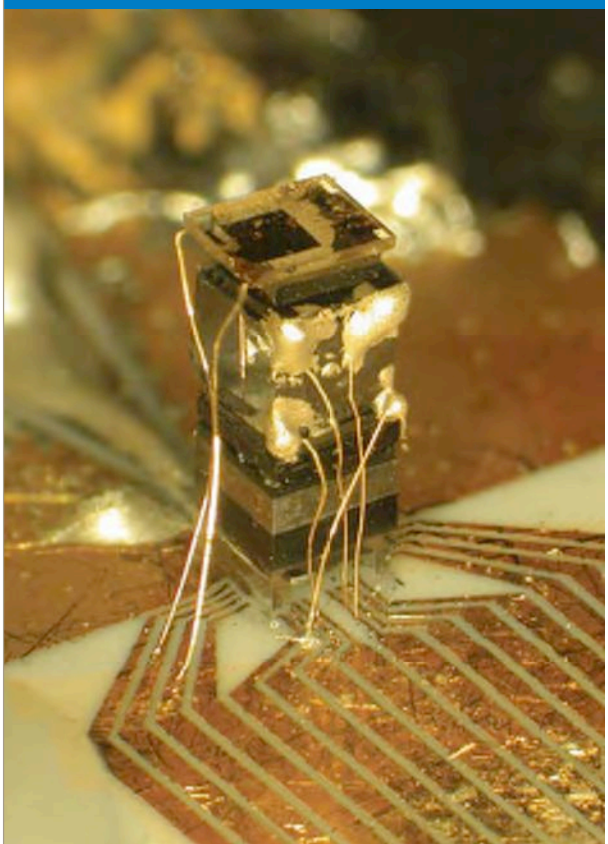
The article proposes implementation of remote synchronization method of atomic clock located at the ground to an inexpensive and compact time reference (VCXO) on board each QZSS satellite



The Japanese Quasi-Zenith Satellite System (QZSS) is a positioning system which will offer a complementary/augmentation service for present GNSS'. The integration of the QZSS with present satellite positioning systems 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 spatial distribution of three QZSS satellites.

Augmentations rely on a technique known as differential GPS and use reference stations that continuously monitor the GPS signals. Since the position of the reference station has been precisely surveyed, the errors in the satellite signals can be calculated and corrections broadcast to users in the area of coverage. The user's differential GPS receiver applies the correction message to improve the accuracy of its own position. The differential broadcast may also include integrity warnings for any satellite signals that should not be used.

Like for classic GNSS', i.e GPS and GLONASS, 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, positioning 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 it is to launch one kg in 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 43 Kg (3.3 Kg for each RAFS and 18 kg for each PHM).

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.

Such a peculiar feature makes it 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. 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. 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 properly steer the remote on-board clock.

The most common way to measure accurately the phase shift between two clocks located away from each other is the Two-Way Satellite Time and Frequency Transfer Method (TWSTFT). The Japanese National Institute of Information and Communications Technology (NICT) is now working on the development of a TWSTFT scheme that will be employed on board QZSS satellites to gain some fundamental knowledge of satellite atomic standard behavior in space. 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. 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 TWSTFT apparatus, is used to remotely control the on-board clock that, in this case, consists of an oven controlled VCXO. The QZSS positioning signal is then built over the VCXO output, no satellite 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 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.

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, the synchronization system should be able to remotely correct the on-board time reference as long as satellite-ground station communication capability is available.

One of the big issues regarding the RTKS architecture is to understand what could happen when the synchronization is temporarily lost. For instance, when QZSS satellites cross the equatorial region, ground-satellite communications (Ku band) have to be turned off (geostationary communication satellites interference avoidance), leaving the positioning 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, the satellite must be resynchronized at least every 2000 s

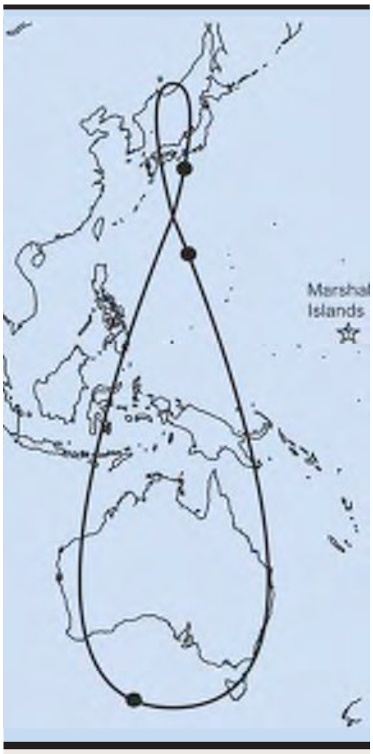


Figure 1. Orbital ground track of the QZSS

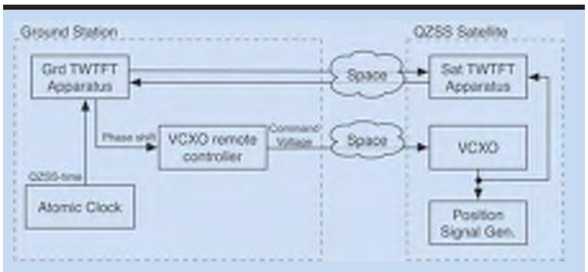


Figure 2. Schematic of the RTKS synchronization apparatus

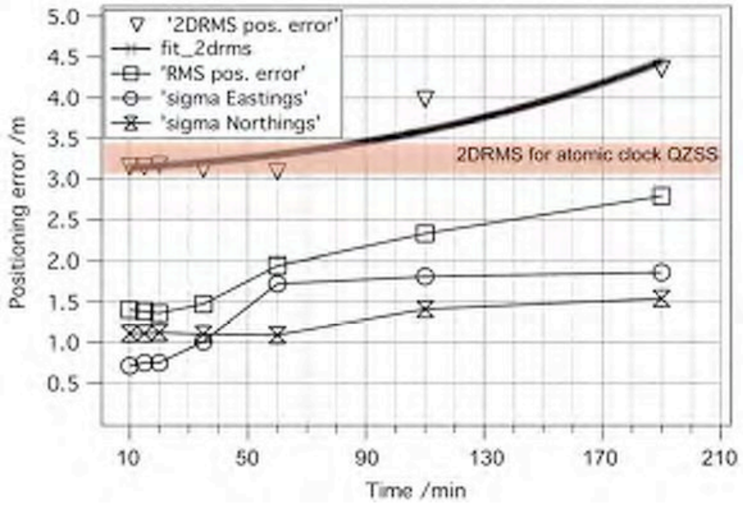


Figure 1. Positioning error, expressed as 2SRMS, RMS, Sigma Eastings and Sigma Northings, of the combined system GPS&QZSS

(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 get when one QZSS satellite onboard clock is left to run free 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 experiment, represents the conditions where the Japanese QZSS is meant to provide the greatest positioning improvement.

For this experiment, 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. 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.

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 uploadable, such controller should be able to keep the VCXO looked to the ground station clock within acceptable limits. However when the synchronization 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.

Conclusion

The proposed method, 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 apparatus that will be developed by the Japanese National Institute of Information and Communications Technology. RTKS is characterized by its simplicity as well as by the ground-based VCXO controller. 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.

NOTE: The article with full references is available at www.location.net.in/magazine/year/2007/jan-feb/index.htm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