Status quo and improvements of timekeeping in GNSSs

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Abstract. A time offset of 1 microsecond could lead to 300-meter positioning offset for a global navigational satellite system (GNSS). Therefore, appropriately evaluating and improving the clock performance onboard GNSS satellites are critical. The research methods and conclusions of papers written in distinct periods about their contemporary satellites clocks are chronologically synthesized. The satellites clocks among the same and different GNSSs are compared, with the time primarily centered around the launching and development of BeiDou-2 and BeiDou-3. It is found that passive hydrogen maser (PHM) and rubidium atomic frequency standard (RAFS) have a better performance than cesium (Cs) clocks, and PHM are among the best clock onboard satellites so more attention may be given to its development. Two major factors affecting timekeeping precision are the selection of clock manufacturers and clock types. The European manufacturing technique is pioneering, but the RAFS and PHM independently developed by China in recent years indicate a good performance. To improve navigation service, an accurate evaluation of satellites performance should be conducted, and the results can be used to assign the weight of satellite differently in computing navigation information.

Keywords: atomic clock; clock performance; timekeeping; time offset; GNSSs.

1. Introduction

Many significant events in the field of satellite navigation systems have occurred over the last several decades; the modernization of Global Positioning System (GPS); the operation of the European satellite system Galileo, the reconstruction of the Russian satellite system GLONASS, and the launch of generations of BeiDou satellites [1]. The Global Navigation Satellites Systems (GNSSs) are primarily used for Positioning, Navigating, and Timing (PNT), having wide applications in numerous areas that are intimately connected to humans' daily lives [2].

For improving the service that GNSS provides, it is crucial to understand how this distant system functions and what empowers PNT’s high accuracy. And it turns out that the technological development of timekeeping, especially the atomic clocks, has a direct influence on PNT quality [3]. A timing error of 1 microsecond can lead to a 300-meters error in positioning which disables important applications such as aircraft landings and missile navigation [4]. Therefore, time metrology is critical to GNSS, and some questions that help to understand timekeeping in GNSS are identified: to what extent does timekeeping performance GNSSs differ from each other, what are the major contributors of the difference, to what extent does timekeeping performance improves for recent GNSSs, and what are some advice to improve the timekeeping. Most of the reviews on satellite atomic clocks have focused on developing and improving approaches to evaluate the performance of atomic clocks and compare them among GNSSs, but rarely is there a review to analyze the common trends concluded by these extensive studies. By researching on what the status quo and performance differences across GNSSs suggest about the future trends and timekeeping improvements regarding the satellite atomic clocks, this review intends to close this gap.

2. Reformation of the operating principle in GNSS

The first navigational system has no strict requirement for time accuracy. In 1957, a group of American scientists observed the radio transmission of the world’s first artificial satellite launched by the Soviet Union, Sputnik. They realized the location of a satellite can be monitored by measuring the Doppler distortion, which can be used to calculate the receiver position. Consequently, U.S. developed the first navigational system, Transit, which was deployed to increase the weapon preciseness [5]. However, the system was made available to civilian users in 1967 and was rapidly adopted for commercial use.

However, Transit has significant drawbacks: long responding time, a limiting two-dimensional navigating ability, and an occasional loss in the availability of signal. These deficiency prompted U.S. to advance a second navigation system. With the pioneering development of space-borne atomic clocks, a new generation of clock-based navigational systems that provides PNT services emerged [6].

3. Status quo of timekeeping and time offset

3.1. Atomic clocks

Precise and stable space-qualified atomic clocks are essential to GNSS. They are the only way to satisfy the requirements for onboard timekeeping. Therefore, uncorrected satellite clock offsets directly limit navigation performance [7-9].

Understanding the features of an atomic clock is critical to future improvements. Atomic frequency standard (AFS) was developed continuously since 1955; it is an atom or molecule undergoing a transition between two quantized energy levels. And atomic clock is a continuously operating AFS [10, 11]. As the frequency released by an atom and the number of resulting oscillations during a change in energy levels is specific, the oscillations can be measured and used as the standard for time. The official measurement of the length of a second is defined by the frequency required to make electrons in a cesium atom jump between two specific energy levels [12]. AFS is characterized by its outstanding stability and accuracy.

3.2. Space-borne atomic clocks onboard GNSS satellites

There are ground-based, deep-space, and satellite atomic clocks. This literature review focuses on the satellite atomic clocks. The standard to evaluate the performance of atomic clocks is different as they are applied to different scenarios. A well-performed terrestrial trapped-ion clock may malfunction when it is transformed for deep-space usage due to space radiation, temperature, and magnetic fields. It is also too large for a terrestrial clock to be carried on an aircraft. The clock technology used for satellite navigation may not befit deep-space navigation as the satellite clock may be updated by the ground clock and a deep space atomic clock can’t [12, 13]. For satellite clocks, the valued features are timekeeping accuracy, dependability, and operational life as well as its size, weight, and power requirements, typically grouped under the abbreviation "SWaP." These features are important because satellite clocks must guarantee a reliable performance throughout their whole mission, but often none of those qualities can be improved without compromising the others [7, 8].

3.3. Atomic clocks onboard different GNSSs

To identify factors that appear to be critical to clock performance, the status quo of the clocks onboard GNSSs should be interpreted. Different generations of satellites within the same GNSS carry different types of atomic clock, and the clock may be different between satellites of the same generation. Many satellites use the same clock initially, but each satellite contains multiple space atomic frequency standards (SAFS) for redundancy, commonly with four clocks onboard; the redundant clocks are used if the clock in operation malfunctions [14].

To give an overview of the recently launched satellite constellations, BeiDou-2 satellites carry four rubidium atomic frequency standard (RAFS) while BeiDou-3 possesses two RAFS plus two hydrogen masers [14, 15]. Excluding the earliest-launched GIOVE-A and GIOVE-B satellites, all those operational GALILEO satellites contain two RAFSs and two passive hydrogen masers (PHM) [14, 16]. For the latest satellite constellations GLONASS-M and GLONASS-K satellites, the GLONASS-M satellites have three cesium (Cs) beam clocks each onboard while the currently developing GLONASS-K satellites carry two Cs beams and two RAFSs [14]. As the oldest navigation system, GPS has many generations of satellites, and block IIF and block III satellites are the two latest operating generations with adequate information, with IIF satellites each possessing two RAFS and one Cs clock and III satellites containing three RAFS [14, 17]. Instead of making a long list of all the names of satellites with their corresponding clocks and GNSSs which do not contribute a lot to understanding atomic clocks and offset-influencing factors, this paper would briefly review the overall current characteristic of different GNSSs in the equipment of atomic clocks. For most medium earth orbit (MEO) GPS satellites, the majority of clocks are RAFS, with several exceptions such as GPS 2F-3 launched in 2012 and GPS 2F-10 launched in 2015 on which the clocks in operation are the Cs frequency standard [15]. BeiDou had launched satellites on geostationary orbit (GEO), inclined geosynchronous orbit (IGSO), and MEO. Those early BeiDou satellites launched are typically equipped with RAFS, but the number of PHM steadily increases for later BeiDou satellites and becomes very common for those that are launched in recent years, with RAFS serving as a backup [14-18]. Most of the GLONASS satellites are operating with Cs clocks [14]. Although Galileo satellites are typically equipped with RAFS and PHM, the majority of satellites are using PHM and relatively few are using RAFS [14, 16].

4. Relative performance of atomic clocks

The difference in performance between clocks among GNSSs is examined in many papers written in distinct periods, which usually compare the clock performances of the latest generations in their time using the data available. Through reviewing the results of these research and extracting common themes, an insight into the comprehensive performance of atomic clocks for the past and contemporary generation of satellites can be acquired, and the common factors contributing to these distinct performances can be analyzed.

4.1. Relative performance among same GNSS

Hauschild et al. [9] note that GLONASS satellites that are launched later have a trend of increasing stability, although some old satellites such as R11 and R19 still have good Allan deviation (ADEV) results. The RAFS of Galileo IOV satellites exhibit an enhanced stability compared to those of earlier GIOVE-A and GIOVE-B clocks. Yifei Lv et al. [19] have conducted a study on the latest BeiDou-3 satellites. The study finds that RAFS onboard BeiDou-3 satellites have a better performance than those onboard BeiDou-2 [19]. Xiaolin Jia et al. [20] compare the frequency drift rate of BeiDou-2 and BeiDou-3 and find BeiDou-3 PHM satellites are around 2 orders of magnitude better than the BeiDou-2 RAFS satellites, and BeiDou-3 RAFS performs better than the BeiDou-2 RAFS. As the volume and weight of BeiDou-3 RAFS have also been reduced, the Chinese atomic clock manufacturing technique demonstrates a significant improvement. Yu Cao et al. [3] acquire a similar result. The phase and frequency sequences of PHM and RAFS for BeiDou-3 are more continuous because the clock offset model precision and average frequency stability indicate an improvement of 65% and 57.5% from BeiDou-2 to BeiDou-3, respectively. G. Huang et al. [21] utilize International GNSS Service (IGS) clock products to analyze the frequency stabilities and clock noise level of IIA, IIR, and IIR-M GPS blocks. The clocks of Block IIA satellites have a significantly worse performance compared to Block IIR and IIR-M satellites in terms of frequency drift random characteristics and clock noise [21]. In addition, Block IIA has more phase and frequency jumps than Block IIR and IIR-M which can be ascribed to the clock-switching operations; those jumps have a direct impact on the reliability of a timekeeping system [21, 22]. Accordingly, the later launched Block IIR and IIR-M have superior performance in terms of continuity and stability. Based on their findings, G. Huang et al suggests weighting GPS clocks differently according to their quality levels to enhance navigation. For example, Block IIA can be removed from serving in the real-time positioning service [21].

4.2. Relative performance BeiDou-2 and contemporary GNSSs

Hauschild et al. [9] present a characterization of GPS, GLONASS-M, GIOVE, Galileo IOV, and BeiDou-2 clocks' short-term stability using polynomial fit and Kalman-filter-based clock approximation. Comparing the ADEV, the performance of COMPASS clocks is comparable to late GLONASS clocks, older GPS clocks, and the Galileo RAFS, but Rb clock of GPS Block IIF has the best performance. Qingsong Ai et al. [23] note that GPS block IIF RAFS clocks are more stable than those of block IIR, and GLONASS shows a good clock consistency by having very small frequency drift, which can be ascribed to the equipment of the same type of Cs atomic clock. Comprehensively, clock stability of Galileo and GPS is better than GLONASS and BeiDou [23]. Comparing the major noise affecting clocks onboard different GNSSs, the GPS and BDS clocks were more influenced by the Random Walk Frequency Modulation (RWFM), Flicker Frequency Modulation (FFM), and White Frequency Modulation (WFM) noise while GLONASS clocks, due to Cs clock characteristics, are mainly affected by WFM [23]. These results derive solely from the 3 randomly selected satellites from each GNSS, which exclusively uses BeiDou-2 satellites C09, C10, and C12 to compare with GPS block IIR and IIF, Galileo FOC, and GLONASS satellites [3, 23].

4.3. Relative performance BeiDou-3 and contemporary GNSSs

Yifei Lv et al. [19] compare the performance of the BeiDou-3 satellites to the late GPS Block IIF, Galileo, and GLONASS satellites and give an insight into the performance of the newly equipped PHM clocks that are developed by Chinese manufacturers. For all averaging intervals, the PHM clocks carried on the BeiDou-3 satellite C32 have the best performance in terms of stability among the BeiDou satellite clocks. In addition, the stability level of BeiDou-3 PHM is comparable to the PHM of Galileo and RAFS of GPS block IIF. For the selected 1-day stability, Xiaolin Jia et al. [20] acquire similar results for BeiDou-3 PHM, Galileo PHM, and GPS IIF RAFS. However, the PHM of BeiDou-3 is worse than that of the Galileo satellites in terms of frequency accuracy. Although the RAFS of GPS and BeiDou possess different advantages, the RAFS of GPS perform better than BeiDou in all indexes except in the 10,000 s stability. The study concludes that PMH is superior in important technical indexes, bringing a positive impact on positioning accuracy. As the analysis includes data of 8 PHM and 10 RAFS from BeiDou-3, the result is comprehensive. Yu Cao et al. [3] research on multiple satellites from BeiDou-3, GPS IIR and IIF, Galileo IOV and FOC, and GLONASS. BeiDou-3 RAFS is ranked the first among all other GNSSs satellites equipped with RAFS clocks. The Cs clocks onboard GPS Block IIF are inferior to those of GLONASS, which might be due to the poor Cs clock manufacturing technique. So, reducing the weight of these GPS satellites may improve the GNSS service. The comparison of several parameters has revealed that Galileo clocks have the best performance, and the second-best clock is from BeiDou-3, followed by GPS Block IIF RAFS satellites, BeiDou-2, GLONASS, GPS Block IIR, and IIR-M [3]. This result is similar to the findings of other works. Wei Wang et al. [17] find PHMs performing better than RAFS and that BeiDou-3 satellites are fairly comparable to the latest type of Galileo satellites and block III of GPS. The literature emphasizes the relationship between clock performance and manufacturing technology. Satellites of BeiDou-2 were made solely by Chinese Association for Science and Technology (CAST), while among the 24 MEO satellites, only 14 were made by CAST, and the other 10 were made by Shanghai Engineering Center for Microsatellites (SECM). The RAFS made by CAST shows an obvious drift in frequency data while the drift in GPS is less significant. The frequency data of PHMs onboard BeiDou-3 satellites and Galileo are both flat, but the result of Galileo is better than BeiDou, which can be ascribed to the more advanced technology used for the Galileo clocks.

4.4. Relative performance of clocks in general

Comparing contemporary PHM and RAFS to Cs clocks such as those onboard GLONASS and Block IIF, PHM has the best stability, with RAFS the second and Cs clocks the worst. The satellites launched later tend to equip with better clocks. The European manufacturing technique in the space-borne atomic clock is ahead of other countries [3].

5. Conclusion

Navigation provided by GNSSs is an extremely important service in many applications, and the timekeeping offset induced by atomic clocks is a major contributor of navigation error. This paper reviews the relative performance of clocks. Studies that compare clock performance from the same GNSS are first synthesized. The comparison of clocks across GNSSs are classified into BeiDou-2 and BeiDou-3 periods, and for each period the literature that contrast clock performances of contemporary generations from different GNSSs are reviewed. The manufacturing technique of atomic clocks are advancing rapidly in recent years, but many real-world applications are demanding a more accurate navigation service.

The two most important factors affecting the precision of clocks are the type of clock used and the manufacturers of the clocks. Among the various types of clocks onboard satellites, PHM has the best overall performance, suggesting that more attention should be drawn to its development. The European manufacturing technology is better than that of other regions, but Chinese clock manufacturing technology is advancing quickly. To improve the navigation service, multiple studies conclude that the weight of satellite clocks can be assigned differently based on their performance. The weight, volume, and life span are all very important characteristics of an atomic clock, and the compromise between these parameters should be as small as possible to provide a better navigation service.

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