Analysis and Suggestions on the Resilience of GNSS Timing

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Abstract. Time is widely used in almost all the critical fields. Among the 16 key fields identified in the U.S. Department of Homeland Security's presidential policy directive No. 21, 11 industries, including communications, mobile phones, power distribution, finance and information technology, rely on accurate timing and time synchronization technology. Therefore, timing system is very important for the national economy, society and security. This paper focuses on resilient timing and time synchronization of satellite navigation systems, and analyzes the failure timing events caused by satellite navigation systems and the external factors (such as jamming and spoofing). On the basis of introducing the latest development of resilient timing of satellite navigation system and the next generation of PNT system at home and abroad, the definition of resilient timing is preliminarily analyzed. Combined with the development of Chinese Beidou satellite navigation system and PNT, some useful suggestions on resilient timing and time synchronization are given.

Keyword: GNSS · Timing · Resilience · Time synchronization · Jamming

1 Introduction

Satellite navigation systems provide positioning, navigation and timing (PNT) information for users. Accurate measuring of time offset is the basis of GNSS to provide the services of positioning and navigation. Based on the measured time offset, the pseudoranges which are the essential for positioning is determined. Presently, timing of satellite navigation systems is widely used in all kinds of fields. Eleven of the sixteen key industries [1] given by the U.S. Department of Homeland Security presidential policy directive No 21, such as communications, mobile phones, power distribution and finance, all dependent on accurate timing and time synchronization technology. The weak signals of satellite navigation systems are easy to be cheated by jamming. Being considered the wide application of GNSS timing and the existed problems [2], resilience is chosen as another index for evaluating GNSS performance after accuracy, integrity, continuity and availability.

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This paper analyzes the existing problems in resilient timing of GNSS in the aspects of GNSS anomalies and external factors, such as jamming and spoofing. Based on the latest development of international GNSS and plan of PNT system, the definition and meaning of resilient timing is preliminarily given and analyzed. According to the state-of-the-art of China, some suggestions are given on GNSS resilient timing and time synchronization.

2 Existing Problems of GNSS Timing

The degradation or interruption of GNSS service performance are mainly caused by two factors. One is the anomalies from satellite navigation systems and the other is the external influences, such as jamming and spoofing.

2.1 GNSS Anomalies

GPS Anomalies
On January 26 of 2016, the UTC time parameters broadcast in GPS navigation message showed a singular deviation of 13.7 μs [3, 4]. An artificial mistake had triggered in the software of ground master station when satellite 23 was removed from the constellation.

Comparing the broadcast ephemeris of GPS with the IGS precise ephemeris products, Li Heng analyzed the performance of GPS SIS from 2000 to 2010 [5, 6]. There are up to 3275 GPS SISURE abnormal events (i.e. SISURE exceeds 4.2*URA) occurred in the past ten years which are failed to provide the service of promised performance to users. With the improvement of GPS SIS performance, the number of abnormal events are getting less.

Galileo Anomalies
On January 18 of 2017, nine atomic clocks on the in-orbit satellites of Galileo stopped operating due to malfunction, including one rubidium clock and six passive hydrogen clocks. According to the analysis of ESA [7], the malfunction of rubidium clocks are related to short-circuited while that of hydrogen clocks are mainly caused by long-time shutdown. The hardware failure of ground control station of Galileo system directly led to the non-update of broadcast ephemeris during the period of May 14, of 2017 to May 16 of 2017 [8]. At the periods of 14:00–15:00 and 17:00 UTC on July 10 of 2019, Galileo experienced a three-hour interruption and all ephemeris were not updated on time resulting in the service interruption.

From UTC 01:50 on July 12 of 2017, Galileo was failed to update satellite its navigation messages. Users experienced the degradation of Galileo service performance to its completely interruption [9]. It is found that a malfunction was occurred in the Galileo ground control center of PTF. This directly affected the prediction of satellite clock and orbit, and cannot generate navigation messages on time. An abnormal was detected in Galileo system time on December 14 of 2020 [10]. Since December 14 of 2020, the time parameters broadcasted by some Galileo satellites shown irregular jumps which resulted in the incorrect system time were received in user terminals.

GLONASS Anomalies

Due to the upload of incorrect ephemeris to all GLONASS satellites, the normal service was interrupted for up to 11 h on April 2 of 2014 [11]. The system did not return to normal until the ground control station of northern hemisphere uploaded correct data to all satellites.

The Russian SDCM system pointed out that the longest on orbit operation satellite launched in 2006 failed at 15:45 of Moscow time on August 1 of 2019 [12, 13].

Other Systems

Four rubidium atomic clocks in IRNSS failed on June 28 of 2017 [14] which was similar to that of Galileo satellite clocks in early June and resulted in the difficulty of providing service. On June 30 of 2015 and December 31 of 2016, BDS-2 had display errors during the adjustments of leap second [15].

Conclusion of GNSS Anomalies

From the above GNSS anomaly events, it can be seen that GNSS anamolies mainly comes from the space segment, control segment and transmit link. Table 1 summarized the reasons and behaviours of anomalies of GNSS.

The space segment anomalies mainly comes from the payload, satellite clock and time-frequency generation module. In addition, the complex space environment can also cause satellites malfunction, such as the unexpected change of pseudo-random code sequence caused by SEU [16]. Anomalies originated from the control segment are mainly caused by software and hardware failures, such as equipments malfunction and software bugs, which essentially belongs to human factors.

As the navigation signal transmit from satellites to receivers, it is inevitably affected by space weather, such as ionosphere scintillation, electromagnetic storm [17]. This kind of bad space weather makes navigation signal unable to pass through the atmosphere and finally results in the degradation or even interruption of normal service.

Table 1. Failures of GNSS

Sources	Reasons	Behaviour
Space segment	Satellite clock failure/payload failure caused by space weather etc.	No signal or non-update of navigation message or partial bad parameters, degradation or interruption of services
Control segment	Malfunction of hardware/bugs in software etc.	
Transmit link	Ionosphere scintillation/Electromagnetic storm /Coronal Mass Ejection /jamming etc.	

2.2 Jamming and Spoofing

The GNSS navigation signal is distributed to the ground from an altitude of more than 20000 km and the signal is very weak and vulnerable when reached ground. It is easy to be interfered and cheated by jamming and spoofing.

Jammers transmit high power jamming signal which makes GNSS receivers unable to receive the real GNSS signal. Spoofing jammers are used intentionally to generate or relay fake signals with the same parameters as that of GNSS to block the normal receiving and leading the GNSS terminals obtain incorrect positions and time information.

Jamming aimed at GNSS timing involves the space segment, control segment and user terminals. Space jamming mainly includes intentionally physical destroying of GNSS satellites, or blocking the normal communication link of time service. Jamming to the control segment are mainly physical destructions or interferences which interrupts the control of master station to satellites and makes GNSS unable to operate normally. The implementation of local suppression or electronic spoofing on user terminals can make users unable to obtain the correct GNSS time information or obtain with large time errors.

The concept of "time warfare" is proposed by the US Air Force Strategy and Technology Center in May 2017. Following the definition of "navigation warfare", the "time warfare" can be defined as preventing the enemy from using GNSS time service and ensuring that the normal use of GNSS timing for friendly targets while without affecting the normal utilization of GNSS time information outside the war zone.

To cope with the coming time warfare, jamming and spoofing, it needs not only strengthen the GNSS system by techniques, such as improving the robustness of the satellite navigation systems, building a wide-area distributed jamming & spoofing monitoring network. In addition, strict anti-jamming laws and regulations should be formulated to weaken the impact of jamming and spoofing on GNSS timing.

3 Progress of GNSS Resilient Timing

Excessive dependence on GNSS will cause serious economic losses and even threaten the safety of life. In view of the wide application of GNSS in all kinds of fields and its fatal weakness [18], it is urgent to develop the backup timing systems to improve the resilience of timing.

America

The United States issued a series of administrative orders to ensure the resilience of PNT. On August 15 of 2019, the U.S. Department of Defense issued the "Department of defense PNT strategy - ensuring the PNT advantage of U.S. military" [19] which requires the provision of resilient PNT services for joint forces. On February 12 of 2020, U.S. president signed the executive order "enhancing national resilience through responsible use of positioning, navigation and timing services" which requires that key infrastructure relying on GPS be free from interference and manipulation. In December 2018, U.S. president signed the "national timing resilience and security act of 2018" [21] which requires to build a terrestrial, resilient and reliable backup timing system for GPS within two years.

The law requires the backup timing system be a terrestrial which uses radio signals to broadcast time information that synchronized to UTC and able to penetrate underground and inside buildings. The timing signal is required to have good resilience, difficult to be disrupted or degraded and expandable to provide position, navigation and timing and able to work in concert with similar systems such as eLoran. At the same time, the construction of eLoran is restarted to improve the security and reliability of timing.

In order to cope with the impact of the “time warfare”, DARPA planned precise timing and time synchronization related projects in PNT system, including: 1) Quantum Assisted Sensing and Readout (QuASAR) project; 2) Ultrafast Laser Science and Engineering (PULSE) project; 3) Micro technology of Positioning, Navigation and Timing (Micro-PNT); 4) Spatial, Temporal and Orientation Information in Contested Environments (STOIC) project.

The U.S. plan of PNT about timing can be summarized into four aspects. Firstly, developing high-precision optical atomic clocks that are independent of laboratory conditions and can be applied to various mobile platforms. Secondly, researching high-precision time and frequency synchronization technology to meet the comparison requirements of optical atomic clocks. Thirdly, developing of low power consumption, miniaturization, high integration and stability of chip scale atomic clocks. Lastly, developing the clock system of ultra-stability, robustness and multi-function in contested environments. All these measures are aim to provide navigation, positioning and timing services that are better than GPS or equivalent to its performance, and become an effective backup of GNSS.

ESA

ESA has been paying close attention to the vulnerability of space-based PNT signal, and is committed to improve the resilience of satellite navigation signals. The timing and time synchronization based on Galileo are taken as an independent service as positioning and navigation by European Union. The European’s ten-year plan - H2020 funded a series of projects on GNSS timing and time synchronization, among which Galileo timing service extension and consolidation (EGALITE) project [22] had researched and developed Galileo time service and mainly concerned on the integrity of timing. The following part will give a brief introduction on this.

(1) Galileo navigation message broadcast timing augmentation flags

EGALITE project proposed the safety architecture of Galileo timing at system level shown in Fig. 1 [23].

Each Galileo satellite distributes timing augmentation flags for the whole constellation. The timing augmentation flags are calculated based on the data from global converged timing integrity monitor stations (TIMS). Raw data from TIMS are streamed in real time to Galileo service center and processed to generate Galileo (GPS) timing flags. Timing augmentation flags are sent to control center for uplink to satellites and broadcast by Galileo satellites. According to the maximum tolerable error (MTE) of timing, the service is divided into three levels: 10ns (Service Level 1), 100ns (Service Level 2) and 1000ns (Service Level 3). The timing flag of each satellite takes 2 bits in navigation messages. (0 0) means don’t use the satellite for timing for service level 3, 2 and 1. (1 0) indicates don’t use the satellite for timing for service level 2 and 1. (0 1)

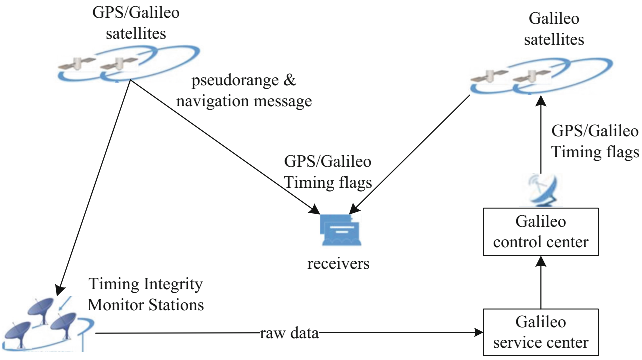

Fig. 1. Safety Architecture of GNSS timing

indicates don't use the satellite for timing for service level 1. (1 1) means use the satellite for timing for any service level. Users can easily know the timing performance of each satellite by receiving the timing flags and therefore have free selection of satellites for timing.

The Galileo Authenticated Robust Timing System (GEARS) project [24] developed a timing system to verify a new Galileo navigation signals which added with anti-spoofing authentication information to improve the ability of anti-jamming of Galileo signals. This design can protect Galileo from threats and ensure the accuracy and reliability of timing in challenging environment. It also provides backup for navigation signal and timing reference when Galileo is unavailable.

(2) Robust GNSS timing and time synchronization service

As a part of European H2020, DEMETRA project [25] has developed a complete set of GNSS timing services including certified time steering, time monitoring and steering, receiver calibration, time integrity and time synchronization.

Figure 2 shows the GNSS based robust time synchronization service system given in literature [26]. This system supports time synchronization by common view (CV), all in view (AV) and carrier phase (CP). The accuracy of time synchronization in world wide is several nanosecond. Due to the use of dual frequency observations of multi-constellations, TRAIM algorithm and augmentation information, this service system is not easy to be affected by interference and spoofing, and thus can provide users with robust and resilient timing and time synchronization service.

(3) Backup timing systems

The DEMETRA project also realizes the alternative backups [25] of GNSS. The standard time coded information is broadcasted via European Radio and TV links. The best performances with FM Radio is about 2ms. This project also provide the service that disseminating time with trusted NTP and the accuracy is below 10ms.

The time and frequency distribution over fiber links realizes time distribution of sub-nanosecond. Besides, this projects also allows to synchronize user stations by means of a geostationary satellite with accuracy of better than 100ns. This service provides technological redundancy to GNSS which increases the robustness of Galileo. All these

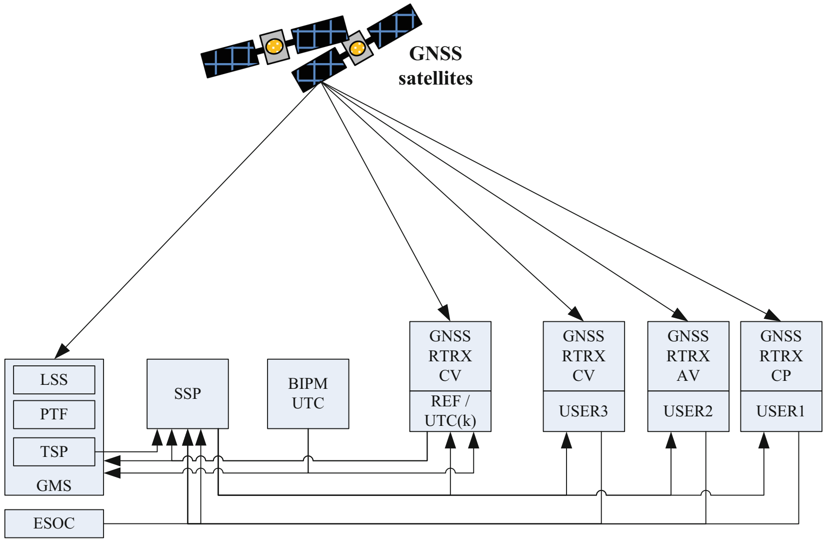

Fig. 2. Robust time synchronization system based on GNSS

methods can be used as the backup of GNSS to enhance the resilience and robustness of GNSS time service.

(4) Policy and others

The UK invested 36 million pounds to build the National Time Center (NTC) to provide a more resilient timing system for national emergency response services and others in February 2020 [27], so that the UK will not be affected by the failure of GNSS. The NTC will adopt the terrestrial technology to enhance the resilience and safety of British timing systems as an important backup of GNSS. Based on the atomic clocks distributed in different places, a clock set is established to keep a stable time scale to ensure that users can obtain accurate UTC time without GNSS.

Prospect of Chinese Resilient Timing System

China has launched a plan of constructing a PNT system by 2035. This plan aims to build a unique, three-dimensional intersect and resilient timing system worldwide in the future which is mainly composed of BeiDou Satellite navigation system (BDS), time & frequency system of space station, terrestrial radio timing system and fiber timing links.

The high-precision terrestrial timing system being under construction will form effective backup of GNSS from two aspects of fiber links and eLoran timing. As far as the eLoran timing, three stations broadcasting eLoran signal system will be built in west of China to realize the national coverage of terrestrial radio timing signal. The timing accuracy will be improved from 1 μs to 100 ns with the application of differential technology. In terms of fiber time synchronization, a backbone network which connecting Beijing, Shanghai, Xi'an and other cities will be established based on the communication optical fiber. The whole length will be more than 20000 km which will be the world's longest and more precise optical timing backbone network. The accuracy of fiber time synchronization will be better than 100 ps and that of frequency accuracy will reach E-19.

Through the construction of this new timing system, combined with the existed BDS, BPL, BPM, BPC and other timing systems, China will finally build an integrated, multi-source complementary, reliable and resilient timing system which providing users with multi-level, multi-dimensional, safety, reliable and resilient time service.

4 Reflection on Resilient Timing

Resilient timing refers to the ability to provide time service with the normal performance when a timing system is failure or subject to external interference. There are two requirements for timing systems. First of all, users should be provided with a warning in time when the timing system is failure or its performance is degraded or interrupted. This ensure that users can keep acquiring time information by switching timing systems or by local time keeping. Secondly, when being cheated by external interference, the timing system should have the ability to detecting and identify the interference so that not be affected by the interference.

As far as the GNSS is concerned, the following two aspects should be considered for resilient timing:

(1) Improving the resilience of GNSS timing at the system level.

It is suggested that the integrity or robust informations should be broadcast to enhance the timing performance of GNSS in information. It also can improve the resilience of GNSS timing by broadcasting authentication or encryption new signal. To deal with the influence of atmosphere on timing signal, it is recommended to monitor the transmission link of timing signal, such as detect the influence of solar and ionospheric anomalies on GNSS timing.

It is required that the timing terminals can receive multi-constellation and multi-frequency navigation signals, and has its local time source to keep time independently. In addition, the function of interference detecting and recognition is inevitable. This can be implemented through algorithm in terminal software to eliminate the influence of interference and ensure the accuracy and safety of timing.

(2) Developing other timing systems.

To solve the vulnerability of GNSS timing essentially, the backup timing system must be developed. This includes developing new type of atomic clocks and the corresponding time synchronization techniques, building territorial radio timing systems and other timing systems. An integrated timing system is formed to realize the complementary of mutual timing system and meeting the requirement of users for different precision in various environments.

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