GPS Signal-in-Space Anomalies in the Last Decade

Data Mining of 400,000,000 GPS Navigation Messages

Liang Heng, Grace Xingxin Gao, Todd Walter, and Per Enge,
Stanford University

BIOGRAPHY

Liang Heng is a Ph.D. candidate under the guidance of Professor Per Enge in the Department of Electrical Engineering at Stanford University. He received his B.S. and M.S. degrees in electrical engineering from Tsinghua University, Beijing, China. His current research interests include GNSS integrity and modernization.

Grace Xingxin Gao, Ph.D., is a research associate in the GPS lab of Stanford University. She received the B.S. degree in mechanical engineering and the M.S. degree in electrical engineering, both at Tsinghua University, Beijing, China. She obtained the Ph.D. degree in electrical engineering at Stanford University. Her current research interests include GNSS signal and code structures, GNSS receiver architectures, and interference mitigation. She has received the Institute of Navigation (ION) Early Achievement Award.

Todd Walter, Ph.D., is a senior research engineer in the Department of Aeronautics and Astronautics at Stanford University. He received his Ph.D. from Stanford and is currently working on the Wide Area Augmentation System (WAAS), defining future architectures to provide aircraft guidance, and working with the FAA and GPS Wing on assuring integrity on GPS III. Key early contributions include prototype development proving the feasibility of WAAS, significant contribution to WAAS MOPS, and design of ionospheric algorithms for WAAS. He is a fellow of the Institute of Navigation.

Per Enge, Ph.D., is a Professor of Aeronautics and Astronautics at Stanford University, where he is the Kleiner-Perkins, Mayfield, Sequoia Capital Professor in the School of Engineering. He directs the GPS Research Laboratory, which develops satellite navigation systems based on the Global Positioning System (GPS). He has been involved in the development of WAAS and LAAS for the FAA. Per has received the Kepler, Thurlow and Burka Awards from the ION for his work. He is also a Fellow of the ION and the Institute of Electrical and Electronics Engineers (IEEE). He received his PhD from the University of Illinois in 1983.

ABSTRACT

For the Global Positioning System (GPS), signal-in-space (SIS) performance is key to the positioning accuracy and the integrity. In practice, SIS anomalies occasionally happens and the consequent user range errors of tens of meters or even more have been observed. In this paper, all potential SIS anomalies in the last decade are screened out by comparing the broadcast ephemerides/clocks with the precise ones.

Validated broadcast ephemerides/clocks are generated from more than 400,000,000 broadcast navigation messages logged by all International GNSS Service (IGS) stations during the period 6/1/2000–8/31/2010. Both IGS and National Geospatial-Intelligence Agency (NGA) precise ephemerides/clocks are used as truth references. In addition, the NGA satellite antenna corrections are employed to convert IGS center-of-mass data into antenna-phase-center. The validated broadcast ephemerides/clocks are used to propagate broadcast satellite orbits/clocks at 15-minute intervals that coincide with the precise ones. A potential SIS anomaly is claimed when the navigation message is healthy and in its fit interval but the consequent worst-case SIS range errors (SISRE) exceeds the SIS not-to-exceed tolerance, 4.42 times the user range accuracy (URA) upper bound (UB).

Finally, 3275 potential SIS anomalies are screened out. Most anomalies between 2004 and 2009 are confirmed by other literature. Some mysterious anomalies during the first year after SA was turned off are discovered and investigated. Cumulative distribution of anomalous worst-case SISRE shows that approximately 10% anomalies result in worst-case SISRE greater than 10 times URA UB, and approx-

imately 1% anomalies result in worst-case SISRE greater than 100 times URA UB. The total number of potential SIS anomalies per year demonstrates that the SIS performance was improving in the last decade.

INTRODUCTION

For the Global Positioning System (GPS) standard positioning service (SPS) users, real-time satellite positions and clocks are derived from ephemeris parameters and clock correction terms in the broadcast navigation messages, which are generated by the Control Segment (CS) on the basis of a prediction model and the measurements at more than a dozen monitor stations [1]. The differences between the broadcast ephemerides/clocks and the truth account for signal-in-space (SIS) errors. SIS errors directly affect the positioning accuracy, especially for stand-alone SPS users. Ideally, navigation messages should be error-free and the consequent SIS range errors (SISRE) meet or surpass the performance standard [2]. In practice, unfortunately, occasional SIS anomalies happened and user range errors (URE) of tens of meters or even more were observed [3, 4]. The knowledge about the SIS anomalies in the history is very important not only for assessing the general performance of GPS but also for developing the next generation integrity monitoring system.

A typical method to evaluate SIS performance is to compare the broadcast ephemerides/clocks with the precise, post-processed ones [5–9]. Unfortunately, broadcast ephemerides/clock data obtained from a tracking network sometimes contain errors caused by receivers or data conversion softwares [10] and these errors usually result in false SIS anomalies. In our previous paper [11], we proposed a systematic methodology to cope with this problem and screened out all the potential SIS anomalies from 2006 to 2009. In this paper, we extend our well-established methodology to all the ephemeris/clock data in the last decade. Some new problems arise with this extension and the solutions to these problems will be presented in this paper.

For the rest of this paper, we start with a brief review of the methodology. Then, our solutions to the new problems are introduced. Finally, all GPS ephemerides/clocks from 6/1/2000 to 8/31/2010 are screened and the results are presented.

METHODOLOGY

The SIS anomalies are screened out by comparing broadcast ephemerides/clocks with precise ones. As shown in Figure 1, the whole process consists of three steps: data collection, data cleansing, and anomaly determination.

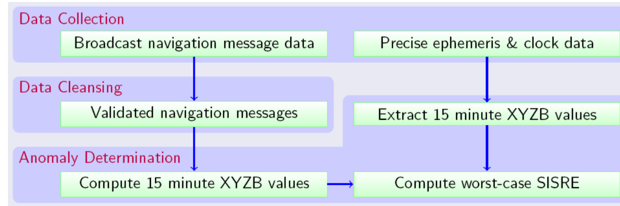


Figure 1. Framework of the whole process

In the first step, the broadcast ephemeris/clock data files are downloaded from the FTP servers of International GNSS Service (IGS) [12]. IGS tracking network comprises more than 300 stations all over the world ensuring seamless and redundant data logging. Besides, the precise ephemeris/clock data files are downloaded from both IGS and National Geospatial-Intelligence Agency (NGA) [13]. The details about the precise ephemeris/clock data will be discussed in the next section.

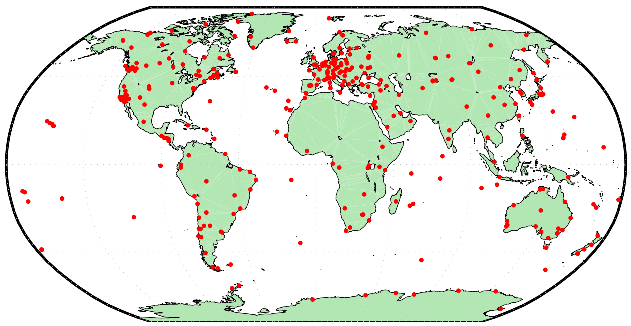
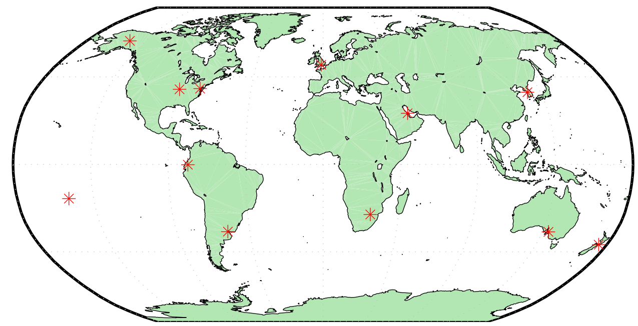
Since each GPS satellite can be observed by many IGS stations at any instant, each navigation message is recorded redundantly. In the second step, a data cleansing algorithm exploits the redundancy to remove the errors caused by receivers, data conversion softwares, network transmission, etc. This step distinguishes our work from most other researchers' [5–9] because the false anomalies due to dirty data can be mostly precluded.

The last step is computing worst-case SISREs as well as determining potential GPS anomalies. The validated ephemerides/clocks prepared in the previous step are used to propagate broadcast orbits/clocks at 15-minute intervals that coincide with the precise ones. A potential GPS anomaly is claimed when the navigation message is healthy and in its fit interval but the worst-cases SISRE exceeds SIS URE not-to-exceed (NTE) tolerance, 4.42 times user range accuracy (URA) upper bound (UB) [2].

The details of the algorithms mentioned above have been discussed thoroughly in our previous paper [11] and will not be repeated in this paper.

PRECISE EPHEMERIS/CLOCK DATA

Precise GPS ephemerides/clocks are generated by some organizations such as IGS and NGA which routinely observe GPS satellites. Precise ephemerides/clocks are regarded as truth since they are an order of magnitude or more accurate than the broadcast ephemerides/clocks [14]. Table 1 shows a side-by-side comparison between IGS and NGA precise ephemeris/clock data, in which the green-colored texts imply the advantages whereas the red-colored texts mean the disadvantages. For NGA's data, the only disadvantage is

IGS tracking network	NGA tracking network
	
Publicly available data since 1992	Publicly available data since 2006
Bad/absent data†: 1.5%	Bad/absent data†: 0.009%
Every 15 minutes synchronized to either GPS time (before 2/21/2004) or IGS time (after 2/22/2004)	Every 15 minutes synchronized to GPS time
Center of Mass only, no Antenna Phase Center	Both Center of Mass and Antenna Phase Center

† Statistics of the data from 11/5/2006 to 10/4/2008

Table 1. Comparison of IGS and NGA precise ephemeris/clock data

that the data are only publicly available since 2006[1]. As a result, for the broadcast ephemerides/clocks in 2005 or earlier, IGS precise ephemerides/clocks are the only references. Nevertheless, care must be taken when using IGS precise ephemerides/clocks due to the following several problems.

The first problem with the IGS precise ephemerides/clocks is the relatively high rate of bad/absent data, as shown in the third row of Table 1. For a GPS constellation of 27 healthy satellites, 1.5% bad/absent data means no precise ephemerides or clocks for approximately 10 satellite-hour per day. This problem can result in undetected anomalies and, unfortunately, there is no way to mitigate this problem unless adding a new data source.

The second problem is that, as shown in the fourth row of Table 1, IGS has switched to IGS time for their precise ephemeris/clock data since 2/22/2004. The IGS clock is not synchronized to GPS time and the differences between the two time references may be as large as 3 meters [9]. Fortunately, the time offset can be extracted from IGS clock data files. Moreover, a similar problem is that IGS precise ephemerides use International Terrestrial Reference Frame (ITRF) whereas broadcast GPS ephemerides are based on World Geodetic System 1984 (WGS 84). The differences between ITRF and WGS 84 are on the order of a few centimeters [15] and hence a transformation is not considered necessary for this paper.

The last but not the least problem with the IGS precise ephemerides is that the data are provided only for center of mass (CoM). Since the broadcast ephemerides are based on antenna phase center (APC), the CoM data must be converted into APC before being used. Both IGS and NGA provide antenna corrections for each GPS satellite [16, 17]. Although IGS CoM data are highly agreed with NGA CoM data, their satellite antenna corrections are quite different, and the differences in z-offsets can be as much as 1.6 meters for some GPS satellites [18]. The reason for these differences is mainly due to the different methods for producing the antenna corrections: IGS antenna corrections are based on statistics from more than 10 years of IGS data, and NGA's are probably the manufacturers' calibration measurements on the ground [18]. In order to know which satellite antenna corrections are better, the broadcast orbits for all GPS satellites in 2009 are computed and compared with three

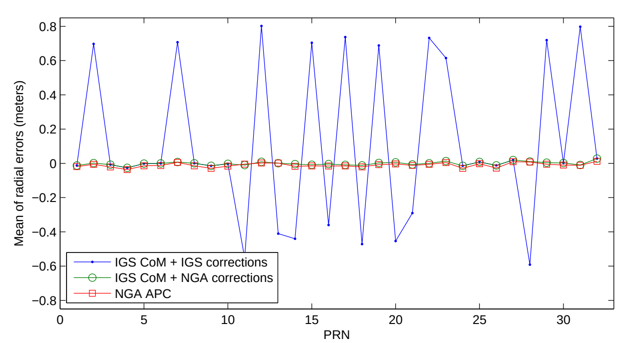


Figure 2. Truncated mean of radial ephemeris error for all GPS satellites in 2009 using three different precise ephemerides. NGA antenna corrections work better than IGS'.

[1] As of September 2009. Now NGA's website [13] provides only the data since 2009.

different precise ephemerides: IGS CoM + IGS antenna corrections, IGS CoM + NGA antenna corrections, and NGA APC. The truncated mean[2] of the radial ephemeris error for each satellite is plotted in Figure 2. Generally, the radial ephemeris error is expected to have a zero mean, just as the green curve and red curve in Figure 2. However, the combination "IGS CoM + IGS antenna corrections" results radial ephemeris errors with non-zero mean for quite a few GPS satellites. Therefore, NGA antenna corrections are selected to convert IGS CoM data into APC.

RESULTS

All broadcast GPS ephemerides/clocks from 6/1/2000 (one month after the selective availability [SA] was turned off) to 8/31/2010 are screened using previously described algorithms. Both IGS and NGA precise ephemerides/clocks are employed for the truth references.

[2] 20% of the ends are discarded in order to exclude the anomalies and outliers. Truncated mean is also known as trimmed mean or Windsor mean.

Before interpreting the results, it should be noted that there are some limitations due to our criterions and the data sources. First, the NTE tolerance [2] was defined differently before 2008; nevertheless, we still consider 4.42 times URA UB for the sake of a consistent comparison. Second, false anomalies might be claimed because there may be some errors in the validated broadcast ephemerides/clocks or the precise ones. Third, some short-lived anomalies may not show up if they happened to fall into the 15-minute gaps. Fourth, some true anomalies may not be detected if the precise ephemerides/clocks are temporarily missing. The fourth limitation is especially significant for the results before 2006, because only IGS precise ephemerides/clocks are available, and IGS data have a high rate of bad/absent data. Last but not least, users might not experience some anomalies because the satellites was not trackable[3] at that time. Therefore, all the SIS anomalies claimed in this paper are potential and under further investigation.

[3] A satellite may indicate it is unhealthy through the use of non-standard code or data [2]. Both of these methods may be missed by our process.

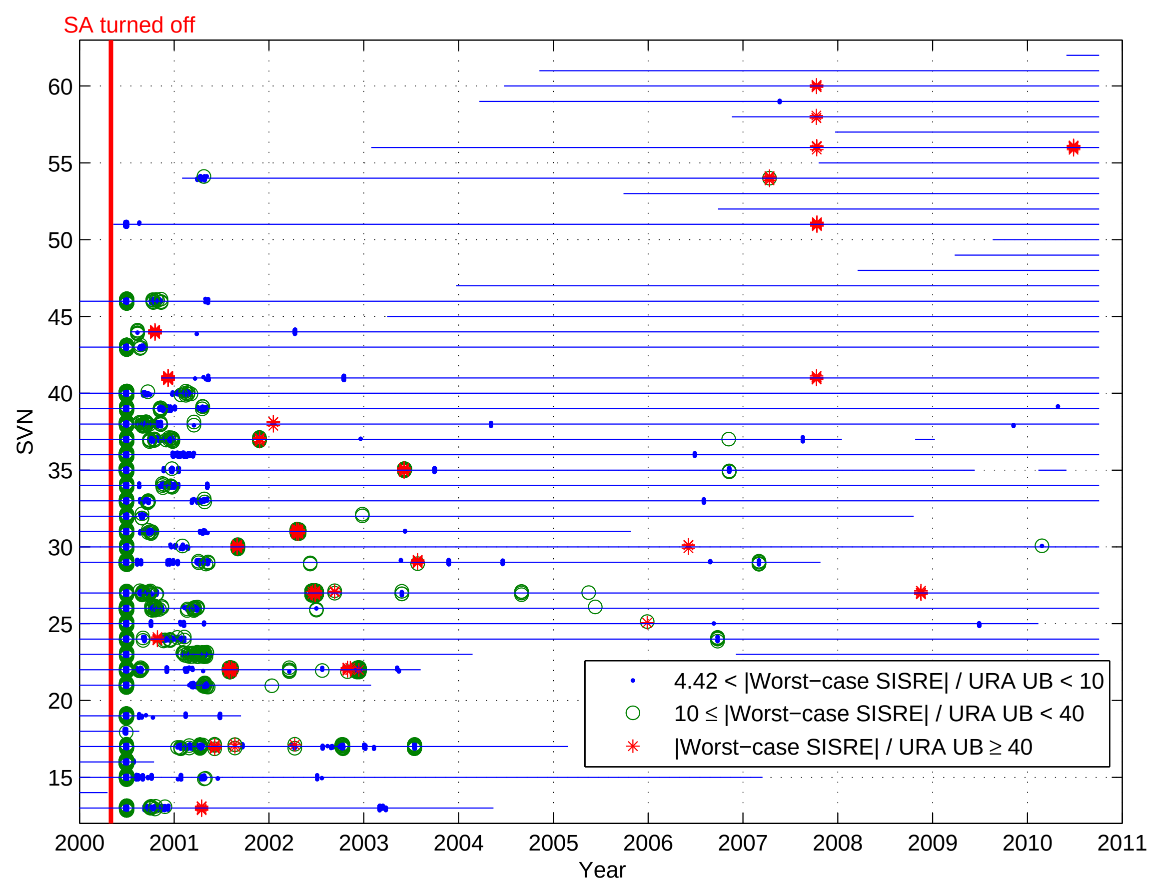


Figure 3. Potential SIS anomalies from 6/1/2000 to 8/31/2010

Potential SIS anomalies in the last decade

Figure 3 shows all potential SIS anomalies in a Year-SVN plot. In the figure, the horizontal blue lines indicate the periods when the satellites are active (not necessarily healthy). Markers of blue dots, green circles, and red stars represent small, medium, and larger SIS anomalies, respectively. It can be seen that during the first year after SA was turned off, SIS anomalies happened frequently for all GPS satellites. The cause of these anomalies will be discussed later.

Moreover, 2004 is apparently a watershed: before 2004 anomalies happened frequently for all GPS satellites (except SVN 45/PRN 21 and SVN 56/PRN 16 which were lunched in 2003) whereas after 2004 anomalies happened much less frequently and more than 10 satellites have never been anomalous. Figure 4 further confirms the better-and-better GPS SIS performance: hundreds or tens of anomalies per year before 2003, and ten or less per year from 2004 to now.

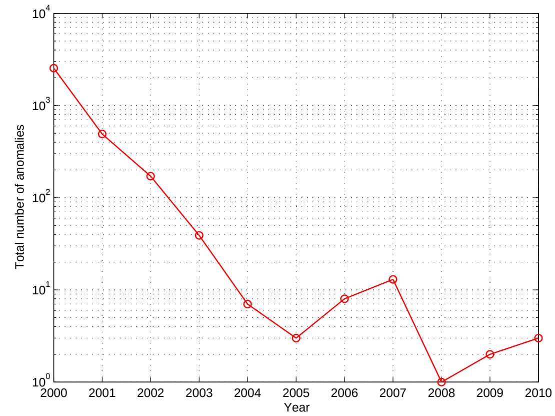


Figure 4. Total number of potential SIS anomalies per year. The SIS performance improved during the last decade.

Date/time	PRN	Duration	Anomaly	URA UB (m)	References	Confirmed
2004-05-03 11:00	08	30 minutes	clock −30.8 m	3.4	IGS	
2004-06-14 11:15	29	2.75 hours	ephemeris −10.8 m	2.4	IGS	
2004-06-17 11:15	29	1.5 hours	ephemeris 12.5 m	2.4	IGS	
2004-07-20 07:15	23	45 minutes	ephemeris 13 m	2.4	IGS	
2004-08-29 00:45	27	1 hours	clock 69.5 m	3.4	IGS	[19, 20]
2005-05-14 20:15	27	15 minutes	clock 27.6 m	2.4	IGS	
2005-06-09 03:45	26	15 minutes	clock −38 m	3.4	IGS	[9]
2005-12-25 21:15	25	30 minutes	clock −129 m	2.4	IGS	
2006-06-02 20:30	30	30 minutes	clock −1045 m	2.4	NGA	[9]
2006-06-27 04:45	06	30 minutes	clock −10.2 m	2.4	IGS, NGA	
2006-07-31 22:15	03	1 hour	clock −12.7 m	2.4	IGS, NGA	[9]
2006-08-25 12:30	29	1.5 hours	clock −11.6 m	2.4	IGS, NGA	[9]
2006-09-22 19:45	24	2.75 hours	ephemeris 41.2 m	2.4	IGS, NGA	[9]
2006-11-07 01:45	05	3.75 hours	clock −30.7 m	2.4	IGS, NGA	[9]
2007-03-01 14:45	29	2.5 hours	clock −42.3 m	2.4	IGS, NGA	[9, 21]
2007-04-10 16:00	18	1.75 hours	ephemeris 688 m	2.4	IGS, NGA	[9, 20–22]
2007-04-22 10:30	25	45 minutes	clock −29.4 m	6.85	NGA	[21]
2007-05-20 03:45	19	15 minutes	ephemeris −13.3 m	2.4	IGS, NGA	
2007-08-17 07:30	07	30 minutes	clock −14.3 m	2.4	IGS, NGA	[8, 9]
2007-10-08 09:45	12	2.25 hours	clock −86 km	2.4	NGA	[23]
2007-10-08 23:00	14	1.5 hours	clock −112 km	2.4	NGA	[23]
2007-10-09 09:45	23	1 hour	clock 27 km	6.85	NGA	[23]
2007-10-09 13:15	16	15 minutes	clock −18 km	4.85	IGS, NGA	[23]
2007-10-10 08:45	20	1.25 hours	clock 48 km	2.4	IGS, NGA	[23]
2008-11-14 05:45	27	3.75 hours	clock −70 km	2.4	NGA	
2009-06-26 09:30	25	45 minutes	clock −22.3 m	2.4	NGA	[20]
2009-11-05 18:45	08	30 minutes	clock −18.5 m	2.4	IGS	[20]
2010-02-22 21:00	30	30 minutes	clock −42.9 m	3.4	NGA	
2010-04-25 19:45	09	15 minutes	ephemeris 11 m	2.4	IGS, NGA	
2010-06-24 18:30	16	2 hours	clock 374 m	2.4	NGA	

Table 2. List of potential SIS anomalies from 1/1/2004 to 8/31/2010

Therefore, we are able to list all potential SIS anomalies from 1/1/2004 to 8/31/2010 in Table 2. It can be seen most anomalies in the table have been confirmed by other literature. One interesting thing in Figure 4 is the relatively large number of anomalies in 2007, and Table 2 explains this: the five anomalies from 10/8/2007 to 10/10/2007 are due to the GPS OCS Architecture Evolution Plan [23].

Cumulative distribution of anomalous worst-case SISRE

Figure 5 shows the cumulative distribution of the anomalous worst-case SISREs for the last decade. For every real

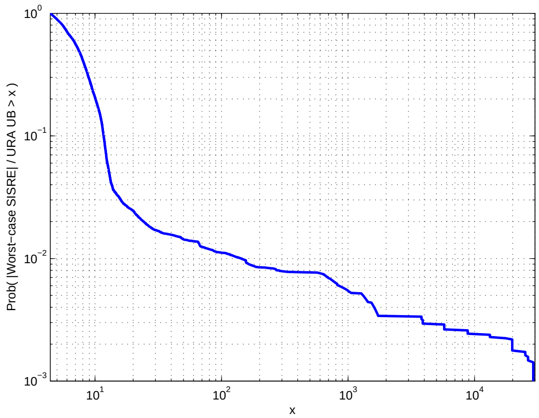


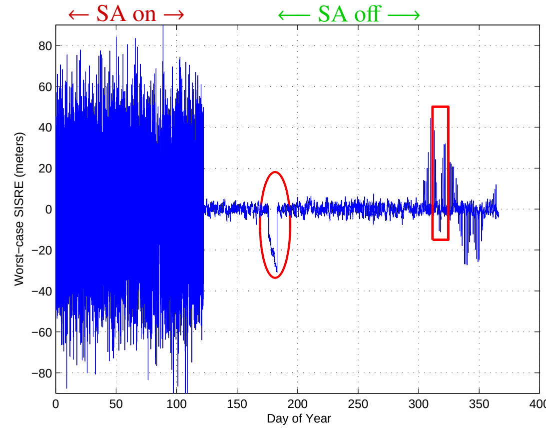
Figure 5. Cumulative distribution of anomalous worst-case SISRE

number $x \geq 4.42$, the curve gives the empirical probability that the worst-case SISRE is greater than $x \cdot$ URA UB. It can be seen approximately 10% anomalies result in worst-case SISRE greater than 10 times URA UB, and approximately 1% anomalies result in worst-case SISRE greater than 100 times URA UB.

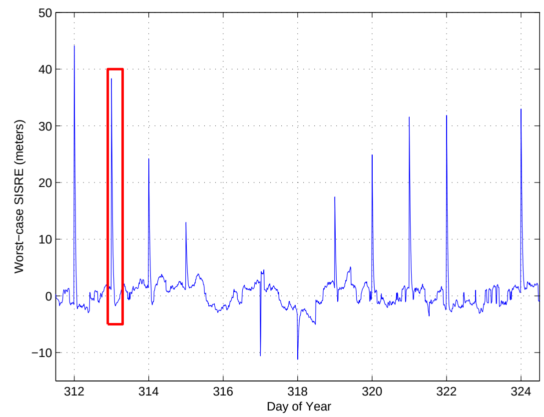
Mysterious SIS anomalies during the first year after SA was turned off

As mentioned previously, a large number of SIS anomalies happened during the first year after SA was turned off. Figure 6 explains most of these anomalies.

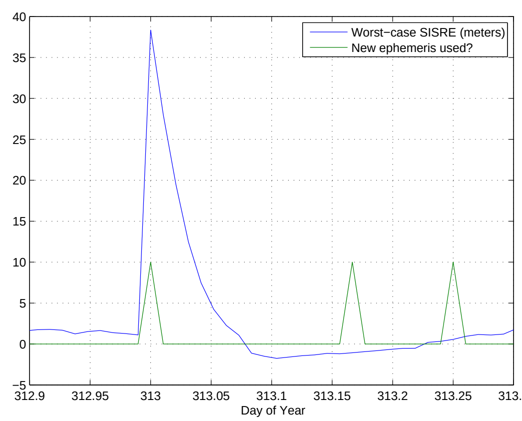
As circled by a red ellipse in Figure 6 (a), the first group of the anomalies happened from Day 176 to Day 183. These anomalies are mainly due to clock errors and the very similar clock errors also occurred for all other GPS satellites[4]. It is possible that these anomalies did not really exist but come from incorrect IGS precise clocks. Even if these anomalies



(a) Year-round



(b) Zoom-in of the red box in Subfigure (a)



(c) Zoom-in of the red box in Subfigure (b)

Figure 6. SVN 39/PRN 9 worst-case SISRE in 2000

really happened, they might not result in significant positioning errors because all the GPS constellation had similar clock errors.

The red box in Figure 6 (a) highlights another typical group of the anomalies. As zoomed into the Figure 6 (b), these anomalies happened at each midnight (in UTC time). We

[4] In Figure 3, it seems that these anomalies did not happened on SVN 18/PRN 18 and SVN 51/PRN 20 because both two satellites were not continuously healthy then.

therefore name them Midnight Anomalies. Figure 6 (c) further zooms in the red box in Figure 6 (b). It can be seen that this anomaly is due to the navigation message issued at midnight. The most mysterious thing is that although this navigation message lead to an SISRE more than 30 meters initially, it fixed itself one hour later. Similar midnight anomalies are also discovered for almost all other GPS satellites. Usually, midnight anomalies happened within 3 to 6 satellites per day. The root reason of these anomalies is still under investigation.

SUMMARY

In this paper, the GPS SIS performance in the last decade is evaluated by comparing the broadcast ephemerides/clocks with the precise ones. We devise and implement a systematic methodology to screen out potential SIS anomalies from dirty logging data. Approximately 1,500,000 validated broadcast ephemerides/clocks for the period 6/1/2000–8/31/2010 are generated from more than 400,000,000 broadcast navigation messages logged by all IGS stations. Both IGS and NGA precise ephemerides/clocks are used as the truth references, and the NGA satellite antenna corrections are employed to convert IGS CoM data into APC. Finally, 3275 potential SIS anomalies are found. Most potential anomalies between 2004 and 2009 are confirmed by other literature. Some mysterious anomalies during the first year after SA was turned off are discovered and investigated. Approximately 10% anomalies result in worst-case SISRE greater than 10 times URA UB, and approximately 1% anomalies result in worst-case SISRE greater than 100 times URA UB. The total hour of potential SIS anomalies per year shows that the SIS performance has been improving for the past ten years.

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