

Digging into GPS Integrity

Charting the Evolution of Signal-in-Space Performance by Data Mining 400,000,000 Navigation Messages

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BUT THE GREATEST OF THESE IS INTEGRITY. There are four important requirements of any navigation system: accuracy, availability, continuity, and integrity.

Perhaps the most obvious navigation system requirement, accuracy describes how well a measured value agrees with a reference value, typically the true value. In the case of GPS, we might talk about the accuracy of a range measurement. A receiver actually measures a pseudorange — a biased and noisy measure of the geometric range between the receiver and the satellite. After correcting for satellite ephemeris and satellite clock errors (the primary so-called signal-in-space errors), receiver clock errors, and atmospheric effects, we can get an estimate of the geometric range. How well we account for these errors or biases, will determine the accuracy of the corrected pseudorange measurement and ultimately, the accuracy of a derived position.



Integrity refers to trustworthiness.

A navigation system's availability refers to its ability to provide the required function and performance within the specified coverage area at the start of an intended operation. In many cases, system availability implies signal availability, which is expressed as the percentage of time that the system's transmitted signals are accessible for use. In addition to transmitter capability, environmental factors such as signal attenuation or blockage or the presence of interfering signals might affect availability.

Ideally, any navigation system should be continuously available to users. But, because

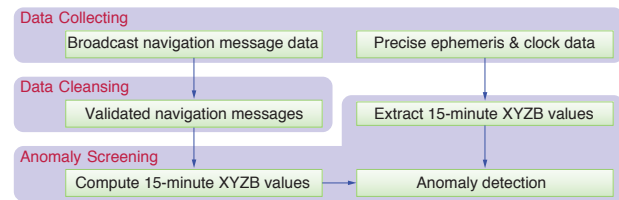
of scheduled maintenance or unpredictable outages, a particular system may be unavailable at a certain time. Continuity, accordingly, is the ability of a navigation system to function without interruption during an intended period of operation. More specifically, it indicates the probability that the system will maintain its specified performance level for the duration of an operation, presuming system availability at the beginning of that process.

The integrity of a navigation system refers to its trustworthiness. A system might be available at the start of an operation, and we might predict its continuity at an advertised accuracy during the operation.

But what if something unexpectedly goes wrong? If some system anomaly results in unacceptable navigation accuracy, the system should detect this and warn the user. Integrity characterizes a navigation system's ability to provide this timely warning when it fails to meet its stated accuracy. If it does not, we have an integrity failure and the possibility of conveying hazardously misleading information. GPS has built into it various checks and balances to ensure a fairly high level of integrity. However, GPS integrity failures have occasionally occurred.

In this month's column we take a look at one particular aspect of GPS integrity: that of the signal in space and find out how trustworthy is the satellite ephemeris and clock information in the broadcast navigation message.

The Navstar Global Positioning System is so far the most widely used space-based positioning, navigation, and timing system. GPS works on the principle of trilateration, in which the measured distances from a user receiver to at least four GPS satellites in view, as well as the position and clock data for these satellites, are the prerequisites for the user receiver to fix its exact position. For most GPS Standard Positioning Service (SPS) users, real-time satellite positions and clocks are derived from ephemeris parameters and clock correction terms in navigation messages broadcast by GPS satellites. The GPS Control Segment routinely generates navigation message data on the basis of a prediction model and the measurements at more than a dozen monitor stations. The differences between the broadcast ephemerides/clocks and the truth account for signal-in-space (SIS) errors. SIS errors are usually undetectable and uncorrectable for stand-alone SPS users, and hence directly affect the positioning accuracy and integrity. Nominally, SPS users can assume that each broadcast navigation message is reliable and the user range error (URE) derived from a healthy SIS is at the meter level or even sub-meter level. In practice, unfortunately, SIS anomalies have happened occasionally and UREs of tens of meters or even more have been observed, which can result in an SPS receiver outputting a hazardously misleading position solution. Receiver autonomous integrity monitoring (RAIM) or advanced RAIM is a promising tool to protect stand-alone users from such hazards; however, most RAIM algorithms assume at most one satellite fault at a time. Knowledge about the SIS anomalies in history is very important not only for assessing the GPS SIS integrity performance but also for validating the fundamental as-



▲ **FIGURE 1** Framework of the whole process. XYZB values refer to the coordinates of satellite position and satellite clock bias.

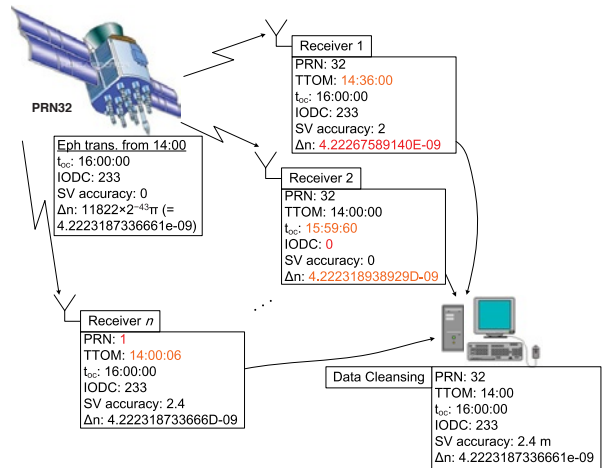
sumption of RAIM.

A typical method for calculating SIS UREs is to compare the broadcast ephemerides/clocks with the precise, post-processed ones. Although this method is very effective in assessing the GPS SIS accuracy performance, few attempts have been made to use it to assess the GPS SIS integrity performance because broadcast ephemeris/clock data obtained from a global tracking network sometimes contain errors caused by receivers or data conversion processes and these errors usually result in false SIS anomalies. In this article, we introduce a systematic methodology to cope with this problem and screen out all the potential SIS anomalies in the past decade from when Selective Availability (SA) was turned off.

GPS SIS Integrity

The integrity of a navigation system refers — just as it does to a person — to its honesty, veracity, and trustworthiness. In the case of GPS, this includes the integrity of the ephemeris and clock data in the broadcast navigation messages. We refer to this as signal-in-space integrity.

GPS SIS URE. As indicated by the name, GPS SIS URE is the pseudorange modeling inaccuracy due to operations of the GPS ground control and the space vehicles. Specifically, SIS URE includes satellite ephemeris and clock errors, satellite antenna performance variations, and signal imperfections, but not ionospheric or tropospheric delay, multipath, or any errors due to user receivers. SIS URE is dominated by ephemeris



▲ **FIGURE 2** A scenario of data cleansing: In the figure, the GPS satellite PRN32 started to transmit a new navigation message at 14:00. Receiver 1 had not observed the satellite until 14:36, and hence the TTOM in its record was 14:36. Additionally, Receiver 1 made a one-bit error in Δn ($4.22267589140 \times 10^{-9} \approx 11823 \times 2^{-43} \pi$). Receiver 2 perhaps had some problems in its software: the IODC was unreported and both the t_{oc} and Δn were written weirdly. Receiver n used an incorrect ranging code, PRN01, to despread and decode the signal of PRN32; fortunately, all the parameters except TTOM were perfectly recorded. Moreover, the three receivers interpreted URA (SV accuracy) differently. A computer equipped with our data cleansing algorithms is used to process all the data from the receivers. The receiver-caused errors are removed and the original navigation message is recovered.

and clock errors because antenna variations and signal imperfections are at a level of millimeters or centimeters.

In broadcast navigation messages, there is a parameter called user range accuracy (URA) that is intended to be a conservative representation of the standard deviation (1-sigma) of the URE at the worst-case location on the Earth. For example, a URA index value of 0 means that the 1-sigma URE is expected to be less than 2.4 meters, and a URA index value of 1 means that the 1-sigma URE is expected to be greater than 2.4



“In 20 years, I’ll be dead.”

Real quote: CEO wondering when Galileo will *actually* help his bottom line

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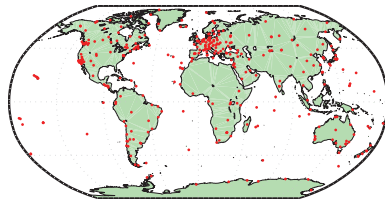
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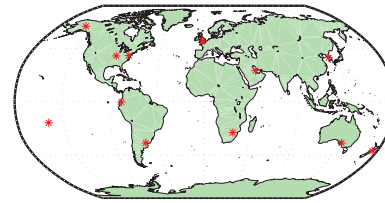
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IGS tracking network



NGA tracking network



Publicly available data since 1994 or earlier

Bad/absent data[†]: 1.5 percent

Every 15 minutes; synchronized to either GPS Time (before 21 February, 2004) or IGS Time (after 22 February, 2004)

Orbits for center of mass only, no antenna phase center

Publicly available data since 2004

Bad/absent data[†]: 0.009 percent

Every 15 minutes; synchronized to GPS Time

Orbits for both center of mass and antenna phase center

[†] Statistics of the data from November 5, 2006 to October 4, 2008

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

meters but less than 3.4 meters, and so on. In the past several years, most GPS satellites have a URA index value of 0. A nominal URA value, in meters, can be computed as $X = 2^{(1+N/2)}$, where N is the index value, for index values of 6 or less. For $6 < N < 15$, $X = 2^{(N/2)}$.

GPS SPS SIS Integrity. In the SPS Performance Standard (PS), as well as the latest version of the Interface Specification (IS-GPS-200E), the GPS SPS SIS URE integrity standard assures that for any healthy SIS, there is an up-to- 10^{-5} probability over any hour of the URE exceeding the not-to-exceed (NTE) tolerance without a timely alert during normal operation. The NTE tolerance is currently defined to be 4.42 times the upper bound (UB) on the URA value broadcast by the satellite. Before September 2008, the NTE tolerance was defined differently, as the maximum of 30 meters and 4.42 times URA UB. The reason for the “magic” number 4.42 here is the Gaussian assumption of the URE, although this assumption may be questionable. (4.42 sigma corresponds to a probability level of 99.999 percent ($1 - 10^{-5}$)).

In this article, a GPS SPS SIS anomaly is defined as a threat of an SIS integrity failure; that is, a condition during which an SPS SIS marked healthy results in a URE exceeding the NTE tolerance. Because the definition of the NTE tolerance is different before and after September 2008, we consider both of the two NTE tolerances for the sake of completeness and consistency.

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 collecting, data cleansing, and anomaly screening.

In the first step, the navigation message data files are downloaded from the International GNSS Service (IGS). In addition, two different kinds of precise ephemeris/clock data are downloaded from IGS and the National Geospatial-Intelligence Agency (NGA), respectively. The details about these data sources 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 on the ground. This step distinguishes our work from that of most other researchers because the false anomalies due to corrupted data can be mostly precluded.

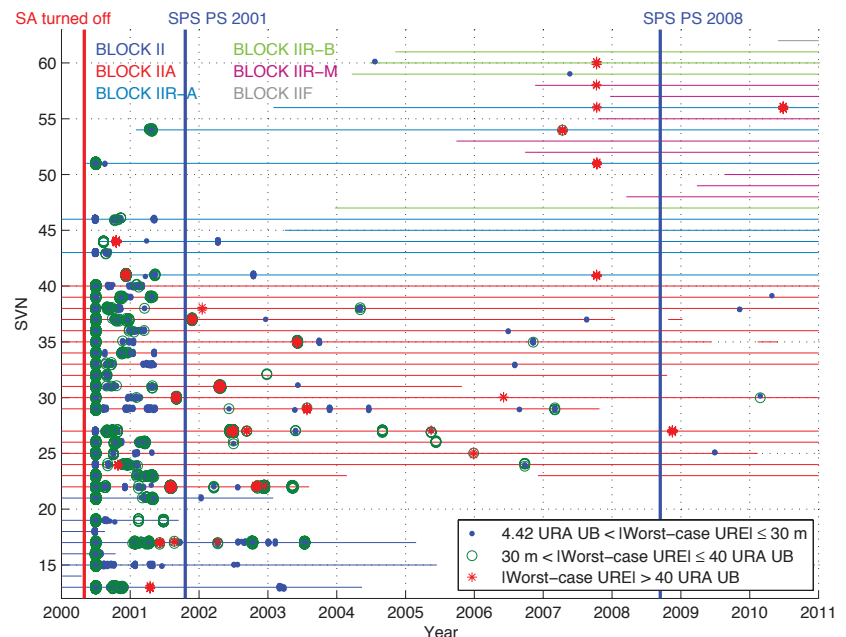
The last step is computing worst-case SIS UREs as well as determining potential SIS anomalies. The validated navigation messages prepared in the second step are used to propagate broadcast orbits/clocks at 15-minute intervals that coincide with the precise ones. A potential SIS anomaly is claimed when the navigation message is healthy and in its fit interval with the worst-case SIS URE exceeding the SIS URE NTE tolerance.

Data Sources

We obtained broadcast navigation message data and precise ephemeris and clock data from publicly available sources.

Broadcast Navigation Message Data.

Broadcast GPS navigation message data files are available at IGS Internet sites. All the data are archived in Receiver Independent Exchange (RINEX) navigation file format, which includes not only the ephemeris/clock parameters broadcast by the satellites but also some information produced by the ground receivers, such as the pseu-



▲ FIGURE 3 Potential SIS anomalies from June 1, 2000, to August 31, 2010. The horizontal lines depict the periods when the satellites were active (not necessarily healthy). The color of the lines indicates the satellites' block type, as explained by the top left legend.

dorandom noise (PRN) signal number and the transmission time of message (TTOM).

The IGS tracking network is made up of more than 300 volunteer stations all over the world (a map is shown in TABLE 1) ensuring seamless, redundant data logging. Since broadcast navigation messages are usually updated every two hours, no single station can record all navigation messages. For the ease of users, two IGS archive sites, the Crustal Dynamics Data Information System (CDDIS) and the Scripps Orbit and Permanent Array Center (SOPAC), provide two kinds of ready-to-use daily global combined broadcast navigation message data files, brdcd00.yyn and autodd0.yyn, respectively, where *ddd* is the day of year *yy*. Unfortunately, these files sometimes contain errors that can cause false anomalies.

Therefore, we devised and implemented a data-cleansing algorithm to generate the daily global combined navigation messages, which are as close as possible to the navigation messages that the satellites actually broadcast, from all available navigation message data files of all IGS stations. The data-cleansing algorithm is based on majority vote, and hence all values in our data are cross validated. Accordingly, we name our daily global combined navigation messages “validated navigation messages,” as shown in Figure 1.

Precise Ephemeris and Clock Data. Precise GPS ephemerides/clocks are generated by some organizations such as IGS and NGA that routinely post-process observation data. Precise ephemerides/clocks are regarded as “truth” because of their centimeter-level accuracy.

Table 1 shows a side-by-side comparison between IGS and NGA precise ephemeris/clock data, in which the green- and red-colored text implies pros and cons, respectively. For NGA data, the only con is that the data have been publicly available only since January 4, 2004. As a result, for the broadcast ephemerides/clocks before this date, IGS precise ephemerides/clocks are the only references. Nevertheless, care must be taken when using IGS precise ephemerides/clocks due to the follow-

ing three issues.

The first issue 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 percent bad/absent data means no precise ephemerides or clocks for approximately 10 satellite-hours per day. This issue can result in undetected anomalies (false negatives).

The second issue is that, as shown in the fourth row of Table 1, IGS switched to IGS Time for its precise ephemeris/clock data on 22 February, 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. Fortunately, the time offsets can be extracted from the IGS clock data files. Moreover, a similar problem is that IGS precise ephemerides use a frame aligned to the International Terrestrial Reference Frame (ITRF) whereas broadcast GPS ephemerides are based on the World Geodetic System 1984 (WGS 84). The differences between ITRF and the versions of WGS 84 used since 1994 are on the order of a few centimeters, and hence a transformation is not considered necessary for the purpose of our work.

The last, but not the least important, issue with the IGS precise ephemerides is that the data are provided only for the center of mass (CoM) of the satellite. Since the broadcast ephemerides are based on the satellite antenna phase center (APC), the CoM data must be converted to the APC before being used. Both IGS and NGA provide antenna corrections for every GPS satellite. Although the IGS and the NGA CoM data highly agree with each other, the IGS satellite antenna corrections are quite different from the NGA's, and the differences in z-offsets can be as large as 1.6 meters for some GPS satellites. The reason for these differences is mainly due to the different methods in producing the antenna corrections: the IGS antenna corrections are based on the statistics from more than 10 years of IGS data, whereas the NGA's are probably from the calibration measurements on the ground. In order to know



▲ FIGURE 4 Number of potential SIS anomalies per year. The SIS performance was improved during the past decade. There were 0 anomalies in 2009 according to SPS PS 2001 and this number is represented by 0.1 in the figure.

whose satellite antenna corrections are better, the broadcast orbits for all GPS satellites in 2009 were computed and compared with three different precise ephemerides: IGS CoM + IGS antenna corrections, IGS CoM + NGA antenna corrections, and NGA APC. Generally, the radial ephemeris error is expected to have a zero mean. However, the combination “IGS CoM + IGS antenna corrections” results in radial ephemeris errors with a non-zero mean for more than half of the GPS satellites. Therefore, the NGA antenna corrections were selected to convert the IGS CoM data to the APC.

Data Cleansing

FIGURE 2 shows a scenario of data cleansing. Owing to accidental bad receiver data and various hardware/software bugs, a small proportion of the navigation data files from the IGS stations have defects such as losses, duplications, inconsistencies, discrepancies, and errors. Therefore, more than just removing duplications, the generation of validated navigation messages is actually composed of two complicated steps.

First step. Suppose that we want to generate the validated navigation messages for day *n*. In the first step, we apply the following operations sequentially to each RINEX navigation data file from day *n* - 1 to day *n* + 1:

- 1) Parse the RINEX navigation file;
- 2) Recover least significant bit (LSB);
- 3) Classify URA values;
- 4) Remove the navigation messages not on day *n*;

Date/time	SVN	PRN	Duration	Anomaly†	URA UB (m)	References	NANU
2004-04-22 13:15	38	08	1.5 hours	clock 29.0 m	4.85	NGA	2004049
2004-05-03 11:15	38	08	15 minutes	clock -30.2 m	3.40	IGS, NGA	2004052
2004-05-05 08:30	38	08	1 hour	clock -29.5 m	2.40	NGA	2004054
2004-06-17 11:15	29	29	1.75 hours	ephemeris 13.0 m	2.40	IGS, NGA	2004071
2004-07-20 07:15	60	23	45 minutes	ephemeris 13.0 m	2.40	IGS, NGA	2004082
2004-08-29 00:45	27	27	2 hours	clock 70.4 m	3.40	IGS, NGA	2004099
2005-05-14 20:15	27	27	1.5 hours	clock 116 m	2.40	IGS, NGA	2005088
2005-06-09 03:45	26	26	1 hour	clock -37.9 m	3.40	IGS, NGA	2005093
2005-12-25 21:15	25	25	1 hour	clock 2.05 km	2.40	IGS, NGA	2005161
2006-06-02 20:30	30	30	30 minutes	clock -1045 m	2.40	NGA	2006052
2006-06-27 04:45	36	06	30 minutes	clock -10.8 m	2.40	IGS, NGA	
2006-07-31 22:15	33	03	1 hour	clock -12.7 m	2.40	IGS, NGA	
2006-08-25 12:30	29	29	1.5 hours	clock -11.6 m	2.40	IGS, NGA	
2006-09-22 19:45	24	24	2.75 hours	ephemeris 41.2 m	2.40	IGS, NGA	2006093
2006-11-07 01:45	35	05	3.75 hours	clock -30.7 m	2.40	IGS, NGA	2006139
2007-03-01 14:45	29	29	2.5 hours	clock -42.3 m	2.40	IGS, NGA	2007030
2007-04-10 16:00	54	18	1.75 hours	ephemeris 688 m	2.40	IGS, NGA	2007053
2007-05-20 03:45	59	19	15 minutes	ephemeris -13.3 m	2.40	IGS, NGA	
2007-08-17 07:30	37	07	30 minutes	clock -14.3 m	2.40	IGS, NGA	2007088
2007-10-08 09:45	58	12	2.25 hours	clock -86 km	2.40	NGA	2007119
2007-10-08 23:00	41	14	1.5 hours	clock -112 km	2.40	NGA	2007123
2007-10-09 09:45	60	23	1 hour	clock 27 km	6.85	NGA	2007125
2007-10-09 13:15	56	16	15 minutes	clock -18 km	4.85	IGS, NGA	2007127
2007-10-10 08:45	51	20	1.25 hours	clock 48 km	2.40	IGS, NGA	2007129
2008-11-14 05:45	27	27	3.75 hours	clock -70 km	2.40	NGA	2008137
2009-06-26 09:30	25	25	45 minutes	clock -22.3 m	2.40	NGA	2009037
2009-11-05 18:45	38	08	30 minutes	clock -18.5 m	2.40	IGS	2009111
2010-02-22 21:00	30	30	30 minutes	clock -42.9 m	3.40	NGA	2010035
2010-04-25 19:45	39	09	15 minutes	ephemeris 11 m	2.40	IGS, NGA	
2010-06-24 18:30	56	16	2 hours	clock 374 m	2.40	NGA	2010099

† "ephemeris" or "clock" means the anomaly is mainly due to broadcast ephemeris or clock inaccuracy, respectively.

▲ **TABLE 2** List of potential anomalies from January 4, 2004, to August 31, 2010.

5) Remove duplications;

6) Add all remaining navigation messages into the set O.

The reason why the data files from day $n - 1$ to day $n + 1$ are considered is that a few navigation messages around 00:00 can be included in some data files on day $n - 1$, and a few navigation messages around 23:59 can be included in some data files on day $n + 1$. The LSB recovery is used here to cope with the discrepant representations of floating-point numbers in RINEX navigation files. The URA classifier is employed to recognize and unify various representations of URA in the files. The duplication removal is applied because some stations write the same navigation messages repeatedly in one data file, which is unfavorable to the vote in the second step.

Second Step. At the end of the first step, we have a set O that includes all the navigation messages on day n . The set O still has duplications because a broadcast navigation message can be reported by many IGS stations. However, as shown in Figure 2, duplications of a broadcast navigation message may come with different errors and are not necessarily identical. Several other examples of such problems can be found in our journal paper listed in Further

Reading. Fortunately, most orbital and clock parameters are seldom reported incorrectly, and even when errors happen, few stations agree on the same incorrect value. In our work, these parameters are referred to as robust parameters. On the contrary, some parameters, such as TTOM, PRN, URA and issue of data clock (IODC), are more likely to be erroneous and when errors happen, several stations may make the same mistake. These parameters are referred to as fragile parameters. The cause of the fragility is either the physical nature (for example, TTOM, PRN) or the carelessness in hardware/software implementations (for example, URA, IODC).

Majority vote is applied to all fragile parameters (except TTOM, which is determined by another algorithm described in our journal paper) under the principle that the majority is usually correct. Meanwhile, the robust parameters are utilized to identify the equivalence of two navigation messages — two navigation messages are deemed identical if and only if they agree on all the robust parameters, although their fragile parameters could be different. Therefore, the goal of duplication removal and majority vote is a set P, in which any navigation message must

Year	sugl*	auto*	brdc*
2006	10.00	22.25	17.00
2007	11.25	225.00	131.25
2008	3.75	23.25	40.50
2009	0.75	52.00	125.75
Total	25.75	322.50	314.50

▲ **TABLE 3** Total hours of anomalies per year computed from three different kinds of daily global combined broadcast navigation messages.

have at least one robust parameter different from any other and has all fragile parameters confirmed by the largest number of stations that report this navigation message.

After the operations above, we have a set P in which there are no duplicated navigation messages in terms of robust parameters and all fragile parameters are as correct as possible. A few navigation messages in P still have errors in their robust parameters. These unwanted navigation messages feature a small number of reporting stations. Finally, the navigation messages confirmed by only a few stations being discarded and the survivors are the validated broadcast navigation messages, stored in files sugldddmm.yyn. For further details of our algorithms, see our journal paper.

Anomaly Screening

The validated broadcast navigation messages prepared using the algorithm described in the previous section were employed to propagate broadcast satellite orbits and clocks. For each 15-minute epoch, t , that coincides with precise ephemerides/clocks, the latest transmitted broadcast ephemeris/clock is chosen to calculate the worst-case SIS URE — the maximum SIS URE that a user on Earth can experience.

Finally, a potential GPS SIS anomaly is claimed when all of the following conditions are fulfilled.

- The worst-case SIS URE exceeds the NTE tolerance;
- The broadcast navigation message is healthy; that is,
 - The RINEX field SV health is 0, and
 - The URA UB ≤ 48 meters;
- The broadcast navigation message is in its fit interval; that is, $\Delta t = t - \text{TTOM} \leq 4$ hours;
- The precise ephemeris/clock is available and healthy.

Results

A total of 397,044,414 GPS navigation messages collected by an average of 410 IGS stations from June 1, 2000 (one month after turning off SA), to August 31, 2010, have been screened. The NGA APC precise ephemerides/clocks and the IGS CoM precise ephemerides/clocks with the NGA antenna corrections were employed as the truth references. Both old and new NTE tolerances were used for determining anomalies.

Before interpreting the results, it should be noted that there are some limitations due to the data sources and the anomaly-determination criteria. First, false anomalies may be claimed because there may be some errors in the precise ephemerides/clocks or the validated navigation messages. Second, some short-lived anomalies may not show up if they happen to fall into the 15-minute gaps of the precise ephemerides/clocks. Third, some true anomalies may not be detected if the precise ephemerides/clocks are temporarily missing. The third limitation is especially significant for the results before January 3, 2004, because only the IGS precise ephemerides/clocks are available, which feature a high rate of bad/absent data. (For example, the clock anomaly of Space Vehicle Number (SVN) 23/PRN23 that occurred on January 1, 2004 is missed by our process because the IGS precise clocks for PRN23 on that day were absent.) Last but not least, users might not experience some anomalies because a satellite was not trackable at that time, or the users were notified via a Notice Advisory to Navstar Users (NANU). (A satellite may indicate that it is unhealthy through the use of non-standard code or data. The authors' future work will include using observation data to verify the potential anomalies found in the results presented here.) Therefore, all the SIS anomalies claimed in this article are considered to be potential and under further investigation.

Potential SIS Anomalies. A total of 1,256 potential SIS anomalies were screened out under SPS PS 2008 (or 374 potential SIS anomalies under SPS PS 2001). **FIGURE 3** shows all these anomalies in a

Year-SVN plot. It can be seen that during the first year after SA was turned off, SIS anomalies occurred frequently for the whole constellation.

Moreover, 2004 is apparently a watershed: before 2004, anomalies occurred for all GPS satellites (except two satellites launched in 2003, SVN45/PRN21 and SVN56/PRN16) whereas after 2004, anomalies occurred much less frequently and more than 10 satellites have never been anomalous. **FIGURE 4** further confirms the improving GPS SIS integrity performance in the past decade, no matter which SPS PS is considered.

Therefore, it is possible to list all potential SIS anomalies from January 4, 2004, to August 31, 2010, in a compact table: **TABLE 2**. Most anomalies in the table have been confirmed by NANUs and other literature. The table reveals an important and exciting piece of information: never have two or more SIS anomalies occurred simultaneously since 2004. Accordingly, in the sense of historical GPS SIS integrity performance, it is valid for RAIM to assume at most one satellite fault at a time.

Validated Navigation Messages. For the purpose of comparison and verification, the IGS daily global combined broadcast navigation message data files brdcd00.yyn and autod00.yyn were used to propagate broadcast satellite orbits and clocks as well. The NGA APC precise ephemerides/clocks were employed for the truth references. The SPS PS 2008 NTE tolerance was used for determining anomalies. The other criteria for anomaly screening that are the same as in the previous section were still applied.

All the potential SIS anomalies for 2006–2009 were found based on the three kinds of daily combined broadcast navigation messages. **TABLE 3** shows a comparison of the total hours of the anomalies per year. It can be seen that brdcd00.yyn and autod00.yyn result in approximately 11 times more false anomalies than true ones. Moreover, all potential anomalies derived from sugld00.yyn are confirmed by brdcd00.yyn and autod00.yyn, which indicates that our sugld00.yyn does not intro-

duce any more false anomalies than brdcd00.yyn and autod00.yyn.

Conclusion

In this article, the GPS SIS integrity performance in the past decade was assessed by comparing the broadcast ephemerides/clocks with the precise ones. Thirty potential anomalies were found. The fundamental assumption of RAIM is valid based on a review of the GPS SIS integrity performance in the past seven years.

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