GPS Signal-in-Space Integrity Performance Evolution in the Last Decade

Data Mining 400,000,000 Navigation Messages from a Global Network of 400 Receivers

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Knowledge of the Global Positioning System (GPS) signal-in-space (SIS) anomalies in history has a great importance for not only assessing the general performance of GPS SIS integrity but also validating the fundamental assumption of receiver autonomous integrity monitoring (RAIM): at most one satellite fault at a time. The main purpose of this paper is to screen out all potential SIS anomalies in the last decade by comparing broadcast ephemerides and clocks with precise ones. Validated broadcast navigation messages are generated from 397,044,414 navigation messages logged by on average 410 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. Finally, 1256 potential SIS anomalies are screened out. These anomalies show an improving SIS integrity performance in the last decade, from tens or hundreds of anomalies per year before 2003 to on average two anomalies per year after 2008. Moreover, the fundamental assumption of RAIM is valid because never have two SIS anomalies or more occurred simultaneously since 2004.

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I. INTRODUCTION

The NAVSTAR Global Positioning System (GPS) 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 distance from a user receiver to at least four GPS satellites in view, as well as the positions and clocks of these satellites, are the prerequisites for the user receiver to fix its exact position [1]. 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 [2]. 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 meter level or even submeter level [3–6]. In practice, unfortunately, SIS anomalies happen occasionally and UREs of tens of meters or even more have been observed, which could lead to an SPS receiver generating a hazardous misleading position solution [7–9]. Receiver autonomous integrity monitoring (RAIM) or Advanced RAIM (ARAIM) 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 [10]. Knowledge about SIS anomalies in history is very important not only for assessing the GPS SIS integrity performance but also for validating the fundamental assumption of RAIM.

A typical method to calculate SIS UREs is comparing the broadcast ephemerides/clocks with the precise, postprocessed ones [3–5, 11, 12]. Although this method has been widely used to assess 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 [13] and these errors usually result in false SIS anomalies. In this paper we propose a systematic methodology to cope with this problem and screen out all the potential SIS anomalies in the last decade from when the selective availability (SA) was turned off.

We start with a few basic concepts of GPS SIS integrity in Section II. After a brief overview of the methodology in Section III, we elaborate on the data sources in Section IV, the data cleansing algorithm in Section V, and the anomaly screening method

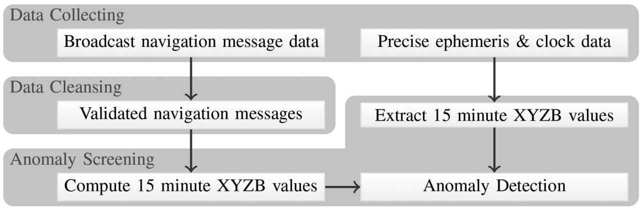


Fig. 1. Framework of the whole process.

in Section VI. In Section VII we present all the potential SIS anomalies found between 6/1/2000 and 8/31/2010, the statistics of these anomalies, and some statistics of our data cleansing algorithm. Finally, conclusions appear in Section VIII.

II. GPS SIS INTEGRITY

A. GPS SIS URE

As indicated by the name, GPS SIS URE is the pseudo-range inaccuracy attributable to the GPS ground control and the space vehicles. Specifically, SIS URE includes satellite ephemeris and clock errors, satellite antenna variations [14], and signal imperfections [15], but not ionospheric or tropospheric delay, multipath, or any errors due to user receivers. SIS URE is dominated by ephemeris and clock errors because antenna variations and signal imperfections are at a level of millimeter or centimeter [14, 15].

In broadcast navigation messages, there is a parameter called user ranging 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 of 2.0 m means that the 1-sigma URE is expected to be less than 2.4 m, and a URA of 2.8 m means that the 1-sigma URE is expected to be greater than 2.4 m but less than 3.4 m. In the past several years, most GPS satellites have a URA of 2.0 m.

B. GPS SPS SIS Integrity

In the SPS Performance Standard (PS) [16] as well as the latest version of the Interface Specification [17], 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 [16]. Before September 2008, the NTE tolerance was defined differently, as the maximum of 30 m and 4.42 times URA UB [18]. The reason for the “magic” number 4.42 here is the Gaussian assumption of the URE, although this assumption may be questionable [19].

In this paper, a GPS SPS SIS anomaly is defined as a threat to an SIS integrity failure, i.e., a condition during which a healthy SPS SIS results in a URE exceeding the NTE tolerance. Since the definition of the NTE tolerance is different before and after September 2008, both of the two NTE tolerances are considered for the sake of completeness and consistency.

III. METHODOLOGY

The SIS anomalies are screened out by comparing broadcast ephemerides/clocks with precise ones. As shown in Fig. 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) [20]. In a addition, two different kinds of precise ephemeris/clock data are downloaded from IGS and the National Geospatial-Intelligence Agency (NGA) [21], respectively. The details about these data sources are discussed in Section IV.

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 [3–5, 11, 12] 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-min 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.

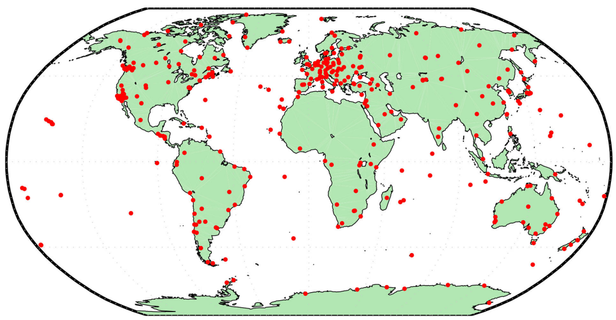
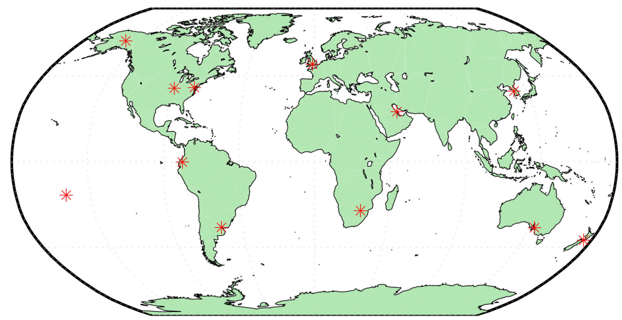
The details of the algorithms mentioned above are discussed thoroughly in Section V and Section VI.

IV. DATA SOURCES

A. Broadcast Navigation Message Data

Broadcast GPS navigation message data files are publicly available at the IGS website [22]. All the data are archived in receiver independent exchange (RINEX) n-type format [23], which includes not only the ephemeris/clock parameters broadcast by the satellites but also some information produced by the ground receivers, such as the pseudorandom 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 Fig. 2) ensuring seamless, redundant data logging. Since broadcast navigation messages are usually updated every 2 hr, no single station can record all navigation messages. For the ease of users, two IGS archive sites, Crustal Dynamics Data Information System (CDDIS) and Scripps Orbit and

IGS tracking network	NGA tracking network
	
Publicly available data since 1994 or earlier	Publicly available data since 2004
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

Fig. 2. Comparison of IGS and NGA precise ephemeris/clock data.

Permanent Array Center (SOPAC), provide two kinds of ready-to-use daily global combined broadcast navigation message data files, `brdc`*ddd*`0.`*yy*`n` [24] and `auto`*ddd*`0.`*yy*`n` [25], respectively. Unfortunately, these files sometimes contain errors that can cause false anomalies.

Therefore, we devise and implement 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 the our data are cross validated. Accordingly, we name our daily global combined navigation messages "validated navigation messages," as shown in Fig. 1. The data cleansing algorithm is explained in detail in Section V.

B. Precise Ephemeris and Clock Data

Precise GPS ephemerides/clocks are generated by some organizations such as IGS and NGA which routinely postprocess observation data. Precise ephemerides/clocks are regarded as truth since they are an order of magnitude or more accurate than the broadcast ephemerides/clocks [26].

Figure 2 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 since 1/4/2004 [21]. As a result, for the broadcast ephemerides/clocks before 1/3/2004, IGS precise ephemerides/clocks are the only references. Nevertheless, care must be taken when using IGS precise ephemerides/clocks due to the following 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 Fig. 2. For a GPS constellation of 27 healthy satellites, 1.5% 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 Fig. 2, IGS switched to IGS time for their precise ephemeris/clock data on 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 m [5]. Fortunately, the time offsets can be extracted from the IGS clock data files. Moreover, a similar problem is that IGS precise ephemerides use 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 WGS 84 are on the order of a few centimeters [27] and hence a transformation is not considered necessary for the purpose of this paper.

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). Since the broadcast ephemerides are based on the antenna phase center (APC), the CoM data must be converted into the APC before being used. Both IGS and NGA provide antenna corrections for every GPS satellite [28, 29]. Although the IGS and the NGA CoM data highly agree with each other, the IGS satellite antenna corrections are quite different from the NGAs, and

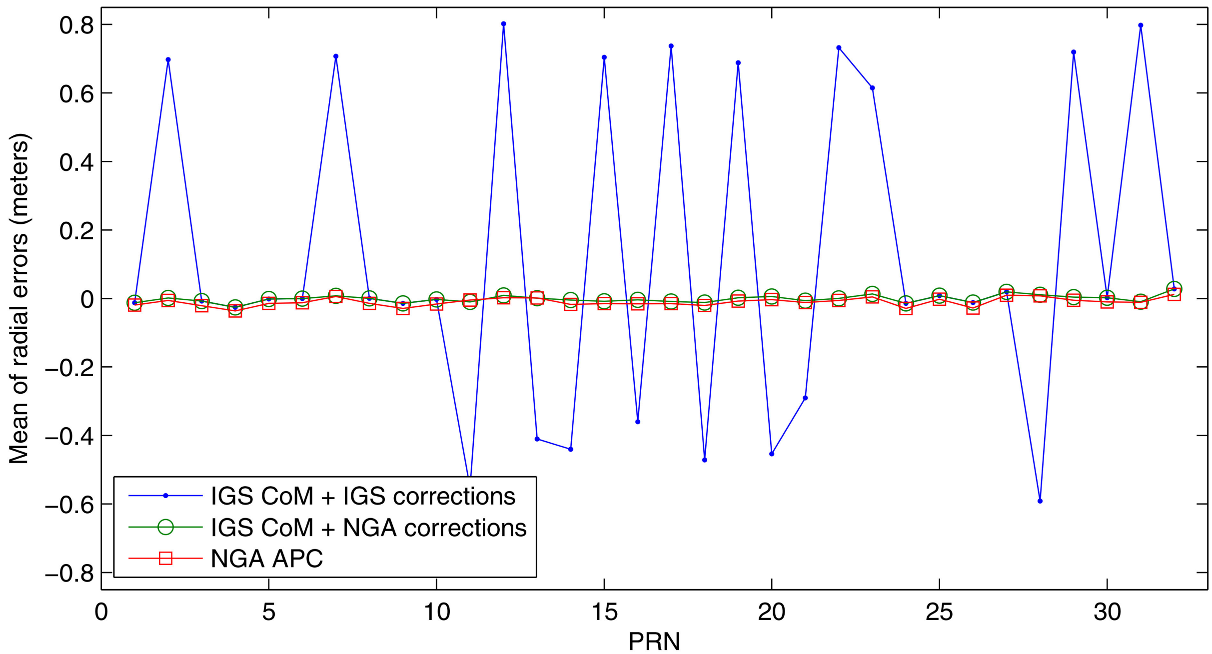


Fig. 3. Truncated mean of radial ephemeris error for all GPS satellites in 2009 using three different precise ephemerides. The NGA antenna corrections work better than those of IGS.

the differences in z-offsets can be as much as 1.6 m for some GPS satellites [30]. 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 yr of IGS data, whereas the NGAs are probably from the calibration measurements on the ground [30]. In order to know whose satellite antenna corrections are better, the broadcast orbits for all GPS satellites in 2009 are computed and compared with three different precise ephemerides: IGS CoM + IGS antenna corrections, IGS CoM + NGA antenna corrections, and NGA APC. The truncated mean[1] of the radial ephemeris error for each satellite is plotted in Fig. 3. Generally, the radial ephemeris error is expected to have a zero mean, just as the green curve "IGS CoM + NGA antenna corrections" and red curve "NGA APC" in Fig. 3. However, the combination "IGS CoM + IGS antenna corrections" results in radial ephemeris errors with a non-zero mean for more than a half GPS satellites. Therefore, the NGA antenna corrections are selected to convert the IGS CoM data into the APC.

V. DATA CLEANSING

Figure 4 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.

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 navigation data file from Day $n-1$ to Day $n+1$:

1) Parse the RINEX n-type file;
2) Recover least significant bit (LSB);
3) Classify URA values;
4) Remove the navigation messages not on Day n;
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 duplication removal is applied here because some stations write the same navigation messages again and again in one data file, which is unfavorable to the vote in the second step. The details about LSB recovery, URA classification, and duplication removal are explained in Section V-A, V-B, and V-C, respectively.

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. The same duplication removal algorithm as the first step (Section V-C) is applied again to remove

[1]In producing Fig. 3, 20% of ends are discarded in order to exclude anomalies or outliers. Truncated mean is also known as trimmed mean or Windsor mean.

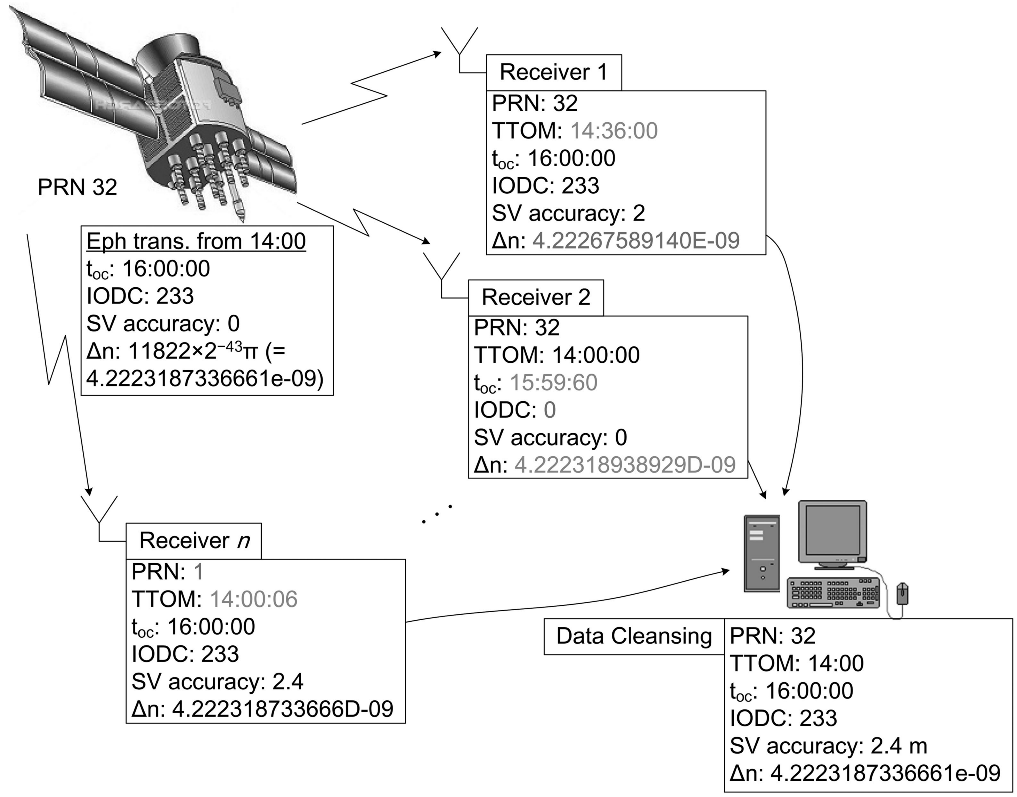


Fig. 4. Scenario of data cleansing. In the figure, GPS satellite PRN 32 started to transmit new navigation message at 14:00. Receiver 1 had not observed the satellite until 14:36, and hence TTOM in its record was 14:36. Additionally, receiver 1 made a one-bit error in Δn ($4.22267589140 \times 10^{-9} \doteq 11823 \times 2^{-43}\pi$). Receiver 2 perhaps had some bugs in its software: the IODC was unreported and both t_{oc} and Δn were written weirdly. Receiver n used incorrect ranging code, PRN 1, to despread and decode signal of PRN 32; fortunately, all parameters except TTOM were perfectly recorded. Moreover, three receivers interpreted URA (space vehicle (SV) accuracy) differently. A computer equipped with our data cleansing algorithms is used to process all data from receivers. Receiver-caused errors are removed and original navigation message is recovered.

all the duplications and to vote correct parameters. Then the TTOM is found for each navigation message (Section V-D). Finally, the correct navigation messages are determined and the navigation messages confirmed by only a few stations are discarded (Section V-E).

A. LSB Recovery

The ephemeris and clock parameters in broadcast navigation messages are fixed-point numbers $\alpha \times 2^{\beta}$, where α is a signed or unsigned γ-bit integer and 2^{β} is the scale factor (LSB). The LSB exponent β and the number of bits γ may vary from parameter to parameter and the maximum value of γ is 32. In RINEX n-type format, however, all the parameters are described by 12-decimal-digit floating-point numbers. In spite of the fact that the 12 digits are precise enough to represent a parameter with even 32-bit precision, due to various software implementations, the real data files may look like the first example in Table I. Another example of an apparent mismatch, as shown in Fig. 4, is the ephemeris parameter Δn, `4.222318938929D-09` in the file `strl3640.08n` versus `4.222318733666D-09` in the file `syog3640.08n`. They look different but are actually the same because Δn in the navigation message has only a 16-bit precision.

To solve this problem, an LSB recovery algorithm is employed, in which all the floating-point ephemeris/clock parameters are converted to the closest $\alpha \times 2^{\beta}$ as they were in the navigation message and then converted back to double precision floating-point numbers. After this process, any two virtually equal representations of floating-point numbers are converted into identical floating-point numbers in computer memory.

B. URA Classification

As mentioned in Section II, URA is the 1-sigma estimate of the SIS URE. In navigation messages, URA is represented by a 4-bit unsigned index[2] [16, 18]. In RINEX n-type format, URA values in meters have been preferred since 1993 [23]. However, some IGS stations still use URA indices in their data files. Even worse, one URA index corresponds to three possible values in meters: the typical, the lower bound of, and the upper bounds of expected URE

[2]There is a plan to extend the URA index to a 5-bit signed integer in order to represent submeter accuracy. [17]

TABLE I
Examples of Inconsistencies/Errors/Losses in Navigation Message Data Files

1) Various floating-point representations of the same parameter values

```
ffmj0190.09n: 17  9 1 19 2 0 0.0 0.446424819529E-04 0.909494701773E-12 0.000000000000E+00
ganp0190.09n: 17 09 1 19 2 0 0.0 4.464248195291D-05 9.094947017729D-13 0.000000000000D+00
glsv0190.09n: 17 09 1 19 2 0 0.0 4.464250000000D-05 9.094950000000D-13 0.000000000000D+00
```

2) Incorrect PRN number

```
adis2000.08n (Line 186-188):
32 8 7 18 3 59 44.0    0.307788141072E-03 0.284217094304E-11 0.000000000000E+00
   0.420000000000E+02 0.883750000000E+02 0.394552148966E-08 0.291634527708E+01
   0.458024442196E-05 0.139177759411E-01 0.104866921902E-04 0.515382606506E+04
ffmj2000.08n (Line 202-204):
 1 8 7 18 3 59 44.0    0.307788141072E-03 0.284217094304E-11 0.000000000000E+00
   0.420000000000E+02 0.883750000000E+02 0.394552148966E-08 0.291634527708E+01
   0.458024442196E-05 0.139177759411E-01 0.104866921902E-04 0.515382606506E+04
```

3) Incorrect/inconsistent time of clock (t_{OC})

```
davr0140.08n: 15 08 1 14  9 59 44.0  -.714603811502D-04  -.102318153949D-11  .000000000000D+00
glsv0140.08n: 15  8 1 14  9 59  4.0 -0.714604000000E-04 -0.102318000000E-11 0.000000000000E+00
bucu0020.08n: 18  8 1  2 10  0  0.0 -2.151140943170D-04  2.728484105319D-12 0.000000000000D+00
trev0020.08n: 18  8 1  2  9 59 60.0 -2.151140943170D-04  2.728484105319D-12 0.000000000000D+00
```

4) Unreported issue of data, clock (IODC) and URA:

```
zouf3410.07n (Line 1407-1414):
1 07 12 7 22 0 0.0 1.711458899081D-04 2.387423592154D-12 0.000000000000D+00
  9.000000000000D+00-1.070312500000D+02 3.856232056115D-09 -1.532781392555D+00
                        ... ... (4 lines omitted) ... ...
  2.000000000000D+00 0.000000000000D+00-3.725290298462D-09 9.000000000000D+00
  5.040000000000D+05 4.000000000000D+00
bucu3410.07n (Line 1420-1427):
1 7 12 7 22 0 0.0 1.711458899081D-04 2.387423592154D-12 0.000000000000D+00
  9.000000000000D+00-1.070312500000D+02 3.856232056115D-09-1.532781392555D+00
                        ... ... (4 lines omitted) ... ...
  0.000000000000D+00 0.000000000000D+00 0.000000000000D+00 0.000000000000D+00
  5.112000000000D+05 0.000000000000D+00 0.000000000000D+00 0.000000000000D+00
```

[16–18]. An interesting example of this chaos is from CDDIS brdc*ddd*0.*yy*n files. In brdc1290.07n, all the URA values are in the set $\{2, 2.8, 4, 5.7, 8\}$, which are the typical expected UREs in meters. Just one day later, in brdc1300.07n, all the URA values are in the set $\{0, 1, 2, 3, 4, 8\}$, which should be the URA indices.

Fortunately, the usage of URA in a single data file is usually consistent. Therefore, this problem can be solved by a simple pattern-recognition-based 6-step classifier: the URA values in a data file are

1) the typical expected URE if all the URA values that are not greater than 4096 are in the set $\{2, 2.8, 4, 5.7, \ldots, 4096\}$;
2) the upper bounds of expected URE if all the URA values that are not greater than 6144 are in the set $\{2.4, 3.4, 4.85, 6.85, \ldots, 6144\}$;
3) the lower bounds of expected URE if all the URA that are not greater than 3072 are in the set $\{0, 2.4, 3.4, 4.85, \ldots, 3072\}$;
4) the URA indices offset by +1 if all the URA values are in the set $\{1, 2, 3, \ldots, 16\}$;
5) the URA indices if all the URA values are in the set $\{0, 1, 2, 3, \ldots, 15\}$;
6) unknown URA representations.

The unknown URA representations are still regarded as the URA in meters and quantized to the nearest typical expected UREs.

Admittedly, this simple sequential classifier is not a panacea. For an extreme example, a data file including the URA indices only in the set $\{2, 4, 8\}$ will be incorrectly classified as the typical expected URE. However, this situation is rare in the real world and the majority vote algorithm in Section V-C can correct these errors. Hence, although a more sophisticated classifier based on the historical statistics of each station could be considered, the resulting performance improvement is too marginal to be worthy of the computational complexity.

C. Duplication Removal and Majority Vote

Data cleansing is the most complicated step in the whole process, while duplication removal and majority vote is the most complicated operation in data cleansing. As mentioned at the beginning of this section, duplication removal and majority vote play a dual role. The first role is removing the duplicated navigation messages from one station because a few IGS stations write several copies of

TABLE II
Procedure for Finding the Correct TTOM

Operation Steps	Examples
0) Original TTOMs (sorted)	[99012 115200 115212 115230 115230 115230 115230 122400]
1) Round to the nearest previous 30 s epoch	[**99030** 115200 **115200** 115230 115230 115230 115230 122400]
2) Find the median value m	[99030 115200 115200 **115230** **115230** 115230 115230 122400]
3) Discard all the values earlier than $m-7200$ or later than $m+7200$	[~~99030~~ 115200 115200 115230 115230 115230 115230 122400]
4) Find the earliest value confirmed by 2 stations or more	[~~99030~~ **115200** **115200** 115230 115230 115230 115230 122400]

a single navigation message into one data file. This phenomenon violates the basic vote rule that each station has one ballot for one navigation message. The second role is removing the duplicated navigation messages from the set O (please refer to the beginning of Section V for the definition of the set O). Because different stations may have different interpretations of a single broadcast navigation message, the second role is more challenging, as described in Table II.

After the LSB recovery and the URA classification, there are still some errors and inconsistencies in the set O. Jefferson and Bar-Sever [13] have reported a few such problems. Several examples of other typical problems are shown in Table I. Fortunately, most orbital and clock parameters in navigation message data files are usually reported correctly, and even when errors happen, merely a few stations agree on the same incorrect value. In this paper, 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 fragile parameters is either the physical nature (e.g., TTOM, PRN) or the carelessness in hardware/software implementations (e.g., URA, IODC).

Majority vote is applied to all fragile parameters except TTOM (the correct TTOM is found by a more sophisticated algorithm described in Section V-D) 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 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. P can be built by the algorithm below.

1) Initialize P to an empty set;

2) For each navigation message e in O, if there is already a navigation message f in P having the same robust parameters as e then add the fragile parameters of e into f's database; otherwise, add e into P;

3) For each navigation message f in P, vote each fragile parameter (except TTOM) according to f's database, and record the number of stations that report f.

D. Finding the Correct TTOM

TTOM is not a parameter in the broadcast navigation message but is recorded by each tracking station whenever it receives a new navigation message. It is important and necessary to identify the correct TTOM because it determines which navigation message should be used in computing broadcast satellite orbits and clocks. Because the IGS stations are not evenly distributed on the Earth and some stations occasionally report an incorrect TTOM earlier than the real one, the correct TTOM cannot be simply determined by finding either the most popular one or the earliest one. A more sophisticated procedure is proposed to solve this problem, as shown in Table II.

The reason for the first step is that each frame begins at the 30-s epoch. In the second step, median is used rather than mean because mean is very sensitive to outliers. The third step eliminates outliers by discarding the values earlier than $m-7200$ or later than $m+7200$ because the navigation message is usually updated every 2 hr. The last step requires the confirmation of at least 2 stations in order to eliminate any remaining outliers.

E. Minority Discard

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. Nevertheless, it is not easy to set an appropriate threshold n_{th}, and delete all the navigation messages confirmed by n_{th} stations or less, because the IGS stations are not evenly distributed and sometimes a correct navigation message may be confirmed by a handful of stations. If n_{th} is too large, correct navigation messages may be discarded; if n_{th} is too small, incorrect navigation messages may be kept. Hence, a uniqueness criterion is helpful to determine the correct navigation messages.

IODC is a good candidate for the uniqueness criterion. According to the GPS interface specification [17], for each GPS satellite, the transmitted IODC is expected to be different from any IODC transmitted during the proceeding seven days. Therefore, all navigation messages in P are screened; whenever several navigation messages have the same PRN and IODC, only the one confirmed by the largest number of stations is kept, whereas the others are discarded.

This IODC-based method is effective in most cases. However, the real GPS system is not as ideal as defined in the specification. As shown in [31], an IODC may be occasionally reused by a satellite within a day. In such cases, the IODC-based method may discard some correct navigation messages. Thus, t_{OC} is chosen as a backup candidate for the uniqueness criterion. Because the probability that two different navigation messages have the same IODC and t_{OC} is very small, the correct navigation messages discarded by the IODC-based method can be retrieved by the t_{OC}-based method.

Since the most incorrect navigation messages are excluded by the uniqueness criterion, a small threshold, e.g., $n_{th} = 9$, is used to remove all remaining incorrect navigation messages.

Finally, two versions of validated broadcast navigation messages, `sugl`*`ddd`*`0.`*`yy`*`n` and `sugl`*`ddd`*`1.`*`yy`*`n`,[3] based on the IODC uniqueness criterion and the t_{OC} uniqueness criterion, respectively, are generated and saved in RINEX n-type format. In the `sugl`*`ddd`*`m.`*`yy`*`n` files, we take advantage of the last two spare fields in RINEX n-type format to store the following creditability information:

$$f_1 = t_0 + t_2/t_0, \qquad f_2 = t_1 + t_3/t_0$$

where t_0 is the total number of stations that report the navigation messages with the same PRN and IODC/t_{OC}, t_1 is the number of stations that report the most common received navigation message (the one kept in `sugl`*`ddd`*`m.`*`yy`*`n`), t_2 is the number of stations that report the second most common navigation message (discarded), and t_3 is the number of stations that report the third most common (discarded, too). By the above definition, four integers, $t_0, \ldots t_3$, are able to be stored in two fields. A large t_0 with $t_1 \approx t_0$, $t_2 \ll t_1$, and $t_3 \ll t_1$ indicates high creditability of this navigation message. Conversely, $t_2 \approx t_1$ may indicate something wrong, such as an IODC reuse problem [31].

VI. ANOMALY SCREENING

The validated broadcast navigation messages prepared in Section V are employed to propagate broadcast satellite orbits and clocks using the algorithm in [17]. For each 15-min epoch t that coincides with precise ephemerides/clocks, the latest transmitted broadcast ephemeris/clock is chosen to calculate SIS URE.

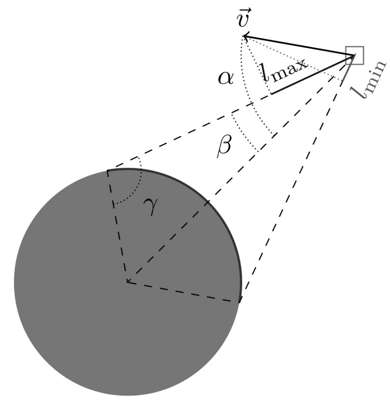


Fig. 5. Geometric method to calculate worst-case SIS URE.

The worst-case SIS URE can be calculated either numerically or analytically. The numerical grid-based method is as follows.

1) Generate a uniform grid over the Earth;
2) For each satellite at each epoch,
   a) Compute the instantaneous URE for the receiver at the nodes in the footprint of the satellite;
   b) Find the URE with the greatest absolute value.

This method is accurate as long as the grid is dense enough; a dense grid, however, means a significant computational burden. Accordingly, the analytical geometric method is preferred. As shown in Fig. 5, we assume the Earth is a perfect sphere and then:

1) Find the plane (as shown) that contains the center of the Earth and the ephemeris error vector $\vec{v}$;

2) Find α using the inner product, and find β using the law of sines (please note that $\gamma = 90° +$ mask angle);

3) Find the maximum and the minimum projection of $\vec{v}$ in the cone:

$$l_{\max} = \max_{|\theta| \le \beta} |v| \cos(\alpha + \theta)$$

$$l_{\min} = \min_{|\theta| \le \beta} |v| \cos(\alpha + \theta);$$

4) Find $l_{\max} - c\Delta B$ and $l_{\min} - c\Delta B$, where c is the speed of light and ΔB is the satellite clock correction. The one with the greatest absolute value is the maximum pseudo-range error, i.e., the worst-case SIS URE.

The geometric method outperforms the grid-based method in terms of the accuracy-complexity ratio. A flaw of this method is the assumption of a perfect sphere for the Earth. Fortunately, the resulting approximation error is not more than 0.6%, so we need not bother to model the Earth as an ellipsoid.

[3]The filename follows the convention of RINEX format. The prefix `sugl` stands for Stanford University GPS Laboratory.

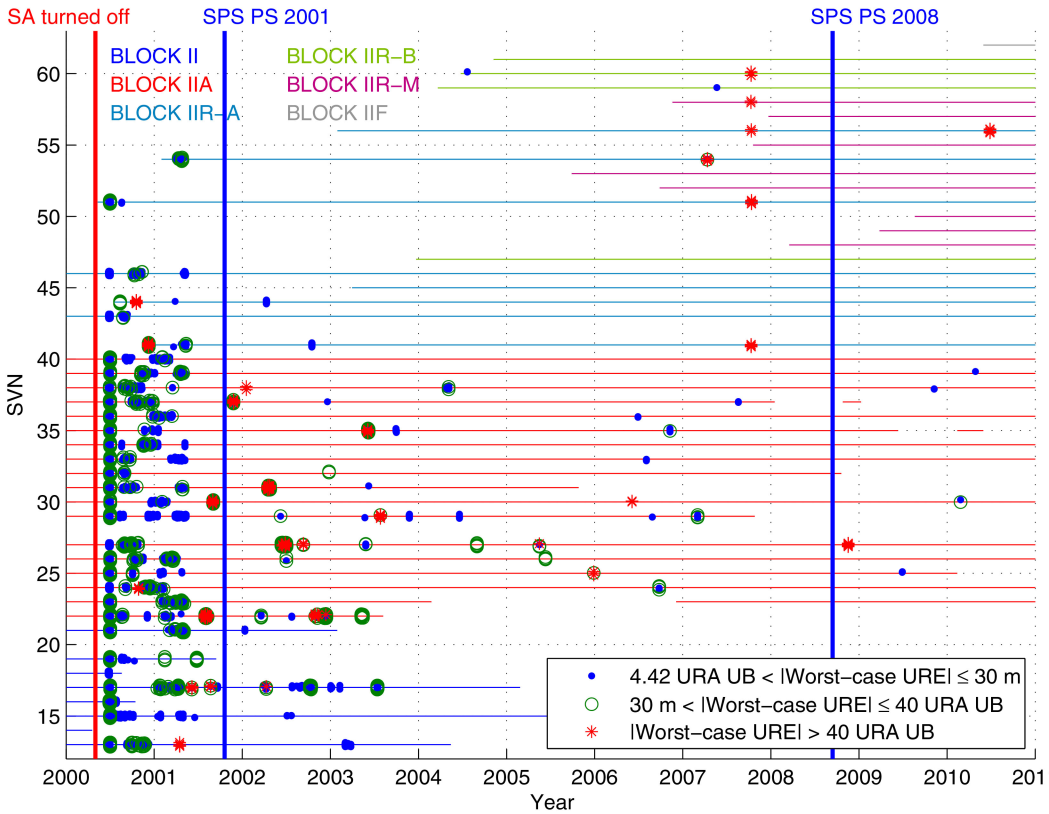


Fig. 6. Potential SIS anomalies from 6/1/2000 to 8/31/2010. Horizontal lines depict periods when satellites were active (not necessarily healthy). Color of lines indicates satellites block type, as explained by top left legend.

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

1) the worst-case SIS URE exceeds the NTE tolerance;

2) the broadcast navigation message is healthy, i.e.,
the RINEX field `SV health` [23] is 0,
the URA UB $\leq$ 48 m [16];

3) the broadcast navigation message is in its fit interval, i.e., $\Delta t = t - \mathrm{TTOM} \leq 4$ hr;

4) the precise ephemeris/clock is available and healthy.

VII. RESULTS

A total of 397,044,414 GPS navigation messages collected by on average 410 IGS stations from 6/1/2000 (one month after turning off SA) to 8/31/2010 have been screened. The NGA APC precise ephemerides/clocks and the IGS CoM precise ephemerides/clocks with the NGA antenna corrections are employed as the truth references. Both old and new NTE tolerances [16, 18] are 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 criterions. 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 happened to fall into the 15-min 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 1/3/2004, because only the IGS precise ephemerides/clocks are available, which feature a high rate of bad/absent data.[4] Last but not least, users might not experience some anomalies because the satellites was not trackable[5] at that time, or the users were notified via the Notice Advisory to NAVSTAR Users (NANU) [34]. Therefore, all the SIS anomalies claimed in this paper are potential and under further investigation.

A. Potential SIS Anomalies in the Last Decade

A total of 1256 potential SIS anomalies is screened out per SPS PS 2008 (or 374 potential SIS anomalies per SPS PS 2001). Figure 6 shows all these anomalies

[4]For example, the clock anomaly of space vehicle number (SVN) 23/PRN 23 occurred on 1/1/2004 [9, 32] is missed by our process because the IGS precise clocks for PRN 23 on that day were absent.

[5]A satellite may indicate that it is unhealthy through the use of nonstandard code or data [16, 33]. The authors' future work will include using observation data to verify the potential anomalies found in this paper.

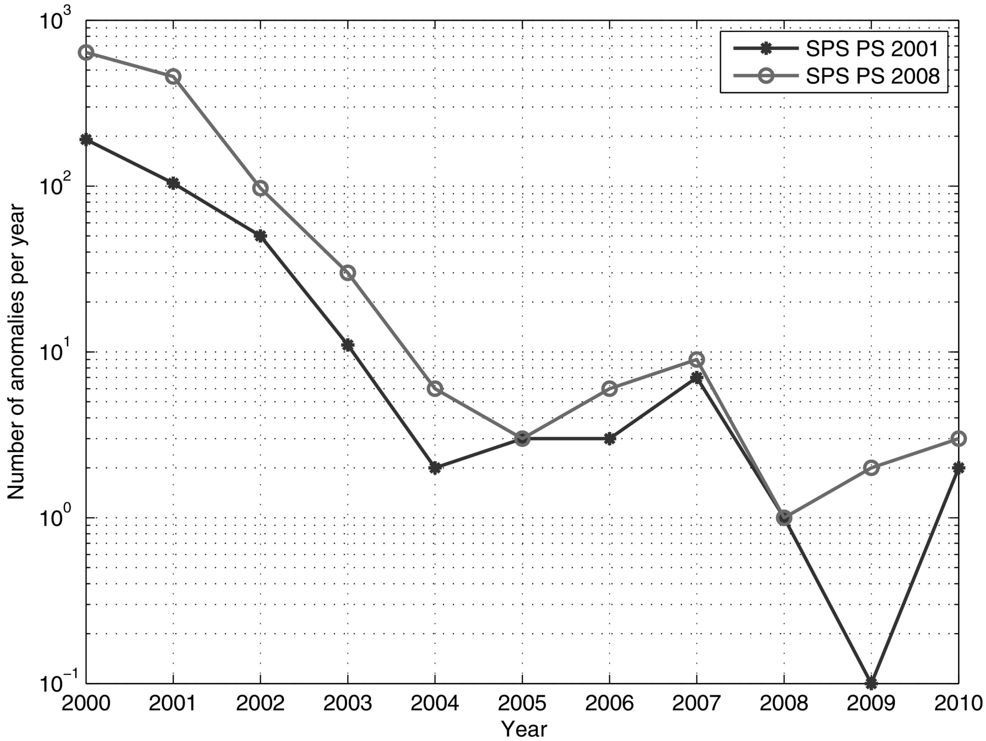


Fig. 7. Number of potential SIS anomalies per year. SIS performance was improved during last decade. There was 0 anomaly in 2009 according to SPS PS 2001 [18] and this number is represented by 0.1 in the figure.

in a year-SVN plot. In the figure, the horizontal lines depict the periods when the satellites were active (not necessarily healthy). In addition, the color of the lines indicates the satellites block type. Markers of blue dots represent the small anomalies with worst-case SIS UREs less than 30 m, which, although violating the SIS URE integrity standard in SPS PS 2008 [16], are not regarded as anomalies per the SPS PS 2001 [18]. Markers of green circles and red stars represent the medium and large anomalies, which are anomalies even according to the SPS PS 2001 [18]. It can be seen that during the first year after SA was turned off, SIS anomalies occurred frequently for the whole constellation. The authors have attempted to discuss the cause of some of these anomalies in [39].

Moreover, 2004 is apparently a watershed: before 2004 anomalies occurred for all GPS satellites (except two satellites launched in 2003, SVN 45/PRN 21 and SVN 56/PRN 16) whereas after 2004 anomalies occurred much less frequently and more than 10 satellites have never been anomalous. Figure 7 further confirms the improving GPS SIS integrity performance in the last decade, no matter which SPS PS is considered.

Therefore, it is possible to list all potential SIS anomalies from 1/4/2004 to 8/31/2010 on just half a page (Table III). Most anomalies in the table have been confirmed by NANUs and other literature. Table III reveals an important and exciting piece of information: never have two SIS anomalies or more 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.

B. Cumulative Distribution of Anomalous Worst-Case SIS URE

Figure 8 shows the cumulative distribution of the anomalous worst-case SIS UREs for the last decade. For any real number $x \geq 4.42$, the curve gives the empirical probability that the worst-case SIS URE is greater than $x \cdot$ URA UB. The red curve shows that, per SPS PS 2008 [16], approximately 10% of the anomalies result in worst-case SIS URE greater than 10 times URA UB, and approximately 1% of the anomalies result in worst-case SIS URE greater than 100 times URA UB. Since many small anomalies are not regarded as anomalies per SPS PS 2001 [18], the blue curve shows that approximately 10% of the anomalies result in worst-case SIS URE greater than 100 times URA UB.

C. Statistics of Data Cleansing for 2009

Table IV shows some statistics of the data cleansing for 2009. Three hundred and sixty-five validated navigation message data files are generated from 118,674 raw data files from all IGS stations, in which 0.34% records have errors and are discarded. The ephemeris/clock parameter error ratio indicates some parameters, such as clock bias, SV accuracy, SV healthy, and TTOM, have more tendency to be erroneous. Besides, the error ratio for most robust

TABLE III
List of Potential SIS Anomalies from 1/4/2004 to 8/31/2010

Date/time	SVN	PRN	Duration	Anomaly†	URA UB (m)	References	NANU	Literature
2004-04-22 13:15	38	08	1.5 hr	clock 29.0 m	4.85	NGA	2004049	
2004-05-03 11:15	38	08	15 min	clock −30.2 m	3.40	IGS, NGA	2004052	
2004-05-05 08:30	38	08	1 hr	clock −29.5 m	2.40	NGA	2004054	
2004-06-17 11:15	29	29	1.75 hr	ephemeris 13.0 m	2.40	IGS, NGA	2004071	
2004-07-20 07:15	60	23	45 min	ephemeris 13.0 m	2.40	IGS, NGA	2004082	
2004-08-29 00:45	27	27	2 hr	clock 70.4 m	3.40	IGS, NGA	2004099	[32], [35]
2005-05-14 20:15	27	27	1.5 hr	clock 116 m	2.40	IGS, NGA	2005088	
2005-06-09 03:45	26	26	1 hr	clock −37.9 m	3.40	IGS, NGA	2005093	[5]
2005-12-25 21:15	25	25	1 hr	clock 2.05 km	2.40	IGS, NGA	2005161	
2006-06-02 20:30	30	30	30 min	clock −1045 m	2.40	NGA	2006052	[5]
2006-06-27 04:45	36	06	30 min	clock −10.8 m	2.40	IGS, NGA		
2006-07-31 22:15	33	03	1 hr	clock −12.7 m	2.40	IGS, NGA		[5]
2006-08-25 12:30	29	29	1.5 hr	clock −11.6 m	2.40	IGS, NGA		[5]
2006-09-22 19:45	24	24	2.75 hr	ephemeris 41.2 m	2.40	IGS, NGA	2006093	[5]
2006-11-07 01:45	35	05	3.75 hr	clock −30.7 m	2.40	IGS, NGA	2006139	[5]
2007-03-01 14:45	29	29	2.5 hr	clock −42.3 m	2.40	IGS, NGA	2007030	[5], [36]
2007-04-10 16:00	54	18	1.75 hr	ephemeris 688 m	2.40	IGS, NGA	2007053	[5], [32], [36], [37]
2007-05-20 03:45	59	19	15 min	ephemeris −13.3 m	2.40	IGS, NGA		
2007-08-17 07:30	37	07	30 min	clock −14.3 m	2.40	IGS, NGA	2007088	[5], [12]
2007-10-08 09:45	58	12	2.25 hr	clock −86 km	2.40	NGA	2007119	[38]
2007-10-08 23:00	41	14	1.5 hr	clock −112 km	2.40	NGA	2007123	[38]
2007-10-09 09:45	60	23	1 hr	clock 27 km	6.85	NGA	2007125	[38]
2007-10-09 13:15	56	16	15 min	clock −18 km	4.85	IGS, NGA	2007127	[38]
2007-10-10 08:45	51	20	1.25 hr	clock 48 km	2.40	IGS, NGA	2007129	[38]
2008-11-14 05:45	27	27	3.75 hr	clock −70 km	2.40	NGA	2008137	
2009-06-26 09:30	25	25	45 min	clock −22.3 m	2.40	NGA	2009037	[32]
2009-11-05 18:45	38	08	30 min	clock −18.5 m	2.40	IGS	2009111	[32]
2010-02-22 21:00	30	30	30 min	clock −42.9 m	3.40	NGA	2010035	
2010-04-25 19:45	39	09	15 min	ephemeris 11 m	2.40	IGS, NGA		
2010-06-24 18:30	56	16	2 hr	clock 374 m	2.40	NGA	2010099	

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

parameters is on the order of 10^{-5}, and the parameters with a greater number of bits are slightly more likely to go wrong. It should be noted that since PRN and IODC are selected as the uniqueness criterion, they have zero error ratio here, but in reality they tend to be erroneous.

D. Excellence of our Validated Navigation Messages

For the purpose of comparison and verification, the IGS daily global combined broadcast navigation message data files `brdcddd0.yyn` and `autoddd0.yyn` are used to propagate broadcast satellite orbits and clocks as well. The NGA APC precise ephemerides/clocks are employed for the truth references. The SPS PS 2008 NTE tolerance [16] is used for determining anomalies. The other criterions for anomaly screening that are the same as in Section VI are still applied.

All the potential SIS anomalies for 2006–2009 are found based on the three kinds of daily combined broadcast navigation messages. Table V shows a comparison of the total hours of the anomalies per year. It can be seen that `brdcddd0.yyn` and `autoddd0.yyn` result in approximately 11 times more false anomalies than true ones. Moreover, all potential anomalies derived from `sugldddm.yyn` are confirmed by `brdcddd0.yyn` and `autoddd0.yyn`, which indicates that our `sugldddm.yyn` does not introduce any more false anomalies than `brdcddd0.yyn` and `autoddd0.yyn`.

VIII. CONCLUSION

In this paper, the GPS SIS integrity performance in the last decade is assessed by comparing the broadcast ephemerides/clocks with the precise ones. Because the broadcast navigation data files from the IGS global network include errors caused by ground receivers and data conversion processes, we devise and implement a data cleansing algorithm based on majority vote to recover original broadcast navigation messages. In comparison to the `brdcddd0.yyn` or `autoddd0.yyn` files from IGS, our validated navigation messages sugldddm.yyn files exclude most receiver-caused errors, making the assessment of the GPS SIS integrity performance possible. Besides, both IGS and NGA precise ephemerides/clocks are used as truth

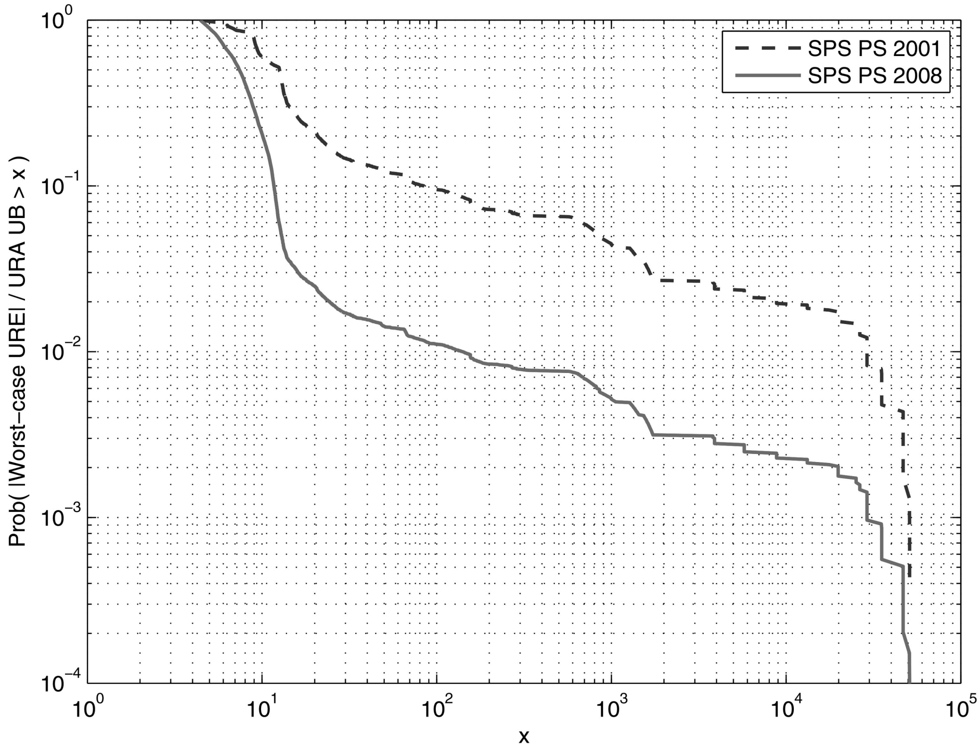


Fig. 8. Cumulative distribution of anomalous worst-case SIS URE.

TABLE IV
Statistics of Data Cleansing for 2009

- 32,559,745 navigation messages in 118,674 data files (20 Gigabyte) have been processed.
- 110,703 navigation messages (0.34%) are corrupted.
- Error ratio of each ephemeris/clock parameter is shown below, where the parameters with a high tendency to be erroneous are bold. The parameters are arranged by the order in the RINEX n-type format. The value in the parenthesis is the number of bits of the parameter in the original broadcast navigation message.

PRN	Toc (16)	**clock bias (22)**	clock drift (16)	clock drift rate (8)
0	4.707652651875E-07	**1.083136722143E-03**	2.353826325937E-07	1.883061060750E-07
	IODE (8)	Crs (16)	Delta n (16)	M0 (32)
	1.417003448214E-05	1.435834058822E-05	1.435834058822E-05	7.099140199027E-05
	Cuc (16)	Eccentricity (32)	Cus (16)	sqrt(A) (32)
	1.435834058822E-05	6.035210699704E-05	1.445249364126E-05	7.230954473280E-05
	Toe (16)	Cic (16)	OMEGA0 (32)	Cis (16)
	1.431126406170E-05	1.445249364126E-05	7.174462641457E-05	1.478202932689E-05
	i0 (32)	Crc (16)	omega (32)	OMEGA DOT (24)
	7.141509072894E-05	1.449957016777E-05	7.169754988805E-05	1.449957016777E-05
	IDOT (14)	Codes on L2 (2)	GPS Week # (10)	L2 P data flag (1)
	1.525279459207E-05	N/A	3.531210254171E-04	N/A
	SV accuracy (4)	**SV health (6)**	TGD (8)	IODC (10)
	3.494019798222E-04	**1.853073313358E-03**	N/A	0.000000000000E+00
	TTOM			
	1.144948201462E-03			

references, and the NGA satellite antenna corrections are employed to convert the IGS CoM data into the APC. Finally, 1256 potential SIS anomalies are screened out from 397,044,414 navigation messages collected by on average 410 IGS stations between 6/1/2000 and 8/31/2010. Most anomalies between 2004 and 2010 are confirmed by NANUs, and about two-thirds of them are also confirmed by other literature. The cumulative distribution of anomalous worst-case SIS URE shows that approximately 10% of the anomalies result in worst-case SIS URE greater than 10 times URA UB, and approximately 1% of the anomalies result in worst-case SIS URE greater than 100 times URA UB. The total number of potential SIS anomalies per year demonstrates the improving SIS integrity performance in the last decade. The

TABLE V
Total Hours of Anomalies per Year Computed from Three Different Kinds of Daily Global Combined Broadcast Navigation Messages

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

fundamental assumption of RAIM is valid based on a review of the GPS SIS integrity performance in the past 7 yr.

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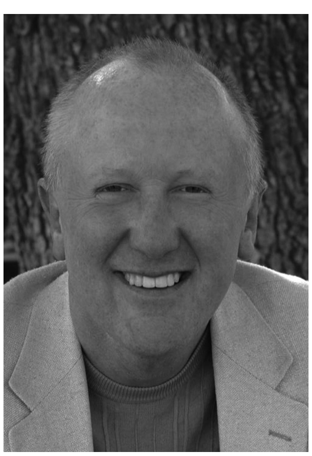
Dr. Walter has received the Thurlow and Kepler awards from the ION. He is a Fellow of the ION and currently serves as its president.



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Dr. Enge has received the Kepler, Thurlow and Burka Awards from the ION for his work. He is also a Fellow of the ION.