GPS Ephemeris Error Screening and Results for 2006–2009

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BIOGRAPHY

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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), real-time satellite orbits and clock biases are derived from predicted ephemeris and clock parameters in broadcast navigation messages. The performance of broadcast ephemerides is critical to billions of GPS users in terms of position accuracy and integrity. A typical way to evaluate ephemeris errors is comparing broadcast ephemerides with precise ones. At times, broadcast ephemerides data obtained from a tracking network include errors caused by receivers. Besides, the receivers at different locations may not receive the same broadcast ephemeris message as a satellite rises and sets. In this paper, a powerful systematic screening methodology is presented to cope with all above problems and the screening results for year 2006–2009 is provided.

The broadcast ephemerides are retrieved from all active International GNSS Service (IGS) stations. The following types of data defects are observed: losses, duplications, inconsistencies, discrepancies, and errors. A data purification algorithm based on error-correction and majority-vote is devised and implemented to remove all erroneous ephemerides and to generate validated daily global combined broadcast ephemerides. The validated broadcast ephemerides are employed to propagate broadcast satellite positions and clocks at 15-minute intervals that coincide with the precise ephemerides from National Geospatial-Intelligence Agency. Then an analytic method is utilized to calculate the worst-case signal-in-space range error (SISRE). Finally, ephemeris anomalies are identified by comparing the worst-case SISRE with the signal-in-space not-to-exceed tolerance, 4.42 times of the user range accuracy upper bound.

All GPS ephemerides from 2006 to 2009 are screened, and all potential anomalies and Issue of Data, Clock (IODC) reuse problems are documented. In comparison with the daily global combined broadcast ephemerides provided by IGS, our validated ephemerides include far fewer errors and greatly reduce the number of false anomalies.

INTRODUCTION

The Global Positioning System (GPS) works on the principle of trilateration. A user receiver must obtain the positions and clocks of at least four satellites in view before fixing its exact position. The 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 accuracy of the ephemeris and clock directly affects pseudorange accuracy, and thus the user position accuracy. Ideally, navigation message should be error-free and the resulting signal-in-space range error (SISRE) meets or surpasses the performance standard [2]. In practice, unfortunately, occasional anomalies in the GPS satellites or CS lead to erroneous ephemeris and clock data that may cause a range error of tens of meters or even more [3, 4]. It is very important to know not only the nominal performance of the broadcast ephemeris/clock data but also all the anomalies in the history.

There has been some prior work evaluating broadcast ephemerides/clocks by comparing them with the precise, post-processed ones [5–9]. However, there are two flaws in these implementations. The first flaw is that some broadcast ephemeris data may be different from what GPS satellites transmitted and hence may result in false anomalies [10]. The second flaw is that the existing implementations mainly focus on the nominal performance rather than the anomalies. With the aim of coping with these two flaws, we present a systematic methodology for comparing the broadcast ephemerides with precise ones and finding anomalies.

In the rest of this paper, we start with the framework of our methodology and then elaborate on the algorithms. Afterwards all GPS ephemerides in 2006–2009 are screened and the results are presented.

FRAMEWORK

As shown in Figure 1, the GPS ephemeris error screening consists of three steps: collection, purification, and computation.

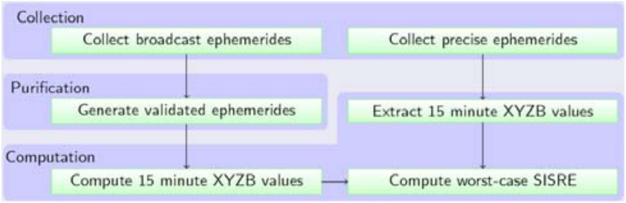

Figure 1: Framework of the whole process

The first step is collecting ephemeris data. Two Perl scripts have been developed to auto-download the broadcast and precise ephemeris data files from the FTP servers of International GNSS Service (IGS) [11] and National Geospatial-Intelligence Agency (NGA) [12], respectively. IGS tracking network comprises more than 300 stations all over the world that ensures seamless observation and navigation data logging for all GPS satellites. The ephemeris/clock parameters in broadcast navigation message and the transmission time of message (TTOM) produced by the receiver are archived in receiver independent exchange (RINEX) n-type format [13]. NGA provides antenna phase center (APC) satellite orbits and clock data every 15 minutes synchronized to GPS time, which are regarded as truth since they are an order of magnitude or more accurate than the broadcast ephemerides [14, 15].

Since each GPS satellite can be observed by several IGS stations at any instant and hence each navigation message is recorded redundantly, the daily global combined broadcast ephemerides are generated in the second step to remove the redundancy. Although two IGS archive sites, Crustal Dynamics Data Information System (CDDIS) and Scripps Orbit and Permanent Array Center (SOPAC), have provided two kinds of daily combined broadcast ephemerides, `brdcddd0.yyn` [16] and `autoddd0.yyn` [17], they are not fully validated and sometimes contain errors that cause false anomalies. In order to remove the receiver-caused errors and generate the combined ephemerides as broadcast as possible, we devise and implement a data purification algorithm based on majority voting among all available navigation data files from IGS. This data purification process is explained in detail in the next section.

The last step is computing worst-case SISRE as well as finding potential GPS anomalies. The validated ephemerides prepared in the previous step are used to propagate broadcast orbit positions at 15-minute intervals that coincide with the precise ephemerides. Then an analytic method is utilized to compute worst-case SISRE. The potential GPS anomalies are found by comparing the worst-cases SISRE with 4.42 times of user range accuracy (URA) upper bound [2].

DATA PURIFICATION

Figure 2 shows the diagram of data purification. Owing to incorrect receiver data and various hardware/software configurations, a small proportion of the navigation data files from IGS stations have defects such as losses, duplications, inconsistencies, discrepancies, and errors. Therefore, the generation of validated combined ephemerides is more than just removing duplications and is actually composed of two complicated steps.

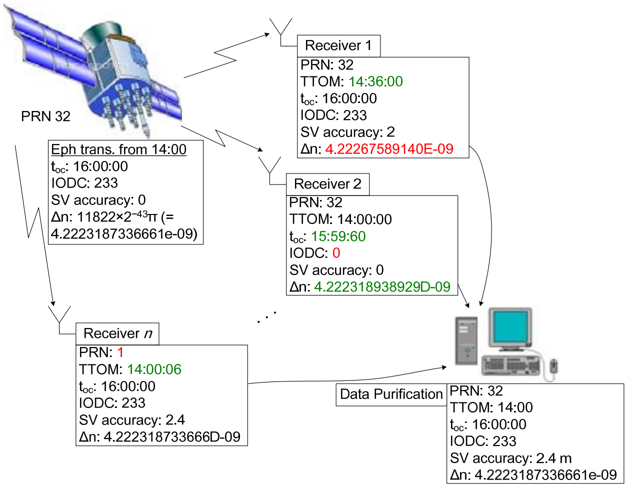

Figure 2: Diagram of data purification

In the figure, the satellite PRN 32 starts to transmit a new ephemeris at 14:00. For receiver 1, the satellite is not in view until 14:36, and hence the TTOM in its record is 14:36. Additionally, Receiver 1 made an one-bit error in Δn (4.22267589140E-09 = $11823 \times 2^{-43}\pi$). Receiver 2 may have some problems in its software: the IODC is unreported and both the t_{oc} and Δn are written differently. Receiver n uses an incorrect ranging code, PRN 1, to demodulate and decode the signal of PRN 32; luckily, all the parameters except TTOM are perfectly recorded. Moreover, these three receivers interpret URA (SV accuracy) differently. A computer equipped with our data purification algorithms is used to process all the data from these receivers. The receiver-caused errors are removed and the broadcast ephemeris is recovered.

Suppose we want to purify the data files of 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 ephemerides not belonging to Day n and remove duplications if there are any;
5. Add all remaining ephemerides into the set O for Day n.

The reason why the data files from Day $n - 1$ to Day $n + 1$ are considered is that some ephemerides around 00:00 are included in the data file of Day $n - 1$ and some ephemerides around 23:59 are included in the data file of Day $n + 1$. The duplication removal is applied here because some stations report the same ephemeris again and again, which is unfavorable to the vote in the second step. The details about LSB recovery, URA classification and duplication removal will be explained in the following several subsections.

At the end of the first step, we have a set O that includes all the ephemerides on Day n, in which there are duplications because each broadcast ephemeris is received by tens or hundreds of IGS stations. The same duplication removal algorithm as the first step is applied again to remove all the duplications and to vote correct parameters. Then the TTOM is found for each ephemeris. Finally, the correct ephemerides are determined and the ephemerides confirmed by only a few stations are discarded.

LSB recovery

The ephemeris and clock parameters in navigation message 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, $-55 \le \beta \le 4$, and the number of bits γ, $1 \le \gamma \le 32$, may vary from parameter to parameter. 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 the parameter with 32-bit precision, due to various software implementations, the real data files may look like the follows.

```
ffmj0190.09n: 17  9  1 19  2  0  0.0 0.44642481
9529E-04 0.909494701773E-12 0.000000000000E+00
ganp0190.09n: 17 09  1 19  2  0  0.0 4.46424819
5291D-05 9.094947017729D-13 0.000000000000D+00
glsv0190.09n: 17 09  1 19  2  0  0.0 4.46425000
0000D-05 9.094950000000D-13 0.000000000000D+00
```

As shown in Figure 2, an example of an apparent mismatch is from the ephemeris parameter Δn, `4.222318938929D-09` in the file `str13640.08n` 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, a LSB recovery algorithm is employed, in which all the floating-point ephemeris/clock parameters are converted to the $\alpha \times 2^{\beta}$ format 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 the same floating-point number in computer's memory.

URA classification

URA is the one-sigma estimate of the user range errors in the navigation data for the transmitting satellite. In navigation messages, URA is represented by a 4-bit index [2, 18]. In RINEX n-type format, URA values in meters have been preferred since 1993 [10]; nevertheless, some stations still use URA indices in their data files. An even worse problem is that one URA index is corresponding to three possible values in meters: the typical expected user range error (URE), the lower and upper bounds of expected URE [2]. One telling example of this chaos is surprisingly from CDDIS `brdcddd0.yyn` files. In `brdc1290.07n`, all the URA values are in the set {2, 2.8, 4, 5.7, 8}, which are apparently the typical expected UREs, whereas just one day later, in `brdc1300.07n`, all the URA values are in the set {0, 1, 2, 3, 4, 8}, which look like the URA indices.

Fortunately, the usage of URA in one data files is usually consistent. Therefore, this problem can be solved by a simple pattern-recognition-based five-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, …, 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, …, 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, …, 3072};
4. The URA indices if all the URA values are in the set {0, 1, 2, 3, …, 15}; or
5. Unknown URA representations.

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

This simple URA classifier is not flawless, admittedly. 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 following majority vote algorithm can easily correct these errors. As a result, a more sophisticated classifier based on the historical statistics of each station could be considered, but the resulting performance improvements may be too marginal to be worthy of the computation complexity.

Duplication removal and majority vote

Data purification is the most complicated step in the whole process, while duplication removal and majority vote is the most complicated operation in data purification. Actually, duplication removal and majority vote plays a dual role. The first role is removing the duplicated ephemerides from one station, because some stations tend to write the same ephemeris repetitively in their data files and the basic vote rule is that each station has only one ballot for one ephemeris. The second role is removing the duplicated ephemerides from the set *O*. Since different stations may have different interpretation of the same broadcast navigation message, the second role is harder to play and more effort is needed, as described below.

After LSB recovery and URA classification, there are still some errors and inconsistencies in the set *O*. Jefferson and Bar-Sever [10] have reported some discrepancies in navigation data files. Several examples of other typical problems are shown in Table I. It should be noted that the most parameters in navigation data are seldom reported incorrectly and even when errors happen, merely a few stations agree on the same incorrect value. In this paper, this kind of parameters is referred to as robust parameter.

Table I: Examples of errors/inconsistencies/losses in navigation data files

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
```

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
```

Unreported Issue of Data, Clock (IODC) and URA:

```
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
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
```

On the contrary, some parameters, such as TTOM, PRN, URA and IODC, are more likely to be erroneous and when errors happen, several stations may make the same mistake. This kind of parameters is referred to as fragile parameter. The reason why there are fragile parameters is due to either physical nature (e.g., TTOM, PRN) or carelessness in hardware/software implementation (e.g., URA, IODC).

The majority vote is applied to all fragile parameters except TTOM (the correct TTOM is found by a more sophisticated algorithm introduced in the next subsection) under the principle that the majority is usually correct. Meanwhile, the robust parameters are utilized to identify the equivalence of two ephemerides—two ephemerides 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 an ephemeris set P, in which any ephemeris 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 ephemeris. P can be built by the algorithm below:

1. Initialize P to an empty set;
2. For each ephemeris e in O, if there is an ephemeris 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 ephemeris f in P, vote each fragile parameter (except TTOM) according to f's database, and record the number of the stations that report f.

Finding 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 ephemeris should be used in the next step to compute broadcast satellite positions and clock bias. Since the IGS stations are not evenly distributed on the surface of the earth and some stations occasionally report an incorrect TTOM that are 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 of the first step is that each frame begins at the 30-second epoch. In the second step, the median value is found rather than the mean value because the mean value can be affected by very large or very small outliers. The third step discards the data earlier than $m - 7200$ or later than $m + 7200$ because the navigation message is usually updated every 2 hours. The last step requires the confirmation of at least 2 stations in order to eliminate the remaining outliers.

Correct ephemerides determination and minority discard

After the operations above, we have a set P in which there are no duplicated ephemerides in terms of robust parameters and all fragile parameters are as correct as possible. A few ephemerides in P still have errors in their robust parameters. These unwanted ephemerides feature a small number of reporting stations. Nevertheless, it is not easy to set an appropriate threshold n_{th}, and delete all the ephemerides confirmed by n_{th} stations or less, because the IGS stations are not evenly distributed and sometimes a correct ephemeris may be confirmed by a few stations. If n_{th} is too larger, correct ephemerides may be discarded, and if n_{th} is too small, incorrect ephemerides may be kept. Hence, a uniqueness criterion is required to determine the correct ephemerides.

IODC is a good candidate for this purpose. According to GPS Interface Control Document (ICD) [18], for each GPS satellite, the transmitted IODC is expected to be different from any IODC transmitted during the proceeding seven days. Therefore, all ephemerides in P are screened; whenever there are several ephemerides have the same PRN and IODC, only the one confirmed by the largest number of stations remains, 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 GPS ICD. As shown in the Result section, every so often the same IODC is reused by a satellite within the same day, which is not supposed to be. In such cases, the IODC-based method may discard some correct ephemerides. Thus, Time of Clock (t_{oc}) is taken as another candidate of the uniqueness criterion. Since t_{oc} is not guaranteed to be unique during one day, this uniqueness

Table II: Procedure for finding the correct TTOM

Operation Steps	Examples
0) Original data	`[99012 115200 115212 115230 115230 115230 115230 122400]`
1) Round to the nearest previous 30 second epoch	[**99030** 115200 **115200** 115230 115230 115230 115230 122400]
2) Find the median value m	[99030 115200 115200 115230 **115230** 115230 115230 122400]
3) Eliminate outliers by deleting all the data 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]

criterion may result in fewer unique ephemerides than there should be. The main purpose of introducing the secondary uniqueness criterion is comparing the resulting t_{oc}-based validated ephemerides with the IODC-based ones and finding if there is any IODC reuse problem.

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

Finally, two versions of validated broadcast ephemerides, `suglddd0.yyn`[1] and `suglddd1.yyn`, based on IODC uniqueness criterion and t_{oc} uniqueness criterion, respectively, are generated and saved in RINEX n-type format. In the `sugldddm.yyn` files, we take advantage of the last two spare fields in RINEX n-type format to store the following creditability information:

$$f_1 = t_0 + t_2/t_0$$

$$f_2 = t_1 + t_3/t_0$$

where t_0 is the total number of the stations that report the ephemeris with the same PRN and IODC/t_{oc}, t_1 is the number of the stations report the most common received ephemeris, t_2 is the number of the stations report the second most common ephemeris and t_3 is the number of the stations report the third most common ephemeris. By the above definition, four integers, t_0 ... t_3, are able to be stored in two fields. A large t_0 with $t_1 \approx t_0$, $t_2 << t_0$, and $t_3 << t_0$ indicates high creditability of this ephemeris.

COMPUTATION

The validated broadcast ephemerides prepared in the previous step are employed to propagate broadcast satellite positions and clocks using the algorithm in GPS ICD [18]. For each 15-miniute epoch that coincides with NGA precise ephemerides, the latest transmitted broadcast ephemeris is selected.

Although the RMS SISRE [19] and the SISRE overbound [9] are widely used in some literature, the worst-case SISRE[2] is selected in this paper because, in our opinion, an important criterion of the ephemeris anomaly is that the worst-case SISRE exceeds the signal-in-space (SIS) not-to-exceed (NTE) tolerance, 4.42 times of the upper bound of the URA value [2].

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

1. Generate a dense grid over the earth;
2. For each satellite at each epoch,
   2.1 Compute the pseudorange error for the receiver at each node of the grid;
   2.2 Find the pseudorange error with the greatest absolute value.

This method is accurate as long as the grid is dense enough; a dense grid, however, means significant computational burden. Accordingly, the analytical geometric method is preferred. As shown in Figure 3, we assume the earth surface is a perfect sphere and then:

1. Find the plane (as shown) contains the center of the earth and the error vector $\boldsymbol{v}$;
2. Find α using inner product, and find β using the law of sines (please note that $\gamma = 90° +$ mask angle);
3. Find l_{max} and l_{min} (not always the projection on the edges);
4. Find $l_{max} - c\Delta B$ and $l_{min} + c\Delta B$, and the one with greatest absolute value is the maximum pseudorange error, i.e., the worst-case SISRE.

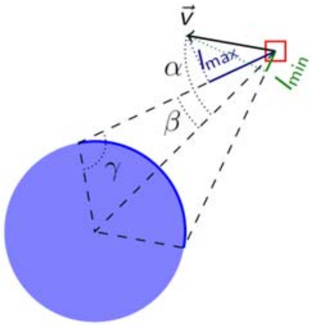

Figure 3: Geometric method to calculate the worst-case SISRE

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

Finally, a GPS ephemeris anomaly is claimed when all the following conditions are fulfilled.

1. The worst-case SISRE exceeds 4.42 × URA upper bound;
2. Broadcast ephemeris unhealthy flag is not set;
3. Precise ephemeris clock event and error flag are not set;
4. The age of the broadcast ephemeris, $\Delta t = t - \mathrm{TTOM}$, is not greater than 4 hours.

RESULTS

Potential Anomalies

All GPS broadcast ephemerides from Jan 1, 2006 to Dec 31, 2009 are screened using the previously described algorithm. All identified potential anomalies are listed in Table III. It can be seen that fewer anomalies are found in 2008–2009 than in 2006–2007. It should be noted that false anomalies might exist in this list because either a

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[1] The prefix `sugl` stands for Stanford University GPS Laboratory.

[2] Also referred to as "maximum instantaneous URE" in some literature [20]

Table III: Potential anomalies in 2006–2009

Start time	Duration (min)	PRN	Anomaly	URA UB (m)	Δt (min)
2006-06-02 20:30	30	30	clock −1045 m	2.40	30
2006-06-27 04:45	30	06	clock −10.2 m	2.40	30
2006-07-31 22:15	60	03	clock −12.7 m	2.40	10.5
2006-08-25 12:30	90	29	clock −11.6 m	2.40	30
2006-09-22 19:45	165	24	ephemeris 41.2 m	2.40	0
2006-11-07 01:45	225	05	clock −30.7	2.40	0
2006-12-27 01:15	15	03	clock 10.2	2.40	75
2007-03-01 14:45	150	29	clock −42.3 m	2.40	43
2007-04-10 16:00	105	18	ephemeris 688 m	2.40	0
2007-04-22 10:30	45	25	clock −29.4 m	6.85	30
2007-08-17 07:30	30	07	clock −14.3 m	2.40	41
2007-10-08 08:45	225	19	clock 403 km	2.40	270
2007-10-08 09:45	135	12	clock −86 km	2.40	225
2007-10-08 23:00	90	14	clock −112 km	2.40	118.5
2007-10-09 09:45	60	23	clock 27 km	6.85	105
2007-10-09 13:15	15	16	clock −18 km	4.85	120.5
2007-10-10 08:45	75	20	clock 48 km	2.40	34.5
2008-11-14 05:45	225	27	clock −70 km	2.40	105
2009-06-26 09:30	45	25	clock −22.3 m	2.40	90

few erroneous ephemerides might escape from data purification or a few precise ephemerides might be incorrect. It should also be noted that some transitory anomalies might not be included in this list because the precise ephemerides are only available every 15 minutes and are occasionally unavailable. Furthermore, some anomalies with a relatively large Δt might not be experienced by the users because the satellite might stop broadcasting erroneous ephemeris before the "Start time".

Excellence of validated ephemerides

For the purpose of comparison and verification, the daily combined broadcast ephemerides `brdcddd0.yyn` and `autoddd0.yyn` are used to propagate broadcast satellite positions and clocks as well. The same conditions of anomalies are applied and all the anomalies for 2006–2009 are found. Table IV shows the total duration of the anomalies resulting from the three kinds of daily combined broadcast ephemerides. It can be seen that `brdcddd0.yyn` and `autoddd0.yyn` result in many false anomalies.

Table IV: Comparison with `auto*` and `brdc*` files

Year	Total duration of anomalies (hour)		
	`sugl*`	`auto*`	`brdc*`
2006	10.25	22.25	17.00
2007	15.50	225.00	131.25
2008	3.75	23.25	40.50
2009	0.75	52.00	125.75
Total	30.25	322.50	314.50

Moreover, all potential anomalies resulting from `suglddd1.yyn` are "confirmed" by `brdcddd0.yyn` and `autoddd0.yyn`, which indicates that `suglddd1.yyn` do not introduce any more erroneous ephemeris than `brdcddd0.yyn` and `autoddd0.yyn`.

Statistics of data purification for 2009

Table V shows some statistics of the data purification for 2009. Three hundred and sixty-five `suglddd0.09n` files are generated from more than 100,000 RINEX n-type files from all IGS stations, in which 0.34% ephemerides 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 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.

IODC reuse problems

All the found IODC reuse problems are documented in Table VI. The severest problem occurred on Sep 17, 2007, on which day two satellites, PRN 17 and PRN 19, reused five IODCs. Fortunately, no IODC reuse problems are found for 2008 and 2009, and there are no anomalies resulting from these IODC reuse problems.

CONCLUSION

In this paper, the performance of broadcast GPS ephemerides for 2006–2009 is evaluated by comparing the broadcast ephemerides with precise ones. We devise and implement a data purification algorithm based on

Table V: Statistics of data purification for 2009

118,674 navigation message data files (20 Gigabyte) processed

0.34% erroneous ephemerides deleted

Ephemeris/clock parameter error ratio:

```
 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  1.111476791108E-04  3.531210254171E-04  0.000000000000E+00
     SV accuracy (4)     SV health (6)       TGD (8)             IODC (10)
     3.494019798222E-04  1.853073313358E-03  0.000000000000E+00  0.000000000000E+00
     TTOM
     1.144948201462E-03
```

* Number in the parenthesis: the number of bits of the parameter

majority vote among all available navigation data files. The resulting validated ephemerides outperform the `brdcddd0.yyn` and `autoddd0.yyn` files from IGS. The total duration of the anomalies from 2006 to 2009 found with our `suglddd0.yyn` files is one tenth of that derived from the `brdcddd0.yyn` files or the `autoddd0.yyn` files. The IODC reuse problems are also discovered in the process of data purification, and all known cases in 2006–2009 are documented. In addition, the GPS satellite anomalies are found by computing the worst-case SISRE and comparing it with SIS NTE tolerance. All found potential anomalies in 2006–2009 are documented. The performance of GPS broadcast ephemerides in 2008–2009 is much better than that in 2006–2007 in terms of satellite anomalies and IODC reuse problems.

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Table VI: IODC reuse problems in 2006–2009

PRN	IODC	t_{oc}	TTOM	Health	Count*
01	164	2006-01-05 07:59:44	2006-01-05 07:40:00	0	285
01	164	2006-01-05 09:59:28	2006-01-05 08:55:00	0	70
01	165	2006-01-05 09:59:44	2006-01-05 08:00:00	0	294
01	165	2006-01-05 11:59:28	2006-01-05 10:00:00	0	277
12	108	2006-12-12 03:59:28	2006-12-12 03:18:30	63	20
12	108	2006-12-12 05:59:12	2006-12-12 04:26:30	63	79
12	109	2006-12-12 05:59:28	2006-12-12 04:00:00	63	21
12	109	2006-12-12 07:59:12	2006-12-12 06:00:00	63	124
19	193	2007-04-11 03:59:28	2007-04-11 03:26:30	0	120
19	193	2007-04-11 05:59:12	2007-04-11 04:46:00	0	108
19	194	2007-04-11 05:59:28	2007-04-11 04:00:00	0	157
19	194	2007-04-11 07:59:12	2007-04-11 06:00:00	0	281
13	189	2007-06-12 01:59:44	2007-06-12 00:00:00	0	199
13	189	2007-06-12 03:59:12	2007-06-12 02:00:00	0	171
23	9	2007-09-06 21:59:44	2007-09-06 21:51:00	0	26
23	9	2007-09-06 23:59:28	2007-09-06 22:53:00	0	26
17	12	2007-09-17 01:59:44	2007-09-17 00:00:00	0	285
17	13	2007-09-17 04:00:00	2007-09-17 02:00:00	0	231
17	14	2007-09-17 06:00:00	2007-09-17 04:00:00	0	40
17	15	2007-09-17 08:00:00	2007-09-17 06:00:00	0	87
17	12	2007-09-17 15:59:44	2007-09-17 15:42:30	0	64
17	13	2007-09-17 17:59:44	2007-09-17 16:00:00	0	65
17	14	2007-09-17 20:00:00	2007-09-17 18:00:00	0	121
17	15	2007-09-17 22:00:00	2007-09-17 20:00:00	0	169
19	47	2007-09-17 00:00:00	2007-09-16 22:00:00	0	249
19	47	2007-09-17 22:00:00	2007-09-17 20:00:00	0	286
01	4	2007-11-25 09:59:44	2007-11-25 08:41:00	0	171
01	4	2007-11-25 11:59:12	2007-11-25 11:18:30	0	52
01	26	2007-11-25 11:59:44	2007-11-25 10:00:00	0	179
01	26	2007-11-25 13:59:12	2007-11-25 12:00:00	0	44

* Count: the number of the stations that reports this ephemeris

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