GLONASS Signal-in-Space Anomalies Since 2009

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ABSTRACT

As GLONASS has fully restored its constellation, there is an increasing desire to use multiple constellations to improve positioning performance. Knowledge of GLONASS signal-in-space (SIS) error behavior is very important for this purpose. However, few study has been done on GLONASS SIS anomalies due to several difficulties. This paper overcomes these difficulties and thoroughly characterizes the GLONASS SIS anomalies since 2009.

In this paper, we compute GLONASS SIS user rang errors by comparing broadcast ephemerides/clocks with precise ephemerides/clocks. As the broadcast navigation data files from a global receiver network include data-logging errors, we developed a majority-voting-based algorithm to recover original navigation messages. Besides, we proposed a set of criteria to detect potential GLONASS SIS anomalies, bypassing the difficulties such as no user range accuracy information and no official integrity performance standard.

Finally, we processed a total of 80,814,366 broadcast GLONASS navigation messages collected between Jan 1, 2009 and Aug 11, 2012, and identified 192 potential SIS anomalies. The results show an improving GLONASS SIS integrity performance over the past three years. Besides, we discovered four events of simultaneous multiple anomalies, including a constellation-wide clock change on Oct 28, 2009 that impacted all satellites. Furthermore, the results show that anomalies occur more frequently when satellites are out of the tracking coverage of the GLONASS monitor stations.

INTRODUCTION

With the modernization of the United States Global Positioning System (GPS), the revitalization of the Russian Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS), and the advent of the Chinese Compass and the European Galileo, there is an increasing desire to use multi-constellation global navigation satellite systems (GNSS) to enhance positioning accuracy, availability, continuity, integrity, and robustness, especially for the use of receiver autonomous integrity monitoring (RAIM) [1, 2], the mitigation of radio frequency interferences [3], and the navigation in high latitudes [4,5]. At the time of writing, 24 GLONASS satellites are operational [6], capable of global continuous navigation [7]. Accordingly, the utilization of both GLONASS and GPS constellations does not just benefit today's GNSS receivers, but it also serves as a ready-made proving ground for tomorrow's multi-constellation GNSS integrity monitoring systems, such as advanced RAIM (ARAIM) [2, 8].

Both GLONASS and GPS employ the concept of time-of-arrival measurements, in which the information about real-time satellite orbits and clocks are the prerequisites for a user receiver to fix its exact position [9]. For most users, this information is derived from ephemeris parameters and clock correction terms in broadcast navigation messages, which are generated by the control segment on the basis of a prediction model and the measurements from ground monitor stations [7, 10]. The differences between the broadcast ephemerides/clocks and the truth account for signal-in-space (SIS) errors, which directly affect the positioning accuracy and integrity. Nominally, users can assume that each broadcast navigation message is trustworthy and user range errors (UREs) resulting from any healthy SIS are at meter level, even sub-meter level [11, 12]. In practice, unfortunately, SIS anomalies occasionally occurred and UREs of tens of meters or even more have been observed, which could result in user receivers outputting hazardously misleading positioning solutions. ARAIM is a promising tool to protect stand-alone users from such hazards; however, its algorithm requires some prior assumptions such as how many satellites can be faulty at a time [2, 8]. Knowledge about SIS anomalies in history is very important for not only assessing the SIS integrity performance of a constellation but also providing the fundamental assumption for ARAIM.

A typical method for calculating SIS UREs is to compare the broadcast ephemerides/clocks with the post-processed precise ephemerides/clocks, because the latter are much more accurate than the former. Although the GPS SIS anomalies have been extensively studied in this way [13–19], few studies have been done for GLONASS due to the following difficulties:

1. Broadcast GLONASS navigation message data obtained from a global tracking network containing errors made by ground receivers and processing software;
2. No generally accepted precise clock solutions for GLONASS;
3. No official GLONASS integrity performance standard;
4. No user range accuracy (URA) information in the Receiver Independent Exchange Format (RINEX) for GLONASS.

In this paper, we have surmounted the first difficulty by voting validated GLONASS navigation message data from raw data, overcome the second difficulty by aligning the clock errors [12] derived from several independent precise clock solutions, and bypassed the last two difficulties by defining an integrity criterion from the statistics of real data.

For the rest of this paper, we will start with a description of the data sources. Then, we will elaborate on the key methods. Finally, we will present identified anomalies as well as an in-depth analysis of these anomalies in terms of anomaly probability, simultaneous multiple anomalies, and geographic dependency.

DATA SOURCES

Broadcast GLONASS ephemerides and clocks

GLONASS broadcast navigation message data are publicly available at International GNSS Service (IGS) [20]. Archived in the RINEX n-type format [21], these data include the immediate information of the GLONASS broadcast navigation message [22] such as reference time, clock corrections, satellite position, satellite velocity, lunisolar acceleration, and healthy flag. Unfortunately, the RINEX n-type format for GLONASS, unlike that for the GPS, does not include URA, probably because the old generation GLONASS satellites did not broadcast URA in 1990s, when the RINEX format was defined.

As shown in Figure 1, the IGS tracking network comprises more than 100 GPS/GLONASS stations all over the world to ensure seamless, redundant data logging. Since broadcast navigation messages are usually updated every 30 minutes, no single station can collect all navigation messages. For ease of using these data, an IGS archive site, Crustal Dynamics Data Information System (CDDIS), routinely generates daily global combined broadcast navigation message data

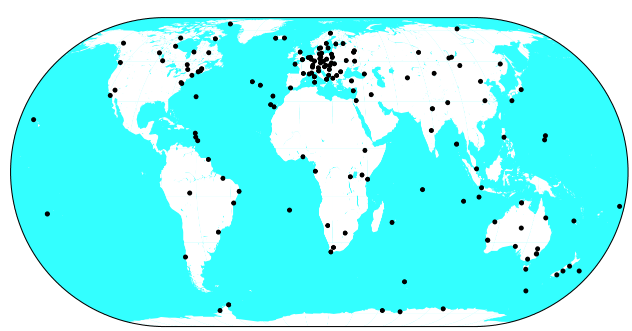

Figure 1. IGS GPS/GLONASS stations as of Jan 29, 2012 (adapted from `http://igscb.jpl.nasa.gov`)

files brdc*ddd*0.*yy*g (or igex*ddd*0.*yy*g before December 2004) [23]. Unfortunately, these files occasionally contain errors made by ground receivers or processing software. For example, the reference time t_b in GLONASS broadcast ephemerides is always an integer multiple of 15 minutes [22], but we observed the following lines in brdc0020.09g:

```
                                   ⋮
4 09  1  2  0 15  0.0 0.119622796774E-03...
                                   ⋮
4 09  1  2  0 15  1.0 0.119622796774E-03...
                                   ⋮
```

The first line indicates an ephemeris with t_b = 2009-01-02 00:15:00, whereas the second line indicates an ephemeris with the same parameters as the first one but an incorrect t_b = 2009-01-02 00:15:01.

Therefore, we have devised and implemented a data cleansing algorithm to generate our own daily global combined GLONASS navigation messages, sugl*ddd*0.*yy*g[1], from all available raw navigation message data files collected by all the IGS GPS/GLONASS stations. In order to make sugl*ddd*0.*yy*g as close as possible to the navigation messages that the GLONASS satellites actually broadcast, the data cleansing algorithm decides every value in a navigation message using majority voting. As all values in sugl*ddd*0.*yy*g are validated by the raw data, we refer to sugl*ddd*0.*yy*g as "validated navigation messages."

The data cleansing algorithm will be explained in detail in the section "Methods."

Precise GLONASS ephemerides

In addition to the broadcast navigation message data, IGS provides precise GLONASS ephemerides igl*wwwwd*.sp3 (or igx*wwwwd*.sp3 before December 2004) since at least 1999. In fact, the IGS precise GLONASS ephemerides are derived from a weighted-mean combination of the independent precise ephemeris solutions produced by a number of IGS Analysis Centers (ACs). The igx*wwwwd*.sp3 data have an accuracy of 5 centimeters [24] and hence are regarded as ground truth in this paper. To compare the broadcast ephemerides with the precise ones, we need to pay attention to the following three issues:

- The precise ephemerides are available at 15-minute intervals synchronized with GPS Time, while the reference time in broadcast ephemerides is synchronized with GLONASS Time;
- The precise ephemerides are based on the International Terrestrial Reference Frame (ITRF), not fully consistent with the "Earth Parameters 1990" (PZ-90) used by broadcast ephemerides;
- The IGS precise ephemerides are based on the measurement of satellite center of mass (CoM), while the broadcast ephemerides are based on antenna phase center (APC).

This paper uses the methods discussed in [25] to address the above issues.

Precise GLONASS clocks

Unfortunately, igl*wwwwd*.sp3 does not include precise GLONASS clocks [24], partially because the independent precise clock solutions produced by IGS ACs are not fully consistent. One of the reasons for the inconsistency is that each AC uses its own strategy and clock reference to post-processes the IGS observation data. The list below shows the IGS ACs whose precise GLONASS product contains at least precise GLONASS clocks.

emx[2] GPS + GLONASS, unbiased GLONASS clocks, data available since Sep 11, 2011

esa[3] GPS + GLONASS, biased GLONASS clocks, data available since Oct 18, 2008

gfz[4] GPS + GLONASS, biased GLONASS clocks, data available since Apr 11, 2010

iac[5] GLONASS only, unbiased GLONASS clocks, data available since Oct 2006 or earlier

All of the four products are used in this paper. The clock alignment algorithm developed in our previous paper [12] is employed to find the biases in esa and gfz precise clocks, and generate trustworthy broadcast clock errors. More specifically, broadcast clock errors from Jan 1, 2009 to Apr 10, 2010 are based on esa and iac precise clocks; clock errors from Apr 11, 2010 to Sep 10, 2011 are based on esa, gfz, and iac precise clocks; clock errors from Sep 11, 2011 to Aug 11, 2012 are based on all the four precise clock products.

METHODS

Figure 2 shows the framework of the whole process. According to the discussion in the section "Data Sources," we firstly vote the validated values in the raw broadcast ephemeris/clock data using a data cleansing algorithm, and then propagate them at 15-minute intervals synchronized to the precise ephemerides/clocks [25]. The precise ephemerides extracted from the igx*wwwwd*.sp3 files are converted from CoM to APC; the difference between the propagated

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

[2] Producer unknown

[3] Produced by European Space Operations Center, ESA, Germany

[4] Produced by GeoForschungsZentrum, Germany

[5] Produced by Information-Analytical Center, Russia

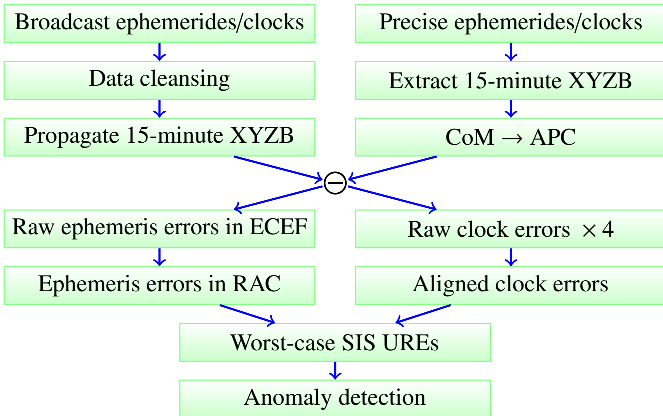

Figure 2. Framework of the whole process. XYZB values refer to the coordinates of satellite position in ECEF and satellite clock bias. RAC refer to the radial, alongtrack, and crosstrack-based satellite centered coordinate system.

broadcast ephemerides and the precise ephemerides in APC are the raw ephemeris errors in the Earth-Centered, Earth-Fixed (ECEF) coordinate. The precise clocks extracted from the `emxwwwwd.sp3`, `esawwwwd.sp3`, `gfzwwwwd.sp3`, and `iacwwwwd.sp3` files are compared with the propagated broadcast clocks, generating four versions of raw clock errors. After converting the ephemeris errors into the satellite centered coordinate system (R—radial, A—alongtrack, and C—crosstrack) and aligning the four versions of raw clock errors [12], the worst-case SIS UREs can be computed and then used for anomaly detection. The algorithms for data cleansing, worst-case SIS UREs, and anomaly detection will be discussed in the following subsections.

Data cleansing

As mentioned in the section "Data Sources," a small portion of the RINEX navigation data files from the IGS volunteer stations include errors owing to accidental bad receiver data and various hardware/software bugs. These errors pose a grave threat to the objective of this paper because they can cause a large number of false anomalies. Borrowing the idea in [17, 19], this paper employs a voting-based data cleansing algorithm to find the navigation messages as close as possible to what the GLONASS satellites actually broadcast. The data cleansing algorithm is composed of two steps: voter registration and majority voting, as described below.

A. Voter registration

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 file;
2. Remove the navigation messages not on Day n;
3. Recover least significant bit (LSB);
4. Remove duplications;
5. Add all remaining navigation messages into the set O.

The reason why the data files on Day $n \pm 1$ are considered is that a few navigation messages around midnights may be mistakenly included in some data files one day before or after.

LSB recovery is the most important operation in this step. The ephemeris and clock parameters in broadcast navigation messages are fixed-point numbers $\alpha\beta$, where α is a signed or unsigned integer within certain effective range and β is a scale factor (LSB). β and the range of α vary from parameter to parameter. In RINEX n-type format, however, all the parameters are described by floating-point numbers with 12 decimal digits. In spite of the fact that the 12 digits are precise enough to represent any parameter, various software implementations may result in different floating-point numbers for the same value. To solve this problem, our LSB recovery algorithm converts all the floating-point ephemeris/clock parameters to the closest $\alpha\beta$ as they were in the navigation message. The value of α is also checked against its effective range. The LSB recovery can solve the problems similar to the wrong t_b mentioned in the section "Data Sources" because the LSB of t_b is 15 minutes. Furthermore, the LSB recovery can also solve the problem similar to the example below.

```
                              ⋮
 5 10  2  2  9 15  0.0-0.430522486567D-04
    -0.909494701773D-12 0.429495661600D+10
                              ⋮
```

The above line is from `khaj0330.10g`. The message frame time t_k = `0.429495661600D+10` here is incorrect because its effective range is $[0, 86400)$ [22].

Then, the duplication removal is applied here because some stations write many copies of one navigation message in one data file, which violates the principle of voting: each station have only one ballot for one navigation message.

At the end of the voter registration, we have a set O that includes all unique navigation messages on Day n, whose parameters are all "legitimate" according to the GLONASS Interface Control Document [22].

B. Majority voting

The goal of majority voting is to find correct navigation messages in the set O. A correct navigation message is usually confirmed by many stations, i.e., have many duplications in the set O. The problem is, these duplications are not necessarily identical owing to data-logging errors.

To solve this problem, we first noticed that some parameters in RINEX navigation message data files are relatively fragile due to either the physical nature (e.g., message frame time t_k) or the carelessness in hardware/software implementations (e.g., the reference time t_b, health flag, and frequency number). The fragile parameters have a higher tendency to be erroneous, and when errors happen, several stations may make the same mistake. Fortunately, most ephemeris and clock parameters in RINEX navigation message data files are usually reported correctly, and even when errors happen, few stations agree on the same incorrect value. In this paper, these parameters are referred to as robust parameters.

Therefore, the majority voting is applied to all fragile parameters 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 majority voting 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 with 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 according to f's database, and record the number of the stations that report f.

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 items feature a small number of reporting stations. Since there is only one navigation message at any valid t_b for a GLONASS satellite, all navigation messages in P are screened: whenever there are several navigation messages with the same t_b, only the one confirmed by the largest number of stations are kept, and the others are discarded.

In this majority voting step, the data cleansing algorithm makes a full use of the redundancy of raw navigation data from IGS, and employs the majority rule twice to generate validated GLONASS navigation messages, which can be considered as maximum-likelihood estimates of the original navigation messages broadcast by the GLONASS satellites.

Worst-case SIS UREs

Given arbitrary ephemeris and clock errors, GLONASS receivers at different locations on the Earth may experience different instantaneous UREs. Worst-case SIS URE is the largest instantaneous URE that a user in the satellite's footprint can experience. Assuming that the earth is a perfect sphere, worst-case SIS URE can be calculated by

$$\max_{|\theta|\leq 14.48^\circ} (R\cos\theta - T + \sqrt{A^2 + C^2}\sin\theta),$$

where R, A, and C are radial, alongtrack, and crosstrack ephemeris errors, respectively, T denotes the aligned clock error in meters, θ is the nadir angle, and the function $\max(x)$ maximizes $|x|$ and returns the corresponding x. An efficient geometric algorithm to compute worst-case SIS URE has been discussed in [17, 19].

Anomaly detection

As mentioned in "Introduction," no official GLONASS integrity standard has been issued yet, and there is even no URA information in the RINEX navigation data. Alternatively, we define a 50-meter threshold for worst-case SIS UREs due to the following reasons.

First, the statistics of nominal GLONASS SIS URE behavior [12] have shown that the standard deviation of SIS UREs are generally less than 4 meters and the excess kurtosis of SIS UREs is around 2. Therefore, we use 4 meters as the URA, and this value also matches most URAs broadcast by GLONASS satellites. Probability theory [26] has shown that a Student's t-distribution with 7 degrees of freedom random variable X has an excess kurtosis of 2, and $\text{Prob}(|X| > 11.2148) = 10^{-5}$. Therefore, a 10^{-5} significance level leads to a threshold of $4 \times 11.2148 \approx 45$ meters for GLONASS SIS UREs.

Second, the nominal GLONASS SIS UREs in the past three years are roughly as twice large as the GPS SIS UREs before 2008 [11, 12]. GPS defined a 30-meter threshold before 2008 [27]; a rule-of-thumb analogy leads to a 60-meter threshold for detecting GLONASS SIS anomalies.

Considering both factors above, we finally choose a 50-meter threshold. Accordingly, a potential GLONASS SIS anomaly is claimed when all the following conditions are fulfilled.

- The worst-case SIS URE exceeds 50 meters;
- The broadcast navigation message is flagged healthy, i.e., the RINEX field `SV health` [21] is 0;
- The time of transmission is within the fit interval, i.e., $|t - t_b| \leq 15$ minutes;
- The precise ephemeris/clock is available and healthy.

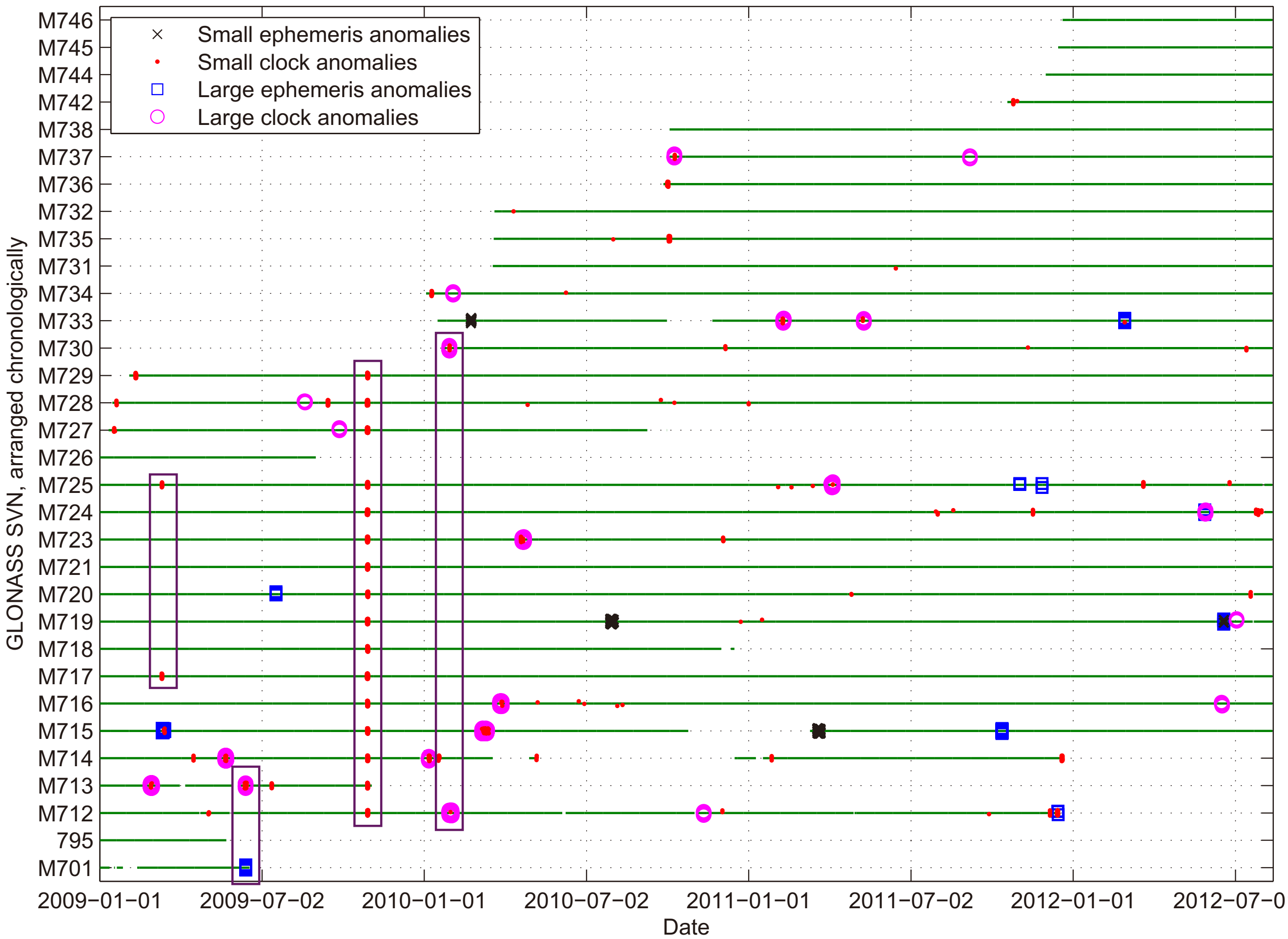

Figure 3. Identified GLONASS SIS anomalies between Jan 1, 2009 and Aug 11, 2012. The horizontal green lines depict the periods when the satellites were active (not necessarily healthy). The purple rectangles indicate simultaneous multiple anomalies, including a constellation-wide event on Oct 28, 2009.

IDENTIFIED GLONASS SIS ANOMALIES

After using the methods described above to process a total of 80,814,366 broadcast GLONASS navigation messages collected between Jan 1, 2009 and Aug 11, 2012, we identified 192 potential SIS anomalies. Figure 3 depict these anomalies. For a deeper insight, we divide the anomalies into four groups: small/large ephemeris/clock anomalies. The "small" means 50 m < |worst-case SIS URE| ≤ 500 m, whereas the "large" means |worst-case SIS URE| > 500 m. The "ephemeris" or "clock" means the anomalous URE is mainly attributable to broadcast ephemeris or clock inaccuracy, respectively.

It can be seen from Figure 3 that most anomalies resulted from clock inaccuracies. In fact, approximately 92% of the anomalies are clock anomalies. In addition, the younger satellites launched after Feb 2010 had fewer anomalies than the older satellites did. The following section will further analyze the identified anomalies in terms of anomaly probability, simultaneous multiple anomalies, and geographic dependency.

ANALYSIS OF IDENTIFIED ANOMALIES

Anomaly probability

The empirical probability of anomaly is not only a figure of merit to assess the GLONASS integrity performance, but also an essential parameter in ARAIM [2,8]. Figure 4 shows the total hours and numbers of anomalies per year[6]. The

[6] The total hours/numbers of anomalies in 2012 is extrapolated from the total hours/numbers of anomalies during the period Jan 1, 2012 to Aug 11, 2012.

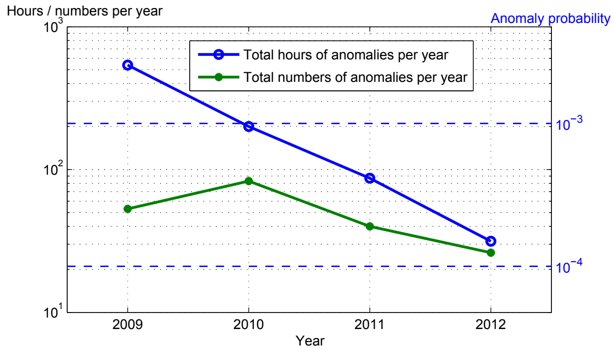

Figure 4. Total hours/numbers of anomalies per year. The anomaly probability is based on a full constellation (24 active satellites) with zero outage.

total hours of anomalies per year, indicated by the blue solid polyline, can be compared to the two horizontal blue dashed lines, which indicate anomaly probability of 10^{-3} and 10^{-4} under the assumption of a full constellation (24 active satellites) and zero outage. Clearly, the anomaly probability has improved from 10^{-3} level to 10^{-4} level during the past three years. Dividing the total hours of anomalies by the total hours of anomalies, one can see that the average duration of an anomaly has also improved, from roughly 10 hours per anomaly in 2009 to 1 hour per anomaly in 2012.

Simultaneous multiple anomalies

Two key assumptions in ARAIM are the number of simultaneous satellite faults and the probability of constellation failure [2, 8]. For GPS, never have simultaneous multiple anomalies occurred since 2004 [19]. For GLONASS, as shown by the purple rectangles in Figure 3, simultaneous multiple anomalies have occurred four times: three were in 2009, and one in early 2010. This discovery can help ARAIM systems make correct assumptions for GLONASS. In addition, the fact that no simultaneous multiple anomalies have occurred since Feb 2010 implies an improving GLONASS SIS integrity performance over the past three years.

The simultaneous multiple anomalies on Oct 28, 2009 are definitely an eye-catcher because all 16 satellites in the constellation were anomalous. As shown in Figure 5, the constellation-wide anomalies were due to an abrupt change of broadcast clocks by approximately −90 meters (−300 ns)[7]. Unfortunately, the satellites made the change one by one, rather than at the same time. Therefore, from 13:30 UTC to midnight, the constellation consisted of satellites

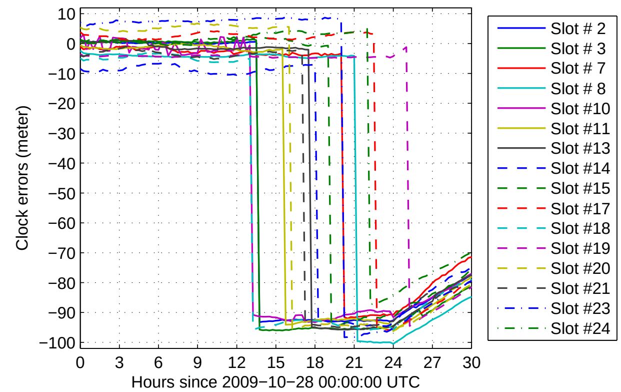

Figure 5. Broadcast clock errors of all 16 GLONASS satellites on Oct 28, 2009.

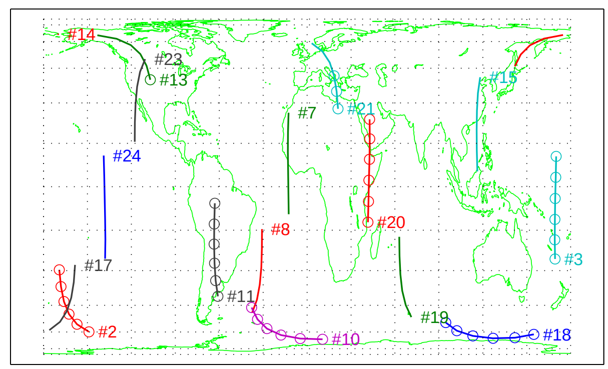

Figure 6. Ground tracks of all 16 GLONASS satellites from 16:30 to 17:45 UTC on Oct 28, 2009, when 8 satellites were anomalous. Circles indicate anomalous status.

with changed clocks and satellites with original clocks, resulting in unusual large positioning errors in many parts on the Earth. Figure 6 shows the worst period, from 16:30 to 17:45 UTC, when half of the constellation was anomalous, and a GLONASS user at any place on the Earth could see both nominal and anomalous satellites.

Geographic dependency

While GPS distributes its monitor stations worldwide [10], GLONASS SIS still relies on five monitor stations within the Russian territory [29]. The blue circles in Figure 7 show the locations of these monitor stations. Assuming a five-degree antenna mask angle, the resulting tracking coverage is illustrated by the shaded area in Figure 7. Our calculation based on the precise GLONASS ephemerides from Jan 2010 to Aug 2012 shows that on average it is 50.2% of the time for a satellite to be out of tracking coverage.

When a satellite is not under surveillance, it is more likely to become anomalous. Even worse, when such an anomaly

[7]The precise clocks show that no onboard atomic clock has a noticeable change during this event. Actually, clock correction terms in broadcast navigation messages suddenly changed because of a jump of GLONASS Time on that day [28].

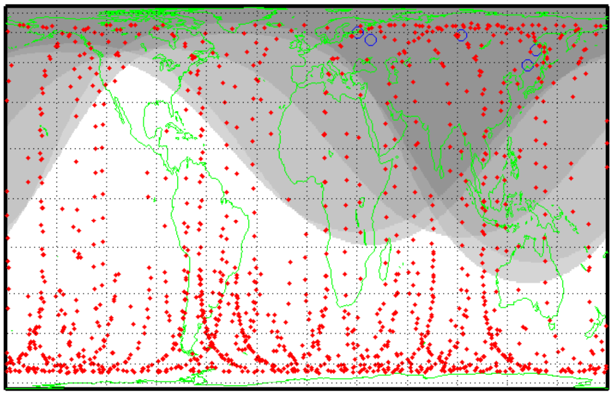

Figure 7. Ground tracks (denoted by red dots) of anomalous GLONASS satellites since Jan 2010. The blue circles represent the five existing GLONASS monitor stations [29]. The shaded areas indicate the tracking coverage of these monitor stations.

Condition	Total anomaly time	Probability
Unmonitored	212 satellite-hour	8.7×10^{-4}
Monitored	94 satellite-hour	3.9×10^{-4}

Table 1. Geographic dependency of anomaly occurrence. The statistics are based on the identified anomalies from Jan 2010 to Aug 2012.

occurs, it may last for hours until the ground control regain tracking of the satellite and fix the problem. Therefore, a reasonable hypothesis is that the occurrence of GLONASS anomalies has a geographic dependency. To verify this hypothesis, the ground tracks of anomalous GLONASS satellites since Jan 2010 are plotted in Figure 7, as shown by the red dots. Obviously, there are more red dots in the unshaded area than in the shaded area. The quantitative results in Table 1 further confirms that anomalies are more likely to occur when satellites are not monitored.

CONCLUDING REMARKS

In this paper, we devised and implemented a systematical data mining of GLONASS SIS anomalies from 80,814,366 navigation messages corrupted by data-logging errors. With defining our own statistics-based anomaly criteria that does not rely on URA, we successfully identified 192 potential SIS anomalies between Jan 1, 2009 and Aug 11, 2012. The results show that 92% anomalies are due to clock inaccuracy, and younger satellites have a better performance. The analysis of total hours of anomalies per year shows that the anomaly probability has been improving, from 10^{-3} level in 2009 to 10^{-4} level in 2012. Besides, we discovered four events of simultaneous multiple anomalies, including a constellation-wide clock change on Oct 28, 2009 that impacted all satellites. In addition, the analysis of geographic dependency shows that anomalies occur more frequently when satellites are not monitored by the GLONASS ground control.

Although the observed GLONASS performance does not quite match the current GPS performance [18,19], the GLONASS SIS does show an improving trend, especially in terms of constellation strength, anomaly probability, and occurrence of simultaneous multiple anomalies. The improvement of GLONASS SIS integrity performance will be very beneficial to not only numerous GLONASS users but also many multi-constellation GNSS applications.

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