Performance Characterization of the BeiDou-3 Constellation

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BIOGRAPHIES

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Todd Walter is a Professor at Stanford University in the Department of Aeronautics and Astronautics and director of the Stanford GPS Research Laboratory. He received his B.S. in physics from Rensselaer Polytechnic Institute and his Ph.D. in applied physics from Stanford University in 1993. He received the Thurlow and Kepler awards from the ION. In addition, he is a fellow of the ION and has served as its president.

ABSTRACT

The recent progress of the BeiDou satellite constellation requires a better understanding of its performance for future incorporation and improvement of the performance of various augmentation systems. These systems, including Advanced Receiver Autonomous Integrity Monitoring (ARAIM), Satellite-Based Augmentation System (SBAS), and Ground-Based Augmentation System (GBAS), all require a characterization of anomalous events and faulted behaviors for each constellation. Because the increase of constellations in service allow for more stringent evaluations of Global Navigation Satellite Systems (GNSS) performance which are required for the improvement of these augmentation systems, multi-GNSS constellation monitoring should be performed continuously. The addition of new constellations such as Galileo and BeiDou enhances the performance capabilities of multi-GNSS services, and, in addition to the GPS constellation, performance characterization of its constellation and associated faults should be analyzed. There is extensive past research on the faults of GPS and Galileo. However, each constellation maintains certain integrity metrics and other infrastructural design characteristics unique to the provider. Furthermore, the GPS and Galileo constellations publish notice advisory to Navstar users (NANU) and notice advisory to Galileo users (NAGU), respectively, on the signal status of satellites in the constellations due to prescheduled maintenance or unexpected events; however, there is no such public message service for the BeiDou constellation as of yet. We adapt our tools characterizing the performance of other multi-GNSS systems to also characterize the performance of the BeiDou constellation.

In this paper, we provide nominal statistics on the performance of the BeiDou constellation, specifically, the BeiDou-3 medium earth orbit (MEO) satellites. Furthermore, we provide a comparison of the analyzation period to the same for GPS and Galileo. Additionally, we provide a discussion of messaging differences between BeiDou and previously existing GNSS constellations to aid the process for determining nominal statistics and other extensions of the BeiDou constellation in the future.

I. INTRODUCTION

The use of receiver autonomous integrity monitoring (RAIM) for lateral navigation only requires the Global Positioning System (GPS). However, improved augmentation systems are under development to provide better navigation capabilities. In particular, advanced RAIM, or ARAIM, aims to support vertical navigation capabilities and its methodologies are currently under development. Such augmentation systems rely on the careful characterization of the performance of the Global Navigation Satellite Systems (GNSS) and increasingly stringent evaluations. The continual characterization of nominal performance for ongoing additions and improvements in multi-GNSS supports such stringent evaluations, and is a main focus of this paper.

Additionally, anomalous and fault events are also required for the development of augmentation systems such as ARAIM. In particular, ARAIM focuses on two types of faults: those which affect satellites independently and those which affect multiple satellites simultaneously. These types of faults are represented by the probability of satellite fault, $P_{sat}$, and the probability of constellation fault, $P_{const}$, respectively. Analysis of these values have been provided in some of the previous research work mentioned below for multi-GNSS constellations other than BeiDou. Faults occur when the average projected error exceeds the fault definition, which is specific to each constellation. Traditionally anomalous events include sudden jumps of clock run-offs and ephemeris jumps, and it is critical to gain an understanding of the onset of anomalous events in this fairly new global constellation to evaluate the timely response of detection monitors. Furthermore, Wang and Walter (2023) details the importance of examining near-fault events, which are defined to be when the average projected error exceeds a more-stringent
fault definition. These near-fault identifications, applied accordingly with the BeiDou fault definition, can also inform nominal performance evaluation. As the likelihood of these faults in the BeiDou constellation can highly impact the performance of ARAIM, therefore, the characteristics of the onset of detected faults, its duration, their likelihood, etc., are worthwhile to discuss.

Finally, the BeiDou constellation contains many differences to the GPS constellation, according to the official BeiDou Navigation Satellite System Open Service Performance Standard (BDS OS PS) (China Satellite Navigation Office, 2021) and the GPS Standard Positioning Service Performance Standard (GPS SPS PS) (Department of Defense, 2020). To give an example, the two constellations each have different ephemeris and clock update time – the GPS update time is two hours while BeiDou updates every one hour, and these differences combined will result in different performance capabilities of the constellations. Since there is no publicly available information by the control segment of BeiDou, the discovery of any anomalous events in its performance history and the characterization of these faults is instructive to understanding how augmentation systems designed for GPS will react to potentially different behaviors. Therefore, notable differences between the GPS and BeiDou constellations encountered during development of this tool will be discussed.

To this end, the long term characterization and statistical quantification of the nominal performance of GNSS and its anomalous events has been analyzed in several past research works. Walter and Blanch (2015) analyzed the GPS faults occurring over 2008-2012 and the nominal performance of the GPS constellation over an eight year period, from 2008-2015. Gunning et al. (2017) developed a constellation monitoring system to detect faults and report nominal performance expanded for multi-GNSS constellations with higher robustness to commonly occurring errors in the processing of millions of precise and broadcast navigation files needed for long-term performance monitoring. Perea et al. (2017) provided detailed user range accuracy (URA) and signal-in-space accuracy (SISA) supporting the development of ARAIM through characterization of nominal performance of the GPS constellation between 2008-2015 and the Galileo constellation for the months of March through June of 2015. Analyses of the BeiDou SIS anomalies between 2013-2016 and fault assessment between 2015-2016 were published by Wu et al. (2016) and Fan et al. (2020), respectively. Most recently, an updated nominal performance characterization and fault characterization of the Galileo constellation from 2018 to April of 2022 and GPS constellation nominal and fault characterizations from 2017 to July of 2023 have been provided by Wang and Walter (2023) and Wang et al. (2024), respectively.

This paper characterizes the nominal performance and detected anomalous events in the BeiDou constellation for two years worth of data from January 2022 to December 2023. A description of the tool to complete this characterization is detailed, and, in particular, the differences in statistical quantification method as compared to GPS and Galileo. Future updates to this paper will include characterization of multi-year performance over recent BeiDou operational history. Characterizing the BeiDou performance of the past few years will provide the integrity community with more insights on the capable services of developing augmentation algorithms and comparing the behavior to both GPS and Galileo history will also be helpful for system design.

II. PERFORMANCE EVALUATION PROCEDURE

1. Data Sources

The precise ephemeris and broadcast navigation files are collected to perform the comparison between the precise and broadcast values. The precise ephemeris and clock products are provided by many different processing centers at various higher sampling rates, such as five-minute and 30-second rates. Historically, the center for orbit determination in Europe (CODE) is most commonly used for similar characterization of other GNSS such as Galileo, but precise products from the Wuhan University (WHU) processing center is chosen here due to varying availability of the orbit and clock solutions. Figure 1 compares the differences in availability of the orbit and clock solutions between CODE and WHU. Although precise products from the WHU processing center seems to carry a greater number of solutions, the data availability rate is roughly the same after gathering the two years worth of data in the analyzation period. All results in this paper for BeiDou are calculated with the WHU precise products since the majority of existing literature also chooses to use WHU precise products. The broadcast navigation files are provided by the International GNSS Service (IGS) Multi-GNSS Experiment Project (MGEX) with receiver stations worldwide.


Figure 1: Comparison of precise product availability between CODE and WHU processing centers for April 10-15, 2023. Green indicates satellites with valid observations, blue indicates satellites which are unhealthy, pink indicates instances where there is no broadcast ephemeris, and red circles indicate a fault. The faint gray line indicates that the satellite was not yet in operation, and black lines represent neither truth nor broadcast data.

Additionally, the precise products are measured to the satellites’ center of mass, but estimates in the broadcast navigation files refer to the antenna phase center. To translate the IGS precise ephemeris from the center of mass to the antenna phase center, IGS-provided antenna phase center offset information saved in the ANTEX format is required. The newer version igs20.atx should be used to obtain the antenna phase center offset information for more recently launched BeiDou satellites.

2. File Cleaning

Before comparing the broadcast and precise ephemeris and clock products, pre-processing procedures are taken to ensure the best and most accurate set of broadcast estimates. This is because navigation messages are subject to logging errors, such as rounding errors due to truncation or when parameters are not stored in a RINEX compliant manner. To cull the broadcast navigation files down to one single combined file, we evaluate all available navigation files collected by the hundreds of receivers in the IGS network at each sampling time and perform our own voting scheme which resolves the two commonly seen issues mentioned above and includes other confidence checks. These mitigation solutions to avoid the use of erroneous files is described in greater detail in Gunning et al. (2017). A map showing the number of stations in the IGS network is shown in Figure 2.
3. Broadcast & Precise Ephemeris Comparison

Finally, the broadcast message logs and precise ephemeris must be propagated before they are ready to be compared. For the BeiDou constellation, the update time between each message is one hour, compared to the two-hour ephemeris message update for GPS and ten-minute ephemeris update for Galileo. The five-minute precise orbit products can be propagated to match the 30-second clock products using a Lagrange interpolation method (Gunning et al., 2017). In practice, this higher-rate sampling rate is only used for characterizing faults or specific anomalies of interest, since millions of data points are compared in this characterization method, especially when the period of interest is over a duration of years. These faults are either identified by characterization at five-minute sampling rate, or through public messages by the control segment (CS) of the constellation service provider (CSP), such as through the notice advisory to Navstar users (NANU) and notice advisory to Galileo users (NAGU) for GPS and Galileo, respectively. Therefore, in this paper, a five-minute interval is used, and the broadcast ephemeris are propagated while the precise ephemeris are already provided at the five-minute rate and do not need to be propagated.

With this set of matching broadcast navigation files at higher confidence and the translated precise orbit and clock products for each desired epoch, the difference is taken between these two sets of files at matching epochs and statistical results to characterize performance of the constellation for the desired period of time is obtained. The next section details the methods used to obtain the performance characterization.

a) Orbital Error

The orbital error may be calculated by taking the difference of the precise and broadcast satellite positions. Using the broadcast orbital parameters and the standard least squares positioning solution provided in the ICD (China Satellite Navigation Office, 2021), the orbital solutions can be propagated to the desired epochs using the broadcast $\dot{\Omega}$, the rate of right ascension.

b) Clock Error

The clock error is calculated by taking the difference of the precise and broadcast clock biases. The WHU precise clock products are produced as B1/B3 dual-frequency ionosphere-free observables (WHU paper). However, the broadcast navigation parameters are a B3 single-frequency observable. Using the broadcast TGD1 value, which gives the total group delay value from B1 to B3, the B1/B3 dual-frequency ionosphere-free observable can be obtained for the broadcast clock offset. An additional correction is made to the broadcast clock offset, which we call the precise time realization correction, which accounts for the the errors accumulated from differences in the global satellite clock reference and processing center clock reference, and is shown in Equation 3 below:
\[ \delta t_i = \delta t_{brdc,i} - \delta t_{pre,i} + \Delta_{preTimeRealCorr,i} \]  

\[ \delta t_{brdc,i} = a_0 + a_1(t - t_{oc} - \Delta_{LPsec}) + a_2(t - t_{oc} - \Delta_{LPsec})^2 + \Delta t_{rel} - \frac{\beta}{\beta - 1} \ast TGD1 \]  

\[ \Delta_{preTimeRealCorr,i} = \frac{1}{n} \sum_{k=1}^{n} (\delta t_{brdc,ik} - \delta t_{pre,ik}) \]  

Equation 2 shows the propagation of the broadcast clock offset to match the rate of the precise clock product, \( i \) shows the epoch of data comparison, \( n \) is the number of SVNs in the dataset, \( \beta = \frac{f_{bic}}{f_{bsl}} \), \( \Delta_{LPsec} \) is currently 4 seconds from UTC time, and \( \Delta t_{rel} \) is defined in China Satellite Navigation Office (2021). \( \delta t_{brdc,i} \) is the propagated broadcast SV clock bias and \( \delta t_{pre,i} \) is the precise SV clock offset.

### III. SATELLITE ERROR SOURCES

The largest error sources affecting the performance of a constellation are typically due to satellite clock and ephemeris errors. Other smaller error sources include but are not limited to errors from the ground control center or physical satellite, ranging signal deformation errors, incoherence between the signal code and carrier, biases between signals at different frequencies, and biases in the satellite’s broadcast antenna described in Hernandez (2012) and Blanch et al. (2013).

Error sources unrelated to the satellite performance can also affect the characterization, such as ionospheric and tropospheric modeling error, multipath, receiver antenna group delay, noise and interference, and receiver antenna biases. Several methods exist to mitigate these error sources. For example, ionospheric errors can be corrected through applying a model of the ionosphere with several (eight) coefficients broadcast in the navigation message in the case of a single frequency receiver; in the case of dual frequency receivers, the simultaneous measurement of the pseudorange from both satellite frequencies can reduce the error.

To account for these errors, the user range accuracy parameter, \( \sigma_{URA} \), \( P_{sat} \), and \( P_{const} \) bounds these errors. Specifically, error sources unrelated to the satellite performance remain as nominal ranging errors and are bounded by the \( \sigma_{URA} \). When errors induced by the satellite clock and ephemeris errors present as faults, they are bounded by \( P_{sat} \) and \( P_{const} \). The following performance characterization serves to validate these parameters guaranteed by the constellation service provider.

### IV. BEIDOU SERVICE HISTORY

Figure 3 shows a performance overview of the BeiDou operational history over the two-year duration from 2022 to 2023. The left vertical axis denotes the satellite vehicle number (SVN). Here, the pseudorandom noise (PRN) codes are displayed to maintain consistency with previous literature. Although an SVN value is assigned to each PRN in the igs20.atx file, there have been no prominent and uniform naming convention of the BeiDou SVN aside from its PRN values. The right vertical axis shows the satellites grouped by defining system characteristics, such as its generation, satellite orbit, clock type, etc. Since only BeiDou-3 MEO satellites were chosen in this paper, only one group is displayed. The horizontal axis shows the duration of analysis, representing a comparison made between the post-processed precise and broadcast files at five-minute intervals. The green color indicates healthy status of the satellite, and the blue color indicates that the satellite was unhealthy. When a comparison is unable to be made, the yellow color indicates the cause to be missing precise data, and the pink color denotes missing broadcast data. Red circles denote when faults have occurred, and there are no faults identified during this period for the BeiDou-3 MEO satellites. Currently, the fault definition of 4.42 \( \ast \sigma_{URA} \) as specified in the International Civil Aviation Organization (ICAO) Standards and Recommended Practices (SARPS) document for the BeiDou B1I signal is used to identify faults in BeiDou (International Civil Aviation Organization, 2023). As mentioned in Wu et al. (2016), from an analysis period of 2013-2016, it was found that the broadcast URA was generally optimistic for BeiDou satellites, especially for those in geostationary (GEO) orbit. Therefore, this is an interim specification and may be updated once the BeiDou constellation provider publishes their own fault definition, since it is not detailed explicitly in the BeiDou Open Service (OS) Performance Standard (PS) (China Satellite Navigation Office, 2021). BeiDou-3 was fault-free during 2022-2023.

Figure 4 shows the same plot as Figure 3 but separated by each year. It is apparent that there was much more missing truth data for 2023 than in 2022. Additionally, though not included in this paper, the CODE precise products were also evaluated for the duration 2022-2023, and it was found that the CODE had 1% more truth data availability, as seen in Table 1.
**Figure 3:** Summary of observations for each satellite during 2022-2023. Green indicates satellites with valid observations, blue indicates satellites which are unhealthy, pink indicates instances where there is no broadcast ephemeris, and red circles indicate a fault. The faint gray line indicates that the satellite was not yet in operation, and black lines represent neither truth nor broadcast data.

**Figure 4:** Summary of Beidou data availability separated for 2022 and 2023.

(a) BeiDou data comparison history in 2022.  
(b) BeiDou data comparison history in 2023.
V. OBSERVED ERROR DISTRIBUTION

The projected user range error is useful to show the degree of guarantee of the $\sigma_{URA}$ as it serves to bound the errors that occur in the constellation. Figure 5 shows the one minus the cumulative distribution function (CDF) for the maximum projected error (MPE) over 2022-2023. Specifically, Figure 5a shows the probability of occurrence of the normalized MPE per satellite during 2022. The black line shows the aggregate MPE of all the satellites, and the red line represents the broadcast $\sigma_{URA}$ bound as a zero mean, one standard deviation Gaussian bound since the MPEs are normalized. Typically, the line representing this bound extends down to and ends at $1 \times 10^{-5}$, which refers to the satellite fault rate specified in the 8th edition of the ICAO (International Civil Aviation Organization, 2023); however, a modified bound is plotted here which more clearly represents the bounds on both nominal errors and fault events described by the $P_{sat}$ and $\sigma_{URA}$ commitments. Figure 5b shows the same statistical data as Figure 5a but over just 2023. Although the maximum MPE error in 2023 was greater than that of 2022, the majority of the satellites improved in accuracy between 2022 and 2023.

![Image of Figure 5a](image1.png)

(a) One minus CDF of normalized user projected range error in 2022.

![Image of Figure 5b](image2.png)

(b) One minus CDF of normalized user projected range error in 2023.

Figure 5: One minus CDF of normalized user projected range error for BeiDou-3.

Figure 6 shows the one and two standard deviation error of the radial-track, along-track, cross-track, clock (RAXC) errors and normalized instantaneous user range error (IURE). More specifically, the thick black vertical line in each row representing one satellite describes the mean error, the green bar is the one standard deviation error, and the red bar is the error two standard deviations away. Above the dotted line at the top of Figure 6 shows the aggregate of the errors by block, and then of all the satellites evaluated. Figure 6a and Figure 6b shows the bar plot of the RAXC errors separated over 2022 and 2023. In this data visualization, it is not apparent whether there was a significant improvement in accuracy between the two years. Furthermore, the clock error accumulates more error than the orbital errors, and contributes the most to the normalized IURE error. This observation in the clock errors is worth examining in greater detail in future work.

<table>
<thead>
<tr>
<th>Processing Center</th>
<th>Data Availability</th>
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<tbody>
<tr>
<td>CODE</td>
<td>97.7%</td>
</tr>
<tr>
<td>WHU</td>
<td>96.7%</td>
</tr>
</tbody>
</table>

Table 1: Percentage of precise products data availability for 2022-2023 for BeiDou-3 satellites.
Figure 6: RAXC error bar plots for 2022 and 2023 performance, where green denotes the one sigma standard deviation error and red denotes the two sigma standard deviation error.

Figure 7 shows the probability distribution function (PDF) of the RAXC errors compared between 2022 and 2023. We see that the tail errors within approximately two standard deviations from the mean is at a lower probability of occurrence in 2023 than those of 2022 for the along-track and cross-track error components, and the radial-track orbital errors improved slightly in 2023.

VI. COMPARISON OF BEIDOU-3, GPS, & GALILEO OBSERVED ERROR DISTRIBUTIONS

The following figures provide a comparison of BeiDou-3 MEO satellite performance to GPS and Galileo performance for the two-year duration of 2022-2023. The red circles representing faulted periods are in Figures 8b and 8c since there were a few faults during this period for GPS and Galileo. It is also apparent that there is much greater availability of truth data in the GPS and Galileo characterization as shown by the barely existing yellow markers on the plot. Table 2 shows the percent of data availability for all three constellations. Considering that faults can occur for very short period of time, i.e. less than one hour, it is necessary to obtain as many valid comparisons as possible to determine whether the constellation was truly fault-free and operating at its commitment level.
<table>
<thead>
<tr>
<th>GNSS Constellation</th>
<th>Precise Products Availability</th>
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<tbody>
<tr>
<td>BeiDou-3</td>
<td>96.7%</td>
</tr>
<tr>
<td>GPS</td>
<td>99.999%</td>
</tr>
<tr>
<td>Galileo</td>
<td>99.996%</td>
</tr>
</tbody>
</table>

**Table 2:** Percentage of precise products data availability for 2022-2023 for each constellation.

From Figure 9, it can be seen that the one sigma URA overbound for the user projected range errors of Galileo satellites is much more conservative than that of the BeiDou-3 MEO satellites. SVN 210 in Figure 9c extends and follows the tail of the Gaussian bound plotted in red since it faulted twice in 2022. In Figure 9b, both SVN 58 and 63 faulted, and therefore also follow the tail behavior. In the case of SVN 63, the faults likely lasted longer than the commitment, thus exceeding the bound. It is also worthwhile to note that while BeiDou-3 accuracy performs slightly better than the plot of GPS MPEs, BeiDou-3 MPEs are currently normalized by the stipulated 7 m, while GPS errors are normalized by its true broadcast URA value, which is typically 2.4 m or 3.4 m.

Figures 10 and 11 show the RAXC error distribution and PDF of the RAXC errors over 2022-2023 for BeiDou-3, GPS, and Galileo, respectively. It is apparent that the one and two standard deviation RAXC errors for Galileo are much smaller than GPS and BeiDou-3, but the RAX errors in BeiDou-3 also have very low error levels. Table 3 reports the one and two standard...
<table>
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<tr>
<th>GNSS Constellation</th>
<th>$1\sigma$</th>
<th>$2\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BeiDou-3</td>
<td>0.78 m</td>
<td>1.32 m</td>
</tr>
<tr>
<td>GPS</td>
<td>0.34 m</td>
<td>0.72 m</td>
</tr>
<tr>
<td>Galileo</td>
<td>0.18 m</td>
<td>0.34 m</td>
</tr>
</tbody>
</table>

Table 3: IURE Errors of Compared Constellations

deviation IURE errors for each GNSS constellation. In Figures 11b and 11c, the large probability of ±20 m errors just shows that there are greater errors beyond this point, but are not plotted since it is affected by the fault events.

Figure 9: Comparison of error distributions of user range error for 2022-2023 between BeiDou-3, GPS, and Galileo.
Figure 10: Comparison of the one and two standard deviation RAXC errors for 2022-2023 between BeiDou-3, GPS, and Galileo.
VII. CONCLUSION

The observed nominal errors are shown in this paper for BeiDou-3 MEO satellites over 2022-2023 and a comparison to two other GNSS constellations, GPS and Galileo, are also provided. Over this duration, no faults were detected in the BeiDou-3 MEO satellites. Regarding the one minus CDF plot of the MPE, given the normalization $\sigma_{URA}$ parameter of a constant 7 m as the value as detailed in the ICAO SARPS, the one sigma URA bound is still less conservative as compared to that of both the Galileo and GPS constellations. Similarly, compared to that of Galileo, the RAXC errors for both one and two standard deviations are still higher in BeiDou-3. Galileo’s higher accuracy and lower errors could be due to its higher ephemeris upload rate, which does contribute to more accurate values in the broadcast navigation message. Contrary to what has been seen for both Galileo and GPS signal-in-space performance characterization, truth data is not available for BeiDou as often. Such frequent occurrences of lack of precise ephemeris and clock products may skew the results of the performance characterization, since it is important to maintain as many valid comparisons as possible during the duration of analysis. In the future, it will be worthwhile to create a tool to process precise products from multiple centers in order to obtain a more populated precise product dataset. However, given the available comparisons, BeiDou-3 MEOs perform well. Additionally, a ”Notice Advisory to BeiDou Users (NABU)” or something of similar function can be considered for greater transparency between the operators and users on the status and performance of BeiDou satellites. Finally, it is worth considering incorporating operational commitments into official BeiDou documentation, such as the various ICD or OS PS documentations. Currently, both GPS and Galileo operational commitments are defined in their official documentation, while the commitments used in this research for BeiDou-3 was only documented in the ICAO SARPS.
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