WAAS Ionospheric Grid Broadcast Characteristics and Performance Evaluation Postprint

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Abstract

Ionospheric grid information determines the service level of SBAS augmentation systems under the RTCA protocol. Through long-term analysis of ionospheric grid information broadcast by WAAS's three GEO satellites, detailed broadcast characteristics of grid ionosphere under the RTCA protocol were obtained regarding message format, update interval, and grid distribution. By parsing actual WAAS ionospheric grid messages and setting different availability conditions, the availability of each grid point was analyzed in detail. The results show that when using GIV EI = 15 as the threshold, WAAS broadcasts 263 ionospheric grid points with 100% availability, covering the entire North American continent and most areas beyond 20° from the coastline. By comparing the grid availability of Kriging used by WAAS and the IDWK interpolation method used by some other augmentation systems, it is concluded that the IDWK method only provides high availability for grid points within the deployment range of reference stations, while the Kriging interpolation method significantly expands the coverage of available grid points at the cost of increased GIVE, but also renders grid points over the Hawaiian Islands, which are separated from the mainland, completely unavailable. Using the GIM model published by CODE to analyze the grid correction accuracy of WAAS available grid points, it is found that when GIV EI < 14, the correction accuracy differences for grid ionospheric vertical delays among different GIVEI values are relatively small, and the correction accuracy of grid ionospheric vertical delays assessed by GIM exhibits strong latitude dependence. Although pierce points are densely distributed in low and mid-latitude regions, their grid correction accuracy is lower than that in high-latitude regions.

Full Text

Broadcast Characteristics and Performance Evaluation of WAAS Ionospheric Grid

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Abstract

Ionospheric grid information determines the service level of Satellite-Based Augmentation Systems (SBAS) operating under the RTCA protocol. Through long-term analysis of ionospheric grid information broadcast by three WAAS GEO satellites, we obtain detailed broadcast characteristics of grid ionosphere under the RTCA protocol in terms of message arrangement, update period, and grid distribution. By parsing actual WAAS ionospheric grid messages and setting different availability conditions, we analyze the availability of each grid point in detail. When using GIVEI = 15 as the threshold, WAAS broadcasts 263 ionospheric grid messages with 100% availability, covering the entire North American continent and most areas extending 20° beyond the coastline. Comparing the grid availability of WAAS using Kriging interpolation with that of other augmentation systems using IDWK interpolation, we conclude that the IDWK method only provides high availability for grid points within the reference station deployment range. The Kriging interpolation method significantly expands the coverage of available grid points at the cost of increasing GIVE, but also renders grid points over the Hawaiian Islands, which are separated from the mainland, completely unavailable. Using the GIM model published by CODE to analyze the correction accuracy of WAAS available grid points, we find that when GIVEI < 14, the correction accuracy differences of grid ionospheric vertical delay among different GIVEI values are relatively small. The correction accuracy of grid ionospheric vertical delay evaluated by GIM shows strong correlation with latitude. Although the distribution of ionospheric pierce points is dense in mid- and low-latitude regions, the grid correction accuracy is lower than that in high-latitude regions.

Keywords: WAAS; ionosphere grid; broadcast characteristics; availability; accuracy

1 Introduction

To improve GPS navigation performance and reduce operational risks, the U.S. Federal Aviation Administration (FAA) initiated the development of the Wide Area Augmentation System (WAAS) in 1992, which was officially approved for safety-of-life applications in July 2003 [1]. WAAS consists of 38 reference stations, 3 master stations, 6 uplink stations, and 3 GEO satellite payloads [2], and has been widely deployed across the continental United States and most of Alaska to provide aviation users with LPV-200 augmentation services from en-route phases through approaches with vertical guidance. Its accuracy, integrity, continuity, and availability represent substantial improvements over basic GPS navigation. Similar wide-area augmentation systems have been subsequently established in Europe, Japan, Russia, and India. These systems broadcast satellite ephemeris, clock corrections, ionospheric corrections, and modified error bounds via GEO L1C/A signals to provide GPS L1C/A single-frequency users with satellite-based augmentation services, with message formatting following the RTCA DO-229E standard [3] published by the Radio Technical Commission for Aeronautics.

Ionospheric delay represents one of the most significant error sources in single-frequency non-differential positioning. In wide-area augmentation services, grid ionosphere determines the service level of the augmentation system. The RTCA DO-229E standard specifies that if ionospheric grid information is not received, the augmentation system can only provide Non-Precision Approach (NPA) services. China's BeiDou Satellite-Based Augmentation System (BDSBAS), currently under development, will achieve compatibility and interoperability with other international augmentation systems, providing both single-frequency augmentation services based on L1/CA signal broadcast and dual-frequency multi-constellation (DFMC) augmentation services based on L5 broadcast [4]. Investigating the message arrangement, broadcast characteristics, grid availability, and vertical delay correction accuracy of ionospheric grid information from the mature WAAS system is beneficial for users to correctly utilize grid ionospheric correction information and provides valuable reference for China's single-frequency satellite-based augmentation system under construction.

2 Ionospheric Grid Information Arrangement Based on RTCA Protocol

Each WAAS message frame consists of 250 bits with a broadcast duration of 1 second. The highest 8 bits constitute the synchronization header sequence, followed by 6 bits indicating the message type, and the lowest 24 bits are cyclic redundancy check bits, leaving 212 bits for the data field. Due to limited uplink bandwidth preventing broadcast of ionospheric grid information for arbitrary locations, the RTCA interface protocol divides the globe into 11 bands (numbered 0–10), with each band containing at most 201 grid points. The system broadcasts grid point masks that define the positions of ionospheric grid points to map the required grid ionospheric delay information, transmitting only ionospheric grid information corresponding to bit values of 1 in the mask sequence for specific bands. This approach provides the most efficient ionospheric model.

Grid point masks are represented by Message Type 18 (Type 18) as defined in . Type 18 specifies the band number to which its mask applies, with the total number of bands indicating how many band masks are broadcast by the current

GEO satellite, enabling users to confirm receipt of all ionospheric-related data. Each Type 18 frame can broadcast the grid mask for one band.

Message Type 26 (Type 26) contains Grid Ionospheric Vertical Delay (GIVD) and Grid Ionospheric Vertical Error (GIVE). GIVE represents the envelope of ionospheric residual errors at 99.9% confidence probability [5], while GIVEI is the grid ionospheric vertical error indicator with a mapping relationship to GIVE defined in RTCA-DO229E. The specific definition of Type 26 is provided in . Both Type 18 and Type 26 frames include the Issue of Data Ionospheric (IODI) to ensure receivers correctly parse ionospheric corrections. Type 26 information is only usable when the IODI in Type 18 matches the IODI in Type 26. Each Type 26 frame can broadcast ionospheric information for 15 valid grid points where the corresponding mask bit is 1 in Type 18, requiring multiple frames to broadcast all grid ionospheric delay information for one band. The "…" in indicates that remaining grid points in the same section follow the same cyclic pattern as Grid Point 1 and Grid Point 2.

3 Analysis of WAAS Ionospheric Grid Broadcast Characteristics

WAAS augmentation messages can be downloaded from ftp://nstb.tc.faa.gov, with all message types for each GEO satellite stored as a daily file. WAAS operates three GEO satellites at PRN 131, PRN 135, and PRN 138, positioned at 117°W, 133°W, and 107.3°W, respectively. We downloaded WAAS messages for all three GEO satellites from January 1, 2019, to January 31, 2019, and parsed them according to the RTCA DO-229E protocol.

Comparative analysis of Type 18 and Type 26 messages from the three GEO satellites on January 1, 2019, revealed that although PRN 131, 135, and 138 have different coverage areas, each satellite broadcasts identical ionospheric information with completely consistent ionospheric data versions and content. Using PRN 135 as an example for analyzing overall grid ionosphere broadcast characteristics, we found through analysis of January 2019 message data that the ionospheric data version number IODI remained unchanged at 0 for the entire period, indicating constant broadcast band totals, band numbers, and specific grids. Overall, WAAS broadcasts ionospheric mask information for five bands numbered 0, 1, 2, 3, and 9, occupying 5 message frames and requiring 5 seconds to broadcast Type 18 per update cycle. Each band and its corresponding total number of sections are shown in , broadcasting a total of 306 grid point messages across 23 sections, occupying 23 message frames and requiring 23 seconds to broadcast Type 26 per update cycle.

The RTCA protocol specifies maximum update times for each message type, with both Type 18 and Type 26 having a prescribed update period of 300 seconds and timeout period of 1,200 seconds. Analysis of Type 18 and Type 26 message update periods in January 2019 revealed that Type 18 ionospheric mask update intervals averaged 219.2 seconds, with a minimum of 144 seconds and maximum of 259 seconds, as shown in [Figure 1: see original paper]. Type 26 ionospheric delay update intervals averaged 288.2 seconds, with a minimum of 288 seconds and maximum of 302 seconds, as shown in [Figure 2: see original paper]. These intervals comply with RTCA protocol requirements.

4 Analysis of WAAS Ionospheric Grid Information Availability

WAAS models the complex ionosphere as a thin shell at 350 km altitude [3] serving as the ionospheric reference surface. This reference surface is divided into grids at specific intervals. Each reference station calculates real-time ionospheric delays for visible navigation satellites while simultaneously computing pierce point latitudes and longitudes on the ionospheric grid surface. Based on pierce point information, the system estimates grid ionospheric vertical delays and GIVEI within the service area. Grid ionosphere availability correlates with reference station and pierce point distribution. [Figure 3: see original paper] shows the distribution of 38 WAAS reference stations, with coordinates obtained from literature [1]. [Figure 4: see original paper] presents the ionospheric pierce point distribution over seven consecutive days from January 1, 2019, to January 7, 2019.

The RTCA DO-229E standard specifies that in precision approach service mode, all WAAS corrections must be used, and a grid point is unavailable when GIVEI equals 15. [Figure 5: see original paper] illustrates the distribution of 306 broadcast grid points and their availability, calculated using Equation (1):

$$AOA = \frac{\sum_{t=t_{start}}^{t_{end}} B_{oot}(t) = True}{t_{end} - t_{start}}$$

where t_{start} and t_{end} represent the start and end times of a test dataset, respectively; T is the fixed epoch time interval, and $B_{oot}(t) = 1$ if GIVEI < 15 at current epoch t, otherwise $B_{oot}(t) = 0$.

Statistical analysis of [Figure 5: see original paper] shows that using GIVEI $<$ 15 as the availability condition, WAAS broadcasts 263 ionospheric grid messages with 100% availability, covering the entire North American continent and most areas extending 20° beyond the coastline. However, in the Hawaiian Islands region, despite having one reference station deployed, surrounding grid points show 0% availability. GIVEI reflects the accuracy of grid point ionospheric delays and is used to calculate user horizontal and vertical protection levels. Larger GIVEI values affect service availability, while GIVEI values too small to envelope grid ionospheric delay errors may trigger hazardous misleading information. Different WAAS grid availability conditions yield different statistical results. lists WAAS grid availability statistics under five conditions.

As shown in , as the GIVEI availability threshold decreases, the number of high-availability grids decreases while low-availability grids increase. When the

GIVEI threshold is 11, only 54 grids remain with availability greater than 99.9%, showing a cliff-like reduction. [Figure 6: see original paper] presents WAAS ionospheric grid availability when the GIVEI threshold is 11.

WAAS initially used the Inverse Distance Weighted (IDW) algorithm to calculate grid ionospheric delay information [6]. To ensure continuity across the entire grid model, a nominal delay model was introduced on the IDW basis, developing the Inverse Distance Weighted with Klobuchar (IDWK) algorithm [7–9]. India's GPS and GEO Augmented Navigation System (GAGAN) [10,11] and China's BeiDou system also use the IDWK algorithm for grid ionosphere calculations. The IDW and IDWK algorithms offer advantages of speed and simplicity, providing good spatial interpolation accuracy for samples with high observation density, but suffer from decreased interpolation accuracy and grid point availability in edge regions and areas with sparse observations. Currently, WAAS employs a Kriging spatial correlation interpolation scheme to calculate grid ionospheric vertical delays [12] and uses a chi-square test algorithm based on ionospheric anomaly states to calculate GIVE [13].

The grid availability shown in [Figure 5: see original paper], [Figure 6: see original paper], and is calculated using the Kriging interpolation method. [Figure 7: see original paper] presents WAAS grid availability solved using the IDWK method (with availability threshold GIVEI = 15). As shown in [Figure 7: see original paper], high-availability grid points are located within the continental United States, Alaska, and areas with pierce point distribution, essentially matching the reference station deployment range. The Hawaiian Islands region, having deployed a reference station, can solve grid ionospheric delay information during some periods. Comparing grid availability between Kriging and IDWK interpolation methods reveals that Kriging significantly expands the coverage of available grid points but renders grid points near the Hawaiian Islands, separated from the mainland, completely unavailable.

5 Analysis of WAAS Grid Ionospheric Vertical Delay Correction Accuracy

This paper evaluates the correction accuracy of GIVD using the Global Ionosphere Map (GIM) published by the Center for Orbit Determination in Europe (CODE) [14,15] for the entire day of January 1, 2019. classifies and statistically analyzes the 306 grid points provided by WAAS according to different GIVEI values. Statistical results show that when GIVEI < 14, the correction accuracy differences of grid ionospheric vertical delay among different GIVEI values are relatively small, with GIM-evaluated RMS values ranging from 0.170 to 0.248 m. When GIVEI = 14, the GIM-evaluated RMS is significantly larger than cases where GIVEI < 14.

Statistical analysis of correction accuracy for all grid points with GIVEI < 15 is presented in [Figure 8: see original paper]. The results show that grid ionospheric vertical delay correction accuracy has weak correlation with reference station and pierce point distribution but strong correlation with latitude. In mid- and low-latitude regions (south of 40°N), grid ionospheric vertical delay correction accuracy is lower than in high-latitude regions.

[Figure 9: see original paper] and [Figure 10: see original paper] show the grid ionospheric vertical delay correction errors at grid points located at 100°W, 25°N and 150°W, 65°N, respectively, spanning the entire day of January 1, 2019. Comparison reveals that ionospheric vertical delay errors can correct most ionospheric delay errors in both mid-low and high-latitude regions. In mid- and low-latitude regions where ionospheric delay values are larger, the residual errors after correction are correspondingly larger. In high-latitude regions where ionospheric delay values are smaller, the residual errors after correction are correspondingly smaller.

This chapter only uses CODE's GIM products to preliminarily analyze GIVD correction accuracy. Future work will employ high-precision dual-frequency observations from GNSS monitoring stations not participating in WAAS grid ionosphere solutions to further calculate and analyze WAAS grid ionospheric vertical delay correction accuracy and evaluate the envelope capability of GIVE.

6 Conclusions

This paper conducts statistical analysis of ionospheric grid information broadcast by three WAAS GEO satellites, evaluates grid ionosphere availability under different availability conditions, and calculates the correction accuracy of WAAS grid ionospheric vertical delay using CODE's GIM model. The main conclusions are as follows:

(1) Regarding broadcast characteristics: The three GEO satellites broadcast identical ionospheric information, and the ionospheric data version number IODI remains unchanged over long periods, indicating constant grid quantities and distributions within each update cycle. WAAS broadcasts a total of 306 grid point messages, requiring 5 frames for Type 18 and 23 frames for Type 26. The update periods for both Type 18 and Type 26 satisfy RTCA protocol requirements.

(2) Regarding grid availability: Using GIVEI = 15 as the threshold, WAAS broadcasts 263 ionospheric grid messages with 100% availability, covering the entire North American continent and most areas extending 20° beyond the coastline—far exceeding the pierce point distribution range. Grid points in areas with sparse pierce points have larger GIVEI values than those in dense pierce point areas. Using GIVEI = 11 as the threshold, WAAS can only broadcast 54 ionospheric grid messages with 100% availability, covering only the continental United States, Alaska, and some dense pierce point areas. Comparison between Kriging and IDWK interpolation methods shows that IDWK only provides high availability for grid points within the reference station deployment range, while Kriging

significantly expands available grid coverage but renders grid points near the Hawaiian Islands completely unavailable.

(3) Regarding grid correction accuracy: When GIVEI = 14, grid ionospheric vertical delay correction errors are larger than when GIVEI < 14. For GIVEI < 14, correction accuracy differences among different GIVEI values are relatively small, with GIM-evaluated RMS values of 0.170–0.248 m. The GIM-evaluated correction accuracy of grid ionospheric vertical delay shows weak correlation with reference station and pierce point distribution but strong correlation with latitude. In mid- and low-latitude regions (south of 40°N), grid ionospheric vertical delay correction accuracy is lower than in high-latitude regions.

References

[1] FAA William J. Wide Area Augmentation System Performance Analysis Report#68. http://www.nstb.tc.faa.gov/, 2019
[2] http://www.nstb.tc.faa.gov, 2020
[3] SC-159. Minimum Operational Performance Standard for Global Positioning System/Wide Area Augmentation System Airborne Equipment [S]. Washington DC: RTCA, 2016: 33
[4] http://m.beidou.gov.cn, 2020
[5] Peter J G, Teunissen O M. Springer Handbook of Global Navigation Satellite. Cham, Switzerland: Springer International Publishing AG, 2017: 1285
[6] Specification for Wide Area Augmentation (WAAS)[S]. US: Federal Aviation Administration, 1994: 58
[7] Chao Yi-chung, Tsai Y, Walter T, et al. Proceedings of ION NTM-95. Anaheim: CA, 1995: 531
[8] M Bakry El-Arini, Patricia O'Donnell, Paul Kellam, et al. Proceedings of ION NTM-95. Anaheim: CA, 1995: 485
[9] 陈金平. 博士论文. 郑州: 信息工程大学, 2001: 94
[10] Prasad N, Sarma A D. Indian Geophys Union, 2004, 8(4): 319
[11] Prasad N, Sarma A D. GPS Solutions, 2007, 11: 281
[12] Blanch J. Proceedings of ION GPS. Portland: UT, 2002: 816
[13] Walter T, Hansen A, Blanch J, et al. Proceedings of ION GPS. Salt Lake City: UT, 2000: 209
[14] Schaer S. How to use CODE's global ionosphere maps. http://aiuws.unibe.ch/ionosphere/, 2017: 1
[15] Schaer S, Gurtner W, Feltens J. Proceedings of the IGS AC Workshop. Darmstadt: University of Berne, 1998: 1

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