Analysis on the Integrity Simulation of BeiDou Dual-Frequency Satellite-Based Augmentation System

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Abstract*—With the continuous development of GNSS applications, in order to satisfy high precision, high integrity demands for different users, especially aviation users, many countries are striving to develop Satellite-Based Augmentation Systems (SBAS). The BeiDou augmentation system is developed based on the BDS. To take full advantage of increasing satellite navigation systems, SBAS is gradually designed from single frequency to dual frequency, which is an important research issue of Satellite Based Augmentation System Interoperability Working Group. Based on the characteristics of dual-frequency SBAS (DF SBAS)system, the connotation of DF SBAS integrity is summarized, and the structure of BeiDou dual-frequency SBAS system is analyzed with the development plan of BDS. Aimed at the problem that SBAS integrity parameters are relatively conservative, a dual-frequency SBAS integrity optimization algorithm is proposed to optimize the SBAS weight matrix. The SBAS Simulator software is used to validate the integrity availability of BeiDou dual-frequency SBAS system in China and the surrounding areas. The results show that the SBAS algorithm can effectively reduce the HPL and VPL value, and improve the system availability.

Keywords—BeiDou satellite navigation system; Satellite-Based Augmentation System; dual-frequency; integrity

I. INTRODUCTION

With the application of GNSS fields expanded, some high-precision users, especially aviation users have some higher requirements in integrity. Consequently, the Satellite Based Augmentation System (SBAS) comes into public vision. Although the integrity anomalies are rare but often fatal, especially for aerospace and other integrity strict applications[1]. Integrity is the capability of sending the alarm to the users timely when the navigation system cannot be used, which is a significant parameter of reliability to the system. The performance is measured in terms of the alert limit、integrity risk and alarm time[2]. SBAS generates vector corrections for satellite clock and ephemeris errors and ionospheric corrections at designated grid points by deploying multiple reference stations over a wide geographic area[3].

Several methods exist to provide integrity. One well-established method of distributing integrity information uses of SBAS, another approach is the GBAS system for local differentia[4]l, and the RAIM algorithm for receivers[5]. Several Satellite Based Augmentation Systems are currently in use by the aviation community and a number of others are under development. WAAS covers the US Air Space, whereas EGNOS covers European Civil Aviation Conference Airspace, MSAS the Japanese Airspace, GAGAN the Indian Airspace and SDCM the Russian Airspace. In 2015 the first Chinese set of SBAS named 'China CM' was released, the international name was 'Atlas'. Atlas provides wide-area differential services for the GPS L1 band primarily through INMARSAT satellites[6].

With the development of GNSS from single system to multi-system, multi-frequency and multi-constellation has become a hot research topic. Multi-frequency multi-constellation not only brings the improvement of accuracy, but also the new concepts and methods of integrity monitoring. In paper[7][8], the improved RAIM algorithm to improve the integrity performance based on integrated navigation system, dual-frequency and tri-frequency observations are exhibited. The paper[9] studied the use of multi-constellation combination to optimize GBAS pseudorange error model and protection level. The integrity monitoring studies pertinent to BeiDou system include integrity analysis of COMPASS and other GNSS combined navigation[10], improved algorithm of integrity protection level for BDS constellation[11] and integrity parameters of BeiDou satellite navigation system[12].

The existing SBAS signals are broadcast from a geostationary satellite using the L1 frequency and are very similar in design to the GPS L1/CA signals. GPS has launched its first two L5 capable satellites and intends to achieve its L5 Full Operational Capability (FOC) in the 2019 (or later) time frame. The different SBAS service providers have formed an Interoperability Working Group (IWG),and the group has set a goal of having the L5 MOPS support all four constellations. At present, IWG has passed the technology and definition document of 'Satellite-Based Augmentation System Dual-Frequency Multi-Constellation Definition Document version 2.0', and 'SBAS L5 DFMC Interface Control Document version 1.3'[13-15].

BeiDou system is developed in three steps, and the construction of satellite-based augmentation system is implementing. Currently, the test work based on GPS and BeiDou have been completed, and the system is being developed and provides service step by step. Based on the characteristics of Dual-Frequency SBAS (DF SBAS) system, the paper summarizes the connotation of DF SBAS integrity. Aimed at the problem that SBAS integrity parameters are relatively conservative, a dual-frequency SBAS integrity optimization algorithm is proposed to optimize the SBAS weight matrix. The SBAS Simulator software is used to

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validate the integrity availability of dual-frequency BDSBAS system in China and the surrounding areas.

Model for Calculating SBAS Integrity

Based on the linearized measurement model of SBAS, the least square solution of the unknown parameters is:

$$\hat{x} = (G^{\mathrm{T}}PG)^{-1}G^{\mathrm{T}}P\cdot y \qquad (1)$$

the covariance matrix of the parameter vector D is defined as:

$$D = (G^{\mathrm{T}}WG)^{-1} \qquad (2)$$

The vertical protection level and horizontal protection level of SBAS are specified by the RTCA standard as:

$$VPL_{SBAS} = K_{VPA}\cdot\sqrt{D_{3,3}} \qquad (3)$$

$$HPL_{SBAS} = K_{HPA}\cdot\sqrt{\frac{1}{2}\left(D_{3,3}+D_{3,3}\right)+\sqrt{\frac{1}{2}\left(D_{1,3}-D_{2,2}\right)^2+D_{1,2}^2}} \qquad (4)$$

Where, K_{VPA} and K_{HPA} are multiplication factor, which represent the vertical and horizontal false alarm probability and follow the Gauss distribution.

It can be seen from the equation above that the magnitude of the protection levels is related to the observation matrix and the weighting matrix. The user observation matrix is mainly determined by position of the user and satellites, and the weighting matrix is determined by variance of errors. SBAS systems estimate the satellite clock, ephemeris errors and ionospheric delay, the users within a large geographic area can apply differential corrections to the measurements to improve accuracy. With the development of multi-frequency GNSS systems, in the future however, to mitigate ionospheric errors, SBAS will leverage the L5 signal in addition to L1. In the next section the weighting matrix optimization model of dual-frequency SBAS will be addressed.

II. OPTIMIZATION MODEL OF WEIGHTING MATRIX

The weighting matrix of the measurements can be written as:

$$P^{-1} = \begin{bmatrix} \sigma_1^2 & 0 & \cdots & 0 \\ 0 & \sigma_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_N^2 \end{bmatrix} \qquad (5)$$

The weighting matrix of the receiver is a diagonal matrix, where each element can be calculated from the residual error in the SBAS message[16]. For the single frequency mode the overall satellite residual is computed as:

$$\sigma_{i,sf}^2 = \sigma_{i,flt,sf}^2 + \sigma_{i,UIRE,sf}^2 + \sigma_{i,trop}^2 + \sigma_{i,air,sf}^2 + \sigma_{i,RIMS}^2 + \sigma_{system}^2 \qquad (6)$$

Where, $\sigma_{i,flt,sf}^2$ includes the User Differential Range Error, which is the error due the ephemeris and clock error for single frequency. $\sigma_{i,UIRE,sf}^2$ is User Ionospheric Range Error (UIRE) which is an overbound of the error remaining in the range delay for single frequency once the ionospheric correction has been applied. $\sigma_{i,air,sf}^2$ is the air residual for single frequency. $\sigma_{i,trop}^2$ is the confidence bound on tropospheric errors for single frequency., $\sigma_{i,RIMS}^2$ is the error contribution from RIMS for single frequency. σ_{system}^2 is the overall constellation system error for single frequency.

For the dual-frequency mode the overall satellite residual is computed as:

$$\sigma_{i,df}^2 = \sigma_{i,flt,df}^2 + \sigma_{i,UIRE,df}^2 + \sigma_{i,trop}^2 + \sigma_{i,air,df}^2 + \sigma_{i,RIMS}^2 + \sigma_{system}^2 \qquad (7)$$

Fast and long term degradation confidence for dual-frequency residual error can be expressed by:

$$\sigma_{flt,df}^2 = \begin{cases} \left(\left(\sigma_{UDRE}\right)\cdot\left(\delta UDRE\right)+\varepsilon_{fc}+\varepsilon_{rrc}+\varepsilon_{ltc}+\varepsilon_{er}\right)^2, & RSS_{UDRE}=0 \\ \left[\left(\sigma_{UDRE}\right)\cdot\left(\delta UDRE\right)\right]^2+\varepsilon_{fc}^2+\varepsilon_{rrc}^2+\varepsilon_{ltc}^2+\varepsilon_{er}^2, & RSS_{UDRE}=0 \end{cases} \qquad (8)$$

Where, $\sigma_{i,flt}$ is the model variance for dual-frequency residual error RSS_{UDRE} is the sum square flag. ε_{fc} is degradation confidence of fast term, which presents the clock error caused by the clock acceleration variation. ε_{rrc} is the degradation confidence of pseudorange change rate correction, which is a function of the start time of the fast corrections and the pseudo-change rate. ε_{ltc} is degradation confidence of long term, which is a function of the start time and end time of the slow correction and the degradation rate. ε_{er} is the degradation confidence for the NPA flight phase.

For the single frequency mode user ionospheric range error confidence is calculated as:

$$\sigma_{UIRE,sf}^2 = F_{pp}^2\cdot\sigma_{UIVE,sf}^2 \qquad (9)$$

Where, F_{pp} is the obliquity factor. σ_{UIVE} is variance of the residual vertical ionospheric error for single frequency.

For the dual-frequency mode user ionospheric range error confidence is calculated as:

$$\sigma_{UIRE,df}^2 = F_{pp}^2\cdot\sigma_{UIVE,df}^2 \qquad (10)$$

Where σ_{UIVE} for the dual-frequency can be expressed by:

$$\sigma_{UIVE,df}^2 = \left(\frac{f_1^2}{f_1^2-f_2^2}\right)^2\cdot\sigma_{UIVE,f_1}^2 - \left(\frac{f_2^2}{f_1^2-f_2^2}\right)^2\cdot\sigma_{UIVE,f_2}^2 \qquad (11)$$

Where, σ_{UIVE,f_1}^2 and σ_{UIVE,f_2}^2 show the error confidence corresponding to frequency f_1 and f_2 respectively.

For the single frequency mode air residual can be calculated as: