Research on Integrity Evaluation Method for PPP-RTK Service End

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Abstract. The integrity requirement should be satisfied especially when PPP-RTK is used in safe of life applications. From the procedure of PPP-RTK, the accuracy and integrity of the service end products play an extremely important role in positioning. So, it is of great significance to analyze the accuracy and integrity of these products. This paper presents an integrity evaluation method for PPP-RTK service end products, meanwhile the definitions and calculation methods of integrity parameters are given as well. Without loss of generality, taking the precise orbit and clock as an example, the integrity parameters for the orbit and clock are obtained through the analysis of the Signal in Space Range Error (SISRE). The integrity evaluation method for PPP-RTK service end products proposed in this paper can be regarded as a general method, which can be used to evaluate different kinds of correction products.

Keywords: PPP-RTK · Integrity · Overbounding · SISRE

1 Introduction

Precision point positioning (PPP) can achieve the accuracy of static centimeter and dynamic decimeter-level using a single dual-frequency receiver under the aid of precise orbit and clock and a lot correction model. Compared with Real - time kinematic (RTK), PPP is a new innovative technology that is not limit to the length of baseline [1]. According to different combinations, PPP models mainly include: ionospheric-free combination model [2], UofC model [3], undifferenced model [4, 5]. The ionospheric-free and UofC model eliminate the influence of the first-order ionosphere through combining pseudorange and carrier observations.

The undifferenced model makes full use of information from original observations without any combination. Although PPP doesn't need a base station, the convergence time to the positioning accuracy of 10 cm is about 30–60 min and only float results can be obtained in traditional PPP, which limits the PPP in real-time applications. To address

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this shortcoming, Wubbena proposed the concept of PPP-RTK in 2005 [6], which can obtain fixed results with high convergence speed under the help of the correction products from service end. PPP-RTK combined the advantages of network RTK (NRTK) and PPP, and greatly improves the positioning accuracy and convergence speed of PPP [7], which makes it has incomparable advantages in real-time applications.

Although PPP-RTK has high accuracy and convergence speed, the vulnerability of the satellite navigation system makes it prone to fault. In some safe of life applications, such as automatic driving, the fault is fatal. Therefore, in addition to accuracy, integrity is also extremely vital. Integrity describes the ability of system to alert the user within a given time when positioning system cannot provide reliable positioning information. Integrity can be described by integrity risk (IR) or protection level (PL) calculated from user [8]. For PPP-RTK, it is known that positioning accuracy of PPP-RTK totally depends on the performance of the correction products. Besides, the two integrity parameters of IR and PL also depend on the integrity of these product. So, it is very important and necessary to evaluate the integrity of correction products from service end.

This paper presents an integrity evaluating method for PPP-RTK service end. The definition of fault and basic conception of paired overbounding are introduced. Without loss of generality, taking the orbit and clock as an example, the integrity parameters for the orbit and clock are obtained through the analysis of the Signal in Space Range Error (SISRE) based on sample data. The integrity evaluation method for PPP-RTK service end proposed in this paper can be regarded as a general method, which can be used to evaluate different kinds of correction products. The main contributions of this research are as follows 1. The definition of faults are based on gradual fault. 2. Taking worst SISRE as the evaluation standard of orbit and clock error 3. Proposing a PPP-RTK server end integrity evaluation scheme.

The rest of this paper is organized as follows: Sect. 1 introduces the background and the importance of integrity evaluation for PPP-RTK service end; Sect. 2 presents the procedure of PPP-RTK, and gives the definition and calculation method of integrity parameters for service end; The integrity parameters about the orbit and clock based on sample data through SISRE is shown in Sect. 3; finally, Sect. 4 draws the conclusion.

2 The Definition of Integrity Parameters for Service End

Integrity can be described by PL, which is decided by the fault probability and error distribution of the service end products. So, the integrity parameters for service end include: product fault probability P_{fault}, system fault probability P_{sys}, overbounding bias b_{nom} and overbounding standard deviation σ_{bound}. This section first describes the procedure of PPP-RTK, and gives the kinds of products that needs integrity evaluation. Then the definition of fault as well as parameters in overbounding theory are introduced.

2.1 Procedure of PPP-RTK

Hardware delay and initial phase error make the ambiguity non-integer, which results a float positioning in traditional PPP. In order to obtain fixed solution and improve the positioning accuracy, it is necessary to correct the ambiguity, and obtain it through ambiguity fixed algorithm. The PPP that has corrected the ambiguity is PPP-AR.

Although PPP-AR can get fixed positioning, its convergence time is still long. Some studies have found that with the aid of ionospheric and tropospheric correction, the convergence speed can be greatly improved [9]. Therefore, fast PPP ambiguity fixed can be realized based on ionospheric and tropospheric information from regional station, which is also named PPP-RTK. The procedure of PPP-RTK is shown in Fig. 1:

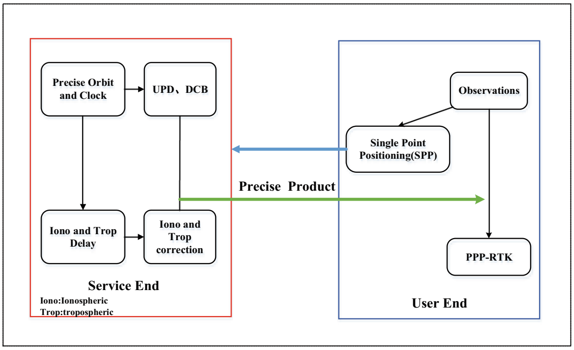

Fig. 1. Procedure of PPP-RTK

2.2 Fault Definition

In order to analyze the fault probability, it is necessary to give the fault definition. In Global Positioning System Standard Positioning Service Performance Standard (GPS-SPS-PS), URA is conservative estimation accuracy of GPS broadcast ephemeris. Under the assumption of zero-mean Gaussian, tolerance threshold is set as $4.42 \times URA$ to make sure the fault probability is lower than 10^{-5} [10]. This is the most common fault definition method, however, this method cannot detect gradual fault. On the basis of this fault definition, Wang SZ et al. proposed a new fault definition method, which can find gradual fault as well [11]. Figure 2 shows the gradual fault. Although the red dots at the beginning are below the tolerance threshold, they are defined as fault as well.

Gradual faults can be detected by multiple epoch differences or slopes based on tolerance threshold detection. When the differences or slopes between multiple epochs are greater than a certain threshold, we think a gradual fault occurs.

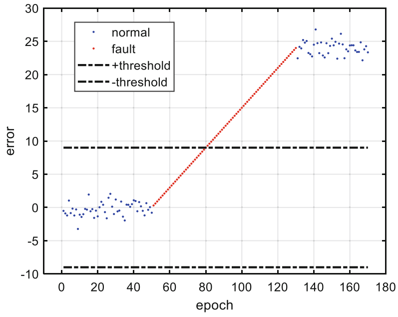

Fig. 2. Gradual fault

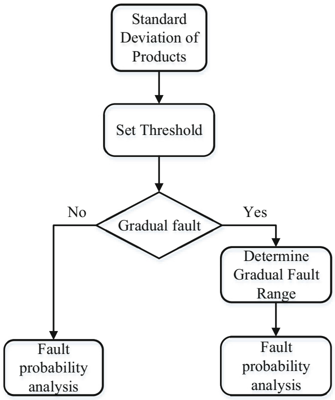

Fig. 3. Procedure of fault probability analysis

The gradual fault defination will be used in this paper to analyse the fault probability. Figure 3 gives the procedure:

Assumed that the fault probability of products is below 10^{-5}, that is:

$$P\left(error_{fault} > Threshold\right) = 10^{-5} \tag{1}$$

Under the assumption that the error distribution is standard normal distribution, the tolerance threshold should be 4.42 times the error standard deviation. However, because of the non-ideal of actual distribution as well as no prior information about overbounding, we can only use the actual standard deviation. In order to conservatively describe the actual distribution, we choose 5.5 times the standard deviation as the threshold (The corresponding fault probability is 10^{-7}), that is:

$$Threshold = 5.5 \times sigma_{error} \tag{2}$$

where:

$sigma_{error}$ is the standard deviation of products error.

2.3 Definition and Calculation of Integrity Parameters

This definitions and calculation method of product fault probability P_{fault}, system fault probability P_{sys}, overbounding bias b_{nom} and overbounding standard deviation σ_{bound} are introduced in this subsection.

Walter et al. gave the definition and calculation method for the fault probability of Signal in Space Error (SISE) [12], the formula of fault probability is:

$$\begin{gathered} R_{sat} = \frac{N_F + 1/2}{T_t} \\ P_{sat} = R_{sat} \times MTTN \end{gathered} \tag{3}$$

where:

R_{sat}: fault rate;

T_t: the total evaluation time;

N_F: the number of faults during the evaluation time;

$MTTN$: the average duration of the fault.

For the constellation fault probability P_{const}, the formula is the same. Constellation fault is defined as a fault occurs at the same time in two or more satellites due to the same reason. The definitions of P_{sat} and P_{const} will be used in this paper to calculate the P_{fault} and P_{sys}, respectively.

The protection level (PL) is under the assumption that SISRE is Gaussian distribution. However, the actual SISRE cannot be an ideal Gaussian distribution. Therefore, it is necessary to use a conservative Gaussian distribution to describe the actual SISRE distribution. DeCleene et al. proposed a cumulative probability distribution (CDF) envelope algorithm [13], and Rife et al. proposed a paired overbounding method [14, 15]. Among them, the paired overbounding describes the true distribution through two parameters: the nominal bias b_{nom} and the standard deviation σ_{URA}. Paired overbounding can be summarized as:

$$G_o = \begin{cases} G_L(x) & \forall\ G_L < \frac{1}{2} \\ \frac{1}{2} & otherwise \\ G_R(x) & \forall\ G_R > \frac{1}{2} \end{cases} \tag{4}$$

$$\begin{cases} G_L(x) = \int_{-\infty}^{x} N(-b_{nom}, \sigma_{URA})dx \geq G_a(x) & \forall x \\ G_R(x) = \int_{-\infty}^{x} N(b_{nom}, \sigma_{URA})dx \leq G_a(x) & \forall x \end{cases} \tag{5}$$

where:

$N(b_{nom}, \sigma_{URA})$: the probability density function (PDF) of Gaussian distribution with mean b_{nom} and standard deviation σ_{URA};

$G_a(x)$: the actual error cumulative probability distribution (CDF); Fig. 4 shows the paired overbounding:

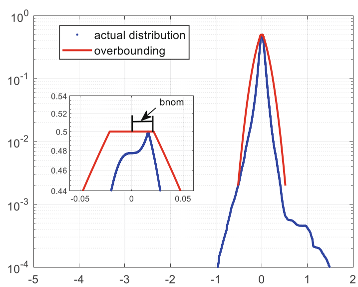

Fig. 4. Paired overbounding

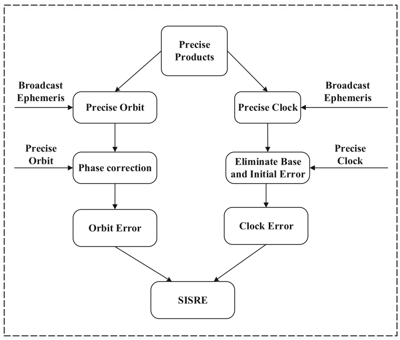

Fig. 5. Procedure of calculating SISRE

Different from the traditional CDF, the CDF in Fig. 4 is folded CDF (FCDF) [16]. This technique folds the second half of the CDF plot by representing $y = 1 - CDF$ for values of $x \in [m_{median}, \infty)$. Where m_{median} is the median of the distribution. The paired overbounding method have a good Conservative overbounding even though the real distribution are asymmetry, multi-peak [15]. Therefore, this paper uses paired overbounding method to describe the products error.

3 Verification of Integrity Evaluation Method

In order to verify the integrity evaluation method for PPP-RTK service end proposed in this paper. Without loss of generality, taking the orbit and clock as an example, the integrity parameters are obtained based on sample data and true value from GFZ in this section.

3.1 Signal in Space Range Error (SISRE)

The SISRE, which is the projection of orbit and clock error in the line of sight (LOS), always be used to evaluate orbit and clock error. GPS-SPS-PS defines SISRE as the mean value of the instantaneous user range error (IURE) of all users within the footprint of the satellites [10]:

$$\begin{gathered} avgURE = \sqrt{\frac{1}{s}\int_{-\pi}^{\pi}\int_{\gamma}^{\frac{\pi}{2}}(IURE - \delta t)^2 \cos\alpha d\alpha d\beta} \\ IURE = \frac{\begin{bmatrix} R & A & C \end{bmatrix}}{\sqrt{1 + r^2 - 2r\sin\alpha}} \begin{bmatrix} -\cos\alpha\cos\beta \\ -\cos\alpha\sin\beta \\ r - \sin\alpha \end{bmatrix} \end{gathered} \tag{6}$$

where:

γ: Longitude of users at the edge of satellite footprint;

S: the area of the coverage footprint;

δt: clock error of satellite;

α, β, r: The latitude and longitude of the user, and distance between satellite and center of earth;

R, A, C: along-track, cross-track and radial errors of satellite orbit;

However, in safe of life applications, the worst case must be considered. Therefore, in this paper, the worst-URE is used to evaluate integrity of orbit and clock:

$$worstURE = \sqrt{\left\{\max_{|\theta| \le \gamma}\left(R\cos\theta + \sqrt{A^2 + C^2}\sin\theta\right)\right\} + \delta t^2} \tag{7}$$

3.2 Procedure of Calculating Real-Time Worst SISRE

There are three steps to calculate real-time precise orbit [17]:

1. Calculate the correction of satellite position in orbital coordinate:

$$\delta O = [\delta O_R, \delta O_A, \delta O_C] + \left[\delta \dot{O}_R, \delta \dot{O}_A, \delta \dot{O}_C\right](t - t_0) \tag{8}$$

   where, t and t_0 are the time when satellite transmit signal and the reference time, respectively; δO_R, δO_A, δO_C, $\delta \dot{O}_R$, $\delta \dot{O}_A$, $\delta \dot{O}_C$ are the correction and their variations in radial, along-track and cross-track, respectively.
2. Transform the correction in orbital coordinate to the Earth Centered Earth Fixed (ECEF):

$$\delta X = S \times \delta O \tag{9}$$

   where, δX is the correction in ECEF, S is the transfer matrix from orbital coordinate to ECEF.
3. Calculate the precise position of satellite in ECEF

$$X = X_{brdc} + \delta X \tag{10}$$

   where, X is the satellite precise position in ECEF, X_{brdc} is satellite position calculated from broadcast ephemeris.

There are two steps to calculate real-time clock error:

1. Calculate the correction of clock error

$$\delta t = \left(C_0 + C_1(t - t_0) + C_2(t - t_0)^2\right)\Big/c \tag{11}$$

   where, t and t_0 are the time when satellite transmit signal and the reference time, respectively; C_0, C_1, C_2 are correction parameters, respectively.
2. Calculate the precise clock error:

$$\Delta t = \Delta t_{brdc} - \delta t \tag{12}$$

   where, Δt is precise clock error, Δt_{brdc} is clock error obtained from broadcast ephemeris.

For orbit error, it can be obtained directly from the difference between the real-time precision orbit and the true value after the correction of antenna phase center [18]. For clock error, it is required to consider the different bases and initial clock error. The time base can be eliminated by double difference based on reference satellite, while the initial clock error can be compensated through extracting the average of double difference. The procedure can be summarized in Fig. 5:

3.3 Results Analysis

This section shows the results of orbit and clock error based on sample data from January 14, 2021 to March 14, 2021:

Table 1. Mean value of orbit and clock of each constellation

Constellation	R	A	C	T	SISRE
	μ	μ	μ	μ	μ
GPS	0.0035	−0.0011	−0.0005	-8.1×10^{-8}	0.0070
GALILEO	0.0019	0.0045	−0.0030	-9.5×10^{-8}	0.0019
BDS	0.0043	0.0184	−0.0096	4.7×10^{-7}	0.0053

Table 2. Standard deviation of orbit and clock of each constellation

Constellation	R	A	C	T	SISRE
	σ	σ	σ	σ	σ
GPS	0.0104	0.0431	0.0209	4.9×10^{-6}	0.0194
GALILEO	0.0148	0.0332	0.0225	5.5×10^{-6}	0.0211
BDS	0.0255	0.0698	0.0483	1.2×10^{-5}	0.0381

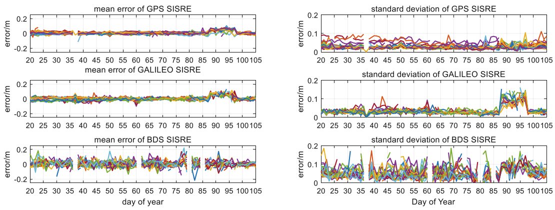

Fig. 6. Daily mean value and standard deviation

It can be seen from Table 1 and Table 2 that the mean value and standard deviation of orbit error is millimeter and centimeter level, respectively, which is approximate to the accuracy of true products. From the daily mean value and standard deviation showed in Fig. 6, most of the worst SISRE in GPS and GALILEO are less than 5 cm while the BDS is about 10 cm. The accuracy of BDS is a little bit poor, which can also be verified from FCDF showed in Fig. 7. This is maybe caused by the newly deployed BDS system with lower accuracy precise products. From the FCDF, it can also be seen that the worst SISRE is mainly based on radial orbit and the clock error.

Figure 8 and Table 3 show the overbounding results and integrity parameters of each system. The fault probability of each system is less than 10^{-5}, while the standard deviations σ_{URA} and bias b_{nom} of conservative Gaussian overbounding of GPS, GALILEO and BDS are about 4 cm, 6 cm, 7.5 cm, and about 1.3 cm, 1 cm, 2 cm, respectively.

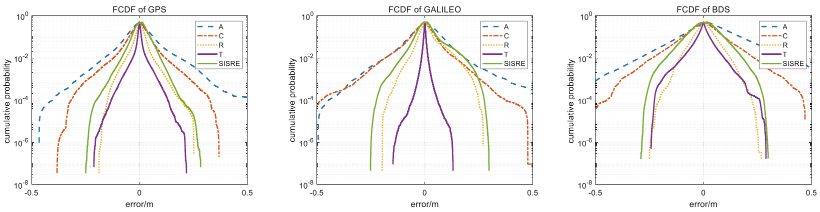

Fig. 7. FCDF of each constellation

Table 3. Integrity parameter of each constellation

Constellation	Data number	p_{sat}	p_{const}	σ_{URE}	σ_{URA}	b_{nom}
GPS	29023995	5.75×10^{-6}	1.7×10^{-8}	0.0362	0.0420	0.0136
GALILEO	20168801	5.45×10^{-7}	2.3×10^{-8}	0.0404	0.0549	0.0099
BDS	5851416	8.5×10^{-8}	8.5×10^{-8}	0.0747	0.0747	0.0199

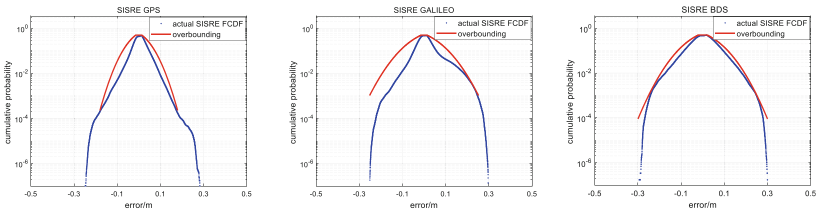

Fig. 8. Overbounding results of each constellation

4 Conclusion

This paper proposed a definition and evaluation method for the integrity of PPP-RTK service end. First, the observation equation of different PPP model is introduced. Then the definition and calculation formula of fault is given as well as the parameters in paired overbounding theory. The orbit and clock are used as an example to evaluate the integrity through worst SISRE. The statistical results, PDF and FCDF shows that the radial error is the smallest which is consistent with theoretical analysis. The three-month statistical results show that the accuracy of the orbit and clock error is consistent with true value, while the BDS is poorer than GPS and GALILEO. The PDF and FCDF confirm that SISRE is mainly affected by radial orbit and clock errors. Finally, the integrity parameters are calculated based on sample data. The fault probability of single satellite and constellation are both less than 10^{-5}, while the overbounding standard deviations σ_{URA} and bias b_{nom} of GPS, GALILEO and BDS are about 4 cm, 6 cm, 7.5 cm, and about 1.3 cm, 1 cm, 2 cm, respectively.

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