Chapter 18
Validation of GNSS ARAIM Algorithm Using Real Data

Bin Li, Jizhang Sang and Yun Wu

Abstract This paper presents the research results on validation of the GNSS ARAIM (Advanced RAIM) algorithm, which is required in extending GNSS applications to areas demanding high integrity and safety, such as precision approach of LPV-200 phase before landing. In the ARAIM algorithm, the integrity risk of the GNSS systems is quantified by applying theory of multiple-hypothesis (MH). The multiple hypotheses are tested individually by using the method of solution separation (SS). Depending on different scenarios of the potential risks in the GNSS system, the given total tolerated integrity risk is allocated among the satellite-failure cases. For each case, the user's XPL (including HPL, and VPL which is more concerned in this paper), accuracy and EMT, are predicted. In this paper, the ARAIM algorithm is studied using real GNSS observation data from a number of IGS stations at different locations, and then the availability levels of the GPS and GPS/GLONASS systems are evaluated based on the navigation performance requirements of LPV-200. Results show that: (1) VPE calculated using GNSS observation data are consistent with the results of the predicted VPL, accuracy and EMT, which validates the ARAIM algorithm. (2) Under the ARAIM, the highest availability achieved in the GPS system is only 63.04 %, while availability in the GPS/GLONASS system achieves more than 99.0 %, which fully meets the navigation performance requirements of LPV-200.

Keywords Integrity · LPV-200 · Multiple hypothesis solution separation · ARAIM

B. Li (✉) · J. Sang · Y. Wu
School of Geodesy and Geomatics, Wuhan University, Wuhan 430079, China
e-mail: libin@whu.edu.cn

J. Sun et al. (eds.), *China Satellite Navigation Conference (CSNC) 2014 Proceedings: Volume II*, Lecture Notes in Electrical Engineering 304,
DOI: 10.1007/978-3-642-54743-0_18,

18.1 LPV-200 Requirements and GNSS Ranging Error Characteristics

18.1.1 LPV-200 Requirements

Federal Aviation Administration (FAA) has claimed to provide LPV-200 capability worldwide without support of SBAS and Instrument Landing System (ILS) depending on GNSS during 2020–2025. Here, LPV-200 stands for Localizer Performance with Vertical guidance and indicates that decision height is 200 feet above ground level. According to International Civil Aviation Organization (ICAO), the performance requirements of LPV-200 are as follows [3]:

- Probability of Hazardously Misleading Information (HMI) must not exceed 1×10^{-7}/approach.
- False Alert Probability must not exceed 4×10^{-6}/15 s.
- Vertical Alert Limit (VAL) equals 35 m.
- Accuracy must not exceed 4 m, and Effective Monitoring Threshold (EMT) must not exceed 15 m.

18.1.2 GNSS Ranging Error Characteristics

Two sets of parameters below are defined in ARAIM algorithm. One is for accuracy, the other for integrity.

URE is the non-integrity-assured standard deviation of the range component of clock/ephemeris error and is used to evaluate accuracy. It is taken to be the half of each URA value [3].

URA is the least standard deviation of a distribution that bounds the distribution of the range component of clock/ephemeris error in the absence of a fault condition, and is used to evaluate integrity. Its values range from 0.5 to 2.4 m [3].

Two levels of bias magnitudes are defined in ARAIM algorithm. One is a typical magnitude of a bias in a nominal condition (nominal error). This magnitude is used for the evaluation of accuracy. It is fixed at 0.1 m. The other is the maximum bias magnitude used for the evaluation of integrity. The maximum bias magnitude is the maximum only under fault-free conditions. It is 0.75 m with a URA of 0.5 m, and will assume to be 0.5 m with a larger URA value.

Besides URA and URE, errors in the measurements also include tropospheric error, airborne multipath error, and user receiver noise. As integrity affects safety-of-life directly, the corresponding calculations overbound the extreme conditions, while accuracy calculations are based on realistic performance estimates. For these errors, two different airborne error models are used, one set for accuracy, the other for integrity [2, 3, 6]:

- Error model for accuracy

$$\sigma_{k,trop} = \frac{(0.08)(1.001)}{\sqrt{0.002001 + \sin^2(EleAngle)}}$$
$$\sigma_{k,noise} = 0.04 - 0.02(EleAngle^\circ - 5)/85$$
$$\sigma_{k,mp} = 0.18 - 0.1(EleAngle^\circ - 5)/85$$
$$\sigma_{k,DF} = a\sqrt{\sigma_{k,noise}^2 + \sigma_{k,mp}^2}$$

then

$$\sigma_k^2 = URE_k^2 + \sigma_{k,DF}^2 + \sigma_{k,trop}^2 \tag{18.1}$$

- Error model for integrity

$$\sigma_{k,trop} = \frac{(0.12)(1.001)}{\sqrt{0.002001 + \sin^2(EleAngle)}}$$
$$\sigma_{k,noise} = 0.04 - 0.02(EleAngle^\circ - 5)/85$$
$$\sigma_{k,mp} = 0.13 + 0.53\exp(-EleAngle^\circ/10)$$
$$\sigma_{k,DF} = a\sqrt{\sigma_{k,noise}^2 + \sigma_{k,mp}^2}$$

then

$$\sigma_k^2 = URA_k^2 + \sigma_{k,DF}^2 + \sigma_{k,trop}^2 \tag{18.2}$$

EleAngle is the satellite elevation angle. $a = \sqrt{\left(\frac{f_1^2}{f_1^2 - f_5^2}\right)^2 + \left(\frac{f_5^2}{f_1^2 - f_5^2}\right)^2}$. The total variance σ_k^2 stands for the nth diagonal element of the weight matrix.

18.2 Realization of ARAIM Algorithm

As vertical geometry strength is weaker than the horizontal, stricter integrity is required in the vertical dimension [3]. So, the study of GNSS ARAIM algorithm in the paper focuses on the vertical dimension.

18.2.1 Multiple Hypothesis Solution Separation

Conventional RAIM assumes that only one fault-satellite happens once a time. It is calculated based on the single-frequency measurement. Its results tend to be conservative. Owing to the limitations above, conventional RAIM is not suitable for integrity monitoring in the LPV-200 anymore. Compared to RAIM algorithm, ARAIM algorithm uses multiple hypothesis solution separation (MHSS), which considers multiple underlying GNSS faults. The GNSS faults can be characterized both in terms of their causes and effects. So it shows a stricter and more flexible superiority to RAIM [4]. Besides, ARAIM focuses on the calculation of Vertical Position Level (VPL) and bases on the smooth pseudorange measurements with carrier phase measurements. It could remove the ionosphere delay. Meanwhile, the threats caused by multiple faults could be allocated through dynamic optimization to reduce the VPL value [1].

The total integrity risk in the ARAIM algorithm is calculated as follows:

$$\begin{aligned} P\{HMI\} =& P\{HMI/H_0\} \cdot P_0 + P\{HMI/H_1\} \cdot P_{sat1} \\ &+ \cdots P\{HMI/H_n\} \cdot P_{sat\mathrm{n}} + P\{HMI/H_{mult}\} \cdot P_{mult} \\ &+ P\{HMI/H_{const}\} \cdot P_{const}. \end{aligned} \tag{18.3}$$

$H_i (i = 1, 2, \ldots N)$ is the failure hypothesis, N is the number of satellites in view, $P\{HMI/H_i\}$ is the integrity risk under the hypothesis of H_i, and P_{sat} is the integrity failure rate on individual satellite.

Assuming that all the hypotheses are independent, integrity risk the user bearing could be calculated through the formula above. According to the requirements of ICAO, during the civil aviation navigation using GNSS, integrity risk in the vertical guidance is

$$P_{HMI\_\mathrm{Req}} = 1 \times 10^{-7}/approach \tag{18.4}$$

If

$$P\{HMI\} < P_{HMI\_\mathrm{Req}}. \tag{18.5}$$

The required GNSS integrity could be reached, and GNSS is available. When P_{sat} is small enough, such as 10^{-5}/approach, the probability of two-satellites-failure is less than P_{HMI_Req} dramatically. Thus, hypotheses of failures of two or more satellites could be removed from the formula (18.3) [7]. Assuming that the removed integrity risk is P_{HMI_Un}, then

$$\begin{aligned} P\{HMI\} =& P\{HMI/H_0\} \cdot P_0 + P\{HMI/H_1\} \cdot P_{sat1} \\ &+ \cdots P\{HMI/H_n\} \cdot P_{sat\mathrm{n}} \\ &< P_{HMI\_\mathrm{Req}} - P_{HMI\_Un}. \end{aligned} \tag{18.6}$$

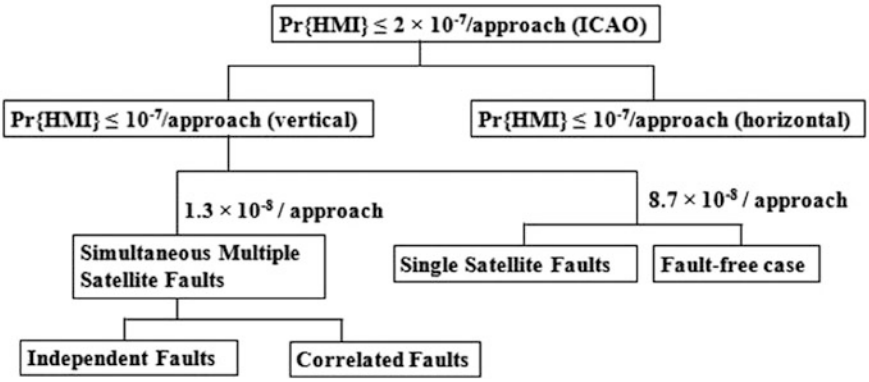

Fig. 18.1 Allocation of P{HMI} requirement for ARAIM [3]

In turn, if P_{sat} is known, given the integrity risk $P\{HMI\}$ and allocated it among all the hypotheses, VPL of corresponding hypothesis could be calculated (Fig. 18.1).

18.2.2 Calculation of VPL

The user' VPL is derived from the fault-free full-set VPL_0 and the faulted subsets VPL_n, given as follows:

$$VPL = \max\{VPL_0, VPL_n\},\ n = 1 \cdots N \tag{18.7}$$

where,

$$VPL_0 = K_{md,0} \times \sigma_{V,0} + \sum_{i=1}^{N} |S_0(3,i)| \times \text{Maximum\_bias}$$

$$VPL_n = D_n + K_{md,n} \times \sigma_{V,n} + \sum_{i=1}^{N} |S_n(3,i)| \times \text{Maximum\_bias}.$$

N is the number of satellites in view. S_0 and S_n are the projection matrixes of each corresponding hypothesis. D_n is the detection threshold for the nth test statistic.

$$D_n = K_{ffd,n} \times \sigma_{dV,n} + \sum_{i=1}^{N} |\Delta S_n(3,i)| \times \text{Nominnal\_error}. \tag{18.8}$$

Tab. 18.1 Necessary parameters settings [3, 5, 6]

P{HMI}	P_{fa}	P_{sat}	Normial error	Maxmium bias	GPS		GLONASS	
					URA	URE	URA	URE
8.7×10^{-8}/ approach	4×10^{-6}/ 15 s	10^{-5}/approach	0.1 m	0.5 m	0.5 m	0.25 m	1.0 m	0.5 m

Three sets of coefficients are introduced here, and they are: $K_{ffd,n}$, $K_{md,0}$, $K_{md,n}$. $K_{ffd,n}$ is determined to meet accuracy and continuity requirement, $K_{md,0}$, $K_{md,n}$ are determined to meet integrity requirement. The continuity and integrity requirements can be met by selecting these coefficients as follows:

$$K_{ffd,n} = -Q^{-1}\left(\frac{Total\_P_{fa}}{2 \times N}\right) \tag{18.9}$$

$$K_{md,0} = -Q^{-1}\left(\frac{P\{HMI\}}{2 \times (N+1)}\right) \tag{18.10}$$

$$K_{md,n} = -Q^{-1}\left(\frac{P\{HMI\}}{2 \times P_{sat} \times (N+1)}\right). \tag{18.11}$$

The total false alert probability requirement is equally divided among the faults of all N satellites in view, and the total integrity risk is equally divided and allocated among the fault-free case and the cases which any single satellite in view has a fault. In the above, Q^{-1} is the inverse of the complement of the one-side standard normal cumulative distribution function (CDF).

All the calculations above are done in the ENU coordinate system.

18.3 Validation of GNSS ARAIM Algorithm Using Real Data

The paper firstly calculates the VPE of hofn station and other stations, including bake, gold and mdvj, using real GNSS (GPS only mode and GPS/GLONASS mode) data of ten continuous days. Then, the validation of ARAIM Algorithm is validated by comparing calculated VPE to the VPL, Accuracy, EMT predicting in the ARAIM. Finally, the availabilities in the GPS only mode and GPS/GLONASS mode of each station are evaluated, according to the LPV-200 performance.

18.3.1 Necessary Parameters Settings

(See Table 18.1)

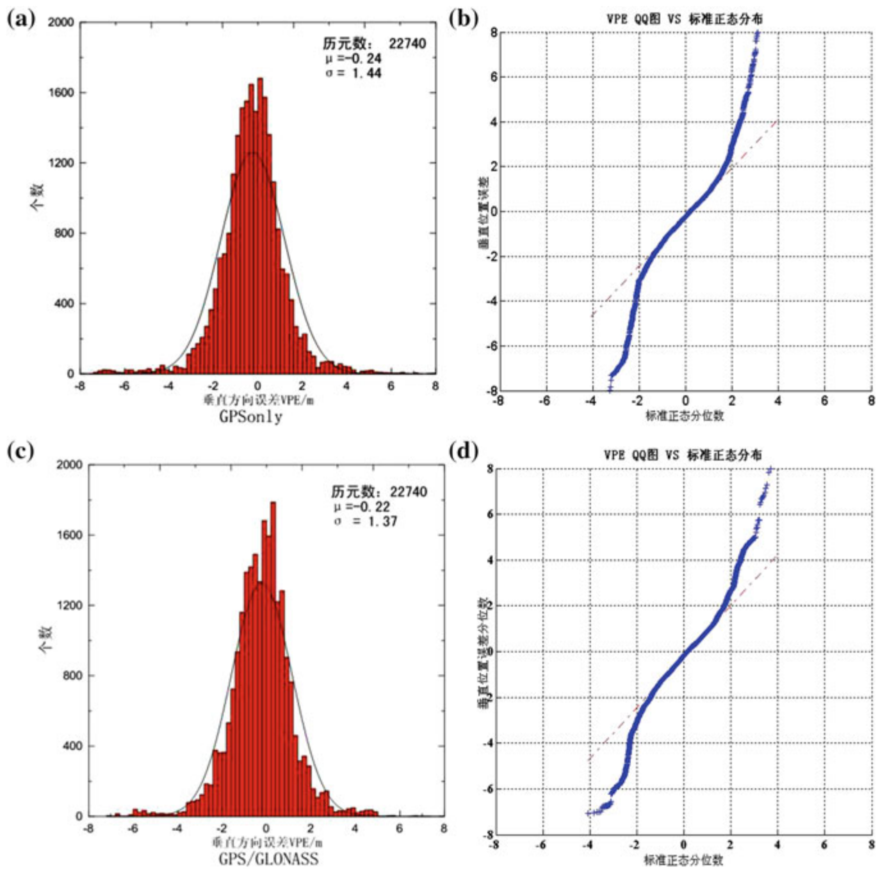

Fig. 18.2 Histogram and Q–Q Plot of VPE in GPS only and GPS/GLONASS modes

18.3.2 Vertical Position Error (VPE)

GNSS VPE of hofn station is calculated by ten continuous days' data. So its performance of range error characterization could be analyzed through two means: histogram and Quantile Quantile Plot.

Figure 18.2a shows the VPE histogram of GPS only mode. The black line stands for normal distribution curve by fitting the VPE histogram. As the mean value and standard deviation of the histogram show, the normalized VPE to the predicted accuracy is more likely to be a standard normal distribution. Figure 18.2b shows the VPE Q–Q Plot of GPS only mode, which displays the quantitative relationship between sample result quantiles of the normalized VPE and theoretical quantiles from a normal distribution. If the distribution of the former is normal, the plot will be close to linear. According to the histogram of the GPS only mode, the corresponding Q–Q plot, Fig. 18.2b, is almost a linear line

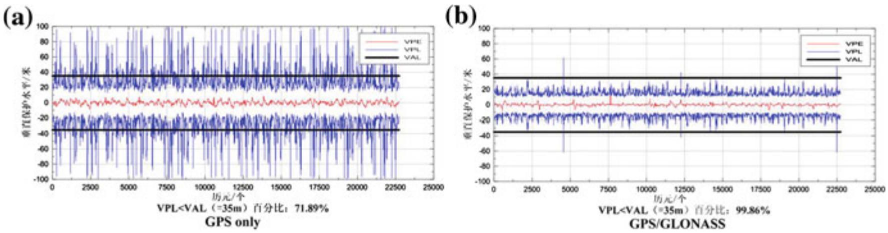

Fig. 18.3 VPL in GPS only and GPS/GLONASS modes

except outside the interval ranging from −2 to 2 m. That means even the histogram approximately looks like a standard normal distribution, though specifically there are some measurements whose range error statistics are not predicted well. Figure 18.2c, d show the VPE histogram and Q–Q Plot of GPS/GLONASS mode. Their explanations are the same as GPS only mode shows.

From the figures above, we can see that the VPE, calculated in two modes, reaches about 2 m. Comparing it with the accuracy estimated by ARAIM, we can analyze whether the accuracy could predict VPE well or not, thus to test the validation of ARAIM in predicting accuracy. Details can be seen in Sect. 18.3.4.

18.3.3 Vertical Protecting Level (VPL)

VPL, the bound of estimated VPE, is related to the requirements in aviation navigation safety. It is one significant aspect of ARAIM evaluation whether or not the VPL bounds the VPE well during navigation operation. VPL must be greater than VPE, but it cannot be too great enough to reduce the continuity of the navigation. However, HMI exists when the VPE is greater than the VPL for longer than the time-to-alert (TTA). So, it should be validated that whether the VPL bounds the VPE well. In the precise approach, we usually calculate the percentage of time that the VPL is less than VAL (35 m) out of total epochs to evaluate the availability GNSS works.

As Fig. 18.3 shows, VPL, predicted in ARAIM of two modes, are both greater than the corresponding VPE which is calculated by real GNSS measurement. We can conclude that HMI does not occur in the situation given the integrity risk and continuity risk. Comparing the predicted VPL and the VAL which is a specified value of LPV-200, there are many cases in which the value of the VPL is less than the VAL. The percentage of time that VPL is less than VAL is 71.89 % in GPS only mode, which is the availability. However, the value of GPS/GLONASS mode reaches 99.86 %, as Fig. 18.3b shows, which meets the requirement of LPV-200. Results above show that more satellites in view, during the GPS/GLONASS navigation, can increase the geometry strength greatly, reducing the VPL value and making it smoother and more steady than that during GPS only navigation.

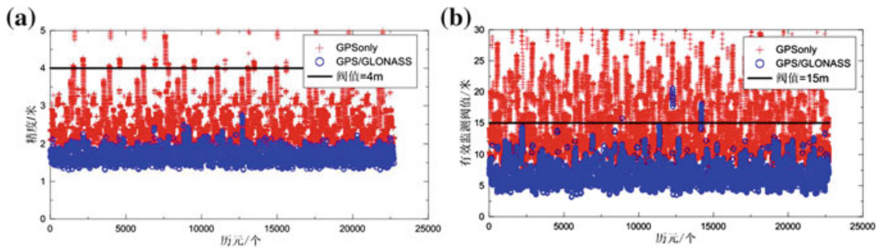

Fig. 18.4 Accuracy and EMT in GPS only and GPS/GLONASS modes

Table 18.2 Percentage of accuracy < 4 m and EMT < 15 m

	Accuracy (%)	EMT (%)
GPS only	97.07	62.74
GPS/GLONASS	100	99.95

18.3.4 Accuracy and EMT

95th percentile vertical accuracy requirement for LPV-200, which is accuracy, is less than 4 m. The EMT is an additional LPV-200 requirement on the vertical position error. GEAS has agreed to require that the 50th percentile absolute value of VPE, which is EMT, should be no greater than 15 m when an integrity alert occurs for the worst-case geometry and for the satellite whose integrity failure is the most difficult to detect. Figure 18.4 displays the accuracy and EMT of each mode.

Statistics of Table 18.2 shows the percentages of time that the accuracy is less than 4 m and EMT is less than 15 m.

From Fig. 18.4a, accuracy of GPS only mode concentrates on about 2 m or more, and 1.5–2.0 m of GPS/GOLNASS mode. The accuracy outside the interval shows a distinct randomness, indicating the accuracy estimated cannot predict the VPE well. Results achieved above are consistent with the statistics of VPE by Q–Q Plot in Sect. 18.3.2, indicating that ARAIM is available and valid in predicting accuracy. From Fig. 18.4b, EMT in the GPS only mode fluctuates dramatically, with its least value 5.7 m and biggest value reaching about 100 m or more. EMT in the GPS/GLONASS mode ranges from 4 to 10 m, shows a little centralized. As more satellites are available when two systems combine, the geometry strength will be enhanced and the reliability and stability of the systems will be improved. From the results above, we can get the conclusion that accuracy and EMT in GPS/GLONASS mode are both superior to the ones in GPS only mode, fully meeting the requirements of LPV-200.

Table 18.3 Availability under GPS only and GPS/GLONASS modes (the last column)

	VPL < 35 m (%)	Accuracy < 4 m (%)	EMT < 15 m (%)	Availability (%)
GPS only	71.89	97.07	62.74	59.18
GPS/GLONASS	99.86	100	99.95	99.82

Table 18.4 VPL, accuracy, EMT, availability of other three IGS stations (*G* GPS only mode *G/G* GPS/GLONASS mode)

		VPL < 35 m (%)	Accuracy < 4 m (%)	EMT < 15 m (%)	Availability (%)
Bake	G	68.74	98.22	46.38	44.78
	G/G	99.77	100	99.83	99.71
Gold	G	74.08	97.59	69.47	63.04
	G/G	99.25	99.97	99.31	99.11
mdvj	G	57.77	99.04	59.01	49.25
	G/G	99.55	100	99.48	99.25

18.3.5 Availability

Availability is the percentage of time that navigation system works normally in the region it covers, when the accuracy, integrity and continuity are fully met. According to requirements of availability in ARAIM, the ideally ARAIM is declared available if the following three conditions are satisfied: VPL < 35 m, accuracy < 4 m, EMT < 15 m. The availabilities of both the modes are evaluated as Table 18.3 shows:

Comparing to the availability of GPS only mode, which is 59.18 %, the availability in GPS/GLONASS mode reaches up to 99.82 %, which meets the requirement of LPV-200 excellently. Results above show that t ARAIM is available and valid in estimating VPL, accuracy and EMT.

Results of other three IGS stations achieved are as Table 18.4 shows.

18.4 Conclusions

The paper firstly gives a deep study of ARAIM algorithm bases on multiple hypotheses. Then VPL, accuracy, EMT in the GPS only and GPS/GLONASS modes are estimated and analyzed by the ten-day's real GNSS measurement of four IGS stations. Finally, the availabilities in the GPS only and GPS/GLONASS modes of each station are evaluated. Results show that:

(1) The predicted VPL in ARAIM can bound the calculated VPE based on real GNSS measurement well. Additionally, in the GPS only mode, the biggest

percentage of time that VPL is less than VAL (35 m) is 74.08 %, and the least is 57.77 %. However, the biggest percentage in GPS/GLONASS mode reaches up to 99.86 % and the least is 99.25 %, more superior to the ones in the GPS only mode.

(2) Accuracy predicted in the ARAIM are both less than 4 m in the two modes. The percentage that accuracy less than 4 m in GPS/GLONASS mode is a little better than that in GPS only mode. This is consistent with the results of the real navigation. Meanwhile, when estimating EMT by ARAIM algorithm, all the EMT in GPS/GLONASS mode are less than 15 m, which are better than ones in GPS only mode.

(3) The biggest availability in GPS only mode of LPV-200 is 63.04 %, while the one in the GPS/GLONASS mode are all greater than 99 %, fully meeting the performance requirements of LPV-200.

Results above are achieved based on the static measurement of IGS stations. However, during the precise approach of LPV-200, the receiver is in the dynamic condition of high-speed. The quality of data the receiver gets is worse than that of the static measurement. So, results in ARAIM are relatively optimistic. With the combination of three or more navigation systems among GPS, Beidou, GLONASS and Galileo in the future, the geometry strength of the satellites will improve obviously. Thus, we can foresee that it will be sure to achieve LPV-200 capability worldwide at airports without local GNSS instrumentation relying on ARAIM.

References

1. Boris S, Pervan SPP, Christie JR (1998) A multiple hypothesis approach to satellite navigation integrity. Navig J Inst Navig 45(1):61–71 (Spring Printed in U.S.A)
2. Choi M, Blanch J, Akos D et al. (2011) Demonstrations of multi-constellation advanced RAIM for vertical guidance using GPS and GLONASS signals. Paper presented at proceedings of 24th international technical meeting of the satellite division of the institute of navigation Portland OR, 19–23 September
3. GEAS Panel (2010) Phase II of the GNSS evolutionary architecture study
4. Juan B, Todd W, Per E (2012) Satellite navigation for aviation in 2025. Proc IEEE 100:1821–1830
5. Todd W, Per E, Juan B, Boris P (2008) Worldwide vertical guidance of aircraft based on modernized GPS and new integrity augmentations. Paper presented at proceeding of the IEEE
6. Young CL, Michael PMc (2007) Feasibility analysis of RAIM to provide LPV-200 approaches with future GPS, ION GNSS. Paper presented at 20th international technical meeting of the satellite division, pp 25–28
7. Yun W, Jinling W, Yiping J (2013) Advanced receiver autonomous integrity monitoring (ARAIM) schemes with GNSS time offsets. Adv Space Res 52(1):52–61