Chapter 18
Application of Carrier Phase Differential Relative Navigation for Shipboard Landing of Aircraft

Bao Li, Kejin Cao, Jiangning Xu and Yinbing Zhu

Abstract Shipboard landing of aircraft needs to acquire the real-time and precise relative position between shipboard and aircraft. If the technique of relative navigation based on differential carrier phase is used to solve the problem, the key point is fixing the ambiguity real-time and reliably. In general, wide lane carrier is used to solve the problem. At single epoch, the observable equations of double frequency wide lane carrier are ill-condition, so the code observable equations are needed to add in. Since the poor precision of the code pseudorange information, the ambiguity solved by it can't reach the performance requirements in shipboard landing. A fitting method by selection of parameter weights is researched based on wide lane algorithm. The method estimates the two kinds of wide lane float ambiguities at first; then solves the individual ambiguity separately. It avoids the problems of poor precision from code equations. The calculation of experiment data shows that the algorithm can solve ambiguity reliably at single epoch and improve accuracy of relative position to centimeter level, which satisfies the requirements for shipboard landing of aircraft.

Keywords GNSS · Shipboard landing of aircraft · Wide lane · Integer ambiguity · Fitting method by selection of parameter weights

18.1 Introduction

When a pilot drives aircraft to land on the shipboard, he faces more pressure compared with driving it to land on earth since the disadvantage factors such as shipboard moving, short runway and airstreams on the sea. For a long time,

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countries spare no effort on developing advanced, precise and reliable shipboard landing system [1]. The shipboard landing system of aircraft has been experienced from Landing Signals Officer, Optical Landing System, Instrument Landing System to Automatic Carrier Landing System. As the development of GNSS, their capabilities of all-weather, all-place and precise three dimensional positioning attract researchers' attentions [2].

In May 1996, the American Department of Defence proposed JPALS (Joint Precision Approach and Landing System) plan officially. JPALS consists of sea based and land Based (SB-JPALS and LB-JPALS) system. It is an all-weather, all-mission, all-user landing system based on differential Global Positioning System and supports fixed-base, tactical, and shipboard applications [3]. At present, JPALS is still being developed, and the public information is few [4–6].

As the precise and dynamic navigation performance requirements in shipboard landing of aircraft, the differential carrier phase technology is needed. The key point is fixing the integer ambiguity reliably at single epoch. From relative papers [7–9], the double frequency wide lane carrier can solve the ambiguity quickly, but the carrier phase equations are ill-condition at single epoch. A general method is adding the code observable equations in, whereas the code observable equations can't apply to fix ambiguity for its poor precision. Some researches proposed methods such as carrier phase smoothed pseudorange and dividing wide lane ambiguity based on variance to solve wide lane ambiguity [7, 8], however, they can't reach the performance requirements in shipboard landing of aircraft either. The paper [9] puts forward an algorithm. It estimates the two kinds of wide lane float ambiguities at first; then solves the individual ambiguity separately. It avoids the problems of poor precision from code equations and satisfies the requirements in shipboard landing of aircraft. This paper discusses the application of the algorithm in shipboard landing of aircraft.

18.2 The Structure and Performance Parameters of SB-JPALS

SB-JPALS is made up of three parts, which are shipboard equipments, aircraft equipments and data transmission equipments. They are showed in Fig. 18.1. The shipboard receives the GPS signal to acquire its position, and transmits its position to aircraft by data transmission equipments. The aircraft can also acquire its position by GPS signal, which is calculated with the shipboard position to work out the relative position vector form the shipboard to aircraft. There is an UHF data link between the shipboard and aircraft.

According to paper [4], the performance parameters of SB-JPALS are showed in Table 18.1. From the table, SB-JPALS applies the high precise P code for double frequency wide lane algorithm. As a result that the P code is special for American army, how to use C/A code to fix the ambiguity reliably at single epoch becomes a serious problem. A new method is proposed as below.

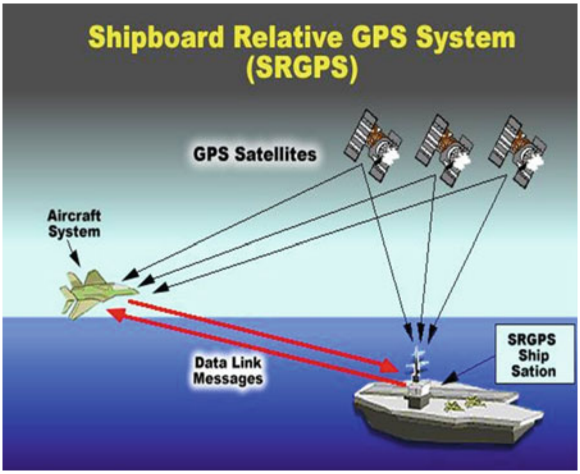

Fig. 18.1 Structure of SB-JPALS

Table 18.1 Performance parameters of SB-JPALS

Accuracy (95 %)	0.4 m
Integrity	10^{-6}
VAL	1.1 m
TTA	2 s
Continuity	$1 \times 10^{-6}/15$ s
Availability	99.7 %
Basic algorithm	Wide lane fixed ambiguity, L1/L2 fixed ambiguity, shipboard and aircraft equipments are both double frequency P code

18.3 Differential Carrier Phase Algorithm for Shipboard Landing of Aircraft

18.3.1 Double Frequency Wide Lane Ambiguity Resolution

Ambiguity is easier to fix when the carrier wave length is longer. If two carriers are combined as a long wave carrier, the ambiguity is easier to fix. It's basic principle for double frequency wide lane algorithm.

In the process of aircraft landing on shipboard, if there are m satellites in view for both observable station 1 and station 2. For two satellites i, j, the L1 and L2 wide lane observable equation at some epoch is described as

$$\lambda_W \varphi^{ij}_{12,W} = \rho^{ij}_{12,W} + \lambda_W N^{ij}_{12,W} + \varepsilon^{ij}_{12,W} \tag{18.1}$$

where λ is the carrier wave length, φ is observable value of carrier phase, ρ is the distance form satellite and station, N is integer ambiguity, ε is the observable noise of carrier phase, W means wide lane. At single epoch, there are m−1 carrier observable equations but m+2 unknown variables, so the carrier observable equations are ill-condition. Combined with code observable equations can solve the problem, and paper [10] proposed the double P code pseudorange algorithm. However, the P code pseudorange is special for army. If C/A code pseudorange is used for ambiguity fixing, it can't satisfy the performance requirements of shipboard landing.

18.3.2 A New Algorithm for Wide Lane Ambiguity Resolution at Single Epoch

If we can't get precise code observables, the algorithm for ambiguity resolution at single epoch is how to solve ill-condition equations [11]. After wide lane combined, the wave length is longer. In this case, the wide lane float ambiguity can be solved with fitting method by selection of parameter weights.

The least squared equation of wide lane float ambiguity can be written as

$$\begin{bmatrix} A^T C^{-1} A & A^T C^{-1} B \\ B^T C^{-1} A & B^T C^{-1} B \end{bmatrix} \begin{bmatrix} X \\ N \end{bmatrix} = \begin{bmatrix} A^T C^{-1} L \\ B^T C^{-1} L \end{bmatrix} \tag{18.2}$$

where X is the baseline vector, N is vector of double differential ambiguity, A, B are coefficient matrix. C^{-1} is the weight matrix and the calculation method how to get it is described in paper [12]. According to the solving principle of ill-condition equation, the weight fitting matrix R can be written as

$$R = \begin{pmatrix} E_{3\times 3} & 0_{3\times(m-1)} \\ 0_{(m-1)\times 3} & 0_{(m-1)\times(m-1)} \end{pmatrix} \tag{18.3}$$

Form Eq. (18.3), the improved normal matrix can be described as

$$M_R = M + \mu R = \begin{bmatrix} A^T C^{-1} A + \mu E & A^T C^{-1} B \\ B^T C^{-1} A & B^T C^{-1} B \end{bmatrix} \tag{18.4}$$

where M is the old normal matrix, μ is regularization parameter, E is the fitting matrix, the setting method for E can be resulted from paper [11].

The covariance matrix is acquired from the improved normal matrix. The wide lane fixed ambiguity can be solved by searching with new covariance matrix. Here the part ambiguity searching method is suggested for efficiency. The method above needs an initial precise position, which can be provided from differential code pseudorange equations.

18.3.3 Resolution for Individual Carrier Phase Ambiguity

Since the noise is amplified by wide lane, the position solved by wide lane ambiguity is not precise enough. So the individual ambiguity of L1 and L2 are required for high precision. Two carriers can make up of different linear combination. If the linear coefficients are α and β, the combined carrier phase can be written as

$$\varphi_{\alpha\beta} = \alpha\varphi_{L1} + \beta\varphi_{L2} \tag{18.5}$$

The wide lane ambiguity $N_{\alpha\beta}$ can be solved by the algorithm in Sect. 18.3.2. If another wide lane ambiguity $N_{\eta\gamma}$ is solved by the same method. So ambiguity N_1 and N_2 can be solved by the equation below

$$\begin{bmatrix} N_{\alpha\beta} \\ N_{\eta\gamma} \end{bmatrix} = \begin{bmatrix} \alpha & \beta \\ \eta & \gamma \end{bmatrix} \begin{bmatrix} N_1 \\ N_2 \end{bmatrix} \tag{18.6}$$

If $\alpha\gamma - \beta\eta \neq 0$, the N_1 and N_2 will be solved out on condition that the $N_{\alpha\beta}$ and $N_{\eta\gamma}$ are solved correctly. Therefore, the high precise baseline vector can be calculated.

18.4 Algorithm Test

18.4.1 Single Epoch Data Processing in Static Test

In static situation the ambiguity solved by long time can be regarded as the true ambiguity. If the ambiguity can be solved at single epoch in static situation, we consider the algorithm satisfies the application in dynamic situation in a way.

At 10 am, Jul 26, 2012, we used two FlexPak-G2 receivers of Novatel Corporation acquire data on the roof of Electrical Engineering College building. The sampling period is 1 s, and the lowest requirement of satellite altitude angle is 15°. We acquired 3775 s data in all. The GPS satellites which can be seen for both two receivers are [20 16 6 31 29 23 30 32]. The satellite 16 is taken as reference, so 7 ambiguities are produced. The ambiguities solved by all data are taken as true ambiguities.

The combined coefficients are selected as $\alpha = 1$, $\beta = -1$, $\eta = 4$, $\gamma = -5$, so the wide lane wave $\lambda_{\alpha\beta} = 86.2\,\text{cm}$ $\lambda_{\eta\gamma} = 183.2\,\text{cm}$ which are far longer than individual wave of L1 and L2. The two kinds of wide lane ambiguities calculated by each epoch are showed in Table 18.2. From the table we can seen, the success ratio of two wide lane ambiguities resolution are 100 %; according to the Eq. (18.6), the success ratio of N_1 and N_2 resolution are 100 %, too. Therefore, it can be concluded that the new algorithm can fix the ambiguity reliably at single epoch.

Table 18.2 The results of two wide lane ambiguities resolution

Satellites team	Epoch number	Wide lane ambiguity $N_{\alpha\beta}$			Wide lane ambiguity $N_{\eta\gamma}$		
		Ambiguity	Success number	Success ratio (%)	Ambiguity	Success number	Success ratio (%)
16–20	3,032	−5	3,032	100	−15	3,032	100
16–06	3,775	4	3,775	100	25	3,775	100
16–31	3,775	2	3,775	100	13	3,775	100
16–29	2,068	−5	2,068	100	−12	2,068	100
16–23	3,775	1	3,775	100	5	3,775	100
16–30	3,775	−5	3,775	100	−15	3,775	100
16–32	2,564	−2	2,564	100	−7	2,564	100

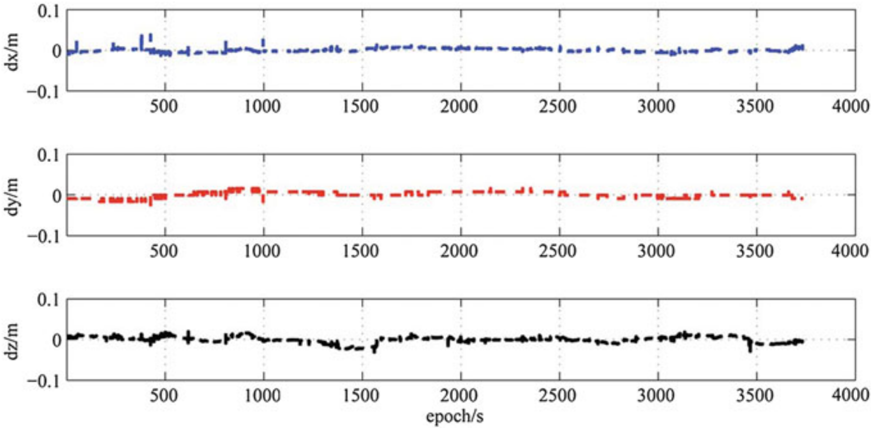

Fig. 18.2 Baseline vector biases of single epoch resolution in static test

The baseline biases of each epoch resolution are shown in Fig. 18.2. From the figure it can be seen that the new algorithm can solve the baseline with centimeter level after fixing the ambiguity successfully.

18.4.2 Dynamic Test

In dynamic situation, we can't acquire the true integer ambiguity because the calculation is not allowed to accumulate on time. So we adjust the truth of solving ambiguity by calculating the baseline vector between two carriers. The experiment system consists of three FlexPak-G2 receivers, two of which are fixed on the top of two cars respectively, and the rest one is fixed as based station. The general carrier phase RTK is processed between based station and two moving station respectively. The absolute position accuracy of general carrier phase RTK can reach

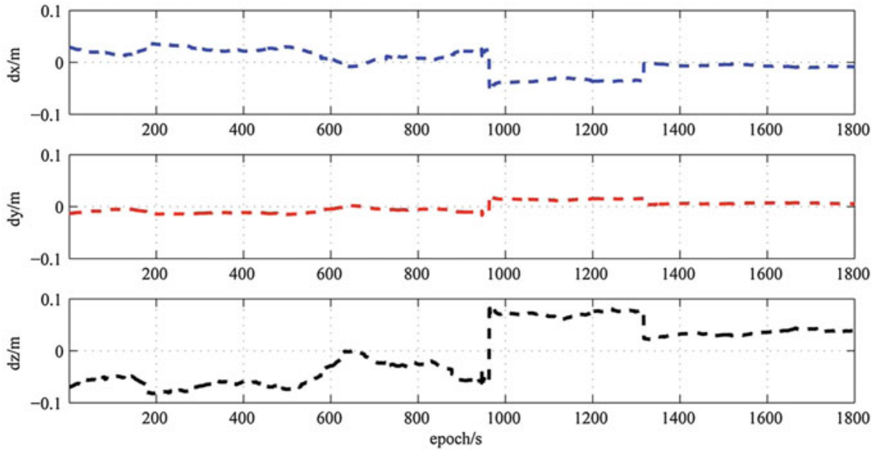

Fig. 18.3 Baseline vector biases of single epoch resolution in dynamic test

1 cm + 1 ppm, therefore the relative position vector calculated from absolute position of the two RTK is regarded as the reference value. The base line get form algorithm above is compared with this reference value, and the performance of the algorithm is adjusted in dynamic situation.

At 11 am, Dec 28, 2012, the dynamic test was carried out on the playground. The sampling period is 1 s, and the lowest requirement of satellite altitude angle is 15°. We acquired 1937 s data in all. The satellites which can be seen for three receivers are [2 4 5 10 12 13 17].

The baseline biases of each epoch resolution are shown in Fig. 18.3. From the figure it can be seen that the new algorithm can also solve the baseline with cm level in dynamic situation.

18.5 Conclusions

The double frequency wide lane carrier increases the wave length, so it's convenient for fixing ambiguity. If the ambiguity is required to solve reliably at single epoch, in general the code observable equations are added in. On the condition without P code, the precision of C/A code can't satisfy the requirements of ambiguity solving. The paper discusses a method which estimates the two kinds of wide lane ambiguities with fitting method by selection of parameter weights, then solves the each ambiguity separately. The method has advantages such as without initialization, simple process and solving the ambiguity reliably at single epoch. It can solve the baseline vector with centimeter level, which satisfies the requirements of application for aircraft landing on shipboard.

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