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# Measurement for Phase Difference Rate without Phase Ambiguity

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ABSTRACT

Firstly, the direction finding solution at the midpoint of a single base array is given for the purpose of this paper and the several functions relation between phase and frequency is also described. Then, the expression of phase difference rate is described based on the multichannel phase difference measurement. With stripping time difference item correspond to the baseline length from phase difference rate, a function is extracted which signifies the differential characteristics of wavelength integer and phase difference in a unit of length. Simulation calculation found that the variation of differential function of path difference in a unit of length is very regular. The corresponding corrected value can is determine directly by distinguishing the range of differential item of phase difference obtained by actual measurement. Thus, the function expression can be obtained that is equivalence with the quondam differential function of path difference and that is nothing to do with the difference item of wavelength integer. On this basic, several parameters are analyzed by using the method of phase difference measurement without phase ambiguity. The research results in this paper may provide a powerful technical support for engineering practical design related to the phase measuring.

## 1. Introduction

The phase difference rate can be used for passive localization [1-5], There are two main methods to obtain the phase difference rate [6]: One is to extract the phase difference rate by measuring phase difference sequences and using algorithms such as difference, Kalman filtering and linear fitting [7]. The other is to calculate the phase difference rate by indirectly measuring the output frequency difference between two comparison channels based on phase discrimination [8-10]. The previous method must be measured in a row to get enough phase difference sequences, and it needs to increase the measurement accuracy by extending the observation time. It's possible that the obtained phase difference is not linear. In the case of the short baseline application, the equivalent measurement time is very short because the frequency difference interval that can be measured is too small, so that the posterior method can make the measurement error become very large. Therefrom, the prediction accuracy of the phase difference rate is hard to improve.

In the existing passive positioning analysis based on the phase difference measurement, the integer value of the wavelength is looked at as a constant value. And it's thought that the phase difference rate will have nothing to do with the integer of wavelengths after the differential treatment. That is, the difference of phase difference is not ambiguous [11-14]. But the analysis shows whether the phase difference rate is derived based on the relationship

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between phase and frequency or is obtained by making differential treatment directly to phase difference measurement based on the time series, it is related not only to the difference item of phase difference, but also to the difference item of the difference value of the integer of wavelengths. Moreover, there is mutual jump phenomenon between the difference item of phase difference and the difference item of the difference value of the integer of wavelengths.

Based on the functional relationship between phase shift and Doppler frequency shift [15], the authors have proved mathematically that the phase difference rate can be obtained in real time by using the short baseline linear array and the multichannel phase shift detection [16]. On the basis of this study, the author further studies the method to detect the phase difference rate without phase ambiguity.

Firstly, the expression of the phase difference rate by using the phase-frequency function is derived based on multichannel phase difference measurement. Then the time difference term corresponding to the baseline length is separated from the phase difference rate. The resulting is to obtain a function that can represent the difference characteristic of difference value in unit length. The subsequent simulation results show that the variation of the difference function on the unit length is very regular. The corresponding correction number can be determined directly by distinguishing the range of difference of phase difference, that the range is obtained by the actual measurement. A function expression can be obtained independent of the difference term of the integer of wavelengths as well as equivalent to the difference function of path difference in unit length.

The author's research results show that, based on the multichannel phase difference measurement, the phase difference rate can be directly obtained only by using the measured value of phase difference, and by using the jump rule of difference including the difference value of the integer of wavelengths as well as the phase difference under the condition that the difference value of integer of wavelengths is unknown. The results of this study lay a very important foundation for the engineering application of phase difference location.

Based on the function relation between the phase shift and the frequency shift, the analysis showed that many parameters in passive location is related to the testing of phase difference rate. Many kinematic positioning parameters can be converted into the function associated with the phase difference rate. Therefore, once the detection to the phase difference rate can be realized without phase ambiguity, these parameters directly related to the phase difference rate can be all solved without ambiguity. Furthermore, the physical meaning of some parameters can be understood more deeply by means of the difference expression of path difference.

## 2. A Simplified Solution for the Direction Finding at the Midpoint of a Single Base Array

### 2.1 Introduction

As the basis of the follow-up chapter, in this chapter, a single base direction finding equation which is only related to the path difference measurement is obtained by simplifying the one-dimensional path difference equation based on double-base array. Although the three-station direction finding method with two baselines obtained by using the path difference measurement and geometrical assistant relation is suitable for arbitrary baseline length, it is most desirable to realize the direction finding of double stations from the perspective of engineering application.

### 2.2 One Dimensional Double-base Direction Finding Solution

For the one-dimensional double-base phase interference array shown in Figure 1, the path difference between the adjacent two baselines is:

$$\Delta r_i = r_i - r_{i+1} \tag{1}$$

$$\Delta r_{i+1} = r_{i+1} - r_{i+2} \tag{2}$$

If the center point of the whole array is used as the origin of coordinates, then the following two geometric auxiliary equations can be listed by the cosine theorem:

$$r_i^2 = r_{i+1}^2 + d_i^2 - 2d_i r_{i+1}\cos(90+\theta_{i+1}) = r_{i+1}^2 + d_i^2 + 2d_i r_{i+1}\sin\theta_{i+1} \tag{3}$$

$$r_{i+2}^2 = r_{i+1}^2 + d_{i+1}^2 - 2d_{i+1} r_{i+1}\cos(90-\theta_{i+1}) = r_{i+1}^2 + d_{i+1}^2 - 2d_{i+1} r_{i+1}\sin\theta_{i+1} \tag{4}$$

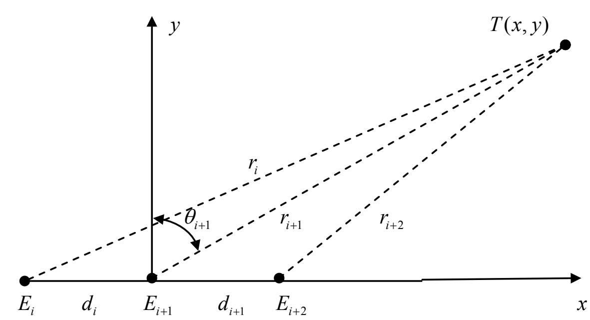


**Figure 1.** One-dimensional double-base array



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Due to: $x = r_{i+1}\sin\theta_{i+1}$, Therefore, the geometric auxiliary equation can be rewritten as:

$$r_i^2 = r_{i+1}^2 + d_i^2 + 2d_i x \quad (5)$$

$$r_{i+2}^2 = r_{i+1}^2 + d_{i+1}^2 - 2d_{i+1}x \quad (6)$$

Where: $d_i$ is the length of single baseline; $x$ is the x-coordinate of rectangular coordinate system.

At this point, if the path difference (1) and (2) between two adjacent baselines are substituted into the geometric auxiliary equations (5) and (6), then the following binary primary linear equations can be obtained after rearrangement:

$$2d_i x - 2\Delta r_i r_i = -d_i^2 + \Delta r_i^2 \quad (7)$$

$$2d_{i+1}x - 2\Delta r_{i+1} r_{i+1} = d_{i+1}^2 - \Delta r_{i+1}^2 \quad (8)$$

From this, the horizontal distance of the target can be directly solved out:

$$x = \frac{\left(d_i^2 - \Delta r_i^2\right)\Delta r_{i+1} + \left(d_{i+1}^2 - \Delta r_{i+1}^2\right)\Delta r_i}{2\left(\Delta r_i d_{i+1} - \Delta r_{i+1} d_i\right)} \quad (9)$$

And the radial distance of the target:

$$r_{i+1} = \frac{\left(d_i^2 - \Delta r_i^2\right)d_{i+1} + \left(d_{i+1}^2 - \Delta r_{i+1}^2\right)d_i}{2\left(\Delta r_i d_{i+1} - \Delta r_{i+1} d_i\right)} \quad (10)$$

From this, the arrival angle of the target can be obtained:

$$\sin\theta_{i+1} = \frac{x}{r_{i+1}} = \frac{\left(d_i^2 - \Delta r_i^2\right)\Delta r_{i+1} + \left(d_{i+1}^2 - \Delta r_{i+1}^2\right)\Delta r_i}{\left(d_i^2 - \Delta r_i^2\right)d_{i+1} + \left(d_{i+1}^2 - \Delta r_{i+1}^2\right)d_i} \quad (11)$$

### 2.3 Approximate Simplified Solution

For one-dimensional double-base direction finding equation:

$$\sin\theta = \frac{\left(d^2 - \Delta r_1^2\right)\Delta r_2 + \left(d^2 - \Delta r_2^2\right)\Delta r_1}{d\left(2d^2 - \Delta r_1^2 - \Delta r_2^2\right)} \quad (12)$$

If the approximate treatment is done for the higher-order terms of path difference: $\Delta r_1 \approx \Delta r_2$, accordingly, after simplification, there is:

$$\sin\theta \approx \frac{\left(d^2 - \Delta r_2^2\right)\left(\Delta r_1 + \Delta r_2\right)}{2d\left(d^2 - \Delta r_1^2\right)} = \frac{\left(\Delta r_1 + \Delta r_2\right)}{2d} \quad (13)$$

For:

$$\Delta r_{13} = r_1 - r_3 = \left(r_1 - r_2\right) + \left(r_2 - r_3\right) = \Delta r_1 + \Delta r_2 \quad (14)$$

From this, the single base direction finding solution only related to the measurement of path difference is obtained:

$$\sin\theta = \frac{\Delta r_{13}}{2d} \quad (15)$$

Note that the reference point for a single base direction finding is at the mid-point of a single baseline, not at the left or right end of a single baseline.

The simulation results show that the single base direction-finding formula (15) obtained from the approximation simplification is correct not only for short baselines, but also for longer baselines.

### 2.4 Summary

One of the important applications of single-base direction finding is the direction-finding using time difference measurement based on long baseline. As a high-precision direction finding method for passive detection of military applications, the research on time difference detection technology has made a significant breakthrough in the past 40 years, but the relevant research so far mainly focuses on the short baseline time difference measurement method [17-20]. On the one hand it's a tactical need, on the other hand it involves the mathematical models. The existing direction finding formula based on short baseline is only a very approximate calculation method. If it is extended to long baseline measurement, the calculation accuracy will become worse and cannot be applied. It seems that the results can be given in form by using the existing approximate short baseline direction-finding formula, but the mathematical description is incomplete, and more importantly, it is difficult to accurately analyze the problems related to the long baseline.

Obviously, based on the principle that the direction finding precision is proportional to the length of the baseline, if the model suitable for the time difference measurement of the long baseline can be given mathematically, the direction finding performance of the ultra-precision should be obtained.

## 3. Some Function Relations between the Phase and Frequency

### 3.1 Phase Difference Positioning Equation

If the phase-interferometer is used for passive detection of the target, and the phase-interferometer is assumed to only use the single-base antenna array as shown in Figure 2, the distance formula based on the phase shift measurement is as follows:

$$r_i = \lambda\left(n_i + \frac{\phi_i}{2\pi}\right) \tag{16}$$

Where: $r_i$ is the radial distance; $\lambda$ the wavelength; $n_i$ the number of wavelengths; $\phi_i$ the phase shift measured by the Phase detector unit.

According to the relation (16) between phase shift and distance, the path difference $\Delta r_i$ between two radial distance corresponding to the array elements $E_i$ and $E_{i+1}$ of a single baseline can be determined by the phase difference measurement, and the phase difference localization equation can be obtained whose form is completely similar to the time difference localization equation:

$$\Delta r_i = r_i - r_{i+1} = \lambda\left(n_i - n_{i+1} + \frac{\phi_i - \phi_{i+1}}{2\pi}\right) = \lambda\left(\Delta n_i + \frac{\Delta\phi_i}{2\pi}\right) \tag{17}$$

Where: $\Delta n_i = n_i - n_{i+1}$ is the difference value of wavelength number contained in the path difference; $\Delta\phi_i = \phi_i - \phi_{i+1}$ the phase difference between two elements.

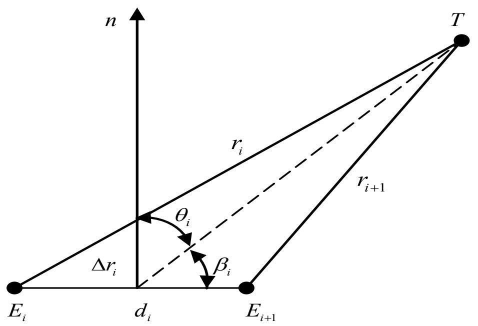


**Figure 2.** Schematic diagram of single base array

### 3.2 Direction Finding Solution Using Single Baseline based on Phase Difference Measurement

Based on phase difference positioning equation, the direction finding solution based on phase difference measurement can be directly obtained by further using the expression form of single base middle point direction finding instead of the existing short baseline phase interference direction finding concept:

$$\sin\theta_i = \frac{\Delta r_i}{d_i} = \frac{\lambda}{d_i}\left(\Delta n_i + \frac{\Delta\phi_i}{2\pi}\right) \tag{18}$$

The direction-finding formula given here can be applied to longer baselines from a purely mathematical definition, but note that the reference point of the measurement is at the midpoint of the baseline.

### 3.3 The Function Relation between Phase Difference and Frequency Shift

A Doppler receiver is installed on the airborne platform to detect stationary or slow-moving targets on the ground, and the Doppler frequency shift received at the middle point of a single base is:

$$\lambda f_{di} = v\cos\beta_i \tag{19}$$

Where: $f_{di}$ is Doppler frequency shift; $v$ the speed of the airplane; $\beta_i$ the leading angle.

According to the reciprocal relationship between the arrival angle and the leading angle: $\sin\theta_i = \cos\beta_i$, using the direction finding formula (19) of the single base midpoint based on the phase difference measurement, the leading angle can be expressed as:

$$\cos\beta_i = \frac{\Delta r_i}{d_i} = \frac{\lambda}{d_i}(\Delta n_i + \frac{\Delta\phi_i}{2\pi}) \tag{20}$$

And once expression (20) is substituted into the Doppler shift expression (19), the functional relationship between phase difference and Doppler shift is obtained:

$$f_{di} = \frac{v}{d_i}\left(\Delta n_i + \frac{\Delta\phi_i}{2\pi}\right) \tag{21}$$

### 3.4 The Function Relation between the Change Rate of Phase Shift and Frequency Shift

If the differentiating with respect to time is applied to both sides of the phase-distance expression (16), then there is:

$$\frac{\partial r_i}{\partial t} = \frac{\lambda}{2\pi}\frac{\partial\phi_i}{\partial t} \tag{22}$$

According to the relation between the change rate of radial distance and Doppler frequency shift:

$$\frac{\partial r_i}{\partial t} = v_{ri} = \lambda f_{di} \tag{23}$$

It can be proved that:

$$\frac{\partial\phi_i}{\partial t} = 2\pi f_{di} \tag{24}$$

### 3.5 The relation between the phase difference rate and frequency difference

If the differential with respect to time is applied to both



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sides of the relation (17) of phase difference - distance difference, then:

$$\frac{\partial \Delta r_i}{\partial t} = \frac{\lambda}{2\pi}\frac{\partial \Delta\phi}{\partial t} \quad (25)$$

According to the relation between the change rate of radial distance and Doppler frequency shift:

$$\frac{\partial r_i}{\partial t} = v_{ri} = \lambda f_{di} \quad (26)$$

Based on the same process, the relation between the phase difference rate and frequency difference can be obtained:

$$\frac{\partial \Delta\phi}{\partial t} = 2\pi\Delta f_d \quad (27)$$

Where: $\Delta f_d = f_{d1} - f_{d2}$ .

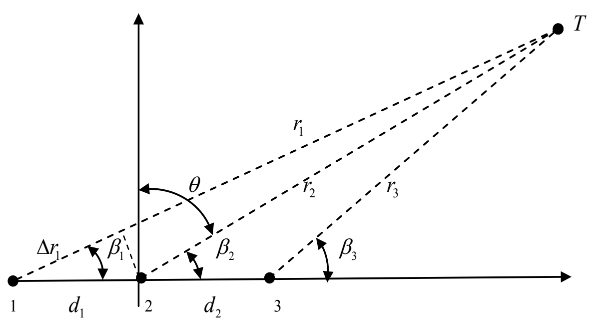


**Figure 3.** The one-dimensional double base array with three units

It is proved that the phase difference rate can be obtained by detecting the Doppler frequency difference. According to the relationship Eq.(24) between Doppler shift and the change rate of phase shift, the Doppler shift value corresponding to a certain radial distance actually needs to be obtained by difference of two phase values. Therefore, in order to obtain the Doppler frequency difference, three phase shifts need to be detected simultaneously, that is, the one-dimensional double base array with three units as shown in Figure 3 needs to be adopted from the implementation method of measurement.

# 4. Phase Difference Rate Based on Multichannel Phase Difference Measurement

## 4.1 The Change Rate of Phase Shift Obtained by Detecting Phase Difference

The change rate of radial distance is the radial velocity of the target:

$$\frac{\partial r_i}{\partial t} = v_{ri} = v\sin\theta \quad (28)$$

Where: $v$ is the flight speed of the aerial carrier, and $v_{ri}$ the radial speed.

Use the relationship between the change rate of distance and the change rate of phase shift Eq.(22) :

$$\frac{\partial r_i}{\partial t} = \frac{\lambda}{2\pi}\frac{\partial \phi_i}{\partial t} \quad (29)$$

And use the direction finding formula Eq.(18) of single-base midpoint based on phase difference measurement:

$$\sin\theta \approx \frac{\Delta r_i}{d} = \frac{\lambda}{d}\left(\Delta n_i + \frac{\Delta\phi_i}{2\pi}\right) \quad (30)$$

It can be proved that the formula of the change rate of phase shift based on the phase difference measurement is:

$$\frac{\partial \phi_i}{\partial t} = \frac{2\pi v}{d}\left(\Delta n_i + \frac{\Delta\phi_i}{2\pi}\right) \quad (31)$$

## 4.2 The Phase Difference Rate Obtained by Detecting the Phase Difference

Directly from formula Eq.(31), there are:

$$\begin{aligned}\frac{\partial \Delta\phi}{\partial t} &= \frac{\partial \phi_1}{\partial t} - \frac{\partial \phi_2}{\partial t} \\ &= \frac{2\pi v}{d_i}\left(\Delta n_i + \frac{\Delta\phi_i}{2\pi}\right) - \frac{2\pi v}{d_{(i+1)}}\left(\Delta n_{(i+1)} + \frac{\Delta\phi_{(i+1)}}{2\pi}\right) \\ &= 2\pi v\left[\left(\frac{\Delta n_i}{d_i} - \frac{\Delta n_{(i+1)}}{d_{(i+1)}}\right) + \left(\frac{\Delta\phi_i}{2\pi d_i} - \frac{\Delta\phi_{(i+1)}}{2\pi d_{(i+1)}}\right)\right]\end{aligned} \quad (32)$$

For the double-base linear array that is equidistant, that is , when $d = d_1 = d_2$ , there is:

$$\frac{\partial \Delta\phi}{\partial t} = \frac{2\pi v}{d}\left[(\Delta n_{12} - \Delta n_{23}) + (\frac{\Delta\phi_{12}}{2\pi} - \frac{\Delta\phi_{23}}{2\pi})\right] \quad (33)$$

For clarity, the subscript of the parameter in the formula has been represented by a double number corresponding to the mark number at both ends of the baseline. Obviously, three phase-shift values need to be detected simultaneously to obtain the phase difference rate , that is, the one-dimensional double-base linear array as shown in Figure 3 needs to be adopted from the implementation method of measurement.

## 5. Difference Function of Path Difference on Unit Length

### 5.1 Decomposition of Functions

The representation of the phase difference rate based on multichannel detection of phase difference can be divided into the product as follow two items:

$$\frac{\partial \Delta}{\partial} = {}_{t0} \cdot \Delta \tag{34}$$

The first item represents the circular angle per unit time when the carrier is moving at speed $v$ and is undergoing the baseline length $d$ :

$$\phi_{t0} = \frac{2\pi v}{d_i} = \frac{2\pi}{\Delta t_i} \tag{35}$$

The latter second term is called the difference term of path difference on the unit length:

$$\Delta^2 r_\lambda = \left(\Delta n_i - \Delta n_{i+1}\right) + \left(\frac{\Delta\phi_i}{2\pi} - \frac{\Delta\phi_{i+1}}{2\pi}\right) = \frac{\Delta r_i - \Delta r_{i+1}}{\lambda} \tag{36}$$

The difference terms $\Delta^2 r_\lambda$ of path difference on a unit length can be divided into the sum of two terms. The previous term is the difference of the integer of wavelength between two adjacent baselines:

$$\Delta^2 n_i = \left(\Delta n_i - \Delta n_{i+1}\right) \tag{37}$$

The latter term is the difference of phase difference between two adjacent baseline:

$$\Delta^2 \phi_i = \left(\frac{\Delta\phi_i}{2\pi} - \frac{\Delta\phi_{i+1}}{2\pi}\right) \tag{38}$$

That is:

$$\Delta^2 r_\lambda = \Delta^2 n_i + \frac{\Delta^2 \phi_i}{2\pi} \tag{39}$$

### 5.2 Change Rule

If $\Delta^2 r_\lambda$ is expressed as a function varying with the angle of arrival, the simulation calculation indicates that the previous term will always jump between 0 and 1, and the latter term $\Delta^2 \phi_i$ will jump within the range of $-1 < \Delta^2 \phi_i < 0.1$ .

According to Matlab program, the theoretical calculation value of $\Delta^2 n_i$ is:

$$\Delta^2 n_i = \left[FIX\left(r_i / \lambda\right) - FIX\left(r_{i+1} / \lambda\right)\right] - \left[FIX\left(r_{i+1} / \lambda\right) - FIX\left(r_{i+2} / \lambda\right)\right] \tag{40}$$

Figure 4 shows the variation curve of the differential of the difference value of the number of wavelength at different angles of arrival. In order to keep the screen simple, the larger interval of the arrival angle is taken. The simulation shows that even if the interval of the angle is 0.01 degrees, $\Delta^2 n_i$ is still a jump back and forth between 0 and 1.

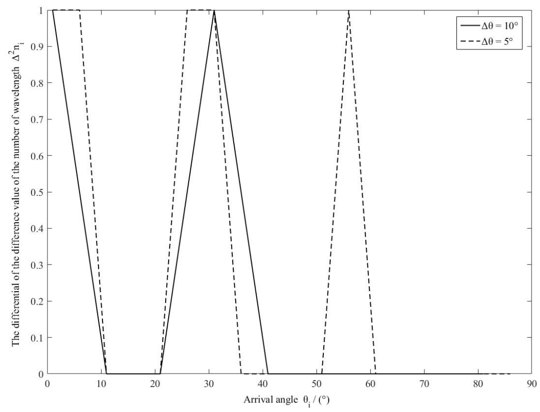


**Figure 4.** The differential of the difference value of the number of wavelength

The theoretical value of phase shift whose numerical value is less than $\pi$ is:

$$\phi_i = 2\pi\left(r_i/\lambda - n_i\right) \tag{41}$$

Thereout, the theoretical calculation formula of differential of phase difference can be obtained:

$$\Delta^2 \phi_i = \left[\left(r_i/\lambda - n_i\right) - \left(r_{i+1}/\lambda - n_{i+1}\right)\right] - \left[\left(r_{i+1}/\lambda - n_{i+1}\right) - \left(r_{i+2}/\lambda - n_{i+2}\right)\right] \tag{42}$$

Figure 5 shows the variation curve of the differential of phase difference at different angle intervals.

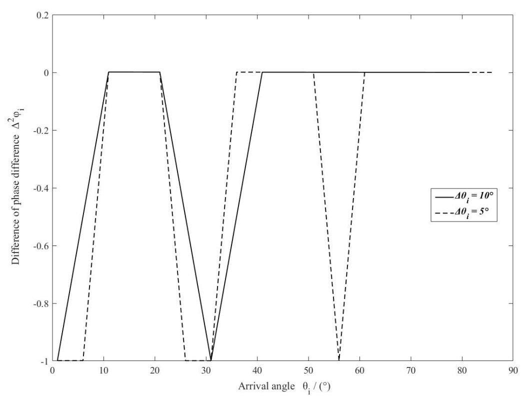


**Figure 5.** The differential of phase difference

### 5.3 Correction of Phase Jump

The analog calculation shows that the value of the differential term $\Delta^2 r_\lambda$ on the unit length is always less than 1.



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As can be seen from the graph, the variation between the number of wavelength and the differential of phase differences is going to correspond to each other. If the preceding term has a jump change, the latter must also have a jump change, and the sum of the preceding and following terms is always to offset the value greater than 1 when the integral part of the differential item $\Delta^2 r_\lambda$ of path difference in unit length is greater than 1. Therefore, according to the numerical change rule that the sum of the two terms must offset the integral part greater than 1, If there is a jump on the differential of phase difference, then the measured data of phase difference can be corrected with the $\pm 1$.

The specific numerical simulation results are as follows:

When the absolute value of difference term of phase difference is $|\Delta\phi_{12} - \Delta\phi_{23}| < \pi$, directly take:

$$2\pi \cdot \Delta^2 \Delta\phi_i = (\Delta\phi_{12} - \Delta\phi_{23}) \tag{43}$$

When the difference term of phase difference is $(\Delta\phi_{12} - \Delta\phi_{23}) > 2\pi$, take:

$$2\pi \cdot \Delta^2 \Delta\phi_i = (\Delta\phi_{12} - \Delta\phi_{23}) - 2\pi \tag{44}$$;

When it is $\pi < |\Delta\phi_{12} - \Delta\phi_{23}| < 2\pi$, take:

$$2\pi \cdot \Delta^2 \Delta\phi_i = 2\pi - |\Delta\phi_{12} - \Delta\phi_{23}| \tag{45}$$

That is, the piecewise equivalent function of the difference term of path difference on unit length is as follows:

$$\overline{\Delta^2} r_\lambda = \begin{cases} \Delta\phi_{12} - \Delta\phi_{23}, & |\Delta\phi_{12} - \Delta\phi_{23}| < \pi \\ (\Delta\phi_{12} - \Delta\phi_{23}) - 2\pi, & (\Delta\phi_{12} - \Delta\phi_{23}) > 2\pi \\ 2\pi - |\Delta\phi_{12} - \Delta\phi_{23}|, & \pi < |\Delta\phi_{12} - \Delta\phi_{23}| < 2\pi \end{cases} \tag{46}$$

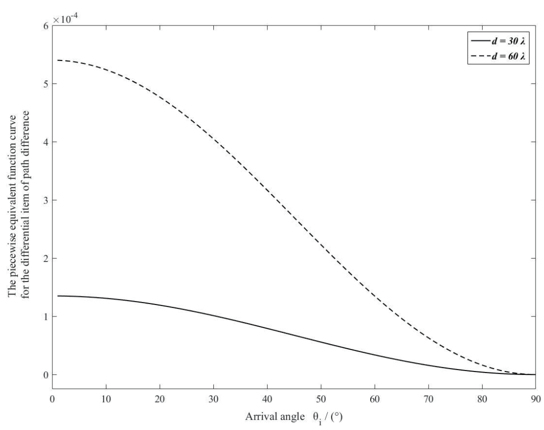


**Figure 6.** The piecewise equivalent function curve for the differential item of path difference

After modification is done in according to the numerical jump of the phase differential item, obtained piecewise equivalent function of the difference term of path difference on the unit length already has nothing to do with the computing of differential item of number of wavelength. The curve is shown in figure 6 shows that the range of the piecewise equivalent function for the differential item of path difference on the unit length is smooth continuous that is obtained only by measuring the phase difference.

## 5.4 Validation

Literature [16] has indirectly verified the correctness of the expression of phase difference rate based on multichannel phase difference measurement by using phase difference ranging method. In this chapter, the correctness of piecewise equivalent function of the differential item of path difference would be emphatically verified. The method is to use the theoretical value of the differential item of path difference on unit length

$$\Delta^2 r_\lambda = \frac{\Delta r_i - \Delta r_{i+1}}{\lambda} = \left(\Delta n_i + \frac{\Delta\phi_i}{2\pi}\right) - \left(\Delta n_{i+1} + \frac{\Delta\phi_{i+1}}{2\pi}\right) \tag{47}$$

Compared with the piecewise equivalent function obtained by phase difference correction, the relative calculation error is shown in figure 7. The simulation results show that the derived equation of the differential of path difference at present is only applicable to the shorter baseline length. When the radial distance is determined, the maximum usable baseline length can be estimated according to the following formula:

$$\frac{d}{\lambda} \le \frac{18r}{2000} \tag{48}$$

Where: $r$ represents the radial distance of the target.

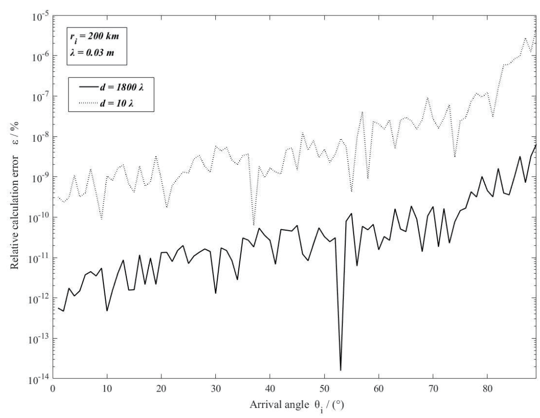


**Figure 7.** Relative calculation error of the differential item of path difference

## 6. Some Parameters Realized by the Phase Difference Measurement without Ambiguity

### 6.1 Relative Angular Velocity

#### 6.1.1 Overview

In the airborne single-station passive positioning system, the observability of the positioning system can be increased and the positioning performance can be improved by introducing the observation information of angular velocity [11, 21] . However, the angular velocity is a physical quantity of time derivative. Unless the gyroscope sensor is used, it usually needs to be obtained by indirect method. The difference method, or least square fitting method, or Kalman filter method, which estimates the change rate of angle by using angle measurement equipment to obtain angle sequence, requires that the angle observation value itself must be linear change during the sampling period, otherwise, the measurement accuracy of angle change rate will be difficult to be guaranteed [22].

#### 6.1.2 Basic Solution

Directly differential for direction finding formula based on phase differential measurement on a single basis, there is:

$$\omega\cos\theta = \frac{1}{d}\frac{\partial\Delta r}{\partial t} = \frac{\lambda}{2\pi d}\frac{\partial\Delta\phi}{\partial t} \tag{49}$$

Where: $\omega$ is the angular velocity.

After the transposition arrangement, by substituting the phase difference rate based on the multichannel phase difference detection into (49) , we obtain:

$$\omega = \frac{\lambda}{2\pi d\cos\theta}\frac{\partial\Delta\phi}{\partial t} = \frac{\lambda v}{d^2\cos\theta}\left[\left(\Delta n_1 - \Delta n_2\right) + \left(\frac{\Delta\phi_1}{2\pi} - \frac{\Delta\phi_2}{2\pi}\right)\right] \tag{50}$$

Furthermore, the non-fuzzy solution of the phase difference rate is substituted into, and the relative angular velocity calculation formula based on measurement of azimuth angle and the difference of non-fuzzy phase difference is obtained:

$$\omega = \frac{\lambda v}{d^2\cos\theta}\Delta^2 r_\lambda \tag{51}$$

#### 6.1.3 Error

In order to facilitate the error analysis, the non-fuzzy solution is first reduced to a form that contains the difference value of the integer of wavelength, and it is regarded as a constant:

$$\omega = \frac{\lambda v}{d^2\cos\theta}\left[\left(\Delta n_1 - \Delta n_2\right) + \left(\frac{\Delta\phi_1}{2\pi} - \frac{\Delta\phi_2}{2\pi}\right)\right] \tag{52}$$

Partial differential to each phase difference is:

$$\frac{\partial\omega}{\partial\Delta\phi_1} = \frac{\lambda v}{2\pi d^2\cos\theta} \tag{53}$$

$$\frac{\partial\omega}{\partial\Delta\phi_2} = -\frac{\lambda v}{2\pi d^2\cos\theta} \tag{54}$$

$$\frac{\partial\omega}{\partial\theta} = -\frac{\lambda v\sin\theta}{d^2\cos^2\theta}\left[\left(\Delta n_1 - \Delta n_2\right) + \left(\frac{\Delta\phi_1}{2\pi} - \frac{\Delta\phi_2}{2\pi}\right)\right] \tag{55}$$

$$\frac{\partial\omega}{\partial v} = \frac{\lambda}{d^2\cos\theta}\left[\left(\Delta n_1 - \Delta n_2\right) + \left(\frac{\Delta\phi_1}{2\pi} - \frac{\Delta\phi_2}{2\pi}\right)\right] \tag{56}$$

According to the error estimation theory, the measurement error of relative angular velocity caused by phase difference, angle and velocity is:

$$\sigma_r = \sqrt{\left(\frac{\partial\omega}{\partial v}\sigma_v\right)^2 + \sum_{i=1}^{2}\left(\frac{\partial\omega}{\partial\Delta\phi_i}\sigma_\phi\right)^2 + \left(\frac{\partial\omega}{\partial\theta}\sigma_\theta\right)^2} \tag{57}$$

Where: $\sigma_v$ is the root mean square value of velocity measurement error, and takes $\sigma_v = 0.1m/s$ when analyzing and calculating; $\sigma_\phi$ is the root mean square value of the measurement error of phase difference, unit is radian, and takes $\sigma_\phi = 5\pi/180$ that can be reached by general engineering measurement; $\sigma_\theta$ is the root mean square value of the angle measurement error, in radian, and takes $\sigma_\theta = 1^0\pi/180$ .

Figure 8 shows the angular velocity measurement error at different baseline lengths. It can be seen from this that the measurement accuracy less than 3 $mrad/s$ can be achieved within a larger angle of arrival if the ratio between baseline and wavelength is large enough.

The parameters used in the simulation calculation are: the target distance is 300 kilometers; Airborne platform mobility speed 300m/s; Wave length 0.03 m.

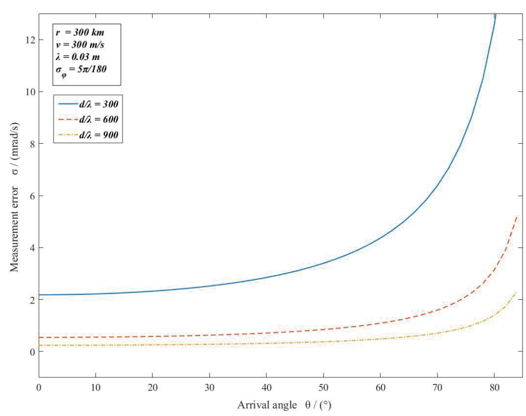


**Figure 8.** the angular velocity measurement error at different baseline lengths



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### 6.1.4 Summary

As far as the analysis process is concerned, the angular velocity calculation method based on multichannel phase difference measurement is not only high accuracy but also real-time. Because it is only requirement to directly measure the phase difference , there is no need to maintain linear variation for the angle measurement.

## 6.2 Radial Acceleration

### 6.2.1 The Introduction

Based on the principle of kinematics, radial acceleration can be used for passive localization, and radial acceleration information can be used to reduce the limitation for observability of observer motion, and to improve the convergence speed of positioning error and positioning accuracy to some extent [11].

However, in the engineering application, according to the existing research analysis, radial acceleration seems to be difficult to detect. The difficulty of detection in the time domain is that the high precision of time measurement is need, which is about 1/10 nanosecond. However, in the frequency domain, most radar signals are pulses with very short duration and the signal frequency changes are difficult to detect. Therefore, it is difficult to obtain accurate parameter estimation from a single pulse signal, which requires long time accumulation for signals and the use of impulse coherence [1]. In addition, although the radial acceleration of the target relative observer can be obtained by measuring the carrier frequency change rate of incoming waves or the pulse repetition rate, in fact the frequency change rate of intra-pulse phase modulation signal cannot directly characterize the Doppler frequency shift change rate [23].

Different from the existing method to obtain radial acceleration by analyzing the phase parameters of the signal based on signal modeling, in this paper, by using the functional relation between phase shift and frequency shift, and by using the mathematical definition of radial acceleration, the analytic expression of radial acceleration only based on phase difference measurement can be obtained by carrying on the quadratic differential to the function between distance and phase shift. On the basis of this, a non-fuzzy phase difference detection method for airborne radial acceleration is presented according to the method of non-fuzzy detection of phase difference rate.

### 6.2.2 Derivation

Use the relation between radial distance change rate and phase shift change rate:

$$\frac{\partial r_i}{\partial t}=\frac{\lambda}{2\pi}\frac{\partial \phi_i}{\partial t} \tag{58}$$

By the mathematical definition of radial acceleration, after differentiating radial velocity, we can obtain:

$$a_{ri}=\frac{\partial^2 r_i}{\partial t^2}=\frac{\lambda}{2\pi}\frac{\partial^2 \phi_i}{\partial t^2} \tag{59}$$

The radial acceleration can be obtained by substituting the expression (29) of the phase shift change rate based on the measurement of phase difference into (59):

$$a_r=\frac{\lambda}{2\pi}\frac{\partial}{\partial t}\left[\frac{2\pi v}{d_1}\left(\Delta n_1+\frac{\Delta\phi_1}{2\pi}\right)\right]=\frac{\lambda v}{2\pi d_1}\frac{\partial \Delta\phi_1}{\partial t} \tag{60}$$

Then, the expression (33) of the phase difference rate based on the phase difference measurement is substituted into, and there is:

$$a_r=\lambda\left(\frac{v}{d}\right)^2\left[\left(\Delta n_1-\Delta n_2\right)+\left(\frac{\Delta\phi_1}{2\pi}-\frac{\Delta\phi_2}{2\pi}\right)\right] \tag{61}$$

By substituting the non-fuzzy solution of the phase difference rate, the calculated formula of radial acceleration based on the difference measurement of phase difference without obscure can be obtained:

$$a_r=\lambda\left(\frac{v}{d}\right)^2\Delta^2 r_\lambda \tag{62}$$

Obviously, radial acceleration is the acceleration on the difference length of the path difference, that is, differential acceleration.

### 6.2.3 Estimation of Detection Accuracy

According to the error estimation theory, the error of acceleration measurement caused by phase difference, velocity and baseline spacing is:

$$\sigma_{ar}=\sqrt{\sum_{i=1}^{2}\left(\frac{\partial a_r}{\partial\Delta\phi_i}\sigma_\phi\right)^2+\left(\frac{\partial a_r}{\partial v}\sigma_v\right)^2+\left(\frac{\partial a_r}{\partial d}\sigma_d\right)^2} \tag{63}$$

Where: $\sigma_v$ is the root mean square value of velocity measurement error, and $\sigma_v=0.1m/s$ is taken when analyzing and calculating; $\sigma_\phi$ the root mean square value of the measurement error of phase difference, unit is radian, and $\sigma_\phi=(2\sim 10)\pi/180$ can be reached for the general engineering measurement; $\sigma_d=0.1m$ the root mean square value of the measurement error of baseline spacing.

Partial differential of each observed quantity is:

$$\frac{\partial a_r}{\partial \Delta\phi_1} = \frac{\lambda}{2\pi}\left(\frac{v}{d}\right)^2 \tag{64}$$

$$\frac{\partial a_r}{\partial \Delta\phi_2} = -\frac{\lambda}{2\pi}\left(\frac{v}{d}\right)^2 \tag{65}$$

$$\frac{\partial}{\partial v} = \frac{}{d}\left[\left(\Delta N_1 - \Delta N_2\right) + \left(\frac{\Delta\phi_1}{2\pi} - \frac{\Delta\phi_2}{2\pi}\right)\right] \tag{66}$$

$$\frac{\partial}{\partial d} = -\frac{}{d}\left[\left(\Delta N_1 - \Delta N_2\right) + \left(\frac{\Delta\phi_1}{2\pi} - \frac{\Delta\phi_2}{2\pi}\right)\right] \tag{67}$$

It can be seen directly from the each measurement error terms that the measurement error is directly proportional to the flight speed and signal wavelength and inversely proportional to the baseline length.

Figure 9 shows the measurement error at different baseline lengths, from which it can be seen that the measurement error of acceleration is less than $1m/s^2$ as long as the baseline is greater than 100 wavelength when the speed of fighter plane is 100m/s.The effect on measurement error is not very big if $\sigma_d$ is less than 1 meter.

The simulation results show that the influence of velocity on the measurement error is relatively large. If the aircraft's flight speed is higher, the obtained acceleration will be imprecise.

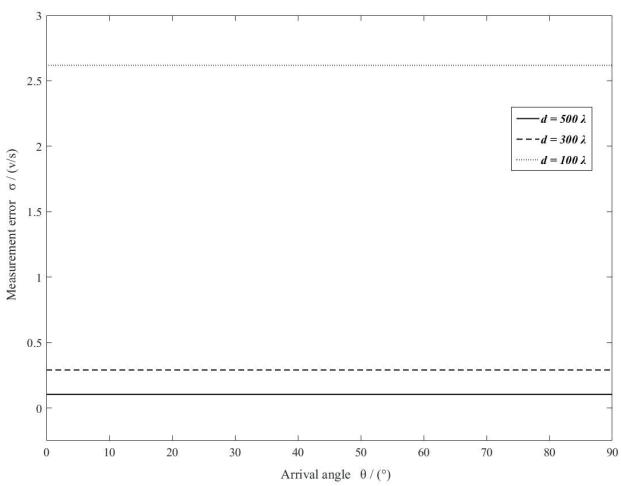


**Figure 9.** Measurement error at different baseline lengths

### 6.2.4 Summary

With the development of electronic warfare technology, more and more radars adopt uncertain signal forms, which will complicate the estimation problem of radial acceleration. However, the method proposed in this chapter for direct detection of radial acceleration based on phase interference can effectively simplify the measurement process, and the obtained analytical solution of airborne radial acceleration does not need to estimate the carrier rate or the pulse repetition rate of the incoming wave. But the error analysis shows that the measurement accuracy of radial acceleration is proportional to the baseline length of the receiving array. In order to obtain higher measurement accuracy, the baseline length must be increased. But, the phase ambiguity problem must be solved effectively when using long baseline measures the phase difference. There is no doubt that the method of non-fuzzy phase difference detection provides technical support for long baseline phase measurement and real-time detection of observed quantity on airborne platform.

## 6.3 Change Rate of Doppler Shift

### 6.3.1 Overview

The change rate of Doppler frequency reflects the radial acceleration information of the moving target relative to the observation station. It is of great significance to obtain the change rate of Doppler frequency for the target localization and the estimation of the motion state. But the change rate of Doppler is very weak, especially for radar pulses. Since the pulse duration is generally very short, it is very difficult to achieve high precision measurement with a single pulse when the SNR and sampling points are fixed.

In general, the main method to detect the change rate of Doppler is that by estimating the frequency change of the received signal obtains the change rate of Doppler frequency based on the principle that the change rate of Doppler frequency is mathematically the same as the change rate of carrier frequency of the signal [24-25]. That is, the change rate of Doppler can be measured indirectly through the measured radiation frequency. However, these estimation algorithms are not only related to the received signal modulation, but also more complex.

One of the main methods to detect the change rate of Doppler proposed in recent years is the application of digital signal processing technology in digital receivers. By using the phase-coherent characteristics between pulse carrier frequencies makes multiple pulses form a continuous signal. From this, the effective observation time of the signal is equivalently extended. The least squares algorithm based on phase difference can be used to obtain higher measurement accuracy [26-27]. However, this method requires high signal-to-noise ratio (SNR) and must ensure that the measurement of phase does not appear blurred.



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### 6.3.2 Deduction

According to the existing analysis, the change rate of frequency shift measured based on the phase difference rate is:

$$\frac{\partial f_d}{\partial t}=\frac{v^2}{d^2}\left[(\Delta n_1-\Delta n_2)+(\Delta\phi_1-\Delta\phi_2)/2\pi\right] \tag{68}$$

On the substitution of the differential item of path difference on the unit length into Eq.(68), there is:

$$\frac{\partial f_d}{\partial t}=\frac{v^2}{d^2}\Delta^2 r_\lambda \tag{69}$$

According to the method in the previous section, the change rate of Doppler is the acceleration on the difference length of the path difference based on the unit wavelength, or the ratio of the difference acceleration to the wavelength.

### 6.3.3 The Error Analysis

According to the error estimation theory, the measurement error of the change rate of Doppler caused by phase difference and velocity is:

$$\sigma_f=\sqrt{\left(\frac{\partial \dot{f}_d}{\partial v}\sigma_v\right)^2+\sum_{i=1}^{2}\left(\frac{\partial \dot{f}_d}{\partial\Delta\phi_i}\sigma_\phi\right)^2} \tag{70}$$

Where: $\sigma_v$ is the root mean square value of velocity measurement error, and $\sigma_v=0.1m/s$ is taken when analyzing and calculating; $\sigma_\phi$ the root mean square value of the measurement error of phase difference, in radian, and takes $\sigma_\phi=\pi/90$.

It could be established:

$$F_d=\frac{v^2}{d^2}\left[(\Delta n_1-\Delta n_2)+(\Delta\phi_1-\Delta\phi_2)/2\pi\right] \tag{71}$$

Each partial differential of phase difference and velocity is:

$$\frac{\partial F}{\partial\Delta\phi_1}=\frac{v^2}{2\pi d^2} \tag{72}$$

$$\frac{\partial F}{\partial\Delta\phi_2}=-\frac{v^2}{2\pi d^2} \tag{73}$$

$$\frac{\partial F_d}{\partial v}=\frac{2v}{d^2}\left[(\Delta n_1-\Delta n_2)+(\Delta\phi_1-\Delta\phi_2)/2\pi\right] \tag{74}$$

From the expression of measurement error, it can be seen that the measurement error is directly proportional to the movement of the airborne platform and inversely proportional to the baseline length. Obviously, the baseline length must be increased to reduce the measurement error. Figure 10 shows the measurement error of the change rate of Doppler at different baseline lengths. It can be seen that the measurement error of the change rate of Doppler can be reduced to a few Hertz after the ratio of baseline to wavelength is greater than 500.

The parameters used in the simulation calculation have been indicated in the figure.

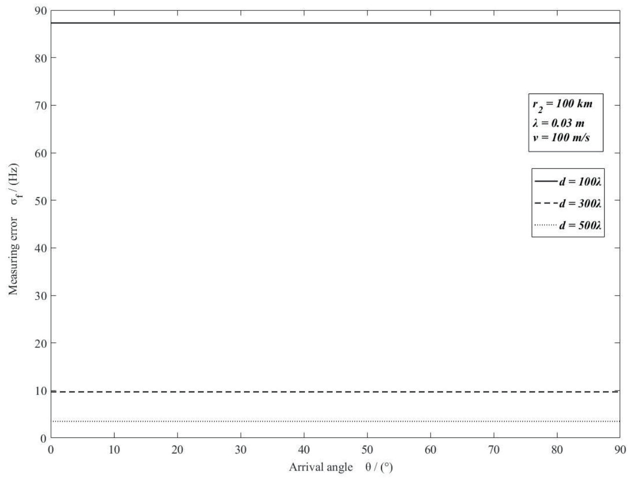


**Figure 10.** The measurement error of the change rate of Doppler at different baseline lengths

### 6.3.4 Summary

Using the method for detecting the change rate of Doppler based on multichannel phase difference measurement, not only can the change rate of Doppler be obtained in real time, but also the theoretical analysis shows that as long as the baseline is long enough, the measurement error for detecting the change rate of Doppler can be controlled within a few Hertz.

## 6.4 Change Rate of Time Difference

### 6.4.1 Overview

The introduction of time difference as well as change rate in single-station passive location will help improve the positioning accuracy, and the passive location method based on time difference as well as change rate has the advantage of being suitable for both wide and narrow band signals [28-31]. However, in general, the change rate of time difference is a physical quantity which is indirectly obtained through continuous measurement of time series, so the sampling detection method will be difficult to be applied to real-time detection of moving target by moving platform. In fact, in the case of short baseline applications for airborne single-station, the measurement of time difference is also a very difficult thing.

This chapter theoretically proves that the time difference as well as change rate on airborne station can be obtained indirectly through the phase difference measurement. In fact, the expression of time difference based on phase difference detection can be solved by using the location equation of phase difference and time difference, and the change rate of time difference based on phase difference detection can be obtained by differentiating and using the functional relation between phase shift and frequency shift. The preliminary error analysis shows that the detection of the change rate of time difference based on phase difference measurement can have a higher measurement accuracy because the magnitude of the light speed is very large in the denominator.

### 6.4.2 Time Difference Detection Based on Phase Difference Measurement

If two equation, the location equation of the phase differential and the time difference, are combined:

$$\Delta r = r_1 - r_2 = \lambda\left(n_1 - n_2 + \frac{\phi_1 - \phi_2}{2\pi}\right) \tag{75}$$

$$\Delta r = r_1 - r_2 = v_c \Delta t \tag{76}$$

The time difference estimation formula based on the phase difference detection can be solved out:

$$\Delta t = \frac{\lambda}{v_c}\left(\Delta n + \frac{\Delta\phi}{2\pi}\right) \tag{77}$$

The time difference measurement error caused by phase difference measurement is:

$$\frac{\partial \Delta t}{\partial \Delta\phi} = \frac{\lambda}{2\pi v_c} \tag{78}$$

The measurement error curve is shown in figure 11. Since it is inversely proportional to the speed of light with a large order of magnitude, the measurement error based on the phase difference detection is about 10ns.

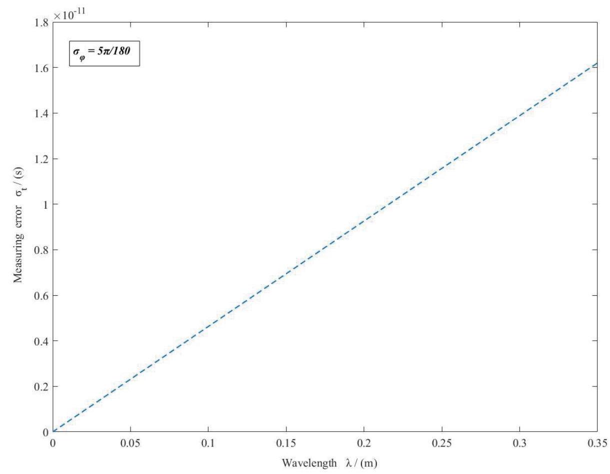


**Figure 11.** Time difference measurement error

### 6.4.3 Detection of Change Rate of Time Difference Based on Phase Difference Measurement

Furthermore, after differentiating both sides of the time difference expression based on the phase difference detection with respect to time, we have:

$$\frac{\partial \Delta t}{\partial t} = \frac{\lambda}{2\pi v_c}\frac{\partial \Delta\phi}{\partial t} \tag{79}$$

By using the relationship (33) of the phase difference rate based on the phase difference measurement, the change rate of time difference based on the phase difference detection can be obtained:

$$\frac{\partial \Delta t}{\partial t} = \frac{\lambda v}{v_c d}\left[\left(\Delta n_1 - \Delta n_2\right) + \left(\frac{\Delta\phi_1}{2\pi} - \frac{\Delta\phi_2}{2\pi}\right)\right] \tag{80}$$

Where: $v_c$ is the speed of light.

Further, the non-fuzzy solution of the phase difference rate was substituted into, as follows:

$$\frac{\partial \Delta t}{\partial t} = \frac{\lambda v}{v_c d}\Delta^2 r_\lambda \tag{81}$$

### 6.4.4 Measurement Accuracy of the Change Rate of Time Difference

For clear writing, set:

$$F_\phi = \frac{\lambda v}{v_c d}\left[\left(\Delta n_1 - \Delta n_2\right) + \left(\frac{\Delta\phi_1}{2\pi} - \frac{\Delta\phi_2}{2\pi}\right)\right] \tag{82}$$

According to the error estimation and synthesis theory, the error components in the calculation formula of the

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change rate of time difference, which can be obtained by partial differentiation of each parameter, are:

$$\frac{\partial F_\phi}{\partial \Delta\phi_1} = \frac{\lambda v}{2\pi d v_c} \tag{83}$$

$$\frac{\partial F_\phi}{\partial \Delta\phi_2} = -\frac{\lambda v}{2\pi d v_c} \tag{84}$$

$$\frac{\partial F_\phi}{\partial v} = \frac{\lambda}{d v_c}\left[(\Delta n_1 - \Delta n_2) + \frac{(\Delta\phi_1 - \Delta\phi_2)}{2\pi}\right] \tag{85}$$

The absolute measurement error caused by phase difference and velocity is:

$$\sigma_t = \sqrt{\left(\frac{\partial F_\phi}{\partial v}\sigma_v\right)^2 + \sum_{i=1}^{2}\left(\frac{\partial F_\phi}{\partial \Delta\phi_i}\sigma_\phi\right)^2} \tag{86}$$

Where: $\sigma_v$ is the root mean square value of velocity measurement error, and $\sigma_v = 0.1 m/s$ is taken when analyzing and calculating; $\sigma_\phi$ the root mean square value of the measurement error of phase difference, in radian, and the general engineering measurement can reach $\sigma_\phi = (2 \sim 10)\pi / 180$.

From the perspective of the error component, both the increase of baseline length and the decrease of movement speed can reduce the measurement error, but limited by the current technical level, the increase of baseline length is very limited. Figure 12 shows the measurement error at different flight speeds. Obviously, low speed can obtain better measurement accuracy.

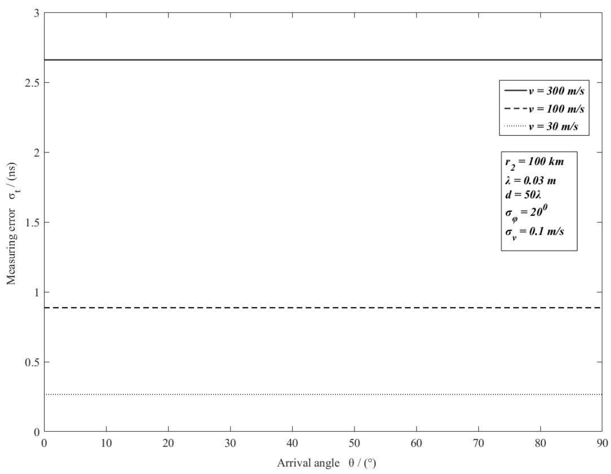


**Figure 12.** The measurement error at different flight speeds

### 6.4.5 Summary

Although the technology of short baseline time difference measurement has made great progress, since the time difference at both ends of the short baseline is very small in the application of the airborne short baseline, therefore, it is difficult to realize real-time detection of time difference and its change rate if we don't get the time series through the continuous flight of the carrier platform according to the existing technology of time difference measurement.

Obviously, only the phase difference measurement method is suitable for short baseline application at present, and it is a fairly mature measurement technology. If the exploration and research in this chapter is correct, it means that the phase difference measurement technology can be used to realize real-time detection for the change rate of time difference on the airborne platform. However, the research in this chapter is only a pure theoretical analysis at present, and how to be applied remains to be further studied.

One of the problems is that the phase difference measurement method can only be applied to detect narrowband signals, which is obviously inconsistent with the characteristics that the time difference and its change rate can be applied to broadband signals. This in fact means that the method of getting the change rate of time difference based on the phase difference measurement may not be suitable for the detection of broadband signals.

## 7. Conclusion

The author's research results show that, based on the multichannel phase difference measurement and only using the measurement value of phase difference, the phase difference rate can be directly obtained by using the differential of the difference value of integer of wavelength and the jump rule of the differential of phase difference under the condition of the unknown the difference value of integer of wavelength.

The author's research results undoubtedly provide a strong technical support for the practical engineering design related to the phase measurement, the most important result is that it lays a very important foundation for the engineering application of phase difference localization. The phase detection method without obscure based on the phase difference rate can indirectly realize the phase difference location without obscure.

Before that, since there is the period ambiguity in phase difference measurement, the observed quantity itself contains the unknown difference value of integer of wavelength in the observation process. And the unknown parameter also changes with the change of geometric observation. Therefore, the positioning equation based on the phase difference measurement is not solvable directly from the mathematical equation.

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