Airborne Passive Localization Method Based on Doppler-Phase Interference Measuring

Tao Yu
Shanghai Research Institute of Microwave Equipment, Shanghai P. R. China

1. Introduction

Airborne passive localization with single station is a key technique which is quickly developing lately. If the exact localization to target can be realized in single mobile platform, its significance is self-evident. Because the information content obtained by single station is lesser, the difficulty would be obviously bigger relative to multi-station observation.

Phase interferometry is mainly in use for direction finding (DF). Moreover, Doppler shift may be used to determine the coordinate setting of target. As far as actual applications are concerned, these two methods are independently applied. Or, they firstly are respectively detected. And then, the obtaining data are syncretized.

Author researches the functional relation between Doppler shift and phase interferometry and presents some method which can syncretize these two methods directly from the equation of mathematical. Based on this fusion in physical relationship, we can obtain the Doppler shift by measuring phase. Or, we can determine the phase by measuring Doppler shift. This book describes these new methods as well as some applications in airborne passive localization system.

Section two describes the relationship between phase and Doppler shift. Firstly, the phase difference localization equation which is analogous to time difference localization equation is introduced by analyzing the phase in radial distance of target. And then, making use of the complementary relationship between the angle of advance at airborne platform and the angle of arrival for target, the approximate functional relation between Phase-difference and Doppler shift can be derived by combining DF formula based on phase interference and expression of Doppler shift. Where after, the calculating method of airborne Doppler rate is researched based on phase difference or Doppler frequency difference

Section three researches the problem of airborne Doppler direct range finding. Three solution methods are presented. First method is direct approximation for mathematical expression of Doppler rate. Second method is introducing differential transformation for Doppler shift equation based on angle rate. Third method is based on the specific value of Doppler rate between two adjacent detection nodes. On this basis, the airborne direct range finding formula based on phase measuring can be obtained by using the relationship between phase difference and Doppler shift.

In allusion to the problem to need solving integer ambiguity in available DF system based on phase interferometer, section four puts forward a DF method combining Doppler shift and phase interferometer. According to this method, the integer of wavelength in radial distant can be directly solved synthetically by making use of speed vector and Doppler shift as well as rate. Hence, the integer of wavelength in path length difference of radial distant between two adjacent antenna elements can be obtained. At the same time, the value less than one integer in path difference can be determined by using phase interferometer. As compared with available phase interferometer which firstly solves phase difference, this new method which firstly solves path difference has not phase ambiguity, nor it needs to limit baseline length.

Section fifthly presents a new airborne passive DF method using two orthogonal baselines based on the rate of direction cosine. This is a passive DF method which is only associated with Doppler frequency difference and is not associated with wavelength.

2. Relationship between phase and Doppler shift

2.1 Phase-detecting for distance

For single baseline interferometer as shown in fig.2-1, if the phase shift measured by descriminator, corresponding to the radial distance r_i , is ϕ_i , the expression of radial distance based on phase measuring is

$$r_i = \lambda(N_i + \frac{\phi_i}{2\pi}) \tag{2-1}$$

where: λ is wavelength; N_i the whole number of wavelength.

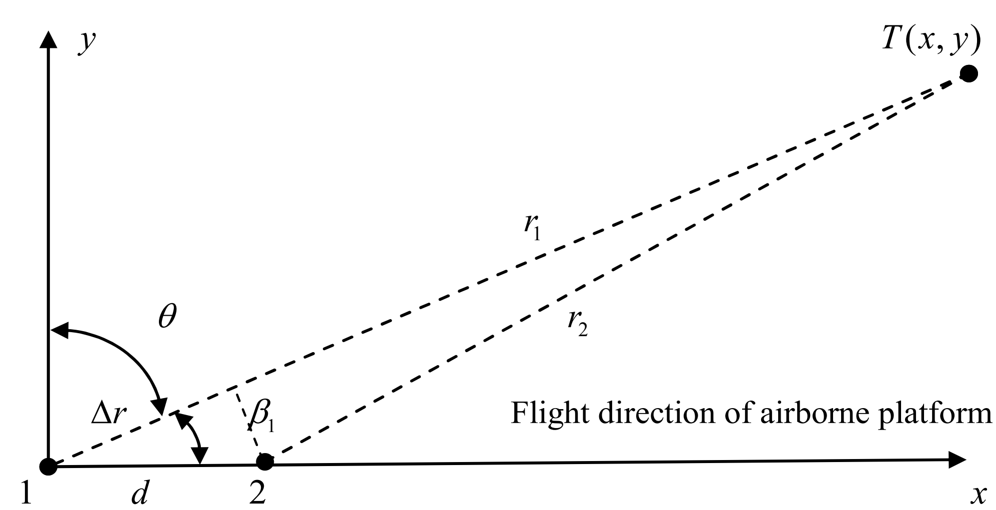

Fig. 2-1. Single baseline array on airborne platform.

Thus, the path length difference Δr of radial distance between two antenna elements can be determined by measuring for phase difference. The localization equation based on phase difference can be obtained whose formed expression is completely analogous to the localization equation based on time difference

$$\begin{aligned}\Delta r &= r_1 - r_2 \\ &= \lambda(N_1 - N_2 + \frac{\phi_1 - \phi_2}{2\pi}) \\ &= \lambda(\Delta N + \frac{\Delta\phi}{2\pi})\end{aligned} \tag{2-2}$$

where: $\Delta N = N_1 - N_2$ is the whole number of wavelength in path length difference; $\Delta\phi = \phi_1 - \phi_2$ phase difference.

Provided that incident wave from the some radiant is approximatively regarded as plane wave, the existing DF expression based on the principle of phase interferometry can be approximatively obtained due to sine theorem

$$\begin{aligned}\sin\theta &= \frac{\Delta r}{d} \\ &= \frac{\lambda}{d}(\Delta N + \frac{\Delta\phi}{2\pi})\end{aligned} \tag{2-3}$$

Or, by simply rearranging, the phase difference between two adjacent antennas can take the form

$$2\pi\Delta N + \Delta\phi = \frac{2\pi d}{\lambda}\sin\theta \tag{2-4}$$

where: θ is arrival angle of target signal; d baseline length between two antennas.

2.2 Phase difference detecting of Doppler shift

2.2.1 Recapitulation

Making use of the complementary relationship between the angle of advance and the angle of arrival, the approximate functional relation between phase-difference and Doppler shift can be obtained by combining the DF formula based on phase interference and the expression of Doppler shift. The analog calculation certificates the correctness of derived formula. The error analysis presents the measurement accuracy of Doppler shift obtained by phase-difference measuring. And calculation shows that the measuring error of Doppler shift obtained based on phase-difference measuring is lower if the detection error for integer of wavelength in path difference is not considered.

2.2.2 Primitive formula

As shown in fig.2-1, a single baseline array with two antenna elements is installed on airborne platform and the spacing of array is d. The direction of axis of baseline is parallel the axis of airborne platform. For the target T at stationary or low speed, the Doppler shift detected by airborne double channel measuring receiver in every element of single baseline interferometry is

$$\lambda f_{d1} = v \cos \beta_1 \tag{2-5}$$

where: f_{d1} is Doppler shift; v the flight speed of detection platform; β the angle of advance between radial distance and travelling direction of flight device.

According to the geometric relationship as shown fig.2-1 and the analysis results in a previous section, results in

$$\begin{aligned} \cos \beta_1 &= \sin(90^0 - \beta_1) \\ &= \sin \theta \approx \frac{\Delta r}{d} \\ &= \frac{\lambda}{d}(\Delta N + \frac{\Delta \phi}{2\pi}) \end{aligned} \tag{2-6}$$

Substituting (2-6) into the Doppler shift expression, we can obtain the calculating formula of Doppler shift based on phase difference measuring

$$\begin{aligned} f_{d1} &= \frac{v}{d}(\Delta N + \frac{\Delta \phi}{2\pi}) \\ &= \frac{v \Delta r}{d \lambda} \end{aligned} \tag{2-7}$$

According to above-mentioned derivation, we can directly written out the formula of Doppler frequency difference based on phase difference measuring by use of the array with double baseline in one-dimensional as shown in fig.2-2

$$\begin{aligned} \Delta f_d &= \frac{v}{d}\left[(\Delta N_1 + \frac{\Delta \phi_1}{2\pi}) - (\Delta N_2 + \frac{\Delta \phi_2}{2\pi})\right] \\ &= \frac{v}{d}\left[(\Delta N_1 - \Delta N_2) + \frac{1}{2\pi}(\Delta \phi_1 - \Delta \phi_2)\right] \end{aligned} \tag{2-8}$$

where: $\Delta N_i = N_i - N_{i+1}$; $\Delta \phi_i = \phi_i - \phi_{i+1}$.

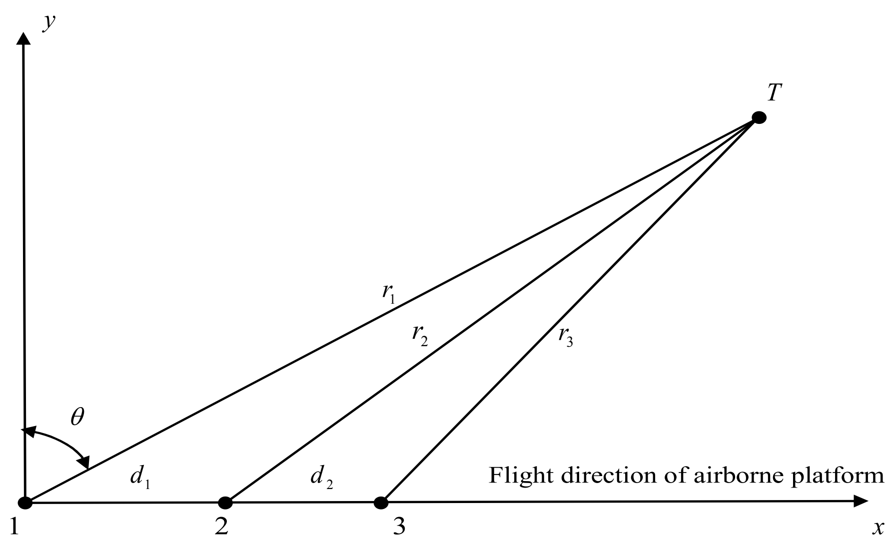

Fig. 2-2. One-dimensional array with double baseline.

2.2.3 Computational error

In order to verify the calculating formula of Doppler shift based on phase difference measuring, we make the analog calculation by replacing measured value with theoretical value. Firstly, we preset following parameter: radial distance r_1, wavelength λ, baseline length d, the flight speed of flight device v. And then, we make the arrival angle θ change in prescribed domain. Hence, the rest radial distance as well as path difference can be obtained according to circular function relationship. Simultaneity, the theoretical value of Doppler shift corresponding to every radial distance can be calculated by Doppler shift formula.

On this basis, the Doppler shift based on phase measuring is computed by Eq.(2-7) and then the relative calculation error is obtained by compared with the theoretical value

$$\varepsilon_f = \left| \frac{f_{di} - f_{dai}}{f_{di}} \right| \times 100\% \tag{2-9}$$

where: subscript a expresses calculating value.

Without the notice, the adopted parameter is as follows: $r_1 = 100\ km$, $v = 100\ m/s$, $d = 5\lambda$, $\lambda = 0.0375\ m$.

Fig.2-3 depicts the calculating error curve of Doppler shift f_{d1} when the baseline length is different. The mathematical simulation shows that calculating error is independent of flight speed and directly related to wavelength and inversely related to radial distance.

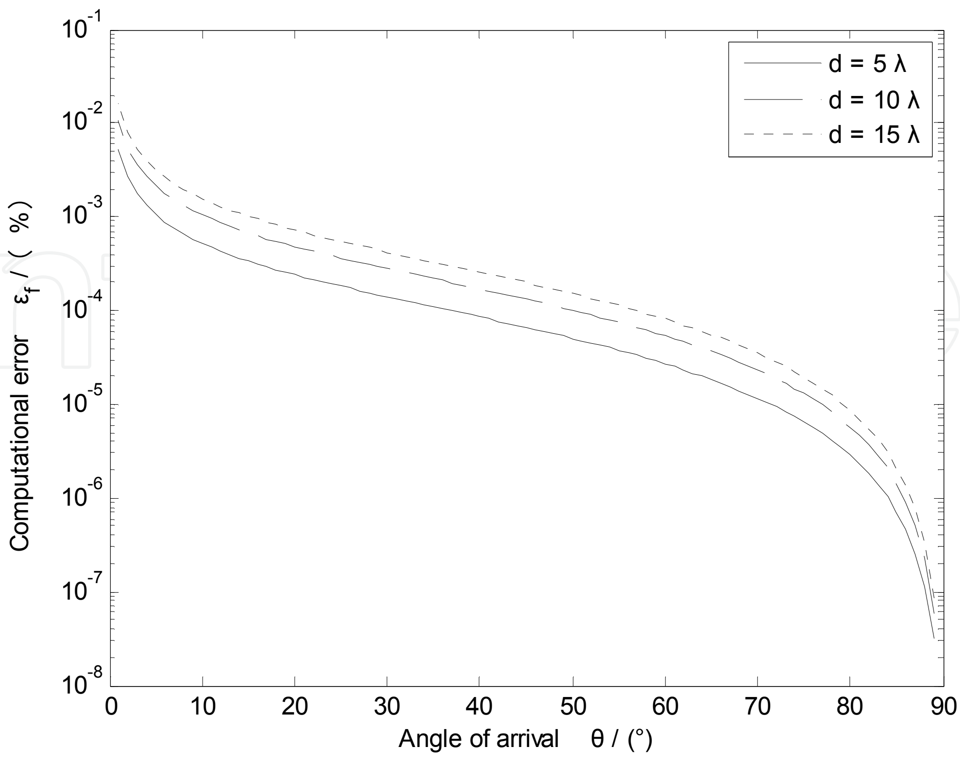

Fig. 2-3. Computational error of Doppler shift with different baseline lengths.

2.2.4 Precision analysis

According to error estimation theory, the measuring error of Doppler shift produced by the measuring error of phase difference, flight speed and integer of wavelength in path difference is

$$\sigma = \sqrt{\left(\frac{\partial f_{d1}}{\partial \Delta\phi}\sigma_\phi\right)^2 + \left(\frac{\partial f_{d1}}{\partial v}\sigma_v\right)^2 + \left(\frac{\partial f_{d1}}{\partial \Delta N}\sigma_n\right)^2} = \sqrt{\left(\frac{v}{2\pi d}\sigma_\phi\right)^2 + \left(\frac{\Delta r}{\lambda d}\sigma_v\right)^2 + \left(\frac{v}{d}\sigma_n\right)^2} \tag{2-10}$$

where: σ_ϕ, σ_v and σ_n is respectively the mean-root-square error measuring phase difference, flight speed and integer of wavelength in path difference. In where, unit for σ_ϕ is radian. Without the notice, the value of mean-root-square error is respectively as follows: $\sigma_\phi = \pi/180^0 (=1^0)$, $\sigma_v = 1 \ \ m/s$, $\sigma_n = 1$.

It can be seen from (2-10) that the Doppler measuring error produced only by measuring error of phase difference is just a constant term. If $\sigma_\phi = \pi/180^0$ (radian), σ value will be less than $2Hz$ making use of the parameter presented in previous section. The Doppler measuring error produced only by integer of wavelength in path difference is also a constant term. Because the speed is usually larger than baseline length for Airborne applications, the Doppler measuring error will be prodigious if the measuring for integer of wavelength in path difference has error. According to the same reason, the larger measuring error of Doppler shift is also produced by the error of speed measuring in axle direction of baseline.

Fig.2-4 depicts the Doppler measuring error with different baseline length. The analysis shows that the measuring error in integer of wavelength has prodigious influence for measuring error of Doppler shift. Also, the change for baseline length is also considerable sensitive.

Fig.2-5 illustrates the change curve versus wavelength for Doppler shift error when the integer of wavelength in path difference can be accurately detected. And the analyzer shows that the measuring error is not associated baseline and the influence produced by change of flight speed is also lesser.

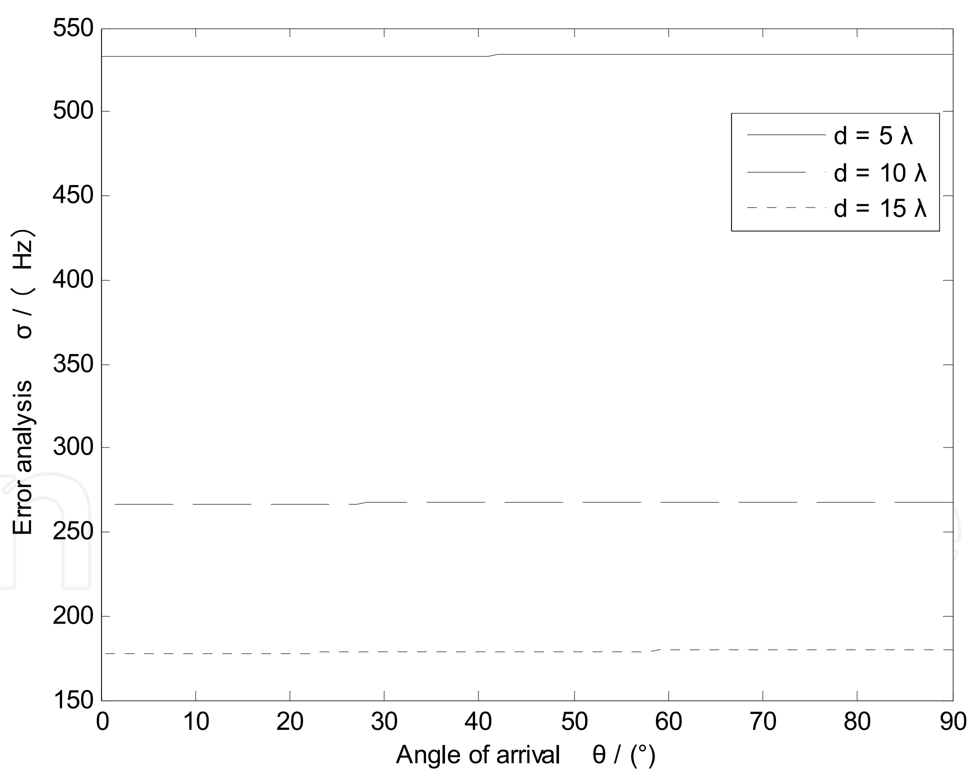

Fig. 2-4. Measurement error of Doppler shift.

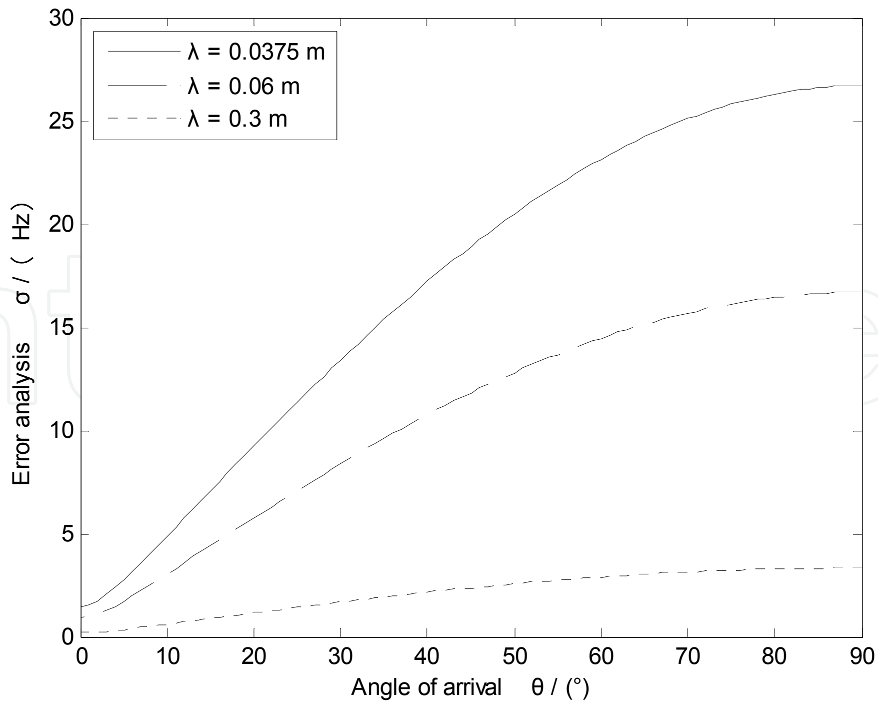

Fig. 2-5. Measurement error of Doppler shift without integer error.

More, relative calculation error of Doppler shift is analyzed by perfect differential, that is

$$df_{d1} = \frac{\partial f_{d1}}{\partial \Delta\phi} d\Delta\phi_i + \frac{\partial f_{d1}}{\partial v} dv + \frac{\partial f_{d1}}{\partial \Delta N} d\Delta N \tag{2-11}$$

When the error of observing variable is zero-mean and unaided reciprocally, the relative calculation error of Doppler shift is

$$\begin{aligned} \sigma_r &= \left| \frac{df_{di}}{f_{di}} \right| \\ &= \frac{1}{f_{di}} \left(\left| \frac{\partial f_{di}}{\partial \Delta\phi_i} \sigma_\phi \right| + \left| \frac{\partial f_{d1}}{\partial v} \sigma_v \right| + \left| \frac{\partial f_{d1}}{\partial \Delta N} \sigma_n \right| \right) \\ &= \frac{\lambda d}{v \Delta r} \left(\left| \frac{v}{2\pi d} \sigma_\phi \right| + \left| \frac{\Delta r}{\lambda d} \sigma_v \right| + \left| \frac{v}{d} \sigma_n \right| \right) \end{aligned} \tag{2-12}$$

The advantage making the expression which contains phase difference transform the expression which includes path difference Δr is that the analysis and calculation for integer and phase difference can be avoided. Fig.2-6 illustrates the change curve versus baseline length for relative calculation error of Doppler shift when the measuring for integer is without error. The calculation shows that the curvilinear change is basically not associated with flight speed and wavelength. The relative calculation error is inversely relative to baseline length. It can be seen that the relative calculation error of Doppler shift is less than 1.5% after the angle of arrival is bigger than 10^0

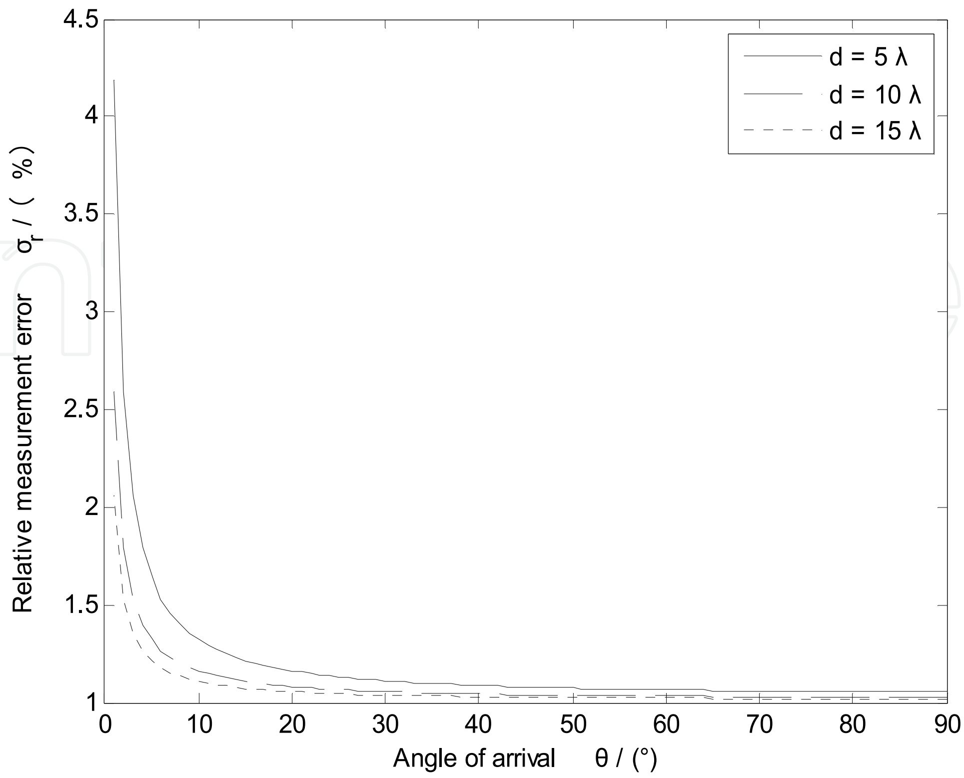

Fig. 2-6. Relative measurement error of Doppler shift.

2.3 Airborne Doppler changing rate obtaining by frequency difference or phase difference

2.3.1 Recapitulation

According to localization theory, the radial distance between measuring platform and measured target can be directly obtained based on Doppler changing rate equation. But, in fact, the localization method based on Doppler rate of change is not the classical method in current target localization for electronic warfare. A main reason is that measuring for change rate of Doppler shift is also relative difficult at present. At the same time, because Doppler rate of change is directly concerned with the tangential velocity, the problem related to direct range finding using Doppler rate equation is that the detecting system has to measure the angle of advance between the traveling direction of detection platform and the radial distance to target, along with measuring Doppler rate. Thereout, the localization equation can be solved. Hence, the localization method based on Doppler rate of change can be completed with other localization method at present.

In addition, for localization and tracker system, it is extraordinary valuable to obtain the Doppler changing rate of received signal in order to estimate the state and position of target. At present, Doppler rate of change is mainly obtained by estimating the frequency variation of received signal based on the principle that Doppler rate of change is the same in mathematical analysis as the rate of carrier frequency of received signal. These estimative algorithms are not only associated with modulation mode, but they are also complicated.

On the basis of researching Doppler direct ranging, this section presents a method determining Doppler changing rate only by detecting Doppler shift value of received signal at some discrete node. Here, an analytic method solving Doppler changing rate only by detecting the frequency difference of Doppler shift or received signal is presented based on azimuth rate. This new method is not only straightforward in detection mode; it is also succinct on expression. More important characteristic is lying in:

1. The Doppler rate of change can be directly obtained when the wavelength of measured signal is yet unknown.
2. It is wholly not associated with light speed. And this is completely helpful for realizing high-accuracy measuring. The existing analyzing indicates that the result of error analysis will become very bad if the resolving result is relative to light speed.

2.3.2 Derivation

According to the geometric relationship as shown in fig.2-1, we have as following the approximate representation of circular function

$$\sin\beta_1 \approx \frac{\sqrt{d^2 - \Delta r^2}}{d} \tag{2-13}$$

$$\cos\beta_1 \approx \frac{\Delta r}{d} \tag{2-14}$$

By applying differential transformation, we can make a deformation to the Doppler shift equation

$$\begin{aligned} \lambda f_d = v\cos\beta_1 &= \frac{v}{\omega}\frac{\partial \sin\beta_1}{\partial t} \\ &= -\frac{v\Delta r}{\omega d\sqrt{d^2 - \Delta r^2}}\frac{\partial \Delta r}{\partial t} \\ &= \frac{v\Delta r\lambda\Delta f_d}{\omega d\sqrt{d^2 - \Delta r^2}} \end{aligned} \tag{2-15}$$

where: $\Delta f_d = f_{d2} - f_{d1}$ is the frequency difference of Doppler shift; $\omega = \partial\beta / \partial t$ angular velocity.

Making use of circular function and by rearranging, we get

$$\omega f_d = \frac{v}{d}\Delta f_d ctg\beta_1 \tag{2-16}$$

Further, the Eq.(2-16) can be deformed by use of angular velocity $\omega = \frac{v_t}{r}$ and expression $\lambda f_d = v\cos\beta$

$$\frac{v^2 \sin^2 \beta_1}{\lambda r_1} = \frac{v}{d} \Delta f_d \tag{2-17}$$

In where: $v_t = v \sin \beta_1$ is tangential velocity.

In fact, when the flight device is uniform motion, the left-hand component of equation is namely basic expression of Doppler rate of change

$$\dot{f}_d = \frac{v^2 \sin^2 \beta}{\lambda r_1}$$

So we obtain the calculation formula of Doppler rate only based on measuring Doppler frequency difference

$$\dot{f}_d = \frac{v}{d} \Delta f_d \tag{2-18}$$

According to the mathematical definition of Doppler rate

$$\dot{f}_d = \Delta f_d / \Delta t$$

There results:

$$\frac{v}{d} = \frac{1}{\Delta t}$$

It can be seen that the time variation of detecting Doppler shift can be equivalently expressed by specific value between flight distance and flight speed of detection platform. Hence, we also prove that Doppler changing rate is only associated with flight speed and it is wholly not associated with light speed.

Again, the frequency difference of Doppler shift can is also obtained from one of radiation frequency

$$\begin{aligned} \Delta f_d &= f_{d1} - f_{d2} \\ &= f_{t1} - f_{t2} = \Delta f_t \end{aligned}$$

where: f_{ti} is measured value of signal.

So Doppler changing rate can be determined by the actual measurement to frequency difference of signal.

As soon as we substitute the expression (2-8) of Doppler frequency difference based on phase difference measuring into (2-18), we can obtain the formula of Doppler changing rate based on phase difference

$$\dot{f}_d = \left(\frac{v}{d}\right)^2 \left[(\Delta N_2 - \Delta N_1) + \frac{1}{2\pi} (\Delta \phi_2 - \Delta \phi_1) \right] \tag{2-19}$$

2.3.3 Analog calculation

In order to verify the accuracy of analysis formula of Doppler rate based on measuring frequency difference, the mathematical simulation is applied with measured value replaced by theoretical value. The wavelength λ, radial distance r_1, the flight speed of flight device v and time interval Δt are set beforehand and making the angle of advance β_1 change in prescribed domain. Hence, the rest radial distance and angle of advance can be obtained according to geometric relationship as shown in fig.2-1. Thus, the theoretical value of Doppler shift and Doppler rate of change can be calculated corresponding to every radial distance.

On this basis, Doppler changing rate is computed by Eq.(2-18) and then the relative calculation error is obtained by compared with the theoretical value.

Without the notice, the adopted parameter is as follows: $\lambda = 0.25\ m$, $r = 100\ km$, $v = 100\ m/s$, $\Delta t = 5\ s$.

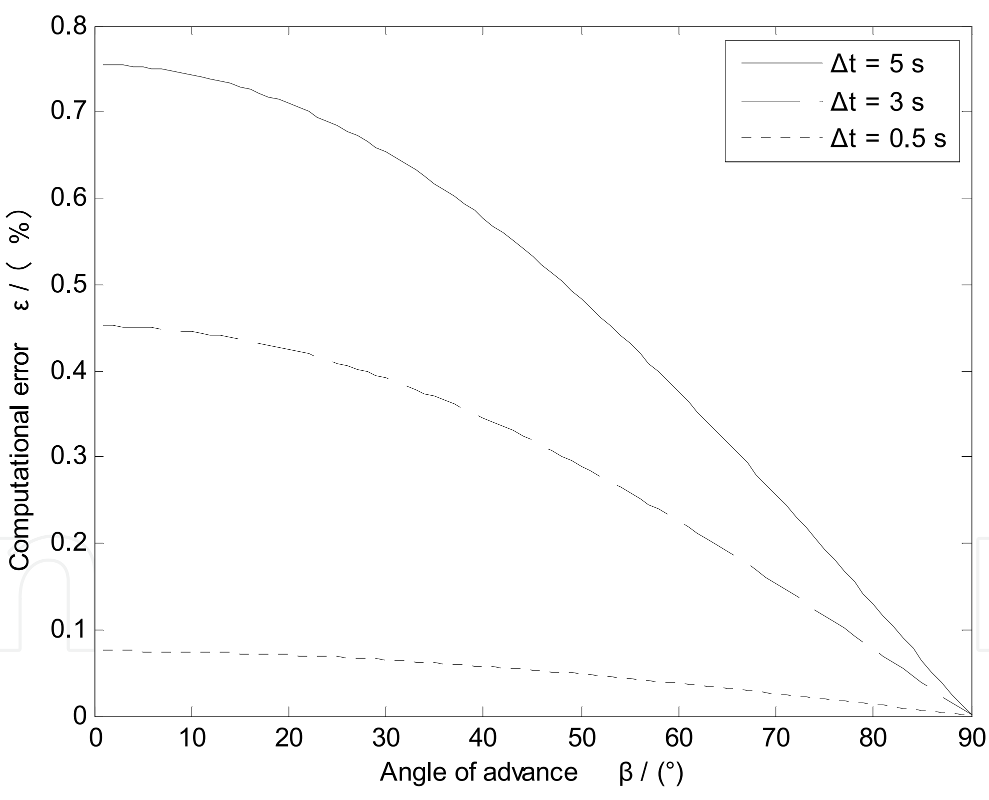

Fig. 2-7. Error curve of Doppler rate against advancing angle in different detecting times.

Fig. 2-7 depicts the relative calculation error curve against the angle of advance for Doppler changing rate when the detecting time interval is different. It can be seen that the error will be conspicuously augmentation if the time interval is too long. Fig.2-8 depicts the relative calculation error is inversely relative to radial distance.

The mathematical simulation shown yet that relative calculation error are independent of flight speed and wavelength. The relative calculation error curve is smoother as compared to the curve given by existing literature. And the behavior is basically identical.

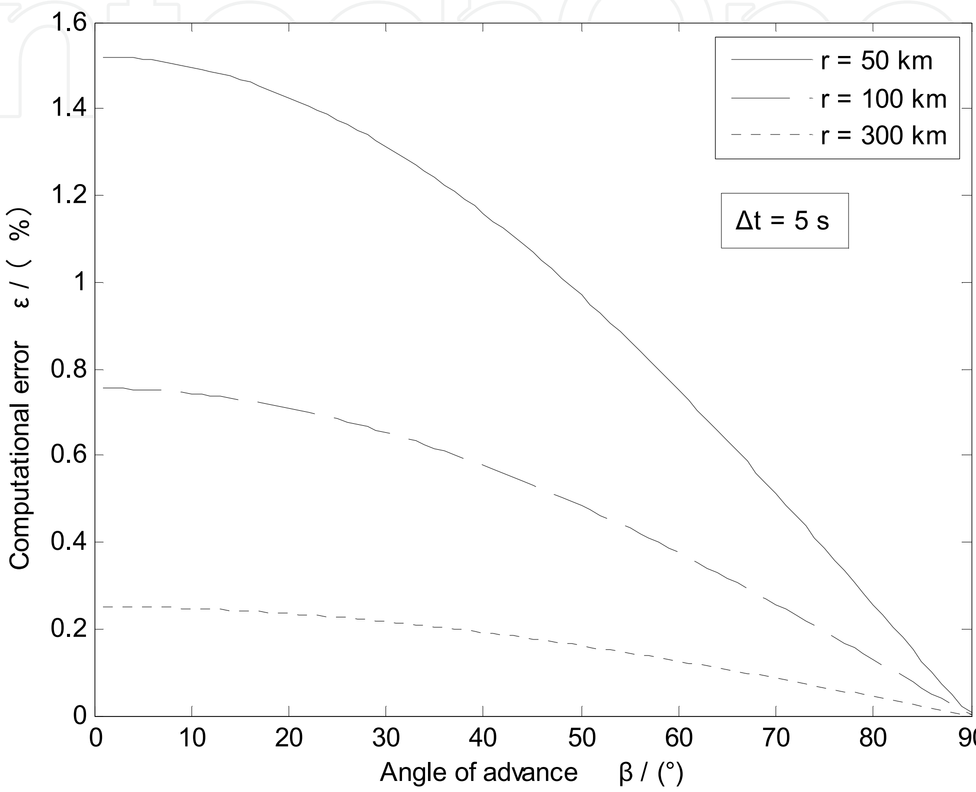

Fig. 2-8. Relative calculation error curve of Doppler changing rate against advancing angle in different radial distance

3. Airborne range finding method

3.1 Principle of Doppler direct range finding

3.1.1 Recapitulation

According to mathematical definition, we can realize airborne single-station ranging only based on Doppler shift measurement by approximatively dealing with Doppler changing rate equation. On this basis, the expressing problem of average for Doppler changing rate in a time interval is researched. On condition that airborne measuring station is uniform flight along linear motion, the analysis shows that the average value of Doppler changing rate is directly related to the product of tangential velocity at two terminals and is inversely relative to radial distance at end position in a time interval. And the analog calculation verifies that the better ranging result can be obtained only from this average expression. As contrasted to existing method, the ranging method derived in this text requires neither to detect Doppler changing rate directly nor to use other localization methods.

3.1.2 Basic range finding formula

Provided that airborne platform is uniform motion along straight line as shown in fig.3-1, the Doppler changing rate equation between detection platform and measured target is

$$\dot{f}_d = \frac{v_t^2}{\lambda \cdot r} \tag{3-1}$$

From the viewpoint of basic mathematical definition, during a time interval Δt , the Doppler changing rate can be approximatively expressed by measured value of Doppler frequency difference between two detection nodes

$$\begin{aligned} \dot{f}_d &= \frac{\Delta f_d}{\Delta t} \\ &= \frac{f_{d2} - f_{d1}}{\Delta t} \end{aligned} \tag{3-2}$$

where: Δt is a time interval.

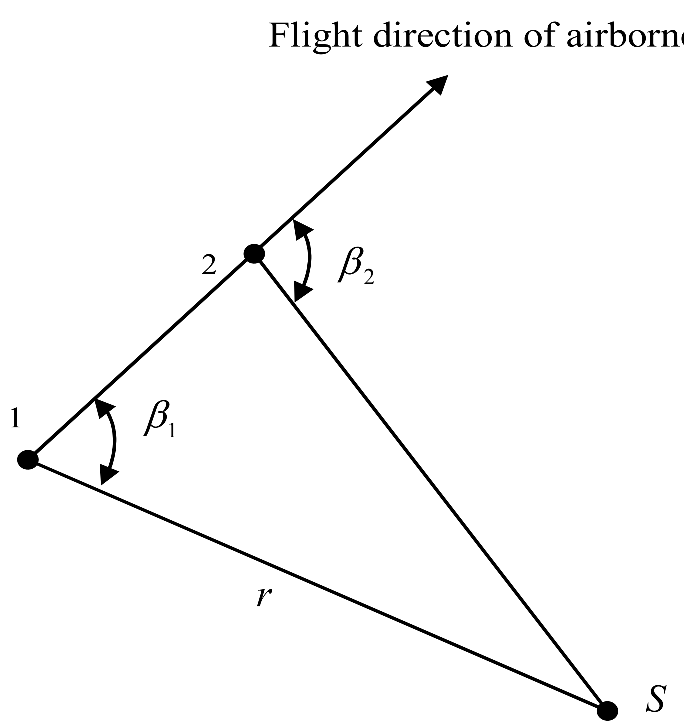

Fig. 3-1. Geometric relationship used for mobile ranging system.

Synthetically applying above-named two equations and speed vector equation $v^2 = v_r^2 + v_t^2$ as well as the relationship between radial speed and Doppler shift $v_r = \lambda f_d$, the basic range finding formula can be obtained

$$r = \frac{v_t^2 \Delta t}{\lambda \Delta f_d} = \frac{(v^2 - \lambda^2 f_d^2)\Delta t}{\lambda \left|\Delta f_d\right|} \tag{3-3}$$

3.1.3 Improvement of measuring accuracy

In fact, Doppler changing rate equation only describes the change of Doppler shift in a certain moment or at a certain point. It can not shows the average change of Doppler shift within a time interval. Later-day research has proved that the speed value derived according to basic physical definition is adverse to one from plane geometry. For speed change within a time interval, the speed value obtaining by plane geometry relationship is more exact.

The Doppler frequency difference can be formulated as

$$\lambda \Delta f_d = v(\cos \beta_2 - \cos \beta_1) \tag{3-4}$$

According to the relationship between interior angle and exterior angle $\beta_2 = \beta_1 + \Delta\beta$ as shown in fig.3-1, using approximate expression $\cos \Delta\beta \approx 1$ and $\sin \Delta\beta \approx \Delta\beta$, we have after rearranging for (3-4)

$$\begin{aligned} \lambda \Delta f_d &= v\left[\cos(\beta_1 + \Delta\beta) - \cos \beta_1\right] \\ &= v(\cos \beta_1 \cos \Delta\beta - \sin \beta_1 \sin \Delta\beta - \cos \beta_1) \\ &\approx -v\Delta\beta \sin \beta_1 \end{aligned} \tag{3-5}$$

Substituting (3-5) into (3-2) it follows that

$$\begin{aligned} \dot{f}_d &= \frac{\Delta f_d}{\Delta t} \\ &\approx -\frac{v\Delta\beta \sin \beta_1}{\lambda \Delta t} \\ &\approx -\frac{v_{t1}\omega}{\lambda} \end{aligned} \tag{3-6}$$

The angular velocity ω is associated with the rotary radius vector r, that is

$$r\omega = v_t \tag{3-7}$$

As a result

$$\frac{\Delta f_d}{\Delta t} \approx -\frac{v_{t1} v_{t2}}{\lambda r} \tag{3-8}$$

The result shows that the average of Doppler changing rate within a certain time is directly related to the product of tangential velocity at two-terminal of flight distance，that is directly related to geometric mean value at two-terminal of flight distance. And it is inversely related to radial distance at terminal position. Right now, the ranging finding equation whose accuracy can be improved can be obtained after expressing tangential velocity in term of speed vector equation and Doppler speed equation

$$\begin{aligned} r &= \frac{v_{t1} \cdot v_{t2} \cdot \Delta t}{\lambda(f_{d1} - f_{d2})} \\ &= \frac{\sqrt{v^2 - \lambda^2 f_{d1}^2}\sqrt{v^2 - \lambda^2 f_{d2}^2}\Delta t}{\lambda(f_{d1} - f_{d2})} \end{aligned} \tag{3-9}$$

3.1.4 Analog verification

In order to validate the accuracy of range finding, the analog calculation is done by replacing measured value with theoretical value. Preassigning following parameter: wavelength λ, radial distance r, flight speed v, flight time Δt or spacing d, and making β_1 continuously change within preassigned interval, the radial distance and angle of advance in other nodes can be calculated in turn according to the geometric relationship as shown in fig. 3-1. Hence, the theoretical value of Doppler shift f_{di} corresponding to every radial distance can be computed according to Doppler shift equation.

On this basis, the range can be calculated according to (3-9). The relative calculation error can be obtained by compared with the theoretical value.

Without the notice, the adopted parameter is as follows: $r = 100 \ km$, $v = 100 \ m/s$, $\Delta t = 5 \ s$, $\Delta t = d/v$ (in where: $d = 1000m$).

Fig.3-2 is the relative calculation error curve again the angle of advance for ranging calculation with different flight time, time interval in graphs has been transformed into mobile distance d. It can be seen that the calculation value obtained from (3-9) has more accuracy if the time interval is less.

Analog calculation proves that the relative calculation error is not associated with wavelength and movement speed of airborne platform. Fig.3-3 presents the comparison of error result between (3-3) and (3-9). Apparently, the calculation accuracy after mean processing has biggish improvement.

In processing analog calculation, we must advert that Doppler frequency difference in denominator of ranging formula must take absolute value. The correct result can be also obtained without absolute value if the operation order of Doppler shift in two detection nodes can be determined according to derivation process presented in 3.1.2 section.

3.2 Direct ranging method based on angle rate

3.2.1 Recapitulation

An airborne Doppler direct ranging method with single baseline is presented. Based on the principle that the angle rate can be determined by Doppler frequency difference between

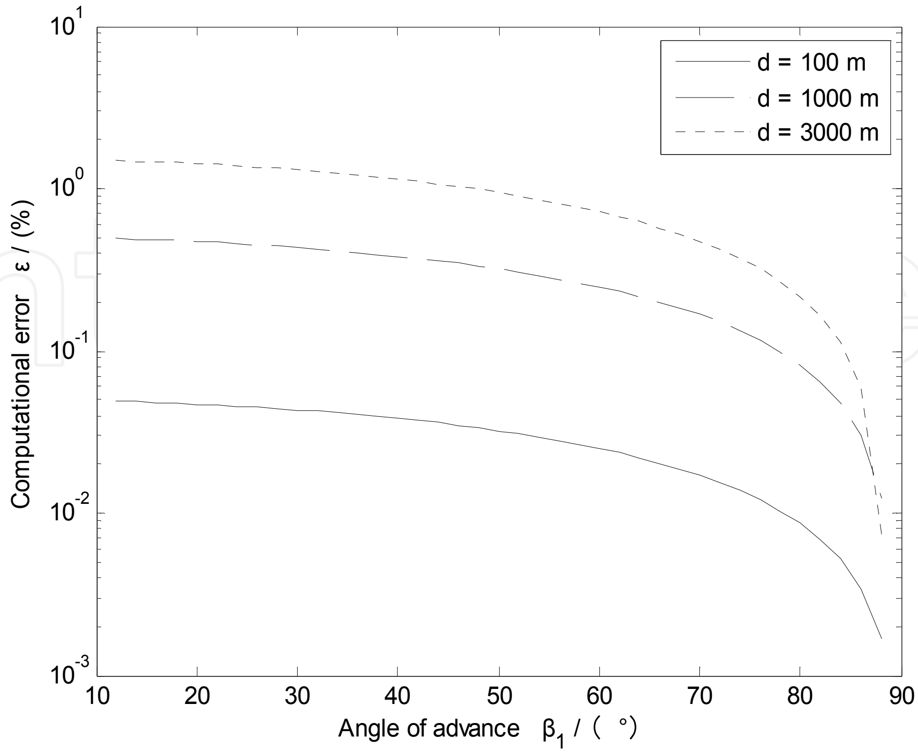

Fig. 3-2 Relative calculation error curve against advancing angle for radial distance with different displacement.

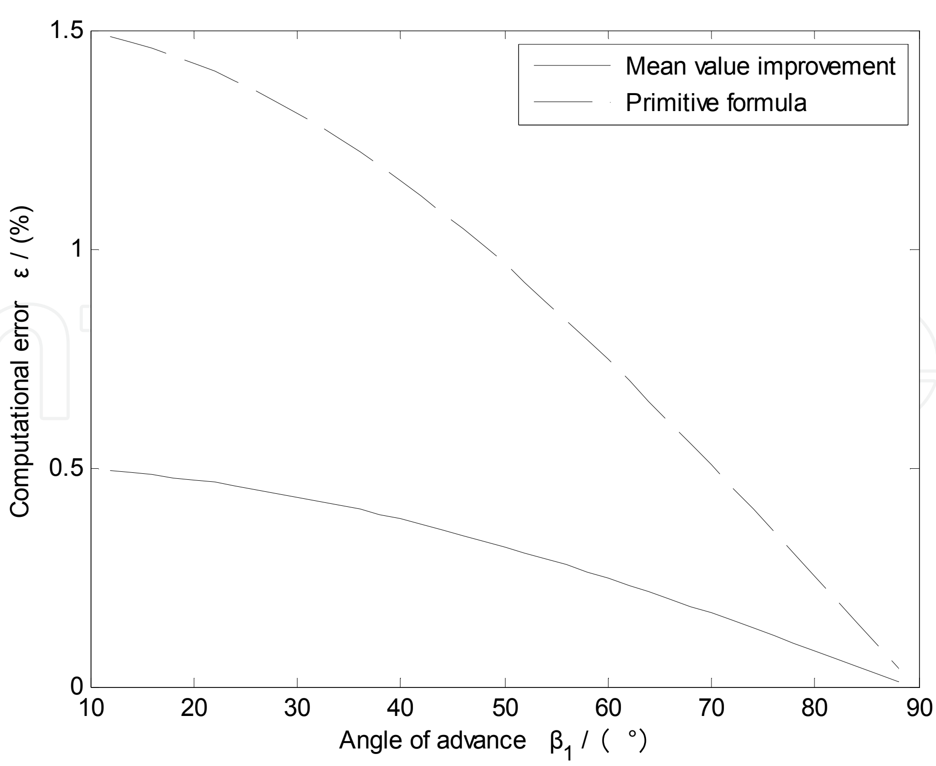

Fig. 3-3. Improvement of calculation accuracy after mean processing.

two antennas, the radial distance from measured target to detection platform can be derived making use of angular velocity that is obtained by differential deformation after introducing sine angle rate of change into Doppler shift equation. The analog calculation verifies that derived formula is correct. Moreover, it is proofed that the direct ranging method based on angle rate of change is equivalent to the one based on Doppler rate of change. As a comparison, the direct ranging method based on angle rate of change has following characteristics:

1. Only requiring a measurement
2. Independent of time measurement
3. It needs not assume that the detecting platform must be uniform motion.

3.2.2 Primitive formula

As shown in fig.3-4, a single baseline array with two antenna elements is installed on airborne platform and the spacing of array is d. The direction of axis of baseline is parallel the axis of airborne platform. For fixed or low speed target T, the Doppler shift detected by airborne double channel measuring receiver in no.1 antenna element is

$$\lambda f_{d1} = v\cos\beta_1 \tag{3-10}$$

By differential transmutation, the Doppler shift is expressed in terms of the sine rate of angle of advance

$$\lambda f_{d1} = \frac{v}{\omega}\frac{\mathrm{d}\sin\beta_1}{\mathrm{d}t} \tag{3-11}$$

where: $\omega = v_t / r_1$.

Regarding the incident signal from target as parallel wave, according to the geometric relationship in diagram, we approximatively have

$$\sin\beta_1 \approx \sqrt{d^2 - \Delta r^2} \Big/ d \tag{3-12}$$

Again

$$\dot{r}_i = v_{ri} = \lambda f_{di} \tag{3-13}$$

Resulting in

$$\begin{aligned} \lambda f_{d1} &= \frac{v}{\omega}\frac{\mathrm{d}\sin\beta_1}{\mathrm{d}t} \\ &= \frac{v}{\omega}\frac{\Delta r}{d}\frac{\lambda\Delta f_d}{\sqrt{d^2 - \Delta r^2}} \end{aligned} \tag{3-14}$$

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

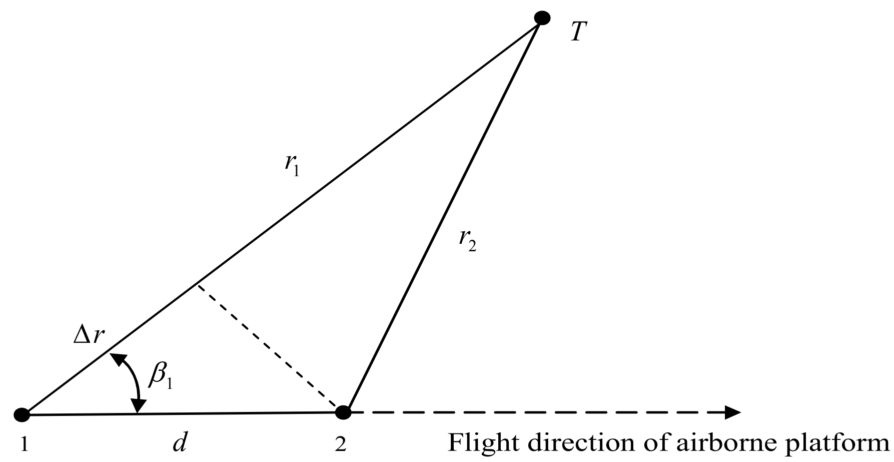

Fig. 3-4. Geometric relationship used for airborne Doppler direct ranging.

Because of

$$ctg\beta = \Delta r \Big/ \sqrt{d^2 - \Delta r^2} \tag{3-15}$$

By rearrangement, the equation can be expressed

$$\omega d \sin \beta_1 = \lambda \Delta f_d \tag{3-16}$$

By substituting $\omega = v_t / r_1$ into (3-16), we obtain

$$\begin{aligned} r_1 &= \frac{d v_t \sin \beta_1}{\lambda \Delta f_d} \\ &= \frac{d\left[v^2 - (\lambda f_{d1})^2 \right]}{\lambda v |\Delta f_d|} \end{aligned} \tag{3-17}$$

The simulation analysis shows that the frequency difference in denominator must introduce absolute value sign.

As soon as the Doppler shift expression based on phase difference measurement is substituted into the Doppler ranging equation derived based on angle change rate, according to the geometric relationship as shown fig.2-2, we can obtain the airborne ranging formula only using phase shift measuring

$$r_1 = \frac{d_1 \left[1 - \frac{\lambda^2}{d_1^2} (\Delta N_1 + \frac{\Delta \phi_1}{2\pi})^2 \right]}{\lambda \left| \frac{1}{d_1} (\Delta N_1 + \frac{\Delta \phi_1}{2\pi}) - \frac{1}{d_2} (\Delta N_2 + \frac{\Delta \phi_2}{2\pi}) \right|} \tag{3-18}$$

3.2.3 Error between computational and theoretical value

Based on the equivalence in computation, the ranging formula (3-18) can be transformed into as follows form

$$r = \frac{d_1\left[1 - \frac{\Delta r_1^2}{d_1^2}\right]}{\left|\frac{\Delta r_1}{d_1} - \frac{\Delta r_2}{d_2}\right|} \tag{3-19}$$

Preassigning following parameter: radial distance r and baseline length d, and making the angle of arrival $\theta = 90^0 - \beta_1$ continuously change within preassigned interval. The other radial distance can be in turn solved making use of cosine law. Then, the path difference is obtained. With that, the radial distance of target can be calculated by (3-19) and the relative calculation error ε between computational and preassigning value can be obtained by comparison

$$\varepsilon = \frac{|X - X_a|}{X} \times 100\% \tag{3-20}$$

where: X and X_a respectively express computational and preassigning value.

The benefit using (3-19) in analog calculation is that the analysis for integer of wavelength and phase difference value can be avoided.

Fig.3-5 shows the error curve of radial distance between computational and preassigning value in which the total length of baseline is different when the angle of arrival is linear variation from 0^0 to 90^0. Its basic feature is that the longer is the baseline length, the greater is the computational error, namely, the computational error is inversely proportional to radial distance.

The basic parameters adopting in simulation analysis is: $r_1 = 50\ \ km$ and $d = d_1 = d_2$.

3.3 Direct ranging method based on Doppler rate of change

3.3.1 Recapitulation

Under the condition that detection platform is uniform motion along straight line and continuing multipoint detection, on the one hand, the ratio of Doppler changing rate between two adjacent detecting nodes can be expressed as the cubic of specific value of tangential velocities making use of circular function relationship. On the other hand, making use of the formula of Doppler rate of change based on measuring Doppler frequency difference, the ratio of Doppler changing rate between two adjacent detecting nodes can be also expressed as the specific value of Doppler frequency difference. On this basis, a direct ranging formula based on Doppler shift as well as frequency difference can be obtained from the identical relation of speed vector.

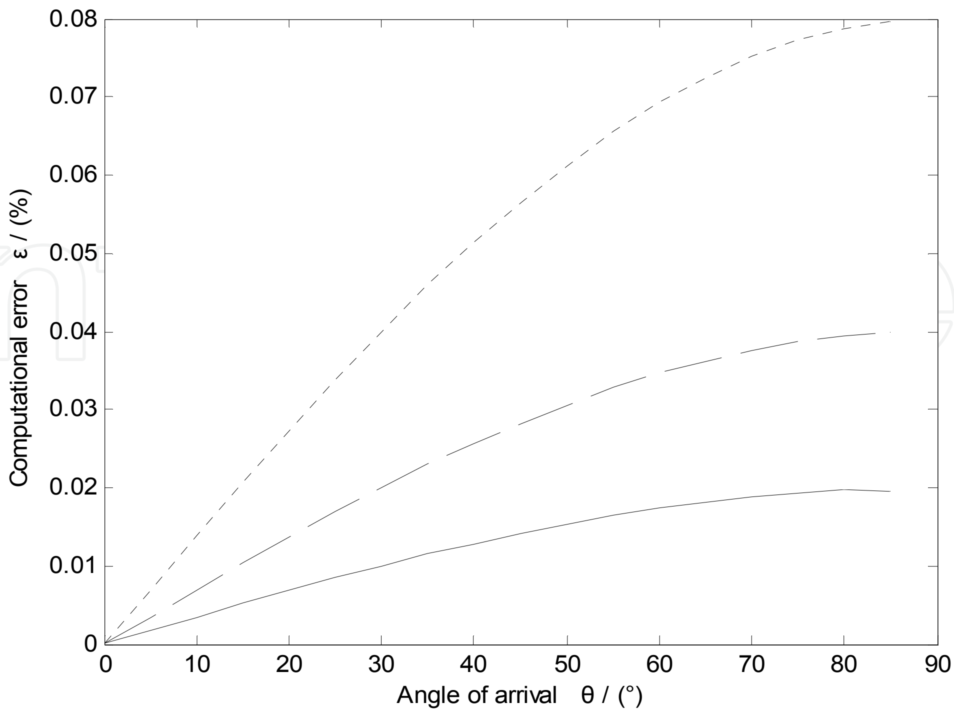

Fig. 3-5. Computational error of ranging formula with different baseline length.

3.3.2 Ratio of Doppler changing rate between two adjacent detecting nodes

As shown in fig. 3-6, provided that the detection platform which is uniform motion along straight line detects the signal of target by fixed cycle and carries out at least three continuing measurement respectively to earth-fixed target. The expression of Doppler changing rate at per node is

$$\dot{f}_{di} = \frac{v_{ti}^2}{\lambda r_i} \quad (i = 1,2,3) \tag{3-21}$$

The ratio of Doppler changing rate between two adjacent detecting nodes is

$$q = \frac{\dot{f}_{d2}}{\dot{f}_{d1}} = \frac{r_1}{r_2}\frac{v_{t2}^2}{v_{t1}^2} \tag{3-22}$$

The ratio of radial distance between two adjacent detecting nodes according to sine theorem is

$$\frac{r_{i+1}}{r_i} = \frac{\sin\beta_i}{\sin\beta_{i+1}} = \frac{v\sin\beta_i}{v\sin\beta_{i+1}} = \frac{v_{ti}}{v_{t(i+1)}} \tag{3-23}$$

Namely, in the case of uniform motion, the ratio of radial distance between two adjacent detecting nodes equals the ratio of tangential velocity. Substituting Eq.(3-23) into (3-22) gives

$$q = \frac{\dot{f}_{d2}}{\dot{f}_{d1}} = \frac{v_{t2}^3}{v_{t1}^3} \tag{3-24}$$

Hence, when detection platform is uniform motion, the ratio of Doppler change rate between two adjacent detecting nodes will equal the cubic of specific value of tangential velocities on two adjacent nodes. Introducing the Doppler change rate expression (2-18) based on Doppler frequency difference, the specific value of Doppler change rate between two adjacent detecting nodes can be also written as

$$q = \frac{d_1}{d_2}\frac{\Delta f_{d2}}{\Delta f_{d1}} \tag{3-25}$$

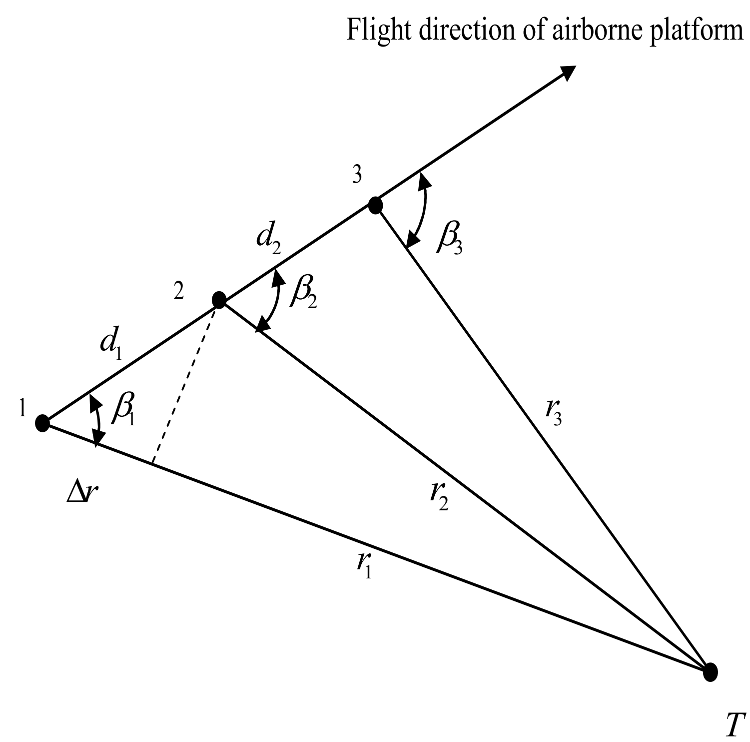

Fig. 3-6. Geometric model used for analyzing Doppler passive localization of moving single station.

3.3.3 Solution of radial distance

According to the velocity component at every node in mobile path of the platform, we have identical relation about speed

$$v^2 = v_{r2}^2 + v_{t2}^2 = v_{r1}^2 + v_{t1}^2 \tag{3-26}$$

Rearranging yield

$$v_{r2}^2 - v_{r1}^2 = v_{t1}^2 - v_{t2}^2 \tag{3-27}$$

Then, separately substituting the Doppler shift which is associated with radial velocity and the Doppler changing rate which is associated with tangential velocity as well as their ratio into (3-27) gives

$$\lambda(f_{d2}^2 - f_{d1}^2) = r_2 \dot{f}_{d2}(u^{-1} - 1) \tag{3-28}$$

where: $u = \sqrt[3]{q^2} = \sqrt[3]{\left(\frac{d_1}{d_2}\frac{\Delta f_{d2}}{\Delta f_{d1}}\right)^2}$.

Hence, we can obtain the calculating formula of radial distance

$$\begin{aligned} r_2 &= \frac{\lambda(f_{d2}^2 - f_{d1}^2)}{(u^{-1} - 1)\dot{f}_{d2}} \\ &= \frac{\lambda d_2 \Delta f_{d1}(f_{d1} + f_{d2})}{(u^{-1} - 1)v\Delta f_{d2}} \end{aligned} \tag{3-29}$$

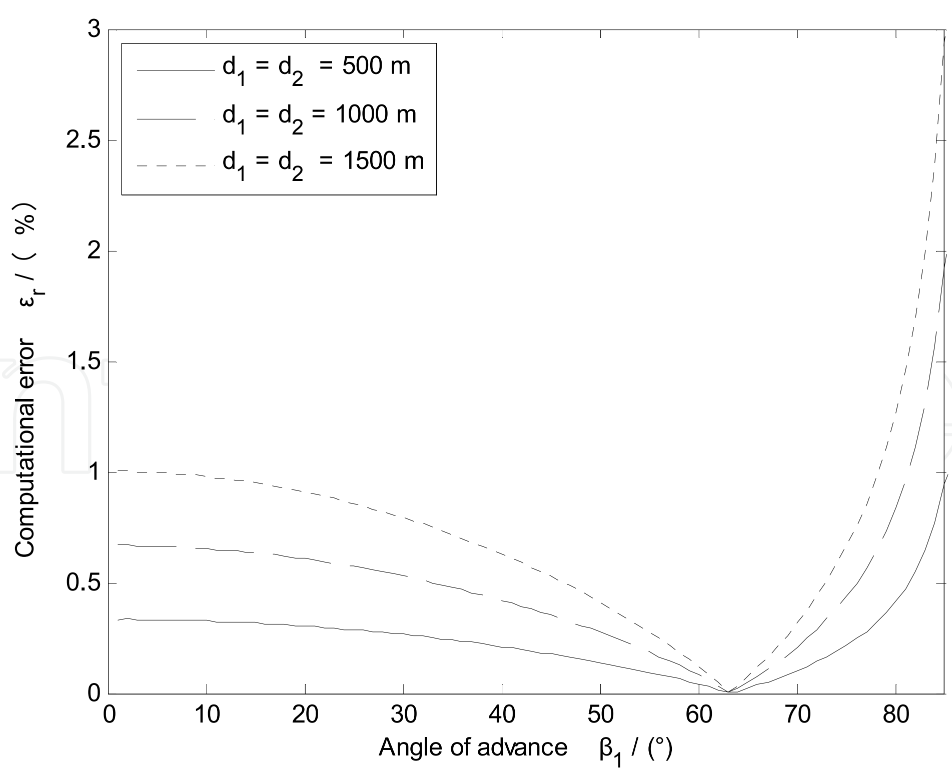

Fig. 3-7. Computational error of ranging formula in equally spaced detection.

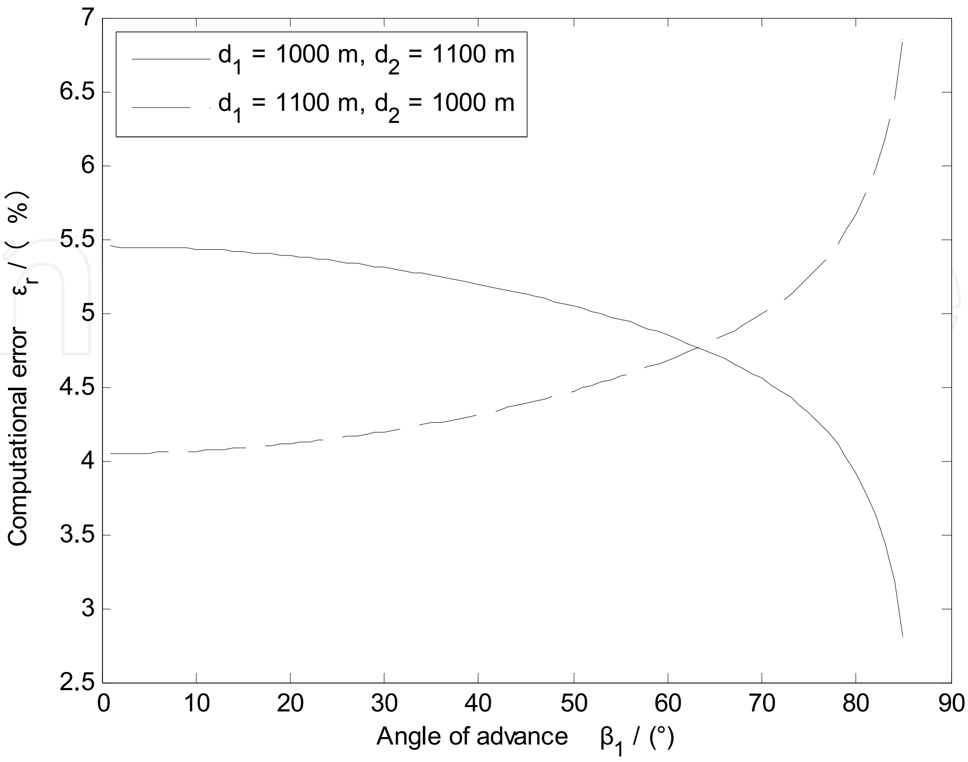

Fig. 3-8. Computational error of ranging formula in unequal spaced detection.

According to calculation error formula between calculated value and theoretical value, fig.3-7 shows the computational error curve between computational and theoretical value when the platform is movement in equal interval. Fig.3-8 is not equal interval. It can be seen that the formula has best accuracy when two adjacent flight distances is equal. If the distance is not equal, the error is larger. There is divergence phenomenon when the angle of advance goes to 90^0. The simulation calculation shows that the error is not connected with the flight speed of mobile platform and wavelength of measured signal.

The basic parameters adopting in simulation analysis is: $v = 100\ m/s$, $r_1 = 100\ km$ and $\lambda = 0.25\ m$.

4. Airborne DF method without ambiguity based on Doppler as well as rate

4.1 Recapitulation

The phase interferometry is a direction finding method with better measurement accuracy. It is widely used for active and passive detection system. But for single baseline phase interferometry, there is the contradiction between accuracy of direction finding and maximum angle without ambiguity. To solve this problem, existing method is to utilize multi-baseline system including the method combining long baselines with short ones and algorithm resolving phase ambiguity with multi-baseline.

In actual application, the method combining long baselines with short ones have two limitations. In fact, corresponding baselines will also become extremely small since wavelength is very short for high-frequency signal. This moment, not only the antenna element must be made to do very small, but also very high demand is put forward for antenna arrangement. It will bring about coupled between antennas and bring down antenna gain. At the same time, higher demand will be required for measurement accuracy of interferometer. For algorithm resolving phase ambiguity with multi-baseline, the computing amount is heavy due to demanding multidimensional integer search.

The study presented in this section shows that applying a single baseline array in airborne platform can realize the high-accuracy DF without the ambiguity of viewing angle after combining with Doppler information. Only from the viewpoint of principle of measurement, selection for baseline length is arbitrary. So it is more suitable for carrying out detection operation in a broadband.

The analysis discovers that the integer of wavelength in radial distance can be directly obtained compositely making use of the velocity vector equation and Doppler shift as well as Doppler changing rate equation. From this, the integer of wavelength in path length difference of radial distance between two adjacent antenna elements can be determined. Further, the value less than a wavelength in path length difference can be obtained by phase difference measurement. As compared with now existing interferometry firstly determining phase difference, this sort of direction finding method associating with Doppler and phase difference and firstly determining path length difference does not exist phase ambiguity nor require restricting baseline length.

4.2 Analytical derivation

According to derivation in section three, in fact, we can obtain two relations from the identical relation about speed

$$\lambda(f_{d1}^2 - f_{d2}^2) = r_1 \dot{f}_{d1}(u-1) \tag{4-1}$$

$$\lambda(f_{d1}^2 - f_{d2}^2) = r_2 \dot{f}_{d2}(1-\frac{1}{u}) \tag{4-2}$$

Thus, we can obtain integer values of wavelength about two radial distances

$$N_1 = \mathrm{int}\left[\frac{r_1}{\lambda}\right] = \mathrm{int}\left[\frac{f_{d1}^2 - f_{d2}^2}{\dot{f}_{d1}(u-1)}\right] \tag{4-3}$$

$$N_2 = \mathrm{int}\left[\frac{r_2}{\lambda}\right] = \mathrm{int}\left[\frac{(f_{d1}^2 - f_{d2}^2)u}{\dot{f}_{d2}(u-1)}\right] \tag{4-4}$$

Substituting these expressions into the existing DF expression based on the principle of phase interferometry, we can obtain the airborne DF formula based on phase shift and Doppler shift as well as its rate

$$\sin\theta = \frac{\Delta r}{L} = \frac{\lambda}{L}\left(\operatorname{int}\left[\frac{f_{d1}^2 - f_{d2}^2}{\dot{f}_{d1}(u-1)} \right] - \operatorname{int}\left[\frac{(f_{d1}^2 - f_{d2}^2)u}{\dot{f}_{d2}(u-1)} \right] + \frac{\Delta\phi}{2\pi} \right) \tag{4-5}$$

5. Airborne passive DF with orthogonal baseline

5.1 Recapitulation

At present, main methods applicable to airborne DF have the amplitude comparison and phase interferometry, etc. The measuring precision of direction-finding system based on amplitude comparison have always had to suffer the biggish influence conduced by incompatible from antenna and reception channel of measuring receiver. Moreover, phase interferometry needs to solve phase ambiguity.

This section presents a Doppler DF method applicable to airborne based on the direction cosine change rate.

If three antenna units are divided into two set and two baselines are placed at right angles to each other, in which the direction of one baseline is parallel to the actual flight direction of air vehicle, the sine and cosine function of target bearing respectively in two baseline directions can be simultaneously obtained according to the analysis principle of the direction cosine change rate. The angle measurement formula only based on Doppler frequency difference can be derived after eliminating the unknown parameters including angular velocity and wavelength by the specific value of two circular functions. The analog calculation shows that the relative calculation error is in direct proportion to the baseline length provided that the incident wave is parallel in derivation. Furthermore, the derived formula has irregularity in airborne axis direction. But the error analysis depicts that the measurement accuracy is in direct proportion to the baseline length. Moreover, the measurement accuracy when the azimuth angle is minor can be usefully enhanced by changing the specific value between two baselines. Since the new method is not associated with wavelength, the direction finding only based on Doppler frequency difference will be more adapted to passive sounding as compared with phase interference method.

5.2 Derivation

If we can use the direction cosine change rate for single baseline array, the incidence angle of measured signal can be expressed as the function depending on the Doppler frequency difference and on the angular velocity and on the baseline length and on the wavelength. According to this result, the study discovery that the airborne direction finding only based on Doppler frequency difference can be realized by making use of the direction cosine change rate for orthogonal double-baseline. Firstly, a planar array with L-shape is structured by use of three antennas. Then, the sine and cosine circular function with regard to the incidence angle of measured signal can be simultaneously obtained due to the direction cosine change rate. Moreover, the unknown angular velocity and the wavelength can be eliminated by the specific value of the sine and cosine circular function. Thus, the derived tangent angle is only associated with known Doppler frequency difference and the baseline length.

As shown in fig.5-1, three antenna units arrange in L form in horizontal plane. Two baselines are placed at right angles to each other. In which, the direction of one baseline is parallel to axes of aerocraft. On condition that measured target is motionless or low speed motion, the Doppler shift received by airborne receiver in every antenna unit is

$$\lambda f_{di} = v\cos\theta_i \tag{5-1}$$

Approximately upon condition that the incident wave is parallel, according to the direction cosine change rate, we have

$$\begin{aligned}\frac{\partial\cos\theta_1}{\partial t} &= \frac{\partial}{\partial t}\left(\frac{\Delta r_1}{d_1}\right)\\ &= \frac{\dot{r}_1 - \dot{r}_2}{d_1}\\ &= \frac{\lambda}{d_1}(f_{d1} - f_{d2})\end{aligned} \tag{5-2}$$

Hence, making use of two antenna units whose baseline is parallel to the axis of aerial vehicle can obtain the sinusoidal triangle function with regard to relative azimuth depending on the Doppler frequency difference and on the angular velocity and on the base length

$$\begin{aligned}\sin\theta_1 &= -\frac{1}{\omega_\theta}\frac{\partial\cos\theta_1}{\partial t}\\ &= -\frac{1}{\omega_\theta}\frac{\partial}{\partial t}\left(\frac{\Delta r_1}{d_1}\right)\\ &= -\frac{\lambda\Delta f_{d1}}{\omega_\theta d_1}\end{aligned} \tag{5-3}$$

where: $\Delta f_{d1} = f_{d1} - f_{d2}$ is Doppler frequency difference; $\omega_\theta = \dfrac{v\sin\theta_1}{r_1}$ angular velocity ; d_1 baseline length parallel to the axis of aerial vehicle..

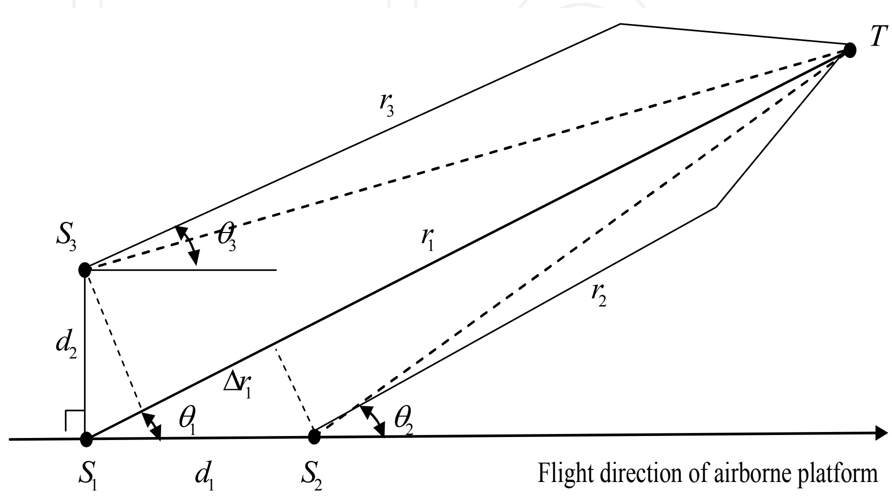

Fig. 5-1. Airborne passive direction finding array with L form.

Further, making use of two antenna units whose baseline is at right angles to the axis of aerial vehicle can obtain the cosine triangle function with regard to relative azimuth depending on the Doppler frequency difference and on the angular velocity and on the base length

$$\begin{aligned}\cos\theta_1 &= \sin(90-\theta_1) \\ &= -\frac{1}{\omega_\theta}\frac{\partial\cos(90-\theta_1)}{\partial t} \\ &= -\frac{1}{\omega_\theta}\frac{\partial}{\partial t}\left(\frac{\Delta r_2}{d_2}\right) = -\frac{\lambda\Delta f_{d2}}{\omega_\theta d_2}\end{aligned} \tag{5-4}$$

where: $\Delta f_{d2} = f_{d1} - f_{d3}$ is Doppler frequency difference; d_2 baseline length at right angles to the axis of aerial vehicle.

By way of the specific value, the tangential triangle function only depending on the Doppler frequency difference and on the baseline length can be obtained

$$\begin{aligned}tg\theta_1 &= \frac{\sin\theta_1}{\cos\theta_1} \\ &= \frac{d_2}{d_1}\frac{\Delta f_{d1}}{\Delta f_{d2}}\end{aligned} \tag{5-5}$$

The relative azimuth between aerial vehicle and measured target is

$$\theta_1 = tg^{-1}\left[\frac{d_2}{d_1}\frac{\Delta f_{d1}}{\Delta f_{d2}}\right] \tag{5-6}$$

This analytic function in form is analogous to the formula of the amplitude comparison and phase interference method. Moreover, it is also not connected with wavelength.

5.3 Simulation analysis

We make the analog verification by replacing measured value with theoretical value. Firstly, presetting following parameter: radial distance r_1 and base length d_i as well as wavelength and speed, the theoretical value of the rest radial distance and azimuth angle can be computed by making azimuth angle continuous change in specified interval. Hence, we can obtain the theoretical value of the Doppler shift corresponding to each radial distance. After that, the value of azimuth angle can be calculated by Eq.(5-6) and the relative calculation error can be obtained by comparison with the theoretical value.

Because the simulation analysis of the relative calculation error is not associated with both wavelength and speed, there is not the specified value of wavelength and speed.

Fig.5-2 and fig.5-3 depict the relative calculation error curve with different baseline and radial distance. When azimuth angle tends to zero, the derived formula has irregularity. Obviously, the farther is the object distance, or the shorter is the baseline length, the smaller is the relative calculation error of formula. There occurs this occurrence provided that the incident wave is parallel in derivation.

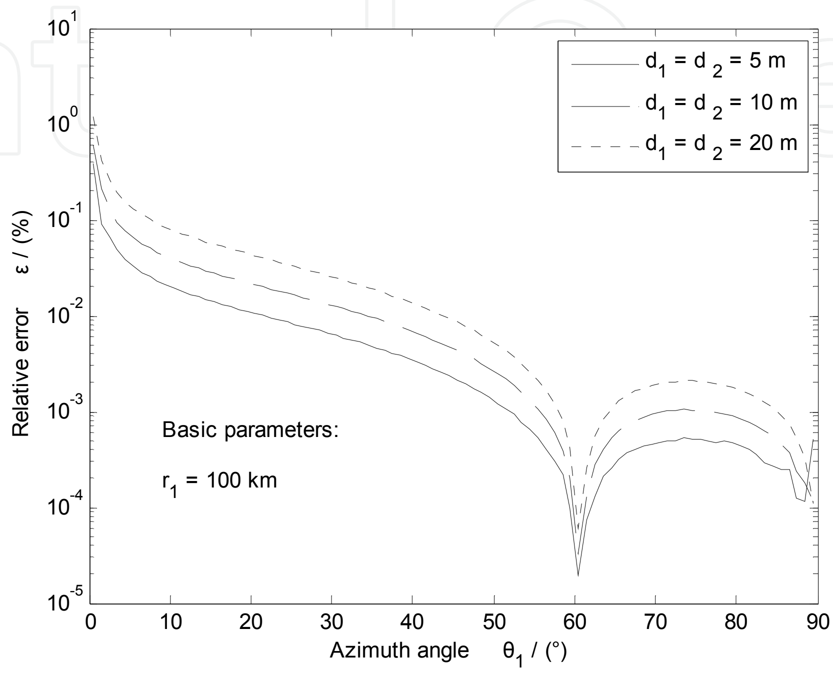

Fig. 5-2. Relative calculation error: different baseline lengths.

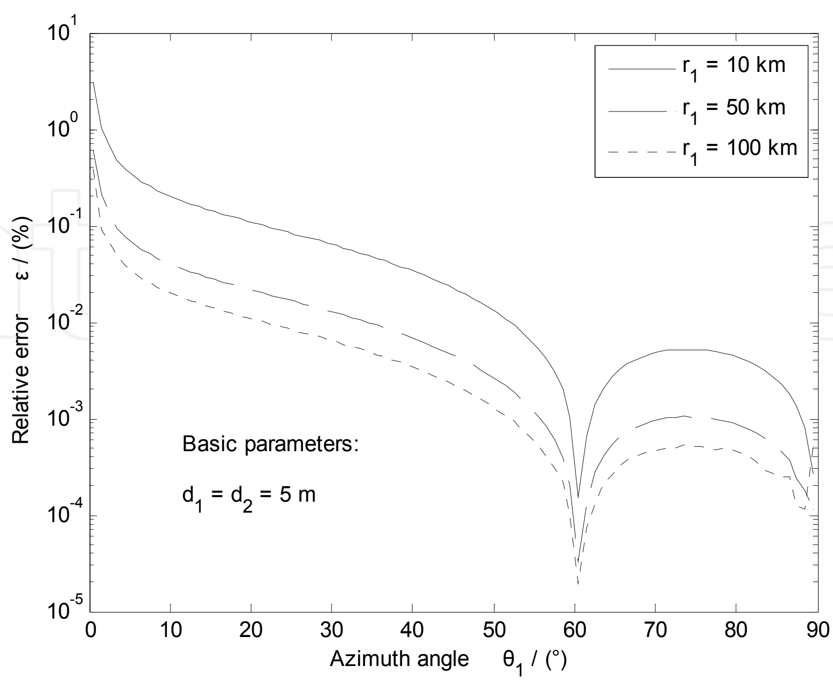

Fig. 5-3. Relative calculation error: different radial distances.

5.4 Error analysis

On condition that the locating error of baseline is neglected, making differential for Doppler frequency difference gives

$$\frac{\partial\theta_1}{\partial\Delta f_{d1}} = \frac{1}{1+A^2}\frac{d_2}{d_1\Delta f_{d2}} \tag{5-7}$$

$$\frac{\partial\theta_1}{\partial\Delta f_{d2}} = \left|\frac{1}{1+A^2}\frac{d_2\Delta f_{d1}}{d_1\Delta f_{d2}^2}\right| \tag{5-8}$$

where: $A = \frac{d_2}{d_1}\frac{\Delta f_{d1}}{\Delta f_{d2}}$

According to error estimation theory, the overall error produced by the measurement of Doppler frequency difference is

$$\sigma = \sigma_f\sqrt{\sum_{i=1}^{n=2}\frac{\partial\theta_i}{\partial\Delta f_{di}}} \tag{5-9}$$

where: σ_f is the mean-root-square error measuring Doppler frequency difference.

Fig.5-4 shows that the error curve falls exponentially. When azimuth angle tends to zero, there is obviously the blind zone for direction finding. And the accuracy is best when azimuth angle is close to right angle. The analysis shows that the measuring error can usefully decrease if the length of two baselines is simultaneously increased. For example, as soon as the length of two baselines can be increased to 15 meter, the maximum angle measuring error is less than 2^0 after azimuth angle is bigger than 10^0.

Fig.5-5 depicts that the measurement error when the azimuth angle is less than 30^0 can be quickly reduced by changing the specific value between two baselines.

Although the relative calculation error is not connected with wavelength, the calculation shows that the measurement accuracy is connected with wavelength. Fig.5-6 shows that the measurement accuracy is inversely proportional to the wavelength.

Moreover, though the relative calculation error is not connected with the flight speed, the calculation shows that the measurement accuracy is connected with the flight speed. Fig.5-7 shows that the measurement accuracy is in direct proportional to the flight speed.

5.5 Summarize briefly

Since the new method presented in this text is not associated with wavelength, the direction finding only based on Doppler frequency difference will be more adapted to passive sounding as compared with phase interference method.

The multi-objective passive localization and wideband operation from single airborne observer is a key and difficulty subject for modern electron reconnaissance. Because the

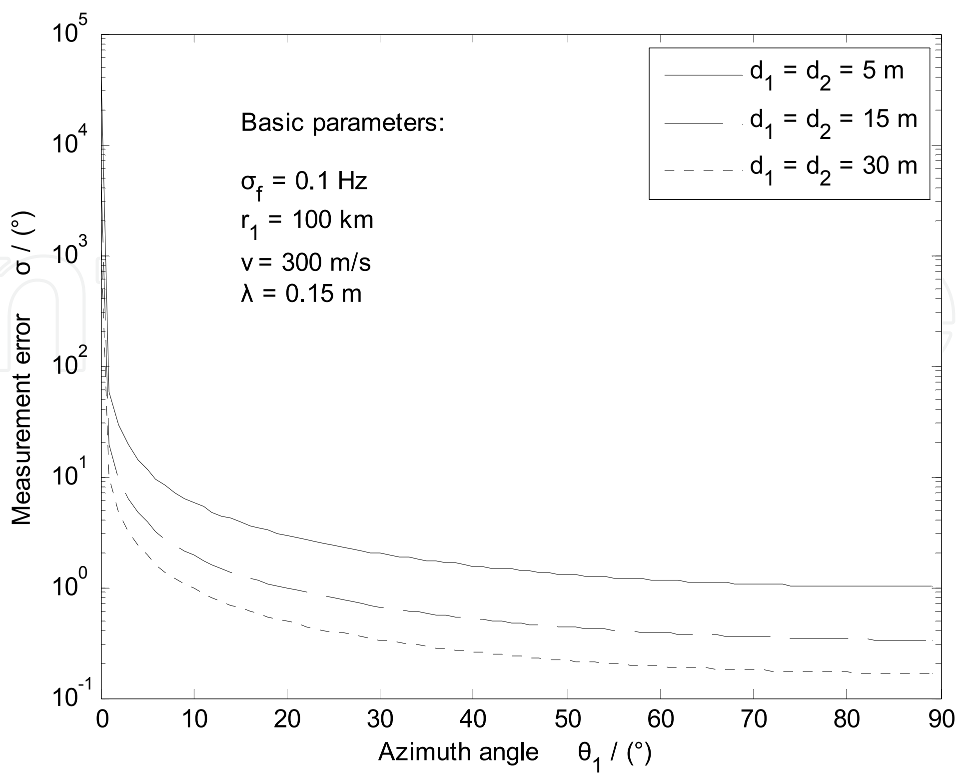

Fig. 5-4. Measurement errors: different baseline lengths.

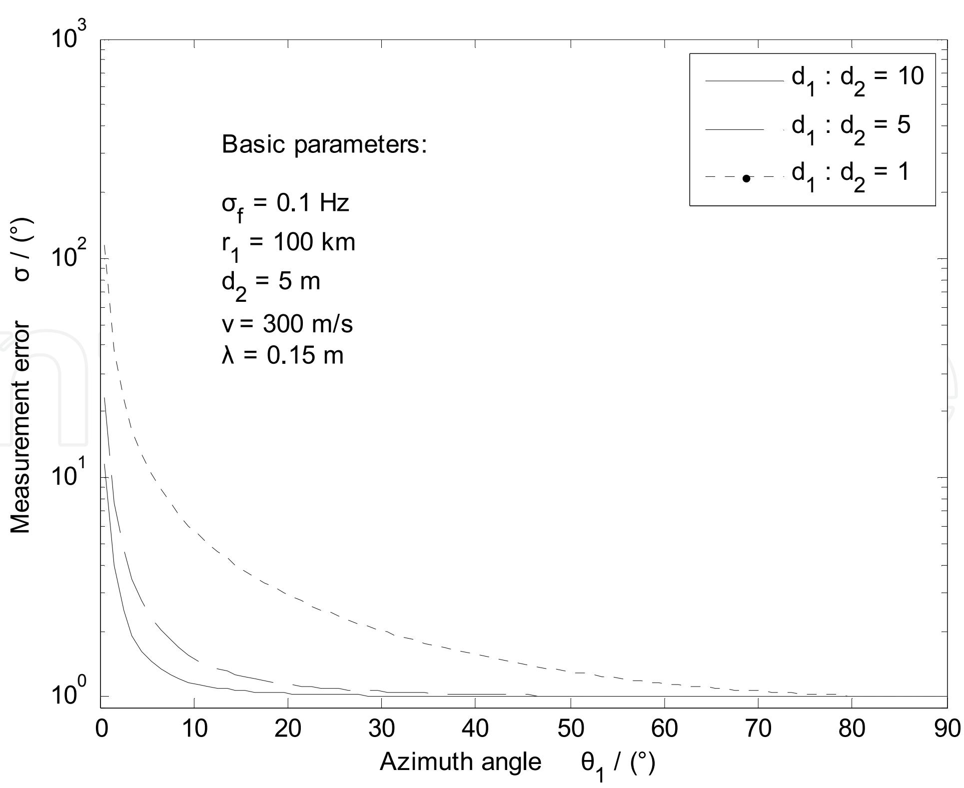

Fig. 5-5. Measurement errors: different ratio between two baseline lengths.

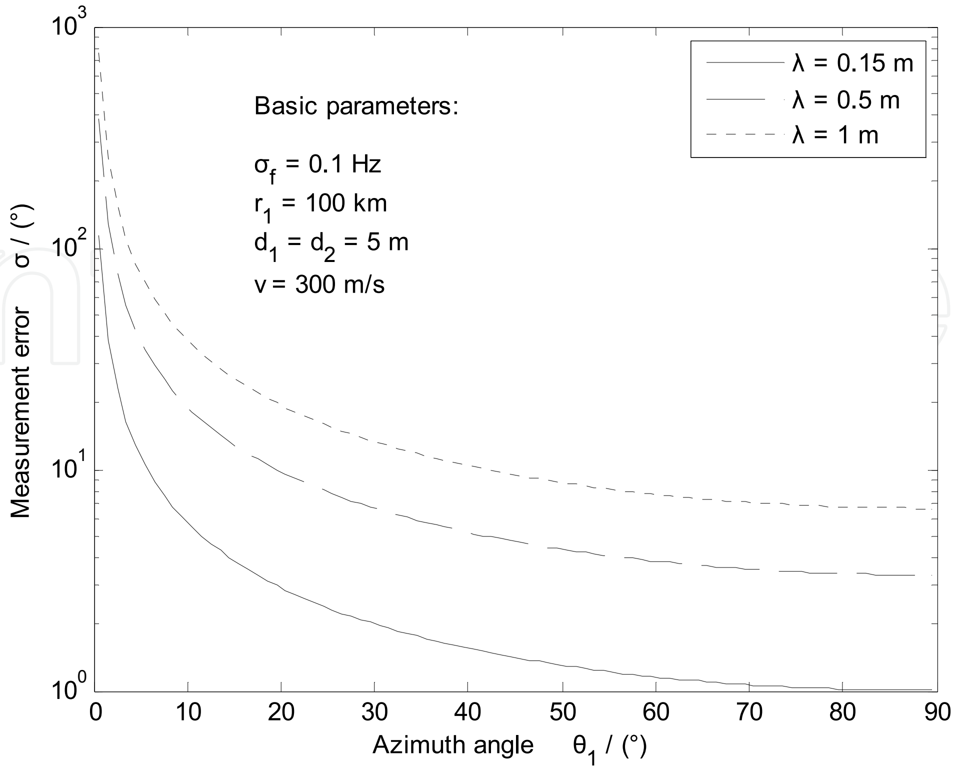

Fig. 5-6. Measurement errors: different wavelengths.

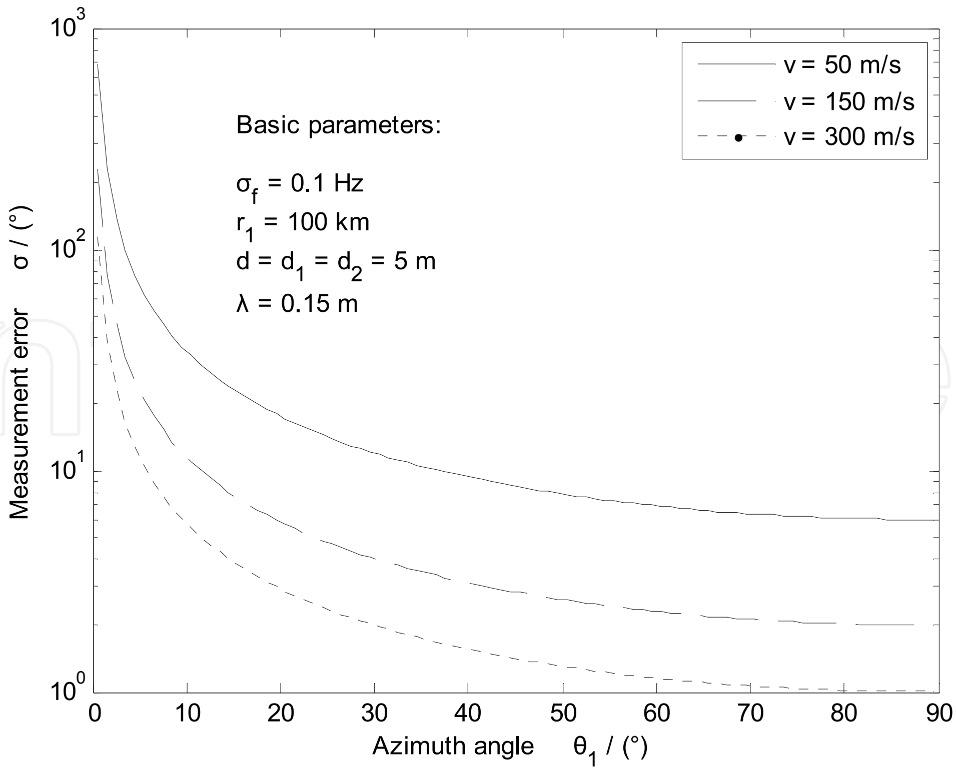

Fig. 5-7. Measurement errors: different flight speeds.

direction finding method presented in this text is only associated with Doppler frequency difference, that is, which is not associated with the setting up the wavelength and baseline length, this method is very applicable to wideband operation.

At the same time, this method is also very applicable to the electron reconnaissance for multi-objective from single airborne observer because the information of frequency measurement is advantageous for signal sorting and recognition.

6. Conclusions

Available localization method based on Doppler as well as its rate of change uses the coordinate variation in rectangular coordinate system for analyzing the angle of advance in polar coordinate system and uses geometric projection for analyzing the speed vector. Because the Doppler shift is the function of position and motion state of target, there are 2n unknown number in n-dimensional plane. For the localization of single station, in order to resolve the position and motion state of target, 2n nonlinear equations must be set up according to the measured value obtained during n measuring cycle. The solution process is comparative complicated and the analytic result can not be obtained.

The method of Doppler direct ranging changes such status. Recently, research done by author shows that the direct range finding for target with analytic form can be realized making use of Doppler frequency difference during a time interval from the viewpoint of the basic definition of Doppler rate. More, the direct ranging formula whose characteristic is better can be obtained by applying angle rate.

Though the auctorial research result has proves that the single station which is moving can realize fast ranging for fixed or slow speed target making use of Doppler shift as well as its rate of change. However, the measurement accuracy for carrier frequency in passive localization is just $\sigma_f = 10^{-4} f$ based on actual technique level. This measuring ability restricts the application of Doppler passive localization technique in engineering. As a rule, the value of Doppler frequency difference may be less than Hz since the baseline length of antenna array is shorter in single moving platform. This conduces that the demand for measurement accuracy of frequency difference is very rigor.

In allusion to such difficulty, author researches the phase detection method for Doppler shift and presents the airborne passive phase interference ranging method based on the principle of Doppler direct ranging. The other one which is being explored by author is the DF method combining Doppler with phase interference in which the path length difference is firstly determined by directly solving the integer of wavelength in path length difference based on measuring Doppler as well as its rate. Though these methods are also imperfect, elementary result has shown that the measuring method of Doppler-phase interference will help to development of airborne passive localization technique as well as correlation technique.

As soon as the phase shift can directly integrate with the Doppler frequency shift in physical relationship, more novel method of localization can be appeared. The mutual equivalent conversion between phase shift and Doppler shift means that the method obtained by a kind of measurement technology can be quickly expanded to another measurement technology.

Hence, the research for passive localization by applying the functional relation between phase shift and Doppler shift may be a more meaningful work.

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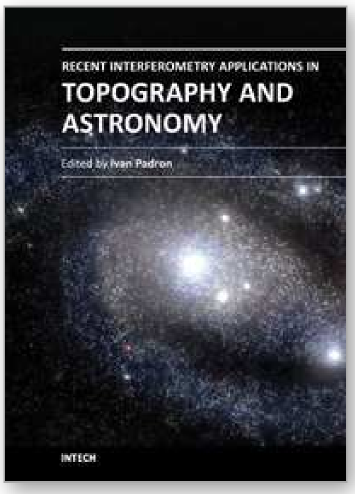

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This book provides a current overview of the theoretical and experimental aspects of some interferometry techniques applied to Topography and Astronomy. The first two chapters comprise interferometry techniques used for precise measurement of surface topography in engineering applications; while chapters three through eight are dedicated to interferometry applications related to Earth's topography. The last chapter is an application of interferometry in Astronomy, directed specifically to detection of planets outside our solar system. Each chapter offers an opportunity to expand the knowledge about interferometry techniques and encourage researchers in development of new interferometry applications.

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InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
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Phone: +86-21-62489820
Fax: +86-21-62489821