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Improved Ambiguity-Resolving for Virtual Baseline

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Abstract

A novel phase interferometer method based on virtual baseline is proposed for technical difficulty in resolving angle ambiguity and antenna layout. In this method, only two baselines are set to solve the problem of angle ambiguity. In high noise areas, there are large numbers of outliers which lead to angle error in the measured data, and a way to detect and eliminate the outliers is applied to improve the effect of solving ambiguity. The simulation results show that the improved method could effectively correct the error of fuzzy phase difference and increase the probability of ambiguity-resolving. Duo to its simple equipment and easy to implement, the proposed method might have certain guiding significance to engineering applications.

Keywords: *virtual baseline; resolving ambiguity; phase difference; outliers*

1. Introduction

With the development of the electronic counter-measures technology and the missile defense technology, the traditional Air-borne radar systems have encountered more and more serious threats in modern high-tech warfare, due to its weak electromagnetic invisibility, weak anti-reconnaissance capability and poor anti-jamming capability. Previous single radar seeker with bearings-only tracking system can not meet the needs of modern warfare, As the consummation and complement of active detection systems, passive location and tracking system is becoming an important part of the multi-mode radar seeker and has been paid much more attention by many countries. The passive observation mode by single observer has many advantages, such as excellent invisibility, simplicity in the facility, large effective radius and wide applicability [1-2].

Figure 1. Presentation of passive location

At present, passive location technology is developing in the direction of the high precision and high speed, and the progress of technology mainly depends on the improvement of measurement technology, especially the measurement parameters with high precision. Phase interferometer of direction finding is a kind of direction finding technique, due to the high precision of direction finding, small volume, light quality; the phase interferometer has very important significance in single station passive location of high precision [3]. The technology measured the same source with a pair of receiver of strictly phase matching to obtain signal

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phase difference, so as to calculate the radiation direction. If electronic warfare system adopts the traditional compare-breadth technology for direction finding, it only can measure the target azimuth with poor precision (12~15. R.M.S), and can't meet the requirements of passive location, therefore, with the direction finding of the high resolution precision technology, phase interferometer direction finding technology can reach high precision(0.5. R.M.S), and it is widely applied in the passive direction finding system. But phase interferometer can only measure the value of phase difference within $(-\pi, \pi)$, so there is a contradiction between direction finding accuracy and the maximum ambiguity.

In order to solve this contradiction, the most multiple baseline interference instruments are used for measuring angle, and the solution is using the combination of long and short baseline, the long baseline assurance the direction finding accuracy, and the short baseline for the phase ambiguity. In view of the fuzzy solutions for the baseline interferometer angle measuring algorithm, there are many scholars focus on the research. Liu and Dong [4]-[5] analyze the feasibility of the virtual matrix element method to resolving ambiguity theoretically which based on a virtual array transformation method and the least squares estimate of the virtual array element method. Jiang.etc [6] proposed a phase interferometer antenna array's baseline meter method by a successive recursive algorithm of fuzzy solution, and derived the analytical expression of the baseline length, analyzed the relationship between the major indexes of the phase_interferometer (accuracy of Angle measuring, an antenna spacing, phase measurement error) and the antenna array parameters (baseline number, virtual baseline, baseline length). Zhou.etc [7]-[8] using the Chinese remainder theorem as the solution of the fuzzy, and study the conditions of the correct solution of fuzzy in noise environment, then borrow from the principle of the length of baseline interferometer for angle measuring which uses short baseline solution to the problem of phase ambiguity, long baseline improves the accuracy of measuring angle, the length of baseline match selected, angle measuring ability and anti-noise performance are analyzed and simulated.

But this approach requires the length of short baseline to be less than $\lambda/2$. Especially for high frequency signal, the wavelength will be very small, and it makes the size of the antenna array should be very small. As a result, it leads to decrease of the antenna gain and antenna mutual coupling. Meanwhile, the too small size of short baseline length increases the cost of system equipment, adds complexity of data processing, and puts forward the high requirements of antenna installation and measurement accuracy [9]-[10]. A multiple baseline phase difference solution based on distance varies is proposed by Gong and Yang [11]-[12], but as a result to its multidimensional integer search, this solution needs huge computation. And yet, it is desperately needed that the algorithm of resolving ambiguity has easy implementation and quick operation in single passive localization and tracking system. The other commonly used method of resolving ambiguity is the dual baseline system based on remainder theorem, this way can ensure high precision, but the distance between the antennas must be strictly co-prime.

A virtual baseline method is present to resolving ambiguity with few numbers of antennas, easy to lay- out to for antennas and high precision [13]. However, the accuracy of this method is affected seriously by the shorter baseline, and in a real environment, larger noise has a great influence for classical method of resolving ambiguity, the effect of ambiguity resolution is reduced under low SNR.

Thus, an improved method is put forward to increased ambiguity-resolving ability of virtual baseline. The characteristic of the virtual baseline is that the influence of the noise mainly exists in the short baseline measurement

Therefore, a better method to improve virtual baseline is undoing noise in the short baseline measurement, and an improvement method is put forward automatically, This method can determine the outliers eliminating outliers which are caused by strong noise according to certain criteria, then eliminate them and get unambiguous angle measurements of higher precision.

2. The Principle of Phase Interferometer

Digital interferometer system for direction finding is actually using phase difference to calculate direction of arrival (DOA), the phase difference is acquired by measuring the path difference of signal wave arrival, which is caused by adjacent arrays. Single baseline direction principle is shown in Figure 2.

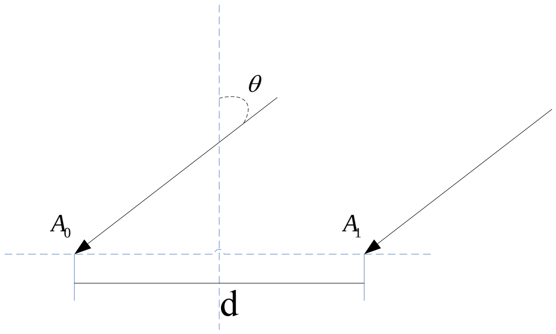

Figure 2. Phase interferometer of single baseline

The space wave is received by antenna array units as A_0 and A_1, the phase difference and angle of arrival are as follows.

$$\varphi_0 = 2\pi d \sin\theta/\lambda \tag{1}$$

$$\theta = \arcsin\left(\varphi\lambda/2\pi d\right) \tag{2}$$

φ is the signal phase difference, λ as the length of signal wave. d means the distance between the two antenna array units. θ is the arrival angle. If $d > \lambda/2$, then φ may be greater than 2π, and it leads to the phase ambiguity.

In the multiple baseline phase interferometer system, the short baseline $(d < \lambda/2)$ is usually used to solve the problem of phase ambiguity, and the long baseline to ensure the high precision of direction finding. The below Figure is a sample of one dimensional phase interferometer of three baselines.

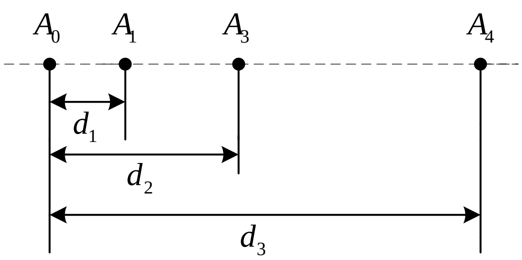

Figure 3. Phase interferometer of multiple baselines

In the above diagram, the three baselines are made up by four array units as A_0 A_1 A_2 A_3, and the length is d_1 d_2 d_3 respectively. The longest of them is d_3, and d_1 is the shortest. Combination with the formula (1), we learn that:

$$\varphi_i = 2\pi d_i \sin\theta/\lambda = 2\pi k_i + \varphi_i' \tag{3}$$

In the above formula, $k_i \le d_i/\lambda$, $i = 1、2、3$, φ_i is a phase difference of different baselines, φ_i' is the observed value correspondingly. k_3 can be determined through simultaneous equations, and also φ_3 at last. The arrival angle θ can be calculated by the formula (2) accordingly.

3. Improved Ambiguity-Resolving For Virtual Baseline

3.1 The direction finding rinciple of virtual baseline interferometer

Multiple baseline interferometer for direction finding can provide high precision bearing, and avoid the phase ambiguity problem. The baseline interferometers of cosine law and length ratio are the two most studied methods. These methods, in algorithm performance, can satisfy the demands of general direction, but there are defects for the two solutions. The method of cosine law[14] requires the length ratio to be co-prime, and it lead that the result is sensitive to phase error; the other way is complex for its multistage operation. Both methods need more units of antenna for ambiguity resolution. Generally, when the array element number is more than five, the direction finding accuracy can be assured. In applications of size limitation, these ways are not suitable for long baseline system.

Virtual baseline method is to use two different baseline phase to obtain a short baseline length by subtracting, and if the length of obtained short baseline is less than the half wavelength of signal, the direction finding result can be obtained without fuzzy phenomenon. Then, the higher precision value of direction finding can be achieved by the operators of solving ambiguity for long baselines.

Virtual base method is composed of three antennas which constitute double baselines. It is shown in Figure 3. However, the relationship between the two baselines needs not be relatively prime, only needs to satisfy the following relation.

$$\left|d_{23}\text{-}d_{12}\right| \le \lambda_{\min}/2 \tag{4}$$

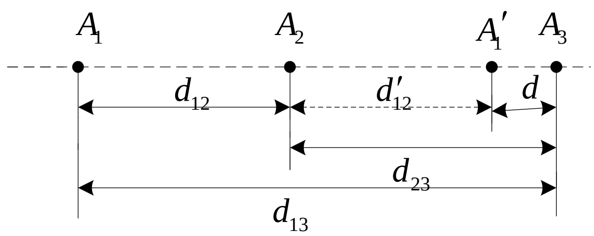

Figure 4. Phase interferometer principle of virtual baseline

Combination of interferometer direction finding principle, we can get the following message is from Figure 3

$$\varphi_0 = 2\pi d \sin\theta/\lambda = 2\pi\left|d_{12}\text{-}d_{32}\right|\sin\theta/\lambda = 2\pi k_0 + \varphi_0' \tag{5}$$

$$\varphi_1 = 2\pi d_{23}\sin\theta/\lambda = 2\pi k_1 + \varphi_1' \tag{6}$$

$$\varphi_2 = 2\pi d_{13}\sin\theta/\lambda = 2\pi k_2 + \varphi_2' \tag{7}$$

Virtual method use short baseline, obtained by subtraction of the two long baselines, to solve the fuzzy problem of the long baseline phase difference. This method has less number of antenna, not strict installation and high accuracy measurement.

Although a virtual base method of angle measuring to solve the fuzzy problem of the longest baseline phase, the existence of each channel interferometer measurement error limits the maximum value of the baseline length ratio.

Proposition *considering the measurement error, The expression of K is*:

$$K_2 = INT\left[\frac{(d_{13}/\left|d_{12}-d_{23}\right|)\varphi_0-\varphi_2'}{2\pi}+\frac{(d_{13}/\left|d_{12}-d_{23}\right|)\Delta\varphi_0-\Delta\varphi_2'}{2\pi}\right] \quad (8)$$

In the above formula, d_{ij} is the distance of antenna array units from i to j . φ_0 is a phase difference of different baselines after resolving ambiguity, φ_2' is the observed value correspondingly. $\Delta\varphi_0'$ and $\Delta\varphi_2'$ are measurement error respectively .

To obtain the correct value of K_2, it need the measuring error had no effect for Integer operation of the formula 8, so the requirement must be satisfied:

$$-\frac{1}{2}<\frac{(d_{13}/\left|d_{12}-d_{23}\right|)\Delta\varphi_0-\Delta\varphi_2'}{2\pi}<\frac{1}{2} \quad (9)$$

If measurement error meets the above conditions, the integer can get the correct value of K_2. From formula 8,the error $\Delta\varphi_0$ of baseline interferometer measurement is amplified with $d_{13}/\left|d_{23\text{-}12}\right|$ times. And the sum of the amplified error and the measurement error of the long baseline phase interferometer will have an impact on the value selection of K ,even the error of the virtual baseline phase interferometer measurement. Considering the accuracy of the phase difference measurement is almost equal between the channels. When the $d_{13}/\left|d_{23\text{-}12}\right|$ is fixed, the requirements must be satisfied for the largest errors of phase difference measurement as:

$$\Delta\varphi<\frac{\pi}{(d_{13}/\left|d_{12}-d_{23}\right|)+1} \quad (10)$$

The above formula can determine the allowed most large phase measuring error under the given baseline length ratio. If the baseline length ratio is set as 21, according to the formula 10, we can get $\Delta\varphi<8.18^{\circ}$,then it can meet the requirements of the solution of fuzzy. However, such condition puts forward strict requirements on carrier phase measurements. Once the carrier phase measurement accuracy can not meet the requirement, it will lead wrong to the gain of K, even bring about the phenomenon of many errors for ambiguity resolution without a certain method to suppress. As a result, angle measuring accuracy is greatly reduced.

3.2 Improved virtual baseline solution for resolving ambiguity

Although virtual baseline method can achieve ambiguity resolution through the virtual short baseline, its angle measurement strictly depends on measurement accuracy of virtual short baseline. In the actual environment, the radar with interferometer is far away from target, the phase noise is lager between the channels, the phase difference of virtual short baseline is not stable, it will expand measure error, and it can't keep all incident angle in the range of interferometer direction finding can be solve ambiguity. Such interference leads the data contains a lot of values which deviating from the target, in engineering, these values are often called as outliers, and they have a great influence on subsequent positioning, like large locating error and even can't locate. According to Cui's research [15] about error analysis of interferometer measuring, the baseline interferometer measurement error $\Delta\varphi'$ will be amplified with $d_{13}/\left|d_{23\text{-}12}\right|$ times by successive calculation for virtual baseline method. For this reason, the better way to remove noise for virtual baseline method is to reduce it in the virtual short baseline measurement. And Han and Wei [16]-[19] put forward a way to eliminate the outliers based on limited memory, which has simple algorithm and good effect. And this paper adapts the method to eliminate outliers of virtual short baseline phase, so as to achieve the purpose of improve the effect of solving ambiguity. And the process is as follows.

Arithmetic:

Step1: First, 100 consecutive measurements of virtual short baseline phase are collected, the top fifty values and the after fifty values are sorted by size respectively.

$$\begin{cases} sort(\varphi_1,\varphi_2,\varphi_3\cdots\varphi_{50})=\varphi_{1s},\varphi_{2s},\varphi_{3s}\cdots\varphi_{50s} \\ sort(\varphi_{51},\varphi_{52},\varphi_{53}\cdots\varphi_{100})=\varphi_{51s},\varphi_{52s},\varphi_{53s}\cdots\varphi_{100s} \end{cases} \quad (11)$$

In the above formula, $\varphi_{1s},\varphi_{2s},\varphi_{3s}\cdots\varphi_{100s}$ means the measured values of the phase difference after sorting, ε is a preset threshold from practical experience. If the following conditions is satisfied

$$\left|(\varphi_{25s}+\varphi_{26s})/2\text{-}(\varphi_{75s}+\varphi_{76s})/2\right| \le \varepsilon \quad (12)$$

The preset value for reference is $\varphi_{ref}=(\varphi_{75s}+\varphi_{76s})/2$, If $\left|(\varphi_{25s}+\varphi_{26s})/2\text{-}(\varphi_{75s}+\varphi_{76s})/2\right|>\varepsilon$, there are outliers in $\varphi_{25s},\varphi_{26s},\varphi_{75s},\varphi_{76s}$, the preset data of reference needs to rethink, and continue to slide the storage unit, until find the initial value which meet the conditions.

Step2: Slid the storage unit and store 100 value of initial phase measurement, and then take an average of the 100 points.

$$\varphi_{ref}=\frac{1}{N}\sum_{k=1}^{100}\varphi \quad (13)$$

Compare the current defuzzified value of the interferometer measurement with the previous threshold. If the value is less than or equal to the threshold (the threshold value for the maximum error of two adjacent phase difference), while it needs to maintain the current measurements. Else, the threshold method is used to replace the current measured value.

: We can get the short baseline phase difference value with outliers eliminating, and the phase difference of high precision is derived by successive operation. Finally, the angle of incidence can be determined according to the formula (2).

4. Simulation Experiment

In order to verify the validity of the algorithm, we have experiments in the following simulation environment: set the range of simulation angle as $[-65^\circ,65^\circ]$, angular velocity is $5^\circ/s$, phase noise standard deviation between channel is 15°, noise and signal statistical are independent, 1 ms for an operation, sampling points N takes 100. So, the charts which compare the phase difference error of before and after improved virtual baseline are as follows.

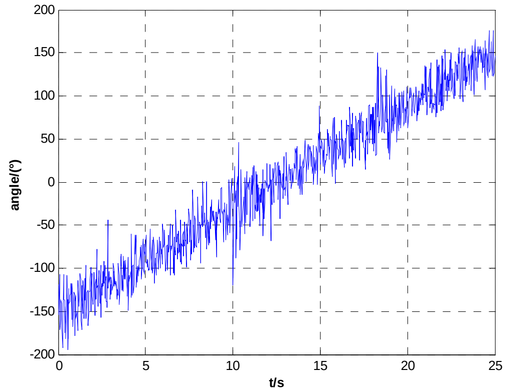

Figure 5. The original virtual baseline phase difference

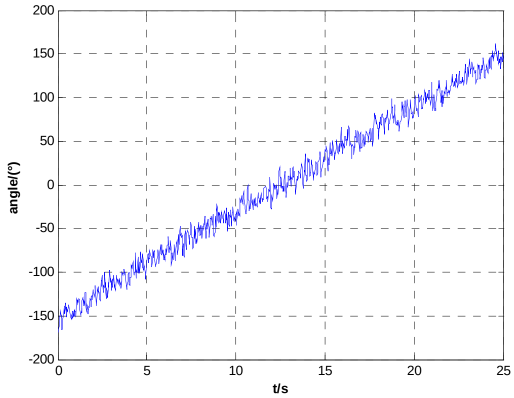

Figure 6. The improved virtual baseline phase difference

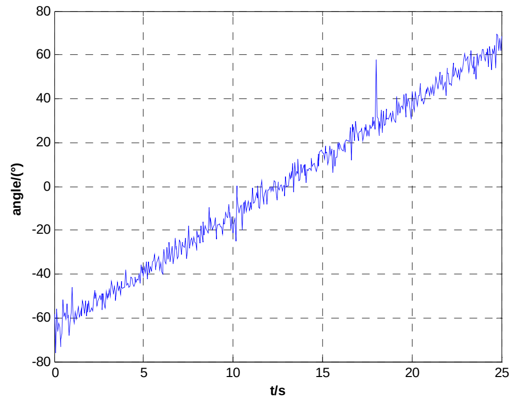

Figure 7. The original virtual baseline angle measurements

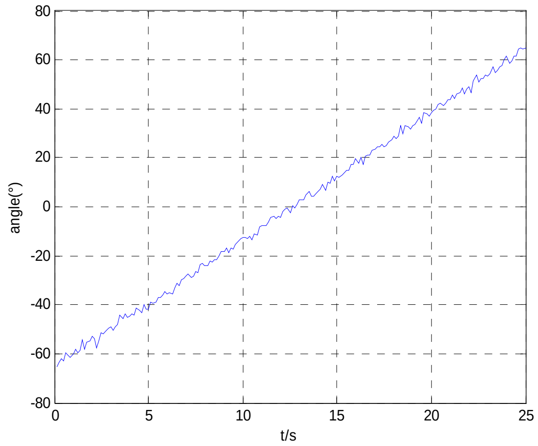

Figure 8. The improved virtual baseline angle measurements

In Figure 5, there are a large number of outliers caused by interference, in which abnormal value even more than 60°, and use this improved way to eliminate outliers and correct error, the results as shown in Figure 6. After processing, the error range of the measured value is greatly narrowed, outliers are completely eliminated and the measured value changes with in a small range. Figure 7 and 8 are the measured value of the angle before and after improvement respectively, it can be seen that improved method completely eliminates outliers of the isolated type existing in the measuring data. Due to the limited memory error correction mode, to some continuous abnormal values, when the wrong time is more than a certain length, this way will be fail to correct error, but increasing memory length will affect the real-time performance of the algorithm, so it need to choose the suitable length according to the application specific environment.

In order to further verify the effect of the algorithm, 1000 Monte Carlo independent tests have been done to contrast the unimproved de-fuzzy effect to the improved result. Figure 9 shows the standard phase error curve with the change of phase noise.

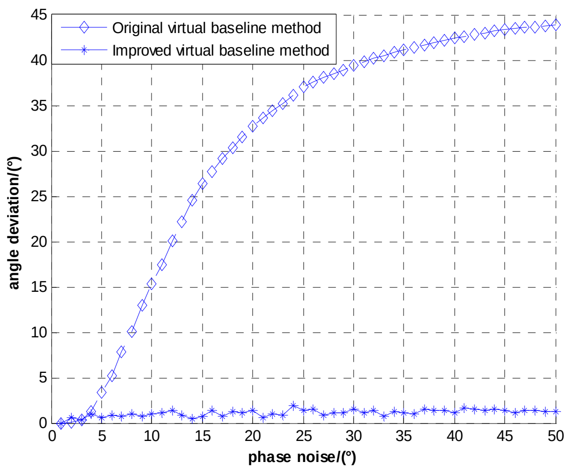

Figure 9. The angular deviation Figure of improved algorithm

According to Figure 9, with the increase of channel noise error , angle measurement error of original virtual baseline solution increases quickly, when the phase error increases to

20°, the standard deviation of measurement value is more than 30°. After dealing with the outlier elimination, angle error is greatly reduced. When the channel phase noise error of up to 50°, the improved measuring angular deviation remained under 5°. Compared with the traditional virtual baseline solution, the improved algorithm significantly improves the data quality of angle measurement, and this is extraordinarily useful for subsequent further processing.

5. Conclusions

In this paper, a new ambiguity resolution based on virtual baseline interferometer is proposed , the algorithm adopts the outliers eliminating to reduce the random error, and it improves the effect of solving ambiguity for the virtual baseline solution. Experimental results prove that this method is effective to improve angle measuring accuracy and can provide the follow-up positioning processing with high-precision measurement parameters. From the engineering point of view, this method has simple equipment, not strictly limited installing, and it can effectively deal with the contradiction of the direction finding accuracy and phase fuzzy. So, this method is of great reference value to practical engineering. And because of the delay of data storage and processing, the real-time performance of the algorithm will be influenced to a certain degree, this request that selecting storage cycle should be considered under in real-time performance and improving effect. With the hardware development of the digital processing technology, this problem will be solved completely in the future.

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