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An Investigation Study on the Ambiguity for the Circular Array Direction Finding System

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Abstract
In the circular array interferometer direction finding, azimuth ambiguity appears when the baseline is 0.5λ or more, and an antenna is added to eliminate the ambiguity. This paper describes a circular array antenna structure of the interferometer direction finding system for an unmanned aerial vehicle. In this study, we analyze the phase difference pattern of the antenna set of the circular array interferometer and propose the PDPC(phase difference pattern comparison) method to remove azimuth ambiguity by comparing the phase difference pattern. To eliminate the ambiguity of the direction finding, the boundary value of the phase difference in which ambiguity appears should be calculated. This method is consistent with the simulation results when the baseline is less than 1.3λ, and this makes the device small and inexpensive. Future work will be to enhance the reception accuracy of the telecommunication system by improving the direction finding accuracy.

Keywords: *Phase Comparison, Direction Finding, Circular Array, Ambiguity, Phase Difference Pattern Comparison(PDPC)*

Mathematics Subject Classification: 39A10, 39A21.

1. Introduction

In the modern telecommunication society, there has always been a growing need for a better way to accurately identify locations in order to prevent disasters such as forest fires and also for more efficient emergency rescues. The direction finding method of the radio frequency signal source using the IoT technology in emergency situations is divided to the active direction detecting method which sends and receives signals like a radar system and also a passive direction detecting method which finds the direction by only receiving the signal. Passive direction finding methods include amplitude comparison, phase comparison, frequency comparison and time comparison [1], [2].

The phase comparison direction finding method is used to detect the direction of the signal source in wide band frequencies and is used due to its high accuracy. The phase comparison direction detector consists of two antennas and a receiver, phase comparator and direction finding signal processor as shown in figure 1.

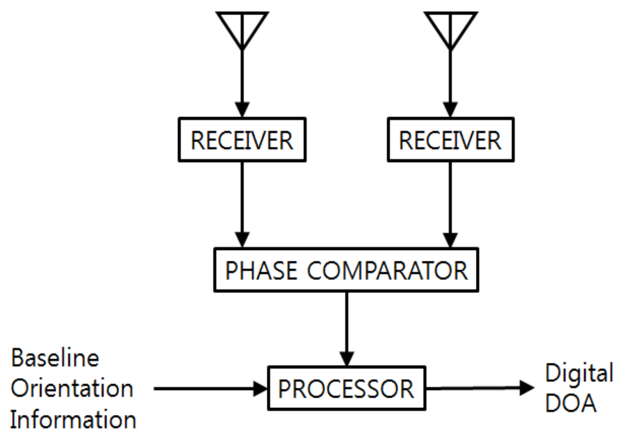

Figure 1. Configuration Diagram of interferometer Direction Finder

When a signal is propagated from an unmanned emitter, the phase of the signal received by the two antennas changes according to the direction of the emitter, and the direction of the emitter can be determined using this phase difference. The phase difference is calculated by the phase comparator with the signals received at the two antennas and then sent to the processor where the Direction of Arrival (DOA) of the signal is computed [3-5].

The interferometer triangle in figure 2 is used to calculate the direction angle of the signal using the relative phase difference between the two antennas in the phase comparison direction finding method. The baseline (or reference line) is a straight line connecting the centers of two antennas. When the length of the baseline line is L, the wavelength of the signal is λ and the incidence angles of the signal is ψ, as the phase difference measured by the two antennas ϕ can be obtained as shown in equation (1) [4]. Also by using the phase difference, the incidence azimuth angle can be derived as shown in equation (2).

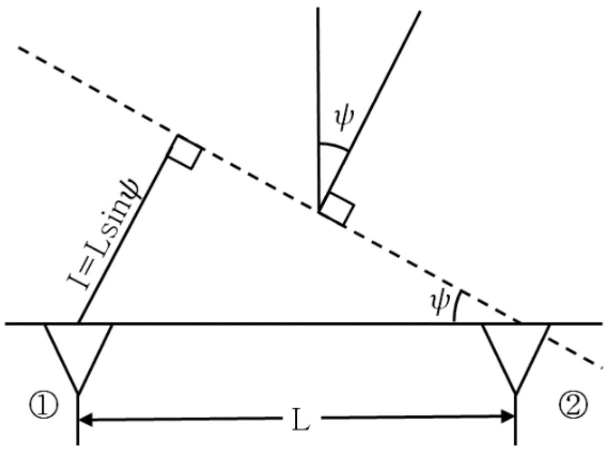

Figure 2. Interferometer Triangle

$$\phi = \frac{2\pi L}{\lambda}\sin(\psi) \quad (1)$$

$$\psi = sin^{-1}\left(\frac{\phi\lambda}{2\pi L}\right) \quad (2)$$

Phase comparison direction finding is advantageous in that the direction finding accuracy increases when the baseline is longer. However, when the baseline is more than half wavelength (λ/2) of the signal, multiple DOAs are calculated for the same phase difference causing a DOA ambiguity. Generally, when the length of the baseline is 0.5λ or more, the baseline is added to the position of 0.5λ to solve the ambiguity. In this case, the number of antennas is increased and the structure becomes complicated and the price increases as well. The antennas for direction finding mainly are placed by the linear array and circular array. In this study, we develop the PDPC(phase difference pattern comparison) method to eliminate the ambiguity by comparing the phase difference pattern of the array antennas when the antenna baseline is 0.5λ or more.

2. An ambigity estimation of a linear array antenna for direction finder

Figure 3 is a linear array direction detector using multiple baselines designed to increase directional finding accuracy and eliminate ambiguity. The length of L_1 is 0.5λ or less to eliminate the ambiguity. When L_n is 0.5λ or more, although ambiguity occurs, the direction finding accuracy becomes high as well. By using the results of L_1 and L_n both together, it is possible to design an accurate direction finder with low ambiguity. However, due to various antennas and receiving channels it is found to be inefficient [5,6].

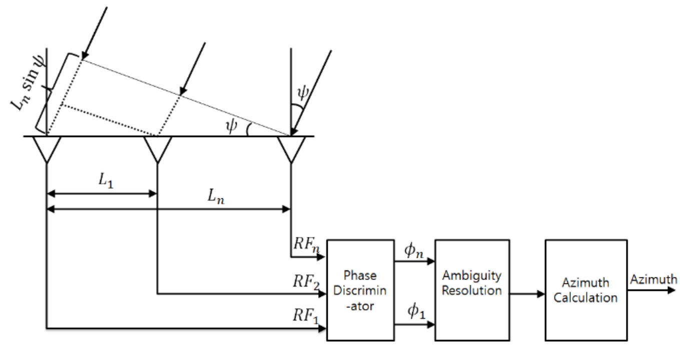

Figure 3. Phase comparison direction finder with multiple baselines

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3. An ambiguity investigation of a circular array antenna for direction finding

3.1 Uniform circular array with five antennas

Figure 4 shows a telecommunication system using a uniform circular array (UCA) with five antennas arranged at regular intervals to measure the direction angles of the incoming emitter signals in the 0-360°. The baseline of antennas 1 and 2 is denoted as #1 antenna set, and the vertical direction of #1 antenna set is denoted by azimuth angle 0°, ($\psi = 0^o$). By designating the #2, #3, #4, and #5 antenna sets for the baseline for antennas 2 and 3, 3 and 4, 4 and 5, and the baseline for antennas 5 to 1, the reference angles of the antenna set are 72°, 144°, 216°, and 288°.

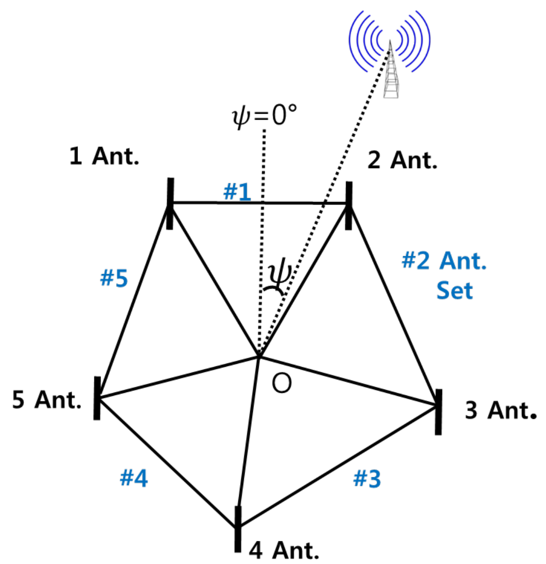

Figure 4. Five - antenna UCA and azimuth angle

Table 1. Reference angles of the antenna set numbers in figure 4

Number of antenna set	#1	#2	#3	#4	#5
Reference angles (degree)	0	72	144	216	288

In figure 4, if the radius of the circle is R, the antenna baseline is L, and the antenna number is k, the phase difference $\phi_{k,k+1}$ between the kth antenna and the k+1th antenna in the azimuth angle ψ can be obtained as equation (3). The relative azimuth angle ψ_{cal} is obtained as equation (4) by using the phase difference $\phi_{k,k+1}$in the #k antenna set [5] [7].

$$\phi_{k,k+1} = \frac{2\pi L}{\lambda} sin\left(\psi + \frac{(k-1)2\pi}{5}\right) \quad (3)$$

Where k is the array antenna number and k = 1, 2, 3, 4, 5.

$$\psi_{cal} = sin^{-1}\left(\frac{\phi_{k,k+1}\lambda}{2\pi L}\right) \quad (4)$$

In the UCA structure shown in figure 4, the azimuth angle of the incidence signal is calculated as following. First, the minimum phase difference ϕ_{min} was found and the number of antenna sets of the five antennas.

$$\phi_{min} = min\{|\phi_{1,2}|, |\phi_{2,3}|, |\phi_{3,4}|, |\phi_{4,5}|, |\phi_{5,1}|\} \quad (5)$$

Second, equation (6) was used to select the antenna set to find the relative angle, ψ_{cal}.

$$\psi_{cal} = sin^{-1}\left(\frac{\phi_{min}\lambda}{2\pi L}\right) \quad (6)$$

Third, the number of antenna sets to obtain the reference angle ψ_{BK} in table 1 was used. The fourth azimuth angle is the sum of the reference angle and the relative angle of the antenna set as shown in equation (7).

$$\psi = \psi_{BK} + \psi_{cal}, \; k = 1,2,\cdots,5 \quad (7)$$

In this case, when the antenna baseline becomes 0.5λ or more, and ψ_{cal} is calculated with ambiguity, ambiguity should be removed by using various methods.

3.2 An ambiguity calculation with amplitude and phase comparison combined method

In the circular antenna array shown in figure 4, ambiguity occurs if the baseline of the adjacent antenna is 0.5λ or more. In this case, additional antennas are needed or the amplitude-phase combination method is used to eliminate the ambiguity [8]. As shown in figure 4, the amplitude-phase complex comparison scheme divides the signals received from the same antenna set into two channels. One channel eliminates ambiguity by comparing amplitude and the other channel measures the correct direction angle by comparing phases. The DOA is then determined by combining the signals of the two channels. In the array antenna, the amplitude comparison method has the advantages of causing no ambiguity but accompanies low accuracy. On the other hand, the phase comparison method has a higher accuracy when the baseline is longer and when the phase difference between the antennas are lower.

3.3 Ambiguity calculation with the comparison of phase difference patterns

In figure 5, the #1 antenna set phase difference(phase difference between antenna #1 and #2) is defined as $\phi_{1,2}$, #2 antenna set phase difference is $\phi_{2,3}$, #3 antenna set phase difference is $\phi_{3,4}$, #5 antenna set phase difference $\phi_{5,1}$, and the regularity of the phase difference pattern of each antenna set d when the baseline is 0.5λ or over analyzed. The newly proposed PDPC method can be used to find the antenna set having the minimum phase difference and calculate the DOA with equation (4) and (7). If there are ambiguous DOA's with the same phase difference, the new method determines the correct DOA by comparing phase difference patterns of the other four antenna sets. Figure 6 shows the phase difference of #1 antenna set with L/λ is 0.5 through #5 when the emitter signal is transmitted from 0-360° azimuth. 11 regions are divided into according to azimuth angle in which the antenna sets having the smallest absolute phase difference are crossed. Generally the accuracy of the direction finding is high when the phase difference of the antenna set is small. The minimum and maximum azimuth angles of 11 regions are shown in table 2, and the order of five antenna sets in which the phase difference is larger are shown from upper line in table 3, and the number of underlined antenna set has the smallest absolute phase difference.

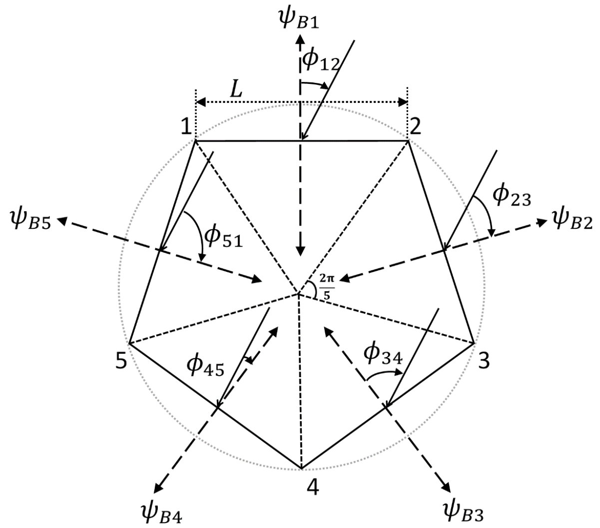

Figure 5. Five–antenna UCA and phase differences

It could be described the proposed PDPC method in figure 6 as following example. If phase difference is 0.97radian, the DOA is calculated with 18° and 162° with equation (4) and an ambiguity arise. However, by using PDPC in table 3, it is fixed to 18° if the phase difference is decreased in the order to 5-4-1-3-2 or 162° if the phase difference decreases to 2-3-1-4-5.

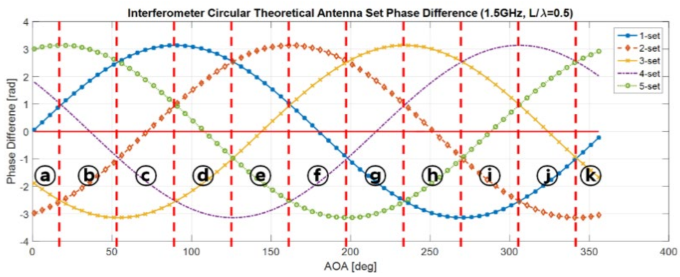

Figure 6. Phase difference patterns of the five antenna sets with L=0.5λ

Table 2. Azimuth angle (AOA) of the partition in figure 6

partition	□	□	□	□	□	□	□	□	□	□	□
Azimuth (min. deg.)	0	18	54	90	126	162	198	234	270	306	342
Azimuth (max. deg)	18	54	90	126	162	198	234	270	306	342	360

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Table 3. Number of antenna set for partition shown in figure 6

Partition	ⓐ	ⓑ	ⓒ	ⓓ	ⓔ	ⓕ	ⓖ	ⓗ	ⓘ	ⓙ	ⓚ
Number of Antenna Set	⑤	⑤	①	①	②	②	③	③	④	④	⑤
	④	①	⑤	②	①	③	②	④	③	⑤	④
	①	④	②	⑤	③	①	④	②	⑤	③	①
	③	②	④	③	⑤	④	①	⑤	②	①	③
	②	③	③	④	④	⑤	⑤	①	①	②	②

Figure 7 shows the phase difference of the five antenna sets when the wave is incident at 0-360º in the case when L/λ is 1.3. Table 4 shows the order in which the phase difference decreases in the regions.

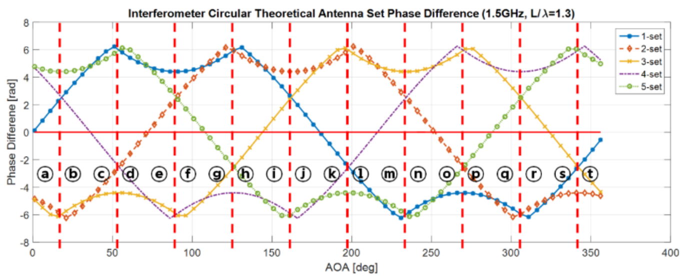

Figure 7. Phase difference patterns of the five antenna sets with L=1.3λ

Table 4. Number of antenna set for the partition shown in figure 7

Partition	ⓐ	ⓑ	ⓒ	ⓓ	ⓔ	ⓕ	ⓖ	ⓗ	ⓘ	ⓙ	ⓚ	ⓛ	ⓜ	ⓝ	ⓞ	ⓟ	ⓠ	ⓡ	ⓢ	ⓣ
Number of Antenna Set	⑤	⑤	①	⑤	①	①	②	①	②	②	③	③	②	③	④	③	④	④	⑤	④
	④	①	⑤	①	⑤	②	①	②	①	③	②	②	③	④	③	④	③	⑤	④	⑤
	①	④	④	②	②	⑤	⑤	③	③	①	①	④	④	②	②	⑤	⑤	③	③	①
	②	③	②	④	③	④	③	⑤	④	⑤	④	①	⑤	⑤	①	②	①	②	①	③
	③	②	③	③	④	③	④	④	⑤	④	⑤	⑤	①	①	⑤	①	②	①	②	②

3.4 Calculation of the cross-points and the index numbers

In the previous section, it is confirmed that the phase difference pattern changes are evident in L/λ=1.3. The following is derived a formula to find the correct cross-point. Phase difference of the kth antenna set, $\phi_{k,k+1}$, and (k+1)th antenna set, $\phi_{k+1,k+2}$, are given as follows.

$$\phi_{k,k+1} = \frac{2\pi L}{\lambda} sin\left(\psi_C + \frac{2\pi(k-1)}{\#ant}\right) \qquad (8)$$

$$\phi_{k+1,k+2} = \frac{2\pi L}{\lambda} sin\left(\psi_C + \frac{2\pi(k)}{\#ant}\right) \qquad (9)$$

To eliminate the ambiguity of the direction finding, the boundary value of the phase difference in which ambiguity appears should be calculated. In order to calculate the boundary value, it is evidently needed to find the azimuth angle that the phase difference coincides with the adjacent antenna set satisfying the following condition.

$$\mathrm{A} = \phi_{k,k+1} = \phi_{k+1,k+2}\ , 0 \le \psi_C \le 2\pi \qquad (10)$$

And assuming k=1, $\frac{2\pi}{\#ant} = 2\alpha$, then $\phi_{k,k+1} = \phi_{k+1,k+2}$ can be calculated

$$\frac{2\pi L}{\lambda} sin\left(\psi_C + \frac{2\pi(2-1)}{\#ant}\right) = \frac{2\pi L}{\lambda} sin\left(\psi_C + \frac{2\pi(1)}{\#ant}\right) \qquad (11)$$

$$\frac{2\pi L}{\lambda} \sin(\psi_C) = \frac{2\pi L}{\lambda} sin(\psi_C + 2\alpha) \qquad (12)$$

$$\sin(\psi_C) = sin(\psi_C + 2\alpha) \qquad (13)$$

By simplifying Eq. (13) as follows

$$\sin(\psi_C) = \sin(\psi_C)\cos(2\alpha) + \cos(\psi_C)\sin(2\alpha) \qquad (14)$$

Since $2\alpha = \frac{2\pi}{\#ant}$, ψ_C can be expressed

$$\psi_C = tan^{-1}cot\left(\frac{\pi}{\#ant}\right) \qquad (15)$$

If k=1, #ant=5, ψ_C is given

$$\psi_C = tan^{-1}cot\left(\frac{\pi}{5}\right) = 0.9425 \qquad (16)$$

$\phi_1 = \frac{2\pi L}{\lambda}\sin(\psi_C)$ and $\phi_2 = \frac{2\pi L}{\lambda}\sin\left(\psi_C + \frac{2\pi}{5}\right)$ are equal in $\psi_C = 0.9425(54^o)$.

When there are 5 antennas and the baseline is 1.3 λ, the histogram of the phase difference of fig. 7 is given in figure 8. The coded Index pattern is expressed with 5 digit number and made by the order of antenna sets at participations in table 4.

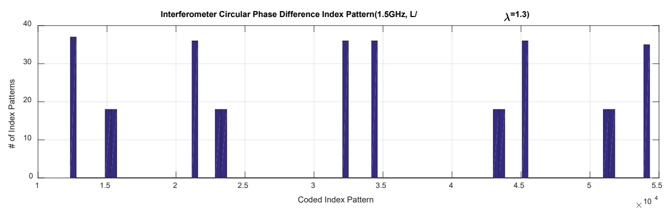

Figure 8. Histogram of coded index pattern with 5 antennas, frequency = 1.5GHz, L=1.3λ

4. Conclusions

This paper describes on the ambiguity calculation method of the circular array interferometer direction finding for an unmanned telecommunication system. In the circular array interferometer direction finding method, ambiguity occurs when L is longer than 0.5λ, and another antenna is added at L=0.5λ or the amplitude-phase composite direction finding method is used together to eliminate the ambiguity. In this study, the phase difference pattern of the antenna set of the circular array interferometer direction finding is analyzed and the ambiguity is disappeared by using PDPC when L is shorter than 1.3λ. These results contribute in making the design of the direction finding system small and inexpensive. This work will give an instinct idea for undergraduate or postgraduate studies in terms of the array antenna theory of circular geometry. The PDPC method suggested here can be the keystone of the phased array antenna theory and it helps understanding the ambiguity by comparing the phase difference pattern of the array antennas having relatively long baseline, 0.5λ or more. Our future work will be to enhance the reception accuracy of the telecommunication system by improving the direction finding accuracy

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