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An Efficient Solution of Phase Interferometry Ambiguity using Zero-Crossing Technique

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ABSTRACT- Direction finding systems applying phase interferometer of long baseline gives high accuracy of the angle of arrival measurements; however, they are suffering from phase ambiguity and phase error due to antenna spacing greater than half wavelength of the intercepted signals. In this paper, the simple two-antenna interferometer system has been adopted with the zero-crossing technique used to solve the phase measurement ambiguities in the processing unit. The zeros-crossing of both channels (lead and lag) were extracted using electronic circuitry. A count gate was formed to count the zeros throughout the phase difference between the two channels. The ambiguity factor was taken to be half of the even count which will be added to the output of the phase comparator to estimate the total phase difference. Multisim software has been used to simulate the proposed processing unit and the ambiguity was calculated for different values of phase difference. Antenna spaces (D/λ) of (1/2, 1, 2, 4, 8, 12, 14, and 16) were applied to the system and the corresponding ambiguity factors have been measured to be (zero, 1, 2, 4, 8, 12, 14 and 16) respectively. Therefore for antenna spaces ($D \leq \lambda/2$) there is no ambiguity. These simulated results show a coincidence with the theoretical values. The lead-lag channels were also solved without the need to add other antennas to the system since the first zero detected by either antenna refers to the lead channel. The proposed technique has advantages over others since it solves ambiguities on the basis of real-time processing without the need for complex, expensive, heavy, and slower response systems.

General Terms: Direction Finding System, interferometer, Airborne Targeting.
Keywords: Direction-finding, Phase interferometer, zero- crossing, Phase ambiguity, Phase error.

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1. INTRODUCTION

Direction finding (DF) systems can be classified mainly into three types: amplitude comparison, time difference of arrival (TDOA), and phase comparison (interferometer) [1-3]. The third technique can be considered the most effective and accurate. This accuracy is gained from the wide antenna spacing. However, they are suffered from the ambiguities that occur for spacing longer than half wavelength of the intercepted signal, since the phase comparator can measure phase difference in the range of (-π, + π) [4]. Therefore, for antenna-spacing more than half-wavelength of the intercept signals (λ/2) a phase measurement ambiguity will occur. Most of the previous work done to solve this ambiguity was concentrated on the antenna system, which made them expensive, complex, and heavyweight.

In 2004, Steven E. Lip sky suggested (in his book) using a linear or circular array of the antenna to solve ambiguity for mono-pulse interferometer angle-of-arrival AOA [4]. A novel hybrid multi-mode interferometer system was suggested [5]. The system needed only three antennas for phase measurement ambiguity solving. However, phase and amplitude were considered to estimate the AOA.

A rotary interferometer DF technique was introduced by Y. Li [6]. The system achieved a high successive rate but further processing was needed which affect the system response time. In 2013, Z. Wei introduced an ambiguity-resolved correction algorithm for phase interferometer based on Kalman prediction [7]. In 2015, DF ambiguity was solved by Sang Van Doan [8]; the system used three and four antennas as well as using rotation and rounding for unambiguous phase difference measurement. These operations are time consumed, which affects the system response time.

In 2017, Le Zuo and Jin Pan proposed 2-D AOA estimation and ambiguity resolution for a single source under fixed uniform circular arrays [9]. Many antennas have been used as well as discrete Fourier transform (DFT) with a large number of trials carried out which affected the system speed.

In this paper, the ambiguities of the simple two-antenna DF systems will be solved in the processing unit using the zero-crossing technique. Zero crossing detection is the most common method for measuring the frequency or period of a periodic signal. Detection and processing can be carried out either in analog or digital forms. Most analog detection and processing systems suffer from slow measurement rates, as well as, the noise effect caused by low voltage signal levels

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(low S/N ratio). On the other hand, digital systems have high voltage levels (0, +5V) which lead to high noise immunity [10-12]. Therefore, the work will be concentrated on the conversion of analog signals into digital form, and detection and processing will be all digitals.

Electronic circuitry has been designed to extract the zeros-crossing of both leading and lagging channels. Having done that, the extracted zeros are counted during a count gate which is enabled by the extracted first zero of the leading channel and disabled by the first zero of the lagging one. This procedure is carried out on the basis of real-time pulse-by-pulse processing to solve phase measurement ambiguities for any antenna spacing to achieve unambiguous and accurate AOA measurements. The proposed system will be simulated using *Multisim 14* software package.

2. PROPOSED TWO-ANTENNA PHASE INTERFEROMETER DF SYSTEM USING A ZERO-CROSSING DETECTOR

Considering the single baseline two-antenna interferometer DF system shown in *figure 1* used for angle of arrival (AOA) estimation of intercepted signals in the first quadrant (0-90°). Let the input signal received by both antennas create an angle θ measured from the horizon. Then, the value of θ can be estimated in relation to the output of the phase comparator Δφ, antennas spacing D, and intercepted signal wavelength λ.

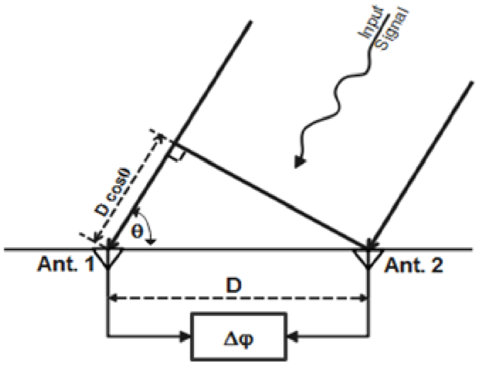

Figure 1: Two-antenna Phase interferometer DF system

The phase compactor measure phase difference (Δφ) in the range of (-π to+π) for AOA in range of (-90°, +90°), but the real phase difference ΔØ is shown as in *eq. (1)*:

$$\Delta\O = (\Delta\varphi/2\pi) + k = (D/\lambda)\cos\theta \qquad (1)$$

Where (k) is any positive integer that is the solution number corresponding to higher frequencies. This will lead to ambiguous measurements since the k solution cannot be estimated. *Figure 2* shows a plot of phase difference ((Δφ/2π) + k) as a function of AOA (θ) measured from the horizon using different values of (D/λ) for a single baseline two-antenna interferometer system. The unique value of phase difference ΔØ is obtained when antenna spacing D is less than (λ /2) of the received signal.

It can be seen from *figure 2* that the ambiguity occurs when the bandwidth is increased to the higher frequencies such that ($\Delta\O \geq 2\pi$) and a greater number of k solutions will result see *table 1*. So, it is impossible to know which k is correct. The other problem is which antenna is the lead and which one is the lag if the system is designed to cover the first and second quadrants θ = (0 - 180°).

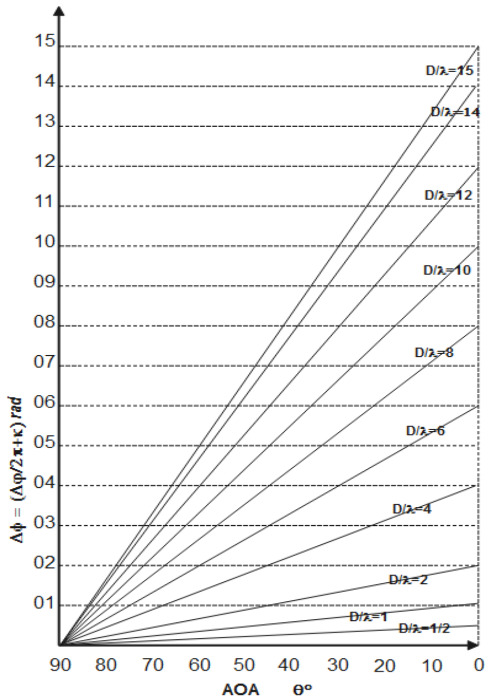

Figure 2: Phase difference (Δφ/2π) + k) as a function of AOA (θ) using different values of (D/λ)

Table 1: The corresponding ambiguities (k) for different values of (D/λ)

(D/λ)	Ambiguity number k
1/2	0
1	1
2	2
4	4
6	6
8	8
10	10
12	12
14	14
15	15

In practical applications of microwave transmission, it is difficult to manufacture two antennas spaced in a very short distance. The other reason is the error σθ occurs due to the short spacing distance D. which would affect the angle of arrival estimation as in *eq. (2).*

$$\sigma\theta = \sigma\Delta\varphi\,(\lambda/\,(2\,\pi\,D\,\mathrm{Cos}\theta)) \qquad (2)$$

To show the advantages of using higher antenna spacing for the two-antenna interferometer system the articulations (rate of change of angle of phase to the angle of arrival) are considered. Referring to *figure 2* from the slope of the line (D/λ = 1/2) the articulation is:

$$(0.5/90^{\circ}) \times (180^{\circ}/\pi \text{ rad}) = 0.32 \text{ degree/degree.}$$

For D/λ = 4, the slope for this case is:

$$(4/90^{\circ}) \times (180^{\circ}/\pi \text{ rad}) = 2.55 \text{ degree/degree.}$$

Therefore, the articulation ratio of the D/λ = 4 to D/λ = 1/2 is (2.55/0.32) = 8, which is eight times better than D = 1/2(4/0.5); therefore, it can be conclude that the interferometer DF technique can achieve very high resolution by choosing large (D/λ) at the expense of solving ambiguity problem. *Table 2* shows different values of (D/λ) with the corresponding articulations and ambiguities values.

Table 2: Antenna spacing with the corresponding articulations and ambiguities

Antenna spacing (D/λ)	Articulation ratio	Ambiguities (k)
D/λ = 1/2	0.32	zero
D/λ = 1	0.64	One
D/λ = 2	1.27	two
D/λ = 4	2.55	four
D/λ = 8	5.09	eight
D/λ = 10	6.37	ten
D/λ = 12	7.64	twelve
D/λ = 14	8.91	fourteen
D/λ = 16	10.1	sixteen

Therefore, to employ the benefit of a long-baseline without ambiguities the zero-crossing technique will be proposed. Zero-crossing detection digital circuit has been simulated using Multisim-14 and added to the two-antenna DF system as shown in *figure 3*.

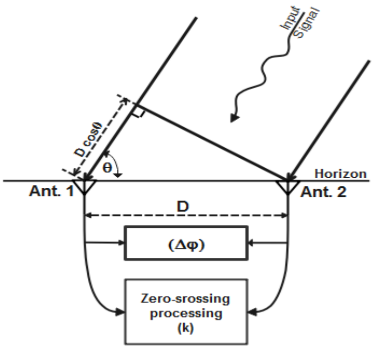

Figure 3: Proposed two-antenna phase interferometer system with a zero-crossing detector

The main operation of the system is that the radio frequency (RF) of the intercepted signals by both antennas are down-converted and applied simultaneously to the phase detector and zero-crossing circuit. Then, the zeros-crossing of both channels (lead and lag) are extracted (two zeros per cycle) and counted during a count gate. The count gate is enabled by the first zero of the lead channel and disabled by the first zero of the lag channel. The ambiguity factor k which is taken to be half of the even count is added to the output of the phase comparator Δφ to estimate the total phase difference ΔØ. The digital zero-crossings detecting circuit has been simulated using multisim.14 and tested for a simulated input signal of 20 MHz (T=50ns) applied to the lead channel with the corresponding delayed signal applied to the lag channel. The extracted zeros of both channels with the count gate and counted zeros are shown in *figure 4*.

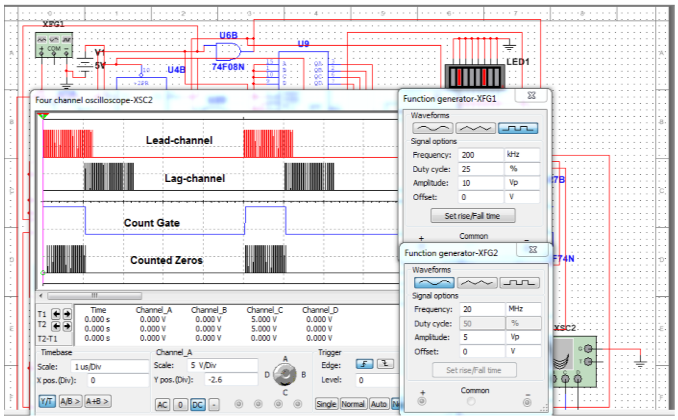

Figure 4: Simulated zero-crossing detector signals.

3. RESULTS AND DISCUSSION

In *figure 5* the 20MHz simulated input signal was applied to the lead channel. The same signal is delayed by 25ns (λ/2) and input to the lag channel. Since there are two zeros per cycle and the input signal period time (T = 50ns) is twice the delay time, therefore, one zero is detected during the count gate. In this case, k=0 and there is no ambiguity. The unambiguous phase difference measured ΔØ is the output of the phase comparator.

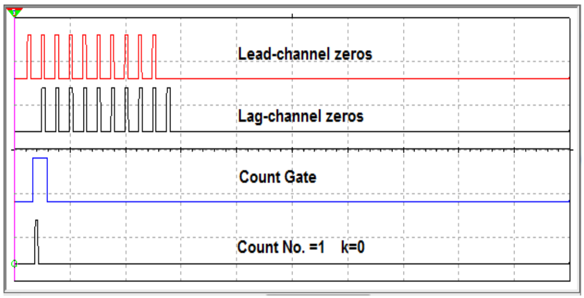

Figure 5: 25 ns delay with one zero-crossing counted and k=0

In *figure 6* the delay was (50ns = λ) which is equal to the input signal period (T =50ns). Therefore, two zeros were detected during the count gate and the ambiguity number (k=1) with 2π rad is added to the output of the phase comparator.

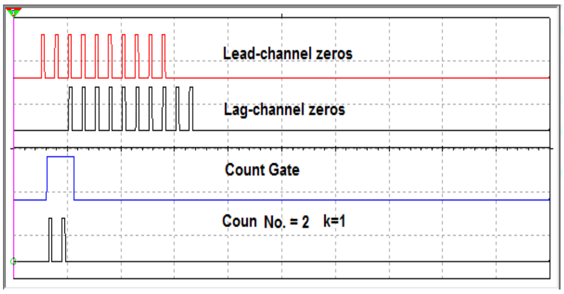

Figure 6: 50ns delay with two zero-crossing counts and k=1

Figure 7 and *figure 8* show a delay of (75ns = 4λ/3) and (100ns = 2λ) with three and four zeros counted respectively and corresponding ambiguity factors are k=1 and k=2 (k=even count /2).

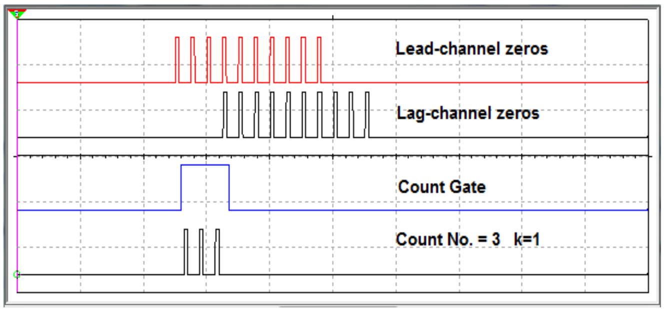

Figure 7: 75 ns delay with three zero-crossing counts and k=1

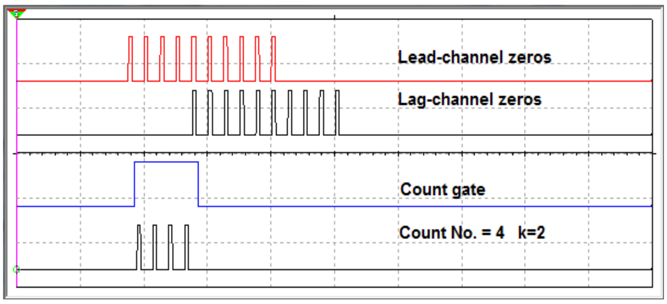

Figure 8: 100 ns delay with four zero-crossing counts and k=2

The delays in *figure 9*, and *figure 10* were (500ns=10λ), and (525ns=21λ/2), with the corresponding k numbers are (10, 10,) respectively.

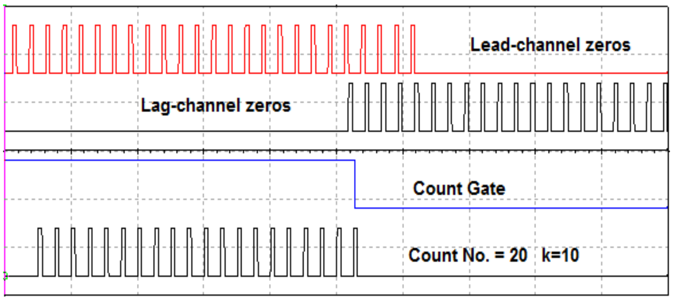

Figure 9: 500 ns delay with twenty zero-crossing counts and k=10

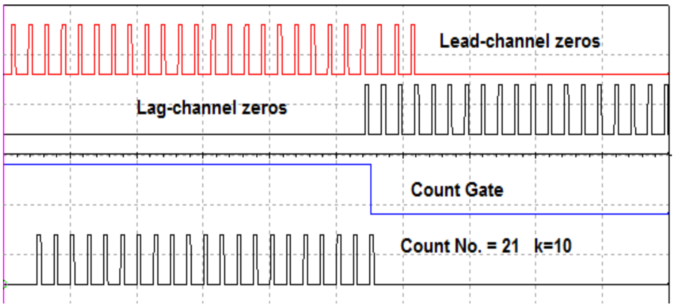

Figure 10: 525 ns delay with twenty-one zero-crossing counts and k=10

Table 3 shows the delay times of the simulated input signal which are applied to the lag-channel with the corresponding wavelength, counted zeros during the count gate, and the ambiguity factor.

Table 3: Applied delays and the corresponding wave-length, count zeros, and K values

Delay (ns)	Corresponding Wavelength (λ)	Counted zeros	Ambiguity number k (Even count/2)
25	λ/2	1	0
50	λ	2	1
75	3λ/2	3	1
100	2λ	4	2
125	5λ/2	5	2
150	3λ	6	3
200	4λ	8	4
225	9λ/2	9	4
250	5λ	10	5
500	10λ	20	10
525	21λ/2	21	10

If a comparison is made between *Table 1* (theoretical values) and *Table 3* (simulated results), it can be seen that when the antenna space (D ≤ λ/2) the ambiguity factor is zero and the phase difference (ΔØ) is the output of the phase detector (Δφ). But as the antenna space increases to λ ambiguity factor changes to one and the phase difference is (λ+Δφ) and so on. Both tables showing a coincidence and the ambiguity have been solved in an optimum way.

The first advantage of this system over others is the ability to manufacture the simple two-antenna system for any antenna spacing and measuring AOA without ambiguity and minimum phase error. Whereas, other systems used multi-antenna systems (greater than two) with algorithms to solve ambiguity which deteriorates the response time of those systems.

The second advantage is the solving of lead-lag channels in the processing unit since the first zero detected by either antenna refers to the lead channel which eliminates the need for additional antenna used by previous systems.

The third advantage is the high noise immunity of the processing unit since the analog received signals will be converted into digital form. Therefore, the zero-crossing technique is an optimum way to solve phase ambiguities for the simple two-antenna DF system without the need for complex, expensive, and slow response systems.

4. CONCLUSIONS

The proposed zero-crossing detecting method is an optimum way to solve ambiguity for phase interferometer two-antenna DF systems on the basis of real-time pulse-by-pulse processing. A count gate has been used to count the zeros throughout the phase difference between the two channels. The ambiguity factor was taken to be half of the even count of zero crossings during the count gate. The antenna spacing can be expanded to any number of wavelengths of the intercepted signal. Therefore, high resolution, and less phase error of AOA measurement can be achieved. The lead and lag channels were also solved in the processing unit without the need to add other antennas. This technique keeps the system less expensive, less complicated, and lightweight (especially in airborne systems) as well as the fast response time gained from real-time processing

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