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Problem Solutions of Phase Ambiguity and Initial Phase Shifts of the Phase Radio Navigation System for Aircraft Blind Landing

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Abstract

This work is a continuation of a design of a phase radio navigation system for aircraft blind landing in case of non-equipped runways proposed in [1], where, the proposed system is based on measuring the phase shifts of signals received from four ground transmitters (antennas), placed on corners of the runway strip, which provide distance measurements accuracy in millimeters. However, there are two important points that need serious consideration. First, the phase measurement is going to give the total phase $(\rho_0 - \varphi)$, while the actual phase shift of interest is 'φ', ρ_0 is the transmitter initial phase. The second problem is that, the measured phase angle $(\rho_0 - \varphi)$ between the transmitted and the received signal can only be measured in the interval from 0 to 2π radians, this problem is called phase ambiguity. The answer of these problems lies in the use of more than one frequency (signal). Two sinusoidal signals with different frequencies (f_1 and f_2) but the same initial phase can be used. Taking the difference of the measured phases, the initial phase ρ_0 can vanish. To get around phase ambiguity would be to make sure that the actual phase difference $\Delta\varphi_{12}$ does not exceed 2π , this technique called equivalent or synthetic wavelength.

Keywords: *Phase Ambiguity; Aircraft blind landing; phase shift; Radio Navigation.*

1. Introduction

There are three main methods used to perform the distance measurement using radio signals. These are received signal strength, time of flight, and phase difference of arrival. Received signal strength is a strong function of the environment. It is the simplest range estimation method but also requires strong calibration. It is a simple but not very reliable method of distance estimation. As an alternative and more accurate way of distance estimation, time of flight measurements. This method is how GPS receivers measure the ranges to the transmitting satellites. The main problems of this scheme, it requires relatively fast processing capabilities to resolve timing differences for fine-grained measurements, this problem is amplified over short distances. The other problem with these systems is the need to have and maintain high synchronization between the transmitter and receiver, which adds an extra burden on the system cost and design. Unfortunately, the time of flight measurement is not accurate enough for the high demands of landing systems. As third approach, by sending one or two signals of different carrier frequencies, and then measuring the difference of phase shifts of the received waveforms the distances estimated. This scheme is more suitable for low power applications since the processing can be performed at reasonably low speeds. The distance estimation using signal phase measurements occasionally has been used in the past. One of the most famous is the worldwide international radio navigation system Omega. In [1], a new radio navigation system for aircraft blind landing for non-equipped runways and squares was proposed.Fig.1, shows the system coordinates of the airport runway, and coordinates of the four ground transmitters. The onboard navigation algorithm used to determine the location of the airplane with respect to the touch point on the runway using the received signals phase shifts. The onboard antenna (a_c) coordinates with respect to the runway coordinate system given as;

$$x_1 = \frac{\left(L^2 - 4N\right)}{4L} \qquad (1)$$

$$z_1 = \frac{M}{2W}$$

$$y_1 = \frac{1}{4}\sqrt{16(Ra_cA_1)^2 - \frac{(L^2-4N)^2}{L^2} - 16\left(\frac{M}{2W} - \frac{W}{2}\right)^2}$$

Where;

$N = (Ra_cA_3)^2 - (Ra_cA_1)^2$; $M = (Ra_cA_2)^2 - (Ra_cA_1)^2$

Ra_1A_1 – measured distance between onboard antenna(a_1), and ground antenna (A_1).

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Ra_1A_2 – measured distance between onboard antenna (a_1), and ground antenna (A_2).
Ra_1A_3 – measured distance between onboard antenna (a_1), and ground antenna (A_3) [1].

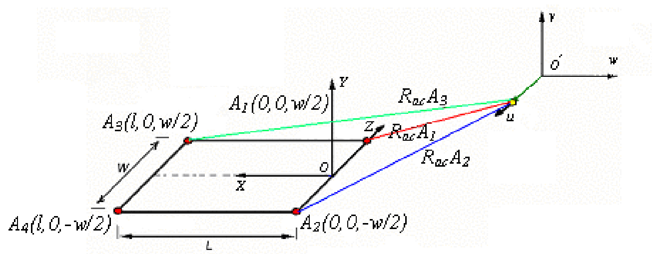

Fig. 1 Runway system coordinates and onboard antenna system coordinates

2. Distance Measurement Using Signal Phase Shifts

In the case of a single frequency sinusoidal signal, the transmitted signal has a phase shift at the receiving end. The amount of the phase shift due to the distance travelled can be determined using the fact that the received signal is a delayed version of the transmitted as shown in fig.2. Hence, the received signal $r(t)$ is written as:

$$r(t) = \sin[2\pi f(t - t_d) + \rho_0] = \sin[2\pi ft - 2\pi ft_d + \rho_0] = \sin[2\pi ft - \varphi + \rho_0] \quad (2)$$

Where

t_d – is the time delay ($t_d = \frac{d}{v_p}$).

d – Distance between the transmitter and the receiver;

v_p – Propagation speed of the radio signal ($\approx 3*10^8$ m/s).

f – is the received signal frequency;

ρ_0 – is the initial phase of the sinusoid;

Then, the phase shift $2\pi ft_d$ can be expressed as a function of distance and speed of radio signal;

$$\varphi = \frac{2\pi f * d}{v_p};$$

$$\varphi = 2\pi \cdot \frac{d}{\lambda} = 2\pi \cdot \left[\mathrm{int}\left(\frac{d}{\lambda}\right) + \mathrm{mod}\left(\frac{d}{\lambda}\right)\right] \quad (3)$$

λ – Wavelength of the used radio signal ($\lambda = \frac{v_p}{f}$)

Where φ is defined as the phase shift from the initial phase. It is clearly seen from the phase shift relation that if the phase shift φ can be measured, the distance can be obtained.

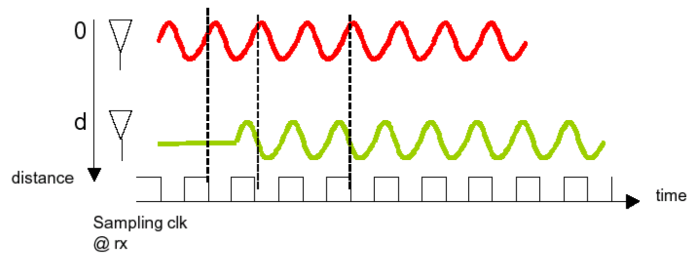

Fig. 2 Phase difference between transmitted and received signals

However, there are two important points that need serious consideration. First, the phase measurement is going to give the total phase $(\rho_0 - \varphi)$, while the actual phase shift of interest is φ. The second problem is that, the measured phase angle $(\rho_0 - \varphi)$ between the transmitted and the received signal can only be measured in the interval from 0 to 2π radians. Therefore, equation (3) reduces to:

$$\varphi = 2\pi \cdot \mathrm{mod}\left(\frac{d}{\lambda}\right)$$

$$\text{or } d = \lambda \cdot \left(n + \frac{\varphi}{2\pi}\right) \quad (4)$$

Where n is an integer.
It is clear that the distance cannot be measured unambiguously, because n cannot be determined with a simple phase measurement.

3. Resolving phase ambiguity and initial phase mismatch

Fortunately, there are ways to overcome the problems of phase ambiguity, and initial phase mismatch. The answer lies in the use of more than one frequency. Two sinusoidal signals with different frequencies (f_1 and f_2) but the same initial phase can be used. Taking the difference of the measured phases, the initial phase ρ_0 can vanish from the rest of the equations.

$$\Delta\varphi_{12} = (\rho_0 - \varphi_1) - (\rho_0 - \varphi_2) = (\varphi_2 - \varphi_1) = \frac{2\pi f_1 * d}{v_p} - \frac{2\pi f_2 * d}{v_p} = \frac{2\pi(f_1 - f_2) * d}{v_p} \quad (5)$$

Where, $\Delta\varphi_{12}$ is defined to be the difference of the measured phases.
One way to get around ambiguity would be to make sure that the actual phase difference $\Delta\varphi_{12}$ does not exceed 2π. Satisfying the following relation can ensure this:

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$2\pi\Delta f * d/v_p < 2\pi \quad ,\Delta f * d/v_p < 1 \quad ,\Delta f < v_p/d$

This technique called equivalent or synthetic wavelength [2]. Using this concept one can obtain an estimated distance, d' from

$$d' = \lambda_{eq} \cdot \left(N + \frac{\Delta\varphi}{2\pi} \right) \qquad (6)$$

Where;

N – is the integer synthetic fringe order

λ_{eq} – is the synthetic wavelength ($\lambda_{eq} = \frac{\lambda_1\lambda_2}{|\lambda_2 - \lambda_1|}$)

d' – is the estimated distance.

If N =0, then one can make an estimate n_1' of the wavelength fringe order by substituting Eq. (6) into Eq. (4) and rearranging:

$$n_1' = \frac{1}{2\pi}\left(\frac{\Delta\varphi \cdot \lambda_{eq}}{\lambda_1} - \varphi_1 \right)$$

Then the final measured distance is

$$d = \left[\operatorname{int}(n_1') + \frac{\varphi_1}{2\pi} \right] \cdot \lambda_1$$

Where;

d – is the final distance measurement.

The function int( ) returns the nearest integer to its argument. The unambiguous range has now been extended to the synthetic wavelength λ_{eq} , which may be much larger than λ . The unambiguous range now determined by the wavelength (synthetic wavelength) λ_{eq} of the frequency difference of f_1 and f_2 :

$$\lambda_{eq} = \frac{v_p}{|f_1 - f_2|}$$

Or, $\lambda_{eq} = \frac{\lambda_1\lambda_2}{|\lambda_2 - \lambda_1|}$.

Now the phase difference repeats at intervals equal to λ_{eq} and the distance can be measured as large as $\frac{\lambda_{eq}}{2}$ without any ambiguities;

$$d_u = \frac{\lambda_{eq}}{2} \qquad (7)$$

Where, d_u – the unambiguous range.

Generally, the landing range starts at 40 km, then the required unambiguous range for any phase measurement based landing system, should be not less than 40 km. So, in the proposed landing system [1], four ground antennas are used. Each of them should transmit two close signals.

4. Frequency allocations

According to the Table of Frequency Allocations in Article 5 of the Radio Regulations issued by the International Telecommunication Union (ITU) [3], 5.328 The use of the band 960-1 215 MHz by the aeronautical radio navigation service is reserved on a worldwide basis for the operation and development of airborne electronic aids to air navigation and any directly associated ground-based facilities. (WRC-2000). For unambiguous range 40 Km, the synthetic wavelength λ_d = 80000 m.

If f_1 =960000000 Hz, then for λ_d = 80000 m, f_2 =960003749.941 Hz, and the frequency difference $f_2 - f_1$ = 3749.941 Hz. f_3 = 961000000 Hz, f_4 = 961003749.941 Hz, f_5 = 962000000 Hz, f_6 = 962003749.941 Hz, f_7 = 963000000 Hz, f_8 = 963003749.941 Hz

However, the sinusoids of very close frequencies are used and they must be filtered and separated from each other using long filters. This problem will be discussed and solved in the coming article.

5. Conclusion

The method of measurement of a phase of complex radio signals is proposed, which allows determining the location of the plane with respect to the runway with sufficient accuracy. However, there are two important points that need serious consideration. First, the received phase includes not only phase shift φ , which occurs due to the distance between the transmitter and the receiver, but also includes the initial phases of the oscillator of the transmitter ρ_0 . The second problem is that, the measured phase angle $(\rho_0 - \varphi)$ between the transmitted and the received signal can only be measured in the interval from 0 to 2π radians, this problem is called phase ambiguity.

The answer of these problems lies in the use of more than one frequency (signal). Two sinusoidal signals with different frequencies (f_1 and f_2) but the same initial phase can be used. Taking the difference of the measured phases, the initial phase ρ_0 can vanish. To get around phase ambiguity would be to make sure that the actual phase difference $\Delta\varphi_{12}$ does not exceed 2π , this technique called equivalent or synthetic wavelength. According to the table of distribution of frequencies of clause 5 Instructions of the International union of a telecommunication (ITU), are chosen operational frequencies for a range of unambiguity of 40 kms.

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