INDOOR SOURCE LOCALIZATION VIA DIRECTION FINDING TECHNIQUE

by

NESLIHAN YILDIRIM GÜLER

Submitted to the Graduate School of Engineering and Natural Sciences
in partial fulfillment of
the requirements for the degree of
Master of Science

Sabanci University
Fall 2004

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to my dear husband for his love and support

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YÖN BULMA YÖNTEMI ARACILIGIYLA KAPALI YERLESKELERDEKI BIR VERICININ YERININ TESPITI

ÖZET

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1. INTRODUCTION

1.1 Motivation

The location of an indoor transmitter such as a mobile phone in a building can be determined by measuring power or relative timing of the transmitted signal from simultaneous receivers located in the vicinity of the transmitter. Two or more direction finding (DF) systems may be placed outside of the building to pinpoint a transmitter located inside the building. Once the bearing angle is obtained from each DF system, the position of the transmitter is simply the intersection of the bearings from the direction finders. Figure 1.1 shows the simulation of such a location finding system. Three direction finders are located around a building. The scaled digital map of the building is displayed on the interface. The source is at the intersection region of three bearings from each DF system.

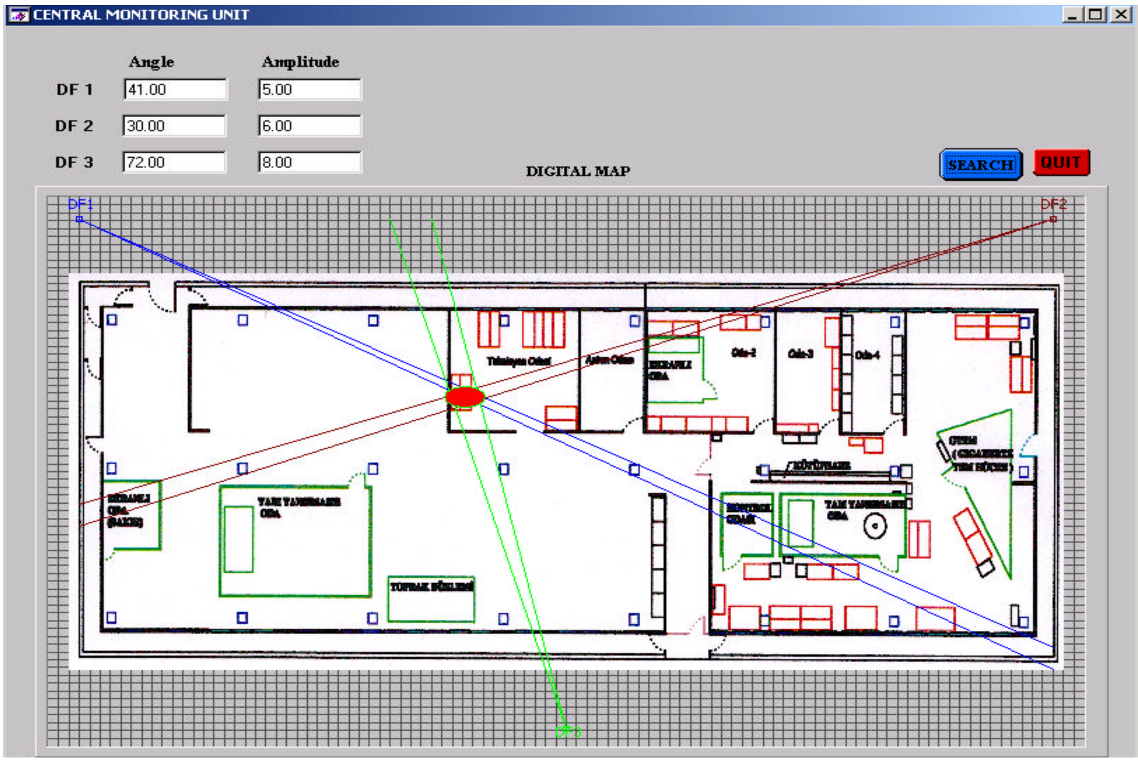


Figure 1. 1: Simulation of a location finding system

The performance of the location finder is directly proportional to the performance of direction finders. In our experiments, we mostly concentrated on the performance measurements of suggested direction finding system at various environments such as indoor and outdoor.

1.2 Radio Direction Finding

Radio direction finding (RDF) is the process of locating, tracking and distinguishing various radio transmissions by means of a radio direction finder. Radio direction finder is a device that determines the AOA or the bearing of a radio frequency signal. An RDF system estimates an emitter's bearing by operating on the energy extracted from the received electromagnetic wave. The bearing information can then be used as a parameter in the identification of communication systems.

Numerous DF techniques have been formulated and many operational systems have been developed to satisfy a wide variety of technical and operational requirements. DF has become increasingly popular in military, governmental, commercial and civilian applications. It is extremely important in COMINT applications for military purposes. A successful electronic attack is possible if a successful electronic warfare support system is used to measure the direction to the victim emitter. Interference source location, emission control, frequency management, spectrum management are some other important application areas. There are also some research issues concerning with DF applications like advanced Communication Intelligence (COMINT) investigations, DF network architectures, radio noise definitions and remote environmental sensing.

Direction finding systems basically determine the AOA information by three measurement methods: amplitude response, phase delays and time delays. A simple literature survey showed that the amplitude response DF systems do not perform very well in most of the practical systems. They are subject to high environmental and instrumental effects yielding a bad resolution performance [1] [2]. Time delay and phase delay methods, on the other hand, are strictly related to each other, since a time delay can be estimated from phase measurements or vice versa. The estimation of time difference between two signals becomes a very easy process by the use of a simple signal processing tool: the digital cross correlation method. Consequently, a basic Time Difference of Arrival (TDOA) based DF system can easily be realized with commercially available instruments in a laboratory environment while the AOA information is extracted by the help of digital signal processing methods.

We implemented a one-coordinate direction finder to determine only the azimuthal angle of arrival (AOA) of the transmitted signal. The signal sent from a transmitter arrives at each antenna at a time proportional to the distance between the transmitter and antenna. The DF system is composed of two antenna array, receivers, and a laptop computer. A 4-channel sampling oscilloscope with a maximum sampling frequency of 4 Gs/s is used to receive and digitize the received signals. The digitized signals are then transferred to a laptop computer over a GPIB interface for further analysis to extract AOA information. Extraction of AOA information is based on time delay measurement technique. An electromagnetic wave impinging on two antennas separated by a distance of d experiences a time delay. The time difference of arrival between the received signals at the antenna terminals are found by cross-correlating the signals. The delay is estimated as the time lag value where the peak of the cross correlation of two antenna signals occurs.

This thesis includes the principles and performance test results of such a two antenna array, TDOA based DF system to be used in the location finding of an indoor transmitter. We also simulated a location finding system composed of three equivalent DF systems modeled in accordance with the experimental data obtained. It is shown that the system will work fairly well in realistic environments.

In Chapter 2, the general principles of radio direction finding are investigated and traditional DF techniques are reviewed. Amplitude response, phase differential to amplitude response, phase comparison and time delay DF methods are discussed in detail throughout this chapter. It also includes the theoretical basis of source localization via DF technique.

In Chapter 3, the basic principles of the suggested DF system are presented. The process of time delay estimation via cross correlation is explained theoretically. Chapter 3 also introduces the limitations of the proposed DF method like the antenna spacing limitation and sampling rate limitation. These two restrictions cause the resolution performance of the system to decrease. Frequency down conversion and signal reconstruction methods are presented to overcome the mentioned resolution problem.

In Chapter 4, the results of many experiments, realized in various environments to measure the performance of the system, are discussed. This chapter also includes the simulation results of frequency down conversion and signal reconstruction methods to optimize the resolution performance. Using the experimental data we have collected, a location finding system is simulated in computer environment. The simulation results are included in Chapter 4.

Conclusions and future work are given in Chapter 5.

2. THEORY OF RADIO DIRECTION FINDING

2.1 Basics of Direction Finding

The main function of an RDF is to determine the AOA of an incident electromagnetic wave as received at the RDF site. A basic RDF consists of four essential functional elements: antenna, receiver, bearing processor, and bearing display as shown in Figure 2.1.

The antenna is the main element of the DF system. The antenna may be composed of a one single rotating antenna or an array of spatially distributed sensors. The output voltages produced by these sensors contain some characteristics (phase and/or amplitude) that are measured. Since these characteristics are unique for every angle of arrival in a well-designed antenna, the bearing can be determined by processing and analyzing the antenna outputs. The DF antenna is the key element in the performance of the overall system. It should be properly designed for chosen measurement technique (phase or amplitude measurement techniques).

The receiver is connected to the output of the antenna and provides the standard signal processing features common to all receivers (input preselection, frequency conversion, IF filtering, etc.). The characteristics of receivers depend on the chosen DF technique. For single-channel amplitude-response DF systems, the receiver is relatively simple and functions as an RF voltmeter to measure the antenna amplitude response. Conversely, for multiple-channel, phase and time differential DF systems, the receiver is relatively complex, providing both analog and digital processing and parameter measurements.

The bearing processor recovers the DF bearing information embedded in the signal to estimate basic AOA information and condition the data for display read-out. The complexity of the processor is determined by the DF technique and application.

The information processing-read-out-display unit prepares the basic AOA data for transmission to users of the DF information.

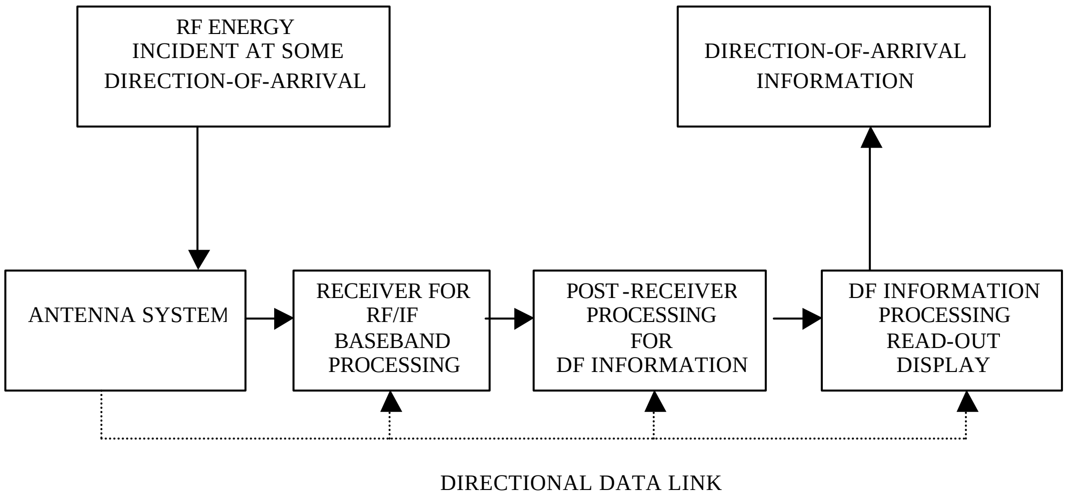


Figure 2. 1: Functional elements of radio direction finding.

2.2 General Direction Finding Principles

Figure 2.2 shows a direction-finding (x,y,z) spatial coordinate system with the RDF located at the (0,0,0) point. The angles of arrival associated with the direction of arrival are the azimuth angle, ϕ, measured from the x axis at -xy plane, and the elevation angle, θ, measured from the z-axis at -zx or -zy planes. An ideal direction finder would be capable of working over a wide band, 360^o of azimuth and 90^o of elevation, of dealing with all forms of modulation and of giving accurate and reliable bearings, even on comparatively brief transmissions.

In general, it is assumed that the electromagnetic field incident on the RDF is a far-field planar wave with linear polarization. The behavior of electric and magnetic components of a electromagnetic planar wave emitted from a current carrying wire are shown in Figure 2.3. Basically, the electric field of a wave may have both tangential and radial components. The wave is said to be linearly polarized, if one of the electric field components is zero. In DF calculations, it is assumed that the position vector of the wave remains perpendicular that gives a planar propagation. So the radial E-field is zero and the polarization is linear. The tangential E-field, E_t, and the tangential H-field are in space quadrature. The field vectors are orthogonal to the propagation direction. The direction of propagation is indicated by Poynting's vector, $\overline{S}$.

Basically, the function of a DF system is to define a vector Q parallel to $\overline{S}$ such that Q is in the direction of incident electromagnetic wave.

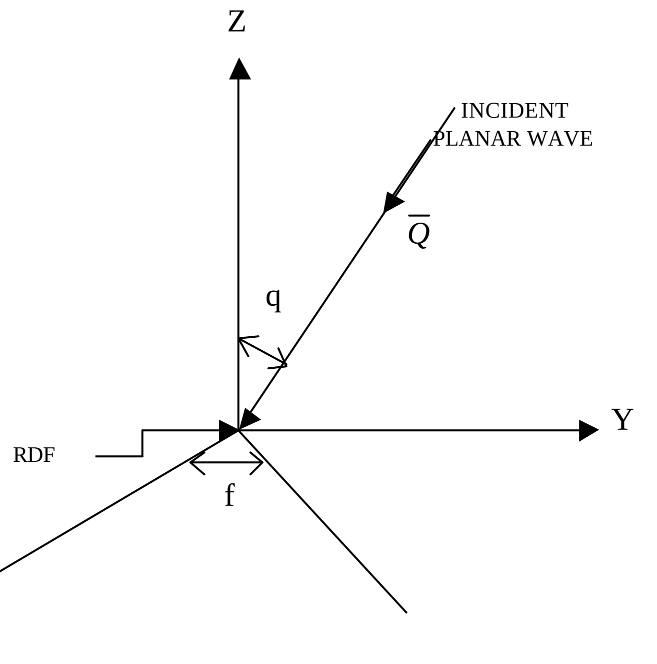


Figure 2. 2: RDF spatial coordinate system

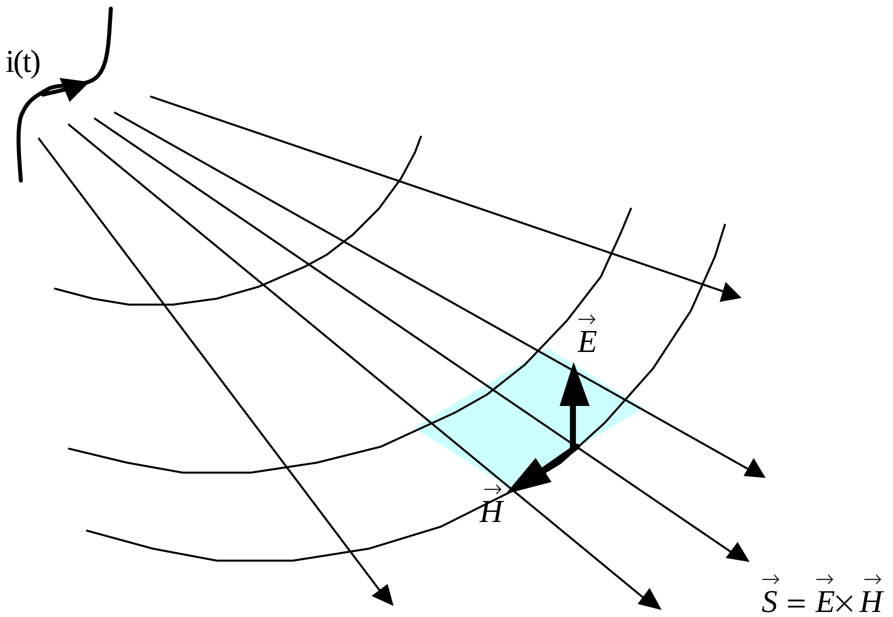


Figure 2. 3: Electromagnetic planar wave [6]

A full-capacity RDF should measure the AOA in three-dimensional space. However, in most of the applications it is required only to measure ϕ, in the azimuth plane. A one-coordinate RDF system provides AOA information in only one plane, usually the azimuth plane. A two-coordinate RDF system on the other hand provides AOA information in both azimuth and elevation plane. Most of the DF systems are one-coordinate systems giving only the azimuthal AOA information.

The measured angle of arrival, ϕ, is also called as the bearing angle or the line of bearing (LOB). The term "bearing" is defined in [4] as *"the horizontal direction of one point from another, expressed as the angle in horizontal plane between a reference line and the horizontal projection of the line joining the two points"*.

2.3 Review of DF Techniques

Radio direction finding began during the early years of twentieth century with the work of Hertz, Marconi and Zenneck on directive antennas [5]. Experience with loop antenna direction finders showed that they are subject to large errors when used on sky wave signals arriving from unknown angles. In 1918, the Adcock antenna was developed in which the various sources of site error and instrumental error were gradually identified and reduced [5]. The Adcock DF was increasingly studied during 1930s and was used extensively during the Second World War. By 1940, the first generation of direction finders was in operation. First generation DF systems were based on amplitude and/or amplitude to phase measurement techniques and they have been used effectively in numerous applications. But there were many limitations when they are used on ionospherically propagated signals. Parallel to the advances in receiver architecture, microprocessors and manufacturing technologies, second generation systems are developed. These systems are concentrated on phase and differential time-of-arrival techniques.

Modern, radio direction finding systems are composed of a DF antenna having an array of spatially distributed elements. When an emitter of interest is not at the boresight of the antenna, the output voltages produced by these elements will have some characteristics in terms of phase, amplitude or both. The AOA information (bearing) can be extracted by processing and analyzing the complex output voltages, since these characteristics are unique for every received azimuth information. We may separate the DF techniques into four main categories :

1. Systems using the amplitude response of the antenna subsystem
2. Systems using the phase difference between antenna elements with the phase differential is converted to amplitude AOA information
3. Systems using the phase differential between antenna elements
4. Systems using the time-of-arrival difference between antenna elements

Each category may be subdivided into classes based on antenna type, receiver channelization level and AOA acquisition technique. The following sections discusses the main principles of each category.

2.3.1 Amplitude Response DF

This category includes most of the earliest DF systems. Amplitude response DF is realized using a single-loop antenna which is rotated about a vertical axis. Approximate AOA information is determined by noting the signal maxima direction on the obtained cardioid pattern.

Amplitude response DF is also realized by using two or more antennas. The antennas are configured in such a fashion that the relative amplitudes of their outputs are unique for every AOA value. Bearings can then be computed by appropriately analyzing the relative amplitudes of these output voltages. Amplitude response DF techniques contain bearing ambiguities [5].

One of the important application of amplitude comparison DF technique is known as Watson Watt DF which provides the instantaneous AOA information by measuring the signal amplitudes at antenna outputs [16]. It is a multiple channel system in which there are two dipole antennas and a mono-pole antenna attached to separate receivers. This antenna is also called as sense antenna. The sense antenna is ideally located in the center of the dipole antennas. If the sense antenna was not used a 180^o ambiguity would result. The dipole antennas are arranged so that their nulls are right angles to each other. Thus one of them comprises the north and south aerials while the other comprises east and west aerials. Each of the dipole antennas has a figure-of-eight pattern. The Watson Watt DF antenna is also called as Adcock DF antenna. The azimuthal gain patterns of dipoles and sense antenna are shown in Figure 2.4.

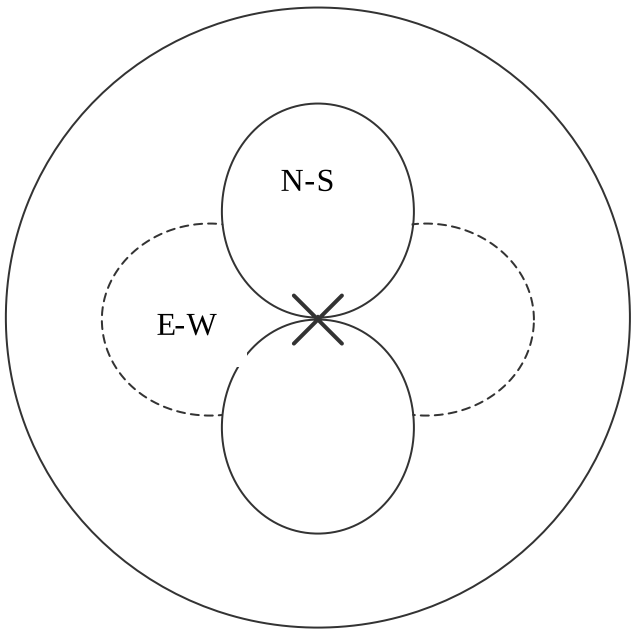


Figure 2. 4 : Adcock DF antenna azimuthal antenna gain patterns

The voltages produced by the three antennas are electronically processed in the DF antenna and then sent to the DF receiver. The output of the DF antenna is a representation of the voltages appearing at the x- and y-axis bi-directional outputs. By the use of a modulation scheme in the DF antenna, all three DF antenna outputs (x-axis, y-axis, and sense) can be combined into a single composite signal and this single signal can be sent to a single channel receiver. The receiver then processes this signal (filtering, digitizing etc.) and convert it to a lower frequency suitable for further processing at DF bearing processor. The single channel DF bearing processor accepts the signal and separate the signals again to convert them into two DC voltages (x- and y-axis DC voltages) that are proportional to the respective amplitudes at bi-directional antennas. The bearing is computed using a 4-quadrant arc-tangent algorithm

2.3.2 Phase Differential to Amplitude Response DF

The systems in this category are similar to the systems of first category in which the AOA information is obtained from signal amplitude. However, for the systems in this category, the amplitude information is obtained from the phase delay t between antenna elements as shown in Figure 2.5. This technique is a well-known Adcock DF technique [1].

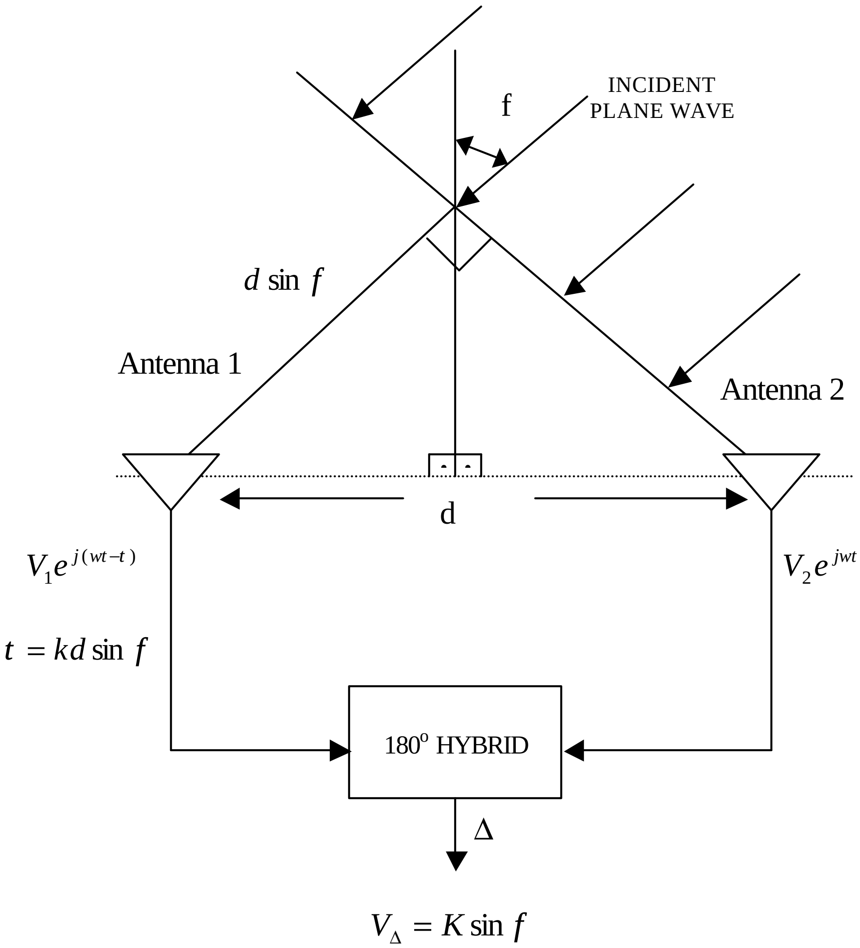


Figure 2. 5: Phase delay-to-amplitude DF technique.

The 180° hybrid is a four-port network as shown in Figure 2.6. 180° hybrid is operated as a combiner, with input signals applied at ports 2 and 3, the sum of the inputs will be formed at port 1, while the difference will be formed at port 4. 180° hybrid produces an output at port 4 that is proportional to the phase difference, $t = kd \sin f$, between incoming signals [8].

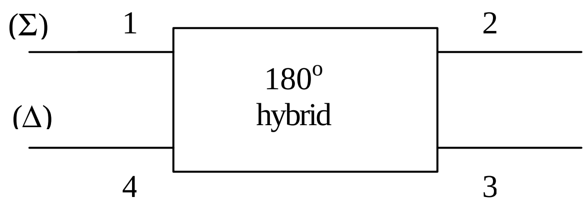


Figure 2. 6: Symbol for a 180° hybrid junction

2.3.3 Phase Comparison DF

Phase comparison DF systems determine AOA information by direct phase comparison of the signals received by separated antennas. At least two separated antennas are needed in this case. Such a two-antenna system is shown in Figure 2.7. The antennas are d meters apart from each other and the incident wave is at an angle of f. The propagating wave is received at antenna 1 first and travels an additional distance ($d \sin f$) to reach antenna 2. So the signal needs additional time to reach antenna 2. Due to this extra time, the phase of the signal received at antenna 2 is different from the phase of the signal received at antenna 1. For example, a plane wave arriving perpendicular to the array axis ($f = 0^\circ$) would result in a phase difference of zero since the signal reaches both of the antennas at the same time.

Suppose that the expression of the signal at antenna 1 is $V_1 = A\exp(jwt)$. The signal at antenna 2 will be the delayed version of the signal at antenna 1. Therefore, $V_2 = aA\exp j(wt - t)$ where a is the amplitude coefficient and t is the phase difference. Due to free space attenuation, the signal amplitude at antenna 2 is usually smaller than the signal amplitude at antenna 1. The phase difference between two antenna signals is expressed as,

$$t = (2pd / l)\sin f \tag{2.1}$$

and

$$f = \arcsin(t\,l/2pd) \tag{2.2}$$

The bearing angle f can be estimated by measuring the phase difference and replacing it in the formula given in (2.2). It is assumed that the distance d between antennas and wavelength l are known.

A phase comparator is used to measure the phase difference, t, between antenna channels. The outputs of each antenna elements are received and processed to convert to an IF signal before entering to the inputs of the phase comparator.

Doppler method is one of the most popular methods using the phase comparison technique [1]. In a Doppler system, the received frequency from a moving antenna experiences a frequency shift created by Doppler effect. If the antenna moves along a radial axis with respect to the emitter position, the Doppler shift will be maximum. No Doppler shift will occur if the antenna movement is tangential to the direction of propagation. The maximum and minimum Doppler shifts may be used to measure the bearing of the incident signal. If the antenna rotates on a circle with radius r, the Doppler frequency shift will vary sinusoidally. If f_r is the rotation rate and l is the signal wavelength, the peak Doppler shift can be given as

$$2prf_r / l \tag{2.3}$$

The signal bearing is tangent to the circle of rotation at the maximum Doppler point and is in the direction of antenna movement.

In practice, a real mechanical antenna rotation is not used, but emulated via fast switching of sensors called as Pseudo-Doppler technique. Pseudo Doppler DF is based on sequential phase measurements from a circular array of fixed antennas sequentially switched to a common receiver. Sequential sampling provides frequency deviations at discrete angles. The amplitudes measured at discrete sample points can be processed and averaged to acquire the maximum doppler shift angles and hence bearing measurements.

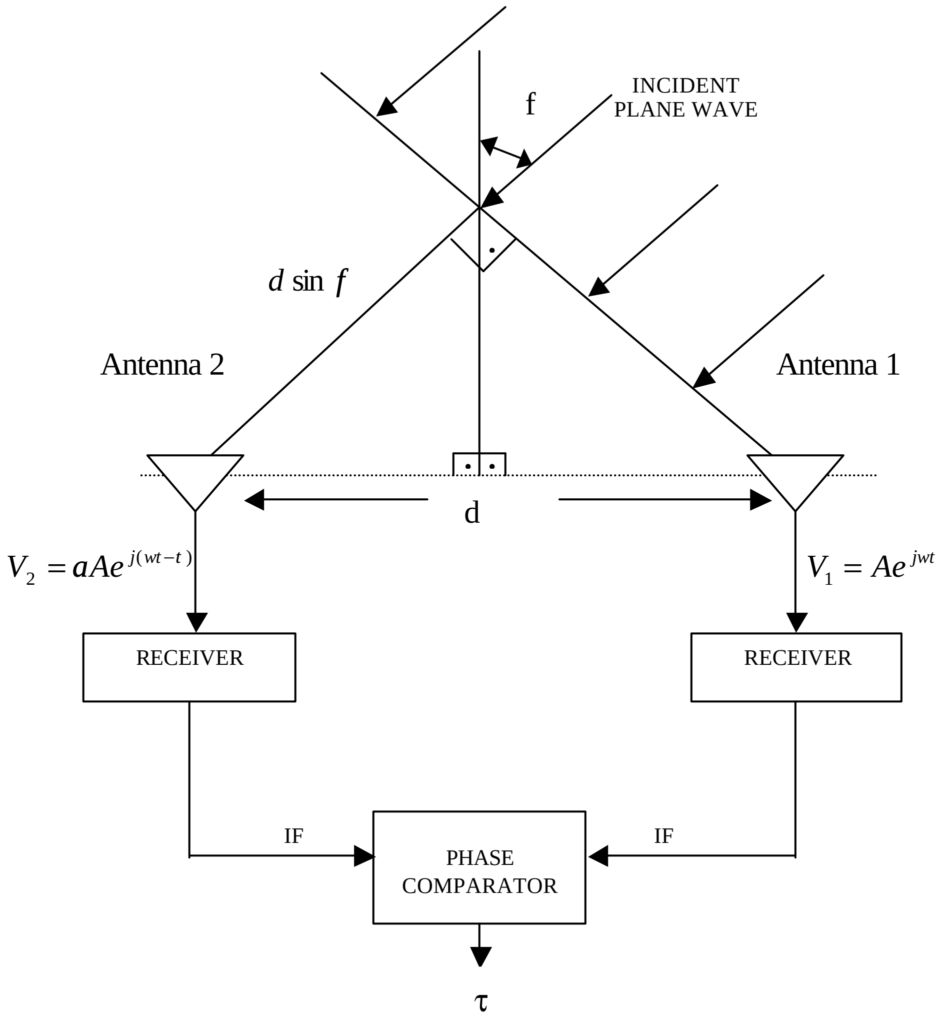


Figure 2. 7: Phase delay DF system.

2.3.4 Time Delay Measurements

Time delay and phase delay are strictly related to each other, since a time-delay can be estimated from a phase measurement if the wavelength and the velocity of the propagating wave are known, or vice versa. DF technique, using time delay measurements to estimate the angle of arrival, is also called as Time Difference of Arrival (TDOA) based DF, which will be explained in Chapter 3 with more details. Instead of measuring the phase difference as in phase comparison method, it measures the time difference of arrivals at two antennas. Figure 2.8 illustrates a DF system with two antennas where the time delay, Δt, between antenna 1 and antenna 2 is given by

$$\Delta t = (d / c) \sin f \tag{2.4}$$

$$f = \arcsin(c\Delta t / d) \tag{2.5}$$

where

f = angle of arrival (bearing angle, in degrees)

d = distance between antennas (in meters)

c = velocity of light

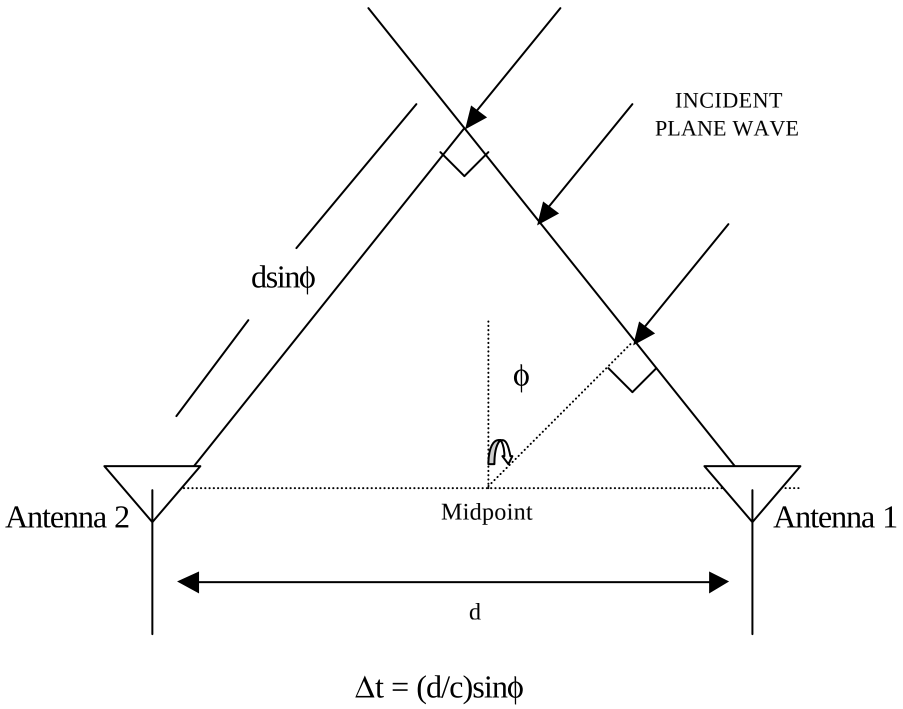


Figure 2. 8: Time delay of arrival DF.

2.4 Source Localization via DF

The localization of an RF emitter is the primary interest for most of the DF applications. Location is specified in terms of distances and angles. Angle information may be found by a single DF system. But the exact location of the transmitter can only be determined by using at least two direction finders. Bearing from each DF site are plotted to find the exact position of the emitter at the intersection of the line of bearings (LOBs). The bearings may be obtained from multiple, dispersed DF sites or from a single DF site moving relative to the subject emitter. The coordinates of the DF locations are known before or determined relative to bearings.

Figure 2.9 illustrates a location finding system composed of two direction finders. The DOA measurement restricts the location of the source to a line. The two DOA measurements from two sensors are used in a triangulation process to estimate the location of the source that lies on the intersection of such lines. If DF sites estimate AOA perfectly (no error), the source lies exactly at the intersection point. But in practice DF measurements always contain some error due to many factors like sampling effects for digital DF systems, mutual coupling of antennas, multipath propagation etc. Thus, the estimated location of the source is actually an area of uncertainty. While only two DOA estimates are required to estimate the location of a source, multiple DOA estimates are commonly used to improve the estimation accuracy. Increasing the number of measurements can decrease the area of the error region.

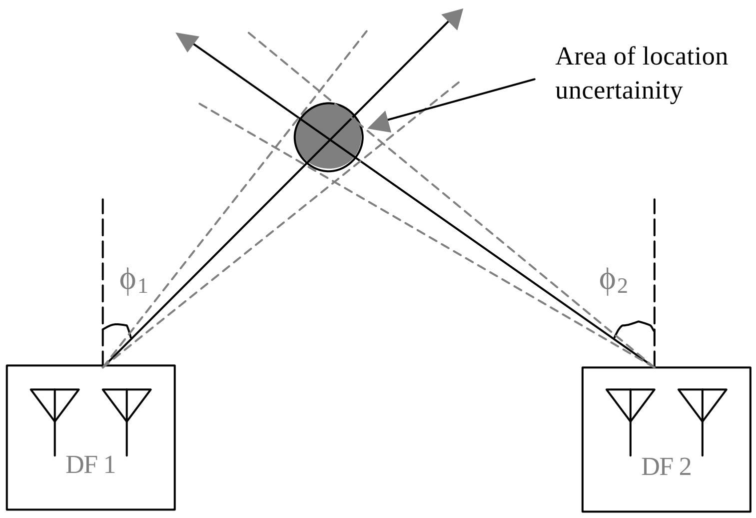


Figure 2. 9: DF based source localization.

3. TIME-DELAY RDF WITH TWO ANTENNAS

In this chapter, the principles of the proposed DF system is presented. As we mentioned before, at Chapter 2, the RDF systems determine the AOA information by utilizing one of four methods: amplitude, phase to amplitude, phase and time delay measurements. In our study, we used a two-antenna RDF system using the time delays between signals from each antenna to find the angle of arrival. This technique is based on the fact that, in a two sensor array, an electromagnetic wave arrives one of the antennas earlier than the other, since there is an amount of separation between sensors.

3.1 An Overview of the Time-Delay DF Principle

The time delay DF system was illustrated in Figure 2.8. Two antennas receive radiated signals from an emitting source. The electromagnetic wave, $s(t)$, arrives first at antenna element 1. The wave arrives at antenna element 2 after travelling an additional distance of $d \sin f$. Then a time delay, Δt, between the reception of $s(t)$ at the two receivers will be apparent. The time delay, being a function of the seperation between two antennas and the velocity of propagation of $s(t)$, can be used to calculate the bearing of the source from the receivers. This technique is known as Time Differential of Arrival DF (TDOA DF) in literature. Since the time difference imposes a phase difference between antennas, it is also called as “radio interferometry”.

The azimuth angle f of the source from the antenna baseline can be calculated from an estimation of Δt by

$$d \sin f = c\Delta t, \tag{3.1}$$

$$f = \arcsin(c\Delta t/d), \tag{3.2}$$

where Δt is the time delay between the two antennas spatially seperated by d meters and c is the velocity of light assumed to be constant at 3 x 10^8 m/s. The antenna signals, $x_1(t)$ and $x_2(t)$ can be modeled as

$$x_1(t) = s(t) + n_1(t) \tag{3.3}$$

$$x_2(t) = as(t + \Delta t) + n_2(t) \tag{3.4}$$

where a is an amplitude coefficient, and $n_1(t)$ and $n_2(t)$ are wide sense stationary, Gaussian, and mutually uncorrelated noise components. The target signal $s(t)$ is also uncorrelated with $n_1(t)$ and $n_2(t)$ and being of finite duration, may be treated deterministically.

3.2 Time Delay Estimation

The time delay apparent from the signals received at different antennas is calculated via cross correlation approach. Since the direction of the emitter is calculated by time delays, the time delay between array elements has to be calculated to a very high degree of accuracy in order to achieve a high performance.

Cross correlation of two signals, is a measure of similarity between them. The expression of cross correlation of two functions like x_1 and x_2, as one of them is delayed by time τ relative to the other is given in Eq. 3.5.

$$R_{x_1x_2}(t) = E\left[x_1(t)x_2(t+t)\right], \tag{3.5}$$

where $E[\,]$ denotes the expected value of the expression in parenthesis.

It can be shown that the time instant, where the peak of the cross correlation occurs, is the amount of time delay Δt between them. The expressions of x_1 and x_2 are given in (3.3) and (3.4) respectively. The frequency transforms of the signal and noise components are,

$$X(f) = F\{x_1(t)\} \tag{3.6}$$

$$S(f) = F\{s(t)\} \tag{3.7}$$

$$N(f) = F\{n(t)\} \tag{3.8}$$

where $F\{\ \}$ denotes the Fourier transform of a function.

We know that the power spectral density can be expressed as

$$P_{x_1x_2}(f) = F\{R_{x_1x_2}(t)\} \tag{3.9}$$

which, according to the Wiener-Khinchine theorem, is also equivalent to

$$P_{x_1x_2}(f) = X_1(f)X_2^*(f) \tag{3.10}$$

When we substitute from (3.3) to (3.8) into (3.10) we obtain

$$P_{x_1x_2}(f) = [S(f) + N_1(f)][aS(f)e^{-jw\Delta t} + N_2(f)]^* \qquad (3.11)$$

Assuming that the signal and noise are not correlated, the cross-spectral density can be written as

$$P_{x_1x_2}(f) = aP_{ss}(f)e^{-jw\Delta t} + P_{n1n2}(f) \qquad (3.12)$$

We can neglect the effect of $P_{n_1n_2}(f)$ because $n_1(t)$ and $n_2(t)$ are zero mean, Gaussian and uncorrelated noise components. (3.11) may be rewritten as

$$P_{x_1x_2}(f) = aP_{ss}(f)e^{-jw\Delta t} \qquad (3.13)$$

which is expressed in time domain as

$$R_{x_1x_2}(t) = aR_{ss}(t) * d(t - \Delta t)$$

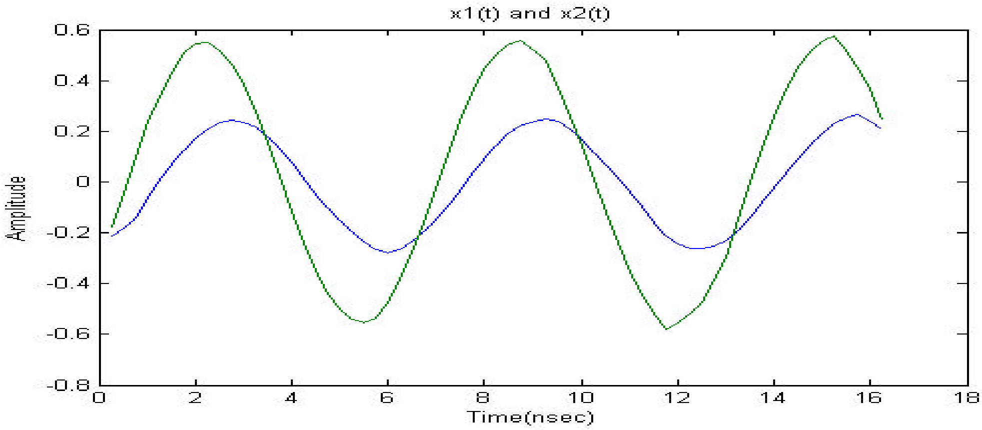
$$= aR_{ss}(t - \Delta t) \qquad (3.14)$$

* denotes the convolution operation. $R_{ss}(t)$ is the autocorrelation of $s(t)$. The autocorrelation function is an even function and it takes its maximum value when the argument is 0. Therefore, $R_{x_1x_2}(t)$ is maximum when $t = \Delta t$.

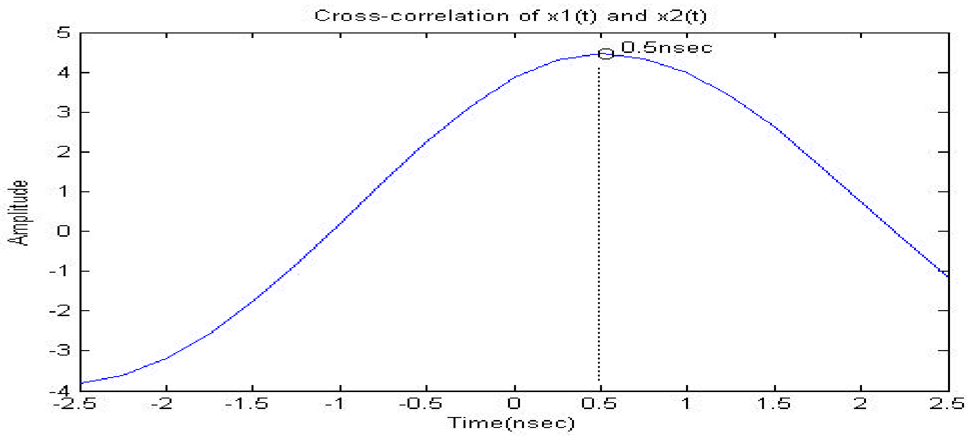
Equations (3.5) through (3.14) show that the correlation of two signals, where one of them is delayed by an amount of Δt relative to the other, takes its maximum value at time instant of Δt seconds. Consequently, the time delay between two signals can be estimated by measuring the time lag value where the peak of the cross correlation of these signals occurs.

An example of the cross-correlation estimation is shown in Figure 3.1. x1(t) and x2(t) (shown in Figure 3.1 (a)) are two digitized sinusoidal signals where one of them is 0.5 ns delayed version of the other. The cross correlation of x1(t) and x2(t) taken over one period is given in Figure 3.1 (b). The delay is estimated from cross-correlation curve by measuring from the peak of the main lobe to the time axis origin.

x1(t) and x2(t) are two real signals we obtained during our experiments. It is useful to note that the amplitude of the delayed signal is smaller. This is because of that it is attenuated more since it travels more in free space. The amplitude of the signals also can give idea about the direction of the source.



(a)



(b)

Figure 3. 1: Time delay estimation using cross-correlation method.

3.3 Antenna Spacing

Time delay radio direction finding method shown in Figure 2.8, suffers from a conflict between accuracy and ambiguity due to the separation distance between two antenna elements [12]. A small separation ($< l/2$) yields poor bearing accuracy; a longer separation causes ambiguity. The statement below shows that the distance between two antennas should satisfy the condition that $d \leq l/2$.

The triangle in Figure 2.8 yields an equation based on distance between antennas, d, the velocity of light, c, the time delay between signals, Δt, and the angle of arrival, f as

$$d \sin(f) = c\Delta t \tag{3.15}$$

$$\Delta t = d \sin(f)/c \tag{3.16}$$

For the noiseless and the lossless case, the sinusoidal signals at the inputs of antennas can be expressed in exponential form

$$x_1(t) = \exp(j2pft) \tag{3.17}$$

$$x_2(t) = \exp(j2pf(t + \Delta t)) \tag{3.18}$$

The electrical phase difference between the signals therefore can be determined using equation (3.16) as;

$$\Delta q = 2pf\Delta t = 2p\frac{d \sin f}{l} \quad (\text{modulo } 2\pi) \tag{3.19}$$

The phase difference will be limited to

$$-p \le \Delta q \le p \tag{3.20}$$

$$-l/2 \le d \sin(f) \le l/2 \tag{3.21}$$

which ensures unambiguous results of bearing measurements over the angular range $-p/2 \le f \le p/2$ when

$$d \le l/2 \tag{3.22}$$

On the other hand, it is also undesirable to have too small separation. Since closely spaced DF antennas sample a smaller portion of the illuminating wavefront, sensitivity is reduced. Therefore, there is also a lower limit on the spacing for the antennas.

Sensitivity increases with antenna spacing up to the point where the phase difference between the signals from adjacent elements begins to approach 180 degrees. A phase difference of 180 degrees corresponds to $l/2$ in ideal case. But a phase of 180 degrees does not correspond to ½ wavelength in real because the mutual coupling between the antennas usually causes the phase to increase over the free space (uncoupled) condition. In most of the practical systems, the spacing for the DF antenna is chosen to be between $l/8$ and $l/4$. [16]

3.4 Finite Sampling Limitation

In digital direction finding systems, received signals are converted into digital format for processing. The sampling frequency f_s imposes a spatial limitation to the resolution of the location system even if the signals received are ideal, i.e. not corrupted by noise or modified by any transfer function. Resolution is the capability of the system to estimate the exact AOA of the source or to separate closely spaced sources. Figure 3.2 is an illustration of the resolution error raised from the sampling limitation. The curve represents the cross correlation of the antenna signals. In practice, the antenna signals are discrete due to sampling in time. The true location of the correlation peak is not constrained to discrete increments and it may fall between the discrete sampling points that result in an estimation inaccuracy.

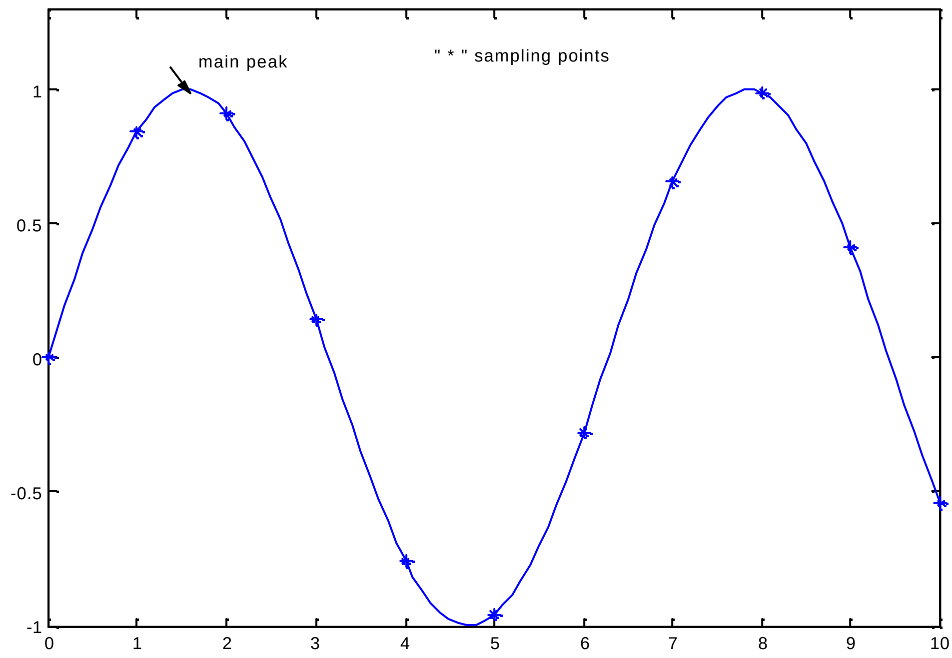


Figure 3. 2: An illustration of finite sampling problem

The peak cross-correlation of two signals $x_1(t)$ and $x_2(t)$ received via a pair of spatially separated antennas at spacing d meters will give a corresponding time delay of t seconds. The range of t is therefore between $-d/c$ and d/c depending on the location of the source where $c = 3.0x10^8\ m/s$.

A resolution limit occurs due to the finite sampling frequency of a practical system of which the estimated t is quantized. This causes t to change in time steps of T_s. The number of time steps, N_s for the given range of t is therefore:

$$N_s = \frac{2d}{cT_s} = \frac{2 f_s d}{c} \tag{3.23}$$

N_s is directly proportional to the sampling frequency f_s and the spacing between the sensors d. This implies that by increasing f_s, d or both, N_s will increase accordingly. With more time steps to describe a fixed range of time delay t , the time resolution of the system is improved.

We need a longer separation for a good bearing accuracy (increase d), but too wide separation causes ambiguity as explained in section 3.2. The maximum distance between antennas is limited to $l/2$. The maximum sampling frequency, on the other hand, is limited to the maximum frequency of the receiver. In our measurements, for example, we used the 4-channel Infiniium Oscilloscope of Hewlett-Packard which has a maximum sampling frequency of 4 Gs/s. Suppose that we are trying to find the direction of an emitter communicating at a frequency of 1 GHz. The wavelength of the radio source signal, the separation between antennas and the number of time steps are therefore;

$$f_s = 4\,Gs/s$$

$$T_s = 0.25\,ns$$

$$l = c/f = 3*10^8 \big/ 1*10^9 = 0.3m$$

$$d = l/2 = 0.15m$$

$$N_s = 2*(4*10^9)*0.15 \big/ (3*10^8) = 4$$

These calculations show that the digital cross-correlation approach for the parameters given above will produce $N_s + 1 = 5$ different time delay values which are

$$(0, \pm T_s, \pm 2T_s) \quad \Rightarrow \quad (0, \pm 0.25ns, \pm 0.5ns).$$

The corresponding angle values to these time delay values are calculated by the help of eq. (3.15) as

$$(0, \pm 30, \pm 90).$$

This example inferes that the estimation of AOA of a 1 GHz radio source will take one of the 5 angle values (0, ±30, ±90); e.g. if true $AOA = 14^0$, the output of the direction finder will be 0^0; or if true $AOA = 17^0$, the output of the direction finder will be 30^0. If we were able to double the sampling rate or antenna spacing , the number of time steps would also be doubled .

For the emitting sources of smaller frequencies, it is possible to have bigger d between antennas since the wavelength is bigger. This ability provides better resolution performance. But at high frequencies resolution is really a big problem. We tried three approaches together to solve this problem in our studies: linear interpolation, IF down conversion and sinc interpolation. Now we will briefly describe these three techniques in the following sections.

3.4.1 Linear Interpolation

We used linear interpolation technique to improve the time delay estimation accuracy. Linear interpolation is based on drawing a straight line between two neighboring samples and returning the appropriate point along that line [11]. Figure 3.3 shows the zoomed version of a graphic consisting of two curves plotted together. The lower curve is the direct cross-correlation of two real antenna output signals obtained during our experiments and the upper curve is the curve obtained after linear interpolation of the direct cross correlation curve. The true time delay between these antenna signals is -2.12 ns. It is apparent from the figure that that the peak is changed from -2.25ns to -2.17ns which is a more accurate value.

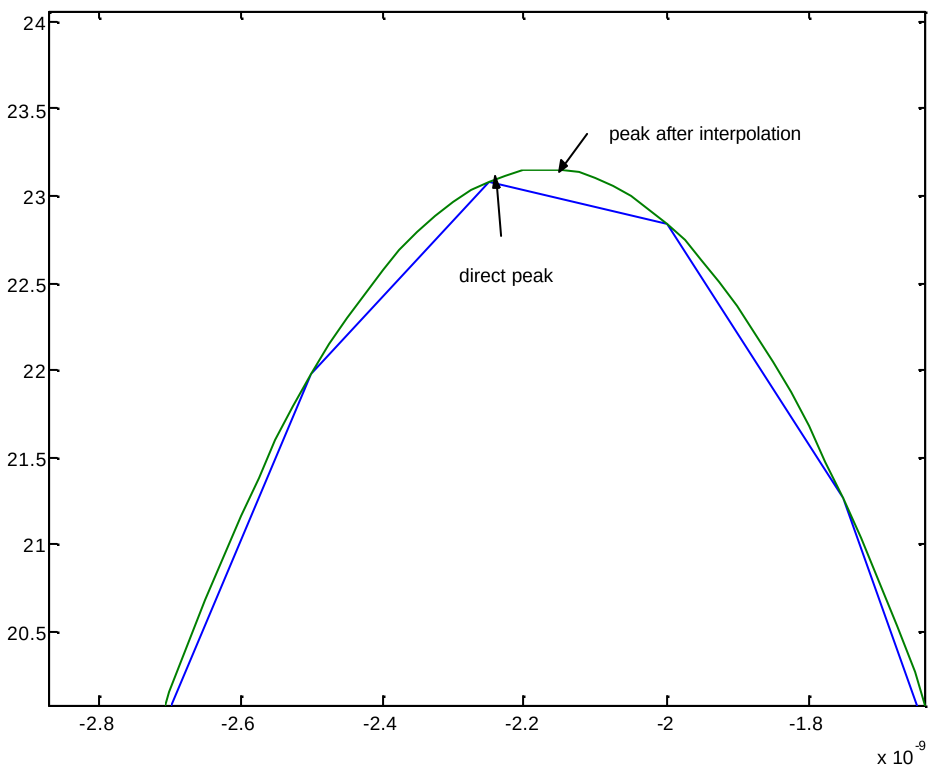


Figure 3. 3: The effect of interpolation

3.4.2 Frequency Down Conversion

For a fixed sampling rate, the resolution of a digital DF system decreases as the frequency of the source increases. A relatively high sampling rate can be achieved by utilizing a simple frequency down conversion. The idea behind the frequency down conversion technique is to translate the frequency spectrum of antenna output signals to a lower frequency, i.e. intermediate frequency (IF). The relative sampling frequency of the receiver is then increased synthetically by the amount of down conversion.

The idea of frequency down conversion may be generalized as follows [7]. Suppose that we have a signal $s_1(t)$ whose spectrum is centered on a carrier frequency of f_1 and the requirement is to translate it in frequency such that its carrier frequency is changed from f_1 to a new value of f_2. This requirement may be accomplished using the mixer shown in Figure 3.4. Specifically, the mixer is a device that consists of a product modulator followed by a band-pass filter. The band-pass filter is designed to have a bandwidth equal to that of the signal $s_1(t)$ used as input. The main issue is the frequency of the local oscillator connected to the product modulator. Let f_{if} denote this frequency. Due to the frequency translation performed by the mixer, the carrier frequency f_1 of the incoming signal is changed by an amount equal to f_{if}; hence we may set

$$f_2 = f_1 + f_{if} \tag{3.24}$$

Solving for f_{if} we thus have

$$f_{if} = f_2 - f_1 \tag{3.25}$$

This relation assumes that $f_2 > f_1$, in which case the carrier frequency is translated to upward. If, on the other hand, we have $f_1 > f_2$, the carrier frequency is translated downward, for which the corresponding frequency of the local oscillator is

$$f_{if} = f_1 - f_2 \tag{3.26}$$

The simulation results for frequency down conversion method are given in Chapter 4. We showed that, the method is able to eliminate the resolution error raised because of finite sampling limitation.

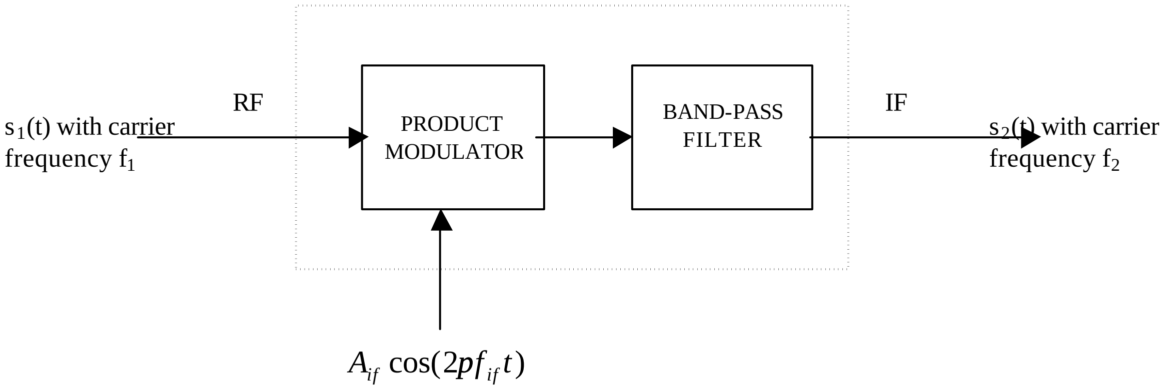


Figure 3. 4: Block diagram of mixer.

3.4.3 Sinc Interpolation (Signal Reconstruction)

According to the sampling theorem, samples of a continuous-time bandlimited signal taken frequently enough ($f_s \geq 2 * f_{max}$) are sufficient to represent the signal exactly in the sense that the signal can be recovered from the samples and from knowledge of the sampling period. If a continuous function only contains frequencies within a bandwidth, B Hertz, it is completely determined by its value at a series of points spaced less than $1/2B$ seconds apart.

Assume $x_s(t)$ to be an ideal sampled signal. This signal can be obtained by multiplying a continuous signal x(t) with a periodic train of Dirac pulses.

$$x_s(t) = x(t)\sum_{k=-\infty}^{\infty} \delta(t-nT) = \sum_{k=-\infty}^{\infty} x(n)\delta(t-nT) \tag{3.27}$$

The nth sample is associated with the impulse at $t = nT$, where T is the sampling period associated with the sequence $x[n]$. If this impulse train is input to an ideal low pass continuous-time filter with frequency response $H_r(j\Omega)$ and impulse response $h_r(t)$, then the output of the filter will be

$$x_r(t) = \sum_{n=-\infty}^{\infty} x[n]h_r(t-nT) \tag{3.28}$$

A block diagram representation of this signal reconstruction process is given in Figure 3.5. The impulse response, $h_r(t)$, of the ideal low pass filter with cutoff frequency π/T is given by

$$h_r(t) = \frac{\sin \pi t/T}{\pi t/T} \tag{3.29}$$

This impulse response is shown in Figure 3.6.

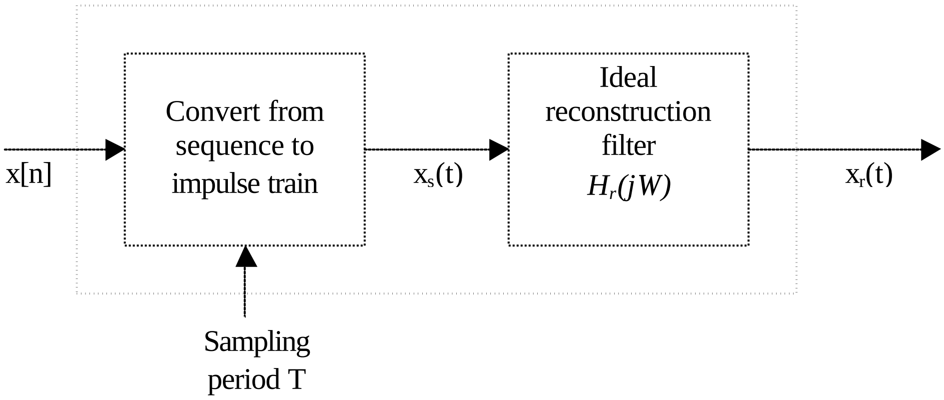


Figure 3. 5: Block diagram of an ideal bandlimited signal reconstruction system.

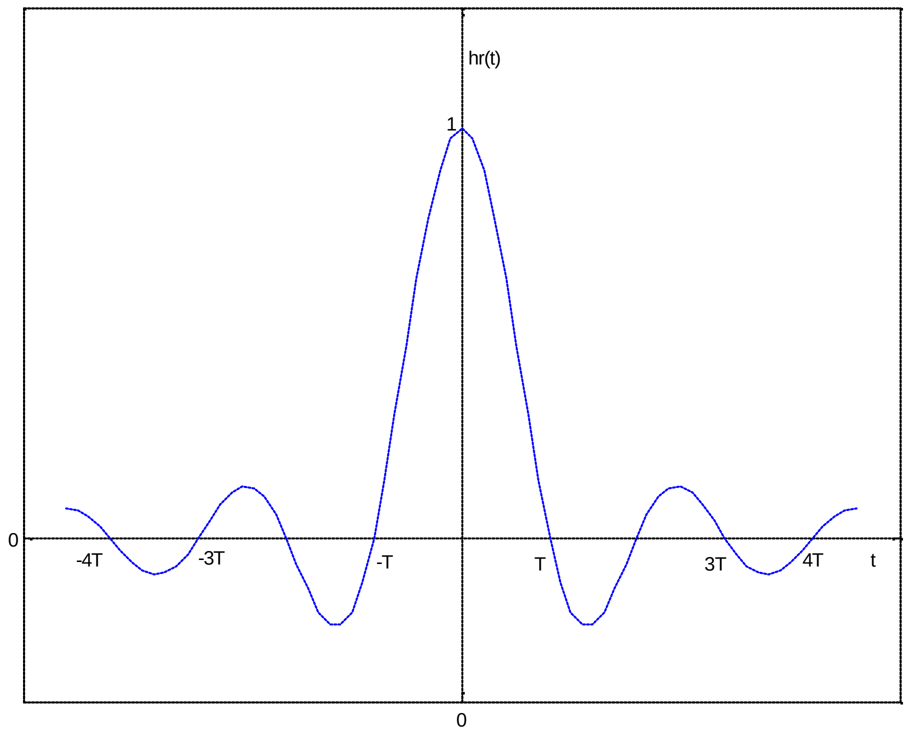


Figure 3. 6: Impulse response of an ideal reconstruction filter.

By substituting Eq. (3.29) into Eq. (3.28) we obtain

$$x_r(t) = \sum_{n=-\infty}^{\infty} x[n] \frac{\sin[p(t-nT)/T]}{p(t-nT)/T} \quad (3.30)$$

Clearly, by using this approach we can calculate the signal value at any instant by performing a single summation over the sampled values. The only requirement is that the samples have been obtained in accordance with the sampling theorem and that they indeed form a complete record (they are the samples taken at least one period duration time). It is important to realize that, under these circumstances, the recovered waveform is not a guess but a reliable reconstruction of what we would have observed if the original signal had been measured at other moments.

The simulation results and discussions for signal reconstruction method are given in Chapter 4.

4. EXPERIMENTAL AND SIMULATION RESULTS

This chapter contains the results and discussions of several experiments carried out at the EMC TEMPEST Test Center of TÜBITAK UEKAE during the studies of that thesis. A basic aforementioned two antenna, TDOA based DF system has been realized with commercially available instruments in a laboratory environment. Different medium have been selected for performance comparisons. The experiments have been carried out in a Compact Full Anechoic Chamber (CFAC), inside the laboratory, and at open area sites. We established the setup shown in Figure 2.8.

4.1 General Measurement Setup

The overall measurement setup is shown in Figure 4.1. To capture the radiated electromagnetic signal, a four-channel digital oscilloscope, having a sampling resolution of 4 Gs/s is used. The antennas, spatially separated by d cm, are connected to the two channels of the oscilloscope through two cables of equal length. In order to ensure unambiguous results of bearing measurements over the angular range of $-p/2 \le f \le p/2$, d is so chosen that it satisfies the condition $d \le l/2$ where l is the wavelength of the received signal. Two identical RF bandpass filters are used to eliminate the effects of signals out-of the band of interest. The antenna signals, digitized by the oscilloscope, are transferred to a laptop computer for further analysis. A computer program is created in LabWindows/CVI environment for this purpose. This program records and processes the antenna signals transferred by GPIB interface and cross correlates them to estimate the time difference of arrival in between. Finally, the AOA is estimated using the formula given in equation (3.1). The estimated angle value contains an amount of error due to many effects some of which are sampling limitation, antenna coupling and multipath propagation. So it is more accurate to express the AOA as a directional beam. The directional beam is drawn on a semi circular plane and sent to the user via the computer screen as the graphical user interface of the process is displayed.

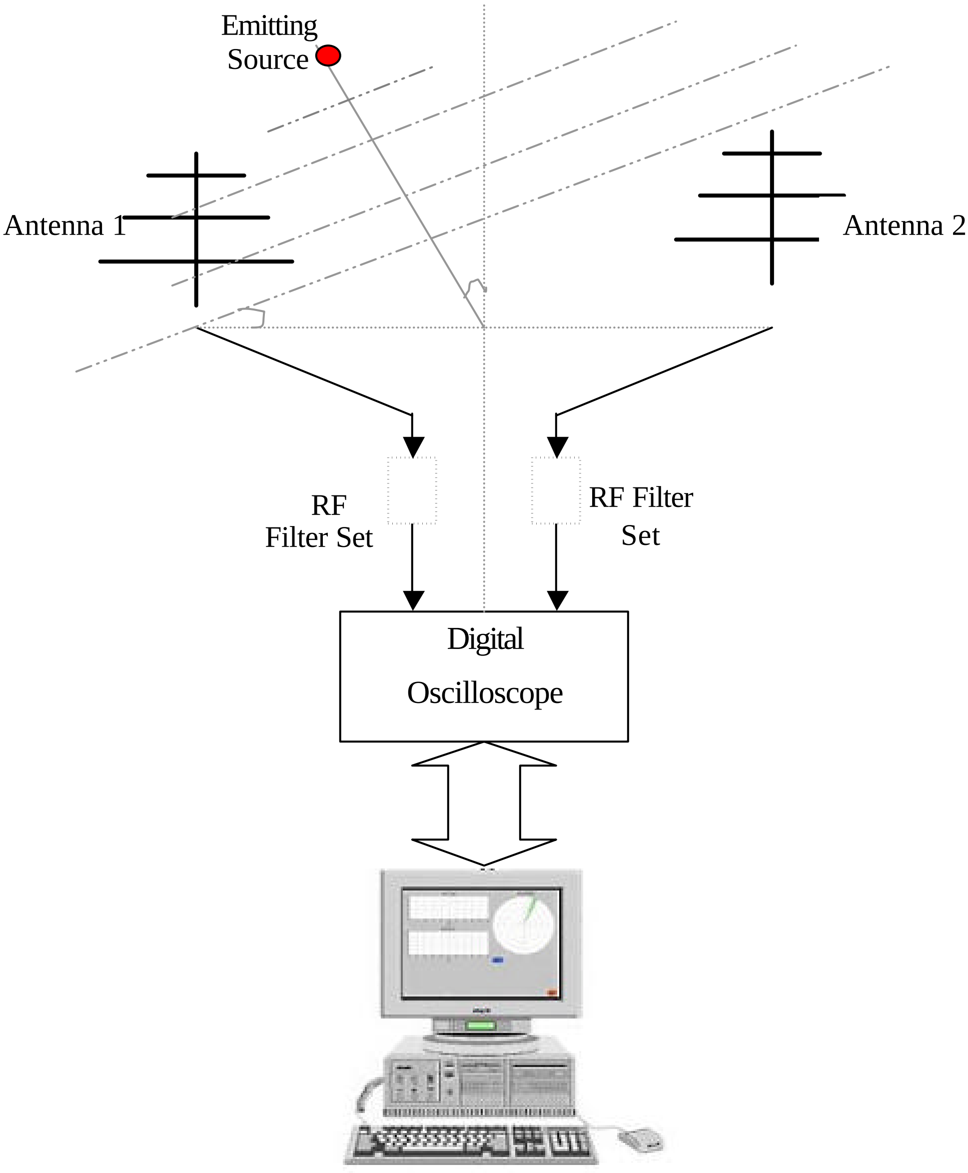


Figure 4. 1: The overall measurement setup

The graphical user interface of the system is shown in Figure 4.2. The program captures the input signals from the receiver and draws them on the same graph in different colors. Frequency spectrums of the signals are same since one of them is just the delayed version of the other. The spectrum is also drawn on another graph so that the user can observe all the frequency domain characteristics of the received signal. The cursors on this graph are used to select a frequency region, by which if the "filtering" control is active it is possible to filter the signal by software. The time domain behavior of the filtered signal is also displayed on the screen. The peak frequency component of the selected region is found and displayed automatically. The delay and the AOA values are estimated as the “RUN” button is pushed and sent to user via “Delay” and “AOA” fields respectively. For easy sense, the directional AOA beam is also drawn on a semi circle. The program has the capability of communicating wirelessly with a client computer connected via a wireless network card. So it is possible to establish the DF system anywhere around and control it remotely.

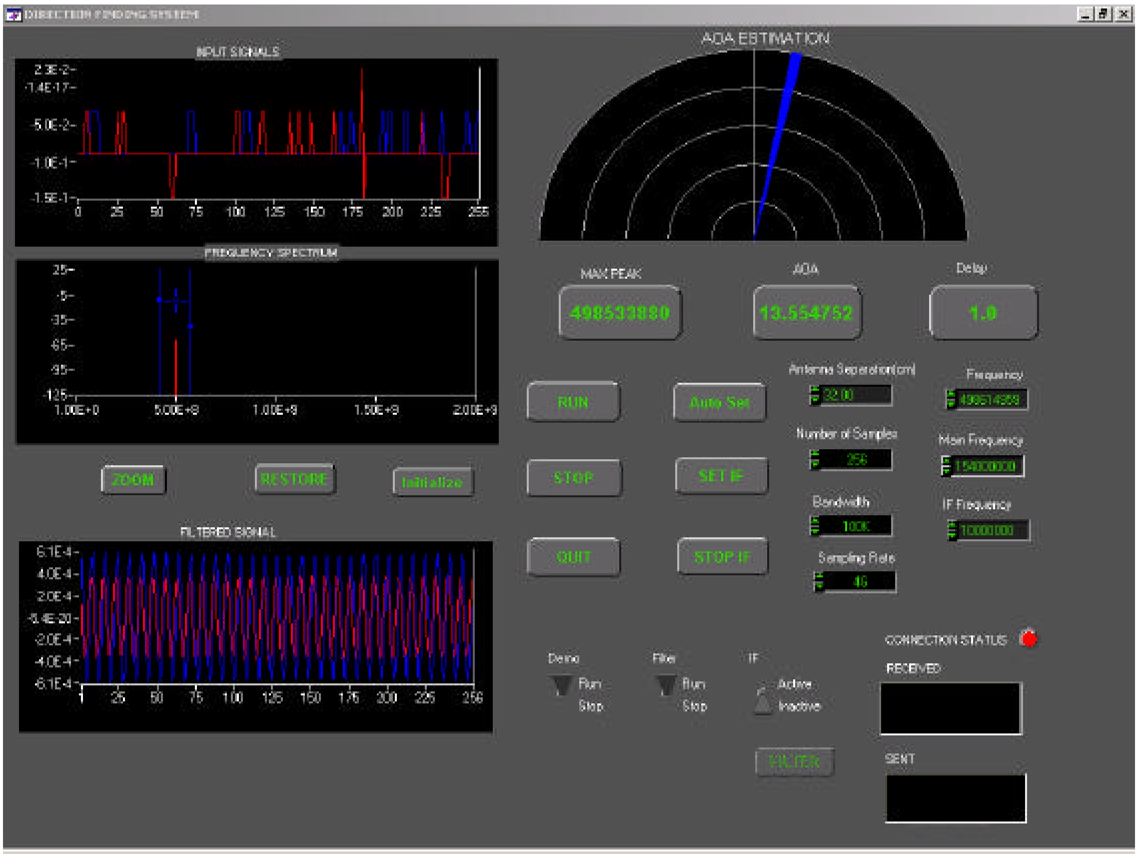


Figure 4. 2: Graphical user interface.

4.2 Numerical Results of CFAC Tests

An anechoic chamber is an ideal environment for DF performance tests since, in it, there will be no emissions contributing to the calculations other than the signal radiated by the transmitter itself. The RF signals traveling in free space like Radio/TV waves, GSM waves or the police transceivers’ waves cannot enter into the chamber. So, a better SNR (Signal-to-Noise-Ratio) value is guaranteed. We realized the test in the Full Anechoic Chamber (FAC) constructed by TÜBITAK/UEKAE (National Research Institute of Electronics and Cryptology) to be used in TEMPEST /EMC (Electromagnetic Compatibility) tests of various equipment.

4.2.1 Experiment 1

Two identical log-periodical antennas, working at 300 MHz-1GHz ranges, are used to capture the electromagnetic signal radiated by the source. An UHF FM transceiver transmitting at 461.925 MHz is used as the emitter. It is located at three different sides to determine its direction simply like from left, right or front (0^o) according to the antenna baseline normal. The values of the parameters are given in Table 4.1 where f denotes the frequency of the source, l denotes the wavelength, d $(\leq l/2)$ denotes the distance between antennas, f_s denotes the sampling frequency and T_s denotes the sampling period.

f	461.925 MHz
l	0.65 m
d	0.25 m
f_s	4 Gs/s
T_s	0.25 ns

Table 4. 1: The values of the parameters for Experiment 1.

The measurement results are given in Table 4.2. The direction of the arrival is estimated as left, right or front according to the sign of the estimated time delay. This is because of that one of the antennas is chosen as the reference antenna triggering the oscilloscope. For example, if the sign of the estimated time delay is - (negative), this means that the signal has reached the reference antenna earlier than the other antenna. Thus the electromagnetic wave is coming from the side of the reference antenna, or vice versa. The antenna at the right side of the antenna baseline was chosen as the reference antenna during the test.

The results obtained from Experiment 1 were "satisfying" for the beginning of the study. This test provided a very important conclusion that the measurement set up perceives the directions correctly. Now the problem is to find the exact value of the azimuthal angle to determine the angular beam.

Size of the chamber was not large enough to simulate all the angle values. On the other hand, in all DF techniques, it is assumed that the electromagnetic field incident on the RDF is a far-field planar wave with linear polarization. But far-field conditions cannot easily be satisfied inside CFAC since the source cannot be located far away enough from the RDF site. So we carried our setup outside the chamber and realized some experiments in an RF laboratory.

Direction of Arrival	Estimated Time Delay (ns)	Estimated AOA (degrees)	Estimated Direction
Front	0	0	Front
Left	0.25	+17.4576	Left
Right	-0.25	-17.4576	Right

Table 4. 2: Results of the test conducted in CFAC with 461.925 MHz transmitter.

4.3 Tests Conducted in RF Laboratory

4.3.1 Experiment 2

We used the same transceiver transmitting at 461.925 MHz as the source, the same log periodical antennas to capture the electromagnetic energy and the same receiver. So, the values of the parameters are the same as the values given in Table 4.1 for Experiment 1. The only difference is that the environmental conditions are changed from an anechoic chamber to an indoor laboratory where all the other electromagnetic waves (radio, TV. etc) are freely traveling in it. Therefore, we are expecting more noise, hence smaller SNR, on the received signal.

We determined twelve points to locate the source on. The geometry of the twelve locations is shown in Figure 4.3. We measured the width and length of each point according to the RDF system to determine the true AOA of signals coming from each point. The true AOA values are calculated by using trigonometric relations. The time delays corresponding to true AOA values are obtained from equation (3.1). The LabWindows/CVI program is then run to estimate the time delay between antenna signals. The estimated time delay is replaced in equation (3.2) to estimate the AOA of the intercepted electromagnetic signal. The estimation results are summarized in Table 4.3. The difference between true AOA and the estimated AOA gives the amount of angular error made during the DF process. The amount of error made for a specific point is written in red under it in Figure 4.3.

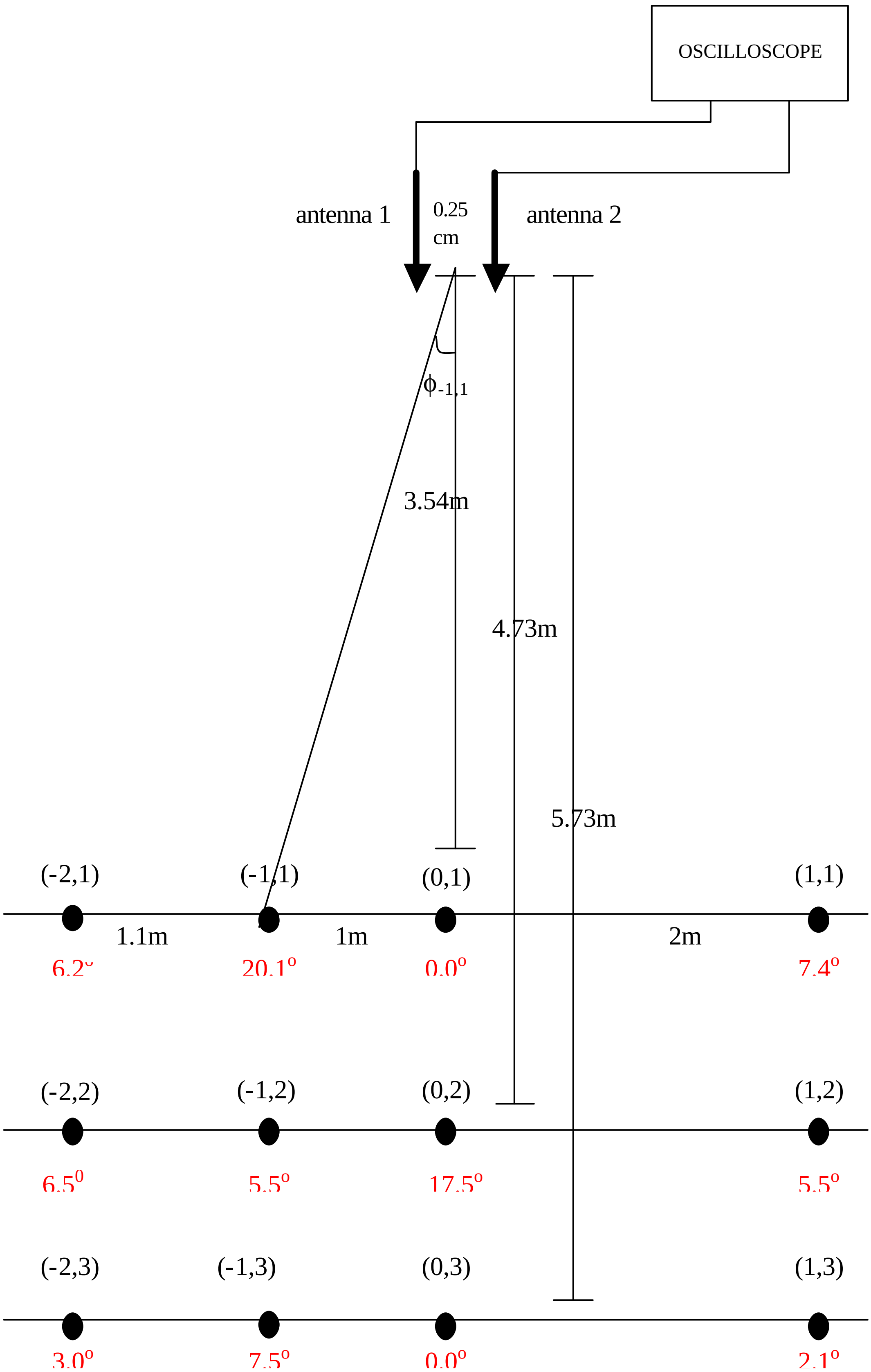


Figure 4. 3: The geometry of the source locations in Experiment 2 and the amount of angular error at each point.

Point	True AOA (degrees)	True Time Delay (ns)	Estimated Time Delay (ns)	Estimated AOA (degrees)	Angular Error (degrees)
(0,1)	0.0	0	0	0.0	0.0
(0,2)	0.0	0	-0.25	-17.5	17.5
(0,3)	0.0	0	0	0	0.0
(1,1)	29.5	0.41	0.5	36.9	7.4
(1,2)	23.0	0.325	0.25	17.5	5.5
(1,3)	19.6	0.28	0.25	17.5	2.1
(-1,1)	-15.0	-0.22	-0.5	-36.9	20.1
(-1,2)	-12.0	-0.173	-0.25	-17.5	5.5
(-1,3)	-10.0	-0.145	-0.25	-17.5	7.5
(-2,1)	-30.7	-0.426	-0.5	-36.9	6.2
(-2,2)	-24.0	-0.339	-0.25	-17.5	6.5
(-2,3)	-20.5	-0.292	-0.25	-17.5	3.0

Table 4. 3: Results of the test conducted in laboratory using 461.925 MHz transmitter.

From the Table 4.3, a very small estimation error in time delay causes a very big error in AOA estimation. For example, the true time delay at point (0,2) is 0 ns which corresponds to an AOA of 0^o. The estimated time delay at that point, on the other hand, is 0.25 ns corresponding to the AOA of 17.5^o. Since the frequency of the source is high, the spacing between antennas is limited to a very small value. As we examined before, small antenna spacing causes low resolution. Let's calculate the number of time steps for the parameters given in Table 4.1 using equation (3.23) as

$$N_s = \frac{2 f_s d}{c} = 6.66 \approx 6 \quad (4.1).$$

Therefore, there are $N_s + 1 = 7$ angle values that represent all the other angles in (-π/2 , π/2) range and they are

$$(0, \pm 17.5, \pm 36.9, \pm 64.2) \quad (4.2).$$

These angles are the angles corresponding to the time delays of $(0, \pm T_s, \pm 2T_s, \pm 3T_s) \Rightarrow (0, \pm 0.25ns, \pm 0.5ns, \pm 0.75ns)$ respectively. So, we are face to face with the resolution problem mentioned in Section 3.3. There are two solutions to this problem; increasing f_s or increasing d. The maximum value of the sampling frequency of the oscilloscope is 4 Gs/s, so it cannot be changed. The value of $d\ (\leq l/2)$ depends on the value of l which is the wavelength of the emitting source. If the frequency of the source is decreased, then d may be increased and so the resolution. For the following tests, we used another transceiver transmitting at a lower frequency of 155.4 MHz to have better resolution performance.

4.3.2 Experiment 3

This time, we used ASELSAN 4014 Transceiver transmitting at 155.4 MHz as the emitter. Two identical biconical antennas, working at 30-300 MHz range, are used to capture the incoming RF signal. Since the frequency of the emitter is decreased, we were able to increase d and consequently guaranteed a better resolution performance. The values of parameters for Experiment 3 are given in Table 4.4. The number of time steps is calculated using equation (3.23) as $N_s = 26$. The value of Ns for Experiment 2 was 6. Since we have more time steps to represent the $(-p/2, p/2)$ angle range, the capability of discriminating between close angles is increased.

The emitter is located at the same twelve points determined in Experiment 2. The results of the test are summarized in Table 4.5. The points where the angular error is greater than 10^o are shown in bold in the table and they are also encircled in Figure 4.4. The amount of angular error for each specific point are included in the figure.

f	155.4 MHz
l	1.93 m
d	1 m
f_s	4 Gs/s
T_s	0.25 ns

Table 4. 4: The values of the parameters for Experiment 3.

As it can be seen from Table 4.5 and Figure 4.4 , the true angle values could not be estimated at most of the locations. But the results are not so bad. The absolute error is smaller than 10^o at most of the points.

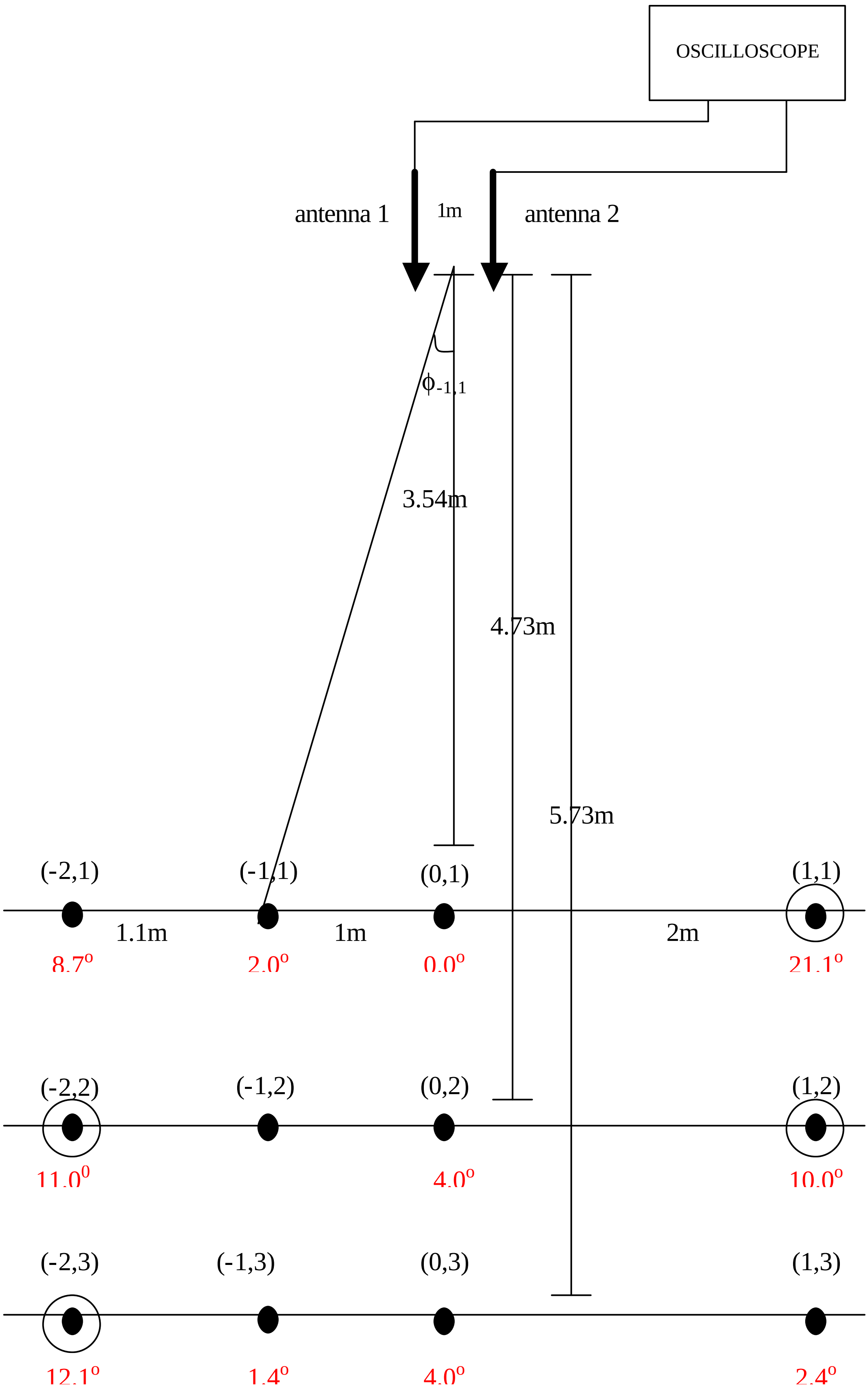


Figure 4. 4: The geometry of the source locations and errors of each location for Experiment 3.

Point	True AOA (degrees)	True Time Delay (ns)	Est. Time Delay (ns)	Estimated AOA (ns)	Angular Error (degrees)
(0,1)	0.0	0	0	0	0.0
(0,2)	0.0	0	0.25	4.0	4.0
(0,3)	0.0	0	0.25	4.0	4.0
(1,1)	**29.5**	**1.64**	**0.5**	**8.6**	**21.1**
(1,2)	**23**	**1.30**	**0.75**	**13.0**	**10.0**
(1,3)	19.6	1.12	1.25	22.0	2.4
(-1,1)	-15.0	-0.863	-1.0	-17.5	2.0
(-1,2)	-12.0	-0.693	-	-	-
(-1,3)	-10.0	-0.579	-0.5	-8.6	1.4
(-2,1)	-30.7	-1.7	-1.25	-22.0	8.7
(-2,2)	**-24.0**	**-1.356**	**-0.75**	**-13.0**	**11.0**
(-2,3)	**-20.5**	**-1.167**	**-0.5**	**-8.6**	**12.1**

Table 4. 5: Results of the test conducted in laboratory using 155.4 MHz transmitter.

We were able to decrease error by using a lower frequency transmitter but there are still some propagation effects, like multipath and scattering, resulting in phase distortions on the signal. An indoor RF laboratory is not an appropriate measurement environment in terms of multipath and scattering since windows, walls and other equipments create multipath waves that distorts the received signal. Consequently, we decided to test the setup at a more obstacle free environment. The setup and the emitting source are carried outdoor to realize that the DF system performs better in terms of multipath when it operates at outside.

4.4 Test Conducted at Open Site Test Area

Open Site Test Area is the name of a test site in TÜBITAK/MAM campus which is founded by UEKAE. The land is relatively obstacle free since it is very far away from the buildings around. So, it is thought that the multipath effects will be less here. A photo of the site can be seen in Figure 4.5.

Figure 4. 5:A view of open site test area.

4.4.1 Experiment 4

The same biconical antennas and the same transmitter are used as in Experiment 3. The location of the antennas, the source and the receiver is shown in Figure 4.6. The values of the parameters are given in Table 4.6. We determined 14 different locations and measured the true angle of arrivals. The geometry of the locations are shown in Figure 4.7 and the estimated results are summarized in Table 4.7.

Figure 4. 6: The position of the antennas and the source.

f	155.4 MHz
l	1.93 m
d	80 cm
f_s	4 Gs/s
T_s	0.25 ns
N_s	21

Table 4. 6: The parameter values for Experiment 4.

Point	**True AOA (degrees)**	**True Time Delay (ns)**	**Est. Time Delay (ns)**	**Estimated AOA (degrees)**	**Angular Error (degrees)**
a1_00	0.0	0	0	0	0.0
a1_01	37.0	1.6	1.75	41.0	4.0
a1_02	**51.0**	**2.08**	**1.75**	**41.0**	**10.0**
a1_03	**60.0**	**2.316**	**1.50**	**34.0**	**26.0**
b1_01	**-37**	**-1.6**	**-2**	**-48.5**	**11.5**
b1_02	**-51.0**	**-2.08**	**-1.75**	**-41.0**	**10.0**
b1_03	**-60.0**	**-2.316**	**-2**	**-48.5**	**11.5**
a2_00	0.0	0.0	0	0	0
a2_01	20.5	0.938	0.75	16.0	4.5
a2_02	32.0	1.413	1.25	28.0	4.0
a2_03	**41.0**	**1.76**	**1.25**	**28.0**	**13.0**
b2_01	-20.5	-0.938	-1	-22.0	1.5
b2_02	-32	-1.413	-1.5	-34.0	2.0
b2_03	-41.0	-1.76	-1.75	-41.0	0.02

Table 4. 7: Results of the test conducted at open site test area using a source of 155.4 MHz.

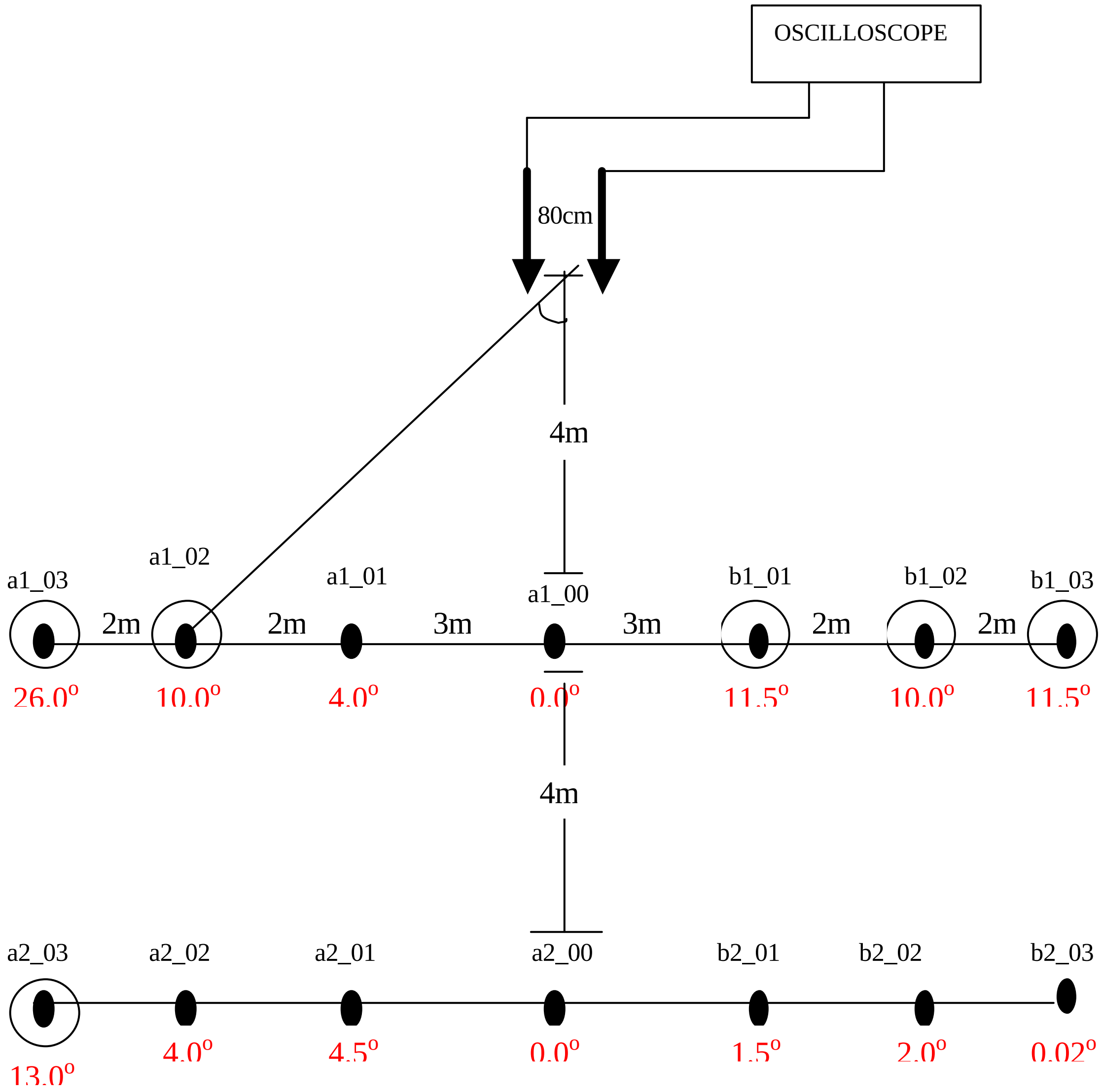


Figure 4. 7: The geometry of the source locations and errors of each location for Experiment 4.

The points where the angular error is greater than 10° are encircled in Figure 4.7. For the remaining points, it is apparent from the results given in Table 4.7 and Figure 4.7 that a better bearing accuracy is obtained during the test realized at open air when compared to the test realized in RF laboratory. This is because of the fact that multipath and scattering effects are less at open air than they are in the laboratory. On the other hand, the test transmitter should be located sufficiently far away from the DF antenna so that it is illuminated by a far field wavefront. As a matter of fact, when the distance of the transmitter to the DF antenna is increased from 4 meters to 8 meters, the error decreases considerably as shown in Figure 4.7.

Another important inference, which can easily be verified when the scheme in Figure 4.7 examined carefully, is that the amount of error increases as the angle of arrival gets greater. Or, to express in another words, the system works very well for smaller angles but it performs worse with increasing AOA. This is mainly due to two important effects. One of them is resolution effect. We know that the relationship between AOA and time delay is non linear and given in (3.1) as:

$$d \sin f = c\Delta t \qquad (4.1).$$

Since the sinus of big AOA values do not vary as much as small angles we need more resolution for big angles. For example, $\sin(1^o) = 0.0175$, $\sin(2^o) = 0.0349$ whereas $\sin(89^o) = 0.9998$, $\sin(90^o) = 1$. In order to separate 2^o from 1^o it is enough to estimate the time difference proportional with delta = 0.0349 - 0.0175 = 0.0174. But if we want to separate the DOA of 89^o from 90^0, then we must estimate the time difference proportional to delta = 1-0.9998 = 0.0002 which requires more resolution capability.

Another reason of decreasing performance with increasing AOA is about the radiation characteristics of DF antenna. When the AOA of incident electromagnetic wave gets greater, it will be very close to one of the antennas relative to other. Since the antenna closer to the source blocks the other antenna, the planar wave cannot reach the other antenna ideally. Such a coupling between antennas increases as the AOA gets greater.

4.4.2 Experiment 5

Another test is realized at a different environment. This test is performed again at an open but a bigger area. The photo of the test site is given in Figure 4.8.

We intended to see the effect of transmitter's distance to DF antenna by this test. Because we know that the transmitter should be far away enough from the DF antenna so that the emitted wave can be considered as a planar wave. On the other hand, it should be as close as possible to the antenna to reduce errors caused by reflections.

Two dipole antennas with a separation of 95 cm are used to capture the electromagnetic energy propagated from the transceiver transmitting at 155.4 MHz. The parameter values are given in Table 4.9. 6 points nearly 15 meters away from the DF antenna are determined to locate the source. The true DOA values for each point are calculated to compare with estimated values. The geometry of the locations is shown in Figure 4.9 and the results are summarized in Table 4.8.

Figure 4. 8: A photo of the test area for Experiment 5.

Point	True AOA (degrees)	True Time Delay (ns)	Est. Time Delay (ns)	Estimated AOA (degrees)	Angular Error (degrees)
0	0.0	0	0	0.0	0.0
1	-59	-2.71	-3	-71	12.0
3	-42	-2.12	-1.75	-33.5	8.5
4	-25	-1.34	-1	-18.4	6.6
5	20	1.08	1	-18.4	1.6
6	29	1.54	1.25	23.0	6.0
7	45	2.24	1.75	33.5	11.5

Table 4. 8: Results of the test conducted at the open area using a source of 155.4 MHz.

f	155.4 MHz
l	1.93 m
d	95 cm
f_s	4 Gs/s
T_s	0.25 ns
N_s	25

Table 4. 9: The parameter values for Experiment 5.

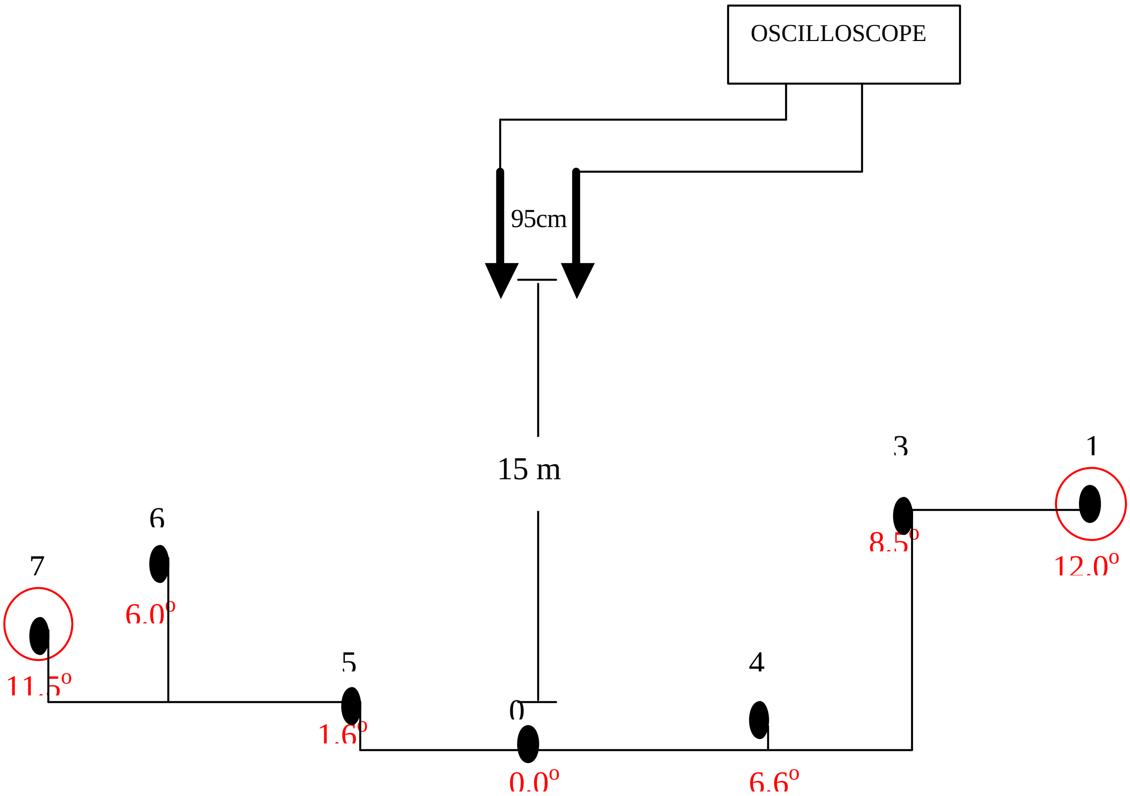


Figure 4. 9: The geometry of locations and angular error for each point.

When the data we obtained from Experiment 5 is compared to data obtained from Experiment 4, the error performance of DF system neither increased or decreased. It stayed nearly the same. Therefore, the increment of the distance between transmitter and DF antenna from 8 meters to 15 meters did not change the results. We may conclude that a 8 meters distance was enough for far field conditions to be satisfied. On the other hand, by the increment of the distance, it is expected that the multipath waves will become more effective and so the error will increase. But as it is stated the error is nearly the same for both cases. So we can also conclude that, the open site is fairly well in terms of multipath propagation.

4.5 Soft Frequency Down Conversion

The data we obtained during our tests showed that a quantization error occurs because of the direct sampling of RF (radio frequency) signals at antenna outputs. For a fixed sampling rate, the resolution was better when a transceiver at a frequency of 155.4 MHz is used instead of 461.925 MHz. A relatively high sampling rate can be achieved by utilizing a simple frequency down conversion process. The basic principles of frequency down conversion method is explained in section 3.4.2. The idea behind the frequency down conversion technique is to translate the frequency spectrum of antenna output signals to a lower frequency, i.e. intermediate frequency (IF). The relative sampling frequency of the receiver is then increased synthetically by the amount of down conversion. The disadvantage of this method is that it requires an extra analog frequency down converter circuit before digitizing and cross correlation operations, which increases the cost. On the other hand, we need two different frequency down converters in analog circuitry, one at the output of antenna 1 and the other at the output of antenna 2. The indispensable condition to be satisfied in this case is that the phase responses of two analog frequency down converters should be exactly the same, i.e coherent outputs. Since the cross correlator operates on the phases of signals, it is required that the phase responses of the signals should never be changed from the outputs of the antennas until the cross correlator. It is possible to overcome this problem by measuring and calibrating the system. We proposed that this problem may also be solved by using all digital methods in DF process.

To eliminate the need for an additional analog hardware, we suggest a software implementation of the frequency down conversion process. Therefore first the signals are digitized by the receiver and then converted to IF (intermediate frequency) signals by signal processing and then cross correlated. Down conversion of the antenna signals does not change the phase difference between them. But the capability of estimating this phase difference increases due to the increase of signal period after down conversion. The disadvantage of soft frequency down conversion method is that it requires more memory (longer signal duration) for the same process. The frequency down conversion technique is shown in Figure 4.10(b) in comparison with direct RF sampling technique given in Figure 4.10(a).

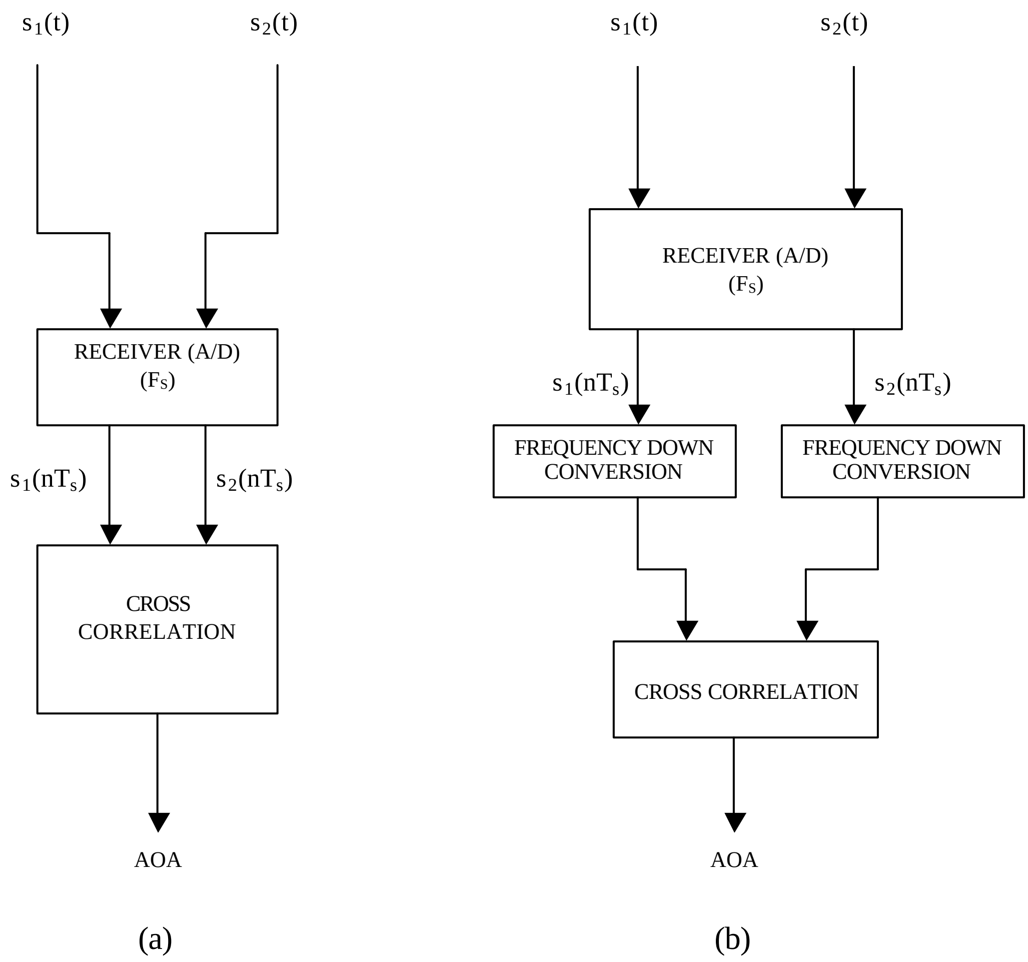


Figure 4. 10: (a) Direct RF sampling, (b) Frequency Down Conversion

4.5.1 Simulation of Soft Frequency Down Conversion Method

The advantages of the frequency down conversion technique can easily be verified by computer simulation. We simulated a direction finder designed to estimate the DOA of an emitter at 1 GHz. This is the same scenario as we described in Section 3.3. Analysis made in Section 3.3 showed that such a direction finder has a very big resolution error, since the frequency of the emitter is relatively high. Thus, all the estimated angle values in the range of (+90,-90) for such a system will take one of the values in $(0,\pm 30,\pm 90)$. We expect a very big resolution error when we use direct RF sampling technique. When we implement the frequency translation method, on the other hand, we will down convert the high frequency signal to a lower frequency; hence, the relative sampling frequency will be increased. As a result of that, the number of discrete interval for one period of the incoming signal will increase and the amount of quantization error will decrease. We down converted a 1 GHz signal into a 25 MHz signal.

Figure 4.11 illustrates the simulation results obtained for noiseless case (resolution error only). The absolute error is drawn for (-90,+90) angle range. All the angles in this range are simulated and the absolute error, corresponding to each AOA value, is calculated for both direct RF sampling and frequency down conversion methods. The dashed curve represents the error in case of direct RF sampling and the solid curve represents the error when frequency down conversion is realized by signal processing. The mean error for direct RF sampling is 13.8895 degrees, whereas it is 1.9667 degrees for frequency down converting method. This simulation showed us that the new technique will increase the performance of the system considerably, especially at high frequencies.

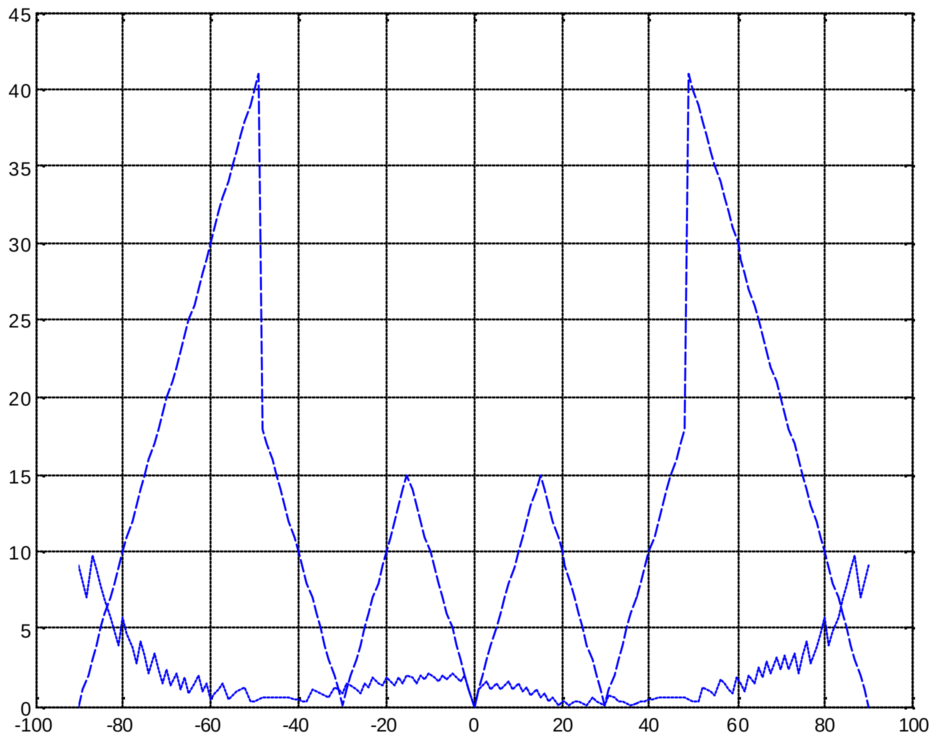


Figure 4. 11: The comparison of direct RF sampling and frequency down converting techniques by simulation (dashed: absolute error of direct RF sampling technique; solid: absolute error for frequency down converting method).

4.6 Simulation of Signal Reconstruction Method

As mentioned before at Chapter 3, we also suggested another method to solve the resolution problem: signal reconstruction. This method interpolates the samples of a bandlimited signal sampled in accordance with the sampling theorem to reconstruct the original signal. The sinc interpolation is used for this purpose. The basic principles of signal reconstruction method is explained in section 3.4.3. It is shown in Figure 4.12(b) in comparison with direct RF sampling technique given in Figure 4.12(a).

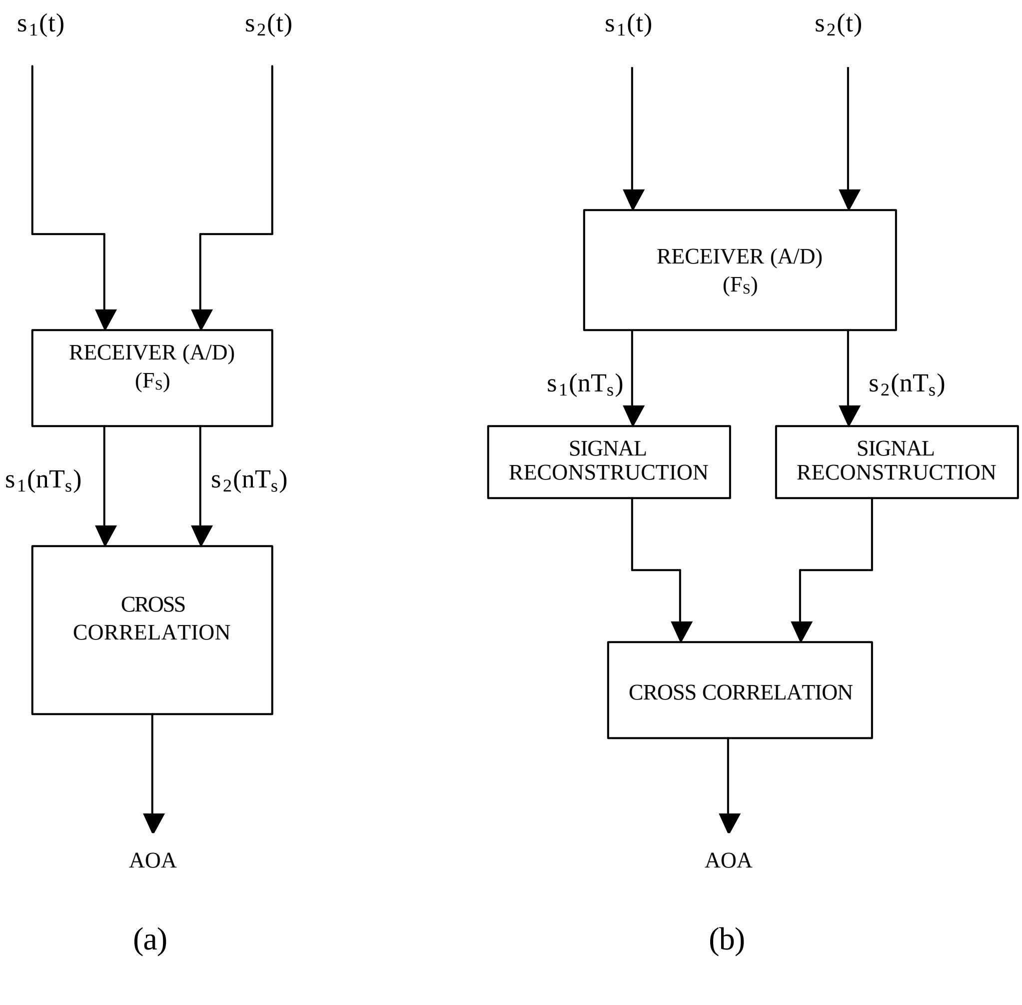


Figure 4. 12: (a) Direct RF sampling, (b) Signal Reconstruction

We tested the method in computer environment first by simulation. We again simulated a direction finder designed to estimate the DOA of an emitter at 1 GHz as told in Section 4.5.1.

Figure 4.13 illustrates the simulation results obtained for noiseless case (resolution error only). The absolute error is drawn for (-90,+90) angle range. All the angles in this range are simulated and the absolute error, corresponding to each AOA value, is calculated for both direct RF sampling and signal reconstruction methods. The dashed curve represents the error in case of direct RF sampling and the solid curve represents the error when signal reconstruction is realized. The mean error for direct RF sampling is 13.8895 degrees, whereas it is 1.46 degrees for signal reconstruction method.

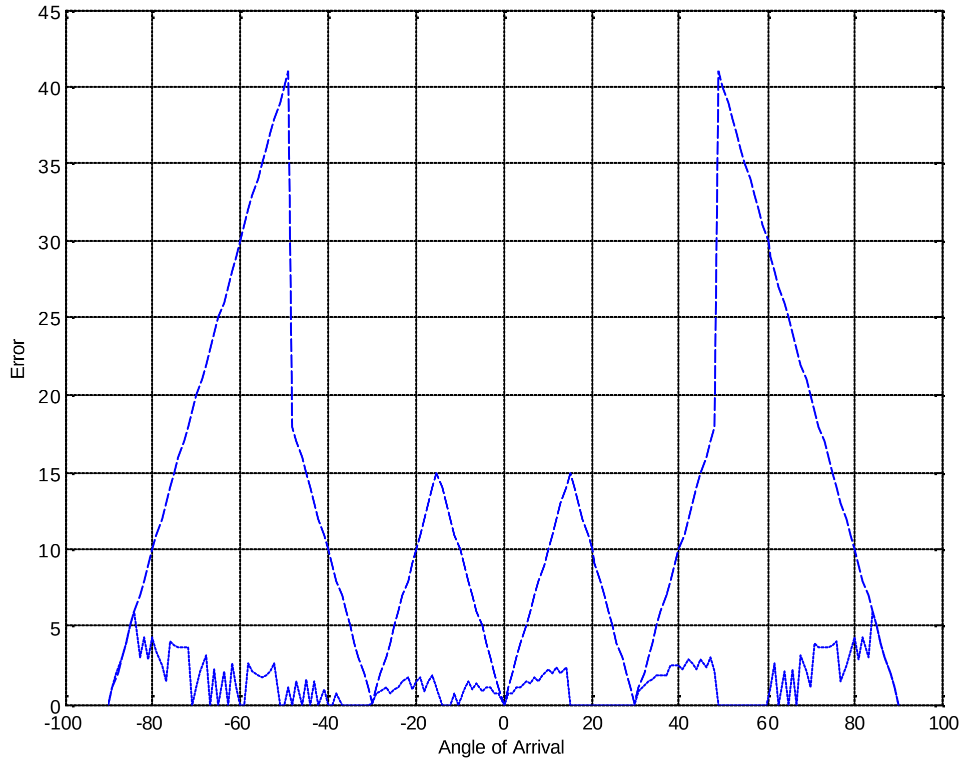


Figure 4. 13: The comparison of direct RF sampling signal reconstruction techniques by simulation (dashed: absolute error of direct RF sampling technique; solid: absolute error for signal reconstruction method).

It will be useful to emphasize that the reconstructed signal is not a guess and it is completely same with the original signal. This means that the exact value of the signal can be found at any time instant. So, theoretically, it is possible to decrease the resolution error to 0^o when the signal reconstruction method is used. But, we are trying to reconstruct the signal in computer environment. In this case, the decrease in error is inversely proportional with the computational complexity of the process.

Let's examine that issue on our simulation scenario. We have a source at 1 GHz and the sampling frequency is 4 Gs/sec. The sampling frequency is in accordance with the sampling theory then. The samples are taken for every 0.25 nsec. We may divide that time interval into 100 and so find the signal values at every 0.025 nsec or divide it into 1000 and find the signal values at every 0.0025 nsec. For the second case the resolution error is much decreased when compared to first case. But the computational complexity of the system is higher which is a big disadvantage especially for real time systems.

Finally, we may conclude that the frequency down conversion method seems to be more advantageous method to solve the finite sampling problem. Because, it is computationally more inexpensive when compared to signal reconstruction method.

4.7 Simulation of an Indoor Radio Location Finding System

Up to now, we proposed a two antenna array TDOA based DF system to determine the AOA of an electromagnetic wave transmitted by an indoor transmitter. We implemented the proposed setup and tested its performance in various environments. From the data we obtained, the proposed DF system works quite well for (-45^o , $+45^o$) angular range and the estimation error increases as the AOA increases.

A location finding system consisting of three equivalent DF systems is simulated in LabWindows/CVI environment. Triangulation method is used to estimate the coordinates of the source inside the building as the intersection of bearings from each DF system. We modeled the DF system such that it works consistent with experimental results. Thus, before triangulation a random error proportional to the AOA is added to the true AOA value as follows:

```
if (AOA = = 0)
    AOA = c1 * randn(1);
else
    AOA = AOA + c2 * AOA * randn(1);
end
```

A building of 96x72 meters^2 in size is simulated and divided into 12 equal 24mx24m rooms. The simulated rooms are shown in Figure 4.14. The two DF systems are located at the symmetric reciprocal corners of the building and third DF system is located to the opposite side on the line from the middle of the building. We know that the DF system works quite well for small AOA values. So, we should locate the DF systems in such a fashion that the AOA of the source at any point in the building stays small. This is possible when only the normal of the DF system passes through the middle point of the building. Therefore, if the source is positioned at the middle of the building, the AOA values with respect to each DF system will be 0 degrees which corresponds to the minimum error case. The size of the building and the distance of direction finders from the building are shown in Figure 4.15. The two DF systems at the corners should be located with an angle of 43.8 degrees to the building in order to satisfy the above mentioned argument.

Room 1	Room 2	Room 3	Room 4
Room 5	Room 6	Room 7	Room 8
Room 9	Room 10	Room 11	Room 12

Figure 4. 14 : Rooms in the building.

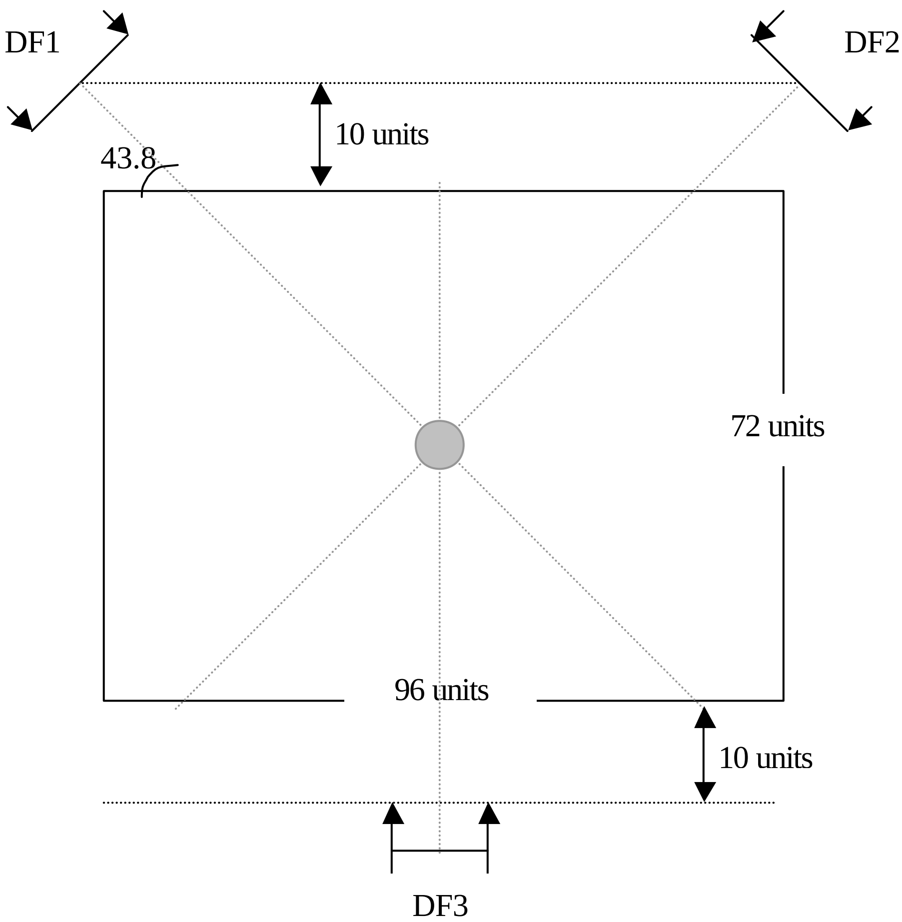


Figure 4. 15: Location of the direction finders around the building.

The graphical user interface of the location finder with 3 DF systems located around the building can be seen in Figure 4.16. We may also mention about the operational principles of the location finding system by examining the specific example given on the Figure 4.16. The true coordinates of the source is chosen as (14,26). Therefore, the AOA to DF2 is the minimum of the angles to each direction finder. And as expected, DF2 makes the minimum error for that point. The coordinates of the emitter is estimated as the middle of the triangle formed by lines of bearing from each DF system. As a result, the true coordinates of the emitter was (14,26), whereas it is estimated as (20.67,29.94). The error made is therefore, the distance between these two pairs.

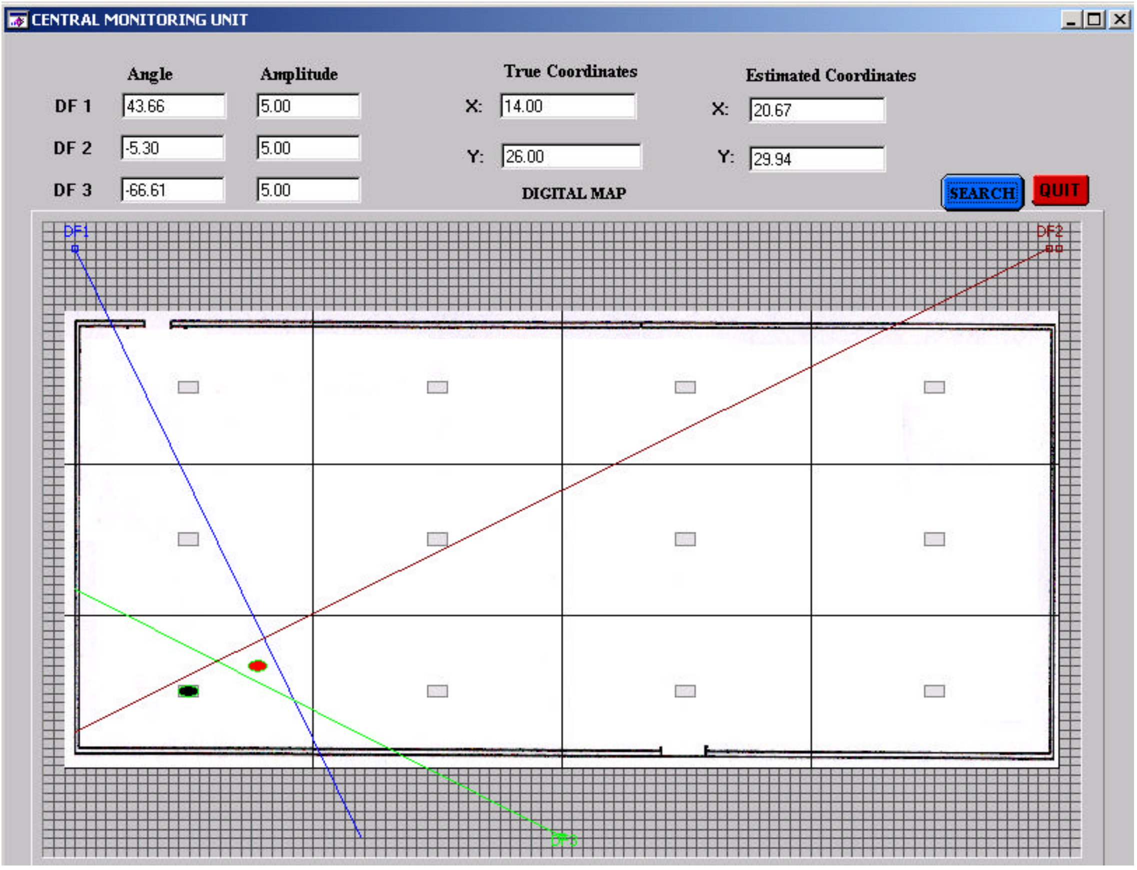


Figure 4. 16: The graphical user interface of the radio location finding system.

For each room, we determined the coordinates corresponding to the middle of the room. Thus we fixed 12 points inside the building. The transmitter is located to each point one by one and the location finder is run 100 times for each point. The mean error and standard deviation is calculated at each point using the formulas in (4.2) and (4.3) respectively.

$$\overline{X} = \sum_{i=1}^{N} x_i \Big/ N \qquad (4.2)$$

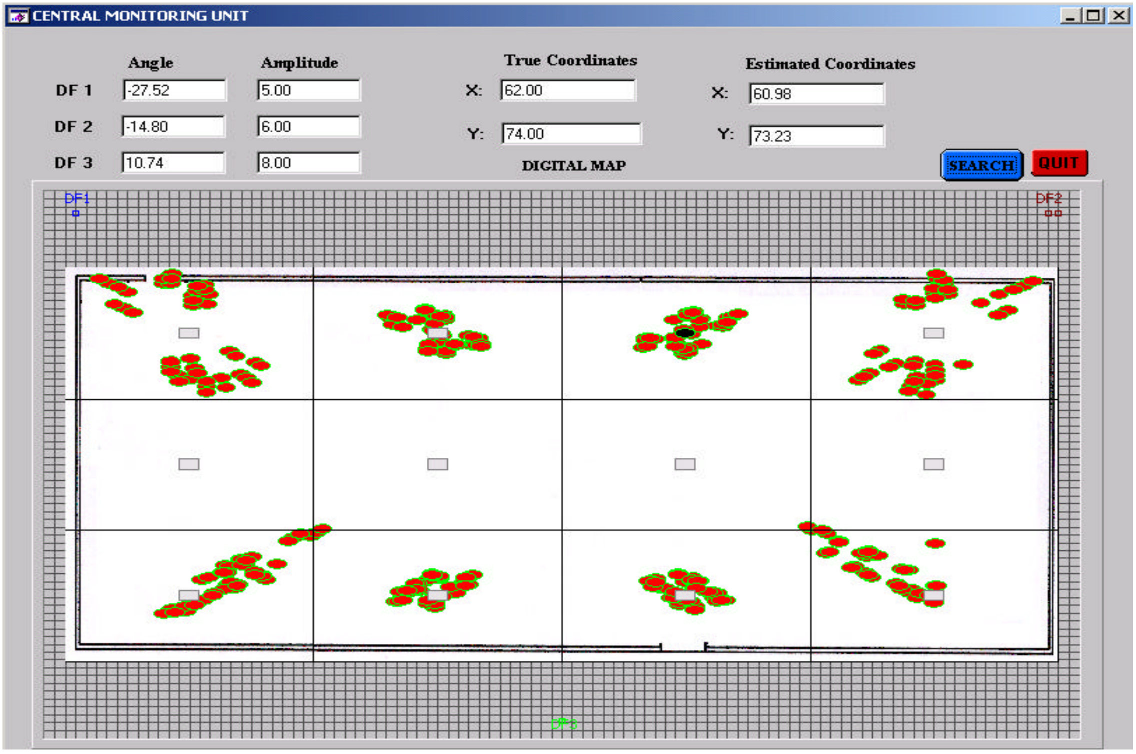
$$s = \sqrt{\frac{\sum_{i=1}^{N} x_i - \bar{x}}{N-1}} \qquad (4.3)$$

The distribution of the estimated coordinates for 12 rooms is shown on Figure 4.17. The mean and standard deviation of the errors at each room are summarized on Table 4.10. Since the DF systems are located symmetrically, the error characteristics at symmetric rooms is nearly the same.

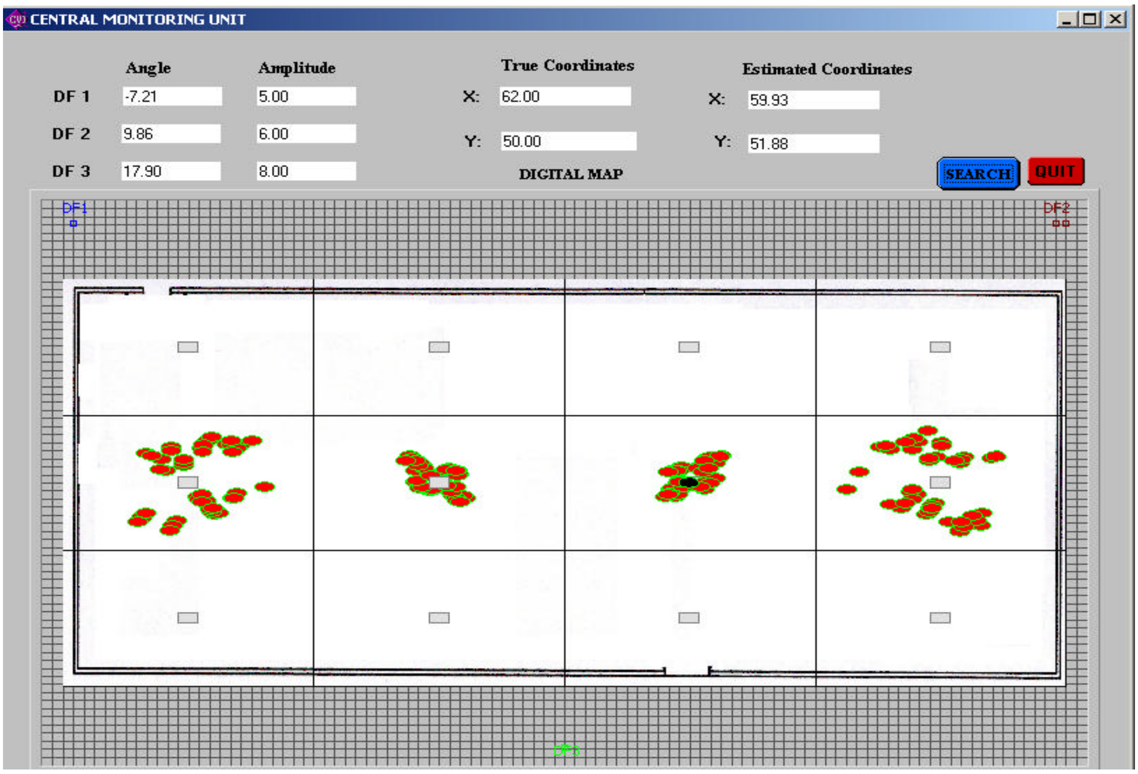
We located the DF systems around the building in such a fashion that the location finder performs best when the transmitter is in the middle of the building, we expect the error to be less in the rooms around middle of the building when compared to the rooms at the edges. The error characterized by the mean and standard deviation values given in Table 4.10 shows that the simulated location finder will work properly well in a realistic environment .

E[x] = 8.27 σ = 2.0 **1**	E[x] = 2.8 σ = 1.4 **2**	E[x] = 3.11 σ = 1.2 **3**	E[x] = 8.36 σ = 2.0 4
E[x] = 6.63 σ = 2.0 **5**	E[x] = 2.11 σ = 1.0 **6**	E[x] = 2.2 σ = 1.0 **7**	E[x] = 6.7 σ = 2.0 **8**
E[x] = 7.03 σ = 4.3 **9**	E[x] = 2.72 σ = 1.1 **10**	E[x] = 2.9 σ = 1.33 **11**	E[x] = 7.06 σ = 4.85 **12**

Table 4. 10: The mean and standard deviation of error at each room.



(a)



(b)

Figure 4. 17: The distribution of estimation results at each room.

5. CONCLUSIONS AND FUTURE WORK

In this thesis, we modeled a radio location finding system to determine the location of an indoor transmitter. The system is composed of three equivalent DF systems placed outside of the building. The position of the transmitter is simply the intersection of bearings from individual direction finders. So the performance of the location finding system is very dependent on the performance of each DF system.

The proposed DF system is a two dipole antenna array designed to estimate the azimuthal AOA of the transmitted signal. The timing of the intercepted signals at each sensor are measured and the cross correlation approach is used to estimate the bearing information. We made some experiments about the performance of the proposed system at various environments such as indoor and outdoor. It is possible to make some inferences about the system by analyzing the experimental results.

Firstly, since we use digital methods in the process, the sampling of the signals introduces a quantization error on the estimation results. This limitation yields a bad resolution performance especially when the frequency of the transmitter is high. As a matter of fact, a higher resolution capability is guaranteed when a 155.4 MHz transmitter is used instead of a 461.925 MHz transmitter during the tests. Increasing the distance between antennas is one way of increasing the resolution. But such an intervention causes the ambiguity of the DF system to decrease. So, to overcome the resolution problem, two methods are suggested: one of them is down converting the incoming signal to a lower frequency and the other is reconstructing the signal from its samples by sinc interpolation. We showed that although the signal reconstruction process reconstructs the signal as if it is original, it increases the computational complexity of the overall system. This is an unwanted case especially for real time systems. In frequency down conversion method, the frequency of the intercepted signals at antenna outputs is converted to a lower frequency. Such a process, does not change the phase difference between antenna signals. But the amount of time delay, yielding the same phase delay, increases. So, it becomes easier to estimate it. It is the same effect as if sampling rate of the receiver is increased. The simulation results showed that the method works well especially at high frequencies.

We also noticed that the performance of the DF system decreases as the AOA of the transmitter increases. This is partly due to the fact that a higher sensitivity is needed to distinguish large angles from each other, and partly due to mutual coupling between antennas which gets more corruptive at large AOA values. The DF systems should be positioned around the building in such a fashion that wherever the transmitter in the building, the AOA remains small in order to satisfy minimum error conditions.

Multipath waves and far field conditions are two other parameters affecting the DF performance. Accuracy of the system in case of locating it outside is higher compared to case of locating it inside the building. This is because of the walls, windows and other equipments reflecting the incident electromagnetic wave to create multipath waves. So, it is suggested to locate the DF systems outside of the building for better conditions in terms of multipath effect. However, multipath waves still affect the performance in case of outdoor location of the DF. But this problem can be overcame by calibrating the system depending on the environmental conditions. Another important issue is that the antenna system should be sufficiently far away from the transmitter so that the far field conditions are satisfied and the assumption of planar wave at antenna terminals is hold.

After modeling our DF system with various tests, we simulated a location finding system composed of three equivalent DF systems and measured its performance in computer environment. From the data we obtained by various experiments and simulations, the suggested DF system will work reasonably well for the location of a transmitter inside a building. The proposed system is a trade-off between highly sophisticated, but not easily deployable system such as a phased array DF and a simple amplitude comparison DF system. Accuracy of the system will be higher compared to that of a phased array system, and also will have an ease of implementation compared to that of a phased array system.

More complex direction finders with more number of sensors may be implemented and tested in the future. The overall performance of the location finder can also be optimized by increasing the number of direction finders around the building. The presented settlement of the DF systems around the building may also not represent the optimum settlement. Some other forms can be tried to find the optimum localization of the DF systems.

As a future work, the mutual coupling between antenna elements should be investigated deeply. The inclusion of coupling effect into the calculations will probably improve the performance to a higher degree.

It is also possible to design a two coordinate direction finder by inserting an extra antenna to determine both the azimuth and elevation angles of arrival. So that, in addition to the azimuthal information, we may also estimate the floor of the building from which the emitter is transmitting with the help of elevation angle of arrival.

6. REFERENCES

[1] Herndon H. Jenkins, *Small Aperture Radio Direction Finding*, Artech House, 1991.

[2] P. J. D. Gething, *Radio Direction Finding and Superresolution*, IEE Electromagnetic Waves Series, Vol.33., 1991.

[3] Joseph D. Moell and Thomas N. Curlee, *Transmitter Hunting*, McGraw-Hill, 2001.

[4] Jay, Frank, "IEEE Standard Dictionary of Electrical and Electronic Terms," *ANSI/IEEE Standard 100-1988*, New York: Institute of Electrical and Electronic Engineers, Inc., 1988.

[5] Boyd, J.A., D.B. Harris, D.D. King, and H. W. Welch, *Electronic Countermeasures*, Los Altos, CA: Peninsula Publishing: 1978, Chapter 10: "Direction Finding" by L.A. deRosa, pp. 10-3- 10-4.

[6] John D. Kraus and Daniel A. Fleisch, *Electromagnetics with Applications*, McGraw-Hill, 1999, pp. 211-214.

[7] Simon Haykin, *Communication Systems*, John Wiley & Sons, 1994, pp. 151-152.

[8] David M. Pozar, *Microwave Engineering*, John Wiley & Sons, 1998, pp. 401-402.

[9] Baruch Berdugo, Miriam A. Doron, Judith Rosenhouse, Haim Azhari, "On Direction Finding of an Emitting Source from Time Delays", *Journal of the Acoustics Society of America (JASA)*, Vol.105, pp. 3355-3363, 1999.

[10] Chye Huat Peck and Philip J. Moore, "A Direction Finding Technique for Wide Band Impulsive Noise Source", *IEEE Transactions on Electromagnetic Compatibility*, Vol.43, No.2, May 2001, pp. 149-154.

[11] Xiaoming Lai and Hans Torp, " Interpolation Methods for Time-Delay Estimation Using Cross-Correlation Method for Blood Velocity Measurement", *IEEE Transactions on Ultrasonic, Ferroelectrics and Frequency Control*, Vol. 46, No. 2, March 1999, pp. 277-290.

[12] N. Levanon, "Interferometry Against Differential Doppler: Performance Comparison of Two Emitter location airborne systems", *IEE Proceedings*, Vol. 136, No. 2, April 1989, pp. 70-74.

[13] Y. T. Chan, Jack M. Riley and J. B. Plant, "A Parameter Estimation Approach to Time Delay Estimation and Signal Detection", *IEEE Transactions on Acoustics, Speech, Signal Processing,* Vol. 28, No. 1, February 1980, pp. 8-15.

[14] D. C. Jenn and P. E. Pace, *Symmetrical Number System Phase Sampled Interferometer Direction Finding Antennas*, Naval Postgraduate School Monterey, California, February 20, 1998.

[15] RF Products, WN-001 Web Note, "Questions & Answers: A User's Guide To Radio Direction Finding Basics", www.rdfproducts.com/wn001_apl_01.pdf. , December 1998.

[16] RF Products, WN-002 Web Note, "Basics of the Watson-Watt Radio Direction Finding Technique" , www.rdfproducts.com/wn002_apl_01.pdf. , December 1998.

[17] RF Products, WN-003 Web Note, "Questions & Answers: A User's Guide To Radio Direction Finding Receivers and Bearing Processors" , www.rdfproducts.com/wn003_apl_01.pdf , December 1998.

[18] RF Products, WN-004 Web Note, "A Comparison of the Watson-Watt and Pseudo-Doppler DF Techniques" , www.rdfproducts/wn004_apl_01.pdf , April 1999.

6. REFERENCES

[1] Herndon H. Jenkins, *Small Aperture Radio Direction Finding*, Artech House, 1991.

[2] P. J. D. Gething, *Radio Direction Finding and Superresolution*, IEE Electromagnetic Waves Series, Vol.33., 1991.

[3] Joseph D. Moell and Thomas N. Curlee, *Transmitter Hunting*, McGraw-Hill, 2001.

[4] Jay, Frank, "IEEE Standard Dictionary of Electrical and Electronic Terms," *ANSI/IEEE Standard 100-1988*, New York: Institute of Electrical and Electronic Engineers, Inc., 1988.

[5] Boyd, J.A., D.B. Harris, D.D. King, and H. W. Welch, *Electronic Countermeasures*, Los Altos, CA: Peninsula Publishing: 1978, Chapter 10: "Direction Finding" by L.A. deRosa, pp. 10-3- 10-4.

[6] John D. Kraus and Daniel A. Fleisch, *Electromagnetics with Applications*, McGraw-Hill, 1999, pp. 211-214.

[7] Simon Haykin, *Communication Systems*, John Wiley & Sons, 1994, pp. 151-152.

[8] David M. Pozar, *Microwave Engineering*, John Wiley & Sons, 1998, pp. 401-402.

[9] Baruch Berdugo, Miriam A. Doron, Judith Rosenhouse, Haim Azhari, "On Direction Finding of an Emitting Source from Time Delays", *Journal of the Acoustics Society of America (JASA),* Vol.105, pp. 3355-3363, 1999.

[10] Chye Huat Peck and Philip J. Moore, "A Direction Finding Technique for Wide Band Impulsive Noise Source", *IEEE Transactions on Electromagnetic Compatibility*, Vol.43, No.2, May 2001, pp. 149-154.

[11] Xiaoming Lai and Hans Torp, " Interpolation Methods for Time-Delay Estimation Using Cross-Correlation Method for Blood Velocity Measurement", *IEEE Transactions on Ultrasonic, Ferroelectrics and Frequency Control,* Vol. 46, No. 2, March 1999, pp. 277-290.

[12] N. Levanon, "Interferometry Against Differential Doppler: Performance Comparison of Two Emitter location airborne systems", *IEE Proceedings*, Vol. 136, No. 2, April 1989, pp. 70-74.

[13] Y. T. Chan, Jack M. Riley and J. B. Plant, "A Parameter Estimation Approach to Time Delay Estimation and Signal Detection", *IEEE Transactions on Acoustics, Speech, Signal Processing,* Vol. 28, No. 1, February 1980, pp. 8-15.

[14] D. C. Jenn and P. E. Pace, *Symmetrical Number System Phase Sampled Interferometer Direction Finding Antennas*, Naval Postgraduate School Monterey, California, February 20, 1998.

[15] RF Products, WN-001 Web Note, "Questions & Answers: A User's Guide To Radio Direction Finding Basics", www.rdfproducts.com/wn001_apl_01.pdf. , December 1998.

[16] RF Products, WN-002 Web Note, "Basics of the Watson-Watt Radio Direction Finding Technique" , www.rdfproducts.com/wn002_apl_01.pdf. , December 1998.

[17] RF Products, WN-003 Web Note, "Questions & Answers: A User's Guide To Radio Direction Finding Receivers and Bearing Processors" , www.rdfproducts.com/wn003_apl_01.pdf , December 1998.

[18] RF Products, WN-004 Web Note, "A Comparison of the Watson-Watt and Pseudo-Doppler DF Techniques" , www.rdfproducts/wn004_apl_01.pdf , April 1999.