PRECISE POSITIONING WITH AM RADIO STATIONS

by

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A Thesis
Submitted to the Faculty of Graduate Studies
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ABSTRACT

Precise low-cost navigation is required for many industries such as farming and mining. Such a system is proposed that utilizes the existing carrier from AM radio stations. A single stationary reference station is used to monitor the phase of the carrier from many AM stations and to broadcast this information to passive mobiles. A digital technique is developed that uses direct conversion wide-band receivers and a Discrete Fourier Transform to measure the phase of the signal very accurately. Sources of error in measuring phase with this technique are investigated. They include quantization error, DC offset error, Direct Digital Synthesis round-off error as well as something called 'end-effect'. The technique was capable of measuring the phase of the carrier to 0.01 to 0.1 degrees even under full modulation.

Field tests were done to determine the amount of range error that would result from propagation differences in the paths from the AM transmitter to the reference and mobile stations. The results from these preliminary tests would suggest that the technique is capable of sub-meter accuracy.

ACKNOWLEDGMENTS

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This work is dedicated to the memory of my father, whose pioneering spirit was always anxious to try something new.

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LIST OF ACRONYMS

A/D	Analog to Digital converter (also **ADC**)
AM	Amplitude Modulation
CW	Continuous Wave
DC	Direct Current
DDS	Direct Digital Synthesis
DFT	Discrete Fourier Transform
DF	Direction Finding
DGPS	Differential Global Positioning System
FCC	Federal Communication Commission
FFT	Fast Fourier Transform
FM	Frequency Modulation
FPGA	Field Programmable Gate Array
GPS	Global Positioning System
IF	Intermediate Frequency
KS/s	1000 Samples per second
LO	Local Oscillator
LOP	Line of Position
LORAN	LOng RAnge Navigation
MAC	Mulitply and Accumulate
MS/s	1,000,000 Samples per second
PC	Personal Computer
PN	Pseudo Noise
PLL	Phase Locked Loop
RADAR	RAdio Detection And Ranging
RAM	Random Access Memory
RF	Radio Frequency
ROM	Read Only Memory
SONAR	SOund Navigation and Ranging
TDM	Time Division Multiplexing
PE	Phase Error
UHF	Ultra High Frequency
VCO	Voltage Controlled Oscillator
VCXO	Voltage Controlled Crystal Oscillator
VHF	Very High Frequency (30 MHz to 300 MHz.)

CHAPTER ONE

INTRODUCTION

Navigation and the need for positioning information is as old as civilization itself. The compass, stars and the position of the sun were used by sailors to obtain a fix of their position in terms of latitude and longitude. More recently radio and satellite techniques have made it possible to locate vehicles, ships and aircraft much more precisely. Within the last few years the Global Positioning System (GPS) has dominated the navigation and positioning scene.

1.1 HISTORY OF NAVIGATION

Technological advances in almost every field came about because of the need to achieve more capabilities than those currently available. These advances established newer and increased capacities; which triggered a further need for technological advancements. The development cycles of these technologies in turn ushered in today's modern world of sophistication and technological advances used in performing various tasks more efficiently. One such development cycle was that of navigation. Its various techniques and methods for achieving new capacities prompted the need for more precise and reliable positioning. This thesis addresses this need and, proposes a new technique which utilizes AM broadcasting, an old technology, to satisfy a newer need in positioning.

In medieval time European people were relatively stationary; there was no need to travel large distances. As trade grew and the exchange of goods with other settlements became more common, people traveled farther distances. Consequently the need for position location (the knowledge of present location with reference to a known location) originated. The knowledge of landmarks and coastal features was used to establish position location during early land and coastal trading missions. As trade routes became more extensive, this technique was enhanced by creating man-made landmarks to guide other traders and travelers to distant locations. At first, directions for the use of these landmarks were passed on orally from master to apprentice. Record keeping of these directions was the next step towards navigating efficiently.

As voyagers ventured across the ocean, the use of landmarks became less practical and the need for better techniques arose. The magnetic compass, introduced in the 12th century, was the main navigational aid to Mediterranean seamen. This led to the technique of dead-reckoning, derived from the term deduced reckoning, which used the ship's course and speed to estimate current position. This estimation was not sufficiently accurate for long voyages, so navigation through the observation of heavenly bodies, particularly the sun, the moon, and the pole star was used. Techniques of celestial navigation enabled 15th century Portuguese seamen to sail beyond Mediterranean waters. These were the early days of the "Age of Discovery" in which seamen carried out methodical exploration of the Atlantic. During this era, the technique of finding latitude and longitude from astronomical observations was established. When out of the sight of land, seamen could determine a ship's position with increased reliability. These techniques became the basis of modern navigation.

The need for determining exact position led to other methods and development of new tools and devices. The sextant and an instrument called "Jacob's staff" had calibrated scales and a sight which were used to line up a heavenly body and the horizon, giving the longitude and latitude of the current location. In the mid 1700s, the first official British nautical almanac was published to help sailors determine longitude from lunar observations. At about the same time, accurate time-keeping devices such as the chronometer aided mariners by providing reliable and accurate determination of latitude and longitude.

In the early 1800s, the concept of "Line of Position" was introduced, which was basically a line indicating a series of possible positions of a craft. The point of intersection of two or more of these lines was known as the 'fix'. This technique of position fixing is the basis of today's modern navigation, the only difference being in the methods of obtaining the lines of position and the accuracy obtained. The need for more accurate and faster readings led to more technological advancements. Hence devices such as the gyrocompass and sonic depth sounders were developed in addition to the existing techniques for position location.

In the early 20th century, the first radio aid to navigation was invented. A radio transmitted a time signal which was used to determine longitude; it in effect replaced the chronometer. Later on with more advancements in technology, the ship's bearings could be determined from two land-based radio transmitters using the line of position technique. Radio techniques had a definite advantage over observation methods in that they were not affected by weather conditions such as fog or cloudiness.

During World War I and after, technological advances in the field of radio navigational techniques and electronics took place rapidly to respond to more stringent navigational needs for aviation. Much faster position location was required during World War II. The problem of enemy detection led to the invention of RADAR (radio detection and ranging), using high frequency radio energy. The RADAR system illuminated the air space with radio waves, and when a target such as an aircraft entered the air space, it scattered and reflected a small part of the radio energy back to the RADAR's antenna. This small reflected signal was used to determine the range and bearing of aircraft.

In the 1940s and 1950s the technique of hyperbolic navigation came into use. This method involved lines of position in the form of hyperbolae. It was based upon the accurate measurement of the difference in time taken by the radio signals from two fixed transmitters to reach the receiver. This hyperbolic technique led to systems like LORAN (LOng RAnge Navigation), OMEGA, and even to the present day technology of GPS (Global Positioning System).

1.2 Range Measurement

Typical navigation systems use either direction (theta) or a range (rho), to calculate a position relative to a number of fixed beacons. Direction Finding (DF) is simple but is typically accurate only to an angle of one degree or more with site errors [1]. In absolute terms this is not that accurate. The accurate navigational systems employ ranging or rho measurements.

The consistent speed of the propagation of waves is the basis for ranging systems. SONAR ranging, infrared ranging and radio frequency ranging are three common range measurement techniques used today. Depending on the frequency of the periodic wave used, these techniques are best suited for certain applications. A brief explanation of some of the major ranging systems is given in [50] and a few are listed below:

- **SONAR range measurement**: The SONAR (an acronym for SOund NAvigation and Ranging) method is based on the reflection of underwater sound waves traveling at the rate of 1,500 m/sec (5,000 feet/sec.) A typical SONAR system emits an ultrasonic wave in the frequency range anywhere from 20 kHz to 1 GHz (audible sound waves extend from 30 to 20,000 Hz.). The attenuation of sound waves increases with the frequency used; higher frequency waves attenuate faster. The sound waves are subject to refraction, reflection, and scattering upon hitting a solid object. A SONAR system transmits a short pulse of sound energy using an underwater hydrophone; the time taken by the waves reflected by a target to reach the transmitter indicates the position of the target. The applications of this method lie mainly in underwater detection and location of objects by acoustical echo. The extent and effectiveness of SONAR can be affected by turbulence in the water, unwanted reflection by the surface, and other sources of noise.

- **Infrared Laser Range Measurement:** Emission of energy as electromagnetic waves in the portion of the spectrum just below the visible red is infrared radiation. The speed of infrared waves traveling through air is the same as that of the speed of light (3×10^8 m/s). The infrared LASER (Light Amplification by Stimulated Emission of Radiation) is generated by inducing electrons to fall to a lower energy level in a synchronized manner, producing coherent photons which can be focused into a narrow beam of infrared light. To measure distance, this beam of infrared light is transmitted and reflected from a highly reflective and focused prism arrangement. The amount of time required for the light to return to the transmitter is converted to the range, i.e. distance traveled. This technique can measure distances very accurately, usually in the order of centimeters. Due to the highly accurate measurement capability, the main application of infrared ranging has been in the field of commercial surveying. The main limitation of this technique is that line of sight is required and that distortion or attenuation of the reflected wave due to any atmospheric condition leads to errors. Presence of heat waves rising from the ground or dust clouds may also result in reduced accuracy or inoperability.

- **RF (Radio Frequency) range measurement:** RF waves extend from 3 kHz to 1000 GHz and the different frequencies have different characteristics. Diverse navigational applications have utilized these differences, and as noted by Dodington[14] " . . . *there are, consequently, many different systems in use, none simultaneously satisfying the requirements for high accuracy, large service area, and low cost.*" All RF signals travel at, or just slightly lower than, the speed of light. This predictable RF propagation velocity is used to measure distance. Measurement of propagation delay from a transmitter to a receiver is directly proportional to the distance between the transmitter and the receiver. Because signaling waveforms that modulate the carrier are also functions of time, the time difference in a signaling waveform in traveling from a transmitter to a receiver can also be used directly to measure distance. The limitation of any RF positioning system is the result of interference from unwanted reflection, fading, and multipath.

RF ranging techniques are currently the most common methods used in navigational systems. A brief investigation of the most commonly used RF ranging applications will illustrate their particular characteristics.

Types of RF Ranging

The different methods used to measure propagation delay of a periodic wave through air result in systems or techniques with different limitations and advantages. The following sections describe briefly the principle and the capability of some common RF ranging techniques:

Radar

This is one of the most commonly known applications of radio frequency ranging. This method was originally developed for military applications. The property of RF waves reflecting from conductive surfaces is utilized. A directional antenna is used to transmit a pulse of RF wave towards a conductive target and the time required for the reflection caused by the target to return to the antenna is then measured. This measured time is a representation of the distance of the target from the antenna. The target is not aware of its detection and no special hardware is required at the target (passive system). This technique is particularly useful for military applications. However, the accuracy of the received reading is normally on the order of tens of meters. Accuracy is limited by the ability of the system to accurately measure the time difference between transmission and reception of a radar pulse. A further limitation of this system is its inability to distinguish signals that are reflected by erroneous objects.

Multiple Frequency / Tone Ranging

This technique uses multiple coherent tones that modulate a carrier. All tones are started at the same phase. At a point from origin, the tones have a phase relationship which is indicative of the range. The collective phase information can be used to reduce the ambiguities. Ambiguity is a problem with single frequency continuous wave systems which are discussed next.

CW (Continuous Wave) Ranging

In this technique, a carrier is transmitted with a known phase. The carrier is reflected from a stationary transponder, and the phase of the reflection received is compared to the phase of the transmitted signal. The phase difference is proportional to the distance traveled by the carrier from the transmitter to the transponder and back. A receive-only mobile can measure the phase difference between the transmissions from both the original transmitter and the transponder. The phase difference determines a hyperbolic line of position for the mobile. Phase differences measured from additional transponders provide additional hyperbolic lines of position; their intersection provide the 'fix' or the position of the mobile.

Highly accurate positioning can be achieved if accurate phase measurements can be made. A CW system has been developed using an accurate phase-measurement technique to achieve position accuracy to within $\pm$ 15 cm [18]. This accuracy is obtained by measuring the phase with digital techniques and by actively compensating for various circuit delays [19].

CW systems are associated with a problem called range ambiguity. Measurement of the phase difference reveals only the fraction of the wavelength; the integer number of wavelengths (mod 2π) remains unknown, and thus the solution is ambiguous. A remedy to this dilemma would be to have the range of operation limited to less than one wavelength. The more practical solution involves starting from a known position, 'initializing', and then tracking the integer number of wavelengths in the range as the mobile moves. This is called 'cycle tracking'. Another limitation of the CW system is that since it operates at only one frequency, the effects of multipath and fading can render the system inoperable in certain areas.

Spread Spectrum Ranging

Spread spectrum techniques were initially developed by the military to send data and messages which would not be affected by jamming (intentional interference) and would not be detected by the enemy. This is done by transmitting the information over a bandwidth that is much larger than normally required. Consequently, the name 'spread spectrum' is used. A Pseudo-random Noise (PN) pattern known to both the transmitter and the receiver is used. The transmitter modulates its carrier with the PN pattern, and the receiver uses the same PN pattern to detect and match the incoming signal. The receiver is said to collapse or 'despread' the signal. Since the carrier energy is spread over a wide spectrum, the effects of multipath and fading are much less than for a comparable CW system.

Spread spectrum systems have applications in advanced communication and in position location. The technique is used in today's GPS which was also developed for military applications—to guide missiles and aircraft during tactical operations. There are three different types of spread spectrum systems: chirp, direct sequence and frequency hopping.

Chirp spread spectrum utilizes a modulating signal that linearly ramps the carrier across an extensive part of the spectrum very rapidly, resulting in a wide transmit bandwidth. This technique is used in some RADAR applications to reduce power [17], but because of difficulties with correlation, this scheme is not commonly used in RF ranging systems.

Direct sequence spread spectrum systems use a binary code to modulate the carrier to achieve a wider bandwidth. The propagation delay of the code, as seen at the receiver, is measured to determine a position. The code cycle and rate determines the performance of a direct sequence spread spectrum system. The ranging resolution is proportional to the bit rate of the binary code.

In frequency hopping spread spectrum systems, a binary code shifts the carrier frequency in a discrete pattern. The code rate employed in these systems is far lower than that of direct sequence spread spectrum systems. Although ranging can be achieved just as in direct sequence systems, position resolution is poorer because of the lower code rates. This technique is mainly used for securely transmitting voice and data.

1.3 PROPOSED AM RADIO POSITIONING SYSTEM

The applications of navigation which were developed mainly for military exigencies have now been extended to many civilian uses such as sports and mining. The application most closely linked to early navigation is surveying. The accuracy needed for surveying and other commercial applications has led to further advancements in technology. More accurate range measurement techniques were developed to obtain accurate position location. Accurate positioning is needed mostly in applications like precision farming, mine sweeping, and driverless vehicles. In mine sweeping, mapping the location of explosive charges requires a high degree of accuracy. Navigating a driverless vehicle to perform repetitious or dangerous tasks also requires high accuracy.

In farming, where repetitious work is involved and expensive chemicals are used to improve yield, it is necessary to precisely guide the operator to avoid waste of time and chemicals. Farming , in its current state, incorporates a series of operations that could be improved tremendously with the use of an accurate positioning system [41]. A complete treatment of this subject is given in the literature [37]--[42]. The following is a list of areas in farm operations that could be improved:

Lateral Overlap

A study was conducted [42], that showed that typical lateral overlap in farm operations was typically 9 to 10 percent of the implement's width. This costs a typical farmer several thousands of dollars annually. Positioning information is required for driving accurately to reduce this overlap.

Turning Overlap

Turns are required at headlands and at the perimeters of obstacles. Farmers currently make the path they are to follow in an ad hoc fashion. The total distance traveled to work a typical field of 160 acres could be shortened by 15 percent. This is shown by Liu [30],[31].

Night Spraying

Spraying at night can reduce the amount or rate of chemical required [21],[35]. The efficacy of the chemical is higher at this time and the winds are generally lighter.

Variable-Rate Application

Overall inputs could be reduced if the application rates matched the required site requirements. This results in saving the farmer money and in being less harmful to the environment.

Spatial Variability and Instantaneous Yield

There is much interest in treating each part of the field as an independent cell [38].

Grid Planting

If plants were planted in a specific grid pattern, the plants themselves could act as mini-guidance beacons to visually guide application equipment [40]. Only plants positioned exactly in the grid position would be considered as good plants; plants in any other position would be considered weeds.

Small Automated Tractors

An accurate positioning system is the key to autonomous robotic equipment. This equipment would be more precise and more efficient in carrying out the field operations.

An economic analysis [41] of a typical 2000 acre Western Canadian farm shows that a current annual profit of $10,000 could be increased to a profit of $80,000 using the above techniques which in turn rely on precise positioning technology. What is needed is a low-cost, precise positioning system [35].

There are many industries that could use a cost effective and accurate positioning system to perform their tasks more efficiently. Some of these industries include mining, logging, dredging, and farming. Being able to monitor the location of a small child, a paroled convict, or a mentally challenged patient would also be valuable. Positioning information is important, but the positioning system must be cost effective and convenient. Currently the Global Positioning System (GPS) is considered by many to be the answer to many of the positioning needs, but for some industries it is too expensive and too inaccurate [35]. With Differential GPS, the accuracy can be improved to 3 meters using a local differential tower [53].

Even though GPS is extremely popular, it too has shortcomings:

- It is difficult and expensive to achieve sub-meter accuracy when motion is involved.
- It uses a high frequency signal in the upper UHF that is easily blocked by trees, buildings or terrain.

The problem is that there is not available, an inexpensive, accurate positioning system that could be used to navigate and position moving vehicles and to locate people when they are in buildings or surrounded by foliage or other obstacles. To this end, such a positioning system is being proposed:

This thesis investigates the use of using existing AM radio stations as beacons in a continuous wave ranging system.

The Question :

"Is it possible to use a single reference station and the existing AM broadcast station transmissions to establish a positioning system with 15 cm accuracy and costing less than the existing DGPS?"

PROPOSAL:

A single fixed station and several AM radio stations could be used to determine an accurate fix using differential ranging. Since the system would use existing AM radio broadcast sites, they would come with no cost. The cost of a single fixed station and the mobile receiver would be the only real costs. Due to the nature of the frequency of transmission of the AM sites; it would be possible to determine a fix inside a building or in trees—essentially anywhere an AM signal could be received.

The proposal brings forth some interesting challenges and questions. Because of the long wavelength of the AM signals' carrier, it is imperative that a very accurate phase measurement technique be utilized. Phase must be measured to within a fraction of one degree.

The stations are not synchronized; the reference station must employ techniques that will in essence synchronize the stations. The stations are at different frequencies; yet the range is determined from a phase measurement. A technique must be devised to measure and compare the phase of signals that are not of the same frequency.

In the process of developing this technique, it became evident that two issues were of dominant concern:

1. Extremely accurate phase measurement;

2. The degree of phase distortion of the carrier of an AM signal over two different paths, these being to the reference station and to the mobile.

Chapter Two explains the principle of operation of the proposed technique; Chapter Three deals with practical issues of the design and implementation of the technique; Chapter Four investigates the second issue above—the degree of phase distortion of the AM signal.

CHAPTER TWO

OPERATING PRINCIPLE OF AN AM RADIO POSITIONING SYSTEM

This chapter explains how a positioning system, employing commercial AM radio stations and a single stationary reference station, can be used to determine position fixes for mobile stations.

2.1 PROPAGATING WAVES

"Wavefront" and "wavelength" are defined in the following way. A wavefront can be considered as an imaginary surface. On every part of this surface, the wave has the same phase. The wavelength is the shortest distance between two wavefronts having the same phase. The distance must be measured perpendicular to the wavefronts—along the line that represents the direction of travel. The length between waves (wavelength) is given by:

$$\lambda = v / f \tag{2.1}$$

where:

λ = wavelength (m),

v = velocity of the wave (m/s),

f = frequency of wave (Hz).

All RF ranging systems rely on a consistent propagation velocity of the radio waves, that being the speed of light, $c = 3 \times 10^8$ m/s. Therefore, for waves traveling in free space (and near enough for waves traveling through air), the wavelength is:

$$\lambda \text{ (m)} = 300 / f \text{ (MHz)} \tag{2.2}$$

The delay of a RF signal in traveling from point A to point B is:

$$t = d/c \tag{2.3}$$

where t is the delay(s), d is the distance between A and B (m) and c is the speed of light.

Commercial AM radio stations have a signal spectrum that has a carrier flanked by two side bands. The carrier, even at full modulation, represents at least 50 percent of the transmitted power and depending on the modulating signal, usually 66 percent or more. It is this carrier that will be used for positioning.

Although the AM band has radio stations that have carrier frequencies from 530 kHz to 1650 kHz, the nominal frequency that will be used in numerous examples to follow will be 1000 kHz which has a corresponding wavelength of 300 m or 30,000 cm.

2.2 Basic Principle of Measuring Range

The supposition is that there is an AM radio station that is transmitting a single frequency (the carrier) to two stations as shown in Figure 2.1. Also (Figure 2.2), it is noted that both the fixed reference station, herein called the *reference*, and the mobile station, herein called the *mobile* have counters that are clocked by the passing wavefront. Now if both counters were initially set with the same value and if the mobile remained stationary, the counters read at any later time, would have an identical value.

If, however, the mobile moved one wavelength closer to the AM station, as is shown in Figure 2.1, the value found in its counter would be one greater than the value in the counter of the reference. The difference in value of the two counters would be indicative of the distance the mobile moved towards the transmitter. The distance traveled would be directly determined by comparing the value in the counters. It is important to remember though, that the counters must be read simultaneously. This is a challenging task.

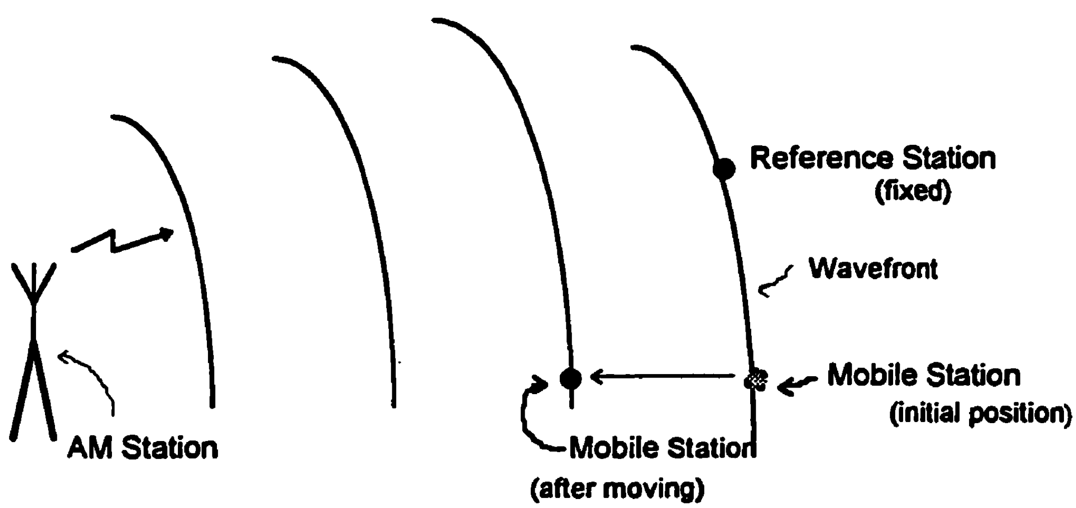

Figure 2.1 Reference Station and Mobile Station Detecting an AM Radio Transmission

In practice one needs to measure a fraction of a wavelength and thus the count stored between wavefronts in the mobile counter. Note also that all counts (or more appropriately differences in counts) are relative to the fixed reference station. Thus the velocity or direction of the mobile does not affect the range measurement. Though there could be a Doppler shift in frequency, due to the reference station being fixed the range measurement is independent of this shift. This can be shown more generally by considering that the mobile moves a distance d, at a velocity v, towards the AM station. Let t_m be the time it takes to travel this distance. During this time of t_m the number of wavefronts crossing the reference would be $c\ t_m / \lambda$ and the number of wavefronts crossing the mobile would be $(c + v)\ t_m / \lambda$. The difference in wavefront crossings between the mobile and the reference would then be:

$$diff = (c + v)\, t_m / \lambda - c\, t_m / \lambda \tag{2.4}$$

Substituting d/v for t_m one gets

$$diff = d / \lambda. \tag{2.5}$$

The difference between the counters in the mobile and the reference would be diff which is the distance the mobile has traveled. It is independent of the velocity of the mobile.

Assuming that the counters were read simultaneously, the range distance of the mobile to the AM station would be:

$$Range\_Distance = (Ref\_Count - Mob\_Count) \times \lambda + Reference\_Range \tag{2.6}$$

where:

Range_Distance is the distance from the AM station to the mobile (meters).

Ref_Count is the latched counter value in the Reference

Mob_Count is the latched counter value in the Mobile

λ is the wavelength of the AM station's carrier (meters)

Reference_Range is the distance between the Reference and the AM station (meters)

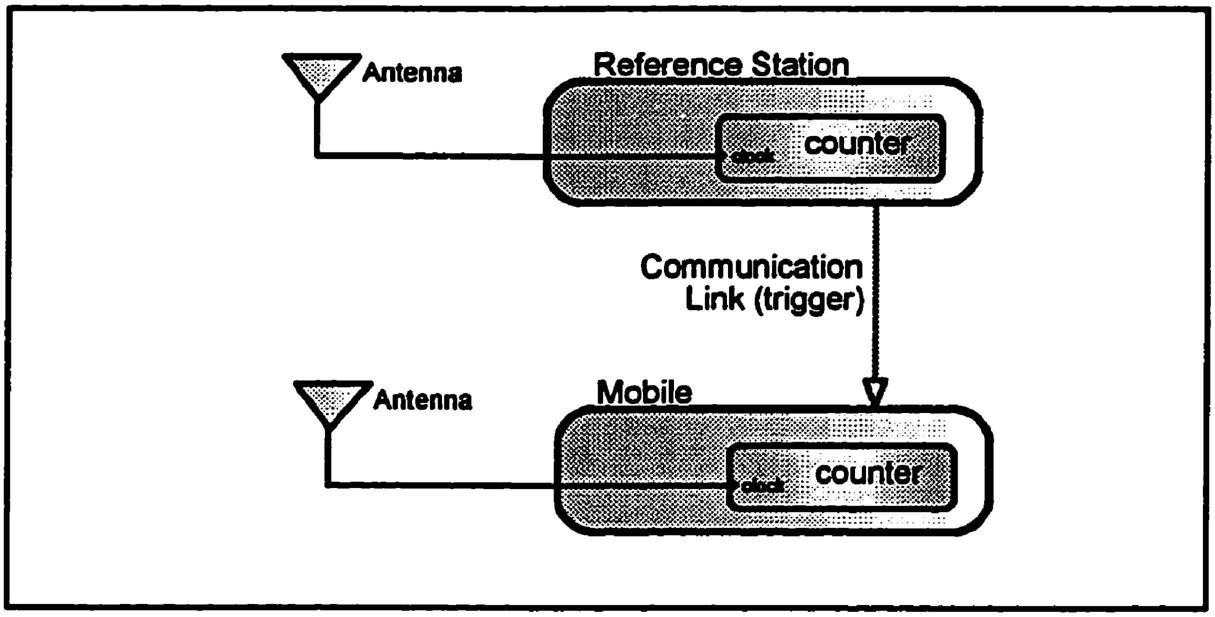

Figure 2.2 Reference and Mobile Counting the Passing AM Radio Wavefronts

2.3 DELAY THROUGH THE COMMUNICATION LINK

If the counters in Figure 2.2 were read at precisely the same time, the difference in the count between the reference station and the mobile would be directly related to the change in the difference in distance the two were from the AM station. It is not possible to have the two counters read simultaneously since the reference and the mobile are separated by some distance, assumed unknown. Thus the propagation time of the trigger signal is unknown. Not only does this propagation delay need to be accounted for but the delay due to the entire communication link between the reference and mobile needs to be considered.

2.4 THE HYPERBOLIC SOLUTION SET

The value of the mobile's counter represents the difference of two unknowns, the propagation delay from the AM station to the mobile and the propagation delay from the reference to the mobile. There are sets of propagation delays that can produce a constant difference -- they are hyperbolic. If the constant difference is c, the distance from the AM station to the reference is d_{AM_ref}, the distance from the AM station to the mobile d_{AM_mob}, and the distance between the mobile and reference is d_{ref_mob}; then the hyperbolic relationship exits in two dimensions:

$$c = (d_{AM\_ref} + d_{ref\_mob}) - d_{AM\_mob} \qquad (2.7)$$

To understand how a solution is obtained from a set of hyperbolae, it will be assumed that the counters were read with the same count. What does this mean? It could mean that the two stations were physically in the same place, or it could be that the mobile was one wavelength further from the AM station and, at the same time, a distance of one wavelength from the reference. This is shown as a '0' in Figure 2.3 at coordinate location (5,0). All the points on the line, starting at the reference and extending to the right would be the set of possible position solutions for the mobile.

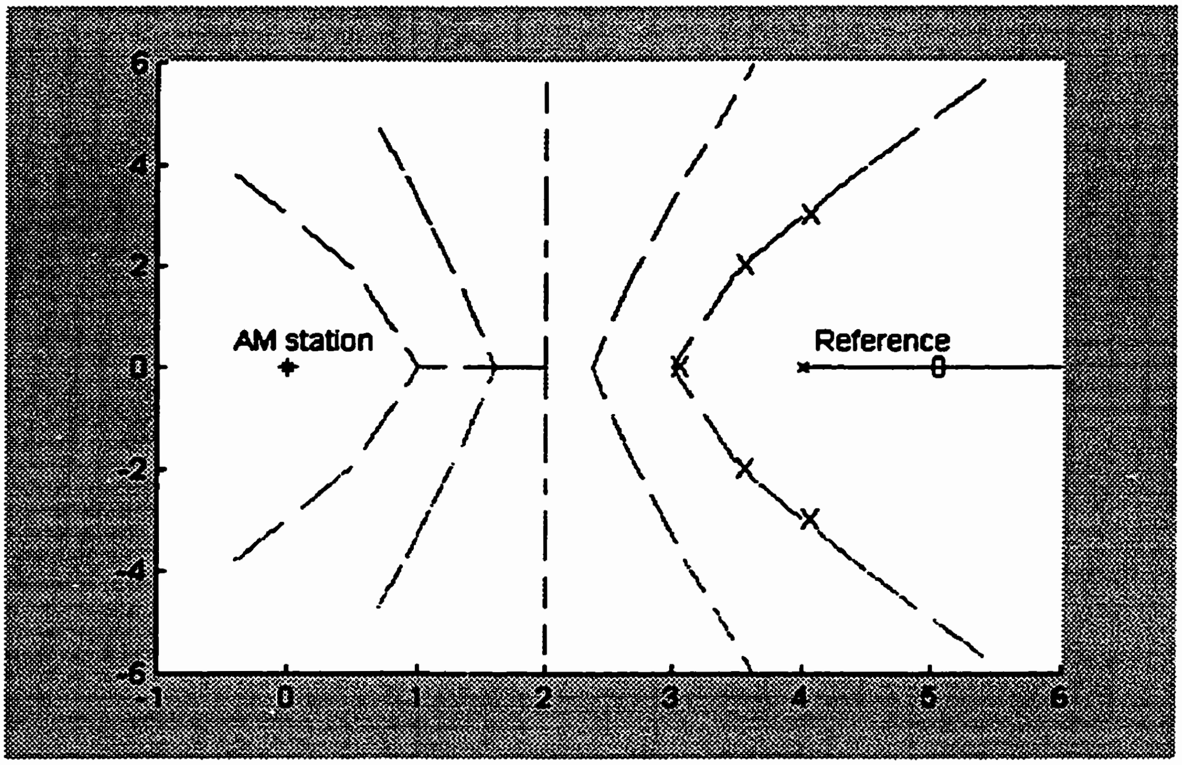

Figure 2.3 Hyperbolic Solutions

Next assume that the mobile count is two larger than the reference count; the difference is two. This could mean that the mobile is at (3,0) as shown in Figure 2.3, or it could be at any other position that has a difference of two wavelengths. This set of solutions is noted in Figure 2.3 with 'X' . The set of solutions forms a hyperbola. Count differences of 3, 4, etc. would form other hyperbolic solutions. It is clear then that there is a family of hyperbolae that satisfy the set of count differences.

2.5 Measuring Fractions of a Cycle

There are several aspects of the technique that require further scrutiny. In the scenario above, only integer numbers of wavelengths were counted. To achieve the desired accuracy in range measurement, it will be necessary to measure a fraction of a cycle, i.e., the phase of the sinusoid.

A technique has been developed [29] that can be used to measure the fraction of a cycle. This is now explained briefly. Each receiver, of the mobile and the reference, directs the carrier to a Phase-Locked Loop (PLL) as shown in Figure 2.4 (with a divide by 256 in the feedback loop). The Voltage Controlled Oscillator (VCO) then operates at a frequency that is 256 times faster than the original carrier. If the VCO provides the clock to the counters and the count is latched into a register at the defined measurement time, then this latched count will have 8 bits that represent the fraction of the cycle.

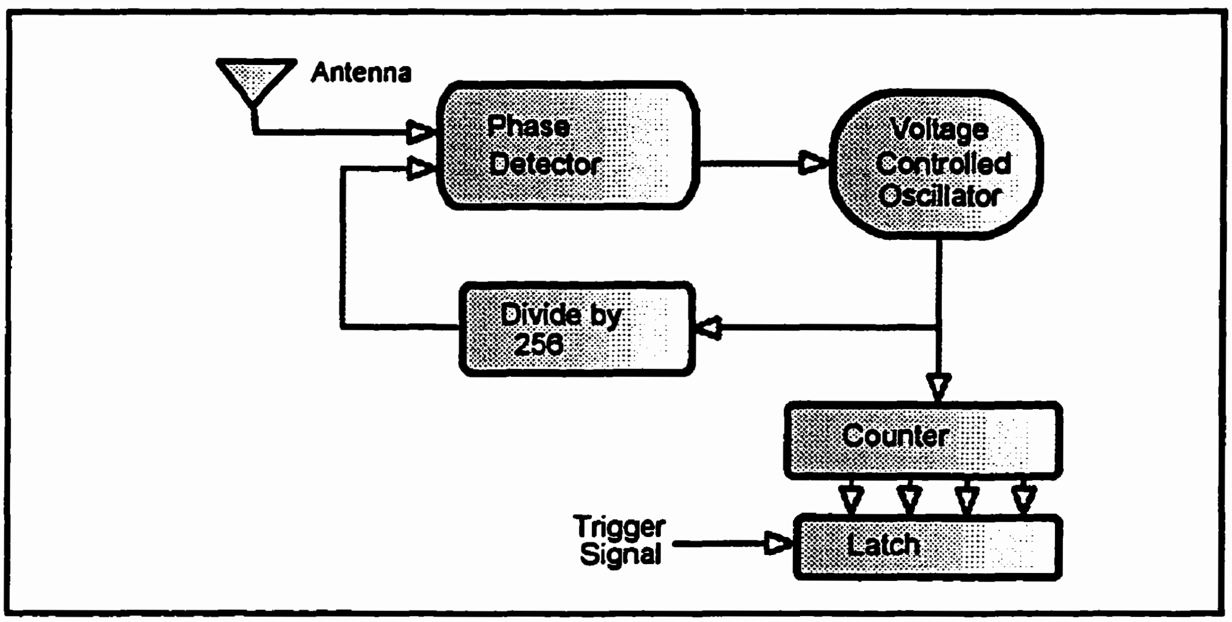

Figure 2.4 Phase-Locked Loop Measuring a Fraction of a Cycle

2.6 Ambiguity Resolution

Ambiguity is an issue with continuous wave location systems. The counters, without being initialized, can only be used to measure the phase difference of the AM station and the reference. The integer number of the phase difference is unknown. Thus while the phase measurement identifies the fractional position of the mobile relative to two hyperbolic iso-phase lines, it does not indicate which of the lines (integers) should be used. The solution is said to be ambiguous.

The most common technique to eliminate the ambiguity is to 'initialize'. This means that in operating the system, the geographic location of the mobile must be known at the beginning of movement of the mobile so that the counters can be set accordingly. Furthermore, the successive wavelengths must be counted as the mobile is moved relative to the grid like pattern of hyperbolic lines. It also means that a mobile entering the radiation pattern of the transmitters cannot utilize the system to determine its position without being initialized.

Another approach to eliminate ambiguity is described by Hawkins [22]. A gross position fix is obtained by using a much lower frequency, which in turn has a much larger wavelength. The lower frequency is the difference frequency obtained by mixing two higher frequencies. It is suggested that this same principle be applied for the proposed AM positioning system. The lower frequencies would be generated by mixing the signals from the AM stations. The implementation of this ambiguity elimination technique is described in detail in Chapter 3, Section 3.12.

2.7 Communication Link

The communication link is an RF channel that is used to send the trigger time and data from the reference to the mobiles. Because the bandwith of this channel is finite; it is difficult for it to accurately convey the exact trigger time.

Synchronization of the mobile to the reference is critical to the operation of the system. One solution would be to have the mobile and reference stations to initially synchronize and then to count carrier cycles of the link. For example, the counters could be arbitrarily read at the zero crossing of every millionth cycle of the link's carrier. In Chapter Three, it is suggested that a spread spectrum method be used which obviates the initialization.

The communication link is used not only to synchronize the mobile(s), but also to carry the count (phase) data. It is only possible to determine a position fix with the knowledge of the reference's count.

The link carries two important types of information, the time mark -- when the counters should be read -- and the value of the counter in the reference.

2.8 Literature Review

There were many different aspects to review—the origin of the concept, the rational for pursuing the work and some of the specific techniques that would be needed to implement the concept such as phase measurement and antenna design.

The overall concept, which is believed to be original[1], borrowed ideas from differential GPS. Treatments of GPS and DGPS can be found in [51],[53] and many papers from the Journal of the Institute of Navigation. To test the originality of the proposed positioning system a patent search was conducted with the following patents returned [8],[24],[54]. It is believed that our patent does not infringe on those patents. Some parts of the concept are a result of working with precise positioning at Accutrak Systems Ltd[2]. Some of this work includes precise phase measurement by Lem [29] and Fischer [18],[19]. Compensation of the radio delay is necessary for the proposed technique to work and it is explained in the

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[1] At time of writing a patent application has been filed with James Middleton -- U.S. patent attorney

[2] Accutrak Systems Ltd. 3303 Grant Rd. Regina, Saskatchewan, Canada

patent by Fischer and Palmer [18]. A paper presented by Cisneros [9] proposes using the 19 kHz pilot tone of FM stations for positioning; but the 19 kHz. wavelength is long and accurate phase measurement is difficult. As a result, accuracy of several meters were the best that could be achieved. One could speculate on the accuracy of the proposed AM system by scaling the accuracy with the frequency ratio. 1 MHz over 19 kHz would suggest 50 times more accuracy—or in absolute terms: 1/50 x 5 m = 0.010 m. Is this the accuracy that can be expected from the AM system?

The ideas for hyperbola intersection positioning came from papers by Fisher [20] and Poppe [43]. The coordinate determination technique was developed with some hints from Blaha [6], and the development of the code was aided by Press [44]. Improvements to the algorithm may result from Kalman filtering of which there is a practical treatment in Brown[7].

The impetus and motivation for trying to develop such a positioning system came primarily from farming. Rational for precise positioning systems used for farming can be found mostly in [37]-[42] but others also support the need for such systems [21],[35].

Precise phase measurement is an integral part of the proposed concept and there is a wealth of literature in this area. An example which presents a fast real time approach is by Alturaigi [2]. Others include Coffield [10] and Michelleti [36]. These approaches to phase measurement did not produce the accuracy that would be required for the proposed system and did not prove useful other than in presenting the current state of the art.

Experience with other navigational systems suggested that propagation anomalies would be of concern. The literature search for this particular aspect involved looking at a number of papers from IEEE Transactions on Broadcasting, and IEEE Transactions on Antennas and Propagation. Unfortunately, most of the papers found on this topic deal with the attenuation of the signal; very few are concerned with the phase distortion. One example of the study of AM propagation is by Trueman [52]. Basic treatments of scattering and propagation can be found in the classic text of Skolnik [49] and Armel [3]. An atlas of the different indices of refraction can be found in [48], but this has little significance for the differential scheme described.

Loran-C is a low frequency (100 kHz) signal. Its ground wave propagation is examined in a paper by Samaddar [47].

The coherent detection and reproduction of pure Local Oscillator signals will rely on Phase Locked Loops and Digital Synthesizers. A good treatment of this is given by Best [5] .

Antenna design and phase centering will be important. A treatment of this subject is in [25] and [27].

2.9 Research Proposal

The idea of using a differential receiver to cancel distortions from a signal is not new. The Global Positioning System (GPS) has been using this concept for years [51]. There is a major difference in the carrier frequency: GPS is in GHz while AM is in MHz, a difference of three orders of magnitude. There are also known propagation effects that are much different. The higher frequency signal essentially propagates along the line of sight while signals in 1 MHz range can bend and diffract. Multipath effects will be different for the two as well.

The proposed concept rests on the notion that the propagation anomalies will be almost identical for both the mobile and the fixed station. Obviously the farther they are apart, the greater the chance that the anomalies will be more independent. The question to be answered is how much. Most of the literature talks of fading and attenuation of a channel. There has been little work on the phase distortion that occurs in a channel, especially at the frequency in question -- 1 MHz.

The research proposal is to develop a positioning technique that uses the existing AM radio broadcast towers. The basic theory of operation was presented earlier. In principle, it works. The question that must be addressed is **how well does it work, i.e. how accurate is it?** The accuracy depends essentially on the **differential phase difference of the AM signal traveling to the fixed beacon and to the mobile.** The entire concept rests on this. The remaining problems of synchronization, phase measurement, and coordinate determination are secondary. The big question is the degree of phase distortion difference between the reference beacon and the mobile. A portion of this thesis (Chapter Four) attempts to answer this by reporting the results of an experiment in which the phase distortions were measured.

It was discovered that the phase measurement , to the desired accuracy, was a more onerous problem than originally anticipated. A test circuit was built to measure phase with counters and phase-locked loops.

Two AM car radios were modified so that the Local Oscillators were made coherent by locking the reference oscillators of the frequency synthesizers. The Intermediate Frequency (IF) from both radios were monitored with two channels of a dual trace scope. When the radios were tuned to the same station, the two IF signals remained stationary in the sense that the phase difference remained the same. When the antenna of one of the radios was moved toward the AM station, the phase difference of the IFs changed accordingly.

With the radios tuned to different stations, the IF signals drifted past each other slowly. The specific stations in Regina were CJME (1300 kHz); and CKRM (980 kHz), and they were observed to differ in frequency from that of their nominal frequency by about 5 Hz.

This initial investigation was useful in the demonstration of the principle, but it was not practical because for actual measurements, a wire was needed between the radios to lock the reference oscillators. A more elaborate measuring scheme was next attempted with the idea that the two units built would be able to act as the reference and the mobile without a wire joining them. One of the radio stations would act as the master clock in which the local oscillators would be derived. This is explained next.

2.10 Measuring the Phase with the PLL/Counter Method

The proposed ranging system is predicated on the realization of a technique that can measure the phase of signal with extreme accuracy. Although the PLL/counter method described earlier provides a convenient vehicle in which to explain the concept, it has many short-comings when put to the test.

A test circuit was built to measure the relative phase of AM radio signals. The counters and phase locked loops were incorporated into a single Field Programmable Gate Array (Xilinx 3090). The block diagram is shown in Figure 2.5.

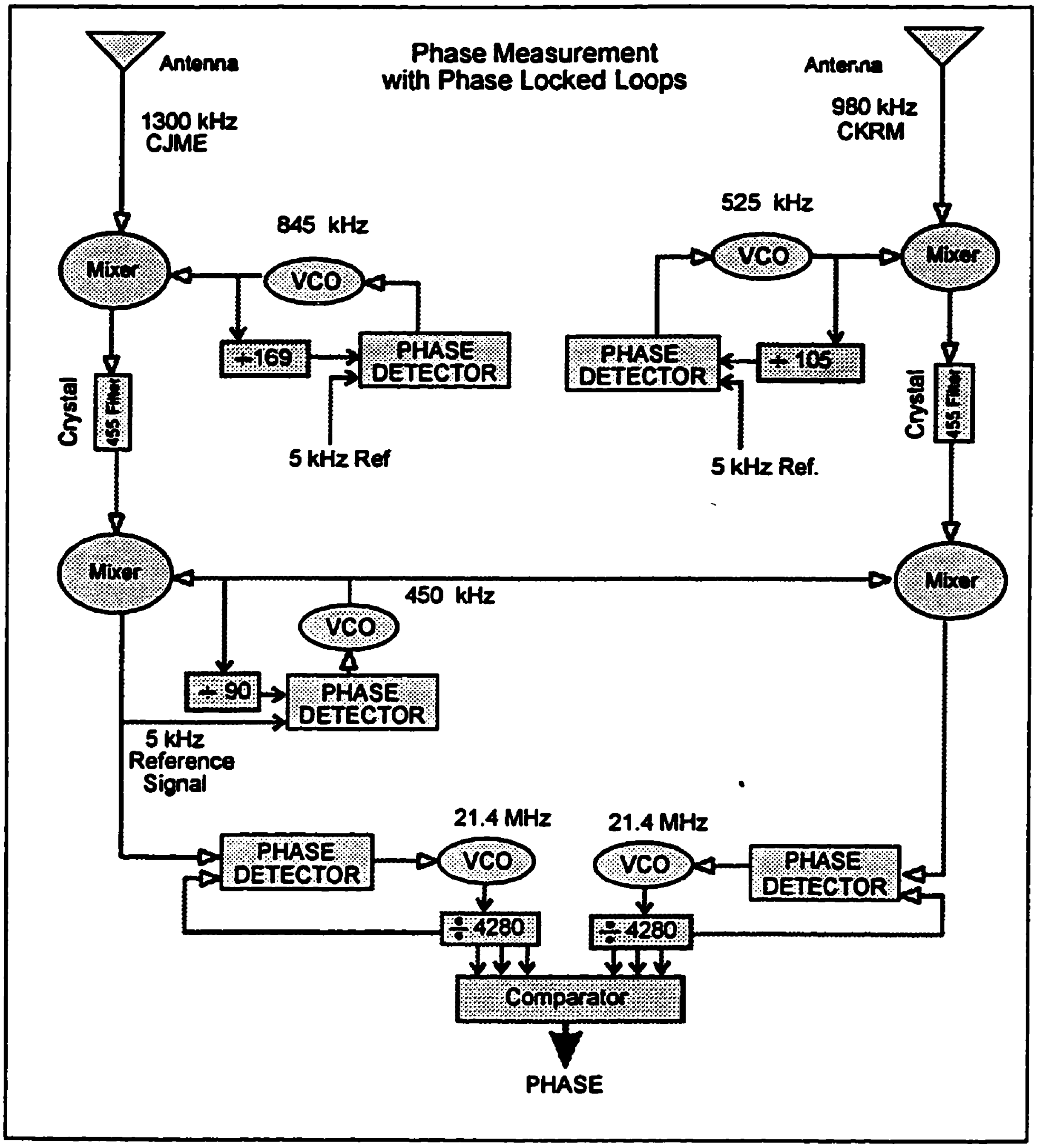

Figure 2.5 PLL / Counter Phase Measurement using an FPGA. The mixers and local oscillators were implemented with Motorola MC3362; the phase detectors and counter / dividers were implemented on Xilinx 3090. The 21.4 MHz oscillators were VCXOs.

The relative phase difference between two radio stations was to be measured with one of the stations carrier signal being used as the reference. It can be noted from Figure 2.5 that the radio signals are mixed down to an IF frequency of 455 kHz. The IF filters were made of quartz crystal and therefore had an extremely narrow bandwidth of only a few hundred Hertz. The 455 IF was mixed to an even lower IF in preparation to drive a PLL with a Voltage Controlled Oscillator (VCO) running 4096 times faster. The common denominator frequency was 5 kHz. The test circuit was built and two AM radio stations were chosen, CKRM at 980 kHz and CJME at 1300 kHz. It was expected that the phase of the 5 kHz IF output would change smoothly at a rate that equaled the error due to the carriers being offset from their nominal frequencies.

After much frustration, it was conceded that the above technique was a failure in terms of accurately measuring the phase of the carriers. The phase-locked loops could not be locked reliably with stability. This failure, while disappointing, was very useful in identifying the crucial aspects of accurate phase measurement. More thought and inquiry was needed to address basic questions such as: what is phase measurement? How can one measure the phase difference of signals of different frequencies? Clues for the understanding of these basic questions are ironically found in the reasons for the PLL method's failure.

The PLL method failed because:

1 The PLL in the above experiment used a "squared-up" sine wave as the edge to which the phase detector started measuring the phase. This is really the same as the 'zero-crossing point'. For overall accuracy, it is important that this zero-crossing point be first determined with extreme accuracy. Even a small error here will result in a large VCO phase error. Realistically, the zero-crossing point can not be determined very precisely; even a small amount of noise will result in the PLL being unstable. It was noted that just one small part

of the signal, the zero-crossing, was being employed in measuring the phase. It was learned here that it would be much better if the entire signal were to be used to measure the phase.

2. The carrier under full modulation disappears momentarily. Yes, narrow band IF filtering helps to hold the carrier, but even then it can become quite small. The crystal IF filters' bandwidth was about 200 Hertz, but occasionally a strong modulating signal with a frequency of less than 100 Hertz was observed. With the carrier being very small, albeit only momentarily, it was not uncommon to miss the zero-crossing edge resulting in unstable PLLs.

3. The narrow IF filters were of concern. It is clear from the previous remark, that the IF filters should be narrow to acquire only the carrier of the AM signal, that is to filter off the side-bands. However, there are problems in using extremely narrow band, high Q filters. First, it must be realized that the carriers of commercial radio stations can be in error by as much as 25 Hz. If a filter is made too narrow, it may exclude the carrier frequency in question. Secondly, a high Q filter would have a very rapidly changing phase response across its bandwidth, the very thing that is to be measured with extreme accuracy. Changes in temperature or aging could alter the phase delay considerably and destroy the integrity of the phase measurement. Since the channel is not common to all the radio stations, but only to a single station, the phase error through the IF filters is additive.

It was concluded that the PLL/Counter method is not practical. Before presenting a practical technique in the next chapter based on digital signal processing methods the concept of phase difference is discussed.

2.11 The Meaning of Phase Difference

Before one can measure the phase of a signal, it is important to have an appreciation for the meaning of phase or phase difference. Mathematically, a sinusoidal signal of frequency, ω, and phase, ϕ, is represented as:

$$\cos(\omega t + \phi) \tag{2.7}$$

Although this might seem somewhat trivial, it is important to note that the phase as shown is a constant, but, is it really? The phase is also embodied in the frequency and is a function of time. At any given time, the signal will have a specific phase. Apparently it can be concluded that a phase measurement has only a relative meaning; a phase measurement is done in relation to something, in this case time.

Another question arises: If a sinusoid is distorted with harmonics and noise, how is it possible to define what the phase of the signal is at any given time? Again, this might seem trivial, but it is an important issue that must be addressed. Now to define the phase of the signal, one must define the fundamental frequency and ignore the harmonics and additive noise. A single sample of the signal at an arbitrary point in time will not yield adequate information to measure the phase; the entire signal with many samples is needed to measure the phase.

Yet another dilemma arises when the phase of two signals is to be measured with the two signals in question being of much different frequency. For example, how is it possible to measure the phase difference between the carriers of a radio station at 620 kHz and at 1300 kHz? It will be noted that commercial AM radio stations have nominal frequency assignments spacing of 10 kHz. Indeed, 10 kHz is the greatest common-denominator frequency of all the AM stations. If the phase were measured with a time period corresponding to 10 kHz (0.1 ms), this would be a common phase measurement time. If the radio stations were exactly on frequency, the phase difference measurements of the radio station's carriers would remain the same when measured periodically every 0.1 ms. A changing phase difference would be indicative of a frequency error of the carrier in question.

The above discussion can be concluded with two observations. First, in order to measure the phase of a distorted signal, it is imperative that the measurement be done in such a fashion that the signal is observed over a prolonged time; one sample or one quick observation like a zero-crossing is not adequate. Secondly, the natural time period for observation would be that of the time period of the greatest common-denominator frequency of 10 kHz which is 0.1 ms.

A means was devised to measure the phase of individual AM carriers using a digital technique with a Discrete Fourier Transform DFT. The implementation of this technique is the topic of the next chapter.

CHAPTER THREE

IMPLEMENTATION

To implement the concept of measuring range with an AM radio signal to an accuracy of centimeters, requires circuitry that can measure the phase to within a fraction of one degree. The PLL technique that was suggested in Chapter Two did not prove to be practical. The major portion of this chapter describes a digital technique that proved to be practical and accurate.

3.1 MEASURING THE PHASE OF THE SIGNAL WITH DIGITAL TECHNIQUES

A digital technique has been developed to perform the functions of phase measurement and counting for the AM radio positioning system as described in Chapter Two. The counters that track each of the AM stations carrier signal are not realized in hardware, but in software using Direct Digital Synthesis (DDS) and Discrete Fourier Transforms (DFTs). These functions are implemented with a Digital Signal Processor (DSP) which also performs other functions, such as the arctan, to determine a fix.

Figure 3.1 shows the basic components of a radio receiver that would be used for the reference station or the mobile. The entire AM band is detected and amplified. The amplifier has a controlled gain and is adjusted so that the incoming signal is at the full scale range for the subsequent A/D. The A/D samples the signal as dictated by the sampling clock with quantized samples passed to the Digital Signal Processor (DSP). The DSP performs a Discrete Fourier Transform on each AM radio station's signal. This is used to estimate the carrier phase and frequency, which ultimately are used to determine range(s) and a position fix.

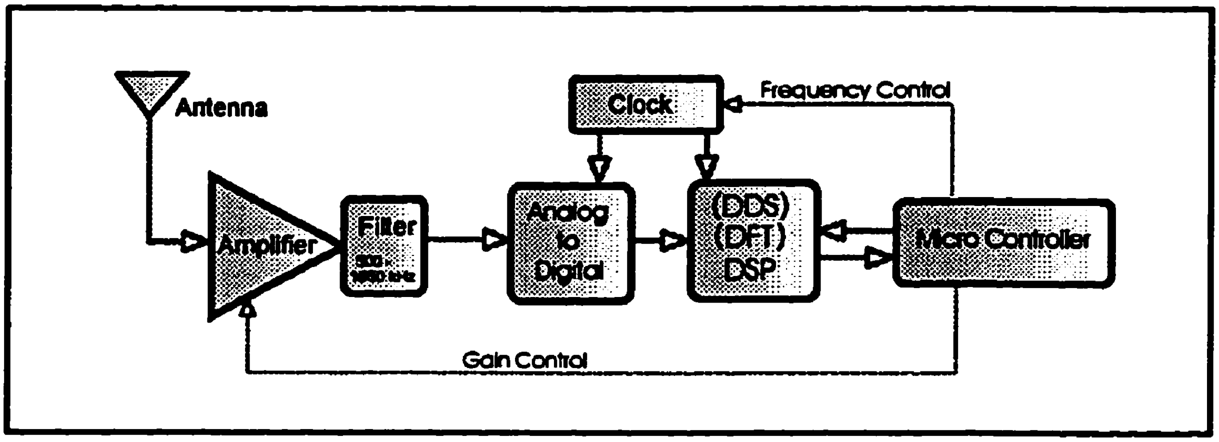

Figure 3.1 Digital Receiver for the Reference or the Mobile.

3.2 Digital Receiver Design

The design of the components and parameters of the digital receiver are constrained by practical component specifications, desired accuracy, update rate, latency of position determination, the number of radio stations in use, regulatory spectrum allocation and cost. Some aspects of the above and how they are reflected in the design paramters of the DDS and DFT are discussed next.

Direct Digital Synthesis

The objective of Direct Digital Synthesis, when used in this application, is to produce a sinusoidal signal that is of the same frequency as that of the AM radio station's carrier. A sinusoidal lookup table is a critical component to this process. Only one lookup table is used for the entire range of AM carrier frequencies. The lookup table stores values of a cosine over one cycle. Since the clock rate is constant, different carrier frequencies are obtained by decimating the samples, i.e., every sample is read out or every second one, or third, etc. An important parameter is the size (n) of the lookup table. It is determined by the maximum number of samples/cycle that is acceptable at the highest AM carrier frequency and by the maximum clock rate that is practically feasible.

It was observed earlier that the common-denominator frequency for the proposed system was 10 kHz. Multiplying 10 kHz by 256 would give a clock rate of 2.56 MHz. If the counter was incremented by one for each clock cycle, a signal of 10 kHz would be synthesized. Incrementing the counter by n for each clock cycle would produce a 10n kHz signal. Thus any nominal AM radio frequency, from 530 to 1650 kHz could be generated or synthesized in this manner.

The desired frequency predetermines the value that is set in the phase register (see Figure 3.2); or the value contained in the phase register determines the frequency of the synthesized signal. The phase is accumulated in the phase accumulator to produce an address to the lookup table for each sample period. The phase register and the phase accumulator register are accessed by software, and more details on their size and the sampling rate are given in Sections 3.4 and 3.7.

Discrete Fourier Transform

The Discrete Fourier Transform (DFT) is the fundamental process of the system. It not only measures the phase and frequency of the selected AM radio station's carrier, but it also does the selection of the AM station in question by acting as a narrow pass-band filter. The DFT is a correlation of two signals $s_1(t)$ and $s_2(t)$ in which one of the signals $s_1(t)$ is a complex sinusoid composed of a phasor of the type $e^{-j2\pi ft}$.

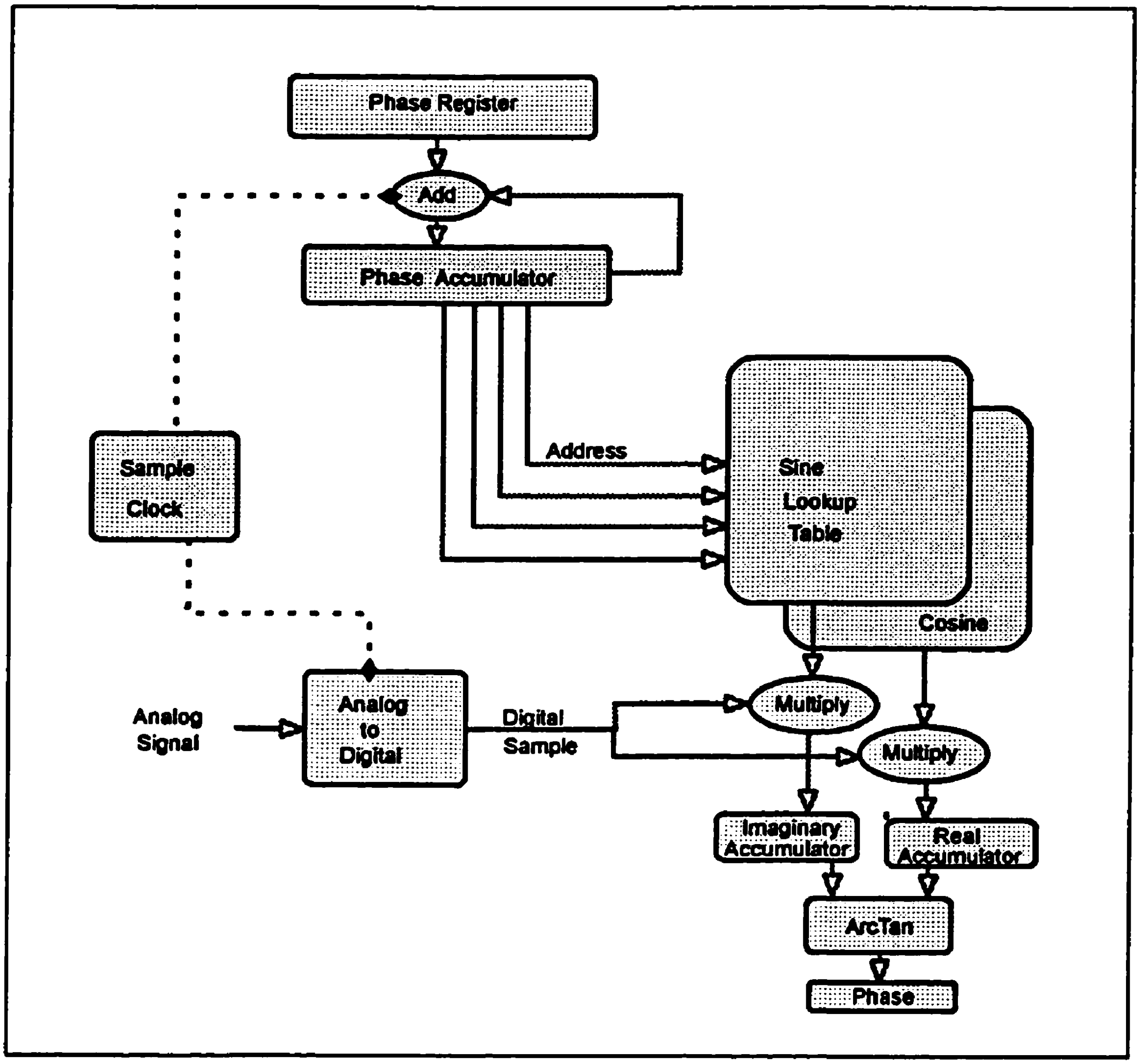

Figure 3.2 Operational Block Diagram of Direct Digital Synthesis and the Discrete Fourier Transform

By means of the Euler identity the Fourier Transform (FT) of $s_2(t)$ can be represented by $\int \cos(2\pi ft)\, s_2(t)\, dt \; - j \int \sin(2\pi ft)\, s_2(t)\, dt$, i.e., a real part which is $s_2(t)$ correlated with $\cos(2\pi ft)$ and an imaginary part which is $s_2(t)$ correlated with $\sin(2\pi ft)$. Equivalently the Fourier Transform can be expressed as an amplitude $(\text{Real}^2 + \text{Imaginary}^2)^{1/2}$ and phase, $\tan^{-1}$ (Imaginary/Real). For the sampled signal the Fourier Transform becomes a Discrete Fourier Transform (DFT) with:

$$\text{Real} = \sum_{n=0}^{N-1} \cos(kn/N)\ s_2(n) \tag{3.1}$$

$$\text{Imaginary} = \sum_{n=0}^{N-1} \sin(kn/N)\ s_2(n) \tag{3.2}$$

where N is the total number of samples, and the factor k sets the frequency of the sinusoid. The phase register as shown in Figure 3.2 would hold the value of k. The sinusoids required for the DFT are synthesized as shown in Figure 3.2. The samples of the cosine and sine are multiplied by the signal sample and accumulated, as shown at the bottom of Figure 3.2.

Besides measuring the spectral content of the incoming signal, the DFT also plays another important role—it selects the AM station from the wide AM band that has all the AM stations. It does this very well, without distortion and with consistent delay. The pass-band of this implicit filter can be made very narrow by extending the time over which the samples are taken.

The center frequency of this filter can be easily adjusted to match that of the AM radio station's carrier in question, so that the carrier is tracked with great precision. The tracking of the frequency of the AM signal's carrier would be a continuous process. Initially the receiver would not know the exact frequency of the station, since a radio station's carrier can differ from the nominal frequency by as much as 25 Hz (See Table 3.2). Therefore, the phase register would be loaded with the nominal frequency and then tuned to the precise frequency of the station.

The tracking of the carrier starts with DFTs being performed on the carrier at a specific rate, for example 10 per second. The phase is measured and noted. The change in phase over the time interval is the frequency error between the DFT's sinusoid and that of the AM station. The phase register is then modified to compensate for this error and subsequently adjusted until there is no change in phase from one DFT to the next. At such time the center frequency of the implicit filter matches exactly that of the carrier in question.

In summary, it is noted that the DFT forms the basis for frequency tracking, phase measurement and selection of the AM station. How well it performs these functions will depend on the number of samples, N, the sampling rate, the precision of k, the resolution of the ADC and the size of the sine/cosine lookup-table. These are issues that are treated in the subsequent sections. Another possible source of error would be the aperture time of the ADC. However since the highest frequency to be measured is less than 1.6 MHz with the aperture time being typically a few ns[1]; over this time the sinusoid being measured could be considered linear. Also since the mobile and reference would be using the same ADC with the same aperture time this effect would be largely compensated. For these reasons aperture time of the ADC will not be considered further.

3.3 Resolution of the A/D and Dynamic Range

How many bits of resolution are needed to digitize the broad band signal -- 8, 12, 16? Certainly one does not want to over specify the resolution, as the cost for Analog to Digital Converters (ADC) increases with precision.

[1] Burr-Brown DEM-ADS800 was used

To determine the number of bits of resolution that would be required for the ADC, a phasor at zero degrees is considered. The phasor has two parts, the real and the imaginary, which should be of magnitude one and zero respectively. Due to quantization, the magnitudes could be in error by as much as one half of one least significant bit (½ LSB). When normalized this would be ½ LSB over the full scale value of ADC. In terms of how this affects the resulting angle, the error in the real part (½ LSB over the full scale value) is not significant and will be ignored. The error in the imaginary part though will affect the resulting angle as shown in Figure 3.3.

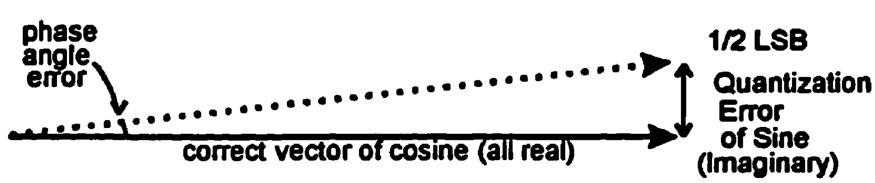

Figure 3.3 Phase Angle Error due to Quantization

A MatLab®[2] program was written to determine the worst case and typical error due to the quantization. The program is listed below and the results are shown in Table 3.1.

```
% AD.m
% A program to determine the number of bits of A/D resolution
% required. Imagine the real and imaginary parts of a phasor at zero degrees
% the real part has an amplitude of one, while the imaginary part should be
% zero, but because of quantization noise, it may be as large as ½ LSB for
% any given sample; this would be the worst case and would result in a phase
% error. If one assumes a wavelength of 300 meters (1MHz) then this phase
% error can be converted to a range error.
% If many samples are used, the average, or typical error will be much less
% than the worst case.
fprintf(' RANGE ERROR DUE to QUANTIZATION ERROR \n\n\r');
fprintf('Bits of A/D  Worst    Average or\n\r');
```

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2 © 1995 by The Math Works Inc. Published by Prentice Hall Version 5

```
fprintf('Resolution   Case(cm)  Typical(cm)\n\n\r');
for r=2:12                          % bits of resolution
worst =  (atan ( 1/(2^r) )/1) *30000/(2*pi);
for i=1:4;                % do it four times for average
for n=1:10;
s(n) = (rand - 0.5)/(2^r);      % imaginary part of samples varies by ½ LSB
end;  average(i) = abs(atan(sum(s)/10)) *3000/(2*pi);
end; fprintf('%2i          %7.2f         %5.2f\n\r',r,worst,sum(average)/4);
end;
```

Bits of A/D Resolution	Worst Case (cm)	Average or Typical (cm)
2	1169.69	9.55
3	593.75	5.39
4	298.03	1.36
5	149.16	1.21
6	74.60	0.53
7	37.30	0.21
8	18.65	0.14
9	9.33	0.05
10	4.66	0.02
11	2.33	0.01
12	1.17	0.01

Table 3.1 Range Error Due to Quantization Error

The resulting phase error was indicative of the range error. For example, if the resulting phase was one degree in error, this would be equivalent to a range error of:

$$1/360 \times \text{wavelength of the carrier, or typically } 1/360 \times 300 \text{ m} = 5/6 \text{ m}. \qquad (3.3)$$

Table 3.1 shows both the worst case error and the average or typical error. If many samples are taken, the probability of having a measurement with the worst case error is extremely small; yet it may be somewhat rash to consider only the average. It is noted that the worst case is about 100 times bigger than the average; so, perhaps it would be prudent to consider the quantization error to be the worst case divided by 10. Doing this, 5 bits gives 15 cm of accuracy, 6 bits--7 cm, and 7 bits--4 cm of range accuracy. For a radio positioning system, 4 cm of error was deemed acceptable, and therefore 7 bits of A/D resolution are needed.

The above simulation was done with the signal in question occupying the full dynamic range of the A/D. In a practical broadband application only the largest signal could be adjusted so that its amplitude was that of the full range of the A/D. The signals from the more distant stations would be much weaker and would extend over only a portion of the A/D's voltage range. By examining the spectrum of the AM band on a spectrum analyzer, it was clear that the strength of the AM radio stations carrier could differ by 30 dB, which is a ratio of 31.6 or equivalently 5 bits worth of A/D resolution. Additional dynamic range could be accommodated with additional A/D resolution. Each additional bit of resolution increases the dynamic range by 6 dB.

It is apparent that 7 bits of resolution are required to measure the phase accurately and that at least 5 bits are required to accommodate the dynamic range of the AM signals—a total of 12 bits. If the radio stations differ in amplitude by more than 30 dB, a 13 or 14 bit A/D should be specified.

3.4 Sampling Rate

The determination of the sampling rate is constrained by the processing power of the Digital Signal Processor (DSP) in performing DFTs and by the required update rate for the positioning system. Other determining factors in selecting the sampling rate are the common denominator frequency of the AM stations and the length of the sine/cosine lookup tables.

For a typical DSP (Motorala 56002) running at 40 MHz a DFT multiply and accumulate (MAC) for 8 radio stations could be performed in 0.5 usec. This would constrain the sampling rate to something less than 2 MSamples/s (MS/s) . The Motorala 56002 was used simply because it was available. Other DSPs would have worked equally as well.

The highest frequency radio station is 1.65 MHz. If sampling were to be done at the Nyquist rate, a sampling rate of at least 3.3 MS/s would be used. If the positioning system being proposed is to be used to guide and control vehicles, several position updates are required per second. Assume ten updates per second are specified. This means that a DFT must be completed in 0.1 seconds. In the simulation done in Section 3.5, it is shown that 8000 samples are the minimum number of samples that should be considered in a DFT session to ensure a reasonably small 'end effect'. Therefore, 8,000 samples taken in 0.1 seconds, would set the sample rate at 80 kS/s.

It would appear that the sampling rate should be at least 80 kS/s, but because of DSP performance, should not exceed 2 MS/s. To measure the phase of signals that are at different frequencies, it is also necessary for the sampling rate to be related to the frequency of the signals measured. The common denominator frequency of the AM radio stations is 10 kHz. In other words, the phase of all signals that are evenly divisible by 10 kHz will be at the same phase every 0.1 ms. The sample clock should be set to a frequency that is evenly divisible by 10kHz. For example, 2 MHz would be acceptable since it can be divided by 10 kHz without a remainder. The multiple of 10 kHz that is selected will be largely determined by the size of the sine/cosine lookup table.

The AM radio station at 620 kHz is used to explain how the sampling clock is related to the size of the sine/cosine lookup-table. First assume that the sample/DFT clock is 10 kHz and that the phase register is such that the phase of the synthesized sine wave is advanced by 1 cycle for each clock period. The phase offset would hold 620,000/10,000 = 62 (for 620 kHz). If this was done for all radio stations, and if they were exactly on frequency, then every 0.1 ms the phases of all the radio stations would be the same. With this scenario the sample rate would be 10 kS/s.

The sine/cosine lookup table could be of any length but to facilitate simple rollover of the address only those of length 2^n are considered here. The above sampling rate of 10 kS/s then needs to be increased by the factor 2^n. A large n will require a very high sampling rate.

The decimation which determines the DDS frequency also interacts with the sampling rate. As an example if the sampling rate is to be reduced by a factor of 4 then the value in the phase register should be increased by a factor of 4. Instead of 62, the value of 248 would be put into the phase register and a lookup-table of length 2^{10} could be used with sample rate of 2.56 MS/s.

Alternatively a factor of 8 (62 x 8) could be used with the 2^n size table and a sample rate of 1.28 MS/s and for a factor of 16 (62 x 16) a sample rate of 640kS/s is used. Because of constraints of the lookup table length and the common denominator frequency of 10 kHz, the choice of sampling rates becomes: 0.64, 1.28, 2.56, 5.12, or 10.24 MS/s. It is better to have more samples taken with the highest sampling rate possible, yet as mentioned previously there will be practical limits set primarily by the processing power available with the DSP in performing DDSs and DFTs. With these considerations the sampling rate of 1.28 MS/s is proposed tentatively.

In order to maximize the efficiency of the DSP to achieve the highest sampling rate possible, the following suggestions are put forward:

- The sampling and processing are separate functions. A batch of samples could be collected and stored in memory while the DSP is processing the previous batch. This makes the DSP much more efficient as it can sweep through the batch of samples accumulating the real and the imaginary parts without having to save and retrieve the accumulator on each iteration. The disadvantages would be the requirement of more memory, additional circuitry for switching between batches of sampled data and a slight increase in latency of position determination.
- The Direct Digital Synthesis places a heavy burden on the DSP. The DDS is primarily an 'add-and-accumulate' and this could easily be implemented with a Field Programmable Gate Array (FPGA). It is strongly recommended that the DDS be implemented in hardware.

Under-Sampling, aliasing

The AM band extends from 530 to 1650 kHz. The sampling rate should be at least twice the highest frequency, or 3.3 MHz. The choice of sampling frequencies is limited to 5.12, 2.56, 1.28, or 0.64 MS/s. Aliasing is not a problem with 5.12 MS/s, but it gets progressively worse with the other four rates. Undersampling, has the effect of having undesirable images being added to the authentic signal before sampling. For example, if the sampling rate is 640 kS/s and the signal to be measured is at 540 kHz then as well as the 540 kHz, images from 1180 kHz and 740 kHz will be aliased onto the spectrum at 540 kHz. When these images are at frequencies of existing strong broadcast transmissions; there is a problem. This is the risk with undersampling. It may be that some radio stations can not be used. Table 3.2 lists a set of radio stations that were locally observable. The columns are the images that would result from various sampling rates. Images that could be radio stations are shown in italics, actual conflicts with the set are shown in bold. It is apparent from the table that 2.56 MS/s, 1.28 MS/s and even 640 kS/s would be acceptable sampling rates with only minor conflicts of image frequencies. To conclude, of those listed the fastest sampling rate should be selected, with the provision that the DSP is able to process the samples. 640 kS/s would be the lowest acceptable rate, but 1.28 MS/s is the preferred choice and the set of stations listed would work with minimal aliasing problems for this location. The criteria for selecting a set of stations in a given area is presented in Section 3.10.

Radio Station kHz	Relative Amp/Freq	Aliased 2.56 MS/s	Frequency 1.28 MS/s	kHz with 640 kS/s	Sample Rate 320 kS/s
540	0.02 0	2020	*740*	*740, 1180*	***860***, *740, 1180*
600	0.03 +16	1960	***680***	***680***, *1240*	***920,680***, *1240*
620	0.14 -23	1940	*660*	*660,1260*	*940,660,1260*
680	0.04 -2	1880	***600***	***600***, *1320*	*1000*, ***600***, *1320*
720	0.075 -10	1840	*560*	*560, 1360*	*1040,560, 1360*
800	0.13 +16	1760	480	160, *1440*	***1120***,160, *1440*
820	0.02 -2	1740	460	180, *1460*	*1140*,180, *1460*
840	0.02 +1	1720	440	200, *1480*	***1160***,200, *1480*
860	0.02 -8	1700	420	220, *1500*	*1180*,220, *1500*
920	0.03 -12	*1640*	360	280, *1560*	*1340*,280, *1560*
980	0.22 +3	*1580*	300	360, *1620*	*1400*,360, *1620*
1120	0.06 -12	*1440*	160	500, 1760	*1440*,500, 1760
1160	0.03 +1	*1400*	120	*540*, 1800	*1480,540*, 1800
1300	0.25 +2	*1260*	20	***680***, 1940	**1620**, ***680***, 1940
Potential	**Conflict ->**	5	5	18	32
Actual	**Conflict ->**	0	2	3	8

Table 3.2 Conflicting AM Radio Station Images Resulting from Various Sampling Rates. The Relative Amplitude and Frequency Error were Measured with an 8000 point DFT on local AM stations.

3.5 End Effect of Phase Measurement

The proposed ranging system demands a very accurate phase measurement. One potential cause of phase measurement error is quantization noise as was discussed in Section 3.2. A more serious error in phase measurement results when the DFT is applied to a signal record length that does not contain an integral number of carrier cycles, a phenomenon called here the 'end effect'.

One would expect that as the signal record length is increased, i.e., the number of cycles considered is increased, the phase error due to the end effect is reduced. This is shown in the analysis that follows. Both the discrete and the continuous case are analyzed, since the two are not necessarily identical, at least not in detail. Besides the end effect the consequences of an arbitrary starting time and also the sampling rate on the resultant phase measurement are analyzed.

End Effect

A simple example is used to explain end-effect. A more general treatment is given later. Consider a signal, $\cos(2\pi ft)$. If this signal is sampled and the samples processed with a DFT, the expected phase would be zero degrees. If a single sample is taken just before $\pi/2$ at 89 degrees, then the DFT has a real part of $[\cos(1.5533)]^2 = (0.0175)^2 = 3.06 \times 10^{-4}$ and an imaginary part of $\sin(1.5533) \times \cos(1.5533) = .9998 \times 0.0175 = 0.0175$.

The resultant phase as measured by the DFT is then:

$\arctan(\text{imaginary/real}) = \arctan(0.0175 / 3.06 \times 10^{-4}) = 1.5533$ radians or 89 degrees; not zero! Why the error?

Maybe the example is absurd. Certainly it is not possible to measure the phase of a signal with only one sample. What if three samples are used?

Again considering the time signal, $\cos(2\pi ft)$, where three samples are taken, at 45 degrees, 135 degrees, and at 225 degrees. The real part of the DFT would then be

$\cos(\pi/4)^2 + \cos(\pi/4)^2 + \cos(\pi/4)^2 = 1.5$ and the imaginary part

$\cos(\pi/4) \times \sin(\pi/4) - \cos(\pi/4) \times \sin(\pi/4) + \cos(\pi/4) \times \sin(\pi/4) = 0.5.$

The measured angle would be $\arctan(0.5/1.5) = 0.3218$ rad or 18.4 degrees.

Still an error of over 18 degrees. However if an additional sample at 315 degrees is taken the correct phase would be measured. Taking the fourth sample resulted in the correct measurement simply because, in accordance with the implied sampling rate, a complete cycle is used to compute the phase.

The end effect is readily analyzed for the continuous case. Consider that the signal $V\cos(2\pi f_c t)$ is observed over the time interval $t \in [T_1, T_2]$ where $T_2 = T_1 + nT_c + \Delta$ where $T_c = 1/f_c$, n is the number of integral cycles of the carrier frequency and $0 < \Delta < T_c$ is the end effect. Then the Fourier Transform at frequency f_c (here it is assumed that the carrier frequency is known exactly) is:

$$FT(n, T_1, \Delta) = \int_{T_1}^{T_2} V\cos(2\pi f_c t)\, e^{-j2\pi f_c t}\, dt \tag{3.4}$$

$$= V/2\left[nT_c + \Delta + \frac{\sin[4\pi f_c(T_1+nT_c+\Delta)] - \sin[4\pi f_c T_1]}{4\pi f_c} + j\,\frac{\cos[4\pi f_c(T_1+nT_c+\Delta)] - \cos[4\pi f_c T_1]}{4\pi f_c}\right]$$

Simplifying the above expression, it can be written as:

$FT(n, T_1, \Delta_n)$

$$= V/8\pi f_c \left[\{4\pi n+4\pi\Delta_n+\sin 4\pi(T_n+\Delta_n)-\sin 4\pi T_n\} + j\{\cos 4\pi(T_n+\Delta_n)- \cos 4\pi T_n\}\right] \quad (3.5)$$

where $\Delta_n = f_c\Delta$ and $T_n = f_c T_1$. Note that $0 < \Delta_n < 1$ and $0 < T_n < 1$.

To investigate the end effect only let $T_n = 0$. The calculated phase is therefore:

$$phase(n, \Delta_n) = \tan^{-1} [(\cos 4\pi\Delta_n -1)/ (4\pi n +4\pi\Delta_n +\sin 4\pi\Delta_n)] \quad (3.6)$$

A plot of (3.6) is given in Figure 3.4

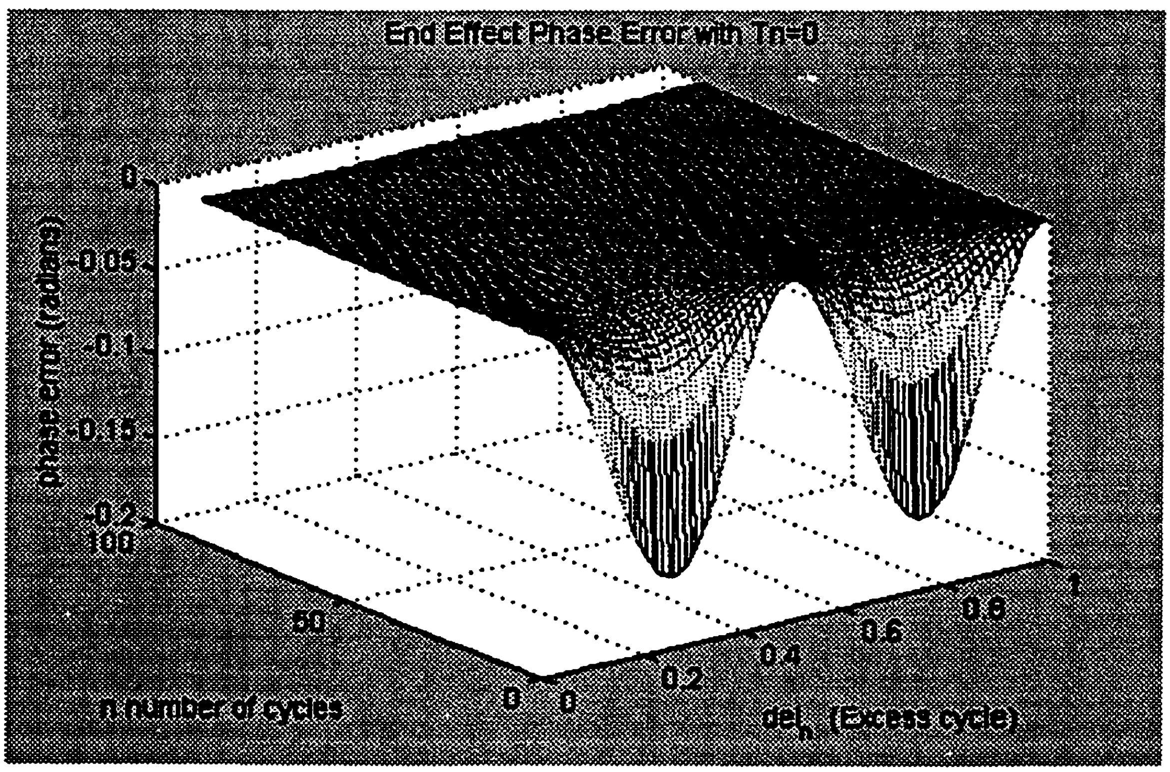


Figure 3.4 End Effect (continuous analysis)

The discrete case also exhibits the end effect when the samples are not taken over a complete cycle. To make accurate phase measurements using a DFT, one is left with two choices:

1) Start and stop the sampling process so that only an integer number of cycles are covered. This is not a practical solution. When several frequencies are measured with a single sample set it will be difficult, if not impossible, to do this.

2) Recognize that an error does occur, but use enough cycles, such that the error due to the end effect becomes insignificant. This would be more practical.

In the discrete case an empirical approach was taken to analyze the end effect. The example with the single sample point was done to illustrate the worst case error. The sample point could have been selected such that no error occurred; but one would like to know the worst case. The resulting phase error in this "worst case" approached $\pi/2$ radians. In the example with the three sample points, again, what is believed to be the worst case was chosen and the phase error was 0.32 radians.

In general, from the continuous analysis one expects the phase error due to this end effect to diminish with an increasing number of sample points(cycles). It is proposed that the typical phase error due to the end effect could be approximated by:

$$PE = \arctan(1 / N) \qquad (3.7)$$

where PE is the end effect phase error and N is the number of samples. Table 3.3 shows the resulting phase error as a function of the number of sample points.

Number of Samples N	Phase Error PE (radians)	Range Error (cm)
3	0.32	1536
500	0.0020	9.54
1000	0.001	4.7
2000	0.0005	2.38
4000	0.00025	1.19
8000	0.000125	0.59

Table 3.3 End Effect Phase Error Estimates with varying Number of Samples. The range error is calculated from arctan(1/N) and this phase is converted to a range error for 1 MHz (λ= 300 m.).

The development of the formula to determine the 'worst case' end-effect error was based on an arrangement of discrete samples that was believed to be the worst case. What is meant by arrangement of samples here corresponds in the continuous case to the starting time T_1. Changing T_1 results in Δ falling over a different segment of the AM carrier's cycle and thus a different phase error. To investigate this influence simulations were done in the discrete case. The simulations were done in MatLab and used only 3 samples, separated by 90 degrees, taken of a cosine signal with the samples shifted to find the worst position for the largest end effect phase error. The program is listed below, with the results shown in Figure 3.5.

```
% RESOL.m -- three samples are taken of a cos signal and are processed thru
      % a DFT to determine end effect error, the samples are slid along
      % the wave starting at 0 deg and ending at 180, the samples are 90 deg apart
      for i=1:180;  p(i)=i;
   for n=1:3;                                                  % number of samples
   s(n) = cos((n-1)*pi/2 + i*(2*pi)/360 );                       % samples are in s
   real_(n)= cos((n-1)*pi/2 + i*(2*pi)/360) * s(n);       % correlate real part with cos
   imag_(n)= sin((n-1)*pi/2 + i*(2*pi)/360) * s(n);       % correlate imag part with sin
      end;   phase(i) = atan(sum(imag_)/sum(real_)) ; end;   plot(p,phase);
```

It is interesting to note that from the analysis, the worst case was suggested to occur at 45 degrees; yet the simulation puts the worst case at about 55 degrees. The phase error of 0.32 radians is as predicted. For completeness the continuous case is also presented. As mentioned the arrangemnt of samples is equivalent to an arbitrary starting time T_1. To obtain the influence on phase error consider eqn. (3.7) and let n = 0. A plot of phase(T_n,Δ_n) is shown in Figure 3.6

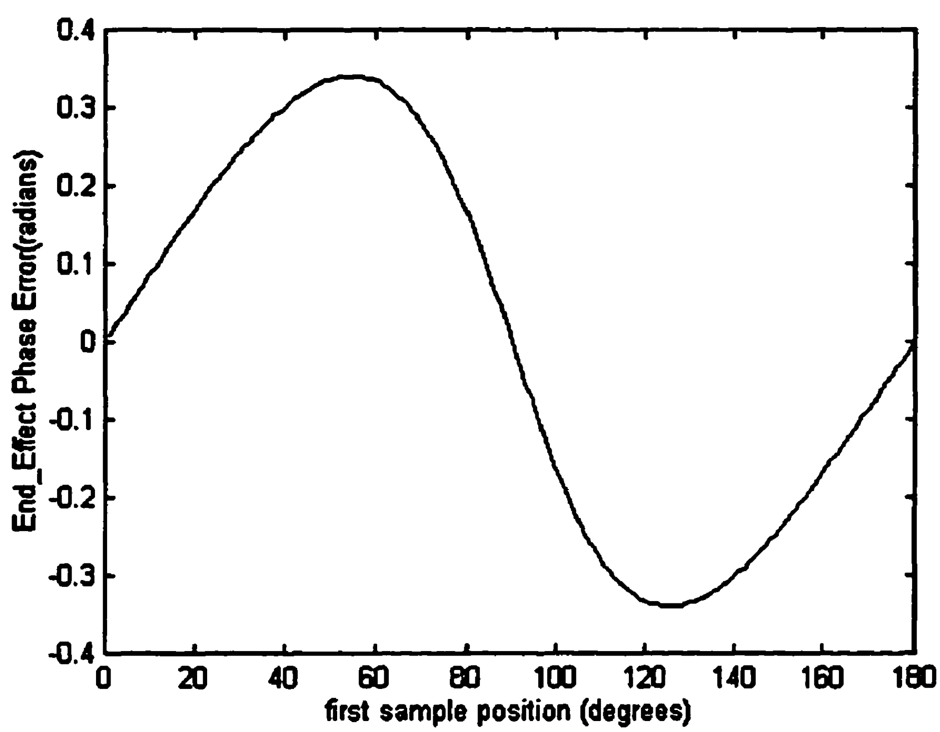


Figure 3.5 End Effect Phase Error with only 3 Sample Points

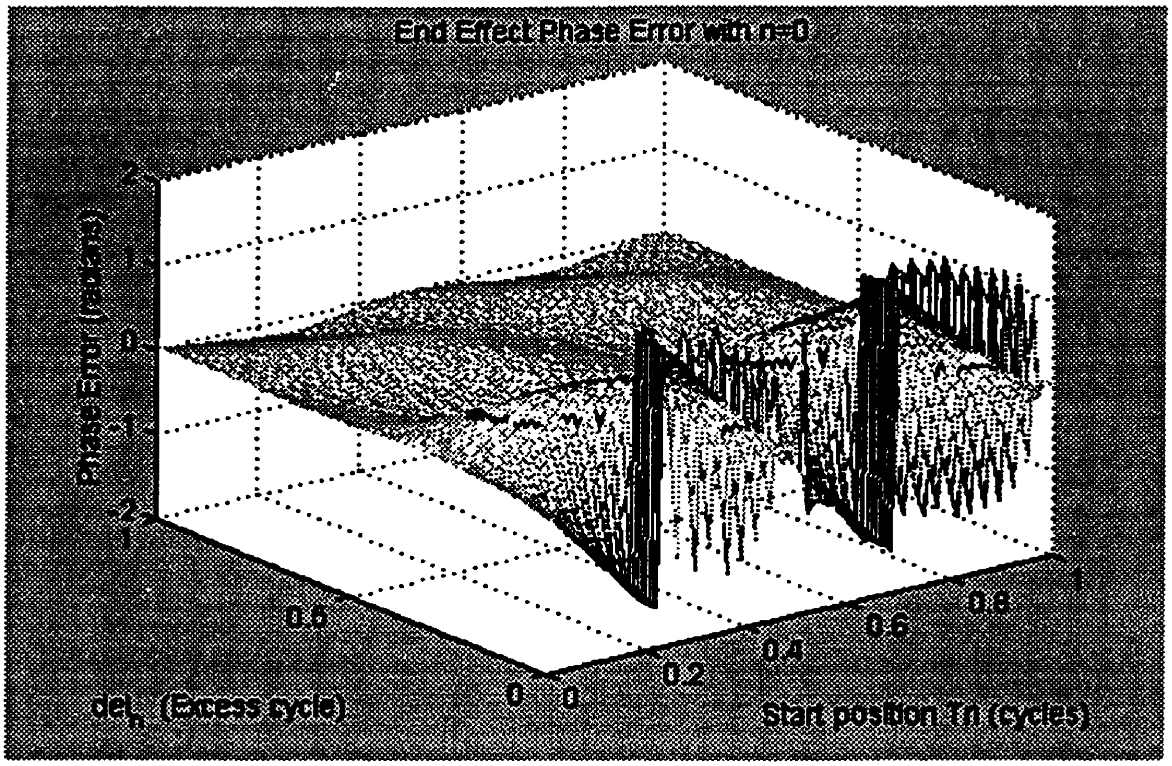


Figure 3.6 End Effect with 0 cycles (continuous analysis)

Besides the end effect and sample arrangement in the discrete case, the sample spacing will also influence the phase measurement. Note that because a constant sampling rate is used the sample spacing will change with the AM carrier frequency considered. The influence of sample spacing was also investigated by a simulation in Matlab. Three samples were used with both the spacing and the position of the first sample varied. The simulation program is listed below with the results shown in Figure 3.7.

```
% a DFT to determine end effect error, the samples spacing is changed from
% 52 deg and ending at 180, three samples are used, the first being at 3 deg
for i=3:3:90; % initial position of first sample(degrees)
for sp =52:4:180; % spacing between samples (degrees)
for n=1:3;
s(n) = cos((n-1)*pi*2*sp/360 + i*(2*pi)/360 ); % samples
real_(n)= cos((n-1)*pi*2*sp/360 + i*(2*pi)/360) * s(n);
imag_(n)= sin((n-1)*pi*2*sp/360 + i*(2*pi)/360) * s(n);
end; phase((sp/4)-12,i/3) = atan(sum(imag_)/sum(real_)) ;
end; end; X=3:3:90; Y=50:4:180; mesh(X,Y,phase);
```

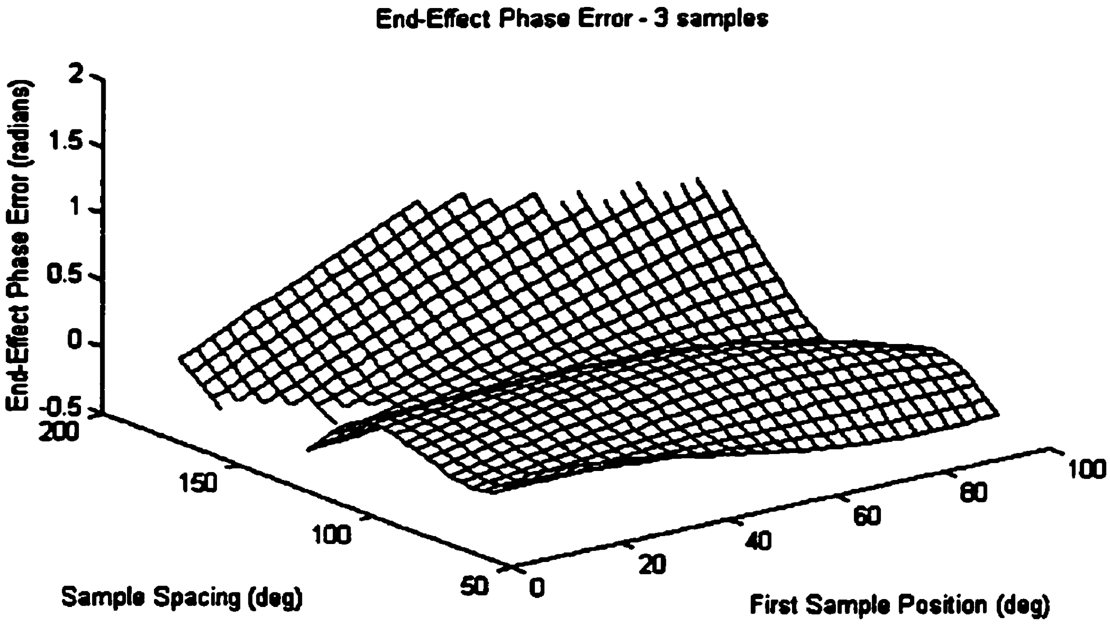


Figure 3.7 End Effect Error with 3 Samples

It is interesting to note that the position of the first sample has little influence on the phase error. It is the sample spacing that greatly affects the error, especially as it approaches 180 degrees. When the sample spacing increases to 180 degrees, the phase error approaches $\pi/2$ radians. Therefore the formula (3.7) for estimating end effect does not apply for a sample spacing that approaches an integer number of π radians.

The reason for studying the end effect is to determine the amount of phase error that could be expected in the proposed AM ranging system. The sampling frequency and the frequency of the AM stations are known, and thus the sample spacing is also known. The starting position of the first sample will occur randomly, so this parameter will remain a variable in the simulations. The important issue thus is to determine the number of sample points needed to subdue the end effect so that the phase error is acceptable.

It was determined earlier that the clock used for sampling, should be the same as that used to clock the DFT. The allowed frequencies were 0.64, 1.28, 2.56, or 5.12 MHz. For the simulations, 1.28 MHz was selected. The sample spacing would then be the radio station frequency divided by 1.28 MHz. For example the sample spacing for 540 kHz would be 0.540/1.28 = 0.42 cycles or 2.64 radians. The following program has the sampling rate set to 1.28 MS/s thus setting the sample spacing for each AM station. The results are graphed in Figure 3.8 below.

```
% R.m a DFT to determine end effect error, the samples spacing is changed to
%  correspond to radio stations 540 to 1440
for i=3:3:90;  % intial position of first sample(degrees)
for sp =540:30:1440; % spacing between samples (degrees)
 for n=1:800;                                              % number of samples
  s(n) = cos((n-1)*pi*2*sp/1280 + i*(2*pi)/360 );  % samples are in s
   real_(n)= cos((n-1)*pi*2*sp/1280 + i*(2*pi)/360) * s(n);   % correlate real
   imag_(n)= sin((n-1)*pi*2*sp/1280 + i*(2*pi)/360) * s(n);   % correlate imag
 end;  phase((sp/30)-17,i/3) = atan(sum(imag_)/sum(real_))  ;
end;  end;
X=3:3:90;  Y=540:30:1440;
mesh(X,Y,phase);
xlabel('First Sample Position (deg)');
ylabel('S Space/ AM Radio Station (KHz)');
zlabel('End-Effect Phase Error (radians)');
title('End-Effect Phase Error - 800 samples 1.28MS/s')
```

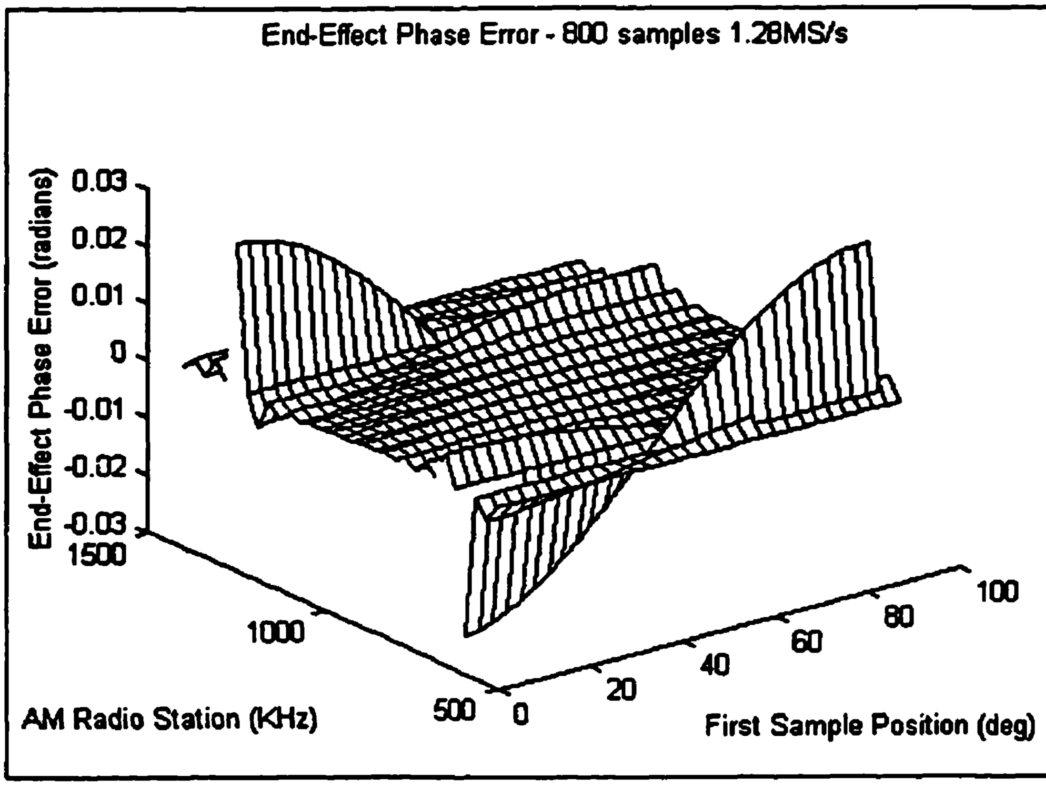


Figure 3.8 End Effect Phase Error with Sample Spacing related to AM Stations

Figure 3.8 shows that there are two stations that have extremely large error. They are at frequencies of 640 and 1280 kHz. It is clear that these two radio stations should not be used. Excluding the two mentioned stations, the stations that appear to have the most error would be those that flank the forbidden 640 and 1280 kHz stations; these being 630, 650, 1270, and 1290 kHz. Arbitrarily 650 kHz will be selected for further study. This then fixes the sample spacing parameter and the remaining two parameters are varied, namely the number of samples(cycles), and the position of the first sample. A simulation was done that varies the number of samples from 3000 to 8000, for the AM station at 650 kHz. The results are shown in Figure 3.9.

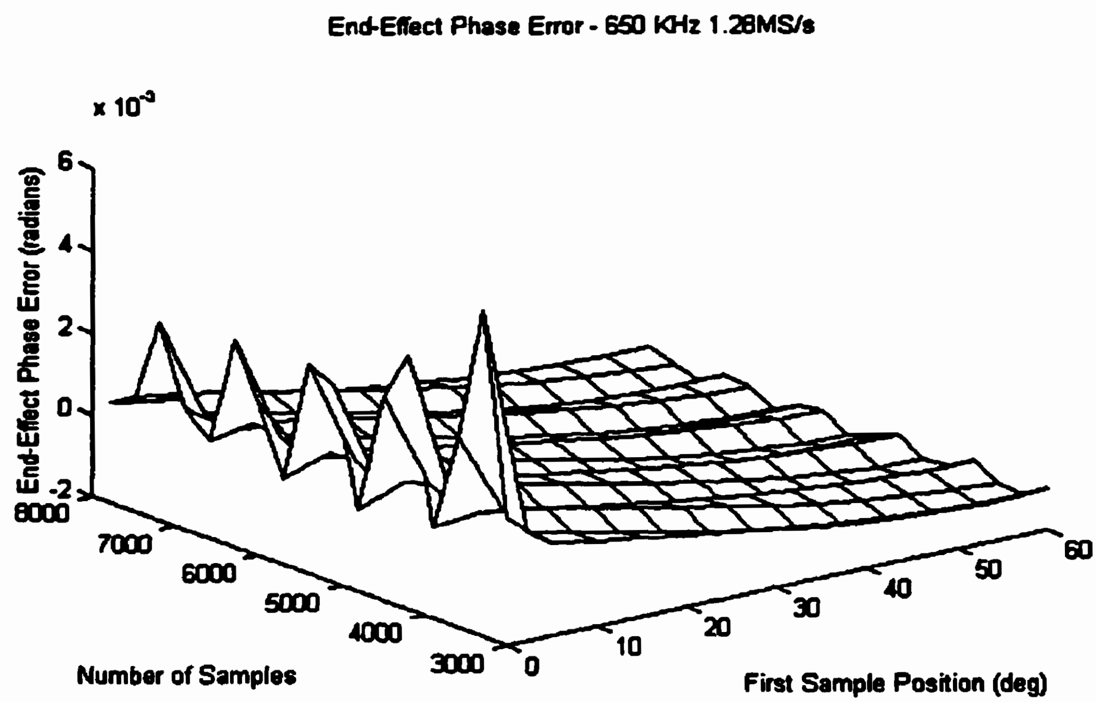


Figure 3.9 End Effect Phase Error -- Station 650 kHz

The maximum phase error is about 0.003 radians which is equivalent to about 22 cm of range error. This is more than desired, but then this is the worst case scenario, with the worst station, with the smallest sample set, and with the worst starting position of the first sample. Typically the error would be much smaller than this, perhaps about 2 cm of range error. Another interesting observation is that above 6000 samples, the end effect error diminishes very slowly.

To summarize this section on end effect the following observations and recommendations are put forward:

- Radio stations 640 and 1280 kHz can not be used by the system with the sampling rate selected (1.28 MS/s).

- The number of sample points must be several thousand to achieve centimeter accuracy. The use of eight thousand samples or more at a sampling rate of 640 kS/s or larger would ensure that the end effect is negligible.

3.6 Resolution Required for Fraction Register in DDS

The contents of the phase register used to generate the sinusoidal signals for the Direct Digital Synthesis (DDS) directly determines the frequency of the sinusoid signal. To provide extremely accurate frequencies, the phase register has appended to it an implied fraction. It is important for the sinusoid of the DDS to match the frequency of the signal to be measured. Even a fraction of a Hertz difference over the duration of the DFT process will degrade the correlation.

Perhaps the best method to determine the size of the fractional part of the phase register would be by example. Assume that the sampling rate and the DDS process rate is set to 1.28 MHz. Also assume that the incoming signal to measure is that of the station at 620 kHz. The sine/cosine lookup table will have a length of 1024 and a 10 bit address.

With a 10 kS/s and a sine/cosine lookup table of length one, the phase register would have a value of 62. But because the sample rate is 1.28 MS/s, this value should be divided by 128 and because the lookup table is of length 1024, the value should be multiplied by 1024, giving:

$$(62/128) \times 1024 = 62 \times 8 = 496 \qquad (3.8)$$

The factor of 8 is equivalent to 3 bits of fraction, but the fraction must be larger than this. The fraction size (bits) and the frequency resolution is given in Table 3.4.

The size of the fraction required depends somewhat on the duration of the DFT. If 16K samples are to be taken at a rate of 1.28 MS/s., the duration would be 0.0125 s (80/s). This means that with 16 bits, the sinusoid of the DDS and that of the measured signal would differ by 0.15 cycles/s x 0.0125 sec = 0.001875 cycle, which is less than one degree.

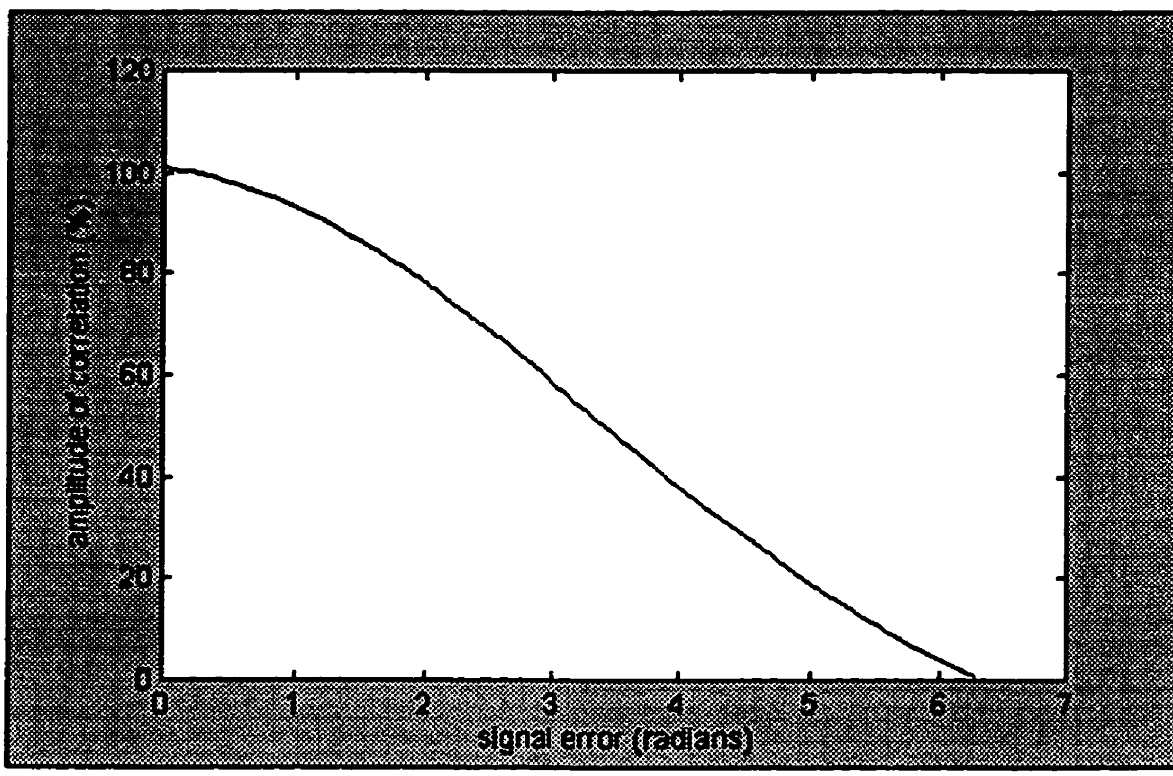


Figure 3.10 Correlation Degradation Versus Signal Mismatch over a DFT Session. An error of one cycle yields no correlation.

A simulation was done in MatLab to check the percentage of correlation as a function of frequency error. As shown in Table 3.4 and Figure 3.10, a 12 bit fraction could have an error of 0.244 cycles over a correlation period of 0.1 seconds and the correlation would be degraded to 87 percent (100 percent correlation occurs with no frequency error). The 16 bit fraction would provide better than 99 percent correlation and it would be acceptable in that regard.

Fraction (bits, b)	Frequency Resolution (Hz) $\frac{10000\ kS/s}{2b}$	Cycle Resolution (cycles/ 0.1 sec)	Correlation (percent)
12	10,000/4096 =2.44	0.244	84.64
14	0.61	0.061	97.87
16	0.15	0.015	99.59
18	0.038	0.0038	99.90
20	0.001	0.0001	99.997

Table 3.4 Phase Fraction Size Relationship

There is another reason for having the frequency discrepancy between the AM carrier and the DDS frequncy small. The changing phase must be reported as data from the reference to the mobile. A large phase change would require more bits of data to be transmitted. Again with a 16 bit fraction the worst case phase to be reported would be 0.015 cycles which is about 450 cm in terms of range. For a 2 cm resolution, this would require 8 bits of data. That is acceptable and it can be concluded that a 16 bit phase fraction would be functional.

A query arises in using the phase measurement. Exactly when does this measurement apply; at the start, end or middle of the DFT sample period? Since the DFT is in essence an average, it would apply to the average of the samples and an average of the sample times. That would put it in the center of the DFT sample set.

3.7 Required Size of Cosine/Sine Lookup table

There are two issues here, the length of the table and the size of the value for each entry. The question concerning the number of bits for each entry would follow the same line of thought as in determining the bit resolution size of the ADC. Since the sample is multiplied by the value of this table, it follows that they be of the same size. It was determined that the ADC should have no less than 7 bits of resolution in quantizing a full scale signal. Accordingly the table's entries should have at least 7 or 8 bit values.

The other problem is the roll over time for the fraction, and the amount of correlation error that would occur if the lookup table is not long enough. The fractional part of the phase accumulator does not serve directly as the address for the lookup table. As the fractional part accumulates, the fractional value will increase until it 'rolls-over' into the higher significant bits and changes the lowest significant address line. The lookup table is presenting a discrete phase, whereas it should be continuously changing. The DFT thus uses an incorrect phase from the lookup table and consequently the phase determined from the DFT is in error. Is it significant?

It is believed that the worst-case phase error occurs when the fractional part is accumulating at its slowest rate—that would be when the value of the phase fraction has all zeros except for the LSB. For example, consider an 8 bit table (256 values), and a 16 bit phase fraction, the fraction rolls into the address and affects the least significant address line, once in every 32,768 samples. Refer to Figure 3.11.

The rollover rate is:

$$1{,}280{,}000 \,/\, 32{,}768 = 39/\text{sec} \tag{3.9}$$

If the DFT duration is 0.1 seconds, then a rollover will occur 3.9 times per DFT. Where these roll-overs occur relative to the DFT sampling could affect the phase measured. A rollover is equivalent to an increment in the lookup table, which in this case would be $2\pi/256 = 0.0245$ radians.

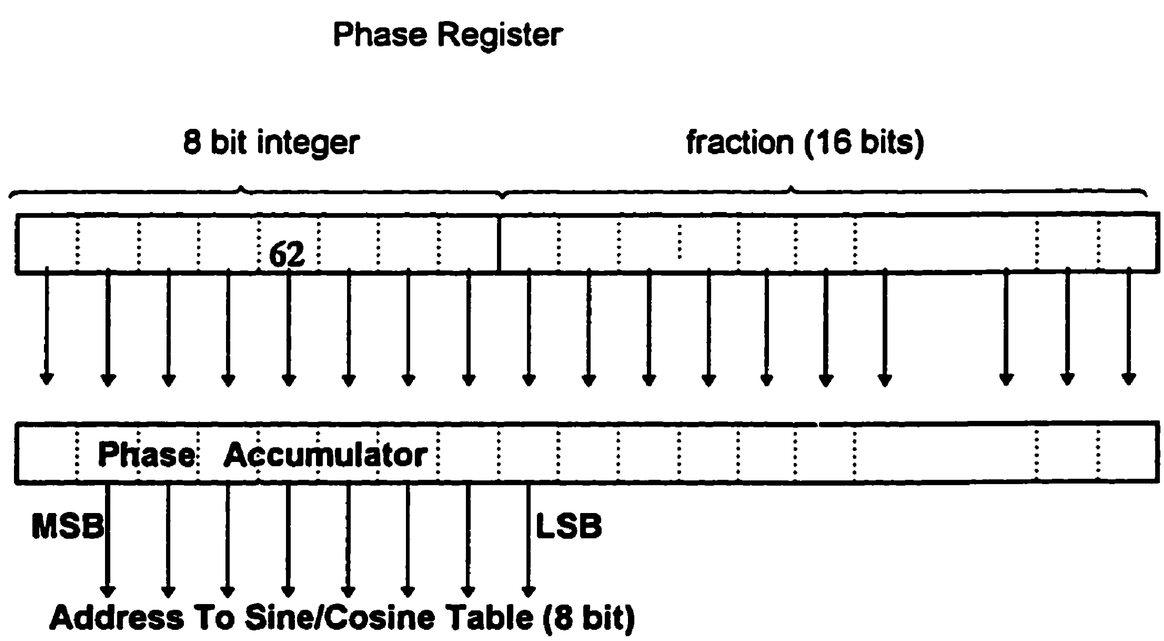


Figure 3.11 Phase Register—Size of Fraction

Refer to Figure 3.12 where a rollover is depicted by a ' | '. In the upper part of the figure the rollover occurs with the first sample, so the value of the first address line is increased.

In the lower part of the diagram, the rollover is delayed and the address line is not affected by the fraction for some time. For only a slight difference in time, albeit the worst possible, the phase will be different by almost one incremental value of the table, which will result in range errors of over one hundred cm at 1 MHz(λ/256 or 30000 / 256).

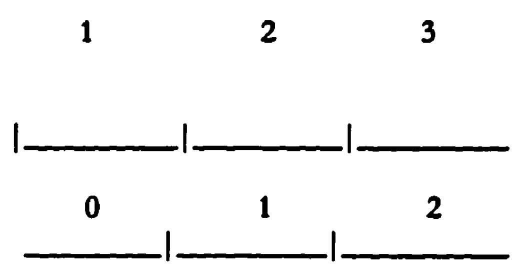


Figure 3.12 Phase Error Due to Position of Roll-overs Relative to a DFT Sample Set

Accordingly a lookup table of length 1024 could produce an error of 30000 / 1024 = 29.3 cm and one of 4096, 7.32 cm. If it is desirable to achieve range measurements to within an accuracy of less than 10 cm; it will be necessary to have sine/cosine lookup tables that have at least 4096 values. This implies a 12 bit address., with a roll-over period of 1280K / 32K = 0.025 sec. With a sample set taken over 0.1 sec., four roll-overs will occur, but the amount of error will depend on how the roll-overs align with the sampling time.

3.8 DC Offset Affect on the Phase Error

The phase must be measured extremely accurately and all sources of phase error must be investigated. The DC voltage offset of the analog signal at the ADC would affect the phase error. To what tolerances must the offset be kept to hold the phase error to an equivalent range error of a couple of cm? A program was written to test for the amount of phase error that would be caused by having an undesired bias on the samples. It follows.

```
% dc2 800 samples will be used on 40 cycles, so there are 20 samples per
% cycle, then some end effect will be added by going an extra 10 samples
% one half cycle, the dc offset(dc) tried at 0.5% to 2% of full scale.
clear;
for c= 1:4; % this is 2% because full scale is two volts
   dc = c/100; % express the dc voltage as absolute volts
   d(c)=c/2;  % true percentage, this will be plotted
   for ef=1:10  % change from 0 to 10 is half cycle
      p(ef)= ef/20;
   for n=1:(800 + ef);
      ss(n) = cos((n)*pi*2/20) + dc;      % sample taken with DC offset
      real_(n)=cos((n)*pi*2/20) * ss(n);  % correlate the real part
      imag_(n) = sin((n)*pi*2/20) * ss(n);% correlate the imaginary part
   end;
   phase(ef,c) = atan(sum(imag_)/sum(real_));
   clear real_;   clear imag_;
end; end;
mesh(d,p,phase);
ylabel ('End Portion(cycles)');
xlabel ('DC offset % of full scale');
zlabel ('Phase Error due to DC offset (radians)');
title ('Phase Error Due to DC Offset');
```

Typically an amplifier might have an offset of 1 mV which would be one tenth of one percent of a full scale of 1 volt. The Matlab program above simulates a DC offset with 800 samples taken across 40 cycles plus a portion of a cycle. As shown in Figure 3.13, this would produce a phase error of about 0.001 radians more than the normal end effect error. In terms of range error, this would be about 5 cm. It will be important to use amplifiers with a small offset voltage and small offset drift.

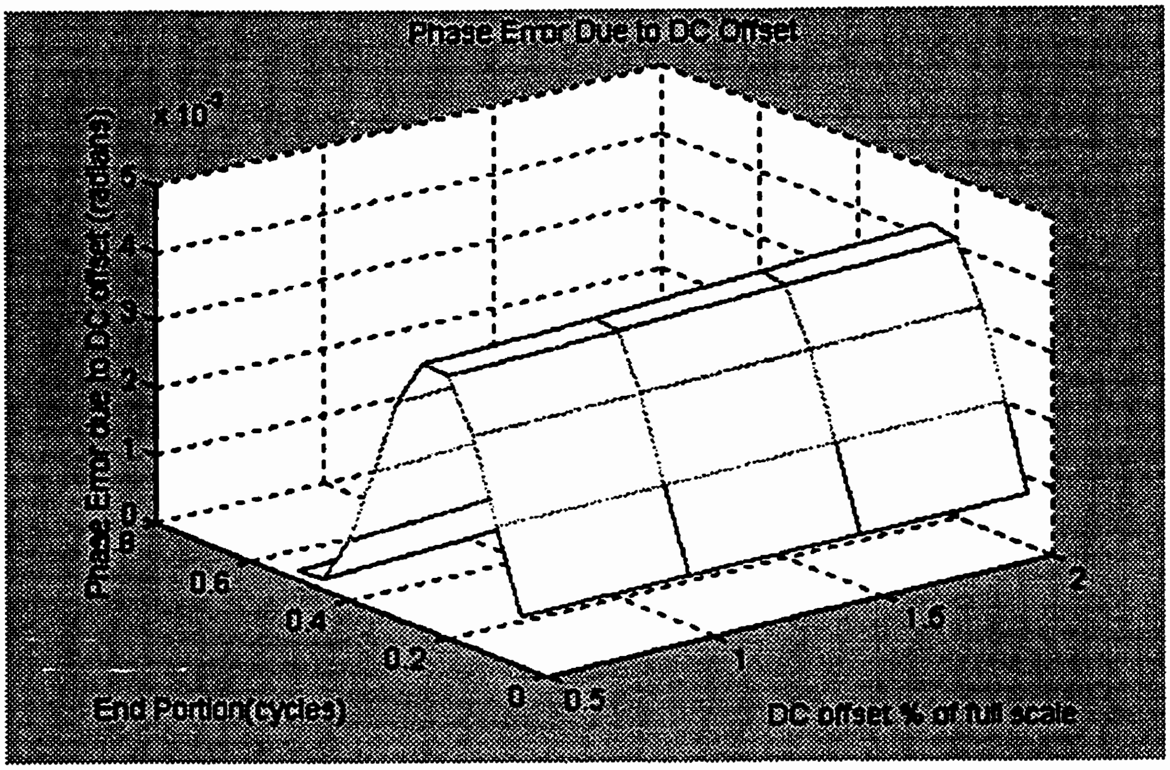


Figure 3.13 Phase Error Due to DC Offset Voltage

The end effect is readily analyzed for the continuous case with a DC offset. Consider the signal $V\cos(2\pi f_c t) + k$ in which k is the DC voltage offset. The terminology and derivation is similar to section 3.5. The Fourier Transform is:

$$FT(n, \Delta) = \int_0^{nTc+\Delta} (V\cos 2\pi f_c t + k)(\cos 2\pi f_c t - j \sin 2\pi f_c t)\, dt \qquad (3.10)$$

With $V' = V/k$ where $100 < V' < \infty$ for a DC offset between 1 percent and zero the above becomes:

$$= V'/8\pi f_c \left[\{4\pi n + 4\pi\Delta_n + \sin 4\pi\Delta_n\} + j\{\cos 2\pi\Delta_n - 1\} \right] + 1/2\pi f_c \left[\sin 2\pi\Delta_n + j\{\cos 2\pi\Delta_n\} \right]$$

where $\Delta_n = f.\Delta$, $0 < \Delta_n < 1$

Let $V'' = 1/V'$, $0 < V'' < 0.01$..

The calculated phase is therefore:

$$\text{phase}(n, \Delta_n) = \tan^{-1}\left\{\frac{(1/4)[\cos 4\pi\Delta_n - 1] + V''[\cos 2\pi\Delta_n - 1]}{(1''/4)[4\pi n + 4n\Delta_n + \sin 4\pi\Delta_n)] + V''\sin 2\Delta_n}\right\} \quad (3.11)$$

To investigate the effect of the DC offset (k), the end portion, Δ_n was varied from 0 to one half a cycle, the number of cycles held constant at 1000, and the DC offset was varied from 0 to 1% of full scale. The results are shown below in Figure 3.14 and they indicate that the contributions are minor.

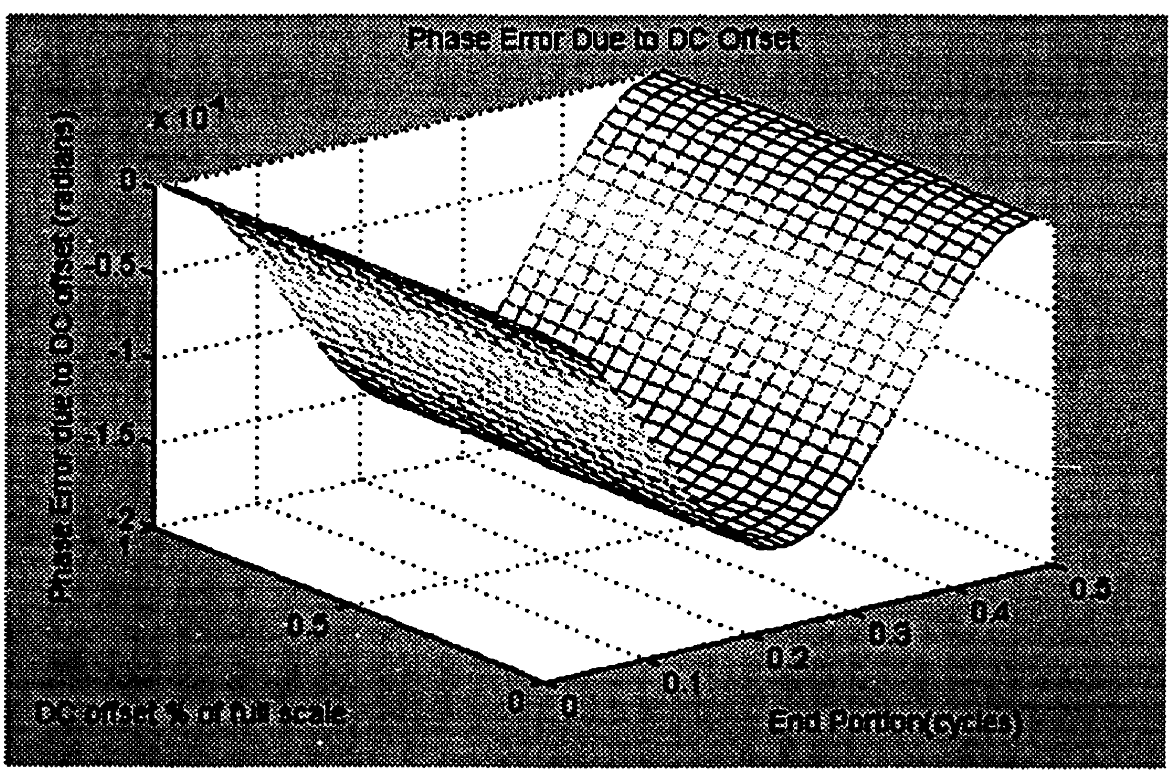


Figure 3.14 DC Offset with End Effect (continuous analysis)

Further the DC offset can also be controlled. A measurement of the average value of the samples could be used to null the DC offset. It is recommended that the samples be averaged with the DSP and that the input amplifier's DC offset be controlled to maintain a zero mean for the sampled values.

3.9 DFT Aperture Time and Update Rate

The time over which samples are collected in order to be processed in one DFT process is termed the DFT aperture time. This time is already set in large part by the determination of the number of samples required, 8000, and the sampling rate, 1.28 MS/s. Accordingly the minimum DFT aperture time would be:

8,000 / 1,280,000 = 0.00625 s or 6.25 ms.

The maximum DFT aperture time, would be established by the range update rate. For the control of a moving mobile, an update rate of 10 per second would be more than adequate. This then would set the DFT aperture time to something less than 0.1 sec or 100 ms. The limits have been established; the question now is to determine whether the minimum or maximum should be favored.

Using the maximum of 0.1 s would certainly be good for reducing the phase error because the longer length should be able to deal better with noise. 128K samples would be taken for each DFT. Also the system would be much better than with the minimum. The downside in going with the maximum would be the extreme accuracy that would be required in setting the phase register to the exact frequency of each station. AM radio stations can easily be in error from their nominal frequency by more than 20 Hz (Table 3.2) With this amount of error the phase between the sinusoid in the lookup table and that of signal in error, would, taken over 0.1 ms, change by two cycles. Therefore, they would not correlate.

To alleviate this problem, it might be necessary to stage a lock-in-period to initially find the exact frequency of each station by using the minimum DFT aperture time, and then with the frequencies established, the aperture time would be increased to its maximum. Notwithstanding the initialization, the recommendation for the DFT aperture time will be 0.1 ms.

3.10 Number of Radio Stations to Use

The proposed system requires a reference station and a number of radio stations, that already exist. Typically a dozen or more radio stations can be detected, depending on the geographical location. Table 3.2 shows 14 stations being detected with varying degrees of amplitude. How many of these stations should be used?

In general, one would use as many as possible, but the gain in accuracy is a rapidly diminishing return. The criteria for the selection of the set of stations used are:

- The set chosen should represent a good geometric pattern. The position fixes are obtained by intersecting hyperbola, and the best accuracy is obtained when the lines of position (LOP) intersect orthogonally. To deal with this demand, the radio stations that form a right angle with the reference station would have the highest priority for considered use. The set chosen should surround the reference station. Selection of a number of stations from one point or one city produces redundant positioning information and should be avoided.

- The radio stations with the largest signal should be selected. This is almost obvious. The stations with the larger signal will offer a more accurate phase measurement, which in turn translates into a more accurate positioning system. The gain of the input amplifier needs to be set to have the station with the largest signal, occupy the full scale range of the ADC. A weaker station will not be resolved as well by the ADC and will suffer degradation in phase error measurement due to quantization noise. It was determined in Section 3.4 that the dynamic range of the stations should be within 30 dB if a 12 bit ADC is to be used.

- The processing power will constrain the maximum number. The processing power required to do the DFTs goes up proportionately with the number of radio staions being used. The same holds true for the data that would be broadcast on the communication link.

- The minimum number of radio stations to acquire a position fix is two. At least two intersecting hyperbolae are needed for a fix. Any number above this would provide a better fix due to the redundancy. The multiple solutions should be close to one another; if a solution differs greatly from the others it can be discarded. If many of the solutions constantly disagree, it is an indication of the system's loss of integrity, to the point in which the system declares itself unusable.

With consideration primarily to the last two points given, it is proposed that the system be designed with the capability to process 8 radio stations.

3.11 THE COMMUNICATION LINK

The mobile can not determine a fix by listening only to the radio stations. It requires information from the reference station, to which it must 'refer' to determine a fix. The two vital pieces of information that come from the reference station are the trigger signal and the phase data for each of the AM radio stations.

The trigger signal is the timing signal that informs the mobile the time at which to latch the count. With the digital implementation, it is the timing signal to which the samples are synchronized, and to which the first sample of each DFT set starts. It must be very accurate; for a desired range accuracy of less than ten centimeters, it must be discernible to within a fraction of one nanosecond.

To send the trigger signal and the data, it is suggested that a spread spectrum modulation scheme be employed for the RF signal broadcast by the reference station to the mobiles.

Spread Spectrum for the Communication Link

Spread spectrum is ideally suited to serving the dual purpose of sending a precise triggering signal as well as sending binary data. It has the added advantage of having a significant process gain, which can be realized with a much lower transmit power than that required by other modulation schemes.

Trigger Signal

The sampling rate was selected to be 1.28 MS/s. One could easily imagine a sampling clock, operating at this frequency in both the reference station and the mobile(s). However, it is imperative that the sampling times be synchronized—precisely—to within about 0.1 nanoseconds.

Now, it might be presumptuous to imagine that the regulatory authorities would allow one to use a carrier at 1.28 MHz (since it is an allocated frequency for an AM station), but for the sake of explanation it is assumed. The sampling clock at the mobile, and the transmitting oscillator at the reference station should be the same frequency and synchronized. The mobile detects and measures the changing phase of the transmitted reference signal, just as from any other AM station. However the changing phases which result from the DFT operation would be indicative of the frequency and phase error resulting between its 1.28 MHz clock and that of the incoming signal. The mobile's clock would be tuned, by setting the voltage on a varactor, such that the 1.28 MHz clocks are exactly synchronized in frequency and phase. This is nothing more than a phase locked loop, with parts of the loop, namely the phase detection, being done in software. It is certainly possible to keep the phase error to less than one part in 10,000 [5].

Other than the problem of being granted permission to use the 1.28 MHz carrier; there remains the problem of synchronizing the start of each sampling sessions. With the synchronization of the carrier, the precise timing for taking each sample is established, but the time of the first sample of each session is not known. The synchronization of the PN code will provide the gross session start time.

With direct sequence PN spread spectrum, the carrier is bi-phase modulated with a unique PN code. Each bit of the code is called a "chip", and the carrier is bi-phase modulated at the "chip-rate". For the proposed system a chip-rate of 20 kHz is selected.

Using the same PN code, the mobile demodulates the spread spectrum signal being transmitted by the reference station. It slowly shifts the PN code in time, until the signal correlates. At this point the mobile is said to be 'locked'. The start of the sample session could be aligned with that of the PN code.

To illustrate how the reference 1.28 MHz oscillator is synchronized with the mobile's clock consider a Maximal Length PN code [23] of length 15 which has a 4 bit shift register and taps at cells 1 and 4. The code would repeat every 1.5 / 2 = 0.775 ms. To synchronize the start of a sample session, is made to coincide with a code cycle.

To line up the code cycle with that of the sample session, it is assumed that the lock of the code, could be done to within one sample time. In one chip there would be 64 cycles of carrier, or 64 potential start-sample times. The chip clock is derived from the carrier or sample clock, and therefore the transitions of the chip will occur at precisely the same phase as the carrier; they are said to be coherent. It is then only necessary to resolve the code lock to a non-ambiguous cycle, or to within one half a cycle. The code lock must then be done to within one part in 128 ot a chip, one half a cycle or in absolute time 0.39 µsec. It has been shown that this is achievable by Dixon [17]. Code lock can be better than one part in 1000 of a chip.

A short PN code was selected to coincide with a reasonable sample session. However, it is important to keep in mind that this establishes a code wavelength. In this case it is λ = 300/ (0.02 /15) = 225 km. This is much farther than the range of the system proposed, and there is no ambiguity.

So, the sample time can be synchronized, as well as the sample start time; but what if the desired frequency of 1.28 MHz. is not available for this use? With an additional slight complication in circuitry, it can be shown that any frequency that is a multiple of 20 kHz can be used as the carrier. For example, such a frequency might be 1660 kHz, just beyond the upper AM band. The reference station has the 1660 kHz as the master clock and by means of a phase-locked loop, hardware or software, it derives the sampling clock of 1280 kHz. as well as the chip clock (Figure 3.15).

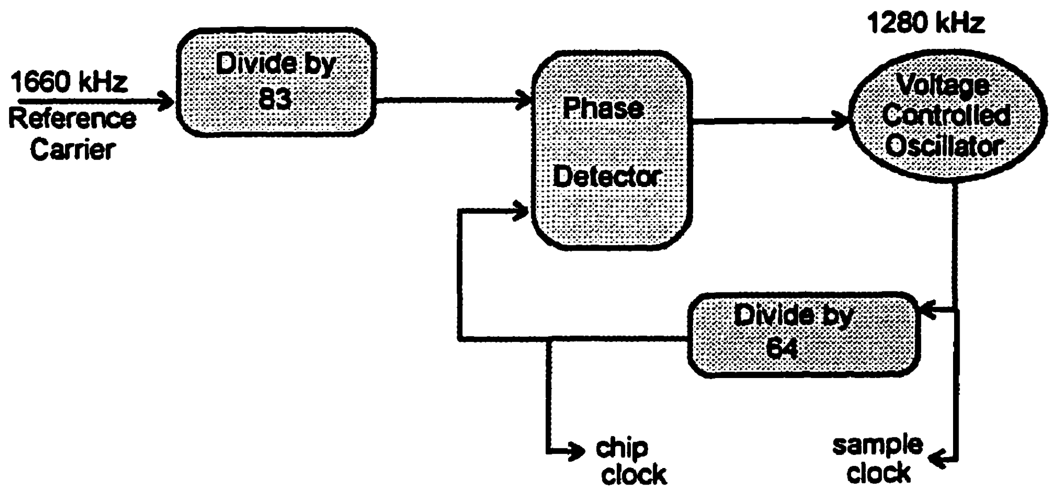


Figure 3.15 Deriving Clocks from the Reference

The divide-by-83 and divide-by-64 blocks are realized by counters and their initialization is important in obtaining the despreading of the PN code. This initialization can be done in hardware or software. The phase detector is just a DFT phase measurement and the adjusts the 1280 kHz clock by adjusting a varactor. One would have a virtual oscillator at 1660 and the increasing or decreasing phases measured with the DFT would be used to adjust the 1.28 MHz real clock. The objective is to have the mobile's 1.28 MHz clock locked to that of the reference.

Data

The phase of each AM radio station transmission, is the primary data, with the secondary information being the frequency of each station. Occasionally the location of each of the stations would also be sent. The phase must be measured to an accuracy that is better than one part in 10,000 which is equivalent to 14 bits of data. This is the absolute phase and it must be sent at least occasionally but it is also possible to send just the relative phase difference which was determined earlier from the section on phase fraction to be 8 bits of data. In any event the worst case would be 14 bits per session per station. If 8 radio stations are used then 112 bits would be sent per sample session. With a sample session being 0.1 ms, the required data rate would be 1.12 kb/s. With the spread spectrum system designed as above and with a data bit being sent for each code cycle, the resultant bit rate is 20 kHz / 31 = 645 b/s. If the code cycle is reduced to 15 (4bit register) , then the rate is 20 kHz / 15 = 1.3 kb/s. This could handle the required data rate of 1.12 kb/s with some overhead, error detection, and the transmission of the secondary information on an occasional basis.

Process Gain

The process gain of a spread spectrum system is defined by the chip rate divided by the data rate. It is a measure of bandwidth expansion. In the example done above the process gain would be 20 kHz/ 1.33 = 15 or 12 dB. In practical terms, it means that the signal at the mobile's receiver can have a SNR that is 12 dB lower than that of a comparable modulation technique to achieve the same performance; or it means that the transmit power at the reference could be reduced by 12 dB.

A rule-of-thumb for VHF radio transmission power is: "one watt per mile" [1] . For a system with a range of 20 miles, typically a 20 watt transmitter would be required. Considering the process gain of the spread spectrum system, only 20/15 = 1.3 watts are required. This taken with the manner in which the spread spectrum spreads the energy over the spectrum, would result in little or no interference being detected by other radios. This should make for a more convincing argument to the regulatory authorities in granting permission for a carrier frequency for the reference.

3.12 Ambiguity Reduction

An approach to eliminate ambiguity is described by Hawkins [22], A gross position fix is obtained by using a much lower frequency, which in turn has a much larger wavelength. The lower frequency is the lower frequency term of the product (mix) of two higher frequencies. It is suggested that this same principle be applied for this AM positioning system. The lower frequencies would be generated by mixing the signals from the AM stations. The mixing would be done in software.

There are complications that are encountered with the AM system that Hawkins did not anticipate. In the description, the two frequencies used to generate the lower frequency originating from the same point. In the case of the AM transmitters this is not the case. The stations are physically in different locations.

The (Line of Position) LOP for the lower frequency would be hyperbolae between the two radio stations used to generate the lower frequency. Since the wavelength is quite long for this lower frequency; the distance between LOPs would be large; for 10 kHz. it would be

30 km. Using several pairs of AM stations in a similar manner would produce additional sets of hyperbolae, which in turn could be used to determine a gross fix.

3.13 PUTTING THE PIECES TOGETHER

The previous sections discussed specific design details of the proposed system. The design targets were based on the intent of having a system that could:

- Determine positions to within 15 cm
- Produce at least four position updates per second
- Have a latency in updates of no more that 0.25 seconds
- Minimize the cost by using the existing AM stations and in general by minimizing the required hardware.

The components of the reference station and the mobile are the same, with the exception that the reference station has a transmitter. With most of the design detail determined, the discussion now turns to assembling the pieces. A block diagram of the design of the reference is shown in Figure 3.16 and of the mobile in Figure 3.18. A description of the operation follows.

The antenna for the mobile is a vertically polarized omni-directional whip antenna, commonly used on automobiles. The antenna for the reference would be a similar type whip, but could be larger. The lead-in coax is connected directly to the low noise broad-band amplifier. The gain on the amplifier is controlled to maintain an output signal amplitude that is equivalent to the full scale voltage of the ADC. As was mentioned previously the amplifier needs a dynamic gain of about 30 to 40 dB. The amplifier is followed by a band-pass filter which allows only the AM band to pass. This then is followed by an A/D that samples the broad band signal at a rate of 1.28 MHz with 12 to 14 bits of resolution. The samples are then processed with a DFT to determine the phase of each of the AM radio stations being used.

The sampling and DFT clock would be derived from a voltage controlled crystal oscillator (VCXO) with a nominal frequency of 10.24 MHz. In the reference station, this oscillator could be left uncontrolled, or, it could be locked to one of the incoming radio stations. In the mobile this oscillator would be adjusted such that the measured phase of the reference carrier is stationary. This would synchronize the sampling clocks of the reference and the mobile.

The reference's carrier is synthesized digitally and is coherent with the 10.24 MHz oscillator. The value in its phase register is held constant, and is the same for the reference station and the mobile. The bi-phase modulator used in most spread spectrum systems is replaced with a "negate" process and since this is digital, it is possible to implement most of the spread spectrum components with a Field Programmable Gate Array (FPGA).

The 10.24 MHz oscillator is divided by eight to provide the clocking signal for sampling and DDS processing. To facilitate high speed processing, the DDS is best implemented in hardware. Each of the eight radio stations has a phase register and a phase accumulator. There would also be a phase register and phase accumulator for the reference signal carrier. The phase registers are loadable, and thus the frequency and phase of the sinusoids produced are completely controlled. The phase register for the reference station is also loadable, but the carrier for the reference will have no error in frequency relative to the sampling clock and, therefore, will hold a constant value. The phase register for the other

AM stations is set to a value that matches the frequency of the station; this would include any frequency deviation from the nominal. The reference station informs the mobile as to what values should be entered into the phase registers (secondary data).

To obtain a chip clock of 20 kHz the sample clock is divided by 64. This clocks the PN code generator, which is 4 bits with taps at position 1,4 and a code length of 15 chips. The chip transition and the zero crossing of the reference carrier would be forced to coincide. It is important to have this done precisely because the mobile uses this information to achieve tight synchronization. There is a problem here though, in that the chip transition is delayed through the filter following the DAC in the reference stations transmit section. This is shown in Figure 3.16. To compensate for this delay, the reference station monitors its own transmission and processes the signal just as the mobile would. Both the reference station and the mobile have a phase register and phase accumulator for the reference channel. They both receive and measure the phase of the reference. The reference adjusts its transmission such that the output of the transmitter will have the carrier's zero crossing exactly aligned with that of the chip's transition.

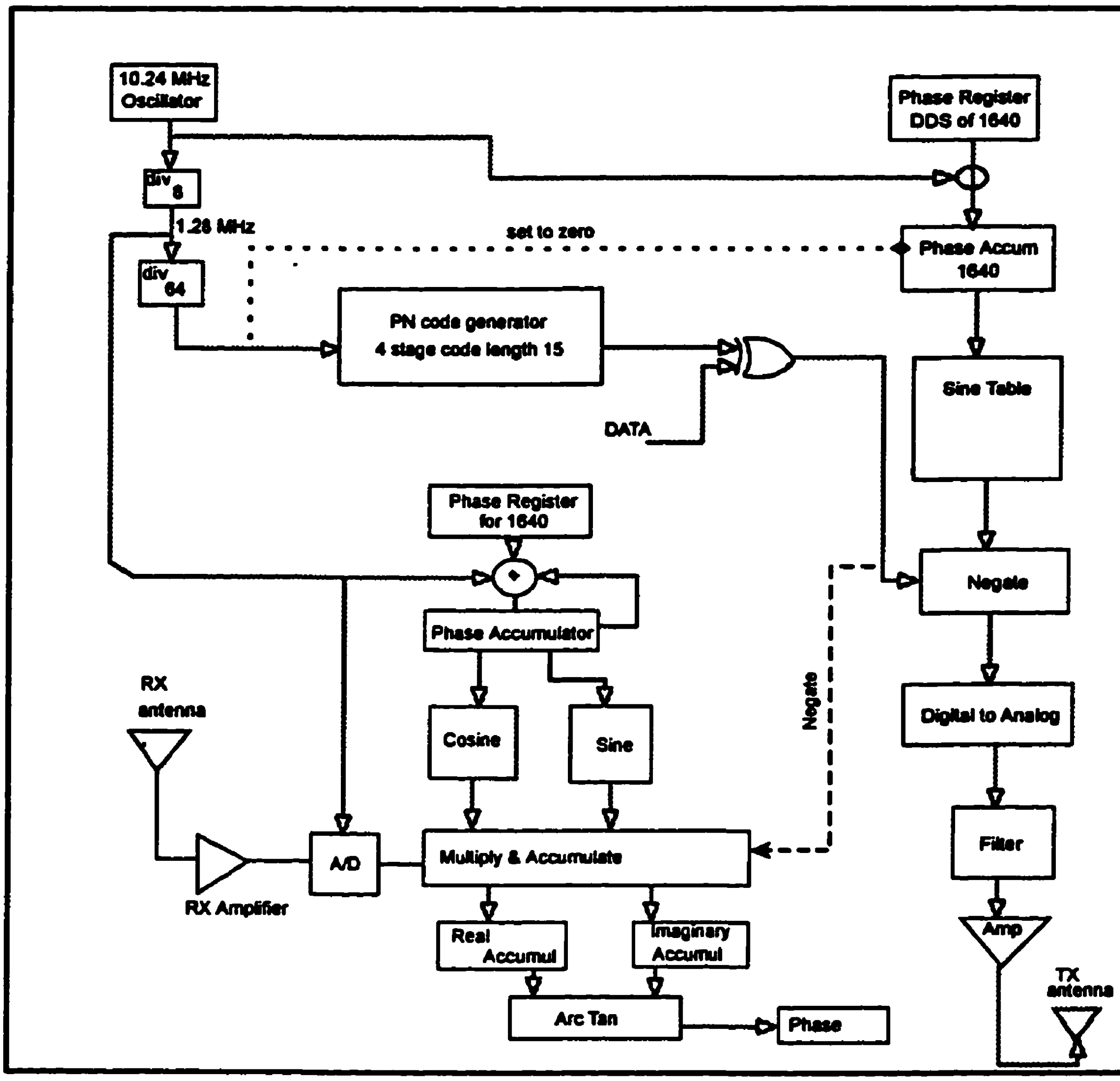


Figure 3.16 Reference Station's Components for Transmitting and Receiving the Reference Signal

The chip clock is 20 kHz, and there are exactly 82 cycles in each chip. The phase register has a known value for the reference's carrier frequency (assumed to be 1640 kHz) in both the reference and the mobile. To initialize the process of synchronizing the carrier with the chip; the chip clock clears the phase accumulator. A zero crossing of the carrier is forced to align with the chip transition. Unfortunately this alignment is distorted as the signal passes through the filter as shown in Figure 3.17; the chip transition is delayed. The amount of the delay is determined by the bandwidth of the filter.

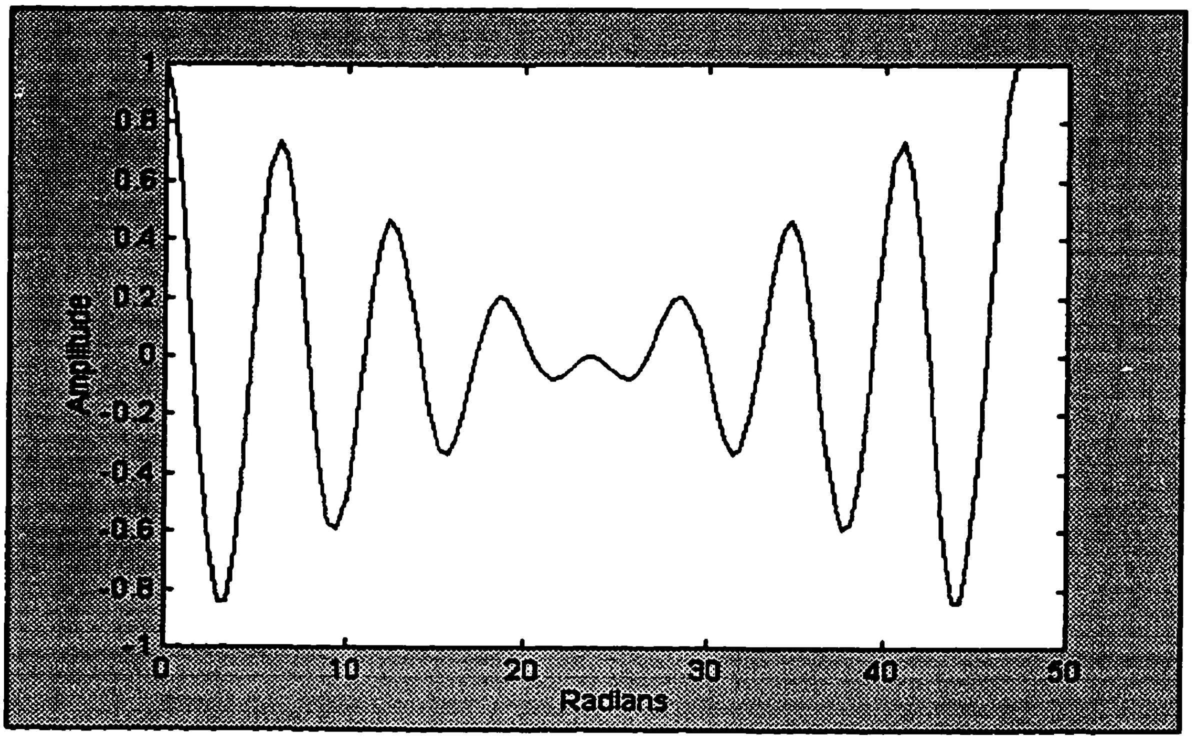


Figure 3.17 Chip Transition Delay Due to Filtering. Zero Point at 3.25 cycles after actual 180 degree flip

To determine the amount of the delay and to compensate for it, the transmitted spread spectrum signal is monitored. The receive antenna detects the transmission and the signal is processed in exactly the same fashion as the mobile. The PN code is slid across and the position with the highest degree of correlation is retained. The initial alignment of the chip was done by clearing the phase accumulator; this alignment is changed by momentarily augmenting or diminishing the phase register in such a way that the phase of the apparent chip transition can be made to exactly coincide with that of the zero crossing of the carrier.

The integer number of cycles of PN code delay can be communicated to the mobiles as data.

The mobile in listening to the spread spectrum signal from the reference has one main objective—to have the sampling clock, chip clock and data clock exactly synchronized to that of the reference. Upon power up the phase register is loaded for a frequency of the refernce's carrier (1640 kHz) and batches of DFTs are done with the PN code slid across in time, looking for the best correlation. The best correlation is the one with the largest DFT amplitude. At the same time the phase of consecutive DFTs are noted and the 10.24 MHz clock is adjusted in frequency to produce the same phase value for each DFT. This ensures that the 10.24 MHz clock of the mobile is locked in frequency to that of the reference. The gross sliding of the PN code could be done by inserting or deleting clock pulses in the divide-by-64 block. For a finer adjustment of the PN code slide, pulses could be inserted and deleted in the divide-by-8 and the divide-by 64 block. The combination that provides the highest degree of correlation is the same as that in the reference. It is important that the this be done properly; several runs should be done to ensure that the synchronization is secure. The final step in synchronization would be that of setting the phase of the 1640 carrier to zero. It is known that the signal from the reference has a DFT phase measurement of zero. By momentarily augmenting or diminishing the phase value, the phase of the reference's carrier can be forced to zero. The chip transition, should coincide with the zero crossing of the reference's carrier as monitored by the MSB of the its phase accumulator.

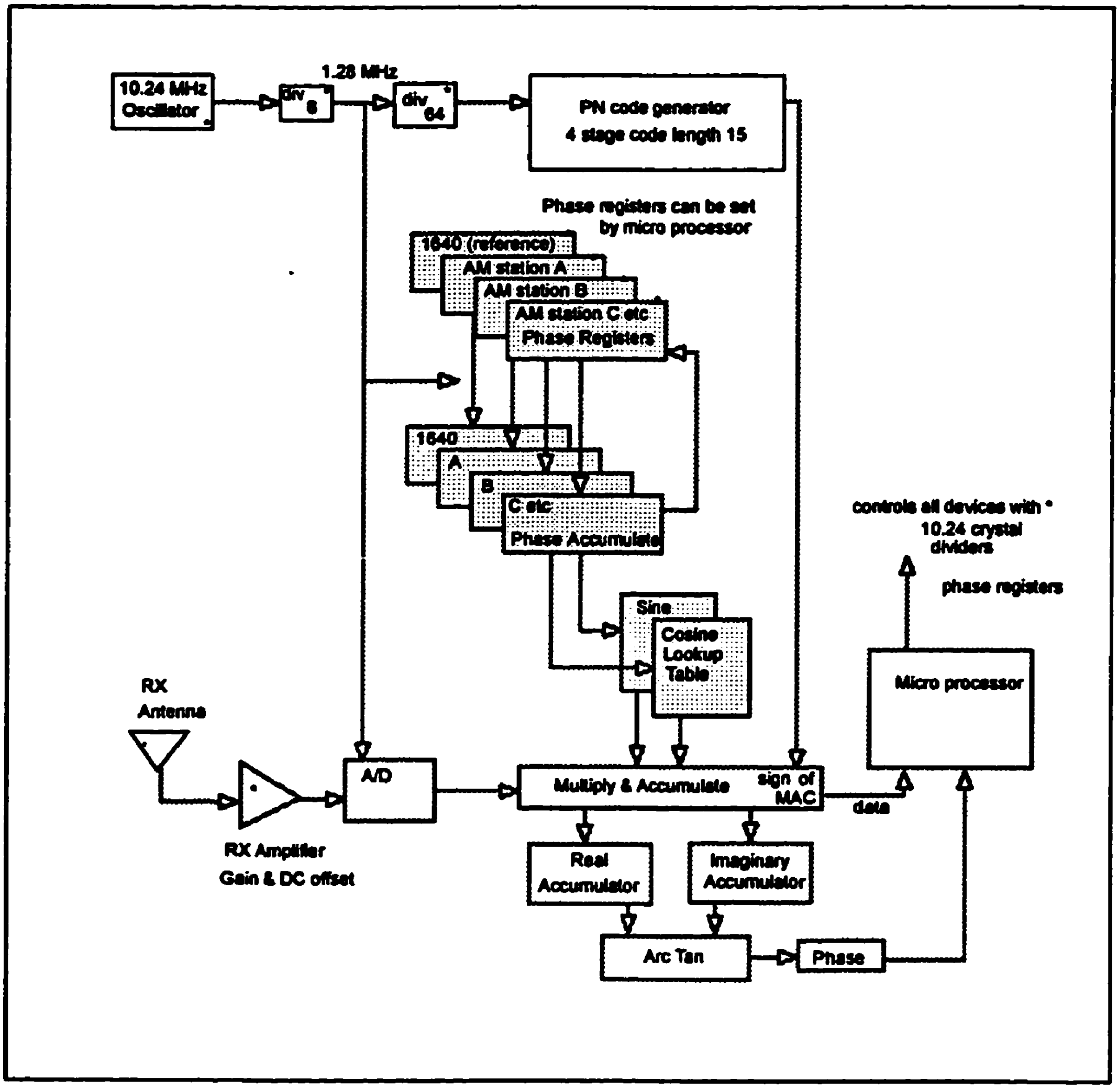


Figure 3.18 Mobile, Including Components for Receiving Reference Signal for Synchronization

The incoming data will eventually disclose the integer number of reference's carrier delays in the chip transitions and the integral part of the delay can be compensated for. Synchronization of the mobile to the reference station is then complete.

The mobile at this time would start measuring the phase of the radio stations and compare this to the phase data for each station being sent by the reference from which hyperbolic iso-phase difference lines could be determined. The intersection point resulting from several of these lines would yield the position. The ambiguities would be eliminated by using the difference frequency, as mentioned in section 3.12.

Although the diagrams indicate a number of components the actual implementation is done with very little hardware. This is in keeping with one of the requirements of keeping it simple. The design objectives have been addressed, but the question of range accuracy has yet to be answered. Will the system provide positions accurate to within 10 cm? The primary source of range error will be due to propagation anomalies that differ between the reference and the mobile. To determine the degree of this error, an experiment was devised to measure it. This is the topic for the next chapter. From the analysis of the data collected an estimate of the position accuracy of the proposed system is established.

CHAPTER FOUR

DIFFERENTIAL PHASE MEASUREMENTS -- RANGE TESTS

The AM radio positioning technique is predicated on the assumption that the signal from the AM radio station will behave in the same manner in propagating to the reference as it does to the mobiles. If the mobile is at the same position as the reference, the propagation path would be identical, as well as the signal detected. Even if the signal is distorted with multipath or other propagation anomalies, the phase difference measured would not be affected.

If the mobile is located a short distance from the reference, the propagation paths from the AM station to the reference and the mobile would be similar, but not quite identical. The further the mobile is located from the reference, the more independent will be the two paths. One would then expect more phase error which results in more range error. This phenomenon has been reported with DGPS [51] but it has not been accurately measured for AM band signals. The objective of this chapter is to determine experimentally the phase error that results when the phase is compared along two propagation paths.

An experimental setup was constructed to emulate part of the proposed system. It received a signal from a single AM station over two channels, one for the reference and one for the mobile and included two amplifiers, two ADCs and two DFTs to measure the phase of each of the channels. The primary objective of the work done in this chapter was to determine the amount of phase distortion difference that occurs on the two channels of the AM propagated signal. But before that can be done, the circuit that measures the phase difference through the two channels needs to be checked to determine the amount of phase difference error that it contributes.

In the proposed system the reference and the mobile must be synchronized. With the experiments in this chapter, a single DSP was used to calculate the phase of the two channels obviating the synchronization issue.

Only one radio station was used in collecting the data but there were several local strong AM stations that could have been selected as seen in Figure 4.1. The station selected was CJME at 1300 kHz.

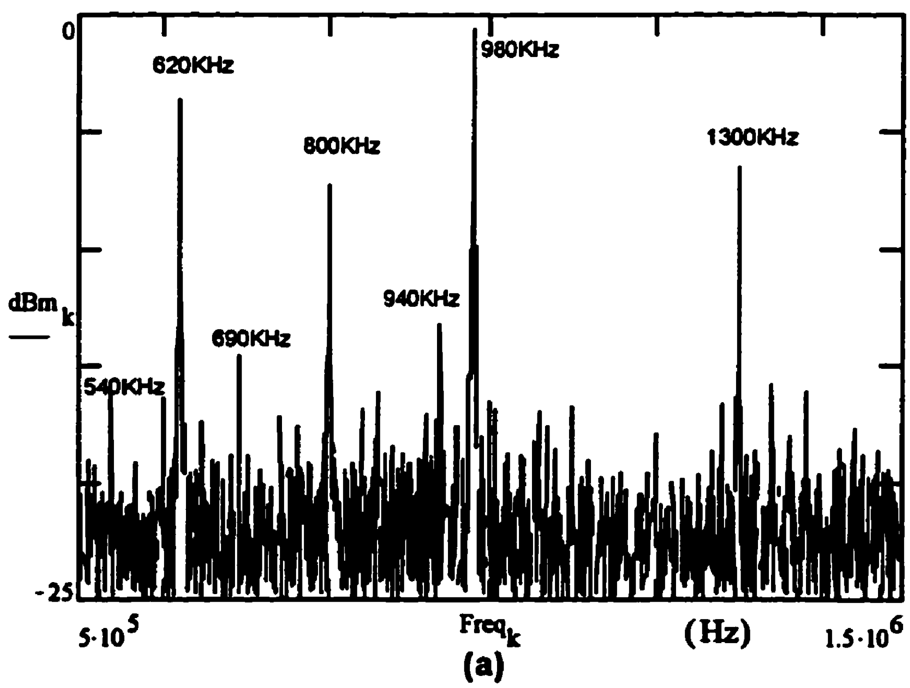


Figure 4.1 Spectrum of AM Band (Regina, Sask. Canada)

4.1 Apparatus

The apparatus to measure the phase difference is shown in Figure 4.2. The antennae were vertical whips that fed into 50 ohm cables of a length of about 75 meters. The amplifiers were housed in a single box and the subsequent ADCs and DSP were physically located together (Figure 4.3) .

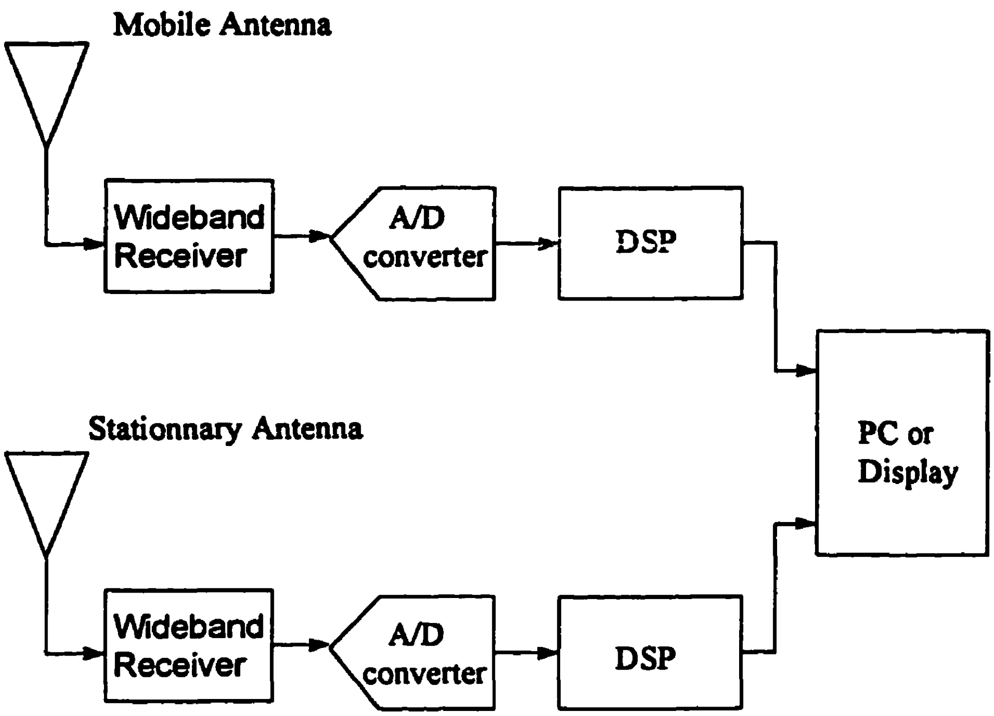


Figure 4.2 Apparatus Setup to Measure Phase Difference from an AM Carrier, Antenna of Reference is shown on the right

Amplifier

Figure 4.4 shows the schematic for the wide-band receiver that was used. It used a RF Integrated Circuit (IC) amplifier AD603AR made by Analog Devices. These ICs are low noise, high sensitivity, variable gain operational amplifiers used in RF/IF applications. The two-stage cascaded amplifier provided an adjustable gain from 10 to 80 dB. Gain variation was achieved by adjusting potentiometer VR2 manually or by applying a voltage at the V_{agc} terminal after opening solder switch R12. This wide-band amplifier was designed and built by Anh Dinh; the design details can be found in his M.Sc. thesis [16].

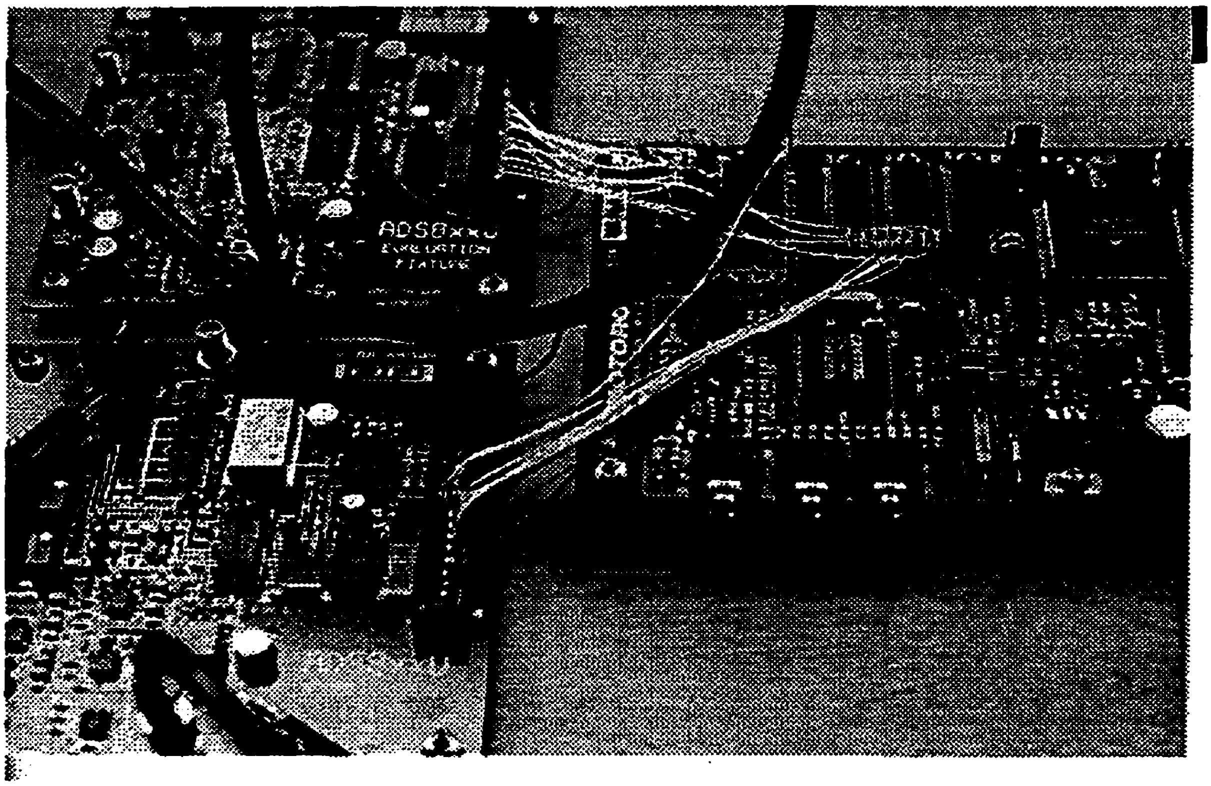


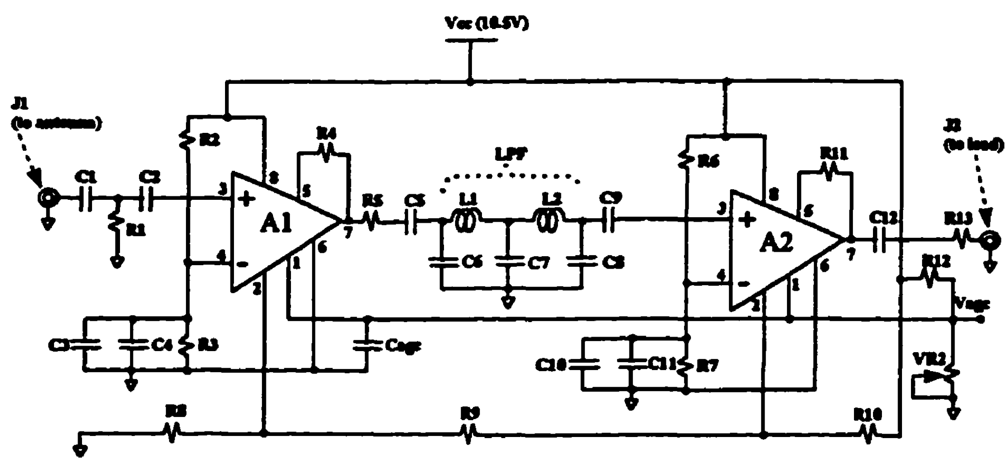
Figure 4.3 ADC boards connected to DSP board

Analog to Digital Converter

A low cost, 12 bit, 40 MSamples per second (MS/s) ADC was used. It is manufactured by Burr-Brown® and has a product number of ADS800. The two ADCs digital outputs were wired into a single 24 bit wide word in a memory mapped fashion to the DSP (Figure 4.3). The clock for both ADCs was produced from an output line of port (D) of the DSP.

Digital Signal Processor

A Motorola 56002 DSP was used to process the ADC samples from both ADCs. Figure 4.2 shows two DSPs and in terms of process there are two DSP functions, one for each channel; but in terms of hardware a single DSP was used.



- C1, C2, C4, C5, C9, C11, C12 = 0.1uF
- C3, C10 = 30uF Tantalum
- Cagc = 0.1uF
- R1, R5 = 100 Ohms
- R2, R3, R6, R7 = 5.0 KOhms
- R4, R11 = 2.4 KOhms
- R8 = 5.5 KOhms
- R9 = 1.05 KOhms
- R10 = 3.48 KOhms
- R12 = 1 KOhm
- R13 = 50 Ohms
- VR2 = 15 KOhms potentiometer
- A1, A2 = AD603AR, Analog Devices
- L1, L2 = 12 uH
- C6, C8 = 1.2nF
- C7 = 1.7nF
- J1, J2 = 50-Ohm BNC Receptacle

Figure 4.4 Wide Band Amplifier Schematic

DSP Software

The software program written in DSP assembler was called 'RON4.asm'; the complete listing of this program is given in Appendix A.

The DFT used to calculate the phase was done in a batch mode. First, 4096 samples from the ADCs were taken at a sample rate of 1.34 MS/s and stored in RAM. Next, the DDS sinusoid was created by stepping through the sine/cosine lookup table at a step size that matched the frequency being used (in this case 1300 kHz) as well as the sampling frequency. The DDS samples were also stored in RAM. Then the first channel of ADC samples were multiplied with the DDS samples and the real and the imaginary parts of the DFT were accumulated in the A and B accumulators of the DSP. The above was then repeated for the second channel. All these DFT results were temporarily stored in RAM.

The final part of the software sent the real and imaginary components of both channels to the PC by means of an RS232 connection. (9600 bps, 8 bit binary).

PC Software

The Personal Computer (PC) Laptop software collected the real and imaginary components from the DSP over the RS232 link. The phase of the DFT was computed using an arc tan and then the appropriate quadrant was obtained because Quick Basic had an arc tan function that only computed the first quadrant of phase.

With both phases computed, the difference in phase was taken. The difference was displayed on the screen as well as stored to a file.

4.2 Static ADC Validation Test

If the phase difference of two channels is to be measured through the air, it would be good to know how much of the error is due to the circuitry itself. To that end a 1300 kHz signal from a signal generator was fed directly into both ADCs. The 10 dBm signal was amplitude modulated at 85% with a 400 Hz signal. Three 8 hour tests were done with the phase differences shown in Figures 4.5. The tests were done one per day.

Short term standard deviations were less than 1/100 of a degree but the long term drift was about one tenth of a degree. The average of the third test should not be used as an indication of error because a cable was changed. This amount of phase error resulted in a range error of:

$$1/100 \text{ of a degree is: } 1/100 \times 1/360 \times 300/1.3 = 6.4 \times 10^{-3} \text{ m.} \quad (4.1)$$

and accordingly 1/10 of a degree is 6.4 cm.

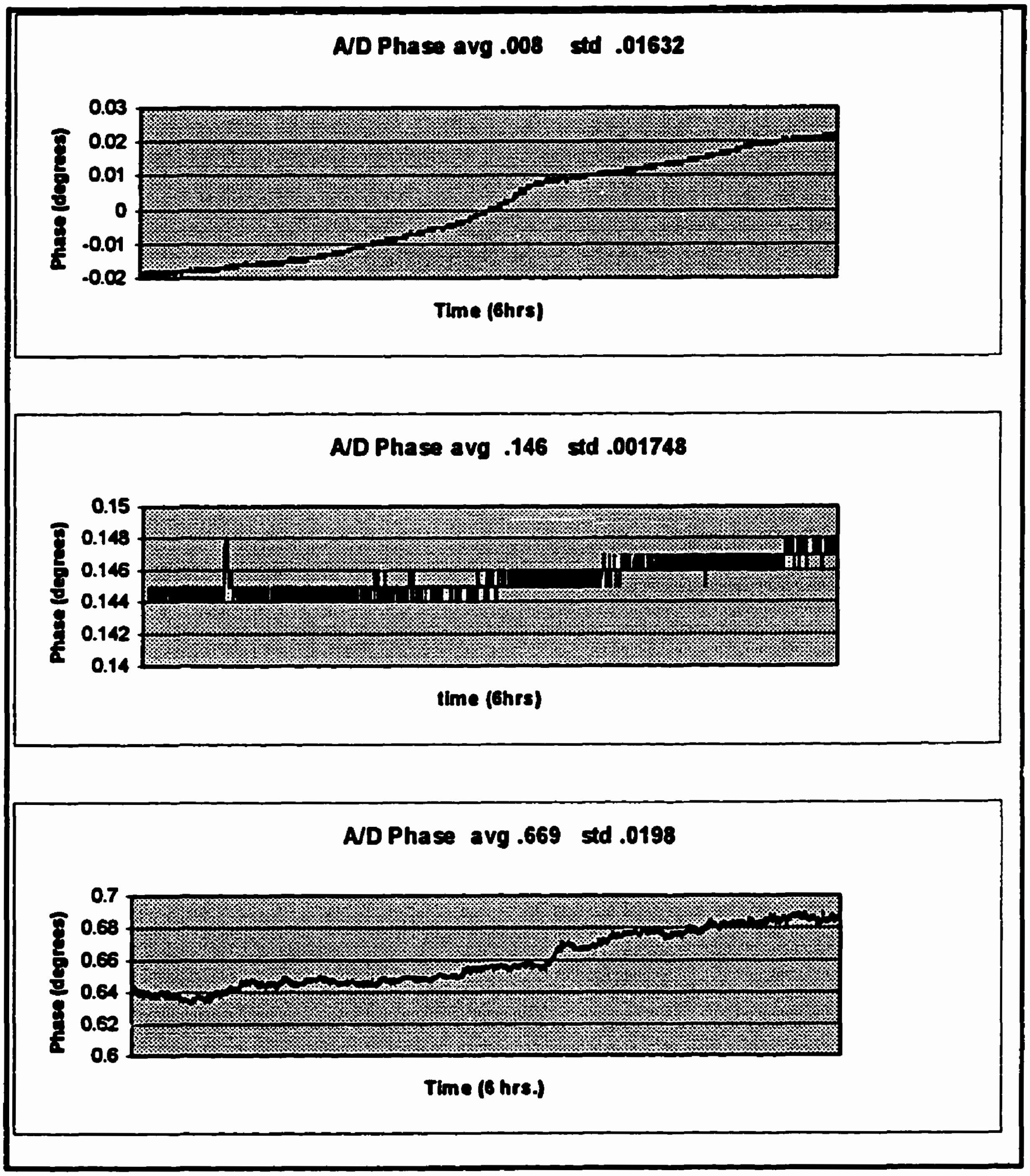


Figure 4.5 Phase Difference Error with ADCs driven directly from a signal generator (85% modulation 400 Hz.)

It might be said in concluding this section that the phase difference error due solely to the ADC and DFT would be less than 1 cm in the short term and less than 10 cm over the longer term of days.

4.3 Static Broad Band Amplifier Validation Test

The next bank of tests fed the signal generator output into the wide band amplifier which in turn drove the ADCs. The input to the amplifiers was at -40 dBm and the amplifier gain was adjusted to provide a 10 dBm signal to the ADCs. Again the signal was amplitude modulated at 85%. The objective of this set of tests was to establish the amount of error introduced by the wide-band amplifiers. The results are shown in Figure 4.6.

The results are similar to the previous set of tests with the short term standard deviation being about 1/100 of a degree and the long term drift being about 1/10 of a degree. In terms of range error this would be less than 1 cm over the short term and 10 cm over the long term.

4.4 Static Cable Validation Tests

In order to separate the antennae for tests of different propagation paths, 75 m coax cables were connected between the antennae and the wide-band amplifiers. Again the signal generator was connected in lieu of the antennae. It drove both channels through a 'T' connector. The results are graphed in Figure 4.7.

The results were somewhat unexpected in that this set of tests had better results than the previous sections. The short term tests still showed about a 1/100 of one degree for the first standard deviation, but the long term drift was only a 2/100 of one degree. To explain this it is suspected that the long cables had better connectors than the short cables used in

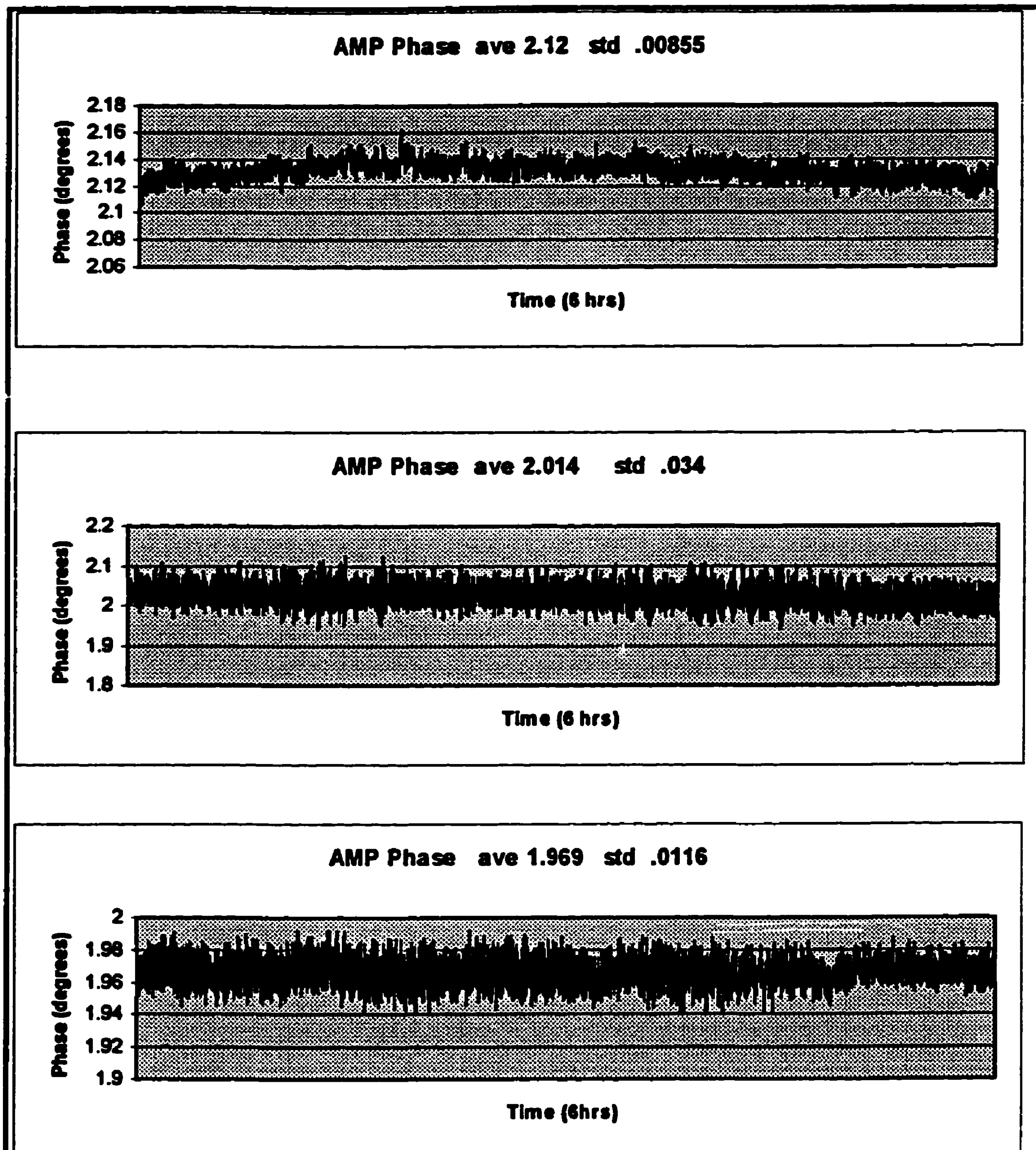


Figure 4.6 Phase Difference Error with Broad Band Amplifiers driven directly from a signal generator 85% modulation 400 Hz

the previous bank of tests. In any event one could conclude, notwithstanding the connections, that the circuit is capable of consistently measuring phase to within 2/100 of one degree which in terms of range is about two cm.

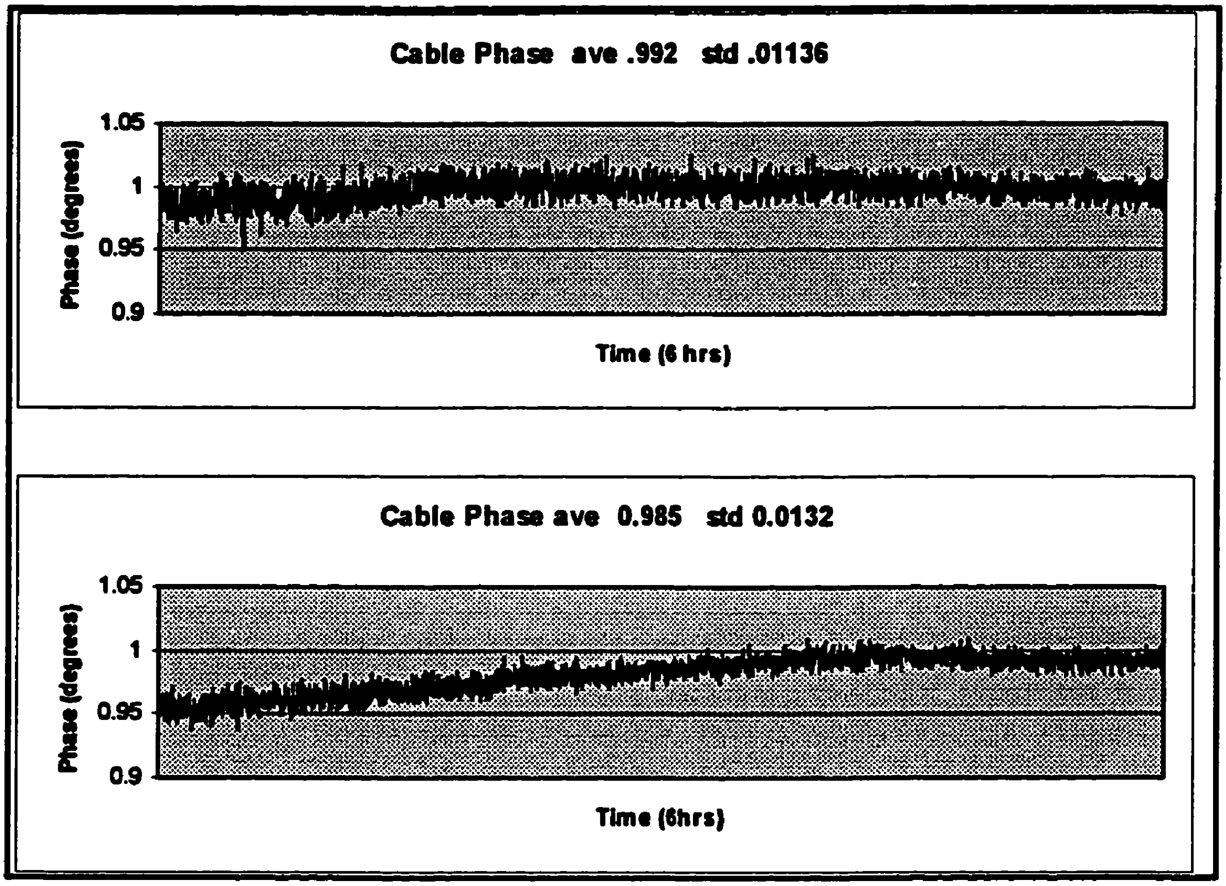


Figure 4.7 Phase Difference Error with Coax Cable and Broad Band Amplifiers driven directly from a signal generator (85% modulation 400 Hz.)

4.5 Static AM Station -- Two Antennae -- Same Spot Tests

This next set of tests used a real AM station for a signal source. The two antenna are placed about 1 meter apart.. The results are shown in Figure 4.8.

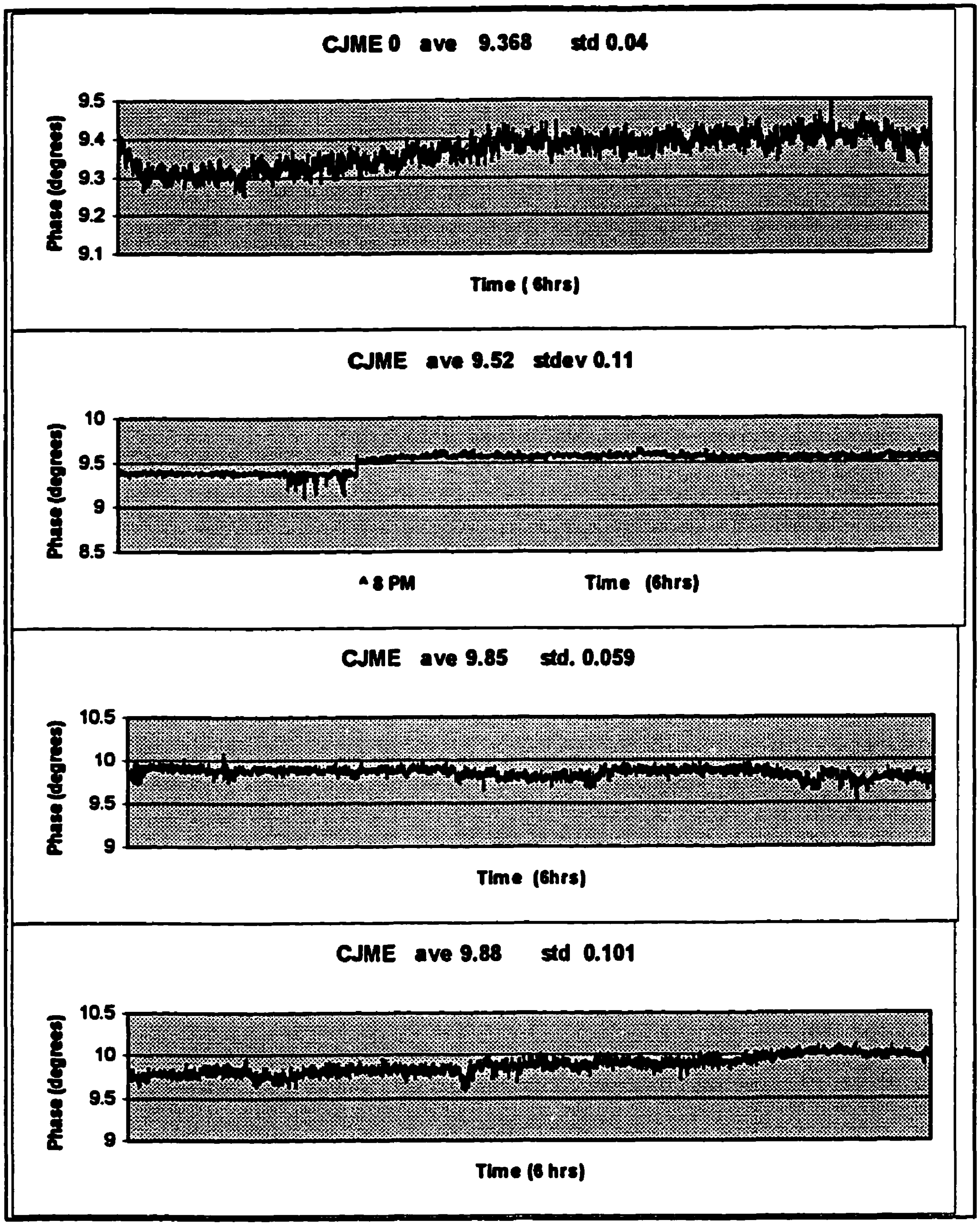


Figure 4.8 Phase Difference Error with Coax Cable and Broad Band Amplifiers driven from CJME -- 1300 kHz.

In the second run (Figure 4.8), one can see that something happened about two hours into the experiment. This would have been about 8 PM in the evening; and it is suspected that someone actually disturbed the antenna located outside. In the next two runs, the gain was adjusted by about 3 dB on the one channel. This seemed to have an effect of about 0.3 degrees on the phase difference. Apparently there is a relationship between the gain and phase delay through the broad band amplifiers. Some of the previous long term drift may have been due to the changing gain of the amplifiers due to sensitive potentiometers used in the gain adjustment.

4.6 AM Station Step Move - Range Tests

The next two tests were done to determine the range accuracy that could be expected. One antenna, the reference, was placed in a field with about 100 meters of coax cable attached to it. The other antenna was placed on a van which contained all the electronics for measuring the phase and a laptop to record the data. A portable generator was used to power all the equipment. The van advanced toward the AM station of CJME, one meter at a time; the phase was logged at each one meter advancement. A tape measure

Figure 4.9 Van Used For Step Tests

was used to accurately advance the van. The cable from the reference station was coiled onto the van floor as the van approached the reference and then uncoiled as it proceeded past it. The mobile (van) was abreast the reference at about the 100 meter point. It took about two hours to collect the data for one run, which was about 150 points. The results are shown in Figures 4..10 and 4.11 for runs done on consecutive days.

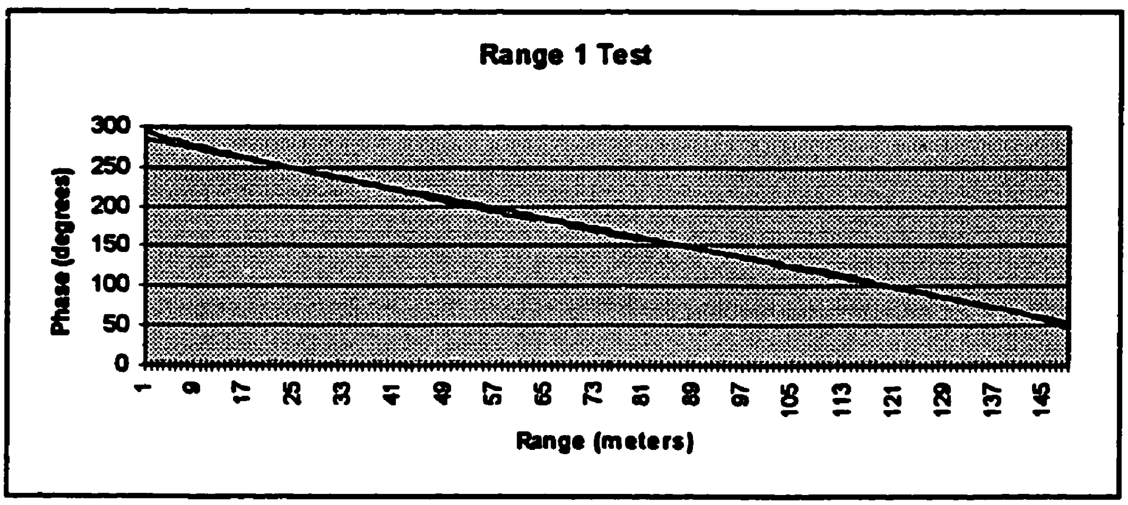


Figure 4.10 Range Test One
(Slope = -1.56619 Least Squares Error = 3.4 deg.)

The expected slope is:

300/1.3 (m/cycle) x 1/360 (cycles/deg) = 1/1.56 m/deg. equals 1.56 deg/m (4.2)

In the first test the slope of best fit linear regression line was 1.56619 and in the second it was 1.56237. This confirms that the direction of travel of the van was indeed toward the station and that the wavelength for CJME was as calculated.

The least squares error from the linear regression line was 4.26 degrees in the first test and 3.4 degrees in the second. In terms of range error this is equivalent to 2.73 m and 2.17 m respectively. This is much more than any of the errors in the previous tests. It should be noted though that the major part of the error is believed to be due to the cable acting as a partial antenna. At one point in the test it was noted that when several meters of cable were coiled into the van, the phase reading changed by about 3 degrees, which in terms of range is about 2 meters.

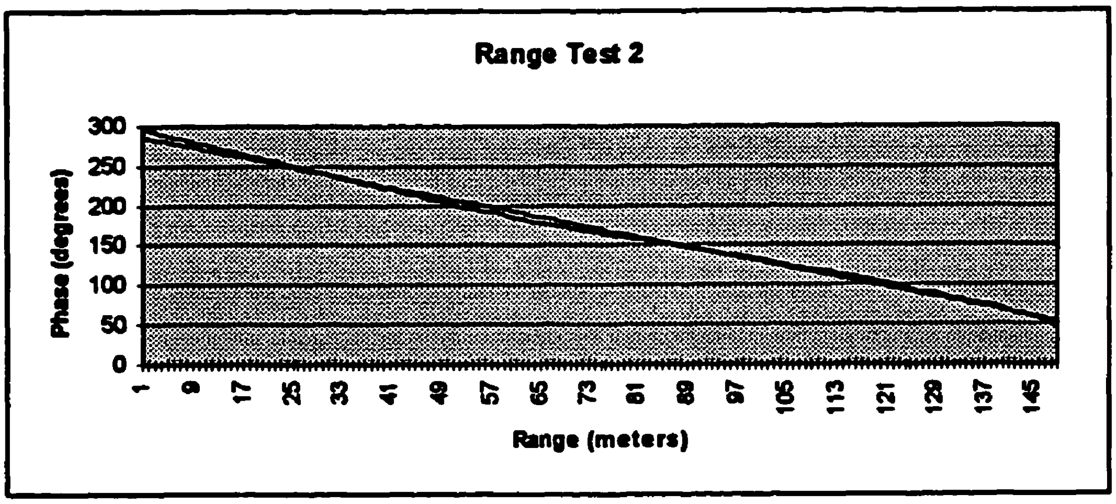


Figure 4.11 Range Test Two
(Slope = -1.56237 Least Squares Error = 4.26 deg.)

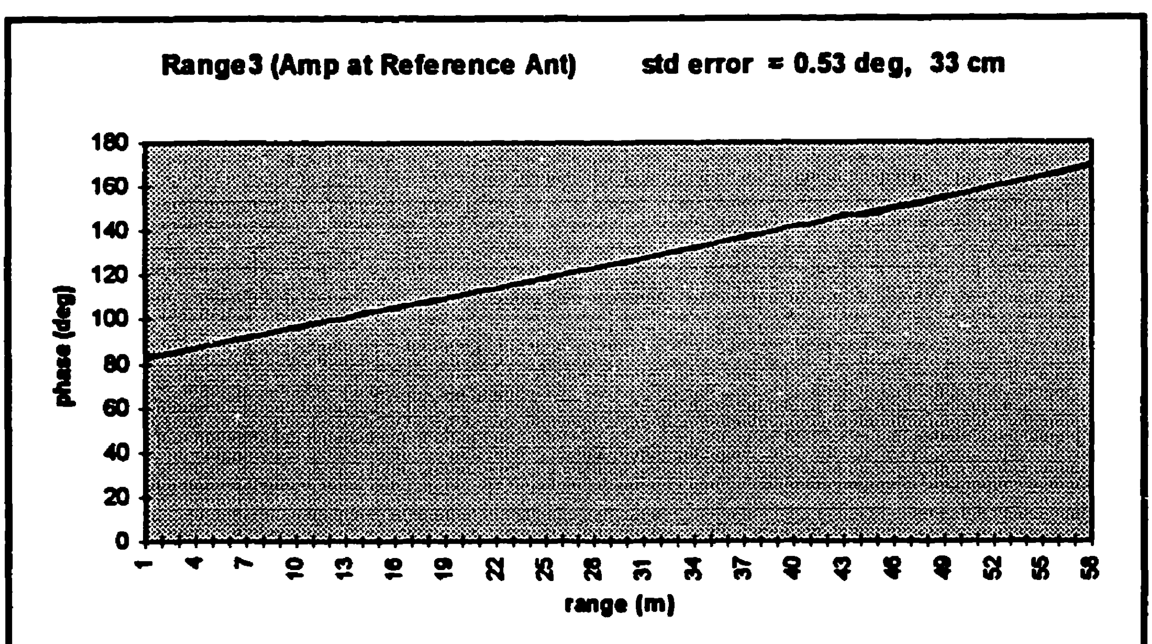


Figure 4.12 Range Test 3 with Amplifier at the Reference

To minimize the effect of the cable, the amplifier for the reference was placed at the antenna. The results were much better as shown in Figure 4.12 with the first standard deviation of error being 0.53 degrees or about 33 cm. This would confirm the suspicion that the cable was interfering. With the amplifier placed right at the antenna, it would allow for much less interference to be picked up by the cable.

4.7 AM Station Static Test with 100m Between Stations

This last test was done to determine the consistency of a range measurement over a time period. If there was skywave reflection, it would change over time and one would expect to see a drift in the phase measured. As can be seen in Figure 4.13, none was detected. The first standard deviation of the phase error was 0.151 degrees, which in terms of range error is equivalent to 10 cm.

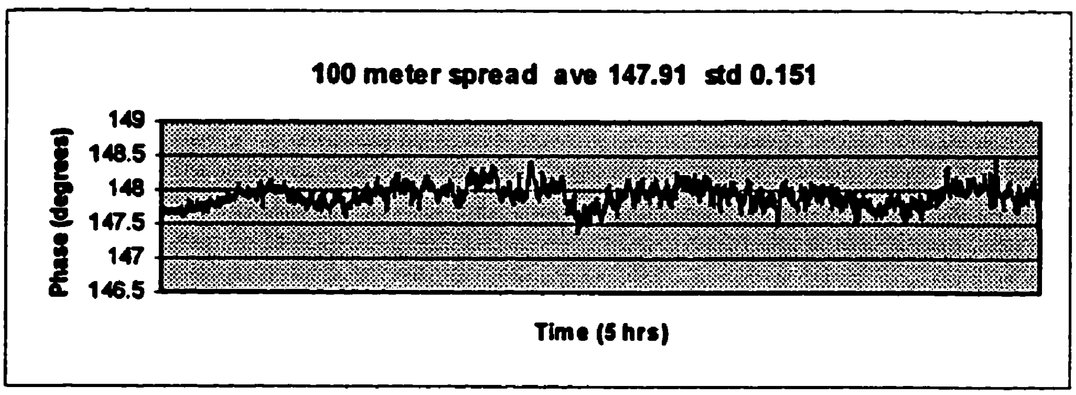


Figure 4.13 Static Test with 100 m between Stations

4.8 Summary

To summarize the previous sections, it could be said that the DFT method of measuring phase is accurate to about 0.01 degrees in the short term and 0.1 in the long term which is equivalent to about 1 cm and 10 cm of range accuracy respectively. This degree of accuracy remained even when the AM station was used as the source provided the antenna of the stations were close together. With the antennae of the stations separated by 100 m, the long term error remained about the same. The step range test produced the proper overall slope, but the absolute range was skewed. Most of this error was accounted for by phase anomalies caused by the linking coax cable.

Chapter Five

Conclusions and Discussion

This thesis proposed a technique and describes the method in which AM radio stations could be used as positioning beacons. To realize the technique, two questions were to be addressed:

1. Can the phase from AM stations transmission be measured with extreme accuracy?

2. Would the phase of the signal going on the path to the reference be distorted in a similar manner as that going to the mobile?

5.1 Conclusions

Various design factors that affect the phase error have been investigated. The analysis of the end effect phenomenon and the resultant phase error due to it is believed to be a contribution of this research.

The results of the previous chapter demonstrate that the DFT method of measuring phase can achieve 0.01 degrees of phase accuracy even when detecting a signal that is being modulated. This is equivalent to a range accuracy of about 1 cm.

The longer term drift was about 0.1 degrees and is equivalent to less than 10 cm of range accuracy. It was noticed that a change in gain had a slight affect on the phase and this was about 0.1 degrees per dB. Another potential cause of the drift would be the noise from the DSP affecting the sampling. Some DSP noise was observed on the signal line entering the

ADC and it was noticed that there were 'quieter' times in the DSP cycle in which the sample could have been taken. Also better board layout and good grounding techniques would have reduced the noise on the signal lines.

Overall it can be concluded that the DFT phase measuring technique would be a good means of measuring the phase[1] for the proposed AM ranging system and the answer to the first question is a resounding yes.

The second question cannot be answered with the same enthusiasm. Long term tests showed drift that was less than 10 cm but this was over a separation distance of only 100 meters. There are many factors that could distort the phase of the signal along any given propagation path with multipath being the most feared. This could include a fair amount of skywave, but the tests done minimized these effects by having the tests done during the day when the skywave would be at its least and by having the separation distance of only 100 meters. So the answer for question two has been only partially answered and more work would have to be done to determine the extent of distortion under a variety of different conditions. That said, the tests performed would suggest that the range accuracy with the proposed system could be sub-meter and possibly in the order of 20 to 30 cm in areas where little multipath is present such as in farm fields.

Preliminary tests would suggest that the proposed AM Radio Positioning Technique is a technique that could be used for positioning. Before commercialization of the system is considered, there are a number of issues that would warrant further investigation.

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[1] DFT phase measuring demonstration was awarded 1st prize ($1000) at the Microelectronics Research & Development in Canada Conference (MR&DCAN 97) paper was titled "AM Radio Naviagtion System Using Software Techniques"

5.2 Potential Problems

It was suggested that the reference station use spread spectrum for the communication link to the mobiles. The reference would then be transmitting and receiving simultaneously, which creates a dynamic range problem for the receiver. The most obvious solution would be to Time Division Multiplex (TDM) the transmitting and receiving. A little process gain would be lost and the data transmission rate lowered. Another solution might have the reference use two antennae, one for transmitting and one for receiving. The receive antenna would be designed so that it would be in the null of the transmitting antenna.

It is very important that the mobile lock onto exactly the right cycle of the reference link. A rigorous study of the chip-to-cycle synchronization should be done. It would be good to characterize the conditions under which the synchronization would fail.

Using an in-band frequency for the reference link, i.e. an AM frequency, ensures that the delays through the mobile amplifier would cancel. If a frequency from a different band is used as well as a different front-end amplifier, then the delays will be different and they will not cancel. This is a problem. Some type of dynamic calibration in which a known signal is fed into the amplifier could be considered.

The Federal Frequency Commission (FCC) and Communications Canada have allocated a portion of the spectrum just above 900 MHz for spread spectrum. There have not been any spread spectrum allocations near the AM band. Would the regulatory agencies allow for spread spectrum at or near the AM band?

Perhaps the most serious problem is the multipath. Only preliminary tests were done with the reference station close to the mobile. What happens when the mobile is several kilometers from the reference? What happens in an urban environment, by railroad tracks, under power lines etc.? It is possible that a single range could be degraded to an accuracy of tens of meters? Even with the averaging of several stations, it may not be possible to achieve reasonable accuracy. This then raises the question -- Is it possible to detect AM stations that have severe multipath and ignore them in determining a position fix? It is apparent that more work is needed.

5.3 SUGGESTIONS FOR FURTHER RESEARCH

1. More tests are required with the reference and the mobile separated by many kilometers. In the proposed system a communication link is used to synchronize the two stations; however, for these tests the synchronization could be done with a predetermined AM station. Both receivers could lock the sampling and DFT clocks to the one radio station, thus being synchronized. Any other AM station could then be monitored and the phase data recorded over known geographical points. Post-processing and comparison of the data would reveal range accuracy. With this apparatus all sorts of conditions could be studied such as night operation, large separation distances, and urban areas with suspected multipath.

2. Multipath, especially skywave reflection, is the most feared culprit for corrupting the phase of the carrier. The AM band is relatively large and there are easily a dozen stations that can be received at any given location. The reference station cannot measure the degree of corruption of the phase directly because it has nothing to compare it to; however, it can measure the amplitude of the DFT which is an indicator of reinforcement or cancellation of the main signal with reflections. If the amplitude of the DFT changes from its normal amplitude, that station would be suspected of multipath corruption and could be removed

from the set of stations being used. The mobiles, being mobile, could not make the same judgment using amplitude, but could be informed over the data channel of the stations to use or ignore. An investigation into the effectiveness of this technique would be interesting.

3. It was noticed that the gain of the amplifier affected the phase by about 0.1 degrees per dB change in gain. This could be investigated and the wide band amplifier could be characterized much better. This has been done somewhat by Dinh 19], but a more detailed study could lead to some recommendations on how to deal with the delay. If the delay can be tightly characterized and the amplifier is consistent over temperature and time, the delay could be accounted for in the phase calculation. If the phase delay is not consistent, the delay could be measured by feeding a known signal with known phase into the amplifier, measuring the phase delay, and making the appropriate compensations in the phase measurements. The delay of the amplifier is of little concern if the reference link frequency is in-band because in measuring the phase difference the phase delay cancels. It would be a serious matter if the link's frequency was out-of-band where separate front end amplifiers are used to receive the radio stations and the reference.

4. Probably the most onerous disadvantage of direct conversion wide-band receivers is the dynamic range required between the strongest and weakest signal received. When working in the vicinity of one radio station, its signal will be very large and the gain of the amplifier will be lowered accordingly. The weaker stations are dwarfed. There are two ways to deal with this issue. The first is to use an ADC that has the dynamic range to resolve the weaker stations adequately. As was discussed, this may result in a specified 13 or 14 bit ADC which at the speeds required could be expensive. The other suggestion would be to investigate the employment of a notch filter that would essentially curtail the dominant signal before going

to the ADC. Could a switched capacitor notch filter be designed to be tunable to block any desired AM station? There is a tradeoff between the use of such a notch filter with the problems it imposes, and that of using a higher resolution ADC. An investigation into these tradeoffs would be enlightening.

5. A single AM frequency can be shared by several stations located geographically in a distance city. For example, the station that was used for this study, CJME at 1300 kHz, has another station that operates at the same frequency in Seattle. Sometimes at night the skywave will reflect the signal to Regina and the Seattle station can be heard in the background on CJME. This is called co-channel interference. The two carriers are not exactly the same frequency, and as noted in Chapter 3 the actual frequency of the carrier is typically several hertz from the nominal. A long aperture DFT would suppress this co-channel interfence. This could be investigated further.

6. It was suggested that the reference link be in the AM band. If the regulatory bodies would not allow this, other frequencies could be used -- maybe in the lower VHF. What ramifications would that have on the design? One problem with the amplifier delay was mentioned in item 4. What other disadvantages, or perhaps advantages, would there be in going to the VHF band for the reference link?

7. It is very important that the reference provide a good synchronization signal for the mobiles so that one is able to go precisely from the gross signal at the chip level to the fine synchronization at the cycle level. This was explained in Chapter Three, but using the results of Chapter Four, one could simulate the actual synchronization process and investigate its robustness.

8. The ambiguity reduction scheme was proposed without knowing the accuracy tests of Chapter Four. Working with these results, the ambiguity reduction technique could be simulated and it could be checked for its robustness.

9. With each DFT session a set of samples taken over a given time period is used and then discarded. What would happen if the last half of the samples were used again. One could think of them as overlapping DFT apertures. Would this improve the accuracy? --- by how much? Also the question of sampling rate could be examined more carefully -- over sampling, under sampling. What are the advantages and disadvantages?

10. The antenna will be affected by people and/or objects being in the near-field. This was noticed in the experiments being conducted but was not documented. The whole area of antenna selection and near-field interactions and interference should be investigated.

11. Many portable radios use a ferrite-rod loop antenna to detect the magnetic field instead of the electric field. Such an antenna is directional but this might turn out to be an advantage. Two of these antenna positioned at right angles can be used to determine direction with what is called the Bellini Tosi system which is described in Tetley [50, Chapter 10]. In guiding a vehicle there a two pieces of information required, position and vehicle angle. Typically an expensive inertial system is configured in a hybrid arrangement to provide the latter. With the addition of very little hardware the direction and position of the vehicle could be determined.

12. The magnetic loop antenna is directional. This could be used to advantage in rejecting multipath by having the antenna rotate to only receive the AM station in question when

pointing toward the station. Such a system could then provide position and direction information as well as rejecting multipath; at the cost of rotating hardware.

13. If the system is to be used on a vehicle, information from the rotating tires and steering angle could augment the position accuracy with dead-reckoning. Kalman filtering [6] could be used to smooth and predict the positions as well as optimally combine all the information.

14. The use of two synchronized stations could be investigated. To what degree could the accuracy be improved if two, or three references were used? Could the multiple references predict the multipath better?

15. In some operations the position of the vehicle must be reported back to a central location. An example of this would be in open-pit mining. Once could investigate a system in which the mobile reports its location back to the reference. The reporting signal could also be used to establish a range to the reference. The use of spread spectrum, with a unique CDMA channel assigned to each mobile could be considered.

In developing this AM technique to obtain position, it has become obvious that more questions have been put forward than answered. The preliminary work has been done and it is believed that with the availability of today's high speed DSPs and electronics that the system is workable. Yet, there is much to be done.

~

References:

[1] A.R.R.L Antenna Handbook -- American Relay Radio League Newington, CT USA 06111 15th ed. July 1988

[2] Alturaigi M.A. "Real Time Phase Angle Measurements" to be published in Canadian Journal of Electrical & Computer Engineering

[3] Armel Picquenard Radio Wave Propagation 1974 Macmillan Press Ltd. # 72-2046

[4] Beier, Wolfgang "Receiver for Bandspread Signals" Canadian Patent 1,244,887

[5] Best, R. Phase Locked Loops -- Theory, Design and Application 2nd Ed McGraw Hill ISBN 0-07-911386

[6] Blaha, Georges -- Envirospace Software Research, Inc. P.O. 3723, Indiatlantic Florida 32903 Ph: (407) 725-9224 Fax: 727-0210

[7] Brown, R. Introduction to Kalman Filtering McGraw Hill 1992

[8] Brown, Alison. "GPS Precision Approach and Landing system for Aircraft" Canadian Application for Patent 2,105,846 March 16, 1994

[9] Cisneros, J. "An Urban Positioning Approach Applying Differential Methods to Commercial FM Radio Emissions for Ground Mobile Use" Proceedings of 50th Annual Meeting -- Institute of Navigation, June 6-8, 1994 Colorado, Springs, Colorado

[10] Coffield,F.E "A High-Performance Digital Phase Comparator" IEEE Trans. I&M Vol 36 pp 717-720, Sept 1987

[11] Collin, R. Antennas and Radiowave Propagation McGraw-Hill

[12] CRC Report on Refractive Index -- Communications Canada, Dept. of Industry & Trade, Ottawa Ontario

[13] Desai,A. et al "Precise Universal Time for Vehicles" US Patent 5,319,374 Oct. 1993

[14] Dodington, Sven Electronic Navigation Systems 25-89 Navigation Techniques, Electronic Engineers Handbook by Fink First Ed McGraw Hill 1975

[15] Doerfel, S. "Remote Actuation Device" Canadian Patent 1,251, 277

[16] Dinh, Anh "AM Radio Navigation Using Direct Conversion Phase Measurement" MSc. Thesis August 1997, Univ. of Regina, Sask. Canada

[17] Dixon, R. Spread Spectrum Systems with Practical Applications J. Wiley & Sons 1994

[18] Fischer,L. and Palmer, R. "Short Ranging System" Canadian Patent # 290101US and United States Patent # 4,833,480 issued May 23, 1989

[19] Fischer,L.; Palmer, R.J. ; Wimmer, K.;"Phase Ramp Extraction and Use in Correcting Unlock Error in a VCO" Proceedings of IEEE Pacific Rim Conference on Communications, Computers, and Signal Processing, Victoria, B.C. Canada, June 4-5 1987, pp. 279-282

[20] Fisher, A.J. "New Algorithms for Hyperbolic Radionavigation" IEEE Toronto Conference, Paper 9375F, 1993

[21] Grainnews "Is there an Advantage to Spraying at Night?", Vol. 20 No 9 May 24, 94 published in Winnipeg, Manitoba

[22] Hawkins, J. "Radio Location System" Canadian Patent 534,707 January 12, 1950

[23] Haykin, Simon "Communication Systems" 3rd Edition John Wiley & Sons 1994

[24] Hori, Kutsuga Canadian Patent 1,266,316 Japan, February 27, 1990

[25] Johnson, R. Antenna Engineering Handbook McGraw Hill 3rd ed. 1993

[26] Kucar, A. "Method and Apparatus for Carrier Synchronization and Data Detection" US Patent 5,115,454 May 19, 1992

[27] Kumar, A.. "Fixed and Mobile Terminal Antennas" Artech House Inc. 1991

[28] Kwack, E., Shakkottai, P., Back, L. "Analog Circuit for the Measurement of Phase Difference Between Two Noisy Sine-Wave Signals" Rev.Sci. Instrum.60(9) ©American Institute of Physics, September 1989

[29] Lem, Kwong "Digital Phase Measurement Techniques" M.Sc. Thesis, Electronic Systems Engineering, University of Regina, Regina, Sask. Canada 1988

[30] Liu, G; Palmer, R.J. "Efficient Field Courses around an Obstacle" Journal of Agricultural Engineering Research Nov. 1989 #42

[31] Liu, Gin "Computer Generation of Efficient Farm Field Courses" M.Sc. Thesis, University of Regina, Engineering, 1988, Regina, Sask. Can

[32] Lorenz, Robert "Global Positioning System Receiver Digital Processing Technique" US Patent 5,134,407 July 28, 1992

[33] Maine, Reuben "Code Tracking Apparatus with Improved Resolution for Spread Spectrum Receiver" US Patent 4,965,808 October 23, 1990

[34] Maine, Reuben "Global Positioning System Receiver" Canadian Patent 1,199,096 January 7, 1986

[35] McNulty, Patrick "Wanted: Decimeter GPS Navigation" Ag/Innovator Vol. 1 No. 8 PO Box 1 Linn Grove IA 51033 USA March 1992

[36] Michelleti, R. "Phase Angle Measurement Between Two Sinusoidal Signals" IEEE Trans. I&M vol. 40 pp. 40-42 Feb. 1991

[37] Morris, R.L.; Palmer, R.J. "A Short Range, High Precision Navigation System for Automated Farming" Proc. of 50th Annual Meeting of Institute of Navigation, June 6-8, 1994 Colorado, Springs, Colorado

[38] Palmer, R. J. "Techniques of Navigating in a Farm Field" The Journal of Navigation Vol. 36, No. 3, Fall ,1989, pp. 70-76

[39] Palmer, R.J. "Applying Farm Chemicals with a Truck Outfitted with Electronic Navigation" SAE Technical Paper Series #891840, International Off-Highway & Powerplant Congress and Exposition, Milwaukee, Wisconsin, Sept 11-14, 1989

[40] Palmer, R.J. "Positioning Aspects of Site Specific Applications" 2nd Conference of Site Specific Management for Agricultural Systems, Minneapolis, Min. March 1994, Proceedings edited by American Society of Agricultural

[41] Palmer, R.J.; Matheson, S.K. "Precise Navigation Guidance and Control, Services within the Agricultural Community" Journal of the Royal Institute of Navigation, London, England January 1989 Vol.. 42 No. 1

[42] Palmer, Ron "Optimization of Farm Field Operations" Energex 85, Regina, Sask. Perganon Press June 3, 1985

[43] Poppe, Martin "The Loran-C Receiver, A Functional Description" Journal of the Institute of Navigation, Vol. 29, #1, Spring 1982

[44] Press et al Numerical Receipts in C Cambridge University Press 1990

[45] Read, Arnold "RF Signal Synthesis" US Patent 5,159,607 October 27, 1992

[46] Russel et al "Vehicle Location System Having Enhanced Position Location Processing" US Patent 5,166,694 November 24, 1992

[47] Samaddar, S. N. "The Theory of Loran-C Ground Wave Propagation -- A Review" Journal of the Institute of Navigation, Vol. 26, #3 Fall 1979

[48] Shibuya, Shigekazu A Basic Atlas of Radio-Wave Propagation published by John Wiley & Sons 1987

[49] Skolnik, M.I. Introduction to Radar Systems McGraw Hill 2nd ed. 1980

[50] Tetley,L. & Calcutt,D. Electronic Aids to Navigation Edward Arnold Publishers 1986 Great Britain ISBN 0-7131-3584-4 (Decca, Omega, Direction Finding)

[51] Thompson, S. D. "An Introduction to GPS" August 1985 ARING Research Corp. 2551 Riva Road, Annapolis, Md21401 (301) 266-4650

[52] Trueman C.W. "Scattering from Power Lines with the Skywire Insulated from the Towers" IEEE Trans on Broadcasting, Vol 40, n 2 June, 1994, pp. 53-62

[53] Wells, D. et al Guide to GPS Positioning Canadian GPS Associates, May, 1987 ISBN: 0-920-114-73-3

[54] Wolf, Michael Canadian Patent 1,327,069 (Germany) February 15, 1994

Appendix A

RON4.asm

DSP program to sample A/Ds, do DDS and DFT to get real and imaginary parts for PC to process phase

```
;------------------------------------------------------------
; DSP56002 Demonstration Program
;------------------------------------------------------------
;
; The program does the following for two radio stations:
;   1. Generates the cosine table for one complete cycle from X:1000 to
;      X:1FFF, the upper half of table is done with cossin macro
;   2. gets the sample -- this is the start of the big loop
;     The phases are loaded in two 4096 0-0FFF in the MSB sections of X and
;     Y memory.  The LSB part is set to zero.
;   3. The second pass will calculate a table that contains the lookuptable
;      value for both the cosine and sine, the address is calculated and
;      the lookuptable is accessed with the resulting value being stored
;      in Y this again will be 4096 and will go from 1000H to 1FFFH in Y
;   4. Do the DFT by getting the samples from the table and
;   5. Send the real and imaginary parts of the DFT out the SCI,
;     the PC will calculate the phase by taking the inverse tan.
;   6. Loop back to 2 and get more samples.
;
;        X            Y
;     0000          0000
;        Empty         Empty
;     0FFF          0FFF
;     1000          1000
;        LookupTable      Cos Value
;     1FFF          1FFF
;     2000          2000
;        Variables       Sine Value
;                  2FFF
;      7000          7000
;       Samples A        Samples B
;      7FFF          7FFF
;
;------------------------------------------------------------
         include 'sincos'


         org    x:$2000        ; Data block starts after lookup table
PHS0         dc     0          ; value sets frequency  24 bit fractio
PHS1         dc     0          ; integer value of phase register
one_real0    dc     0          ; storage area for the accumulated
```

```
one_real1       dc    0        ; parts of the DFT, these values will
one_real2       dc    0        ; be sent out the SCI port
one_imag0       dc    0        ; and the PC will calculate the
one_imag1       dc    0        ; inverse tan
one_imag2       dc    0
two_real0       dc    0
two_real1       dc    0
two_real2       dc    0
two_imag0       dc    0
two_imag1       dc    0
two_imag2       dc    0
AverageA        dc    0        ; the accumulated value of samples A
AverageB        dc    0        ; the accumulated value of samples B
AveragA2        dc    0
AveragB2        dc    0
AVA             dc    0
AVB             dc    0
DEG90           equ   $0400      ; 1024 or 1/4 of 4096 for 90 deg
MASK            equ   $0FFF      ; only want a 12 bit address
COSe            equ   $1000
SINe            equ   $2000
reset           equ   0
start           equ   $40
data_o          equ   $55
zero            equ   $00
ones            equ   $7F
points          equ   4096          ;1000 nbr of samples to take = 4096
idata           equ   $7000         ;input data starting at x:$0000
costbl          equ   $1000         ;cosine table start
coef            equ   $1800
cnt1            equ   4095
cnt2            equ   20            ;right shift counter
cnt4            equ   8             ;left shift counter
cnt3            equ   2048          ;cosine generation counter
;-----------------------------------------------------------------
;
;
; Load the cos table -- upper half
;      then initialize all the stuff
;-----------------------------------------------------------------
        sincos  points,coef     ; macro to generate sin/cos lookuptable in RAM

        opt    mex
        org    p:reset          ; Program block starts at zero
RESET   jmp    START            ; Skip over interrupt vectors
        org    p:start
START
;       MOVE #$620F5C,X0  ; frac = .22667
          MOVE #$8dD813,X0     ; for CJME 1300
;       MOVE #$467381,X0  ; frac = .2752 set the value of the frequency
         MOVE  X0,X:PHS0   ; set the phase register, this is the value that
;       MOVE #3030,X0     ; will be read as the phase for phase accumulation
          MOVE #4021,X0    ; for CJME 1300
         MOVE  X0,X:PHS1          ; based on Fs of 1.319 MS/s
                              ;980 4096/1319 = 3043.2752    3030.22667
```

```
        movep  #$261009,x:$fffd       ; set to 40MHz clock
        movep  #$8888,x:$fffe         ; set wait states
        movep  #$0,X:$FFE0            ;select port b for gen i/o
        movep  #$7FFF,X:$FFE2         ;PB0..PB14 as outputs

        movep  #$0040,X:$FFF2         ;set 9600,N,8,1
        movep  #$0302,X:$FFF0         ;enable sci TX, RX, 10 bit async
        movep  #$0002,X:$FFE1
LOOP:                          ; come back to this point in the
    DO #10,END17                    ; big loops
;------------------------------------------------------------
;Generate the first 180 degrees of the cosine table from the last
;180 degrees of the cosine table using the negate command.
;------------------------------------------------------------
        move   #coef,R0          ;point to the data
        move   #costbl,R1        ;point to front of table
        do     #cnt3,END5        ;set up the loop
        clr    A                 ;clear accumulator
        move   X:(R0)+,A0        ;get a word
        neg    A
        move   A0,X:(R1)+        ;move data then increment          inc R0 to point at the next
END5
        move   #$7FFFFF,X0       ;fix first value of costbl
        move   X0,X:costbl       ;;addressing mode use extra command
; **************************************************************************
; calculate values that result from the cos/sin table and store them away
; to be used later by the DFT
; ------------------------------------------------------------
        clr    a                 ; Clear accumulator A
        MOVE   #DEG90,X1         ; this 90 deg offset gives sine
        MOVE   #MASK,X0
        MOVE   #COSe,R1          ; where the cos value of table stored
        MOVE   #SINe,R2          ; where the sin value of table stored
    DO #4095,END7
        MOVE   X:PHS0,Y0         ; get fractional part of phase accum
        MOVE   X:PHS1,Y1         ; phase accumulator is now in Y
        ADD    Y,A               ; add phase to accumulator -> A
        TFR    A,B               ; transfer A->B so A doesn't get wrecked
        MOVE   #$001000,Y1       ; need to mask one onto the table address
        AND    X0,B1             ; B1 contains the address for the table
        OR     Y1,B1             ; stick a one onto the address for 1000
        MOVE   B1,R0             ; R0 contains address of table
        NOP
        MOVE   X:(R0),Y0         ; Y0 contains the value of COS
        MOVE   Y0,Y:(R1)+        ; put the cos value away in cos storage
        ADD    X1,B              ; now move 90 degrees in the table for sine
        AND    X0,B1             ; but we must mask, cause it could have roll
        OR     Y1,B1             ; stick a one onto the address
        MOVE   B1,R0             ; address in now in R0 with the 90 deg offset
        NOP
        MOVE   X:(R0),Y0         ; sine value is in Y0
        MOVE   Y0,Y:(R2)+        ; put it into the sine storage area
END7
;------------------------------------------------------------
```

```
;at this point the lookuptable has been built, and we will now enter the
;big loop, which starts by getting the samples into memory from the A/D
;-----------------------------------------------------------
;move 4096 point of valid data from A/D mapped at $A000 into
;data buffer starting at location idata ($0000)
;-----------------------------------------------------------
lp:
        move  #idata,R0          ;POINT TO INPUT DATA BUFFER
        do    #cnt1,END1
        bclr  #$0,x:$ffe4        ;write zero to port b
        move  x:$A000,X0         ;move a/d input to temp register
        bset  #$0,X:$FFE4        ;toggle a/d clock
        move  X0,X:(R0)+         ;store input data in ram
END1
        nop                      ;used for break point
;-----------------------------------------------------------
;now move the least significant 12 bits of data to Y:$0000..Y:$1000
;and perform the 12 bit asl
;-----------------------------------------------------------
        move  #idata,R0          ;point to the data
        do    #cnt1,END2         ;set up the loop
        clr   A                  ;clear accumulator a
        move  X:(R0),A1          ;get a word
        move  #$000FFF,X0        ;put mask in X0
        and   X0,A1              ;clear top 12 bits
        do    #cnt2,END3         ;set up for 12 bit ASL
        asl   A                  ;shift A reg one bit left
END3
        do    #cnt2,END10
        asr   A
END10
        move  A1,Y:(R0)+         ;put 12 bit value in Y: area
END2
;-----------------------------------------------------------
;now channel 1 data has been masked, asl by 12 bits, and stored in Y: memory
;starting at loc Y:$0000 ...Y:0FFF
;next, mask off the least significan 12 bits of each word from
;X:$0000..X:$0FFF
;-----------------------------------------------------------
        move  #idata,R0          ;point to the data
        do    #cnt1,END4         ;set up the loop
        clr   A                  ;clear accumulator a
        move  X:(R0),A1          ;get a word
        move  #$FFF000,X0        ;put mask in X0
        and   X0,A1              ;clear bottom 12 bits
        do    #cnt4,END13        ;set up for 12 bit ASL
        asl   A
END13                            ;shift A reg one bit left
        do    #cnt2,END11
        asr   A
END11
        move  A1,X:(R0)+         ;put 12 bit value in X: area                 ;;and inc R0 to
point at the next
END4
```

```
;****************************************************************************
; Everything at this point is stored away, but we will check the DC offset
;------------------------------------------------------------
        CLR A
        CLR B
        MOVE #$7008,R0
    DO #4086,END12
        MOVE X:(R0),X0
        MOVE Y:(R0)+,Y0
        ADD X0,A          ; A1 contains the accumulated value, should be 0
        ADD Y0,B          ; B1 contains accumulate val for other channel
END12
    DO #12,END14
     ASR A
     ASR B
END14
        NEG A            ; A1 and B1 are the correction offsets that should
        NEG B            ; be added to each of the samples

        MOVE A1,X0
        MOVE X0,X:AverageA  ; after the shift of 12 (divide by 4096)
        MOVE A2,X0
        MOVE X0,X:AveragA2
        MOVE B1,X0
        MOVE X0,X:AverageB  ; A1 and B1 have the average DC offset correction
        MOVE B2,X0
        MOVE X0,X:AveragB2
        MOVE #$7000,R0

    DO #4095,END15
        CLR A
        CLR B
        MOVE X:AverageA,A1
        MOVE X:AveragA2,A2
        MOVE X:AverageB,B1
        MOVE X:AveragB2,B2
        MOVE X:(R0),X0    ; get the two samples from memory
        MOVE Y:(R0),Y0
        ADD X0,A          ; add the offset to the sample
        MOVE A1,X0
        MOVE X0,X:(R0)    ; put back into memory
        ADD Y0,B
    MOVE B1,Y0
        MOVE Y0,Y:(R0)+
END15
        CLR A
        CLR B
        MOVE #$7008,R0
    DO #4086,END16       ; this is a check to see if the DC offset has
        MOVE X:(R0),X0    ; indeed be set to zero
        MOVE Y:(R0)+,Y0   ; AVA and AVB when shifted right 12, (3 hex)
        ADD X0,A          ; should be less than 1, or the upper 3 bits
        ADD Y0,B          ; should be FFFxxx or 000xxx
END16
```

```
        MOVE A1,X:AVA
        MOVE B1,X:AVB

        CLR  A
        CLR  B
        MOVE #$7008,R0    ; the first 8 samples are garbage
        MOVE #COSe,R1
        MOVE #SINe,R2

    DO #4086,END8           ; do loop 4095
        MOVE X:(R0)+,X0     ; get the sample stored away in X memory
        MOVE Y:(R1)+,Y0     ; cos value of table is put into Y0
        MOVE Y:(R2)+,Y1     ; sin value of table is put into Y1
        MAC  X0,Y0,A        ; real part being accumulated    in A
        MAC  X0,Y1,B        ; imaginary part being accumulated   in B
END8

        MOVE A0,X:one_real0
        MOVE A1,X:one_real1
        MOVE A2,X:one_real2  ; don't really need this since only accum to 48
        MOVE B0,X:one_imag0
        MOVE B1,X:one_imag1
        MOVE B2,X:one_imag2  ; don't need this either
; Now do the same thing for sample 2 ++++++++++++++++++++++++++++++++++++++++

        CLR  A
        CLR  B
        MOVE #$7008,R0
        MOVE #COSe,R1
        MOVE #SINe,R2

    DO #4086,END9
        MOVE Y:(R0)+,X0     ; get the other sample from Y memory
        MOVE Y:(R1)+,Y0
        MOVE Y:(R2)+,Y1
        MAC  X0,Y0,A  ; real part being accumulated
        MAC  X0,Y1,B  ; imaginary part being accumulated
END9
        MOVE A0,X:two_real0
        MOVE A1,X:two_real1
        MOVE A2,X:two_real2   ; don't need
        MOVE B0,X:two_imag0
        MOVE B1,X:two_imag1
        MOVE B2,X:two_imag2   ; don't need

; section goes here that pumps the values above out the SCI (RS232)
        move    #$FFFF5A,X0         ;load X0 with 'Z'
        JSR  OUT1
; we now have STX pumped out the serial port, next is the imag part of ch A
        MOVE X:one_imag0,X0
        JSR OUT3
        MOVE X:one_imag1,X0
        JSR OUT3
        MOVE X:one_imag2,X0
```

```
        JSR OUT1
        MOVE X:one_real0,X0
        JSR OUT3
        MOVE X:one_real1,X0
        JSR OUT3
        MOVE X:one_real2,X0
        JSR OUT1
; did the first channel, now get the bytes out serial port for second channel
        MOVE X:two_imag0,X0
        JSR OUT3
        MOVE X:two_imag1,X0
        JSR OUT3
        MOVE X:two_imag2,X0
        JSR OUT1
        MOVE X:two_real0,X0
        JSR OUT3
        MOVE X:two_real1,X0
        JSR OUT3
        MOVE X:two_real2,X0
        JSR OUT1
        move   #$FFFF7A,X0          ;load X0 with 'ETX'
        JSR OUT1
        NOP
        NOP
    DO #4095,END18
        NOP
        NOP
    DO #20,END19
        NOP
        NOP
END19
        NOP
END18
        NOP
END17
        NOP
        JMP  LOOP       ; continuous loop, goes and gets more samples

OUT3:
att    jclr   #1,x:$FFF1,att  ;wait for tx empty
        move X0,X:$FFF4              ;tx a byte
att1   jclr   #1,x:$FFF1,att1 ;wait for tx empty
        move X0,X:$FFF5
att2   jclr   #1,x:$FFF1,att2 ;wait for tx empty
        move X0,X:$FFF6
        RTS
OUT1:
at    jclr   #1,x:$FFF1,at  ;wait for tx empty
     move X0,X:$FFF4              ;tx a byte
     RTS
end ;-----------------------------------------------------------
```

Appendix B

TEST13.bas

PC program to calculate phase -- given real and imaginary parts of DFT from DSP

```
DIM ImTot AS DOUBLE
DIM ReTot AS DOUBLE
DIM phase AS DOUBLE
DIM mag AS DOUBLE
DIM ImTot2 AS DOUBLE
DIM ReTot2 AS DOUBLE
DIM phase2 AS DOUBLE
DIM mag2 AS DOUBLE
DIM range AS DOUBLE
DIM diffphase AS DOUBLE
DIM phaseavg AS DOUBLE
DIM flagneg1 AS DOUBLE
DIM flagneg2 AS DOUBLE
DIM flagneg3 AS DOUBLE
DIM flagneg4 AS DOUBLE
DIM Im1 AS DOUBLE
DIM Im2 AS DOUBLE
DIM Im3 AS DOUBLE
DIM Im4 AS DOUBLE
DIM Im5 AS DOUBLE
DIM Im6 AS DOUBLE
DIM Im7 AS DOUBLE
DIM Re1 AS DOUBLE
DIM Re2 AS DOUBLE
DIM Re3 AS DOUBLE
DIM Re4 AS DOUBLE
DIM Re5 AS DOUBLE
DIM Re6 AS DOUBLE
DIM Re7 AS DOUBLE
DIM ImB1 AS DOUBLE
DIM ImB2 AS DOUBLE
DIM ImB3 AS DOUBLE
DIM ImB4 AS DOUBLE
DIM ImB5 AS DOUBLE
DIM ImB6 AS DOUBLE
DIM ImB7 AS DOUBLE
DIM ReB1 AS DOUBLE
DIM ReB2 AS DOUBLE
DIM ReB3 AS DOUBLE
DIM ReB4 AS DOUBLE
DIM ReB5 AS DOUBLE
DIM ReB6 AS DOUBLE
```

```
DIM ReB7 AS DOUBLE
INPUT "Enter Filename"; F$
OPEN F$ FOR OUTPUT AS #2

   'Use this example for trouble shooting serial communications problems.
   'Slow baud, hardware handshaking is ignored and buffers are enlarged.
   OPEN "COM2:9600,N,8,1,CD0,CS0,DS0,OP0,RS,TB2048,RB2048" FOR RANDOM AS #1
   DIM VALs(30) AS STRING

'CLS 0
FOR numloops = 1 TO 1000
phaseavg = 0!
FOR count = 1 TO 100

start:

'**********************************
'check for correct starting byte
'**********************************

first:
VALs(1) = INPUT$(1, 1)
' PRINT INPUT$(1, 1);        'input$(nbr chr,file nbr)
' PRINT " ";
IF (ASC(VALs(1)) = ASC("Z")) THEN
'     PRINT "found Z"
     GOTO readdata
ELSE GOTO first
END IF

'**********************************
' read in data
'**********************************

readdata:
FOR I = 2 TO 30
   VALs(I) = INPUT$(1, 1)
  ' PRINT INPUT$(1, 1);        'input$(nbr chr,file nbr)
  ' PRINT " ";
NEXT I
IF (ASC(VALs(30)) = ASC("z")) THEN
'     PRINT "found z"
     GOTO calcdata
ELSE GOTO first
END IF


'**********************************
'calculate Channel A
'**********************************

calcdata:

   Im1 = ASC(VALs(2))
```

```
  Im2 = ASC(VALs(3))
  Im3 = ASC(VALs(4))
  Im4 = ASC(VALs(5))
  Im5 = ASC(VALs(6))
  Im6 = ASC(VALs(7))
  Im7 = ASC(VALs(8))
  flagneg1 = 1!

  IF (Im7 > 127) THEN
     Im1 = 256 - Im1
     Im2 = 255 - Im2
     Im3 = 255 - Im3
     Im4 = 255 - Im4
     Im5 = 255 - Im5
     Im6 = 255 - Im6
     Im7 = 255 - Im7
     flagneg1 = -1!
  END IF

'PRINT flagneg1

  Re1 = ASC(VALs(9))
  Re2 = ASC(VALs(10))
  Re3 = ASC(VALs(11))
  Re4 = ASC(VALs(12))
  Re5 = ASC(VALs(13))
  Re6 = ASC(VALs(14))
  Re7 = ASC(VALs(15))
     flagneg2 = 1!

  IF (Re7 > 127) THEN
     Re1 = 256 - Re1
     Re2 = 255 - Re2
     Re3 = 255 - Re3
     Re4 = 255 - Re4
     Re5 = 255 - Re5
     Re6 = 255 - Re6
     Re7 = 255 - Re7
     flagneg2 = -1!
  END IF
'PRINT flagneg2

'****************************
'calculate Channel B
'****************************

  ImB1 = ASC(VALs(16))
  ImB2 = ASC(VALs(17))
  ImB3 = ASC(VALs(18))
  ImB4 = ASC(VALs(19))
  ImB5 = ASC(VALs(20))
  ImB6 = ASC(VALs(21))
  ImB7 = ASC(VALs(22))
  flagneg3 = 1!
```

```
   IF (ImB7 > 127) THEN
      ImB1 = 256 - ImB1
      ImB2 = 255 - ImB2
      ImB3 = 255 - ImB3
      ImB4 = 255 - ImB4
      ImB5 = 255 - ImB5
      ImB6 = 255 - ImB6
      ImB7 = 255 - ImB7
      flagneg3 = -1!
   END IF
'PRINT flagneg3

   ReB1 = ASC(VALs(23))
   ReB2 = ASC(VALs(24))
   ReB3 = ASC(VALs(25))
   ReB4 = ASC(VALs(26))
   ReB5 = ASC(VALs(27))
   ReB6 = ASC(VALs(28))
   ReB7 = ASC(VALs(29))
   flagneg4 = 1!
   IF (ReB7 > 127) THEN
      ReB1 = 256 - ReB1
      ReB2 = 255 - ReB2
      ReB3 = 255 - ReB3
      ReB4 = 255 - ReB4
      ReB5 = 255 - ReB5
      ReB6 = 255 - ReB6
      ReB7 = 255 - ReB7
      flagneg4 = -1!
   END IF
'PRINT flagneg4

'PRINT HEX$(Im1), HEX$(Im2), HEX$(Im3), HEX$(Im4), HEX$(Im5), HEX$(Im6), HEX$(Im7)
'PRINT HEX$(Re1), HEX$(Re2), HEX$(Re3), HEX$(Re4), HEX$(Re5), HEX$(Re6), HEX$(Re7)
'PRINT HEX$(ImB1), HEX$(ImB2), HEX$(ImB3), HEX$(ImB4), HEX$(ImB5), HEX$(ImB6),
HEX$(ImB7)
'PRINT HEX$(ReB1), HEX$(ReB2), HEX$(ReB3), HEX$(ReB4), HEX$(ReB5), HEX$(ReB6),
HEX$(ReB7)

'************************************
' Calculate imaginary, real, magnitude and phase
' for channel A (note: the magnitude is divide by
' the variable range to give a smaller number)
'************************************

range = 4294967296#
ImTot = (Im1 / range) + (256! * Im2) / range + (65536! * Im3) / range + (16777216# * Im4) / range +
Im5 + 256! * Im6 + 256! * 256! * Im7
IF (flagneg1 = -1) THEN
      ImTot = -1! * ImTot
END IF
```

```
ReTot = (Re1 / range) + (256! * Re2) / range + (65536! * Re3) / range + (16777216# * Re4) / range +
Re5 + 256! * Re6 + 256! * 256! * Re7
IF (flagneg2 = -1) THEN
    ReTot = -1! * ReTot
END IF

'**************************************
' if imaginary or real value is zero then through data away
' and get new set of data for both channels
'**************************************

IF ((ImTot = 0!) OR (ReTot = 0!)) THEN
    GOTO start
END IF

mag = (ImTot * ImTot + ReTot * ReTot) ^ .5
phase = 57.3 * ATN(ABS(ImTot) / ABS(ReTot))

'************************************
' adjust the channel A phase for the correct quadrant
'************************************

IF (flagneg2 = -1) THEN
    IF (flagneg1 = 1) THEN
        phase = 180 - phase
    END IF
    IF (flagneg1 = -1) THEN
        phase = phase + 180
    END IF
END IF
IF (flagneg1 = -1) THEN
    IF (flagneg2 = 1) THEN
        phase = 360 - phase
    END IF
END IF

'************************************
' Calculate imaginary, real, magnitude and phase
' for channel B (note: the magnitude is divide by
' the variable range to give a smaller number)
'************************************

ImTot2 = (ImB1 / range) + (256! *ImB2) / range + (65536! *ImB3) / range + (16777216# *ImB4) /
range + ImB5 + 256! *ImB6 + 256! *256! *ImB7
IF (flagneg3 = -1) THEN
    ImTot2 = -1! * ImTot2
END IF
ReTot2 = (ReB1 / range) + (256! *ReB2) / range + (65536! *ReB3) / range + (16777216# *ReB4) /
range + ReB5 + 256! *ReB6 + 256! *256! *ReB7
IF (flagneg4 = -1) THEN
    ReTot2 = -1! *ReTot2
END IF

'****************************************
```

```
' if imaginary or real value is zero then through data away
' and get new set of data for both channels
'***************************************

IF ((ImTot2 = 0!) OR (ReTot2 = 0!)) THEN
      GOTO start
END IF

mag2 = (ImTot2 * ImTot2 + ReTot2 * ReTot2) ^ .5
phase2 = 57.3 * ATN(ABS(ImTot2) / ABS(ReTot2))

'*************************************
' adjust the channel B phase for the correct quadrant
'*************************************

IF (flagneg4 = -1!) THEN
      IF (flagneg3 = 1!) THEN
            phase2 = 180 - phase2
      END IF
      IF (flagneg3 = -1!) THEN
            phase2 = phase2 + 180!
      END IF
END IF
IF (flagneg3 = -1!) THEN
      IF (flagneg4 = 1!) THEN
            phase2 = 360 - phase2
      END IF
END IF

'***********************************
' calculate phase difference, first adjust phases
' if they cross over the 360 degree boundary
'***********************************

IF (phase < 90) THEN
      IF (phase2 > 270) THEN
            phase = phase + 180
            phase2 = phase2 - 180
      END IF
END IF

'IF (phase2 < 90) THEN
'      IF (phase > 270) THEN
'            phase2 = phase2 + 180
'            phase = phase - 180
'      END IF
'END IF

diffphase = (phase - phase2)

IF (diffphase < 0) THEN
      diffphase = diffphase + 360
END IF
```

```
'************************************
' print out the imaginary, real, phase and magnitude
' for both channels as well as well as the phase difference
'*************************************

'PRINT "Real A      =", ReTot
'PRINT "Imaginary A =", ImTot
'PRINT "Magnitude A =", mag
'PRINT "Phase A     =", phase
'PRINT "Real B      =", ReTot2
'PRINT "Imaginary B =", ImTot2
'PRINT "Magnitude B =", mag2
'PRINT "Phase B     =", phase2
'PRINT "Phase Difference = ", diffphase

phaseavg = phaseavg + diffphase

'PRINT "count       = ", count
NEXT count

PRINT USING "###.###"; (phaseavg / 100!);
PRINT #2, USING "###.###"; (phaseavg / 100!)
NEXT numloops

'DO
'LOOP UNTIL INKEY$ = CHR$(27)   '27 is the ASCII code for Esc.
'GOTO start
CLOSE #2
CLOSE

END
```