Simulation of a Binary Phase Shift Keyed Receiver with an IF Correlator for Position Location

by

John Vareed Thommana

Thesis submitted to the Faculty of the
Virginia Polytechnic Institute And State University
in partial fulfillment of the requirements for the degree of
Master of Science
in
Electrical Engineering

APPROVED

Dr. Timothy Pratt, Chairman

Dr. Brian D. Woerner

Dr. Hugh VanLandingham

December, 1993
Blacksburg, Virginia

Simulation of a Binary Phase Shift Keyed Receiver with an IF Correlator for Position Location

by

John Vareed Thommana

Dr. Timothy Pratt, Chairman

Electrical Engineering

ABSTRACT

This thesis conducts a feasibility study of using a binary phase shift keyed receiver with an IF correlator in a position location application. The feasibility study is done using mathematical simulation. Traditionally the correlator, in a binary phase shift keyed receiver, is placed after the data demodulator. It correlates the incoming bit stream with a fixed reference bit sequence (synchronization header) to find the beginning of a data message. For position location applications this correlator is used to record the time of arrival of the signal at the receiver. These correlators can maintain the correlation peaks at best only to 1% of the bit period. At 4800 bits per second this translates to an inherent range error of 625 meters. This thesis investigates the feasibility of using an additional correlator after the IF bandpass filter which will correlate the IF waveform sample by sample so as to maintain the correlation peaks to better than 1% of the bit period.

Acknowledgements

I dedicate this thesis to my loving parents, Vareed and Annu Thommana, and wife, Lizy. But for their love, affection and encouragement, this work would not have been possible.

I wish to express my most sincere gratitude and appreciation to Dr. Timothy Pratt for his guidance, patience and encouragement throughout the development of this thesis. I would also like to thank Dr. Woerner and Dr. VanLandingham for their assistance in the development of this document.

I would like to thank Dr. Kenneth Reifsnider and Dr. Yong Li Xu for supporting me financially during the entire period.

I would like to thank my friends Jiten Patel, Adrian D' Souza, Adit Tarmaster, Prashant Bagade, Alok Bhandary, John Mani, Narayan Vure, Suresh Subramaniam, Anil Tiwari, Jyothikumar Jaggannathan, Hari Reddy, Shekhar Kapoor, Sanjay Nagpal, Haroon Azaz, Shankar Srinivasan, Anand Joshi and Farookh Kavrana for making my stay in Blacksburg a pleasant and memorable one.

Table of Contents

List of Figures

List of Tables

Chapter 1

Overview

1.1 Introduction

Navigation is defined as the art or science of directing the course of a ship. Today the term ship includes everything from a bicycle to a spaceship. In order to get to a given point one has to first ascertain one's current position, chart out the course to the point, and then monitor one's movement to correct for drift from the course plotted to the point. The key to accurate navigation is determination of one's current position.

The current position of any object is always defined with respect to some known reference position. Therefore position location basically involves finding the distance (range) to the reference and direction to the reference (orientation). Ranging can be done actively or passively, as illustrated in Figure 1.1. In active ranging the receiver (user) sends a pulse to the reference and gets back a return pulse from the reference. This return pulse can be a reflection from the reference or a retransmission of the pulse by the reference. Based on the time taken to receive a return pulse the user computes his range from the reference. This is a very simple method to be implemented as the time measurement is done only with respect to the clock in the receiver. The main disadvantage is that at any instant only one receiver can be in use. In passive ranging the

reference transmits a pulse at known intervals of time and the receivers listen for these transmissions and determine their range to the reference. The disadvantage of this method is the increased complexity due to slight differences in the time kept by the reference clock and the receiver clock. In order to measure the range accurately, the two clocks have to be in perfect synchronism. Since there will always be more than one user using the system at any instant of time, most navigation systems use only the passive ranging technique.

Consider a fixed transmitter and a fixed receiver, as shown in Figure 1.2. The transmitter transmits a pulse at time t_1 and the receiver receives this pulse at time t_2, where t_1 and t_2 are measured using the same clock. The distance, d, between the transmitter and the receiver can be computed as

$$d = c\Delta t \tag{1.1}$$

where $\Delta t = (t_2 - t_1)$ and c is the velocity of light. Now if there are two clocks, one in the transmitter and the other in the receiver, then equation (1.1) will be valid only if the two clocks are perfectly synchronized. But if there is a bias between the two clocks, there will be an error in the computation of the distance between the transmitter and the receiver. This range error, Δd_1, is given by

$$\Delta d_1 = c t_b \tag{1.2}$$

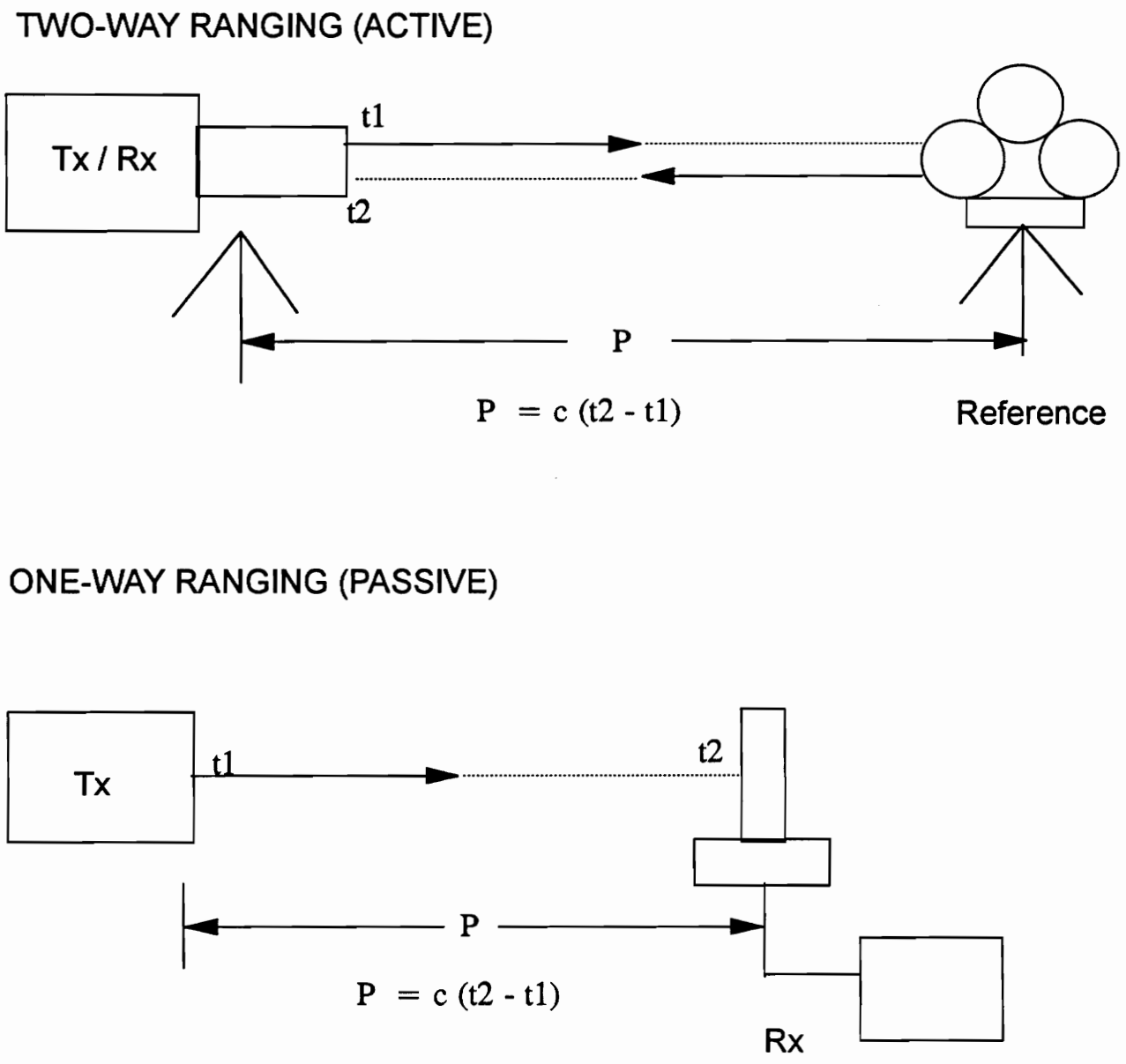


Figure 1.1: Ranging Techniques [3]

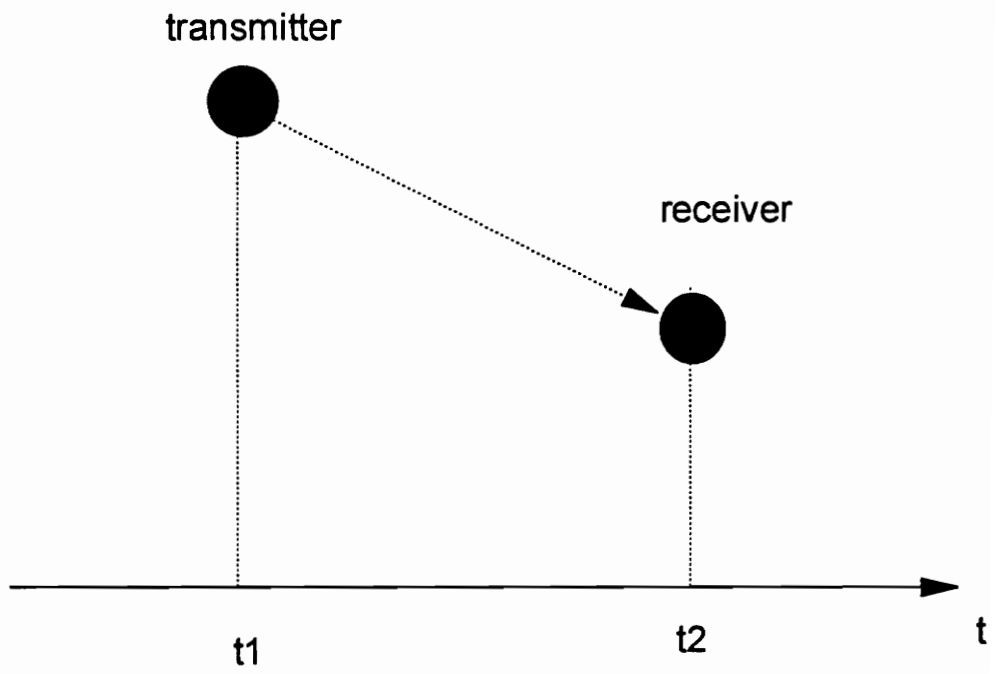


Figure 1.2: Time Representation

where c is the velocity of light and t_b is the clock bias error. A bias of 1 microsecond between the two clocks introduces a range error of 300 meters. If the receiver instead of recording the time of arrival as t_2 records it as t_3, a range error, Δd_2, similar to Δd_1, is introduced due to variation in the time of arrival recording. This range error, Δd_2, is given by

$$\Delta d_2 = c\Delta t_1 \qquad 1.2$$

where $\Delta t_1 = (t_3 - t_2)$, the error in recording the time of arrival. Suppose there is a medium between the transmitter and the receiver which introduces an additional unknown delay in the time taken by the pulse to reach the receiver. The range error, Δd_3, due to the medium is given by

$$\Delta d_3 = c t_4 \qquad 1.3$$

where t_4 is the delay introduced by the medium. So the range measured is the sum of the true range, d, plus the range errors Δd_1, Δd_2, and Δd_3. This measured range is called the pseudo range, p. The pseudo range, p, is given by

$$p = d + \Delta d_1 + \Delta d_2 + \Delta d_3 \qquad 1.4$$

where d is the true range between the transmitter and the receiver, Δd_1 is the range error due to clock bias, Δd_2 is the range error due to difference in time of arrival recording, and Δd_3 is the medium dependent range error. In order to get the true range, d, one has to compensate for the other causes of range error. If the transmitter clock and the receiver clock is synchronized to a stable master clock, then we can compensate for

range error due to clock bias. In practice the satellite clock is synchronized to a master reference clock mathematically. The broadcast data message contains the coefficients of the polynomial used for synchronizing the two clocks. Rather than using expensive atomic clocks in the receivers and keeping them in perfect synchronism with the reference clock, inexpensive quartz crystal clocks are used which are set approximately to the reference clock. The clock bias in the receiver clock and the master reference clock is removed by taking multiple range measurements with respect to different references. If we can accurately model the delay caused by the medium between the transmitter and the receiver, then this error can also be compensated for. So, the only factor that can introduce range errors is the determination of the time of arrival of the signal at the receiver. Since the position of the receiver is determined with respect to the position of the transmitter, any of the above mentioned errors introduces an error in the computation of the receiver's position.

1.2 Navigation by satellite

The advent of satellite communication led to the investigation of the use of satellites as navigational aids. If the transmitter is placed on a satellite then any receiver which can receive the signal from the satellite can compute its distance to the satellite. The key to accurate computation of the receiver's position depends on the knowledge of the time of transmission, the position of the satellite at the time of transmission, the clock bias between the satellite's clock and the receiver's clock, the propagation delay introduced

by the medium between the satellite and the receiver, accurate recording of the time of arrival of the signal at the receiver, and accurate measurement of the range between the satellite and the receiver. Currently, three globally available satellite navigation systems are in use. They are the TRANSIT system [1] [2], the Global Positioning System (GPS) [3][4], and the GLONASS System [4].

The TRANSIT system is a satellite based navigation system. It was originally developed by the US Navy to provide accurate position fixes for their Polaris submarine fleet by measuring the Doppler shift of the received signal. The low earth orbit satellites used by the TRANSIT system broadcast a message every two minutes. This broadcast message contains the time of transmission and other information necessary to synchronize the clocks and compute the position of the satellite at the time of transmission. The range to the satellite is estimated by measuring the doppler shift of the transmitted signal over a period of time. The information provided in the broadcast message and the measured doppler shift are sufficient to compute the position of a receiver.

The GPS system is a joint development venture between the US Navy and the US Air Force. This is also a satellite based navigation system which employs the passive ranging technique for range measurement. The GPS also broadcast a message which contains all the information required by a receiver to compute the position of the satellite and clock correction parameters. The measured range in conjunction with the contents of the data

packet is used by the receiver to compute its position. By receiving the broadcast message from four different satellites the position of the receiver can be computed.

The GLONASS system [4] is a Russian position location system which is very similar to the GPS. The GLONASS system also has an 18 low earth orbit satellite constellation (plus 3 in orbit spares) like the GPS . All the satellites are in near circular orbits at an altitude 10,313 nautical miles. These satellites have an orbital period of 11 hours and 15 minutes. The GLONASS satellites also broadcast a data message which contain information necessary for the receiver to compute its position. Unlike the GPS system which uses Code Division Multiple Access, GLONASS uses Frequency Division Multiple Access as a signal access method. Table 1.1 shows the comparisons between the GPS and the GLONASS systems [4].

1.3 Thesis Overview

As mentioned above, GPS is a satellite based system using a passive ranging technique. One of the factors that enables a GPS receiver to predict the user's position with a very high degree of accuracy is that it can record the time of arrival of the signal broadcasted by the satellites very accurately. This is done by using a procedure called correlation. The GPS satellites broadcast a coded message containing the information required by the receivers to compute their coordinates. Conceptually, the delay between a received GPS signal and a locally generated coded sequence is a measure of the range to the satellite.

Table 1.1: Comparisons between the GPS and the GLONASS system[4]

	GPS System	GLONASS System
Planned Constellation	18 + 3 active spares	18 + 3 active spares
Number of orbital rings	6	3
Orbital altitude	10,898 nautical miles	10,313 nautical miles
Orbital inclinations	63°(Block I) and 55°(Block II & Block IIR)	64.8°
Orbital period	12 hours	11 hours and 15 minutes
First launch	February 1978	October 1982
Signal access methods	CDMA	FDMA
C/A code repetition interval	1,023 bits	511 bits
C/A code bandwidth	2 Megahertz	1 Megahertz
Data stream bit rate	50 bits per second	50 bits per second
L band polarization	Right hand circular	Right hand circular
Civilian position accuracy	330 meters	330 meters

GPS uses two coded signals called the Precision code (P code) and the Coarse/Acquisition code (C/A code) for broadcasting [9]. The P code and C/A code are pseudo-random sequence, of + or - 1's, having a clock rate of 10.23 Mbps and 1.023 Mbps respectively. The time of arrival measurement is dependent on the time required for correlator to align the locally generated reference code to the code transmitted by the satellites. The best available correlator can maintain the correlation peaks only to 1% of the bit period. So a GPS receiver has an inherent range error of 0.3 meters if the P code is used and an inherent range error of 3 meters if the C/A code is used.

By the year 2000 all cars will be having a position location receiver as a standard feature. As of now, the best receiver choice will be a GPS receiver. It is a proven system and has a very high position location accuracy. Unfortunately, GPS belongs to the US Department of Defense and they have allowed civilian use of their system as a matter of courtesy. Tomorrow, if a new technique is found that can increase the accuracy or the sensitivity of the system the Department of Defense has the right to modify this system. The GPS is an extremely complex system. The factors that make this system extremely complex are having a high position location accuracy and making the system impervious to jamming. This complexity also increases the cost of the receiver.

A position location receiver fitted in a vehicle does not need a position location accuracy in meters and it need not be equipped with anti-jamming features. So a new position

location receiver has to be designed which is much more simpler and cheaper than the GPS receiver. The aim of this thesis is to propose a cheaper and simpler position location system using low earth orbit satellites. Motorola has proposed the IRIDIUM system which is a constellation of 77 low earth orbit satellites in polar orbits at an altitude of 765 kilometers [8]. Constellation Communications has also proposed a similar system called ARIES which consists of 48 satellites in polar orbits at an altitude of 1019 kilometers [8]. These satellites will be used for providing mobile communication services. Many other companies are sending up satellites for similar applications. If data channels of these satellites can be used for sending the broadcast information then a considerable cost reduction can be achieved. Most of these data channels are 4800 bits per second data channels using binary phase shift keying modulation. So the simplest receiver for position location will be the traditional binary phase shift keyed receiver.

Figure 1.3 shows the receiver architecture of a conventional binary phase shift keyed receiver. The radio frequency signal arriving at the antenna will be down converted to baseband in two stages by the two mixers. The baseband signal is then sent to a data demodulator which decodes the incoming bit stream. The expected incoming bit stream is a data packet having a known header. The information contained in this data packet are primarily the time of transmission and the position of the satellite at the time of transmission. In addition to this information the range to the satellite is necessary for determining the position of the satellite. The range is measured by recording the time of

arrival of the signal and multiplying the time taken for the signal to reach the receiver by the velocity of light. When the sync-word correlator detects the known header it records the time as the time of arrival and uses it in the range measurement calculation. Unfortunately, the best possible correlator can maintain the correlation peaks to only 1% of the bit rate. At 4800 bits per second data transmission this corresponds to a range error of 625 meters. Thus, a conventional binary phase shift keyed receiver cannot be used for position location as its inherent accuracy is around 625 meters.

Can a traditional binary phase shift keyed receiver be modified to reduce this inherent range error? The answer is yes. By incorporating an additional correlator after the IF bandpass filter we can reduce the inherent range error form 625 meters to around 60 meters. Figure 1.4 shows the block diagram of a binary phase shift keyed receiver with an IF correlator that can be used for position location. The working of this receiver is explained in detail in chapter 5.

Chapter 2 gives a brief overview of the TRANSIT Navigation System. Chapter 3 describes the GPS System. Chapter 4 discusses the basics of orbital dynamics and a technique for determining the position of a user from a broadcast message. Chapter 5 describes the binary phase shift keyed receiver with an IF correlator and the simulation method for verifying its feasibility. Chapter 6 discusses the simulation results and Chapter 7 concludes the thesis.

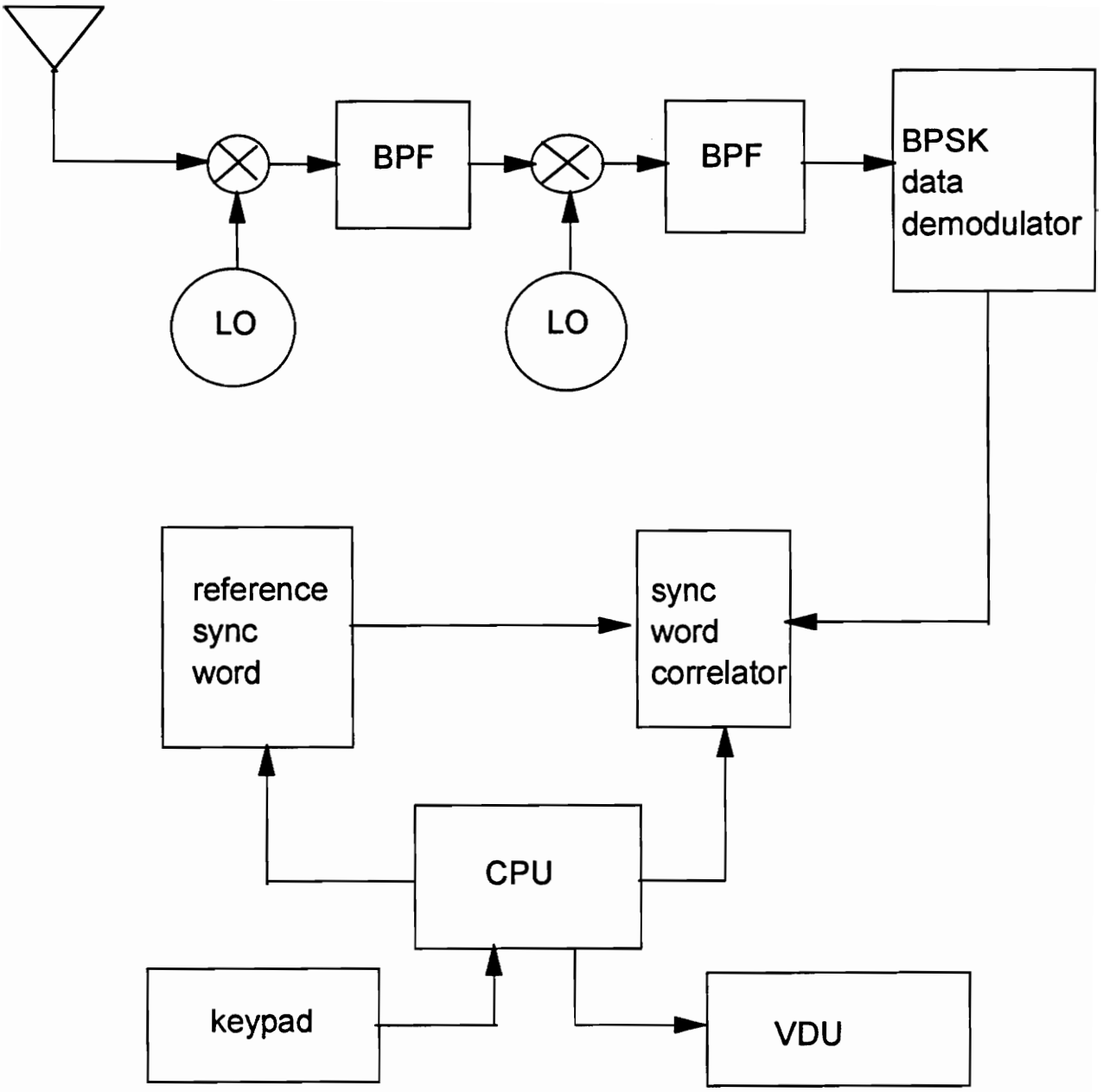


Figure 1.3: A Traditional Binary Phase Shift Keyed Receiver

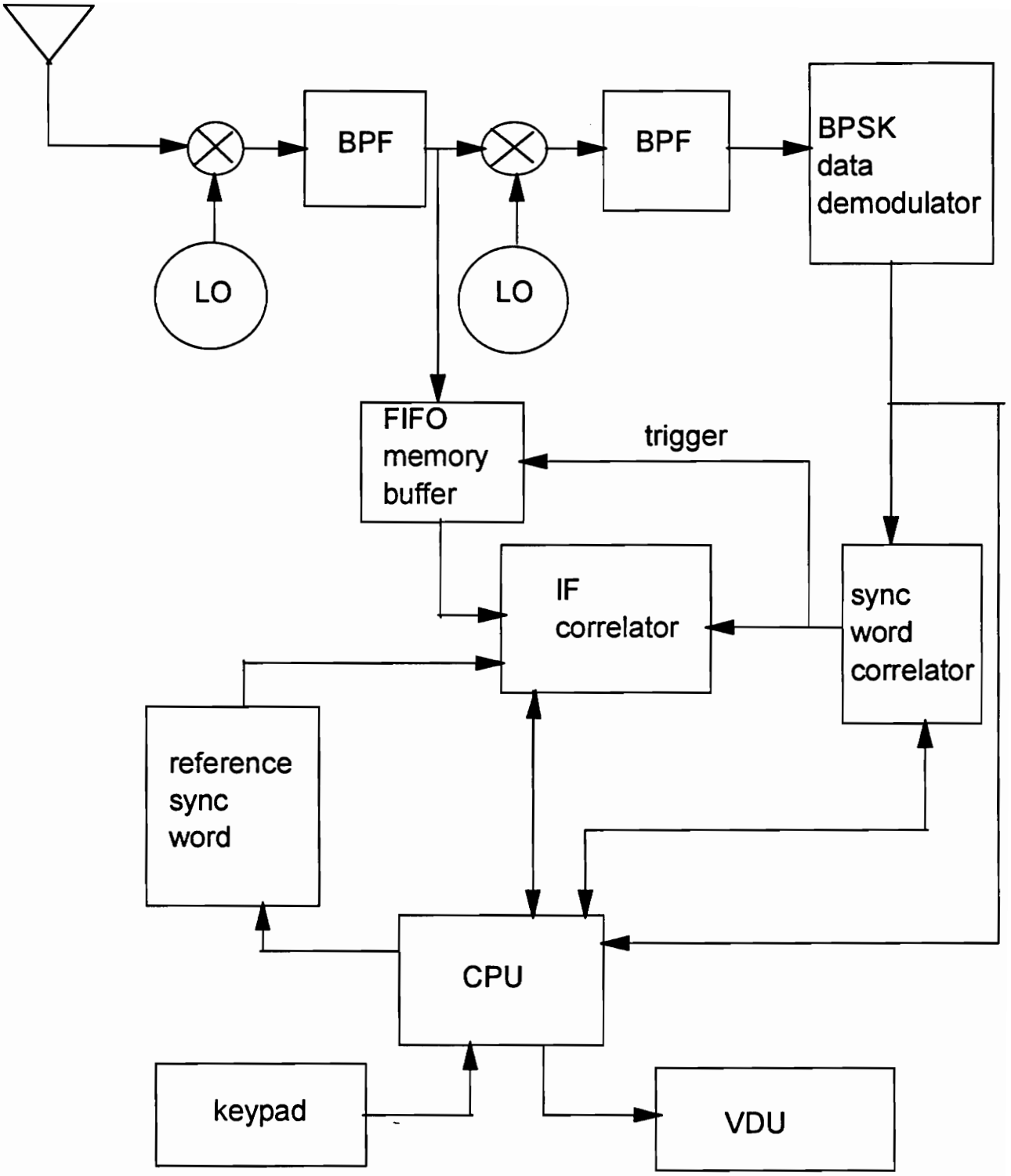


Figure 1.4: Proposed Architecture of Receiver

Chapter 2

The TRANSIT Navigation System

2.1 Introduction

In 1957, Dr. William H. Guier and Dr. George C. Weiffenbach of the Johns Hopkins Applied Physics Laboratory were studying the radio transmissions from the first Russian satellite Sputnik 1[7]. They found that the radio signals were subjected to a highly predictable and measurable Doppler shift due to the motion of the satellite. Further analysis of this Doppler shift led to the realization that knowing the location of the observing station and accurately measuring the doppler shift of the signal over one entire satellite pass one could predict the orbit of the satellite. This also implied that knowing the position of the satellite in orbit and the Doppler shift measurements, one can determine the location of an observation station. This discovery soon found application for providing accurate position fixes for the Polaris submarine fleet [7]. The US Navy deployed the Navy Navigation System (TRANSIT) for this task.

2.2 TRANSIT System

The TRANSIT system consists of six satellites, four tracking stations located in Maine, Minnesota, California and Hawaii, a computing center at Point Mugu in California, and two injection stations (place from where the broadcast messages and other control

messages are uploaded to the satellite) at Point Mugu, California and Rosemount, Minnesota. All the satellites are in a virtually circular polar orbit at an altitude of 600 nautical miles (approx. 1100 kilometers) and their anticipated orbital spacing is 30° to one another. This altitude was selected after great deliberation [6]. If a lower orbit was chosen, the air drag on the satellite will be too great. At higher orbits the received doppler frequency shift would have been too small. The altitude also affects the navigation area covered and the amount of power needed. The orbital velocity of these satellites is about 7.3 km/sec and the orbital period is about 107 minutes. Hence, these satellites make about 13.5 revolutions around the earth every day. At any location on the earth, the signals from the satellites can be received for 10 to 15 minutes during every pass. The satellites are in polar orbits and the time between two passes will is maximum at the equator and minimum at the poles, as the satellite spends more time over the poles than the equator. The orbits and altitudes of these satellites were selected such that a satellite will be visible to a receiver at the equator every ninety minutes. These satellites are passive satellites. They have no thrusters to correct their drift from their allotted orbits. The orbital drift over the years has increased the time between passes considerably [1].

The satellites carry an extremely stable oscillator [1]. This 5 MHz oscillator has a drift rate that is less than 1 part in 10^{10} per day. The carrier frequency selected for transmission should be higher than 40 MHz as any frequency below 40 MHz would be

partially reflected back by the outer surface of the ionosphere [2]. Dual frequency transmissions are used to correct the dispersive effect of the ionosphere.

Each satellite transmits two coherent frequencies, viz ., 149.988 MHz and 399.968 MHz. This 80 parts per million reduction from the 150 MHz and 400 MHz frequencies is done to ensure that the doppler frequency shift that is produced will always have the same sign when compared with the 150 MHz and 400 MHz frequency references generated in the receiver. Superimposed on both the carrier frequencies, using balanced phase modulation, is a broadcast message which contains all the information needed by the receiver to determine its coordinates on earth. The satellites continuously transmit a two minute broadcast message which begins and ends at the instant of each even minute [5]. The fact that position location is done by doppler shift measurement implies that the modulation scheme used must not vary the carrier frequency, hence phase modulation is used. The broadcast message is 6103 bits long. It consists of 156 words of 39 bits and a final word of 19 bits. The last 25 bits are the synchronization word {0111111111111111111111110} which is used for indicating the start of the next message. Figure 2.1 shows the broadcast message format. The first three data words give the timing information. The satellite's deviation from its elliptical orbit is given in the first eight words of column six , the fixed orbital parameters of the satellite are given in the next 14 words of column six, lines 22 to 25 are used for indicating the unavailability of the satellite for reasons like data updating. Otherwise lines 22 to 27 are used for synchronization.

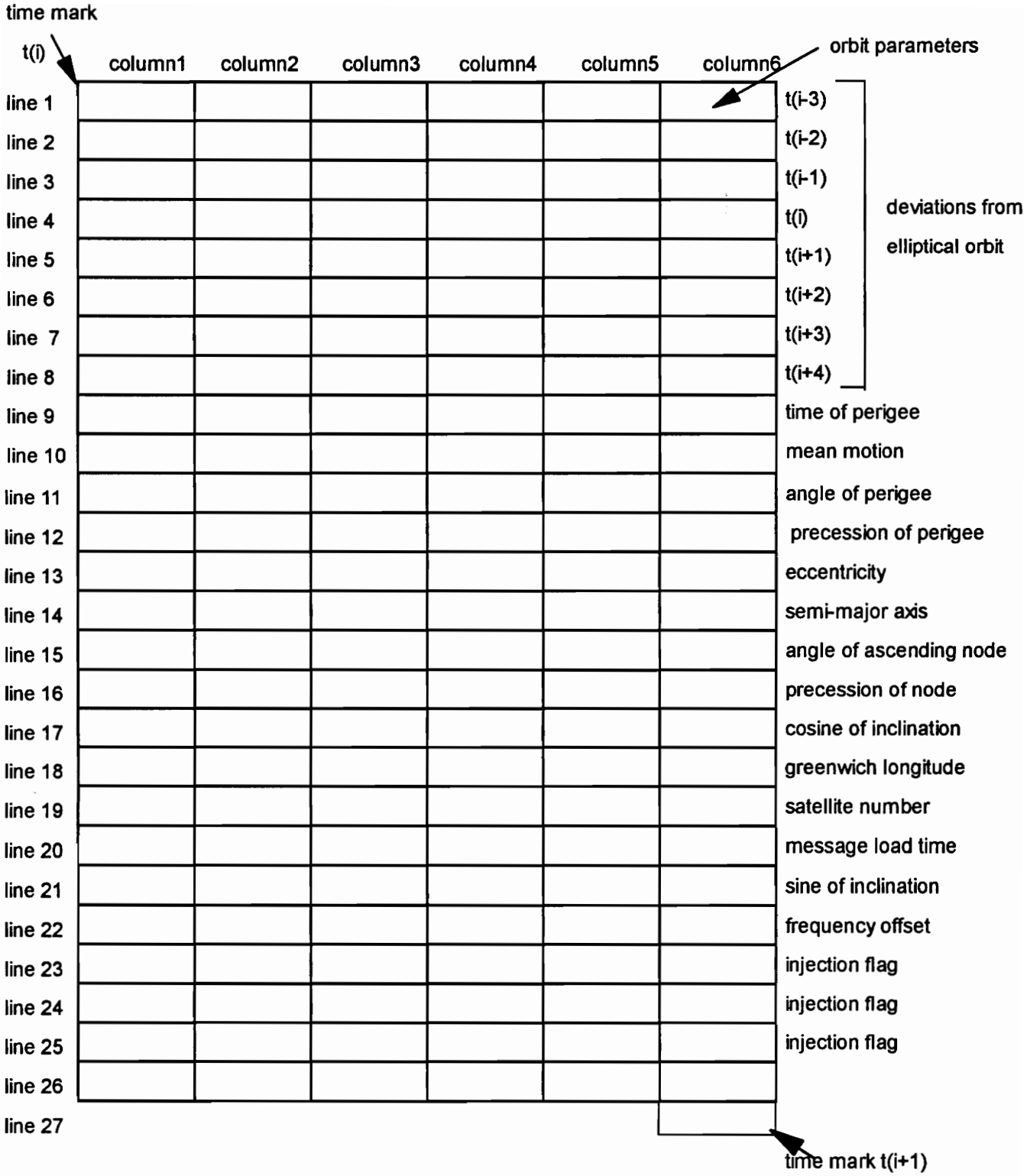


Figure 2.1: TRANSIT Systems Two Minute Broadcast Format [2]

Accurate range information is dependent on accurate measurement of the doppler shift. In order to accurately measure the Doppler shift, the beat frequency technique is used (accurate measurement of the instantaneous received frequency is not possible) [1][2]. Let f_r be the received frequency, f_{rx} be the locally generated receiver carrier frequency (e.g. 400 MHz), and f_{tx} be the transmitted carrier frequency (e.g. 399.968 MHz). Depending on the position of the satellite with respect to the receiver a doppler frequency bias will be introduced. The beat frequency is the difference between f_{rx} and f_r . The maximum value of $(f_{rx} - f_r)$ is 32 KHz. The receiver counts the number of beats (zero crossings of the received signal) $N_{t1,t2}$ during the two minute interval between t_1 and t_2. If R_1 is the distance between the satellite and the receiver at t_1 and R_2 the distance at t_2 then $N_{t1,t2}$ is given by the formula

$$N_{t_1,t_2}=(f_{rx}-f_{tx})(t_2-t_1)+\frac{(R_2-R_1)}{\lambda_{rx}} \qquad 2.1$$

Where λ_{rx} is the wavelength of the locally generated receiver carrier signal. All the parameters except $(R_2 - R_1)$ are known. Hence the range difference $(R_2 - R_1)$ can be calculated.

In order to compute the position of the receiver, an initial estimate of the receiver's position (latitude, longitude, and altitude) has to be entered [9]. These values are used to compute the range to the satellite. The difference in the computed range difference and the measured range difference gives the residual, e_i. The residual, e_i, is reduced by

varying the latitude, longitude, and the frequency offset (f_{rx}- f_{tx}), till it tends to zero. The equations to be solved are of the type [9]

$$\hat{e}_i = e_i + \frac{\partial e_i}{\partial \phi}\Delta\phi + \frac{\partial e_i}{\partial \lambda}\Delta\lambda + \frac{\partial e_i}{\partial F}\Delta F \qquad 2.2$$

where Φ is the latitude, λ is the longitude, F is the frequency offset (f_{rx}- f_{tx}), and e_i is the residual error. By varying the latitude by $\Delta\Phi$, the longitude by $\Delta\lambda$, and frequency offset by ΔF we get a new estimate of e_i. The sum of squares of the estimated residuals can be minimized by setting the partial derivative with respect to the three variables equal to zero. If during one pass m doppler counts have been taken then we get the following three equations

$$\frac{\partial}{\partial \phi}\sum_{i=1}^{i=m}\hat{e}_i^2 = 2\sum_{i=1}^{i=m}\left[\hat{e}_i\frac{\partial \hat{e}_i}{\partial \phi}\right] = 0$$

$$\frac{\partial}{\partial \lambda}\sum_{i=1}^{i=m}\hat{e}_i^2 = 2\sum_{i=1}^{i=m}\left[\hat{e}_i\frac{\partial \hat{e}_i}{\partial \lambda}\right] = 0$$

$$\frac{\partial}{\partial F}\sum_{i=1}^{i=m}\hat{e}_i^2 = 2\sum_{i=1}^{i=m}\left[\hat{e}_i\frac{\partial \hat{e}_i}{\partial F}\right] = 0$$

Considering only the first order terms we get

$$\sum_{i=1}^{m}\frac{\partial e_i}{\partial \phi}\left[e_i + \frac{\partial e_i}{\partial \phi}\Delta\phi + \frac{\partial e_i}{\partial \lambda}\Delta\lambda + \frac{\partial e_i}{\partial F}\Delta F\right] = 0$$

$$\sum_{i=1}^{m} \frac{\partial e_i}{\partial \lambda} \left[e_i + \frac{\partial e_i}{\partial \phi} \Delta\phi + \frac{\partial e_i}{\partial \lambda} \Delta\lambda + \frac{\partial e_i}{\partial F} \Delta F \right] = 0$$

$$\sum_{i=1}^{m} \frac{\partial e_i}{\partial F} \left[e_i + \frac{\partial e_i}{\partial \phi} \Delta\phi + \frac{\partial e_i}{\partial \lambda} \Delta\lambda + \frac{\partial e_i}{\partial F} \Delta F \right] = 0$$

As only linear first order terms are used, the values of $\Delta\Phi$, $\Delta\lambda$, and ΔF that satisfy these equations will be an approximation to the exact solution. The above three equations converge to give the correct answers even if the initial estimates are in error by 200 or 300 kilometers.

2.3 Errors Affecting Position Location Accuracy

Some of the factors that introduce errors in the calculation of position of an earth located receiver are:

1. Imperfect modelling of the tropospheric and ionospheric delays.

2. Height of the antenna. This causes an error in longitude calculation which can be very large in the case of airborne receivers.

3. The elevation of the satellite. If it is less than 10° or greater than 70° then the doppler curve is very flat and we cannot determine the time when the distance to the satellite is minimum. This causes an error in latitude calculations.

4. Incorrect estimation of the forces acting on the satellite in its orbit.

5. Errors in the prediction of the satellite's position.

6. Round off errors in orbital parameters.

2.4 Conclusion

The calculations in section 2.2 shows that the TRANSIT system can only find the latitude and longitude of the receiver. There is still an altitude discrepancy. The average time for the satellites to pass overhead is one hour, hence only one position fix per hour can be obtained. In order to overcome the inherent errors of the TRANSIT system the Global Positioning System was developed. Chapter 3 discusses the Global Positioning System in detail.

Chapter 3

Global Positioning System

3.1 Introduction

The Global Positioning System (GPS) [3] is a passive satellite based ranging system. Work on GPS started in 1973 when the Department of Defense merged the US Navy's TIMATION Project and the US Air Force's 621B Project, both of which had the same aim of developing a passive navigation system.

In its final constellation the system will have 18 satellites (plus 3 in orbit spares) in six orbital planes inclined 55° to the equator [3]. There are 3 types of GPS satellites, Block I, Block II, and Block IIR [30]. Eleven Block I satellites were launched between 1978 and 1985. These Block I satellite's orbital planes are inclined 63° to the equatorial plane. There will be twenty eight Block II satellites. The first Block II satellite was launched in 1989 and the final launch is planned for 1995. These satellites have an orbital inclination of 55° to the equatorial plane. The replacements of the Block II satellites are called Block IIR satellites. The first Block IIR satellite will be launched in late 1995. These satellites will be equipped with a much superior Hydrogen Maser clock than the older Block I and II satellites. Unlike the TRANSIT system satellites which were passive with no thrusters, the GPS satellites have been provided with Hydrazine thrusters to

allow correction of the drift from their defined orbits for more accurate position prediction. All the 18 satellites are in near circular orbits at an altitude of around 20,000 kilometers. Their orbital period is approximately 12 hours which is one half of the earth's rotation period. The constellation has been selected in such a way that at any instant of time, anywhere in the world, at least four satellites with an elevation greater than 10° will be visible. There are five monitor stations around the world (Hawaii, Colorado Springs, Ascension Island in the Atlantic Ocean, Diego Garcia in the Indian Ocean, and Kwajalein in the Pacific Ocean) to control the 18 satellites (plus three in orbit spares) with the Master Control Station being located at Colorado Springs [31]. There are three ground control stations (Ascension Island, Diego Garcia, and Kwajalien). The message that has to be broadcast from each satellite is generated at the Master Control Station in Colorado Springs. This information is sent to the ground control stations which upload the information to the appropriate satellites [12].

3.2 GPS Signal Structure

Navigation data is transmitted from each satellite on two L band frequencies, viz., L1 1575.42 MHz and L2 1227.60 MHz [9]. Both these carriers are derived from a highly stable caesium clock oscillator having a frequency output of 10.23 MHz and a drift rate less than one part in 10^{12} per day. The carrier frequencies L1 and L2 are obtained by multiplying this master frequency by 154 and 120 respectively, as illustrated in Figure 3.1.

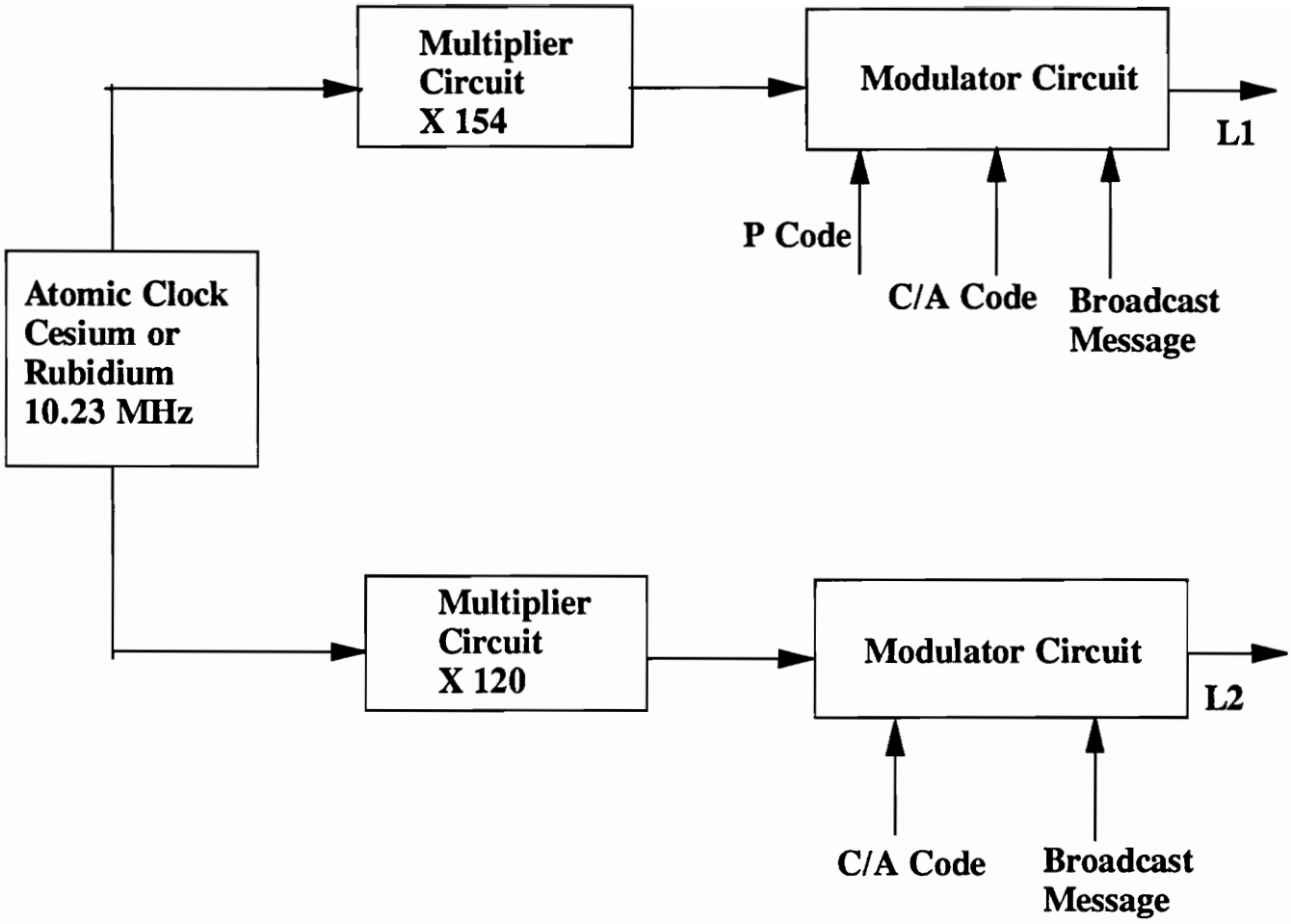


Figure 3.1: Basic GPS System [3]

Actually this clock is offset to 10.22999999545 MHz to account for the relativity effect (difference in gravitational potential and relative velocity between the satellite and receiver) [13]. Dual frequency transmission enables dual frequency receivers to correct for ionospheric delays, thereby achieving a more accurate position fix.

The L1 carrier is modulated by two pseudo-random noise (PRN) codes, viz, the Coarse/ Acquisition (C/A) and the Precision (P or Y) code. The Y code is a classified code which is very similar to the P code. The GPS satellites can turn off the P code and use the Y code instead, to prevent unauthorized usage of the system (anti - spoofing). The L2 carrier is only modulated by the P or Y code. The C/A code is an exclusive OR combination of two pseudo random noise sequences G1 and G2. The G1 and G2 sequences are generated by using ten bit tapped feedback shift registers whose feedback is governed by the polynomial, $1 + x^3 + x^{10}$ and $1 + x^2 + x^3 + x^6 + x^9 + x^{10}$ respectively [15][16]. The C/A code is a one millisecond long sequence of (+1's) and (-1's) having a clock rate of 1.023 Mbps. Thirty two different sets of C/A codes have been selected for use in GPS and they have one very important property: ie., any two of these codes have a very low cross correlation and have noise like properties. The P code is also an exclusive OR combination of two pseudo random noise sequences X1 and X2. Both the X1 and X2 sequences are generated by using twenty four bit shift registers. The X2 sequence is 37 bits longer than the X1 code. The X1 and X2 sequences are combined to generate a 267 days long sequence. This 267 days long sequence having

a clock rate of 10.23 Mbps is divided into 38 seven day segments by combining the X1 sequence with a delayed version of the X2 sequence. Each satellite is allotted a separate delay which ensures a unique week long code for each of the satellites. The Y code is very similar to the P code but the polynomial used for generating this sequence is classified to prevent unauthorized usage of the system. The pseudo random noise sequence is modulated by using binary phase shift keying where a code transition is indicated by a 180° phase reversal. A broadcast message, 50 bps, is modulated onto both the carriers which carries all the information receivers (users) need to determine their position.

3.3 GPS Broadcast Message

In addition to the measured range to the satellite, the parameters needed by the receiver to compute its position are the coordinates of the satellite, the time at which the satellite was at the given coordinates, the variation of the satellite's clock with respect to a common clock, and the current information of the orbital parameters. All this information is broadcast by the satellite at regular intervals of time so that receivers can use them for computing their position. The broadcast message frame is 1500 bits long and at 50 bps it takes 30 seconds to transmit one frame. Each frame is further subdivided into five subframes of 300 bits (10 words of 30 bits) each. Subframe1 contains information about the satellite clock correction. Subframes 2 & 3 contain the orbital parameters of the satellite. Subframes 4 & 5 are parts of a 25 frame message which contains a satellite

almanac, model for implementing ionospheric corrections, and flags to indicate whether the P or Y code is used. The satellite almanac contains the approximate position of each satellite in the constellation and its condition. This is very useful during cold startup to detect the presence of nearby satellites after detecting the first one (reduces the time for searching the entire sky to locate a satellite).

Each subframe contains two special words, the telemetry word (TLM) and the hand over word (HOV). The TLM consists of an 8 bit synchronization pattern followed by a 14 bit message which contains information about whether the satellite is uploading information, and some error and diagnostic flags. The HOV contains the Z-count which indicates how many times the X1 code has repeated since the beginning of the week (useful for knowing the starting point of the week long P or Y code).

Subframes 2 & 3 contains the orbital parameters of the satellite. The parameters broadcast are M_o, the mean anomaly, Δn, the mean motion difference, e, the eccentricity, $\sqrt{a}$, the square root of the semi major axis, Ω_o, right ascension parameter, i_o, inclination, ω, the argument of perigee, $\dot{\Omega}$, the rate of right ascension, $\dot{i}$, the rate of inclination, C_{uc} and C_{us} corrections to the argument of latitude, C_{rc} and C_{rs} corrections to the orbital radius, C_{ic} and C_{is} corrections to the inclination, and t_{oe}, the ephemeris reference time.

3.4 GPS Clocks

One of the main criteria for accurate range measurement is frequency stability. The main causes of oscillator frequency drift are temperature and aging. In satellites the oscillators are subject to a large range of temperature variations and radiation from the sun. Hence, extremely stable clock oscillators have to be used which can withstand these variations. GPS satellites and all control stations use high precision atomic oscillators.

There are four types of precision oscillators, Oven Controlled Quartz Crystal Oscillators, Rubidium Vapor Cell Oscillator, Caesium Beam Tube Oscillator, and the Hydrogen Maser Oscillator [17][18]. All GPS Block I and Block II satellites have four high precision oscillators onboard (2 Caesium and 2 Rubidium) and the satellite's master computer can be programmed by the Master Control Station to select any one of them to be the Master Oscillator. The Block IIR satellites will be equipped with Hydrogen Maser oscillators whose degree of precision is at least one order of magnitude higher than the currently used Caesium and Rubidium oscillators [10]. All clocks on board a GPS satellite have a drift rate less than 1 part in 10^{12} per day. Most GPS receivers use high precision, oven controlled quartz crystal oscillators having a drift rate less than 1 part in 10^{10} per day. These oscillators have a very small short term drift that can be ignored, but corrections for long term drift have to be applied. Synchronization of the satellite's clocks with respect to the Master Control Station's clock is done mathematically and not physically. These corrections are broadcast by the satellites so

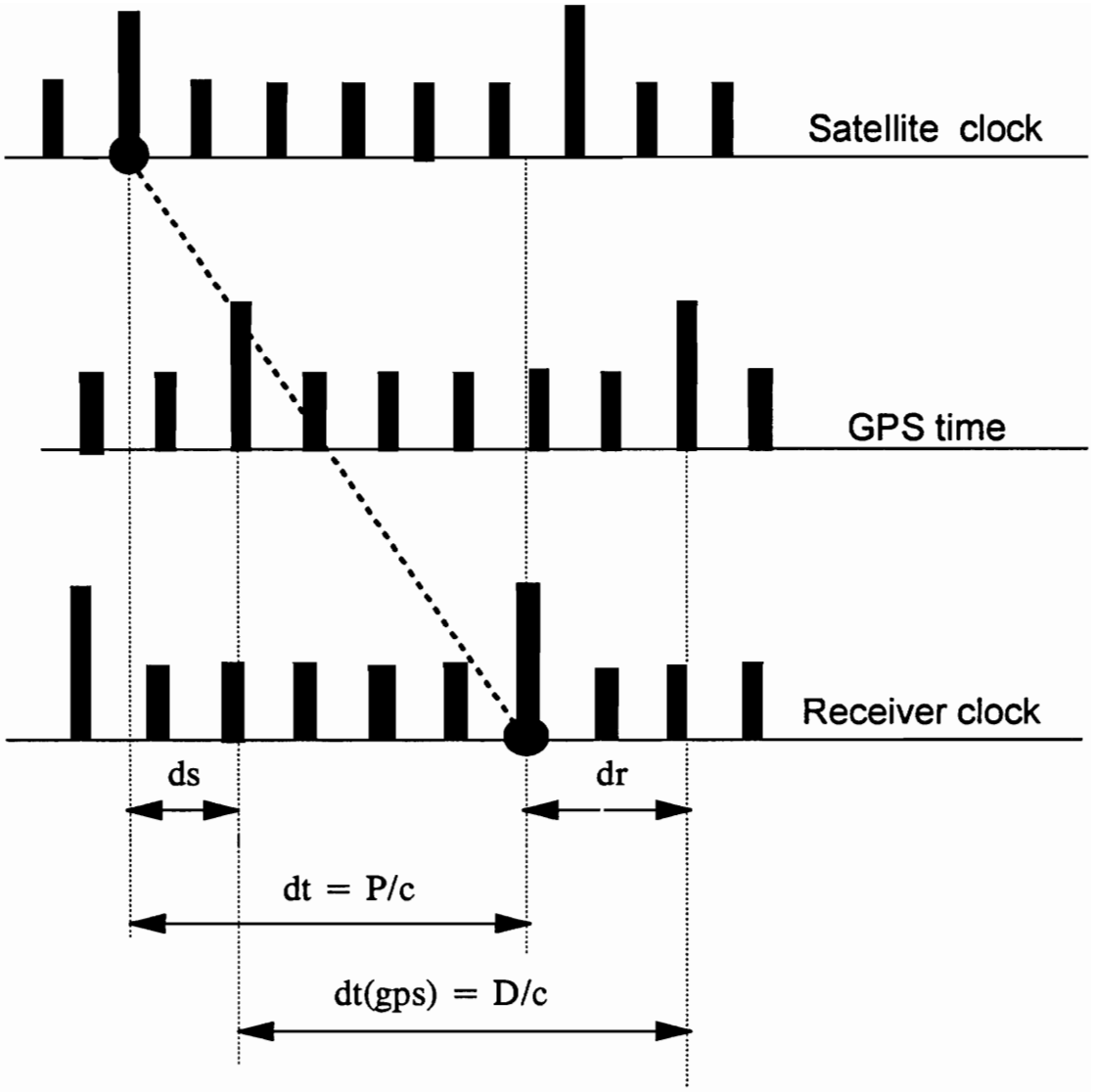
that all receivers can correct for the satellite's clock bias. The receiver's clock bias is removed by measuring range to multiple references (satellites). A table showing the comparison of various frequency sources used in GPS systems is given in Table 3.1 [17].

3.5 Position Location Using GPS

GPS is a passive navigation system: therefore it uses the one way ranging technique, illustrated in Figure 1.1, of pseudo-range measurement. The range measured is called pseudo-range because it is not the true range to the satellite. The measured range will be greater or lesser than the true range depending on the drift of the receiver clock with that of the common GPS clock. There are three different time bases, viz, the satellite clock time base, the GPS time base, and the receiver clock time base, as shown in Figure 3.2 [3]. The GPS time base is the correct time base and the other time bases have to be corrected to match this. As mentioned before, any bias in the clocks directly translates into a range error. Let t_s be the time of transmission of the data packet and t_r be the time of arrival of the packet at the receiver. If δ_s and δ_r are the variations of the satellite's clock and the receiver's clock with respect to a common clock then the time taken for the signal to reach the receiver Δt is given by

$$\Delta t = t_r - t_s = \left[t_{rg} - \delta_r\right] - \left[t_{sg} - \delta_s\right]$$

where t_{rg} and t_{sg} are the time of arrival and time of transmission according to the common reference clock. This can be written as



$$P = D + (ds - dr)c + Dtrop + Dion$$

Figure 3.2: Time Synchronization [3]

$$\Delta t = [t_{rg} - t_{sg}] + [\delta_s - \delta_r] \qquad 3.1$$

The satellite clock is kept mathematically synchronized with respect to a common clock. The synchronization is done by modelling the delay between the satellite's clock and the common clock using a polynomial. The coefficients of this polynomial are broadcast by the satellite and is available at the receiver. Thus, δ_s is known. As it is not feasible to equip each receiver with an atomic clock the only term that introduces error is the δ_r term. This error causes the measured range to be greater or lesser than the actual range. Therefore the measured range is called pseudo-range. It is given by

$$p = c\,\Delta t_g + c\,\delta_r$$

where $\Delta t_g = (t_{rg} - t_{sg})$ and c is the velocity of light. The above equation does not take into account the delays caused by the ionosphere, (d_{ion}) and the troposphere, (d_{trop}). Considering all these the equation for pseudo range is given by

$$p = c[\Delta t_g + \delta_r + d_{ion} + d_{trop}] \qquad 3.2$$

The receivers coordinates have to be extracted from the true range $\rho = c\ \Delta t_g$. If the satellite coordinates R(X,Y,Z) are perfectly known then $\rho = \| r - R \|$, where r(x,y,z) are the receivers coordinates. In order to account for slight inaccuracies in the orbital parameter determination a factor $d\rho$ is added. The pseudo range p is then given by

$$p = \| r - R \| + d\rho + c[\delta_r + d_{ion} + d_{trop}]$$

Basic logic tells us we need data only from two satellites to determine the user's latitude

and longitude, but at least three satellites data will be needed to account for the receiver's clock error with respect to the satellite's clock. In the case of a terrestrial or an aerial user the height above mean sea level also has to be determined therefore requiring data from a fourth satellite, hence a minimum of four satellites must be visible at all times for accurate position location, as shown in Figure 3.3. Let (X_1, Y_1, Z_1), (X_2, Y_2, Z_2), (X_3, Y_3, Z_3) and (X_4, Y_4, Z_4) be the known coordinates of four satellites and (x,y,z) be the user's unknown coordinates. All these coordinates are in the cartesian coordinate system. Therefore, the orbital coordinates of the satellite have to be transformed to the user's coordinate system. Then the four equations to be solved are

$$(X_1-x)^2+(Y_1-y)^2+(Z_1-z)^2=c^2.p_1^2 \qquad 3.3$$

$$(X_2-x)^2+(Y_2-y)^2+(Z_2-z)^2=c^2.p_2^2 \qquad 3.4$$

$$(X_3-x)^2+(Y_3-y)^2+(Z_3-z)^2=c^2.p_3^2 \qquad 3.5$$

$$(X_4-x)^2+(Y_4-y)^2+(Z_4-z)^2=c^2.p_4^2 \qquad 3.6$$

Where p_1, p_2, p_3 and p_4 are the pseudo ranges from the four satellites respectively. The four unknown parameters are x, y, z and δ_r. The above mentioned equations have no closed form solutions. One way to solve this is to input an estimate of the user's coordinates and then solve iteratively using the following algorithm [19].

Equations (3.3) to (3.6) can be written as

$$\sqrt{(X_1-x)^2+(Y_1-y)^2+(Z_1-z)^2} + b = r_1 \qquad 3.7$$

$$\sqrt{(X_2-x)^2+(Y_2-y)^2+(Z_2-z)^2} + b = r_2 \quad 3.8$$

$$\sqrt{(X_3-x)^2+(Y_3-y)^2+(Z_3-z)^2} + b = r_3 \quad 3.9$$

$$\sqrt{(X_4-x)^2+(Y_4-y)^2+(Z_4-z)^2} + b = r_4 \quad 3.10$$

where b is the user's clock bias error, and r_1, r_2, r_3,and r_4 are the ranges to the four satellites. Let $U = [x, y, z, b]^T$ and $R = [r_1, r_2, r_3, r_4]^T$.

The algorithm is as follows:

1. Guess an initial position of the user, U_1 (x_1,y_1,z_1).
2. Substitute U_1 (x_1,y_1,z_1) in equations (3.7) to (3.10) and calculate $R_1 = [r_1, r_2, r_3, r_4]^T$.
3. Compare with the measured r_1, r_2, r_3, and r_4. .
4. Calculate $\Delta R = R - R_1$.
5. Calculate $H = [h_1, h_2, h_3, h_4]^T$ using the formula

$$h_i = \left[\frac{x-x_1}{r_i-b} \quad \frac{y-y_1}{r_i-b} \quad \frac{z-z_1}{r_i-b} \right]$$

6. Calculate the geometric dilution of precision G using the Hotelling's algorithm [13].
7. Calculate $\Delta U_1 = G\Delta R$.
8. Update position estimate $U_1 = U_1 + \Delta U_1$
9. Repeat steps 2 to 8 till $\Delta U_1 < \epsilon$.

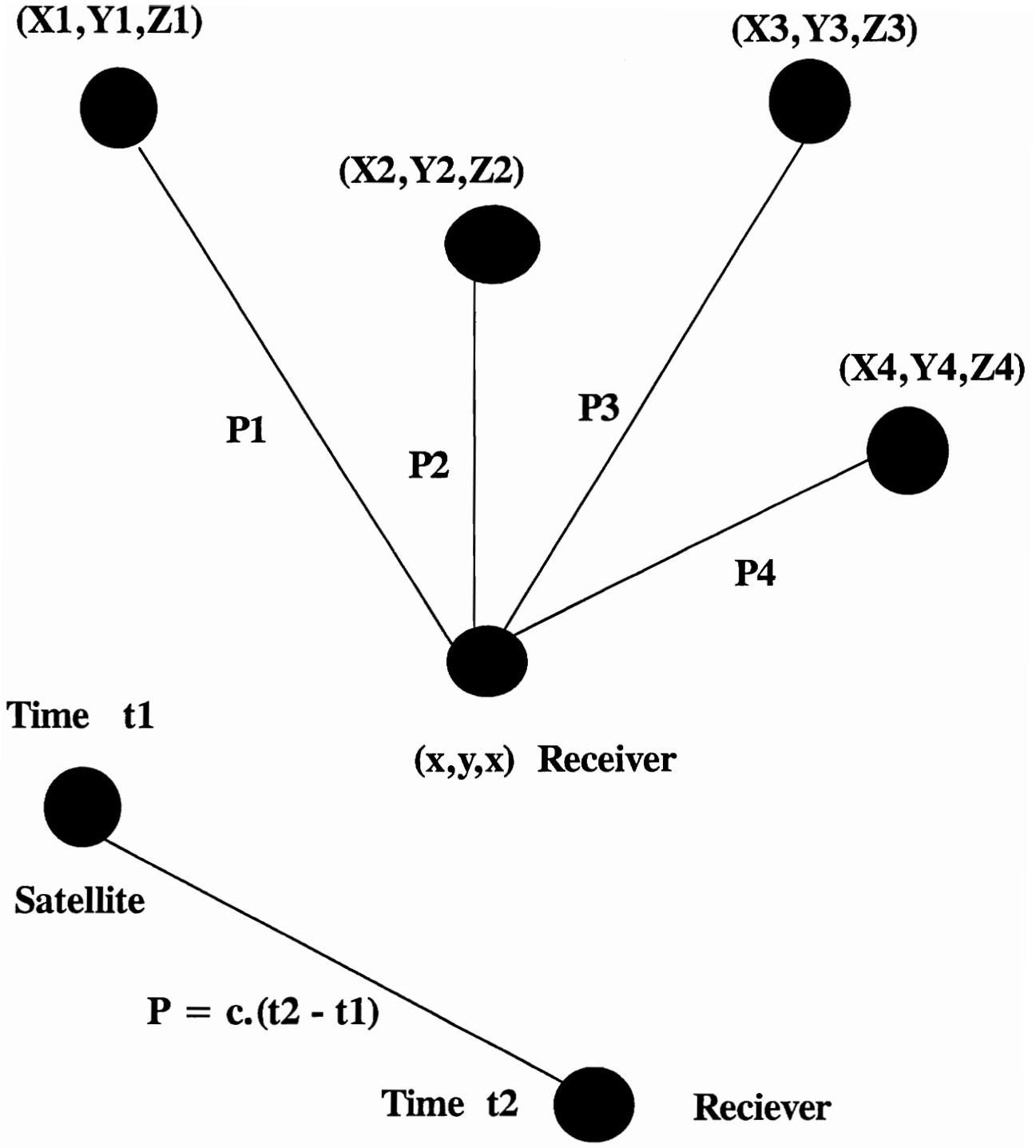


Figure 3.3: Positioning using GPS

3.6 Correction for Ionospheric Delay

The ionosphere [3] extends from about 50 to 1000 kilometers in altitude and contains electrons and positrons. These electrons and positrons are generated by ionization of gas molecules by the ultra-violet rays emitted by the sun. The reflection and refraction of radio signals by the ionosphere is a function of frequency. At high frequencies (less than 30 MHz) the change in electron and positron density within the distance of a wavelength is so great that the ionosphere behaves like a partially reflecting mirror which reflects back some of the incident radio signal. At super high frequencies the change in the ionization density is negligible in the course of a wavelength and in this case the ionosphere behaves as a dielectric with a continuously varying refractive index. The GPS frequencies lie in between these two frequency bands. At these frequencies the ionosphere behaves as a set of thin layers with each layer having a constant ionization density that varies from layer to layer. The effect of this layering is that at each boundary part of the signal is reflected back and part is refracted to the next layer. This layer has losses at each boundary due to reflection. The variation of the phase refractive index n, through these layers of variable ionization density is given by the Appleton - Hartree formula [21].

$$n(f,r,t)=\sqrt{\left[1-\frac{f_N^2(r,t)}{f^2}\frac{1}{\alpha}\right]} \simeq \sqrt{\left[1-\frac{81N(r,t)}{f^2}\right]}$$

where r is the altitude, f_N (r,t) is the electron plasma resonance frequency at r at time t. $f_N(r,t)$ is function of the electron density N(r,t) and α is a value which is dependent on

the magnetic field strength at r, orientation of the magnetic field with respect to the direction of propagation, and the frequency f. The dispersive effect of the ionosphere causes the measured range to the satellite to vary between 150 meters (during high sunspot activity, in the afternoon, and when the satellite is near the horizon) to around 5 meters (during periods of minimum sunspot activity, in the night and when the satellite is at the zenith). The frequency dependent ionospheric range effect can be estimated by

$$d\rho_{ion}(L1) = [\rho(L1) - \rho(L2)] \left[\frac{f_2^2}{(f_2^2 - f_1^2)^2} \right]$$

Using dual frequency receivers gives a much more accurate range measurement thereby improving the positional accuracy.

3.7 Correction for Tropospheric Delay

The troposphere [21][22] is an 80 kilometer layer of gases extending from the surface of the earth. The constituents of the troposphere are nitrogen, oxygen, carbon dioxide, carbon monoxide, water vapor, hydrogen, helium, argon, neon, xenon, krypton etc. The tropospheric delay is dependent on the temperature, pressure, humidity and the altitude of the user above mean sea level. For the purpose of simulating the effect of the troposphere on GPS signals, we can consider the atmosphere to be composed of two gases only, dry air and water vapor. More than 90% of the tropospheric refraction is due to dry air, but the remaining 10% cannot be accurately modelled, as the distribution

of water vapor in the atmosphere cannot be accurately predicted. The tropospheric delay is independent of frequency and the dispersive effect of the troposphere begins only above 10 GHz due to resonance of water vapor molecules. The refractive index of the troposphere is slightly greater than unity: it is about 1.0003 so the only correction that needs to be incorporated is to account for the variation in measured distance due to the slight change in refractive index. Some tropospherical models also exist, which can be used to the benefit of the user to increase the accuracy in position location, based on the local meteorological conditions.

3.8 Measurement Biases

Some of the measurement biases that affect the accuracy of position location in GPS are biases in the prediction of the satellite ephemeris, biases in clock correction, biases due to precision of the measurement standard used, bias in the calculation of the tropospheric and ionospheric delays, effect of multipath and relativity error. The effect of multipath [3][14] on GPS systems is small as the signals are coded using spread spectrum techniques and these techniques can reject multipath signals to a considerable level by implementing a window based correlation on the arriving signal sequence. The theory of relativity proposed by Einstein says that time on earth is compressed due to the mass of the earth [1][13]. Time on the surface of the earth is compressed by 1.4×10^{-9} ms^{-2} when compared to the time in free space. At 20,000 kilometers above the earth the time compression is about 0.4×10^{-9} ms^{-2} . This 1 nanosecond difference between the satellite's

clock and receiver's clock results in a position error of 0.3 meters. Another source of error in time bases of the satellite clock and the receiver clock is the orbital velocity of the satellite (26.6 kilometers per second). To offset the effect of relativity the main oscillator (10.23 MHz) is offset to 10.2299999945 MHz.

3.9 Conclusion

This chapter discusses the basic working of the GPS system. It explains the pseudo-ranging technique used by the satellite to measure the range to the satellite. In order to compute the position of the receiver the receiver needs to know the position of the satellite. The computation of the position of the satellite from the contents of the broadcast message is discussed in chapter 4.

Table 3.1 : Comparison of frequency sources used in GPS [17]

Characteristics	Crystal Oscillator	Caesium Oscillator	Rubidium oscillator
Basic Frequency	0.01 - 100 MHz	9,192,631,770 Hz	6,834,682,608 Hz
Output Frequency	0.01 - 100 MHz	1, 5, 10 MHz	1, 5, 10 MHz
Resonator Q	10^4 to 10^6	10^7 to 10^8	10^7
Short term stability	10^{-6} to 10^{-12}	$5x10^{-11}$ to $5x10^{-13}$	$2x10^{-11}$ to $5x10^{-12}$
Long term stability	10^{-6} to 10^{-12}	10^{-13} to 10^{-14}	$5x10^{-12}$ to $3x10^{-13}$
Principal causes of long term instability	aging of crystal and electronic components, environmental effects	component aging	light source aging, filter & gas source aging, environmental effects
Time for clock to be in error of 1 μsec	1 sec to 10 days	7 days to 1 month	1 to 10 days
Fractional frequency reproducability	N/A, must be calibrated	$1x10^{-11}$ to $2x10^{-12}$	$1x10^{-10}$
Fractional frequency drift	$1x10^{-9}$ to $1x10^{-11}$ per day	less than $5x10^{-13}$ per year	$1x10^{-11}$ per month
Principal environmental effects	motion, crystal drive level, and temperature	magnetic fields, accelerations and temperature changes	magnetic fields, temperature change, and atmospheric pressure
Start up time after being off	seconds to hours, may have a systematic offset	half an hour to one hour	10 minutes to one hour
Resonator reliability, time for replacement	very reliable	3 years	3 years
Typical size in cc	10 to 10,000	10,000 to 700,000	1000 to 20,000
Typical weight in Kg	0.1 to 10	16 to 400	1 to 20
Power consumed in Watts	0.1 to 15	30 to 200	12 to 35

Chapter 4

Orbital Dynamics

4.1 Introduction

The motion of an artificial satellite around the earth is governed by the Kepler's Laws of planetary motion which state:

1. The orbit of any satellite around the earth is an ellipse with the earth at one of its foci.

2. The satellite will move along its orbit with a constant areal velocity, ie., the area swept out by the radius vector $\vec{r}$ is a constant for a given time interval.

3. The ratio of the square of the orbital period, m, of a satellite to the cube of its semi major axis, a, is a constant.

$$\frac{m^2}{a^3} = Constant \qquad 4.1$$

4.2 Mathematics of an ellipse

An ellipse, as shown in Figure 4.1, is defined as the locus of a point which moves such that the sum of its distances from two fixed points, called foci, is a constant. An ellipse is characterized by its semi major axis, a, and its eccentricity, e. The eccentricity, e of an ellipse in terms of its semi-major axis, a, and its semi-minor axis, b, is given by

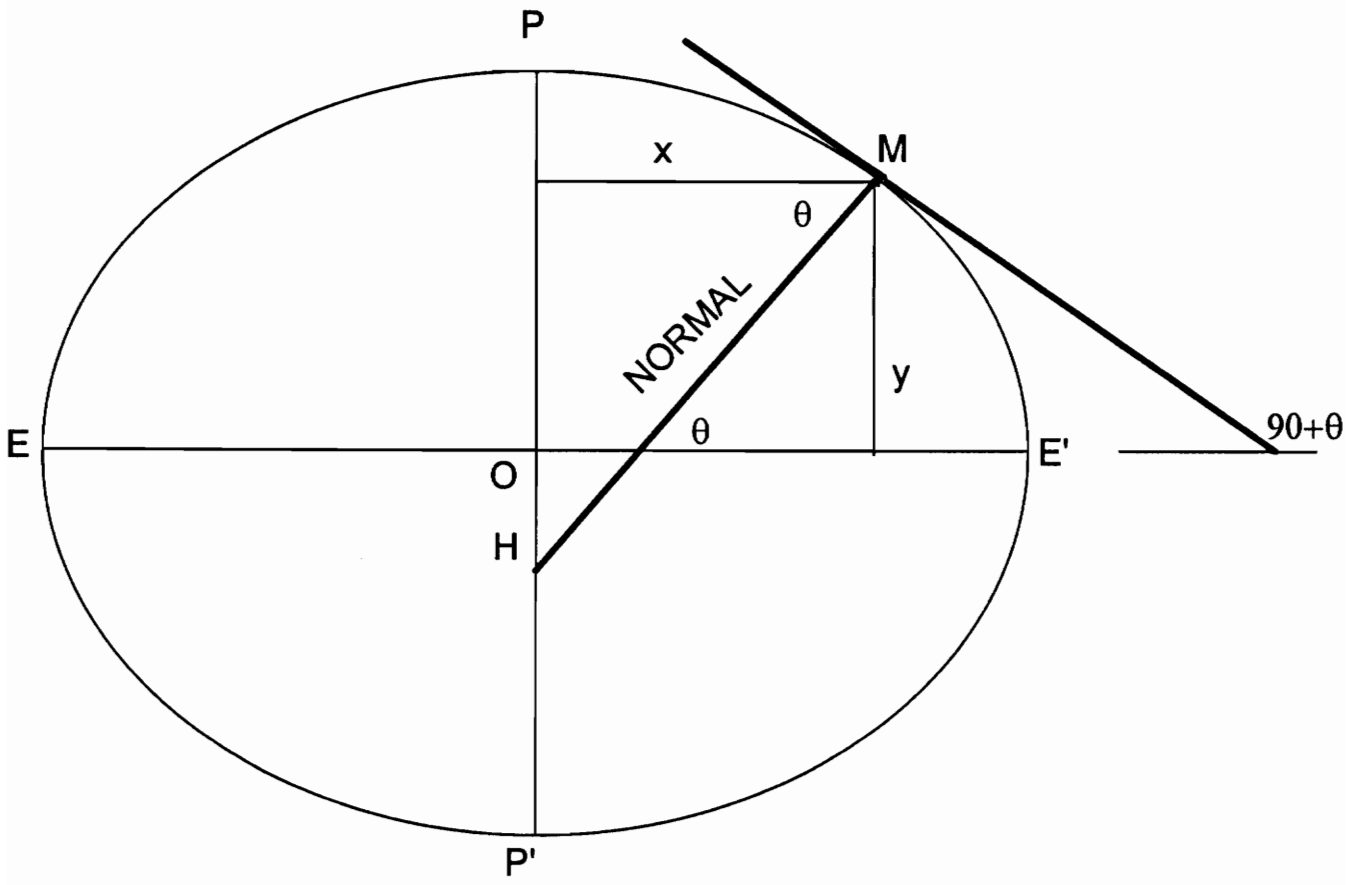


Figure 4.1: An Ellipse [8]

$$e = \frac{\sqrt{a^2-b^2}}{a}$$

The equation of an ellipse in Cartesian coordinates is given by

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \qquad 4.2$$

The tangent (dy/dx) to any point on the ellipse makes an angle ($90^0 + \theta$) with the major axis. Therefore

$$\tan(\theta) = -\frac{dx}{dy} \qquad 4.3$$

Differentiating (4.2) and substituting the value of e and dy/dx we find

$$\frac{y^2}{x^2} = (1-e^2)^2 \tan^2(\theta) \qquad 4.4$$

Equation (4.2) can also be written as

$$y^2 = (a^2-x^2)\ (1-e^2) \qquad 4.5$$

Solving (4.4) and (4.5) for x and y we have the polar form

$$x = \frac{a\cos(\theta)}{\sqrt{1-e^2\sin^2(\theta)}} \qquad 4.6$$

$$y = \frac{a(1-e^2)\sin(\theta)}{\sqrt{1-e^2\sin^2(\theta)}} \qquad 4.7$$

4.3 Orbital Theory

In order to describe the motion of an artificial earth satellite around the earth the following assumptions are made [23]

1. There are only two bodies, viz, the earth and the satellite.

2. These two bodies are considered to be point masses having their mass located at the center of their mass.

3. The mass of the satellite is negligible compared to the mass of the earth.

4. Both the earth and the satellite are not affected by the sun, moon, or any other celestial bodies.

5. The satellite is orbiting in vacuum and the only force acting on it is gravity.

Figure 4.2 shows the satellite orbit geometry and Figure 4.3 the orbital orientation. There are three coordinate systems used for orbit description. The first coordinate system $\{\xi, \eta, \varphi\}$ has its origin at the center of the ellipse with the semi major axis and the semi minor axis of the ellipse lying on the ξ and the η axes. The φ axis is perpendicular to the other two. The second coordinate system $\{q_1, q_2, q_3\}$ has its origin in the foci of the ellipse which corresponds to the center of mass of the earth. The q_1, q_2, and the q_3 axes are parallel to the ξ, η,and φ axes. The orientation of the orbit can also be fixed using a third coordinate system called the celestial coordinate system $\{x, y, z\}$. The origin of this coordinate system is also at the foci of the ellipse. Its x axis points to the vernal equinox, its z axis points to the celestial ephemeris pole and the y axis lies along the equator [24][25]. The transformation from one coordinate system to another is accomplished by shifting and rotating the appropriate axes.

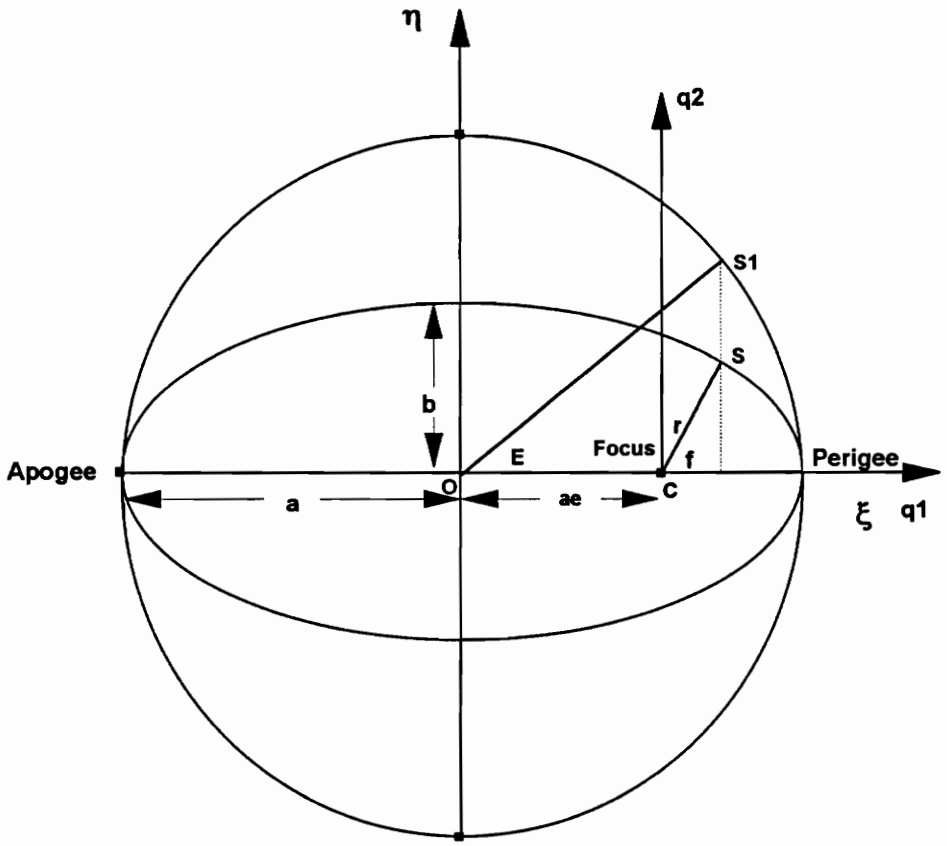


Figure 4.2: Satellite Orbit Geometry [24]

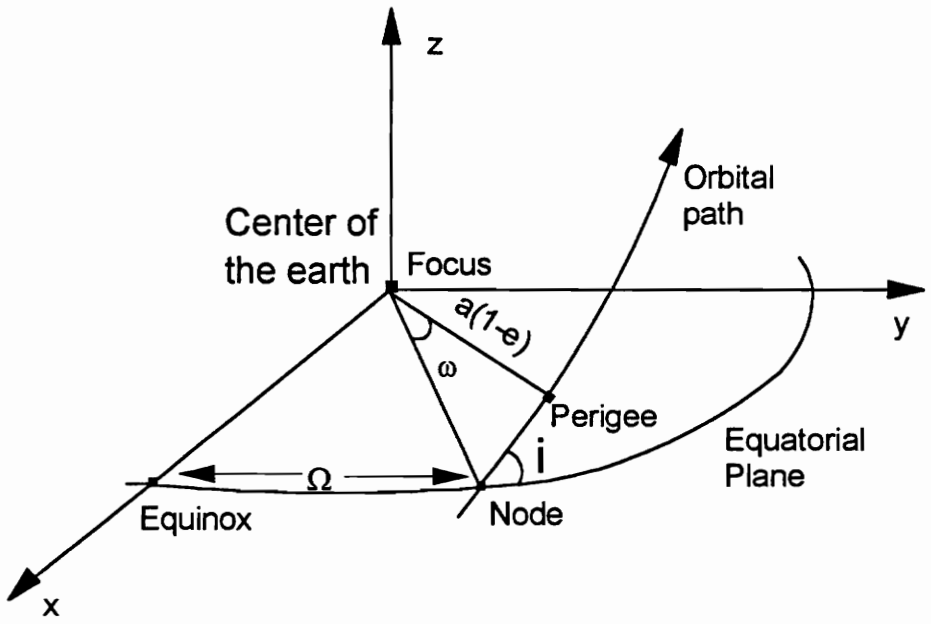


Figure 4.3: Orbital Orientation [24]

The position of a satellite in its orbit round the earth can be described completely by the following six parameters, most of which are shown in Figure 4.2 and 4.3:

1. The right ascension of the ascending node, Ω. It is defined as the angle between the true vernal equinox and the nodal line.

2. The argument of perigee, ω, the angle between the line of apsides and the nodal line.

3. The inclination, i, the angle between the orbital plane and the equator.

4. The semi-major axis, a, of the elliptical orbit.

5. The eccentricity, e, of the elliptical orbit.

6. The true anomaly, f.

The position of the satellite in the $Q\{q_1, q_2, q_3\}$ coordinate system, referring to Figure 4.2, is given by

$$\begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = r \begin{bmatrix} \cos(f) \\ \sin(f) \\ 0 \end{bmatrix} \qquad 4.8$$

In the $\{\xi, \eta, \varphi\}$ coordinate system the equation of the ellipse is given by

$$\frac{\xi^2}{a^2} + \frac{\eta^2}{b^2} = 1 \qquad 4.9$$

Since the satellite lies on the elliptical orbit we can write

$$\frac{(ae + r\cos(f))^2}{a^2} + \frac{r\sin(f)^2}{b^2} = 1 \qquad 4.10$$

Solving (4.10) for r we find [24]

$$r = \frac{a(1 - e^2)}{1 + e\cos(f)} \tag{4.11}$$

Substituting (4.11) in (4.8) we have

$$\begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = \begin{bmatrix} a\cos(E) - ae \\ a\sqrt{1 - e^2}\sin(E) \\ 0 \end{bmatrix} \tag{4.12}$$

but r can also be written as

$$r = \sqrt{q_1^2 + q_2^2}$$

which can be written as

$$r = a\sqrt{(\cos(E) - e)^2 + (1 - e^2)\sin^2 E}$$

which reduces to

$$r = a\left[1 - e\cos(E)\right]$$

The velocity of the satellite is given by [24]

$$\dot{q} = \dot{r}\begin{bmatrix} \cos(f) \\ \sin(f) \\ 0 \end{bmatrix} + r\dot{f}\begin{bmatrix} -\sin(f) \\ \cos(f) \\ 0 \end{bmatrix} \tag{4.13}$$

and the acceleration is given by

$$\ddot{q} = \ddot{r}\begin{bmatrix} \cos(f) \\ \sin(f) \\ o \end{bmatrix} + 2\dot{r}\dot{f}\begin{bmatrix} -\sin(f) \\ \cos(f) \\ 0 \end{bmatrix} + r\ddot{f}\begin{bmatrix} -\sin(f) \\ \cos(f) \\ 0 \end{bmatrix} - r\dot{f}\dot{f}\begin{bmatrix} \cos(f) \\ \sin(f) \\ 0 \end{bmatrix}$$

The conversion from the Celestial coordinate system {x, y, z} to the Q{q_1, q_2, q_3} coordinate system is given by

$$\begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = R_3(\omega)\ R_1(i)\ R_3(\Omega) \begin{bmatrix} x \\ y \\ z \end{bmatrix} \qquad 4.14$$

where R_1 and R_3 are the rotation matrices given by [24]

$$R_1(a) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(a) & \sin(a) \\ 0 & -\sin(a) & \cos(a) \end{bmatrix} \qquad R_3(a) = \begin{bmatrix} \cos(a) & \sin(a) & 0 \\ -\sin(a) & \cos(a) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

4.4 Receiver's Position Determination

As mentioned earlier, the position of a receiver has to be computed by determining the exact time of arrival of the signal broadcast by the navigation satellite, and decoding the broadcast message to get the time of transmission, position of the satellite at the time of transmission and the clock bias. The primary issue to be resolved is: Given the position of the satellite, how can we determine the position of the user on the earth. The satellite broadcasts the following information to all the users:

M_o, the mean anomaly, Δn, the mean motion difference, e, the eccentricity, $\sqrt{a}$, the square root of the semi major axis, Ω_o, right ascension parameter, i_o, inclination, ω, the argument of perigee, $\dot{\Omega}$,the rate of right ascension, $\dot{i}$, the rate of inclination and t_{oe}, the ephemeris reference time.

The position of the satellite at instant ti is computed using the following steps [3]

1. Find ti with respect to t_{oe}

$$ti = t - t_{oe}$$

2. Find the mean anomaly Mi at instant ti

$$Mi = M_o + n\ ti$$

where

$$n_0 = \sqrt{\frac{\mu}{a^3}} \quad , \quad n = n_0 + \Delta n$$

3. Solve Kepler's equation for eccentric anomaly

$$M_i = E_i - e\ \sin(E_i)$$

This can be done using the following algorithm [3]

Compute M for time ti using the formula

$$M = n\ (ti - T)$$

where T is the time of perigee passing and ti is any time instant after T. Then compute an approximate E_1 using

$$E_1 = M + e\ \sin(M) + \frac{e^2}{2}\sin(2M) + \frac{e^3}{8}(3\ \sin(3M) - \sin(M)\ ) + \ldots.$$

Use the computed value of E_1 in Kepler's equation and compute M_1 . $\Delta M = M_1 - M$. Use ΔM to compute ΔE from

$$\Delta E = \frac{\Delta M}{1 - e\ \cos(E)}$$

Now compute $E_2 = E_1 + \Delta E$. Use E_2 in Kepler's equation. Repeat step 3 till we get $\Delta M < \epsilon$.

4. Compute the true anomaly using

$$f_i = \tan^{-1}\left[\frac{\sqrt{(1-e^2)}\,\sin(E_i)}{\cos(E_i)-e}\right]$$

5. Compute the argument of latitude using

$$u_i = \omega + f_i$$

where ω is the argument of perigee.

6. Compute the radius using

$$r_i = a\left[1 - e\,\cos(E_i)\right]$$

7. Compute the inclination using

$$i_i = i_0 + \dot{i}\,t_i$$

8. Compute the longitude of the ascending node λ_i using Figure 4.4.

The longitude of the ascending node of the orbital plane, λ_i, as shown in Figure 4.4a, is given by

$$\lambda_i = \Omega_i - GAST_i \qquad 4.11$$

where Ω_i is the angle between the vernal equinox and the ascending node at ti, and $GAST_i$ is the angle between the vernal equinox and the Greenwich meridian and is known as Greenwich Apparent Sidereal Time. Since the broadcast message does not contain the values of Ω and GAST at ti the receiver has to calculate it from the other parameters. Ω_i, as shown in Figure 4.4b, can be calculated by using the rate of change of right ascension $\dot{\omega}$.

$$\Omega_i = \Omega_{oe} + \dot{\Omega}\,(t_i - t_{oe})$$

From Figure 4.4c we can see that the value used for GAST is for the beginning of the week, (midnight of Saturday/ Sunday, when the codes are reset), t_{week}, so the following transformation is required

$$GAST_i = GAST_{week} + \omega_e\,(t_i - t_{week})$$

where ω_e (7.292115147 x 10^{-5} radians per second) is the earth's rotation rate and $GAST_{week}$ is the GAST at t_{week}. Since t_i and t_{oe} are elapsed time since t_{week}, we can set t_{week} equal to zero. From Figure 4.4d we can see that the parameter Ω_0 which is broadcast is actually (Ω_{oe} - $GAST_{week}$). Hence the equation for λ_i becomes

$$\lambda_i = \Omega_0 + (\dot{\Omega} - \omega_e)(t_i - t_{oe}) - \omega_e\, t_{oe} \qquad 4.12$$

9. The orbital plane coordinates can be calculated using

$$x_i = r_i \cos(u_i)$$

$$y_i = r_i \sin(u_i)$$

10. The satellite's coordinates can be calculated using

$$\begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} = R_3(-\lambda_i)\, R_1(-i_i)\, R_3(-u_i) \begin{bmatrix} r_i \\ 0 \\ 0 \end{bmatrix}$$

11. Now the position of the satellite (x, y, z) are known and we can determine the position of the receiver (X,Y,Z) by solving the four equations given below.

$$(x_1 - X)^2 + (y_1 - Y)^2 + (z_1 - Z)^2 = c^2 p_1^2$$

$$(x_2 - X)^2 + (y_2 - Y)^2 + (z_2 - Z)^2 = c^2 p_2^2$$

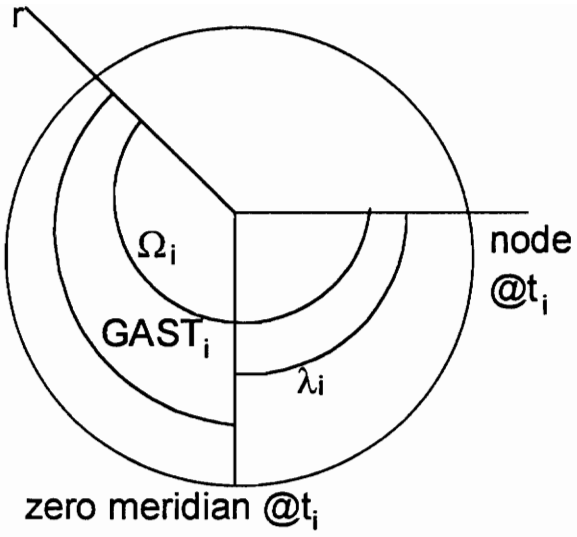
$$(x_3 - X)^2 + (y_3 - Y)^2 + (z_3 - Z)^2 = c^2 p_3^2$$

$$(x_4 - X)^2 + (y_4 - Y)^2 + (z_4 - Z)^2 = c^2 p_4^2$$

where p_1, p_2, p_3, and p_4 are the pseudo ranges to the four satellites and they are measured using the one way ranging technique. The algorithm to solve the above four equations has been discussed in section 3.5.

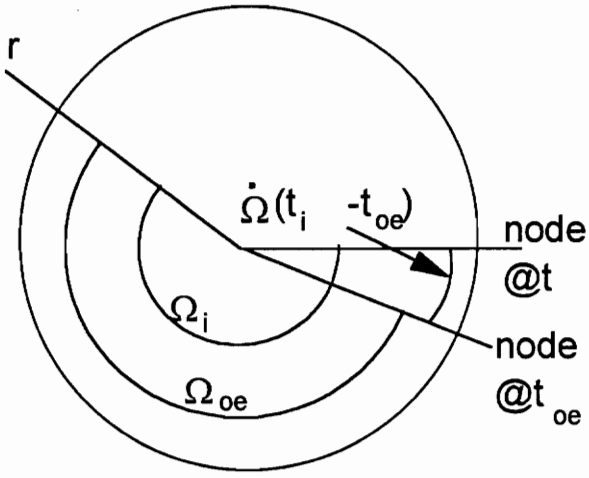
4.5 Conclusion

The navigation system proposed in this thesis will be very similar to GPS. It will be using the one way passive pseudo-ranging technique for measuring the range to the satellite. The information packet will be sending the same information sent by a GPS broadcast message, the only difference being that the message bit rate will be 4800 bits per second rather than 50 bits per second. The position of the receiver will also be computed using the algorithm discussed in section 4.4.



$$\lambda_i = \Omega_i - GAST_i$$

Figure 4.4a

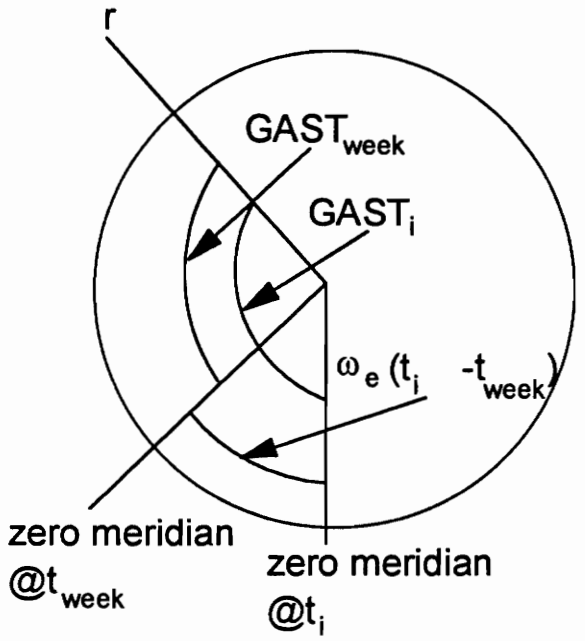


$$\Omega_i = \Omega_{oe} + \dot{\Omega}\,(t_i - t_{oe})$$

Figure 4.4b

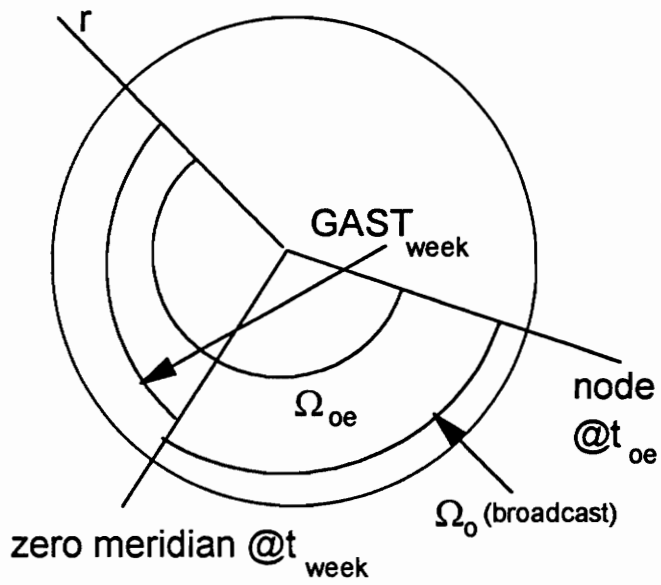
$$\lambda_i = \Omega_{o(broadcast)} + (\Omega - \omega_e)(t_i - t_{oe}) - \omega_e (t_{oe} - t_{week})$$

Figure 4.4: Computation of Longitude of Ascending Node [3]



$$GAST_i = GAST_{week} + \omega_e (t_i - t_{week})$$

Figure 4.4c



$$\Omega_{o(broadcast)} = \Omega_{oe} - GAST_{week}$$

Figure 4.4d

$$\lambda_i = \Omega_{o(broadcast)} + (\Omega - \omega_e)(t_i - t_{oe}) - \omega_e (t_{oe} - t_{week})$$

Figure 4.4 (contd.): Computation of Longitude of Ascending Node [3]

Chapter 5

System Details

5.1 Introduction

The purpose of this thesis is to investigate the feasibility of using a binary phase shift keyed receiver with an IF correlator for position location. The key features of a navigation system are global coverage, all year round usage, real time position location capability, high accuracy, and large number of users. The choice of using a passive ranging system will satisfy the criteria that a large number of users can simultaneously use this system. By appropriately selecting a satellite constellation we can ensure global coverage and year round usage. If the position of four satellites, their ranges to the user, and variation of their clocks are known, then we can determine the position of the user in real time. As a result the feasibility of this system is dependent only on the ability to determine the time of arrival of the signal with a very high degree of accuracy.

As mentioned in Chapter 1, the navigation system proposed will be using low earth orbit satellites. These low earth orbit satellites, shown in Figure 5.1, will be transmitting a data packet at 4800 bits per second at regular intervals of time. The data packet will be having a Barker 5 or a Barker 7 sequence header. This header is used for detecting the arrival of the data packet at the receiver and recording the time of arrival of the signal.

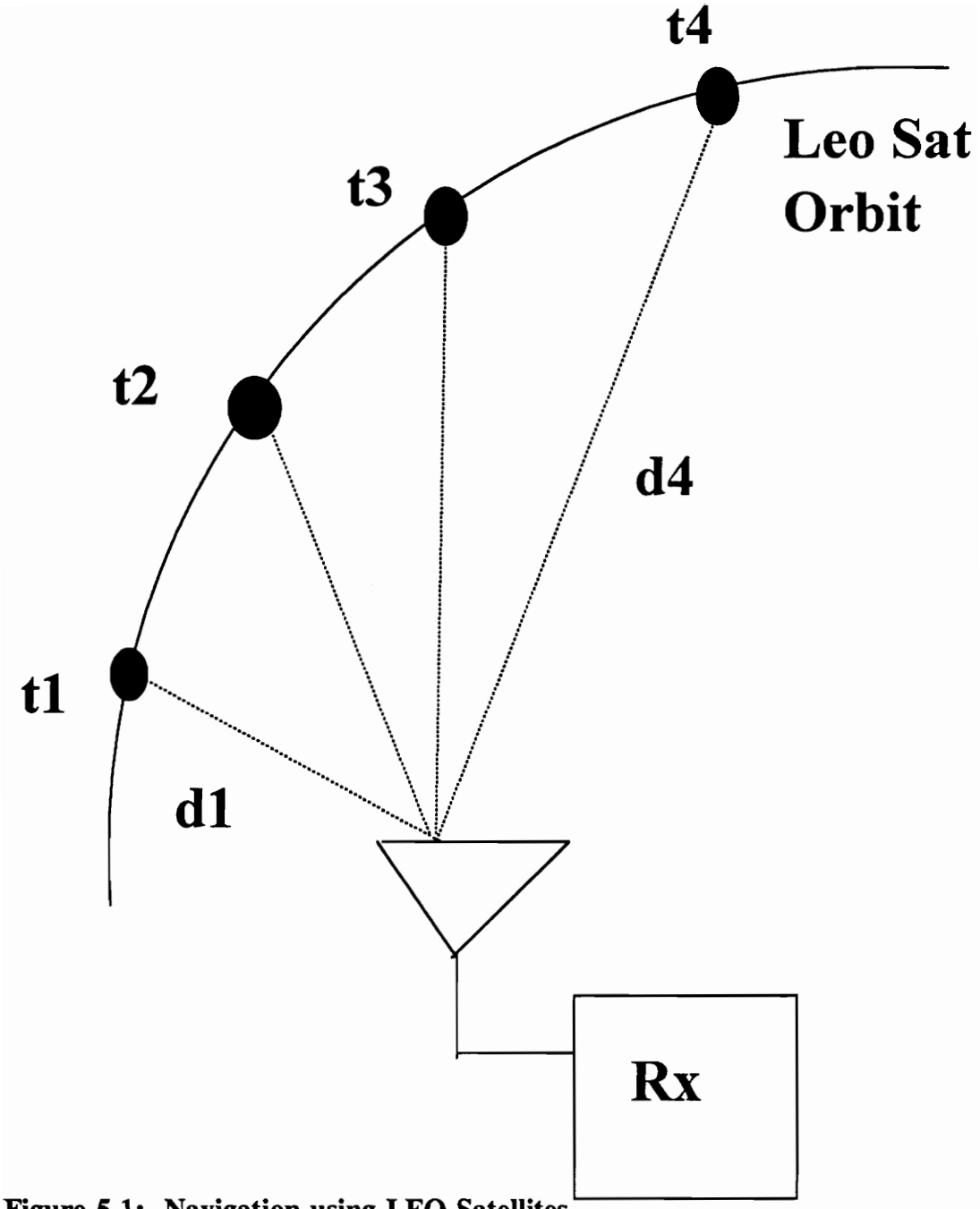


Figure 5.1: Navigation using LEO Satellites

The data packet primarily contains information of the time of transmission, the position of the satellite at the time of transmission and the coefficients of the polynomial used for synchronizing the satellite's clock with a reference clock. The receiver computes the time taken for the signal to reach the receiver and uses it to measure the range. The measured range is called pseudo-range as it is not the true range. The variation of the pseudo-range from the true range is dependent on the variation of the receiver's clock with respect to the reference clock and also on the time delays that are introduced due to the ionosphere and the troposphere.

The true range is extracted from the pseudo-range by compensating for the ionospheric delay, the tropospheric delay and measuring the range to various satellites to remove the receiver's clock bias. The position of the satellite at the time of transmission can be computed from the orbital parameters broadcast by the satellite. By knowing the range to four different satellites and their position in orbit, the position of the receiver can be calculated. The working of the proposed navigation system is very similar to the GPS. The only difference is, that instead of modulating the carrier with a pseudo-random noise sequence and then further modulating it with the broadcast data message (GPS), the carrier is directly modulated with the broadcast data message.

Section 1.3 showed that a traditional binary phase shift keyed receiver cannot be used for position location applications as it has an inherent range error of 625 meters. By

incorporating an additional correlator after the IF bandpass filter, this inherent range error can be reduced to around 60 meters. Figure 5.2 shows the architecture of the modified binary phase shift keyed receiver. The working of this receiver is as follows: The received signal is down converted twice to get the baseband signal. The baseband signal is passed through a BPSK data demodulator to get the data stream. This data stream is passed through a sync word correlator that looks for the Barker sequence header. After the first down conversion, the IF signal is continuously recorded in a first in first out memory buffer. As soon as the sync word correlator detects the Barker sequence header it freezes the memory buffer and simultaneously records the initial time of arrival. If this time of arrival was used to compute the range to the satellite, then the measured range would have had an inherent range error of 625 meters. At this time we are sure that the memory buffer contains the IF waveform corresponding to the Barker sequence header. By correlating the received IF waveform with a locally generated waveform of the data packet header we can correct the initial time of arrival. The time taken to align both the waveforms perfectly is subtracted from the initial time of arrival to give the corrected time of arrival of the signal at the receiver.

5.2 Binary Phase Shift Keying

In binary phase shift keying the phase of the carrier signal is alternated between two values $\{0, \pi\}$ depending on the input data sequence. If the input is a binary 1, then the binary phase shift keyed waveform is represented by

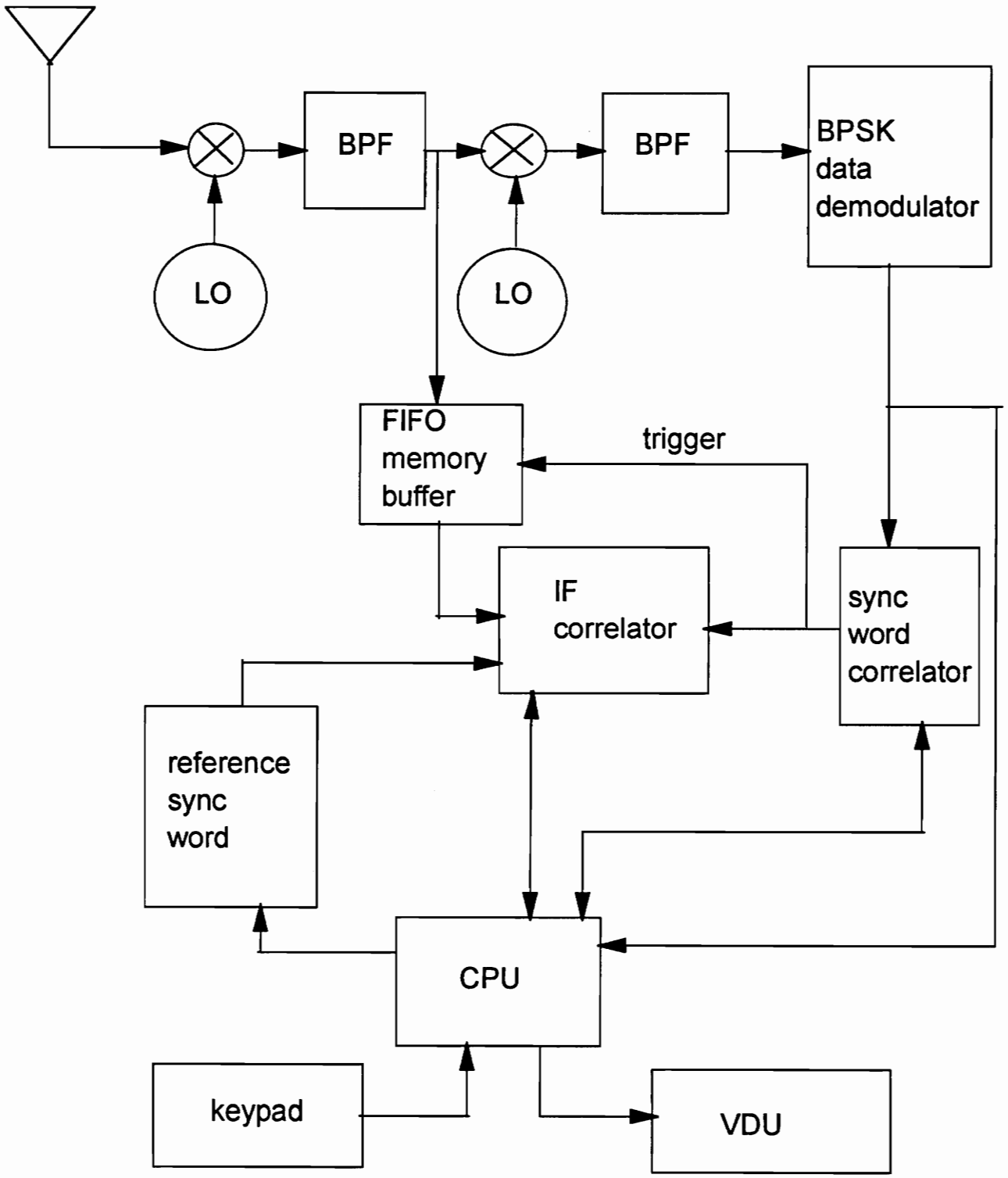


Figure 5.2: BPSK Receiver with an IF Correlator

$$Y_1(t) = A\cos(\omega_c t)$$

if the input is binary 0 then it changes to

$$Y_0(t) = A\cos(\omega_c t + \pi) = -A\cos(\omega_c t)$$

Hence, for transmitting a bit sequence 1010 at 4800 bits per second the transmitter transmits $Y_1(t)$ for 208.33 μsecs then transmits $Y_0(t)$ for 208.33 μsecs then transmits $Y_1(t)$ for 208.33 μsecs and then transmits $Y_0(t)$ for 208.33 μsecs, where 208.33 μsecs is the bit period. When the receiver receives $Y_0(t)$ for 208.33 μsecs it knows that a binary zero has been received and when a $Y_1(t)$ for 208.33 μsecs is received it knows that a binary one has been received. In order to detect that a 1010 sequence has been received it correlates the received bit sequence with 1010 and gets a maximum correlation peak when the received bit sequence is also 1010. This is the conventional method of correlation. Now instead of correlating bit by bit, if we sample the receiver's IF waveform during a bit period and correlate the received samples with the expected samples can we reduce the minimum range error? The aim of this thesis is to investigate this through simulation.

5.3 Correlation

The correlation between waveforms can be defined as the measure of similarity between the waveforms [26][34]. The correlation (average cross correlation) between two waveforms $x_1(t)$ and $x_2(t)$ is given by

$$R_{12}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} x1(t)x2(t+\tau)dt$$

If $x_1(t)$ and $x_2(t)$ are periodic with the same fundamental period T_0 then

$$R_{12}(\tau) = \frac{1}{T_0} \int_{-\frac{T_0}{2}}^{\frac{T_0}{2}} x_1(t)x_2(t+\tau)dt$$

The correlation of a waveform with itself is known as autocorrelation. If $x_1(t) = x_2(t)$ then the autocorrelation is given by

$$R(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} x_1(t)x_1(t+\tau)dt$$

In case of digital bit streams the crosscorrelation of two digital sequences f_i and g_j is given by

$$R_{ij}(\tau) = \sum_{\tau=-T}^{\tau=T} f_i \, g_{(j+\tau)}$$

and if $f_i = g_j$ then the autocorrelation is given by

$$R_{ii}(\tau) = \sum_{\tau=-T}^{\tau=T} f_i \, f_{(i+\tau)}$$

The autocorrelation of the 7 bit Barker sequence {1110010} is given by

R(0) = (1*1) + (1*1) + (1*1) + (-1*-1) + (-1*-1) + (1*1) + (-1*-1) = 7

$$R(1) = (1*0) + (1*1) + (1*1) + (-1*1) + (-1*-1) + (1*-1) + (-1*1) + (0*-1) = 0$$

Similarly

$R(-1) = R(1) = 0$ $R(-3) = R(3) = 0$ $R(-5) = R(5) = 0$

$R(-2) = R(2) = -1$ $R(-4) = R(4) = -1$ $R(-6) = R(6) = -1$

Figure 5.3 shows the autocorrelation of the 7 bit Barker sequence {1110010} graphically. The Barker sequences are a set of sequences that exhibit very good autocorrelation peaks and very low crosscorrelation peaks and sidelobes. It can be seen that the correlation peak is at R(0) when the two sequences are identical. Similarly the crosscorrelation of bit sequence {110} with {001101}, shown in Figure 5.4, is given by

$R(0) = -3$ $R(2) = 1$ $R(-1) = -1$ $R(-3) = -1$ $R(-5) = 1$

$R(1) = 0$ $R(3) = R(4) = R(5) = 0$ $R(-2) = 3$ $R(-4) = 0$ $R(-6) = 0$

it can be seen that the correlation peak is at R(-2).

5.4 IF Correlation

The aim of this thesis is to show that by adding an additional correlator after the IF bandpass filter the inherent range error of 625 meters can be reduced. The IF correlator can be either analog or digital. The analog correlator is comprised only of a SAW device whose output is a measure of the correlation between the two signals [29][30], whereas the digital correlator needs additional circuitry for analog to digital (A/D) conversion,

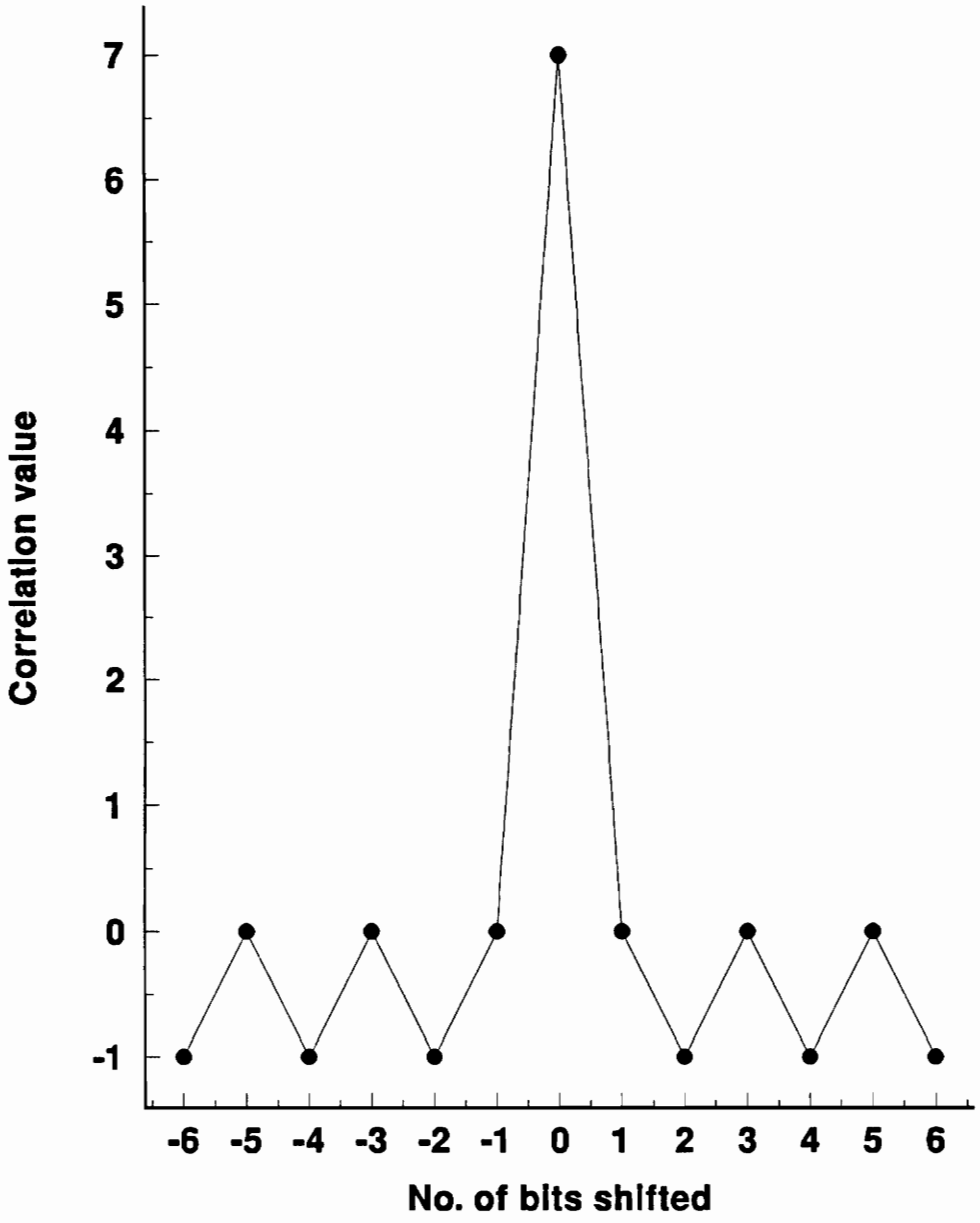


Figure 5.3: Autocorrelation of a Barker 7 sequence

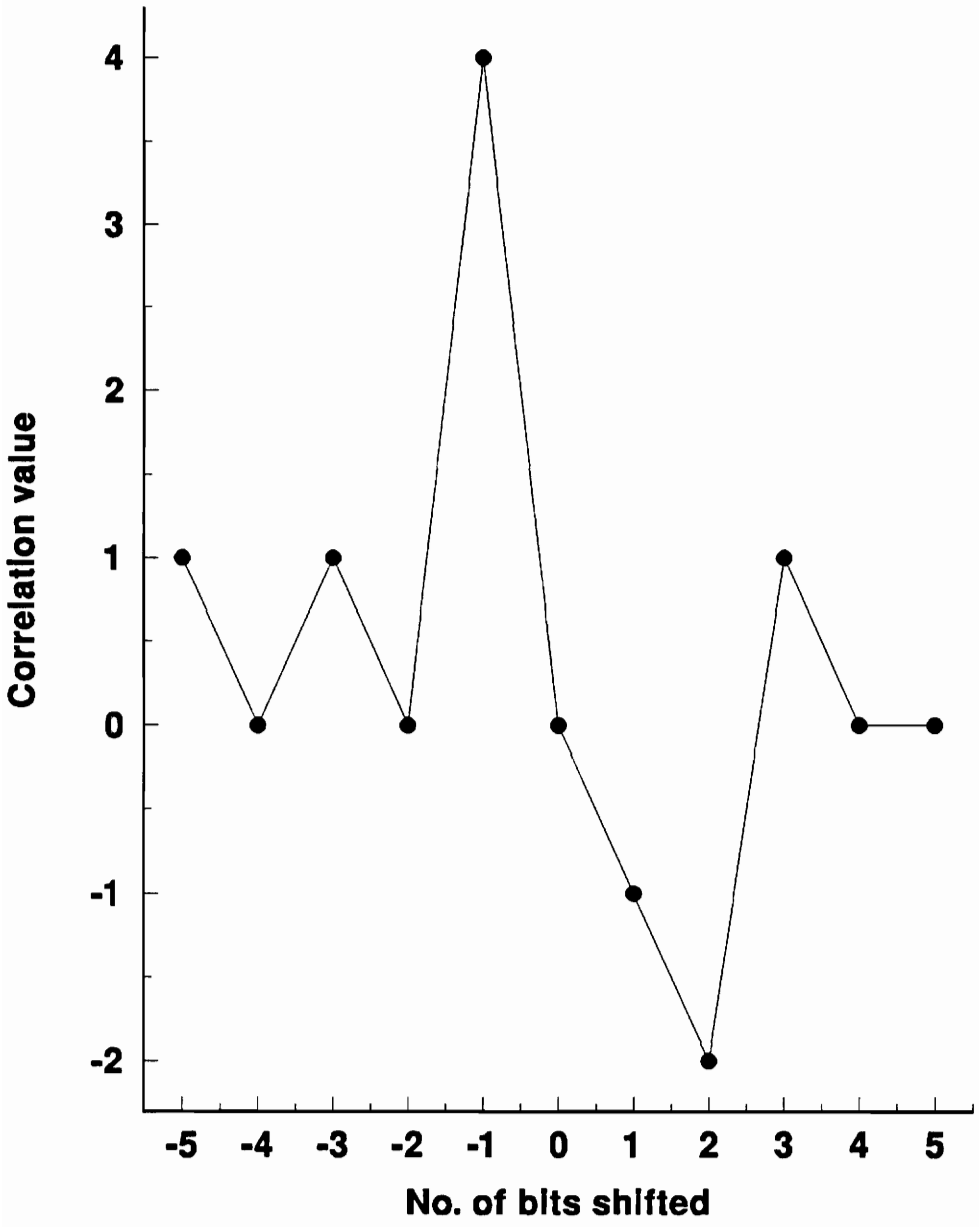


Figure 5.4: Crosscorrelation of {1110} sequence with {011101} sequence

memory for storing the digital values, logic for implementing the correlation function and logic for accepting less than perfect correlation.

In analog correlation, both the received signal and the expected reference signal is passed through an analog correlator (SAW memory correlator or a SAW matched filter), whereas in digital correlation the received signal and the expected reference signal are digitized and then passed through a digital correlator (adder tree correlator) [31].

SAW correlators have been used in radars for a very long time to improve the range resolution of the radars [27][28]. A SAW memory correlator or SAW matched filter is a device which sequentially compares an input signal waveform with a local reference waveform. Convolution of two signals f_1 (t) and f_2(t) is given by

$$f(t) = f_1(t) * f_2(t) = \int_{-\infty}^{+\infty} f_1(\tau)\, f_2(t-\tau)\, d\tau$$

Autocorrelation of two signals f_1 (t) and f_2(t) is given by

Cross

$$R(\tau) = \int_{-\infty}^{+\infty} f_1(\tau) f_2(t+\tau)\, dt$$

From the above two equations it can be seen that time reversal of one signal and its convolution with the other is equivalent to crosscorrelating the two waveforms. So a matched filter can be used as a correlator.

Figure 5.5 shows a SAW matched filter and Figure 5.6 shows a SAW memory correlator. The SAW matched filter has two input ports and one output port. Both the inputs have to be applied simultaneously. In order to make it behave like a correlator the reference signal is applied after time reversal. The level at the output is a measure of the correlation between the two signals. The SAW memory correlator has only one input port and one output port. The input signal and the reference signal are applied sequentially to the input port (the reference signal is applied directly and not after time reversal). The SAW wave generated by the input signal propagates under a diode array on the surface of the piezoelectric substrate. A trigger is used to map the input signal waveform level onto the diode array by charging the diode array. The reference waveform is then applied to the input port. The resultant potential across the diode array is proportional to the product of the two waveforms. The sum of the outputs across the diode array is a measure of the degree of crosscorrelation.

A digital correlator [31] is shown in Figure 5.7. This correlator is implemented using the Adder-Tree Method. The input serial data is passed through a shift register. The Q and $\bar{Q}$ of the individual flip flops are selected in such a manner that they will all be 1's when the correct sequence appears.

The correlation process can be easily implemented using an analog correlator, but can it be implemented digitally?

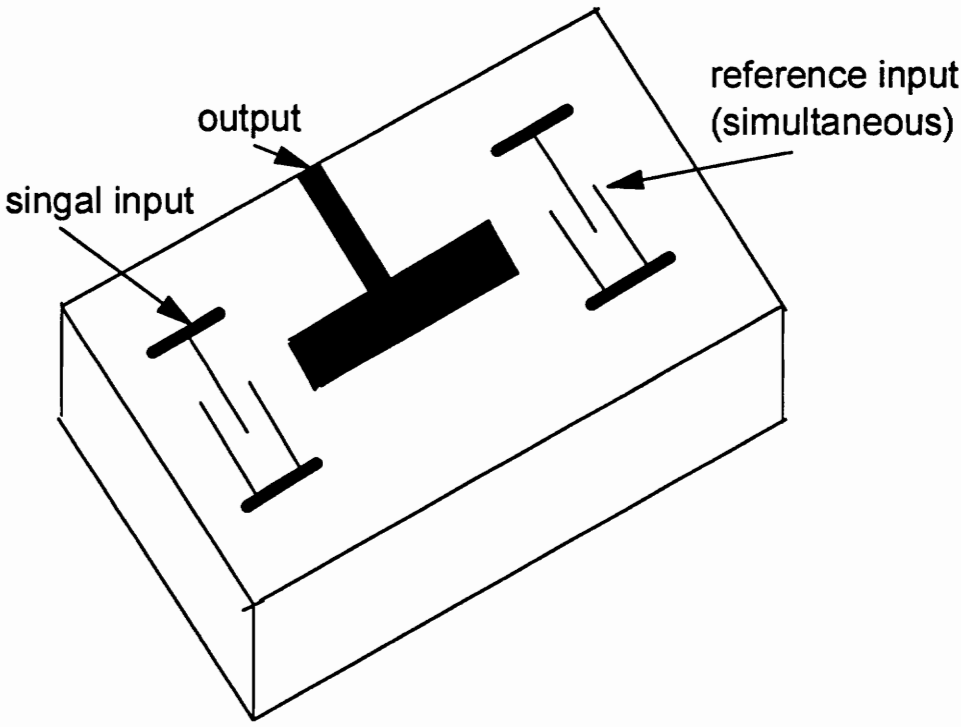


Figure 5.5: A SAW Matched Filter

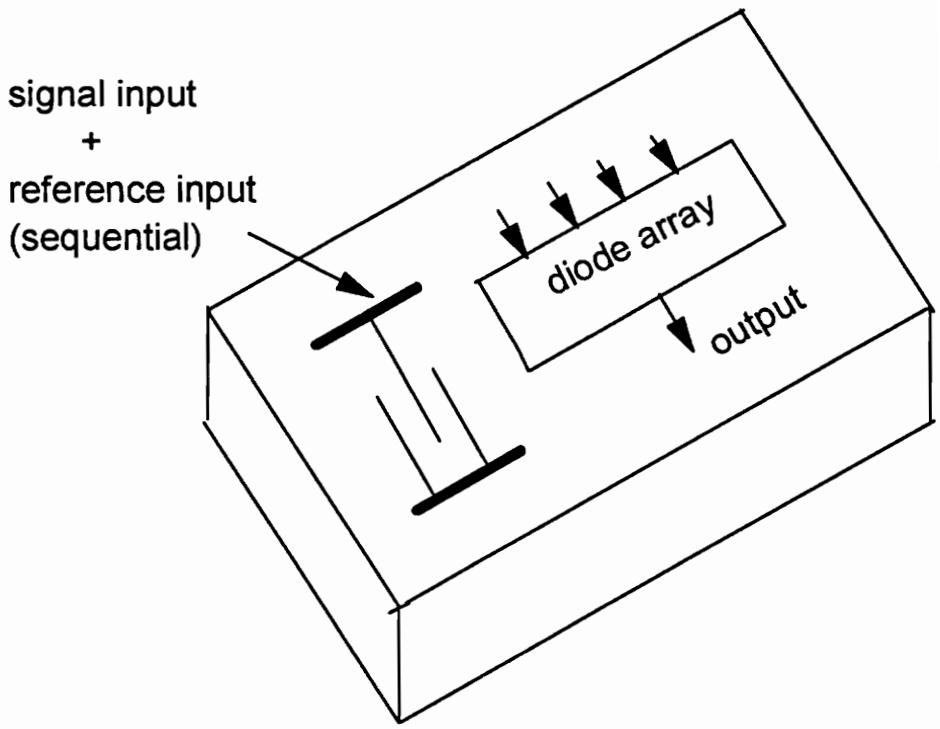


Figure 5.6: A SAW Memory Correlator

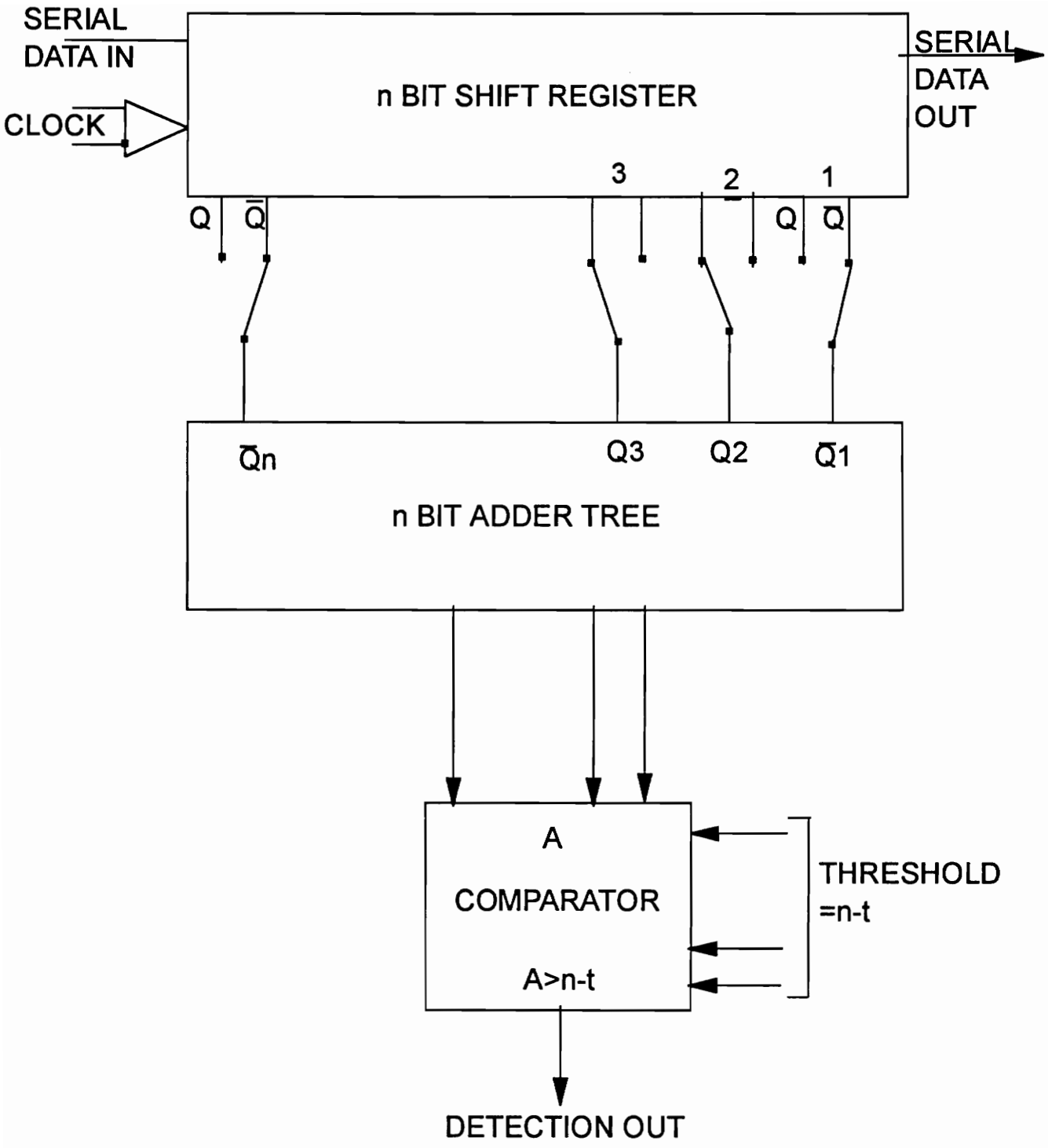


Figure 5.7: An Adder Tree Digital Correlator [31]

The fundamental principle behind correlation is using sequences that have very good autocorrelation peaks and very low crosscorrelation peaks (sidelobes). In order to implement the correlation function digitally the analog IF waveform has to be sampled and quantized. The process of quantization is done by coding each sample into an 8 bit code-word depending on its value. After quantization the digital samples no longer have the autocorrelation and crosscorrelation properties exhibited by the analog waveform. When the digital correlation process was simulated, the correlation peak could not be found successfully and the resultant range errors were of the order of tens of kilometers. So a digital correlator cannot be used as an IF correlator.

5.5 Data Packet Characteristics

The navigation satellites broadcast an information packet at regular intervals of time. The contents of the information packet, when decoded, gives the time of transmission, the current orbital parameters of the satellite, the clock variations and other allied data required by the receiver to determine its position accurately. The information packet comprises of many frames with the first frame being designated as the master frame. Each frame has a synchronization header followed by a fixed pattern of data fields. The synchronization header of the master frame is different from that of the other frames of the information packet. The arrival of the information packet is detected by correlating a received sequence with an expected reference sequence (the master frame synchronization header). Since, detection of the arrival of the information packet is based

on the correlation properties of the master frame synchronization header, the synchronization header should be selected in such a manner that its crosscorrelation with other sequences is minimum and its autocorrelation with its own replica is a maximum. Minimizing the crosscorrelation output is not enough; the sidelobes due to crosscorrelation should be minimized so as to prevent false synchronization on the sidelobes.

One such set of sequences, which exhibits a high autocorrelation peak, low crosscorrelation sidelobes and low crosscorrelation with other sequences, is the Barker sequence [31]. There are only eight known Barker code sequences and the maximum known Barker sequence length is 13. The known Barker Sequences are

Length	Sequence
2	1 1
3	1 1 0
4	1 1 1 0
4	1 1 0 1
5	1 1 1 0 1
7	1 1 1 0 0 1 0
11	1 1 1 0 0 0 1 0 0 1 0
13	1 1 1 1 1 0 0 1 1 0 1 0 1

Figure 5.8 shows the autocorrelation property of a Barker 13 sequence. Other synchronization codes like the Maury-Styles Sequence [31][32] and Lindner Sequence [31][33] can also be used. The simulation reported here uses a Barker 5 or Barker 7 sequence for header synchronization.

5.6 Simulation Algorithm

This thesis verifies the feasibility of a binary phase shift keyed receiver with an analog IF correlator for position location using software simulations. The following software models were developed: a BPSK transmitter, a white gaussian noise generator, an analog to sample converter, an impulsive noise generator, an analog correlator, and a range error determination unit. The transmitter generates a raised cosine binary phase shift keyed waveform of the input binary bit sequence. A bit rate of 4800 bits per second and a roll-off factor of 0.5 was used for simulation. The raised cosine binary phase shift keyed waveform is then passed through a white gaussian noise generator. Two extreme values of IF signal to noise ratio, (+5 dB and -8 dB) were selected to verify the effect of signal to noise ratio. The amplitude of the waveform and the variance of the white gaussian noise was set depending on the IF signal to noise ratio selected. The noise generator used the Box-Muller method to generate the white gaussian noise having a set variance. The Box-Muller method uses two uniform random variables, u_1 and u_2, having zero mean and unity variance and generates two zero mean and sigma variance gaussian random variables, g_1 and g_2, using the following transformation

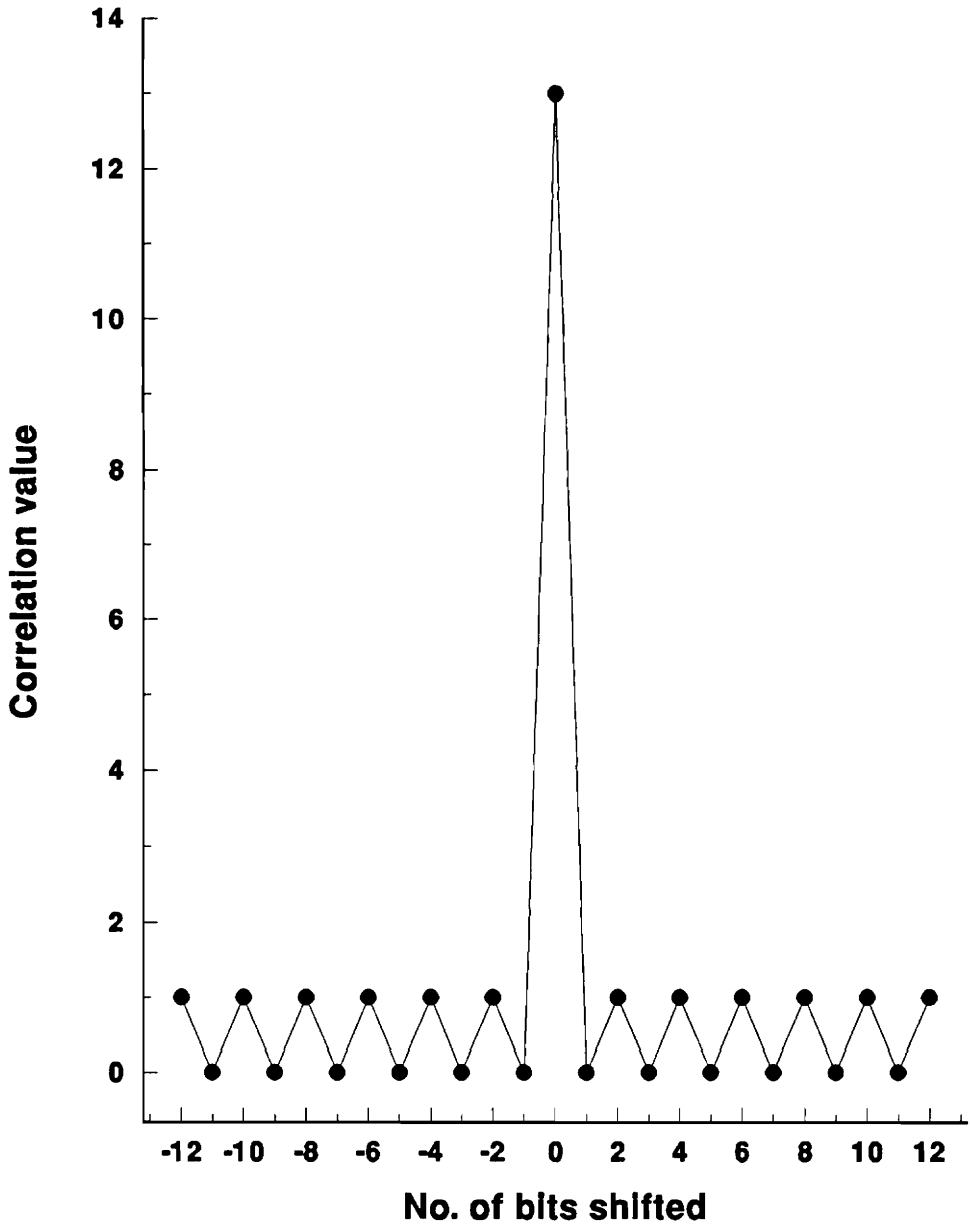


Figure 5.8: Autocorrelation of a Barker 13 Sequence

$$g_1 = \sqrt{-2\ln(u_1)\,\sigma^2}\cos(2\pi u_2)$$

and

$$g_2 = \sqrt{-2\ln(u_1)\,\sigma^2}\sin(2\pi u_2)$$

The analog to sample converter is used to store the IF waveform as samples. The IF waveform can be sampled at twice the IF, three times the IF, four times the IF, or five times the IF. This feature was implemented to verify the effect of the IF waveform sampling rate on range error. The output of the analog to sample converter can be passed, if needed, through an impulsive noise generator. The impulsive noise generator will corrupt a specified number of samples from a random location in the sample stream. The corrupted samples will have a value of + or - twice the carrier signal amplitude. The effect of impulsive noise on range error can be simulated using this unit.

The output of the impulsive noise generator is passed through an analog correlator. This unit does an analog sample to sample correlation on the input with a stored uncorrupted reference sample stream having the same signal to noise ratio as the received sample stream. The reference sample stream is not passed through the impulsive noise generator. In order to simplify the simulation the memory buffer length is set to (n+2) bits, where n is 5 or 7 bits depending on whether a Barker 5 or Barker 7 sequence was used. The arrangement of the (n+2) bit sequence is as follows {0, Barker sequence, 0}, {0, Barker sequence, 1}, {1, Barker sequence, 0} and {1, Barker Sequence, 1}. All of the four

combination sequences were used during the simulations. The output of the analog correlator is passed through the range error determination unit. This unit compares the simulated correlation peak position with the actual correlation peak position and calculates the range error due to correlation. The range errors will be discrete values as the input parameters are discrete sample values dependent on the IF sampling rate selected.

The algorithm for measuring range errors due to correlation is as follows:

1. Select an Intermediate Frequency, eg. 455 KHz or 1 MHz.

2. Select a Barker Sequence, eg. Barker 5 or Barker 7.

3. Select a sampling rate, eg. twice, thrice, or five times the IF.

4. Select the required signal to noise ratio and then set the carrier amplitude and noise variance.

6. Select the transmission bit rate and the roll-off factor $\tilde{\alpha}$.

5. Generate a raised cosine binary phase shift keyed waveform for the barker sequence selected using the appropriate parameters (synchronization header).

6. Pass the waveform through the white gaussian noise generator so that the reference sequence has the selected signal to noise ratio.

7. Generate various combinations of the received raised cosine binary phase shift keyed waveform which contain the synchronization header in it.

8. Pass the received waveform through the white gaussian noise generator so that the

received sequence has the selected signal to noise ratio.

9. Pass the reference waveform and the received waveform through the analog to sample converter which samples the waveforms with the selected sampling rate.

10. Pass the received sample sequence through the impulsive noise generator and set the number of samples to be corrupted.

11. Pass the reference waveform and the output of the impulsive noise generator through the analog sample by sample correlator.

12. Pass the output of the correlator through the range error determination unit.

13. Repeat 1 to 12 many times.

5.7 Conclusion

The effect of the following parameters on range error was simulated:

1. Effect of sampling rate.

2. Effect of higher intermediate frequency.

3. Effect of IF signal to noise ratio.

4. Effect of impulsive noise.

5. Effect of Doppler.

6. Effect of non integer multiple sampling.

The effect of Doppler can be simulated by adding the doppler shift to the intermediate frequency selected and using this as the IF frequency of received waveform. The effect of non integer multiple sampling is also similar to the doppler effect case.

Chapter 6

Simulation Results

6.1 Introduction

The results of simulations performed to investigate the feasibility of a binary phase shift keyed receiver with an analog IF correlator is presented below. A part of the investigations were devoted to test the feasibility of using a digital IF correlator instead of an analog IF correlator. The investigations proved that the usage of a digital correlator was not feasible as the correlation properties of the synchronization word were not preserved by the digitizer.

The output of the binary phase shift keyed receiver's data demodulator is fed to the synchronization word correlator (bit by bit digital correlator). This correlator can only maintain the correlation peaks with an accuracy of about 1% of the bit period. This is equivalent to having a receiver which has an inherent range error of 625 meters. In order to reduce this inherent range error the following technique is used.

1. Digitize (A/D operation) the reference waveform and store it.
2. Digitize the received IF waveform after the IF bandpass filter and store it in a first in first out memory buffer.
3. When the sync word correlator (after the binary phase shift keyed data demodulator)

detects the synchronization word, record the time of arrival, t_1, and freeze the memory buffer.

3. Pass the stored reference waveform and the contents of the memory buffer through a D/A converter to get the original waveforms. These waveforms are then passed through the SAW memory correlator and the correlation outputs are obtained.

4. Find the correlation peak and record the number of time shifts, n, required to align the reference waveform with the received waveform.

5. Subtract an interval corresponding to the number of time shifts to get the final time of arrival, $t_2 = t_1 - n$.

6. Let t_3 be the actual time of arrival. Let $t_4 = (t_3 - t_2)$. The timing error due to correlation is given by t_4.

7. Range error, $R = ct_4$, where c is the velocity of light.

The reason for using an analog IF correlator is to achieve a better correlation precision than 1% of the bit rate. The analog correlator may also not find the exact correlation position due to variations in signal to noise ratio, data corruption due to impulsive noise etc. Thus, there can be a positive or negative excursion from the actual correlation position. This gives rise to a proportional range error in the calculation of the receiver's coordinates. If we take the actual correlation position as the zero range error line then variations in time of arrival will cause the recorded positions to lie on either side of the zero range error line. An error of 10 nanoseconds will then give a range error of 3

meters. If we consider this error to be an absolute error then we can say that the actual position is within a sphere of radius of 3 meters from the computed point. The simulation reported here uses an absolute range error convention. Figure 6.1 shows the output of an ideal baseband correlator (using a Barker 7 sequence). Figure 6.2 shows the output of an analog sample by sample correlator.

The following parameters have been used for simulation :

1. 455 KHz and 1 MHz as the Intermediate Frequency.
2. Sampling rates of thrice, four times and five times the IF.
3. IF signal to noise ratios of 5 dB and -8dB.
4. Barker 5 and Barker 7 sequences as synchronization words.
5. Broadcast message bit rate of 4800 bits per second.

6.2 Effect of Sampling Rate

The sampling theorem says 'If a time function f(t) contains no frequency components higher than f_m Hz, then f(t) can be completely determined by its values at uniform intervals less than 0.5 f_m seconds apart' [26]. The sampling rates used during simulation are thrice, four times and five times the intermediate frequency. Figures 6.3 and 6.4 shows the effect of sampling rate on range error. It can be seen that the absolute range error decreases when the sampling rate is increased. There is also a marked decrease in the absolute range errors when the signal to noise ratio is higher. In both the cases the

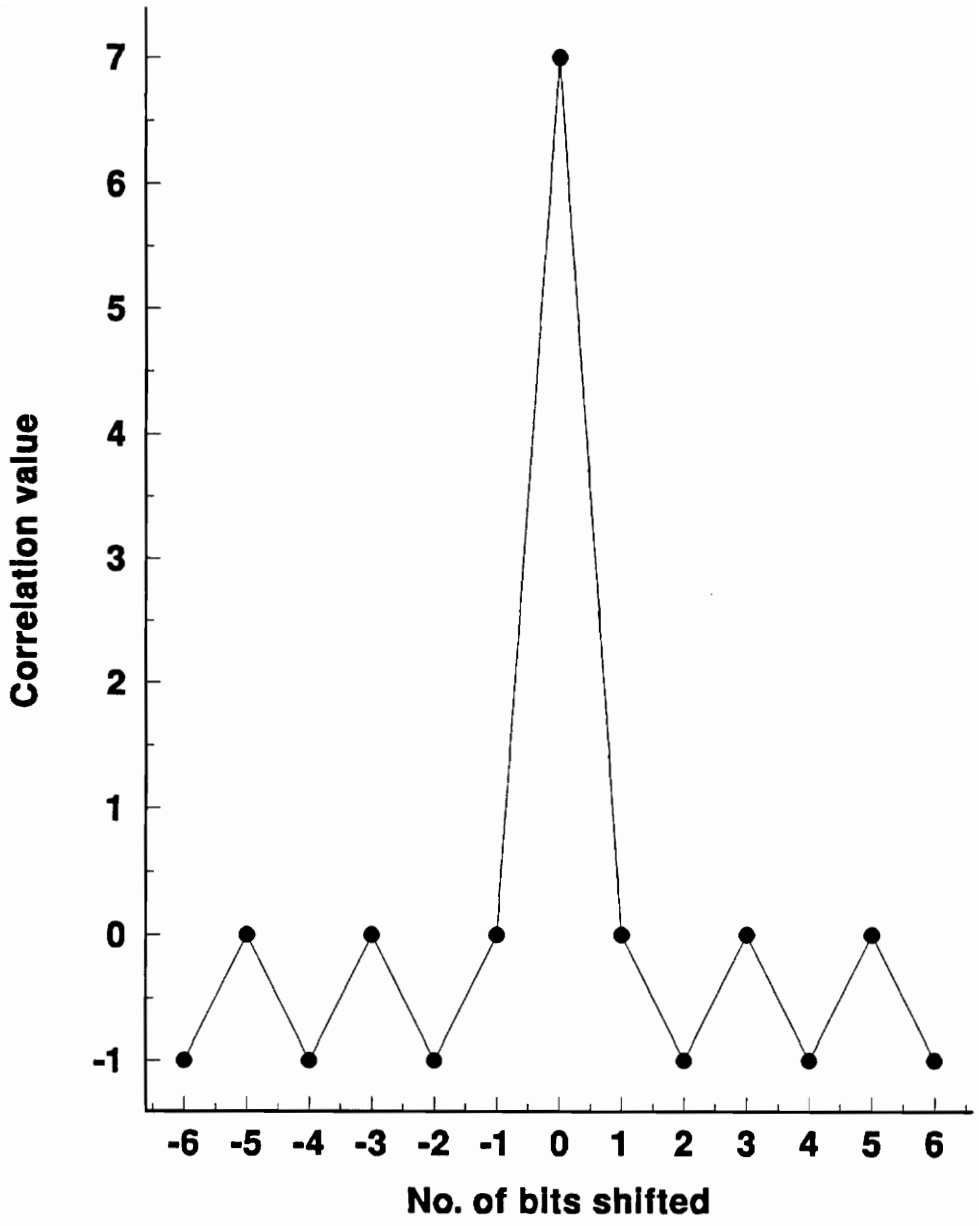


Figure 6.1: Output of a Baseband Correlator

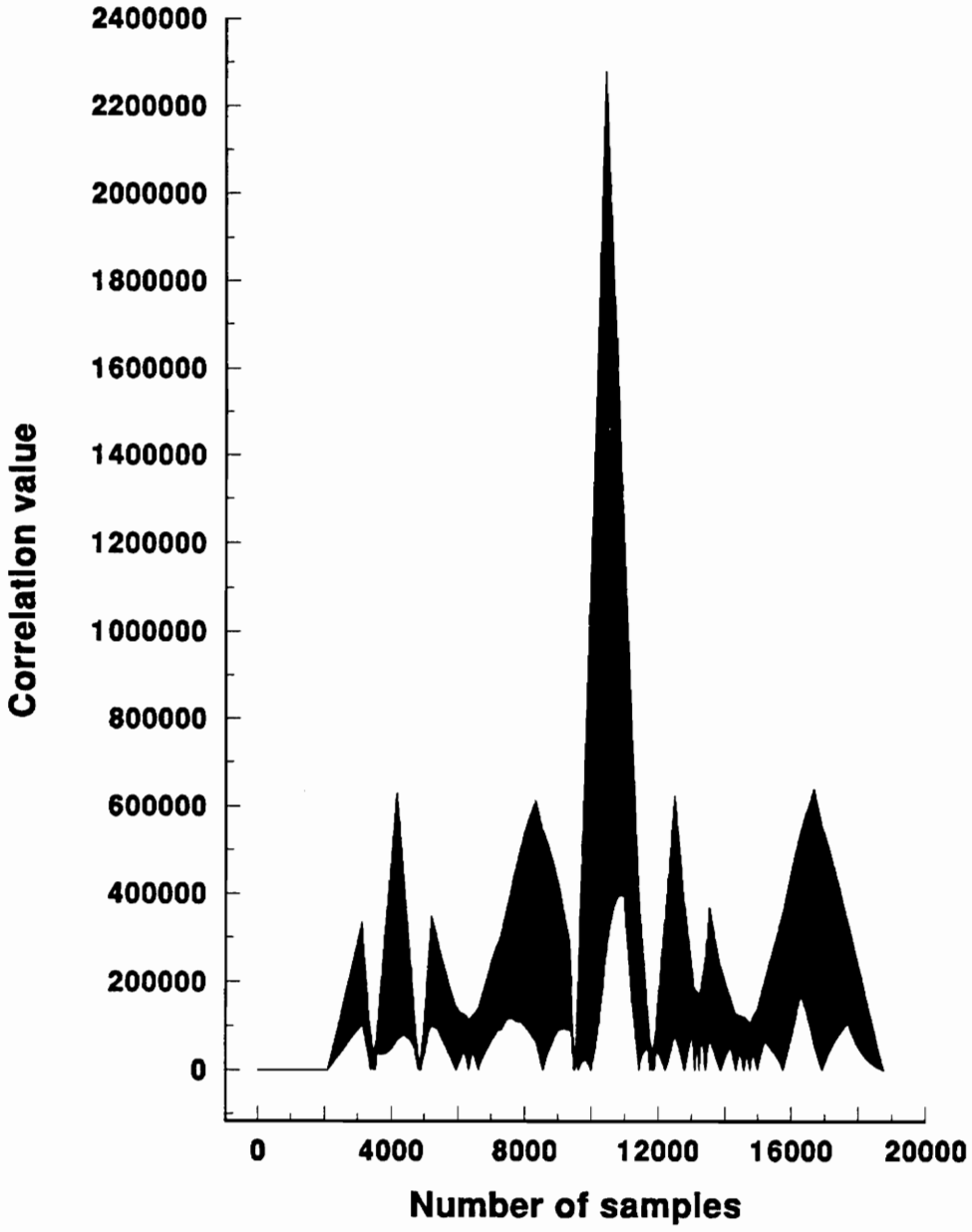


Figure 6.2: Output of an Analog IF Sample by Sample Correlator

average absolute range error reduces from 99 meters to 60 meters as the sampling rate is increased from three time to five times the intermediate frequency.

6.3 Effect of Higher Intermediate Frequency

The effect of using a higher intermediate frequency is equivalent to having a higher sampling rate as the number of samples per bit increases with an increase in the intermediate frequency. There will be 286 samples per bit at 455 KHz and 632 samples per bit at 1 MHz, if the sampling rate is kept constant at three times the intermediate frequency. Figures 6.5 and 6.6 confirms the hypothesis mentioned above. It can be seen that the average range error decreases with an increase in the intermediate frequency.

6.4 Effect Of Higher Signal To Noise Ratio

Figures 6.7 and 6.8 shows the effect of signal to noise ratio on the correlation process. The analog correlator gives a much more accurate measurement of the correlation position at higher signal to noise ratios which results in a more accurate coordinate determination. It can also be seen that having a higher sampling rate in conjunction with a higher signal to noise ratio gives a lower average absolute range error.

6.5 Effect of Impulsive Noise

In real life there is always a possibility that many consecutive samples will get corrupted

due to noise. This type of noise is called impulsive noise. The received sequence is passed through an impulsive noise generator. The impulsive noise generator corrupts a specified number of consecutive samples from a random location in the sequence. The simulation corrupts samples equivalent to 1 or 2 bits from a random place in the sequence. The corrupted samples have a value equal to +/- two times the carrier amplitude. From Figures 6.9 and 6.10 we can see that absolute range error increases with increase in impulsive noise (ie., when more samples are corrupted). But the effect of impulsive noise is also governed by the signal to noise ratio. It can be seen from Figure 6.11 that the average absolute range error is much smaller at higher signal to noise ratios.

6.6 Selection of Intermediate Frequency and Sampling Rate

The above mentioned investigations have shown that the absolute range error can be reduced by increasing the intermediate frequency and the sampling rate. An additional advantage is obtained if the signal to noise ratio is high. Based on the above facts we can select 1 MHz as the standard IF and 5 times sampling as the standard sampling frequency. Figures 6.12, 6.13, 6.14, 6.15, 6.16, and 6.17 shows that a better average absolute range error is obtained at higher signal to noise ratios and higher sampling rates.

6.7 Doppler Effect

Having selected 1 MHz as the standard IF and 5 times IF as the standard sampling rate,

we have to investigate the effect of doppler on absolute range error. The signals broadcast by the low earth orbit navigation satellites undergo a doppler shift due to relative motion of the satellite with respect to the receiver. This effect is similar to having a slightly different IF for the received sequence. If we generate the reference sequence samples at 5 times 1 MHz and the received sequence samples at 5.002 times 1 MHz we can simulate the effect of a 2 kHz doppler shift. Figures 6.18, 6.19, 6.20, and 6.21 simulate the effect of 2 kHz, 4 kHz, -2 kHz, and -4 kHz doppler shift on the received sequence. The doppler effect causes the absolute range error to increase. The doppler shift is a direct function of the relative motion between the satellite and the receiver which is dependent on the altitude. Hence, by selecting a suitable altitude the effect of doppler shift can be minimized. The effect of doppler shift can also be improved by having a higher signal to noise ratio.

6.8 Effect of Non Integer Multiple Sampling

All the investigations performed above used a sampling rate which was an integer multiple of the sampling rate. This section investigates the effect of having a sampling rate which is not an integer multiple of the intermediate frequency. Figures 6.22, 6.23, 6.24, and 6.25 show the effect of a drift of 1 kHz, -1 kHz, -10 kHz and 10 kHz from the standard IF. This is equivalent to having a sampling rate of 5.001 times, 4.999 times, 5.01 times, and 4.99 time the intermediate frequency. The absolute range error increases with increasing drift from the standard IF.

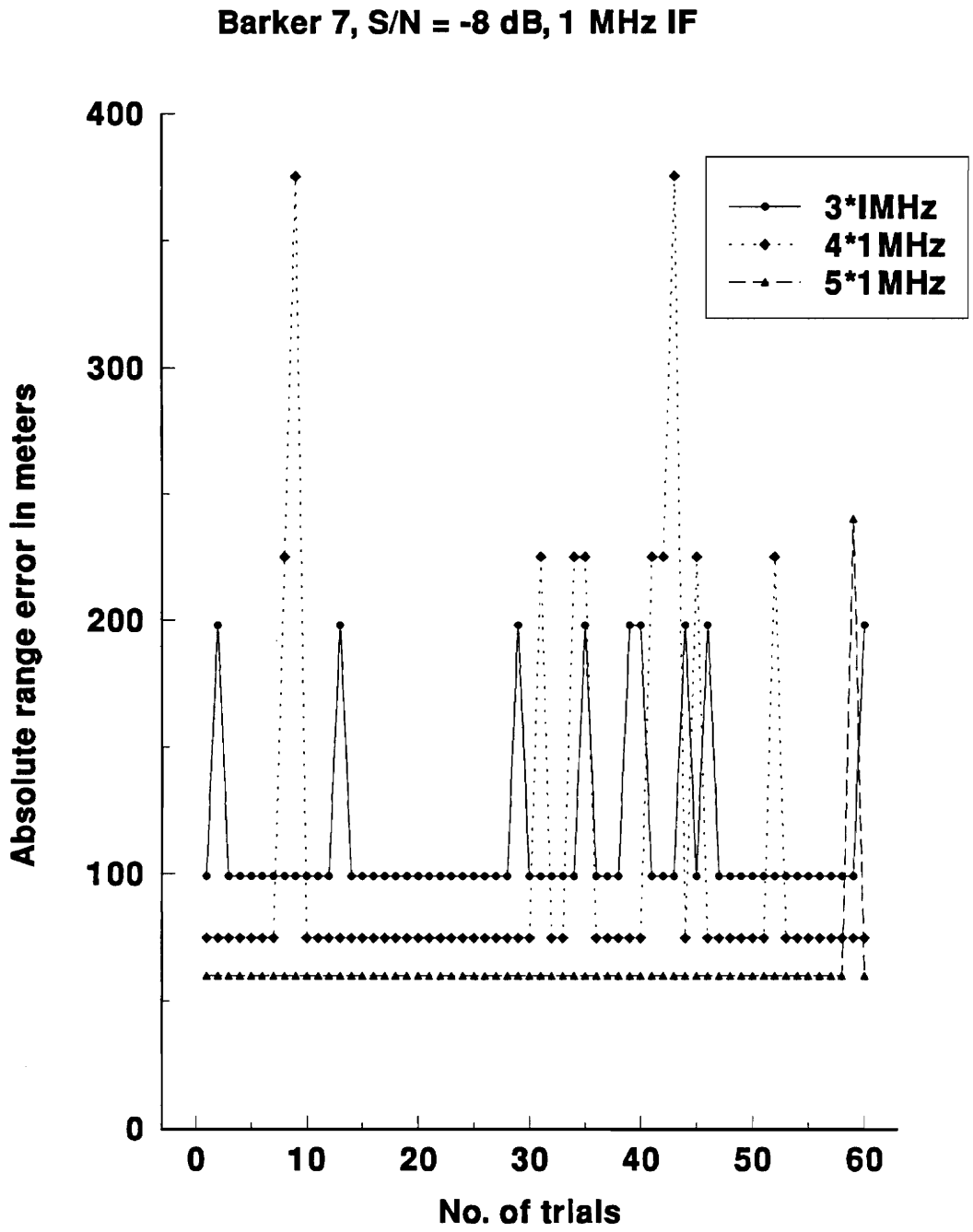


Figure 6.3: Effect of Sampling Rate

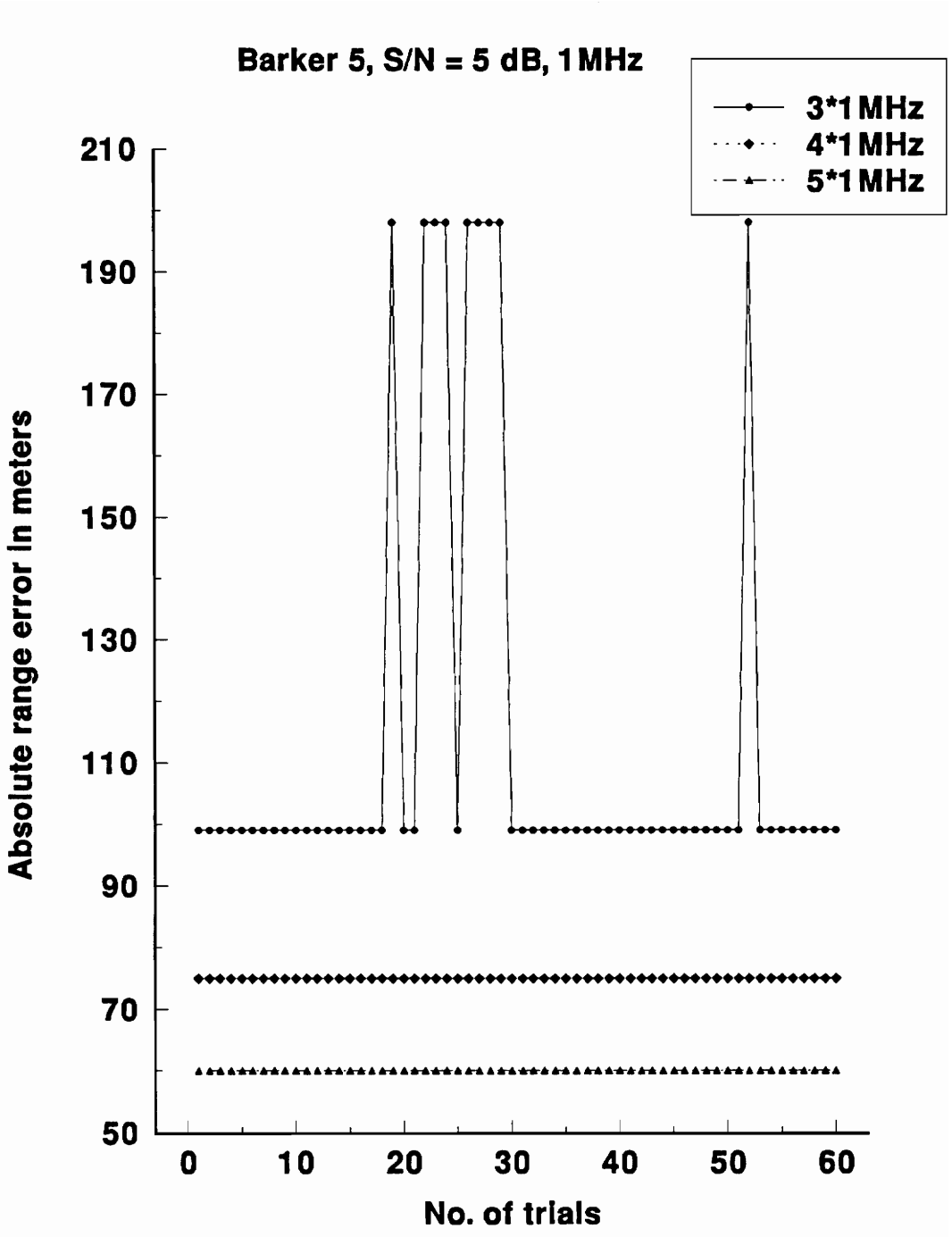


Figure 6.4: Effect of Sampling Rate

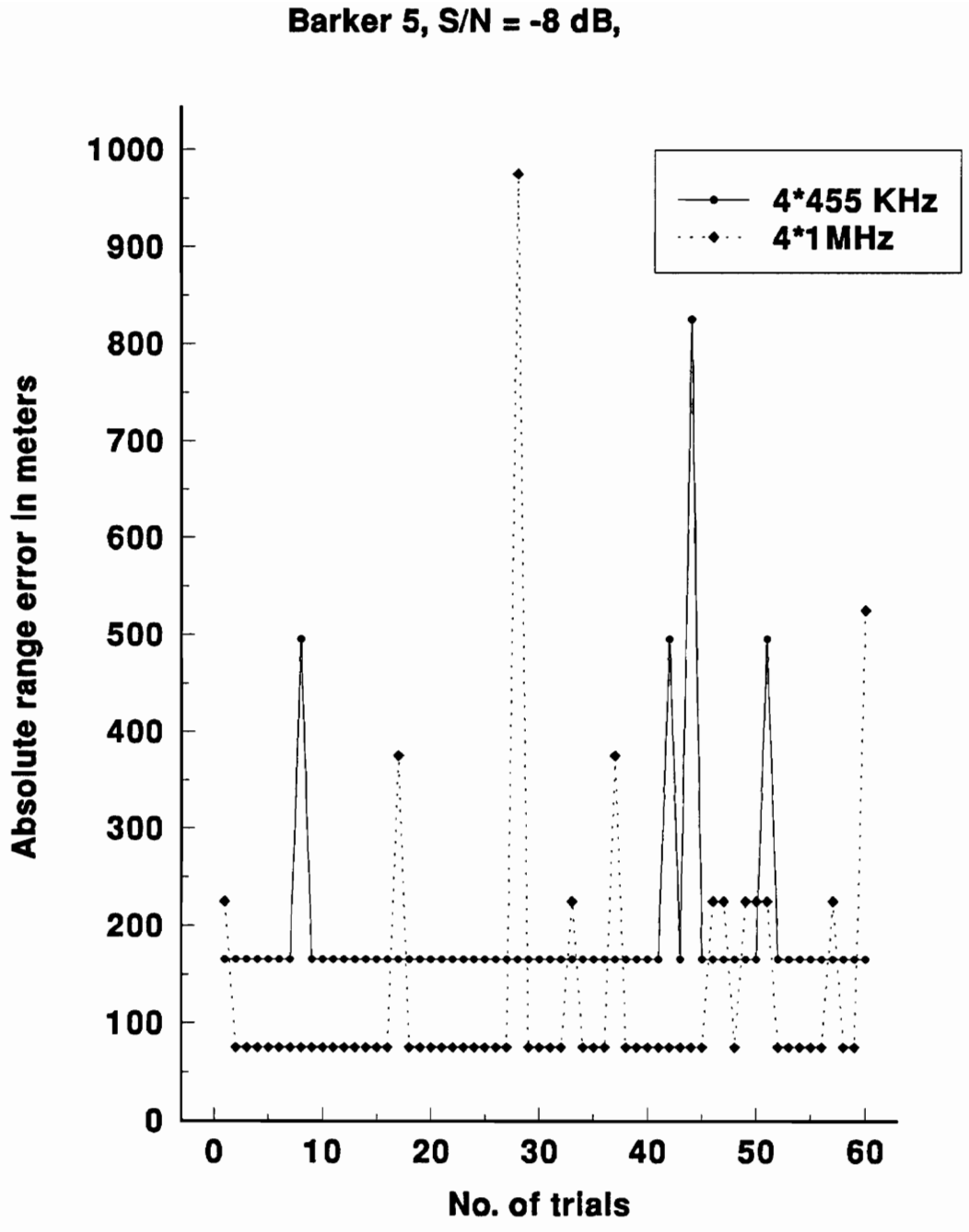


Figure 6.5: Effect of Higher Intermediate Frequency

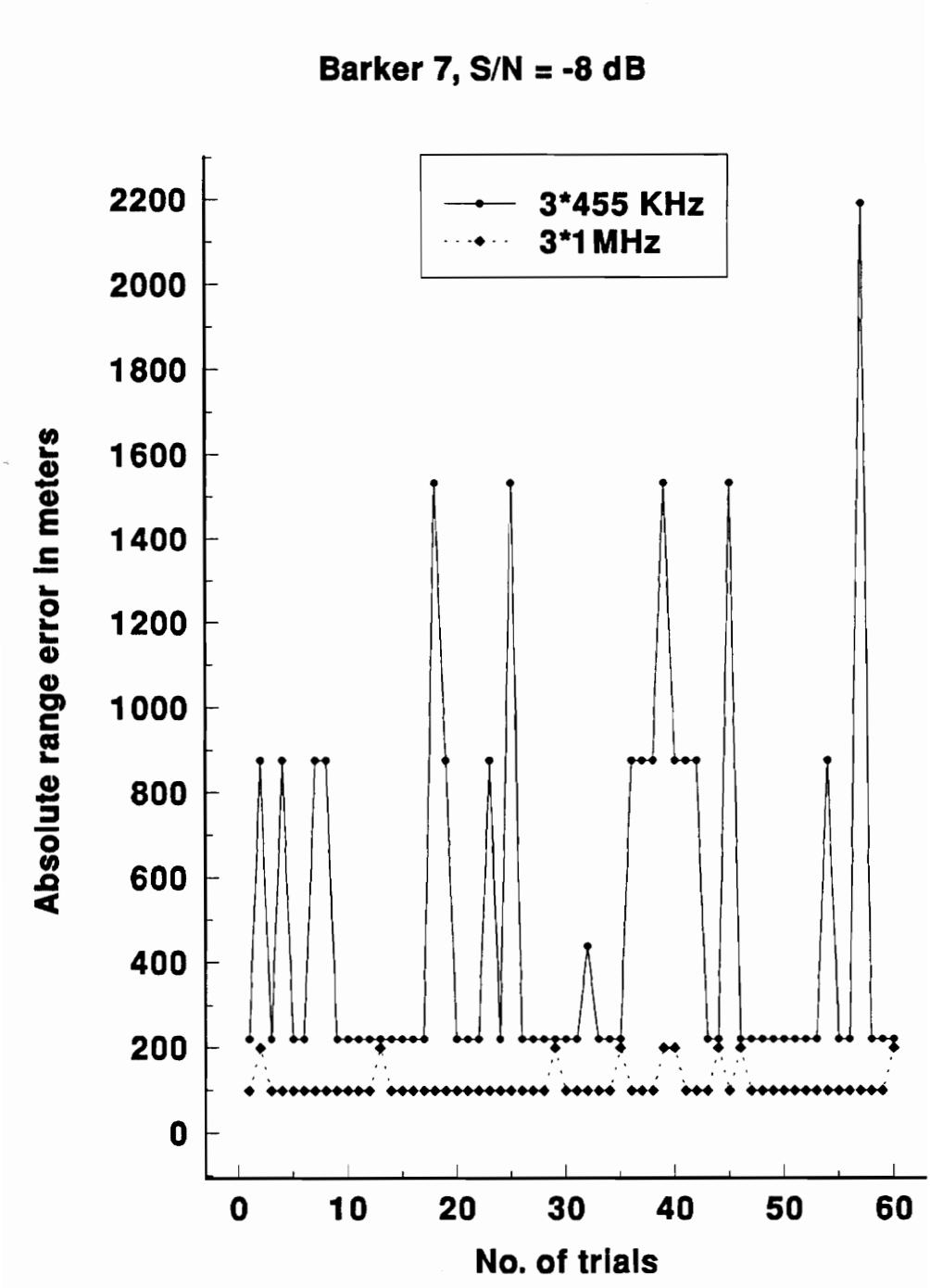


Figure 6.6: Effect of Higher Intermediate Frequency

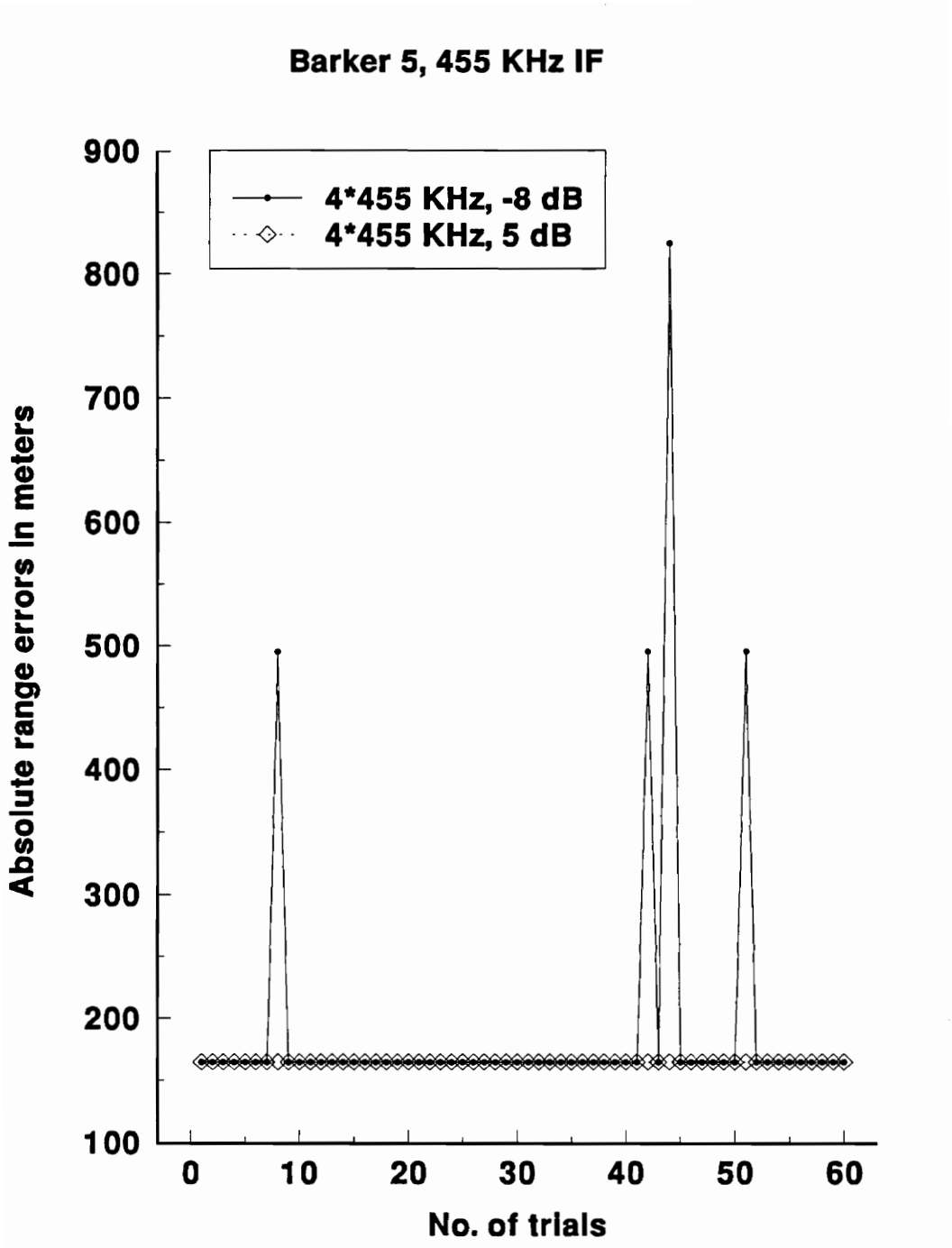


Figure 6.7: Effect of Higher Signal To Noise Ratio

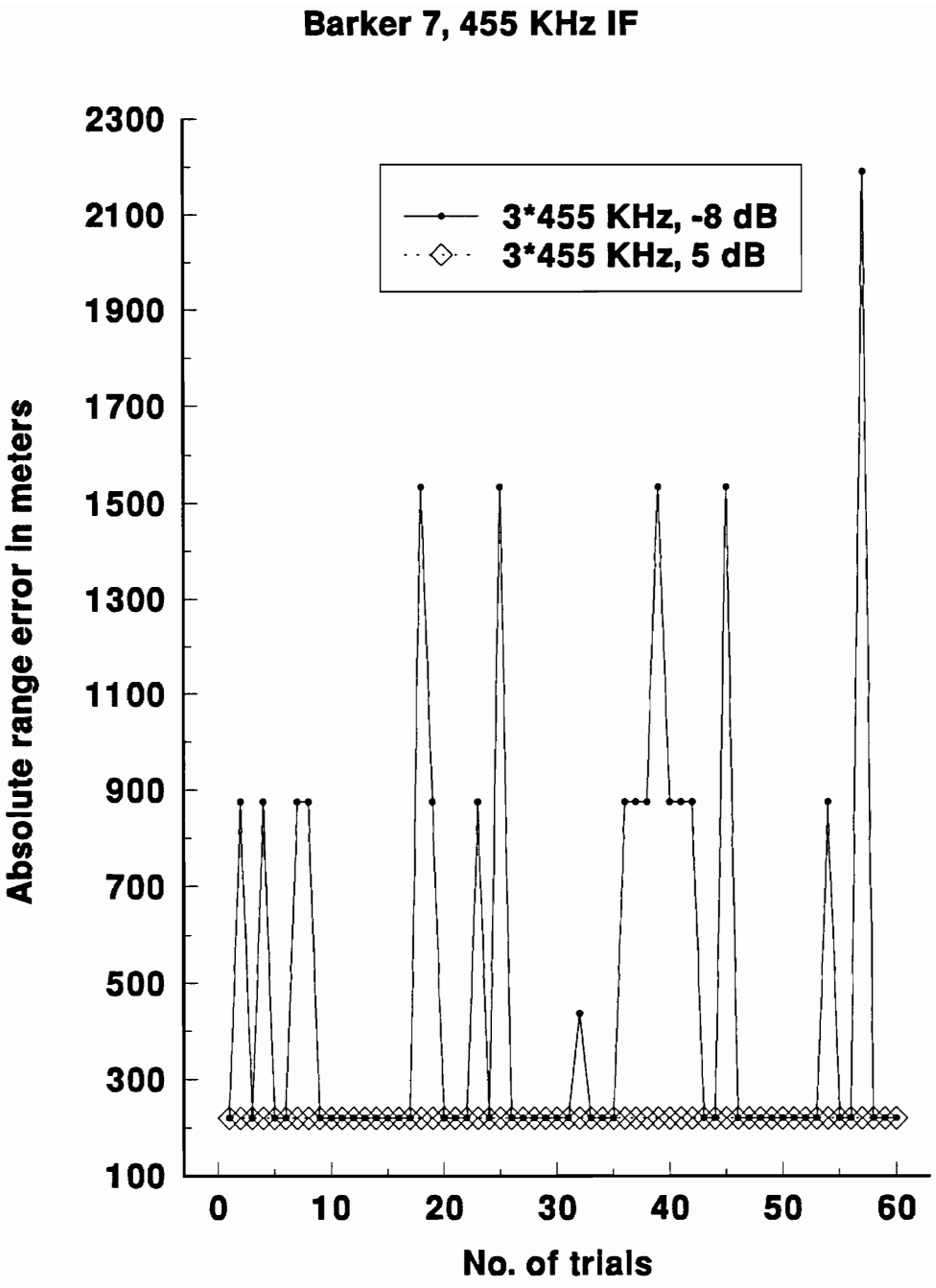


Figure 6.8: Effect of Higher Signal To Noise Ratio

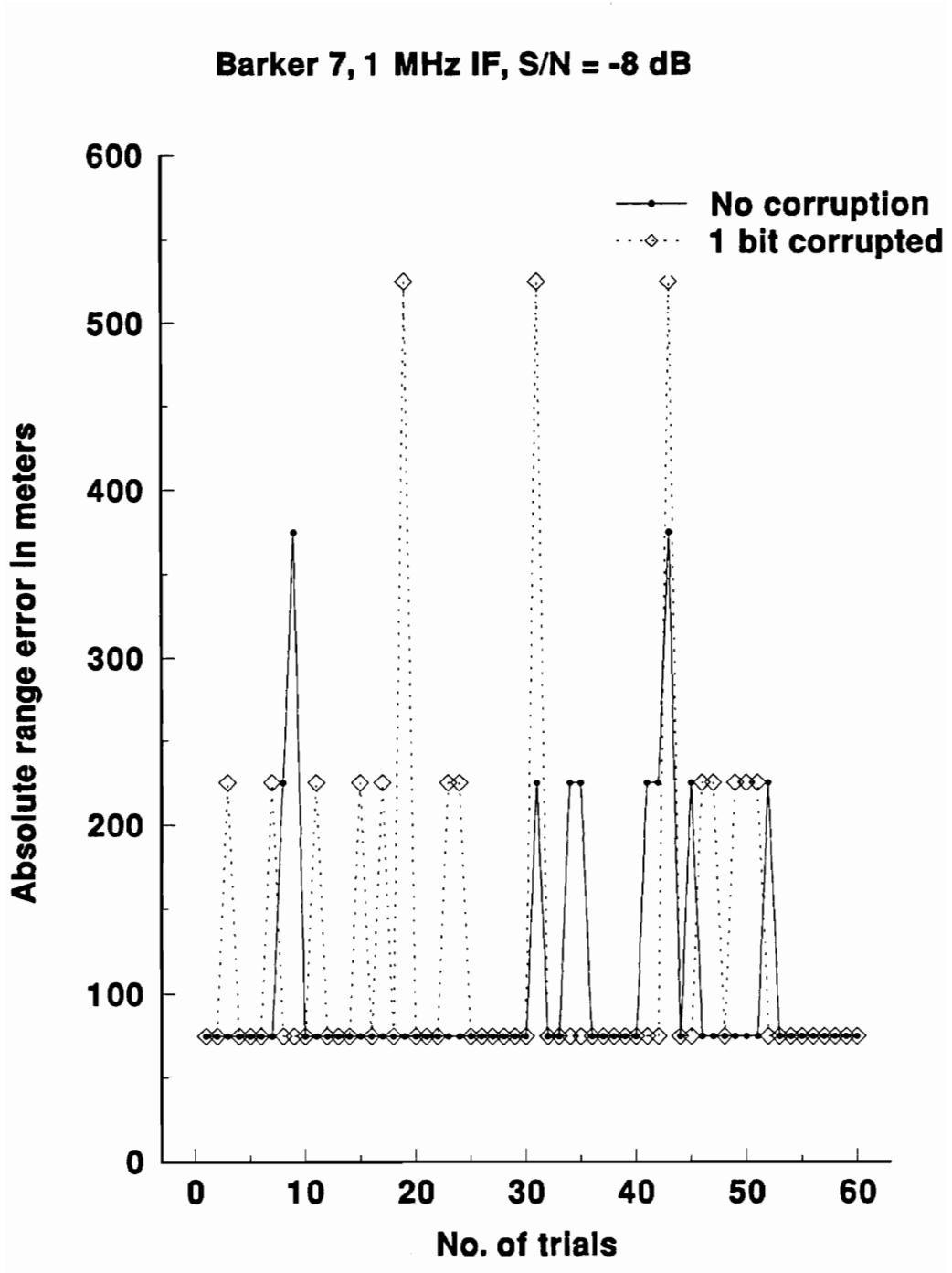


Figure 6.9: Effect of Impulsive Noise

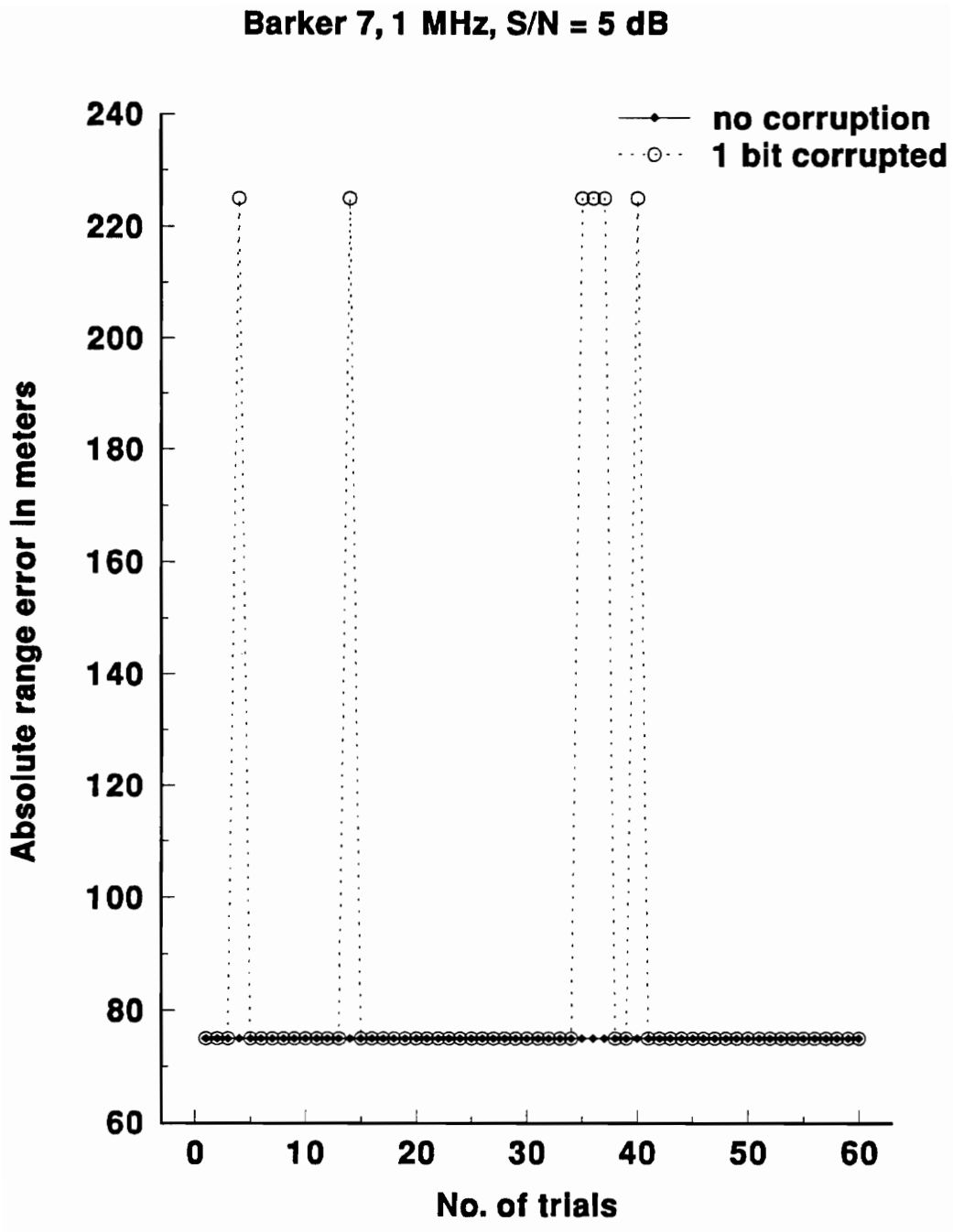


Figure 6.10: Effect of Impulsive Noise

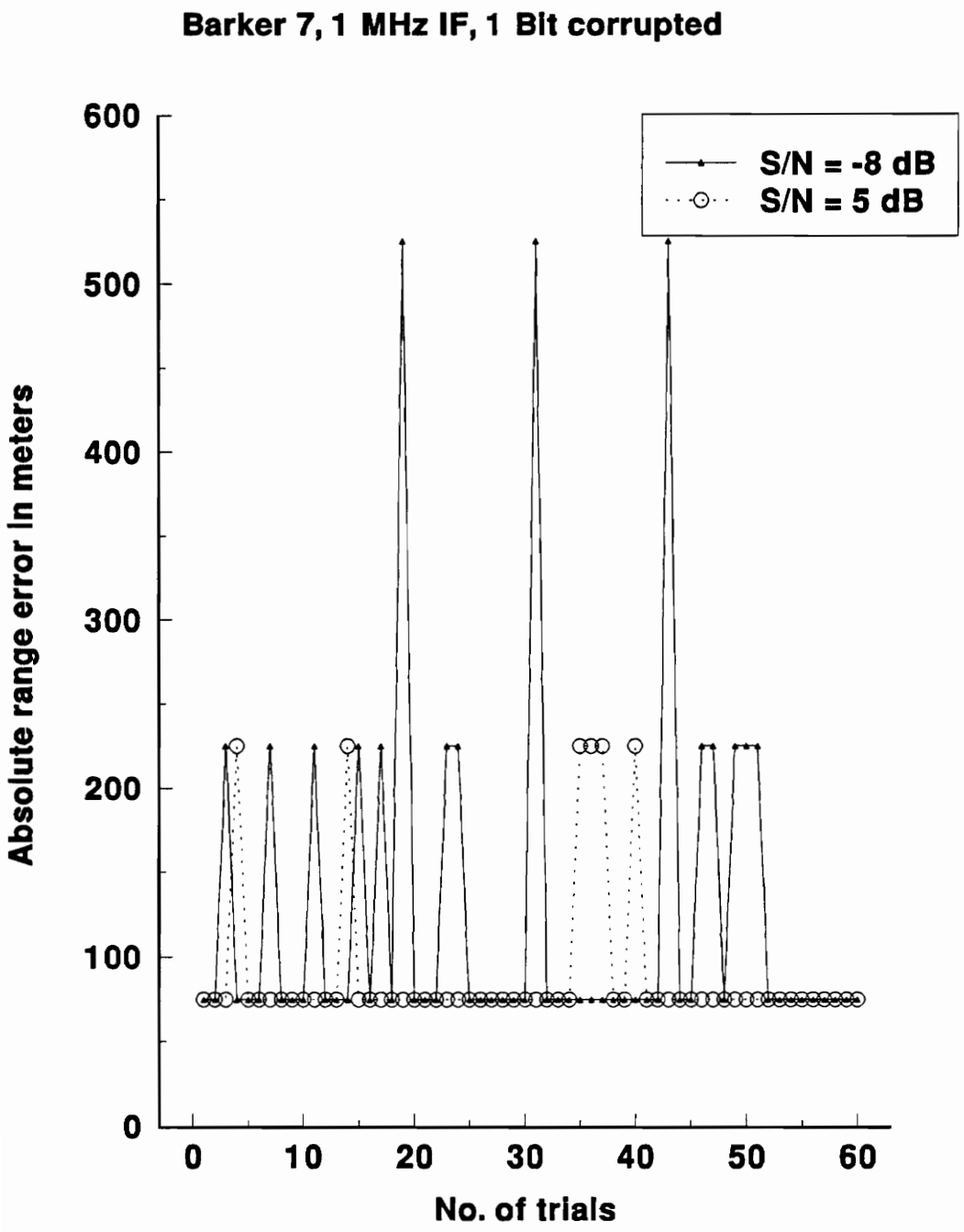


Figure 6.11: Effect of Impulsive Noise

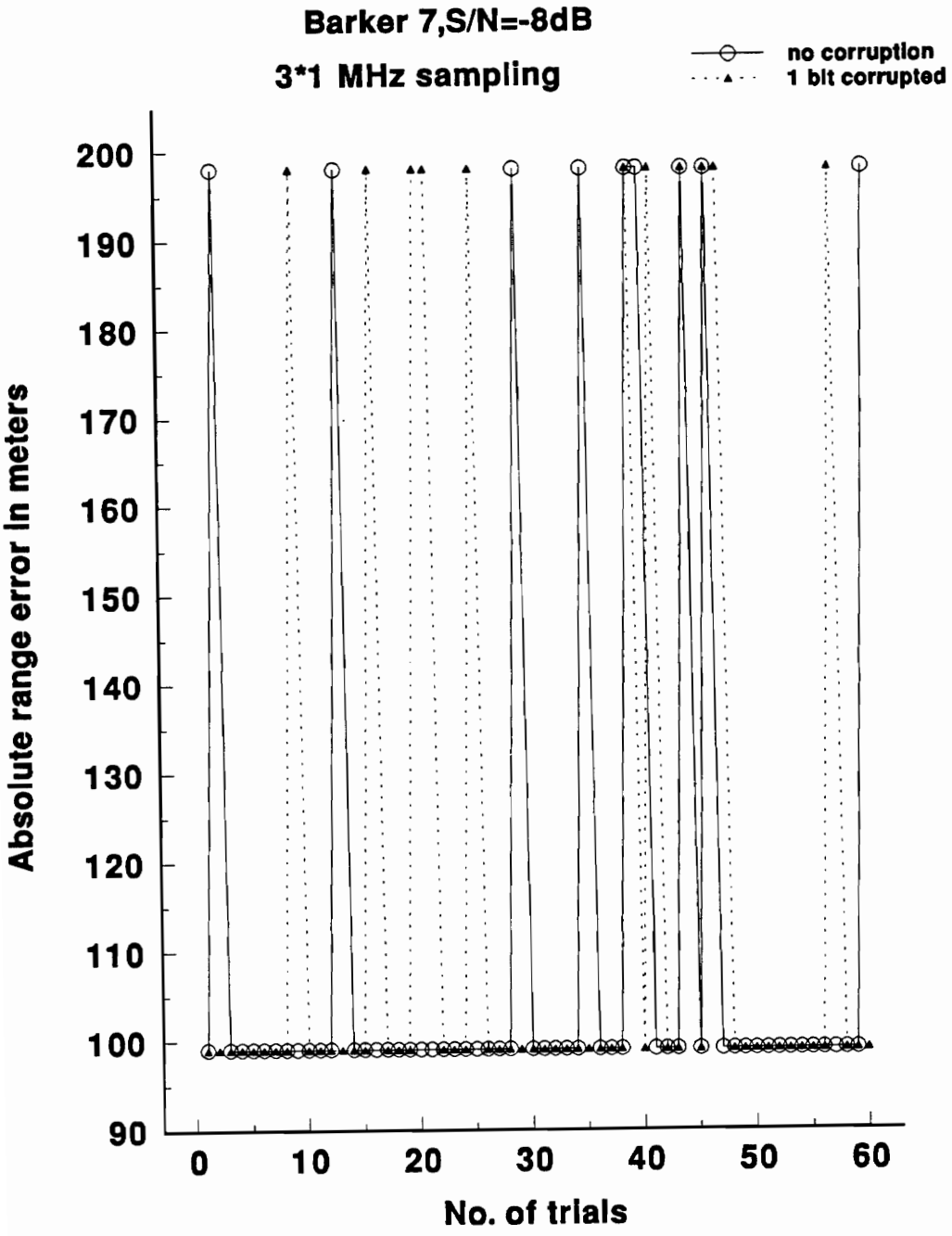


Figure 6.12: Position Error at 1 MHz, 3* 1 MHz Sampling Rate, S/N = -8 dB

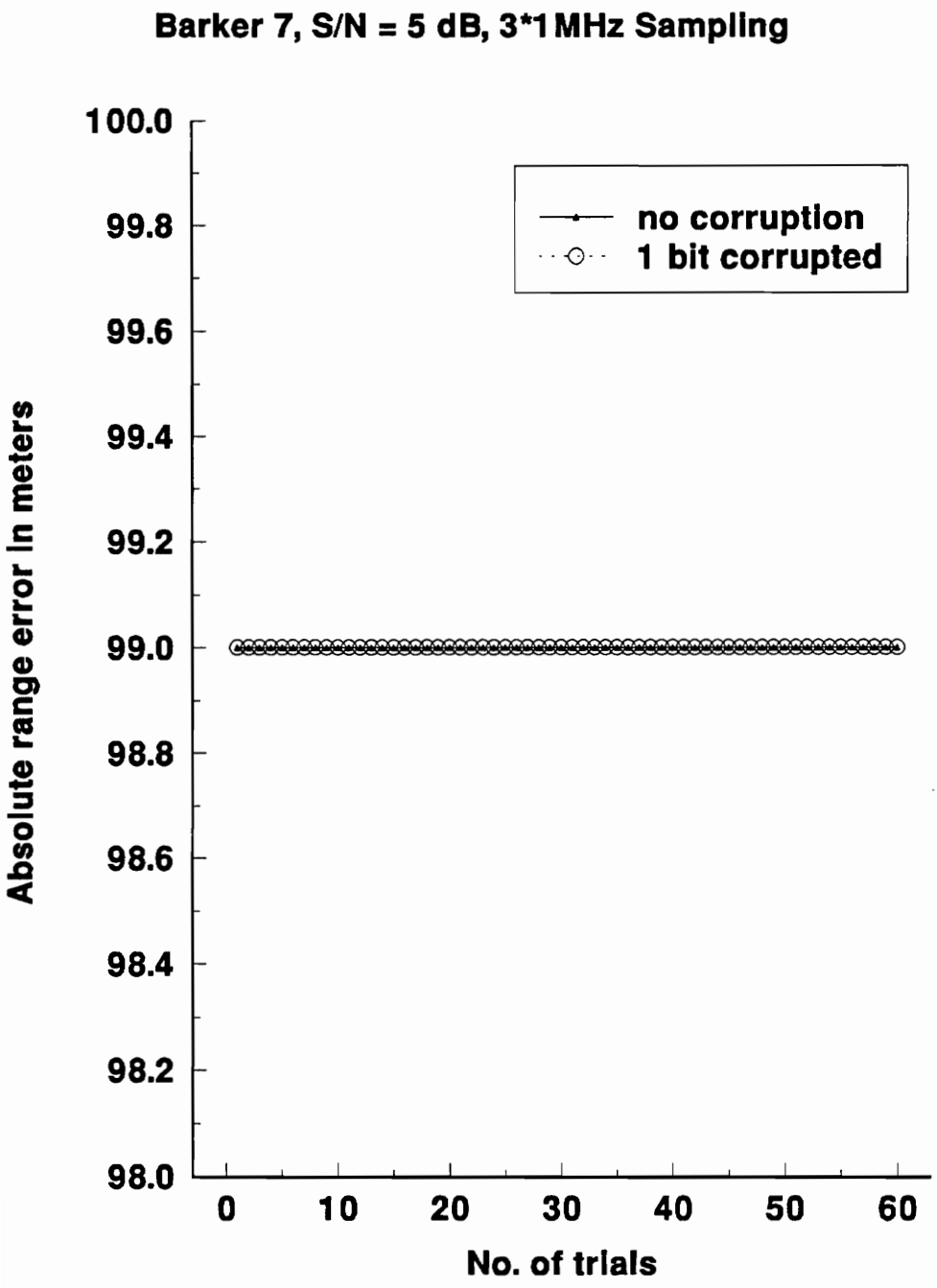


Figure 6.13: Position Error at 1 MHz, 3* 1 MHz Sampling Rate, S/N = +5 dB

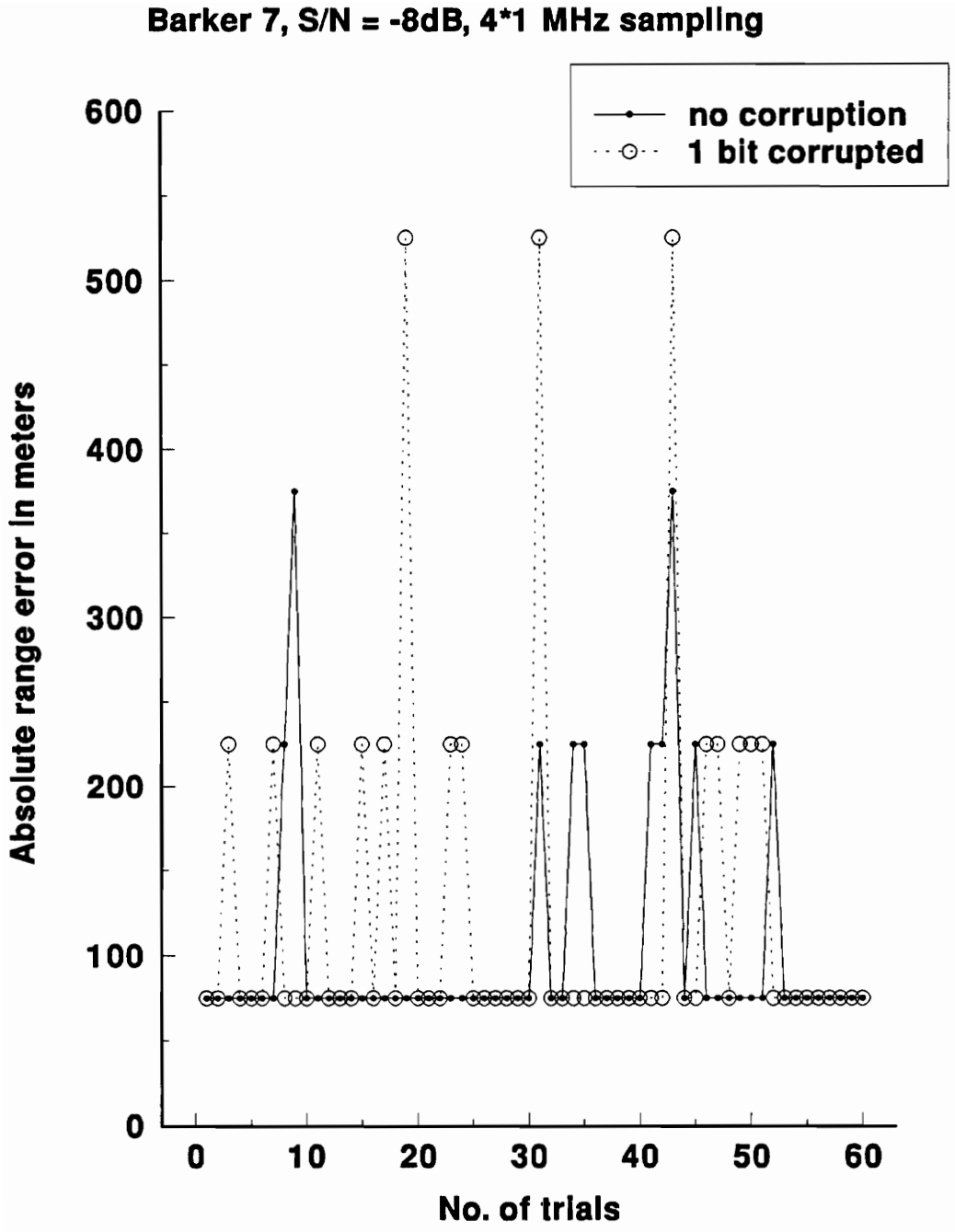


Figure 6.14: Position Error at 1 MHz, 4* 1 MHz Sampling Rate, S/N = -8 dB

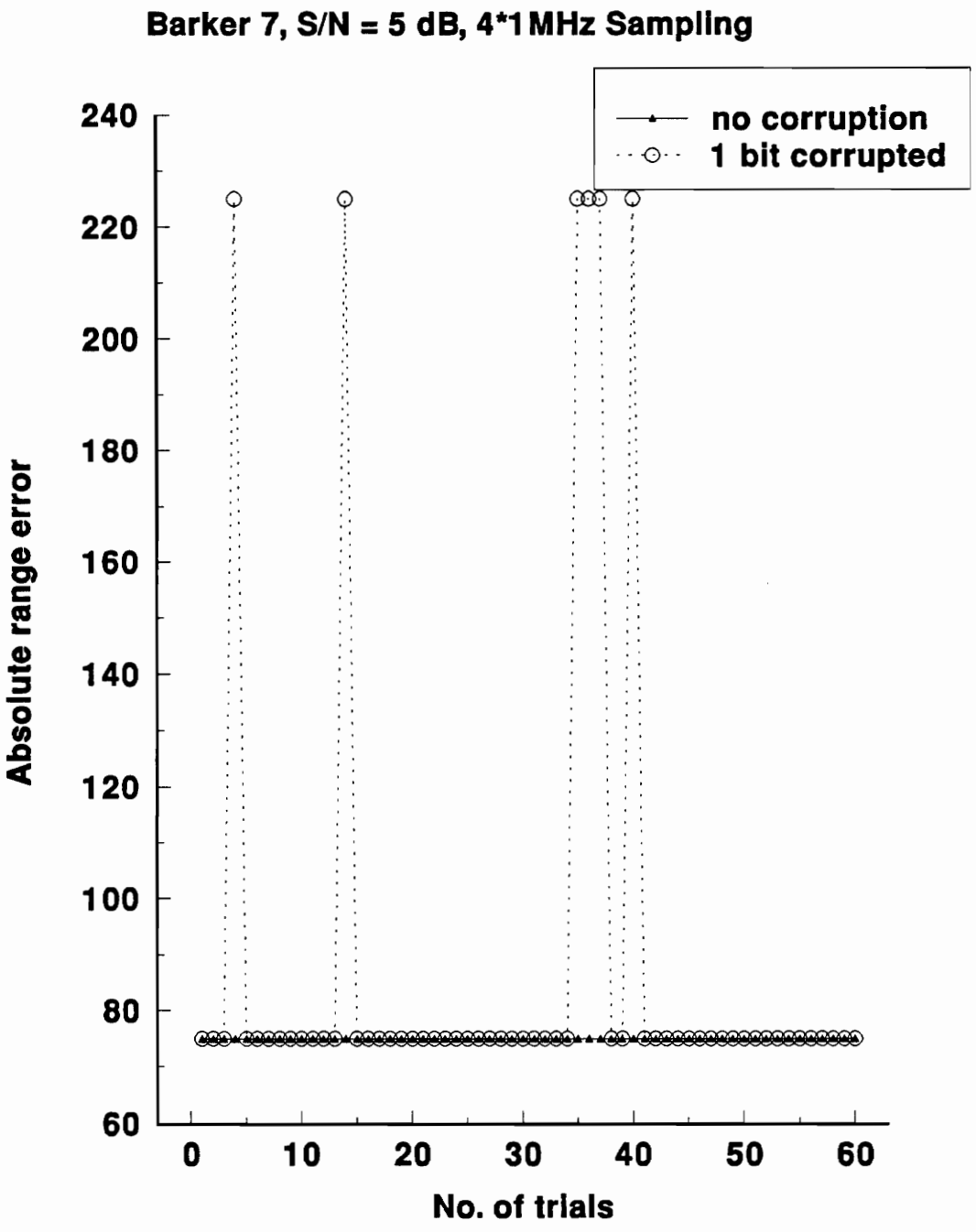


Figure 6.15: Position Error at 1 MHz, 4* 1 MHz Sampling Rate, S/N = +5 dB

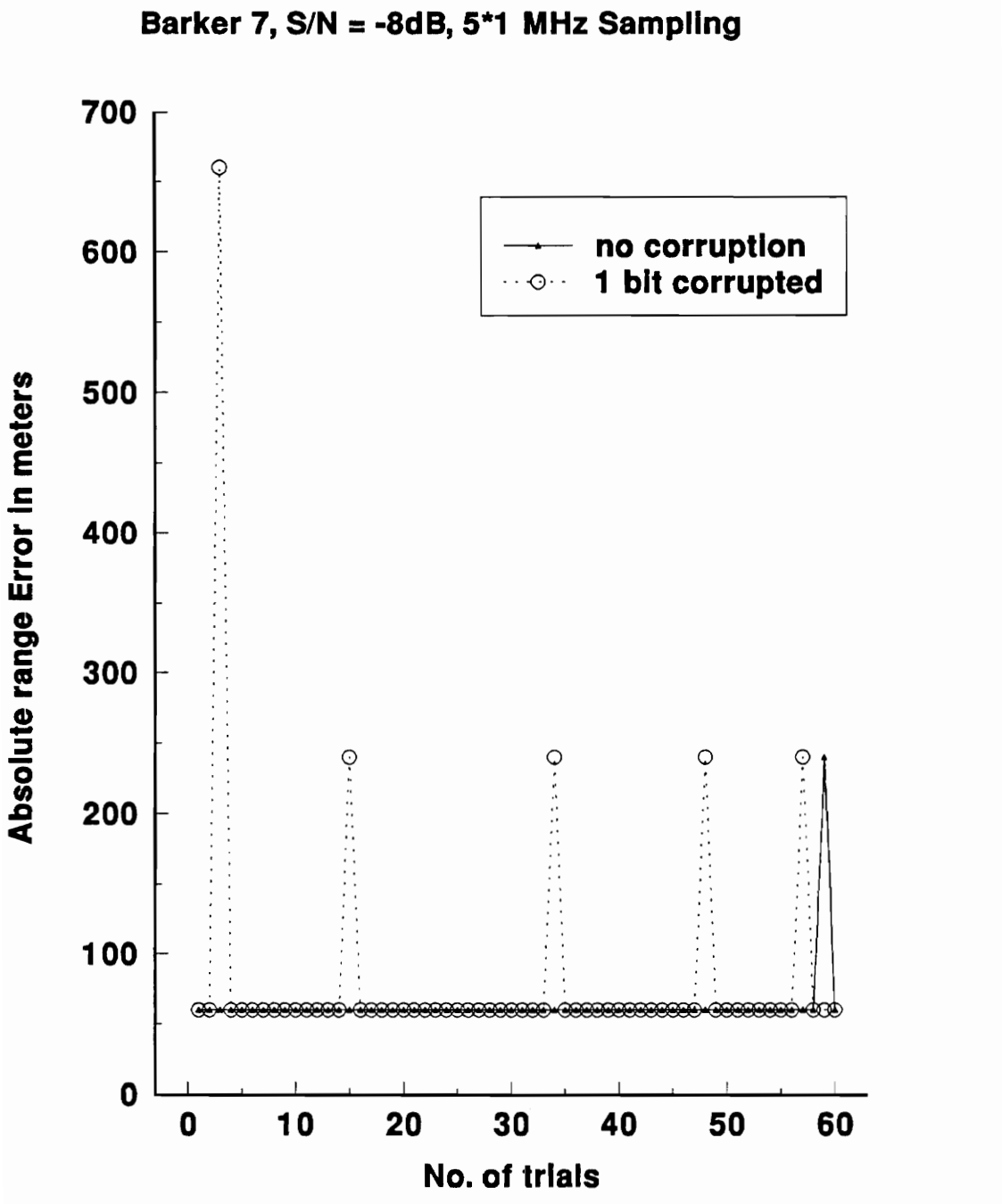


Figure 6.16: Position Error at 1 MHz, 5* 1 MHz Sampling Rate, S/N = -8 dB

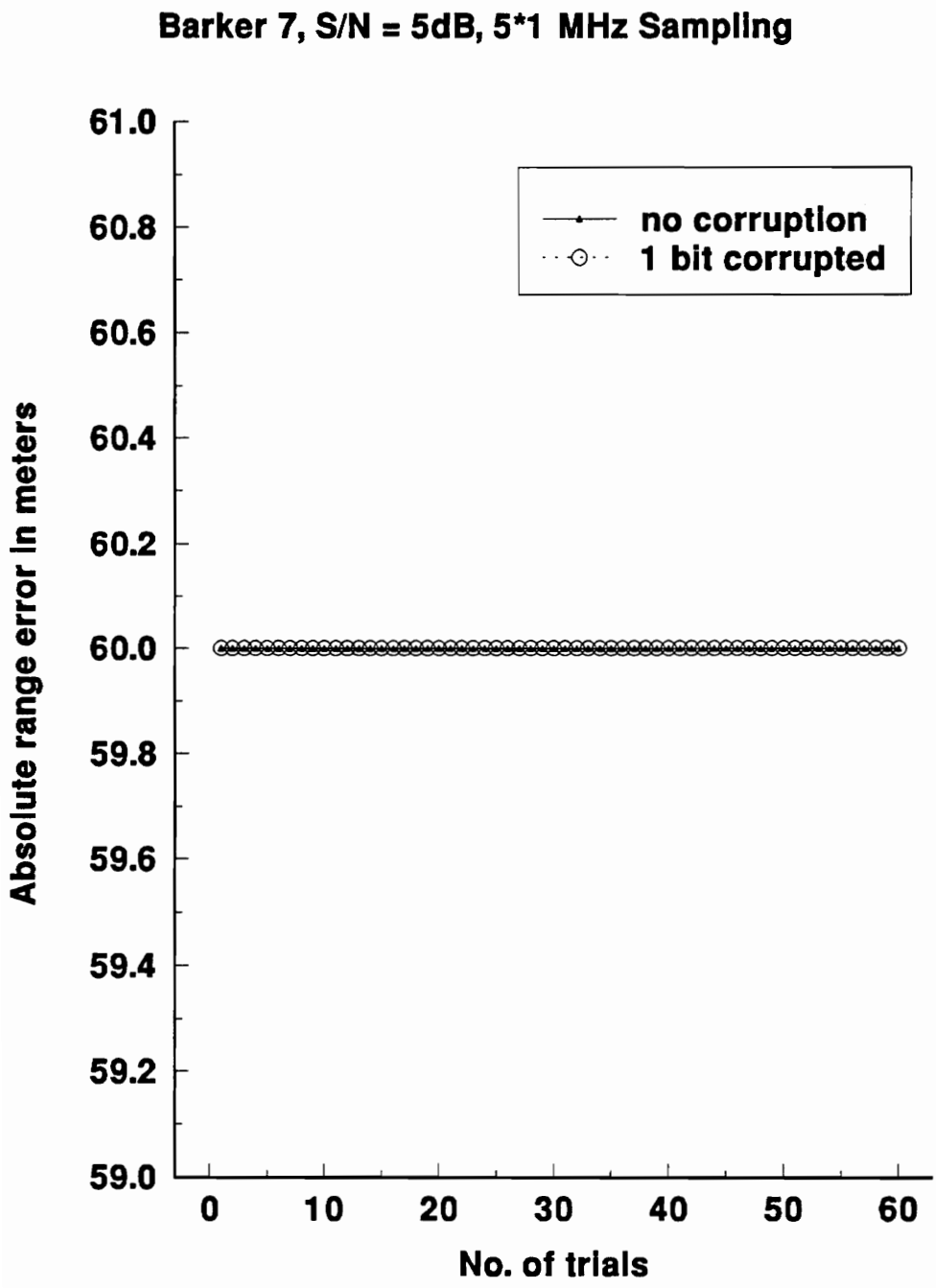


Figure 6.17: Position Error at 1 MHz, 5* 1 MHz Sampling Rate, S/N = +5 dB

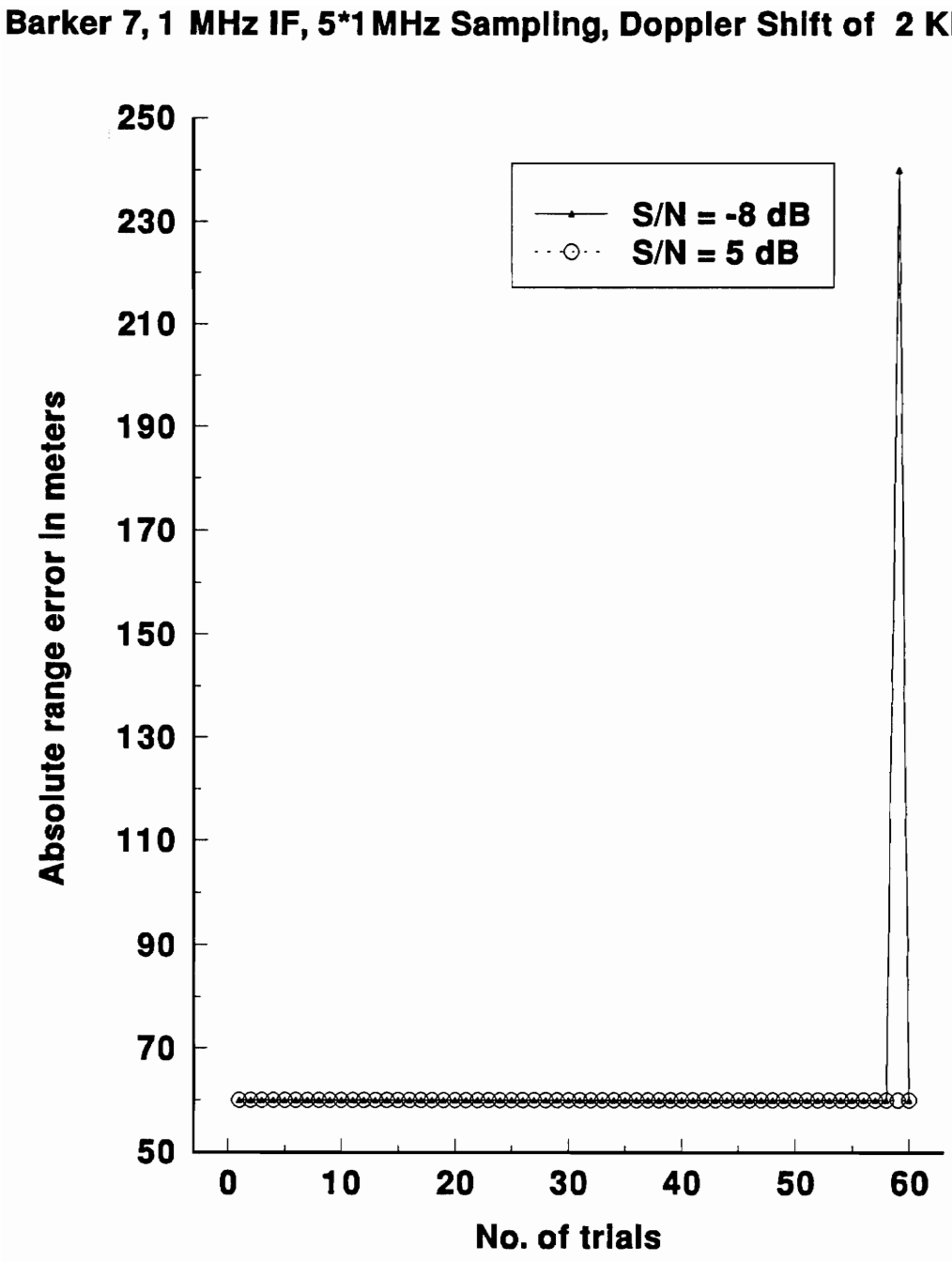


Figure 6.18: Effect of 2 KHz Doppler Shift

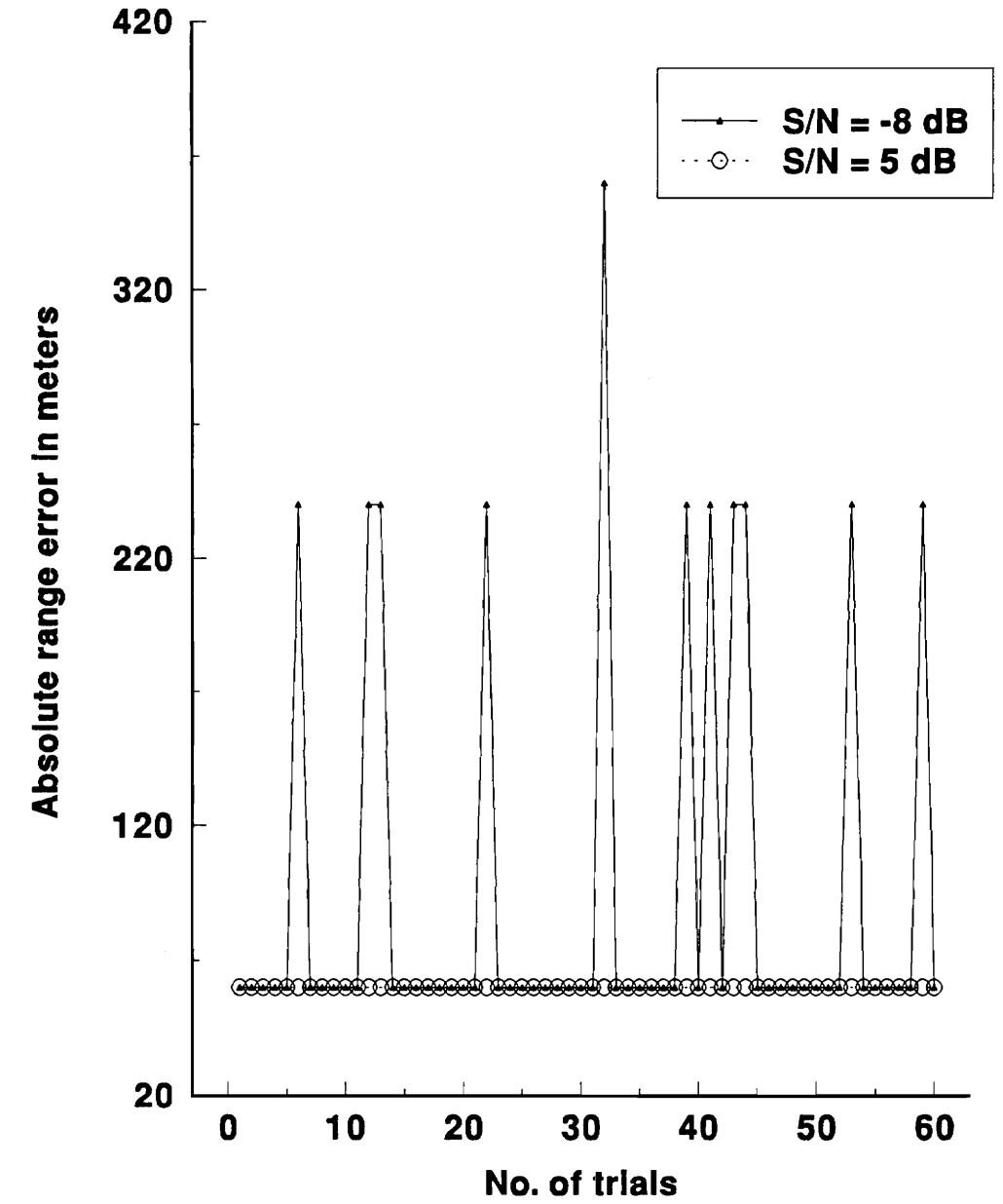


Figure 6.19: Effect of 4 KHz Doppler Shift

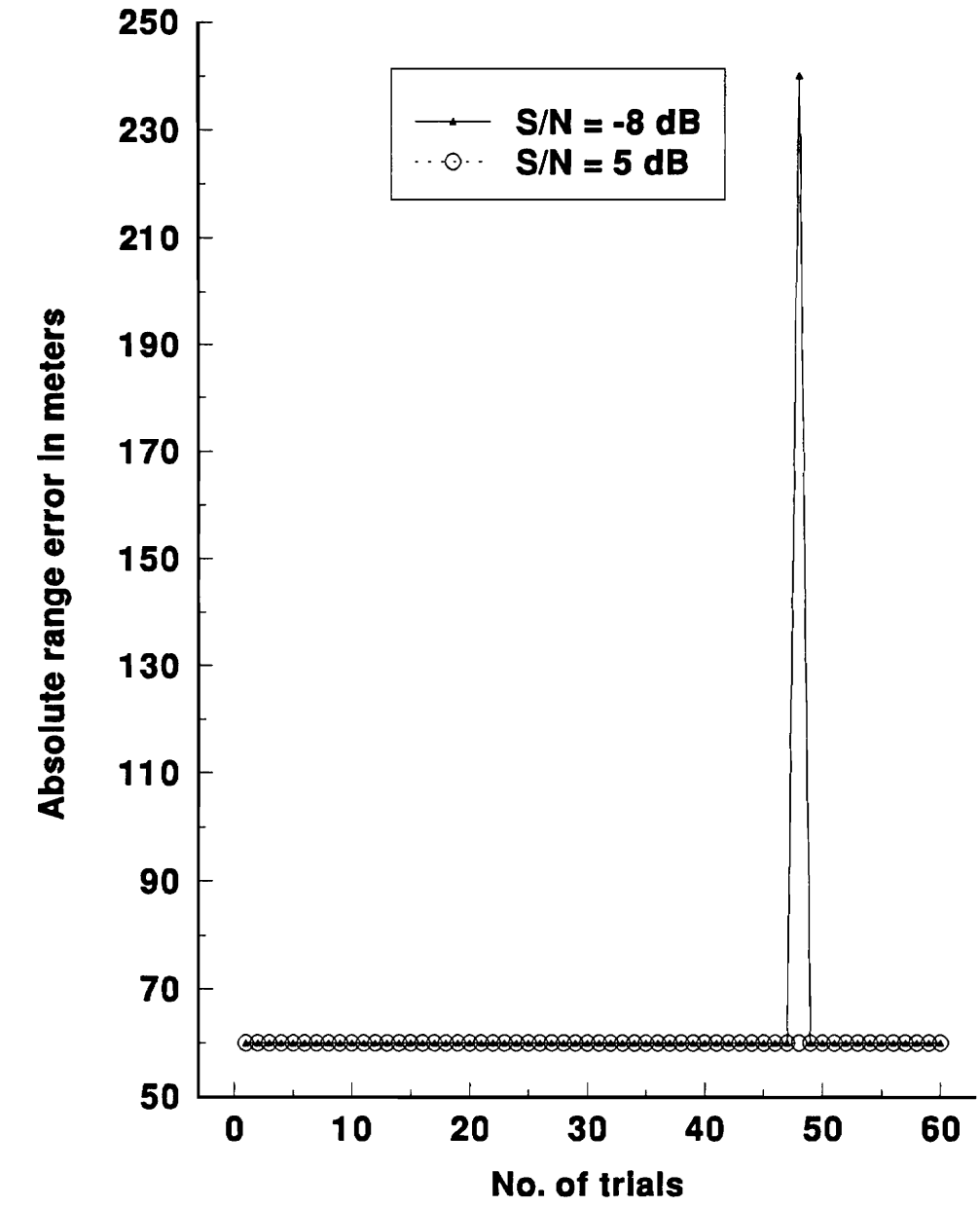


Figure 6.20: Effect of -2 KHz Doppler Shift

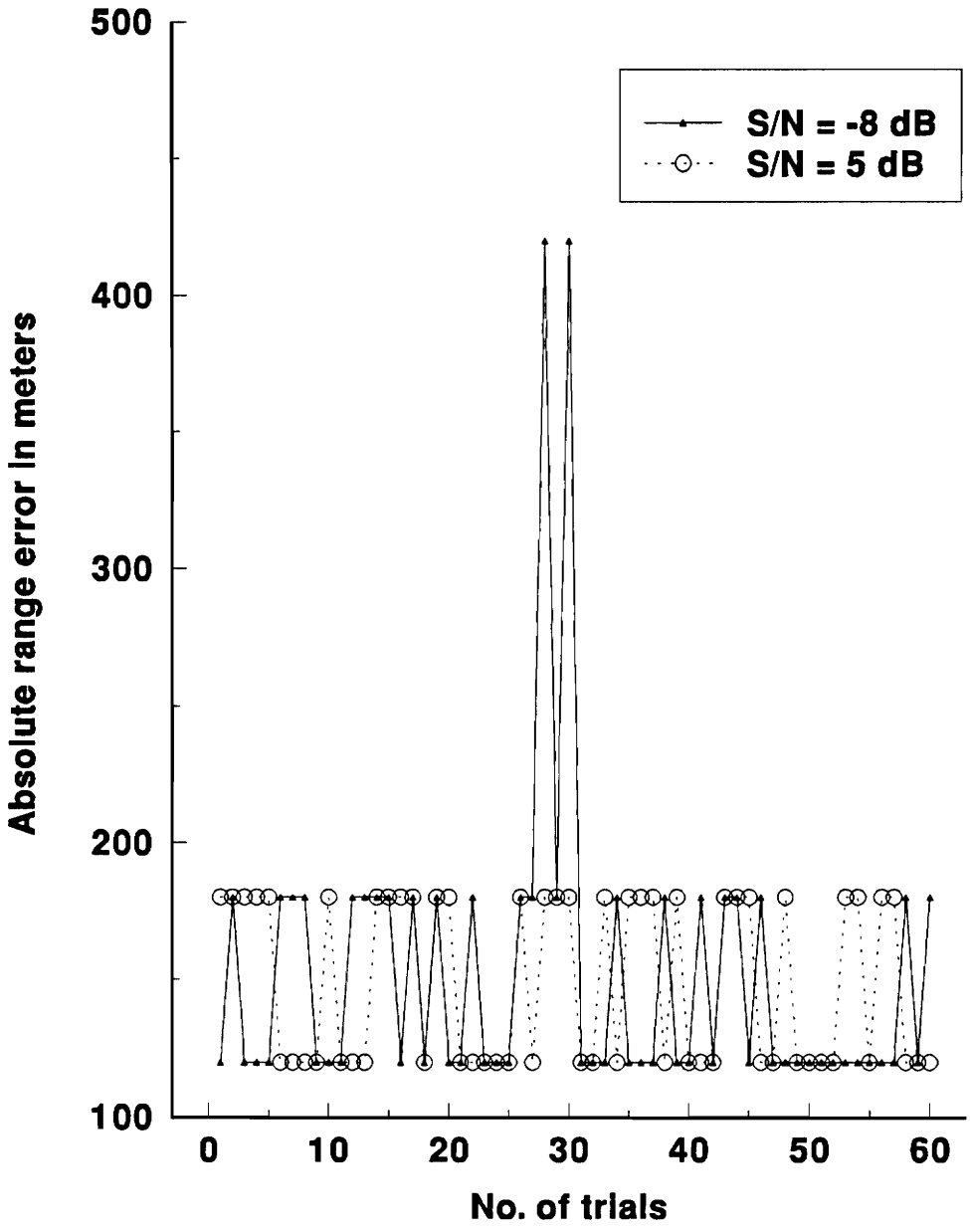


Figure 6.21: Effect of -4 KHz Doppler Shift

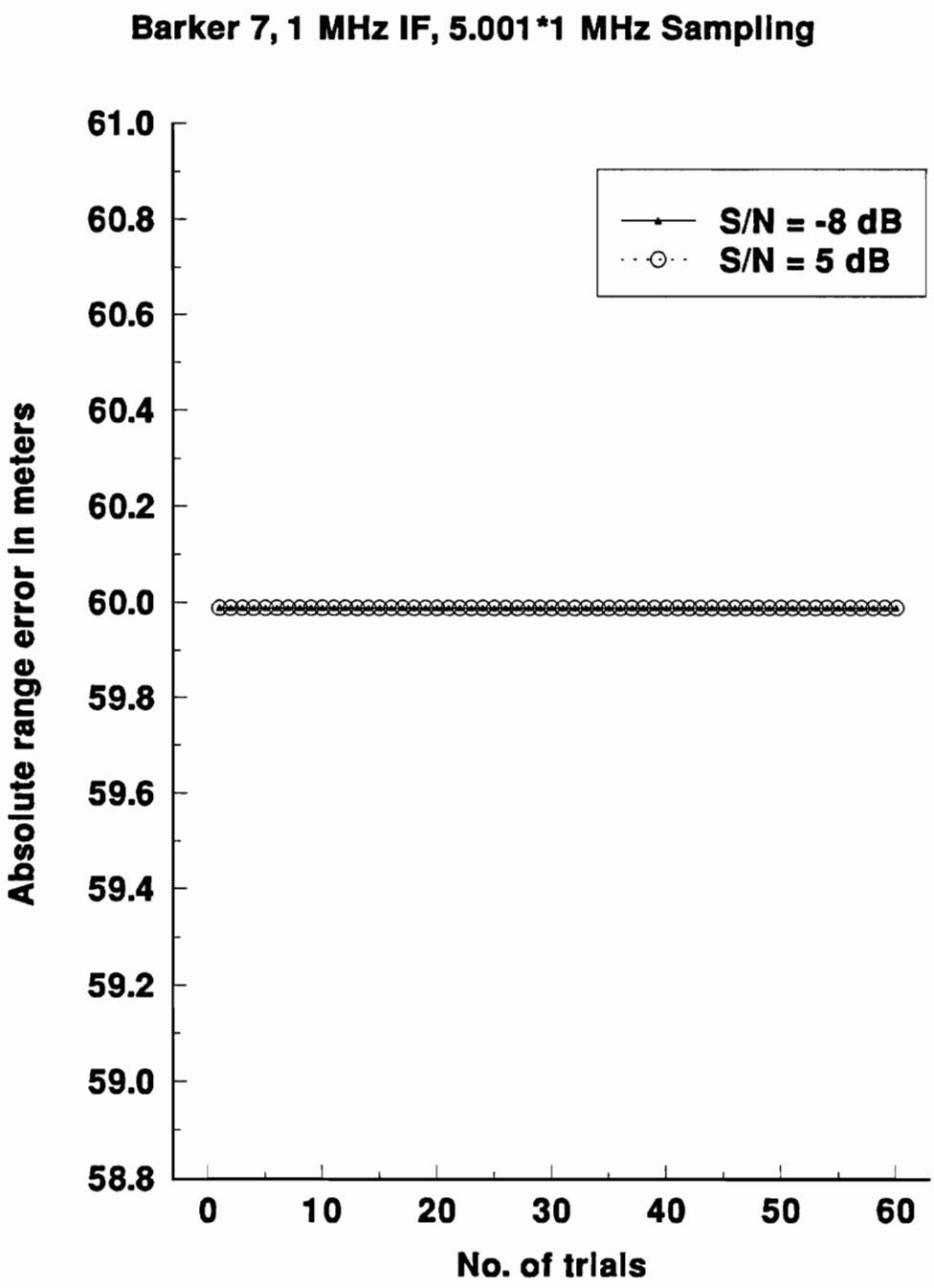


Figure 6.22: Effect of Non Integer Multiple Sampling (5.001* 1 MHz)

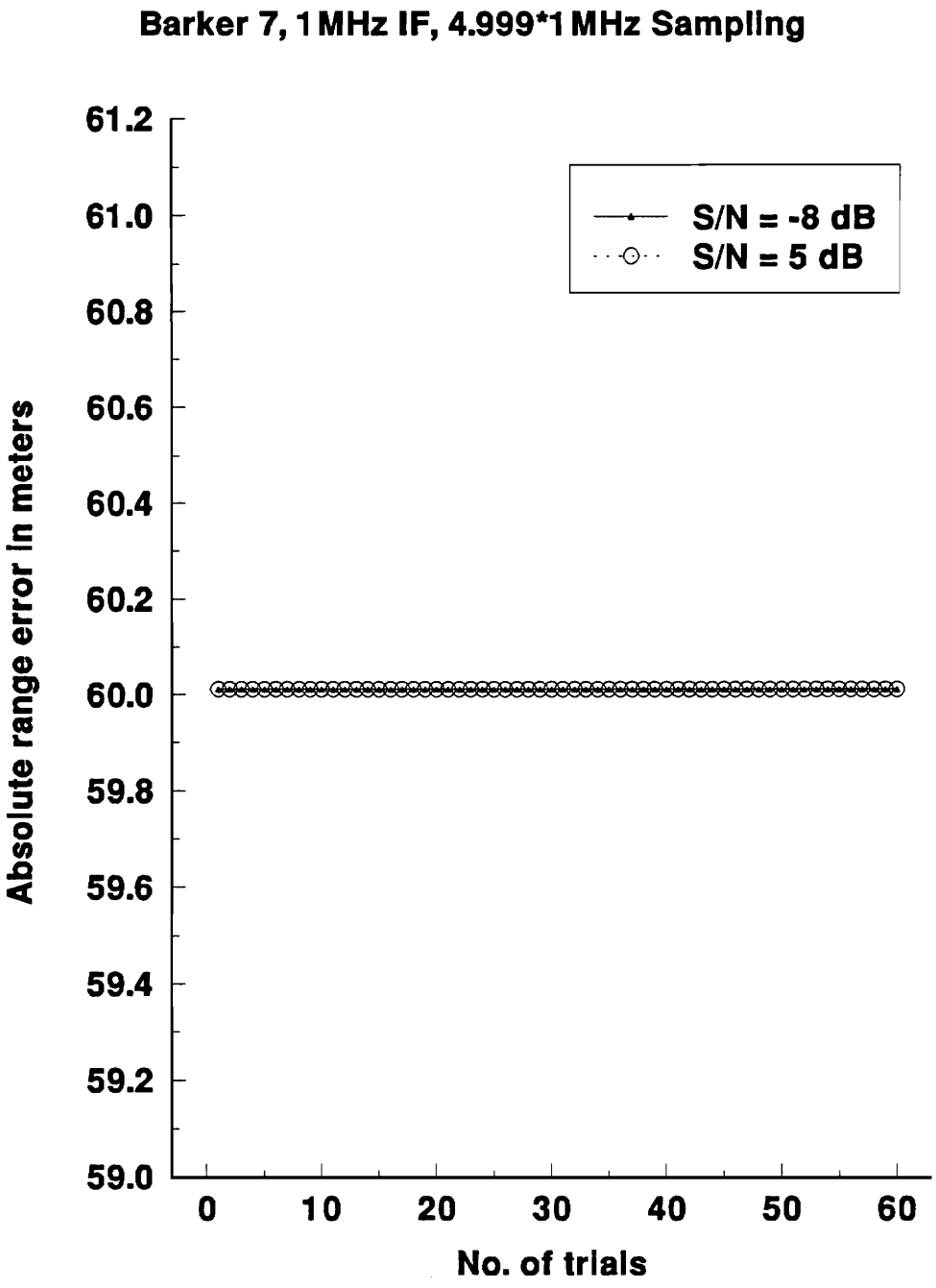


Figure 6.23: Effect of Non Integer Multiple Sampling (4.999* 1 MHz)

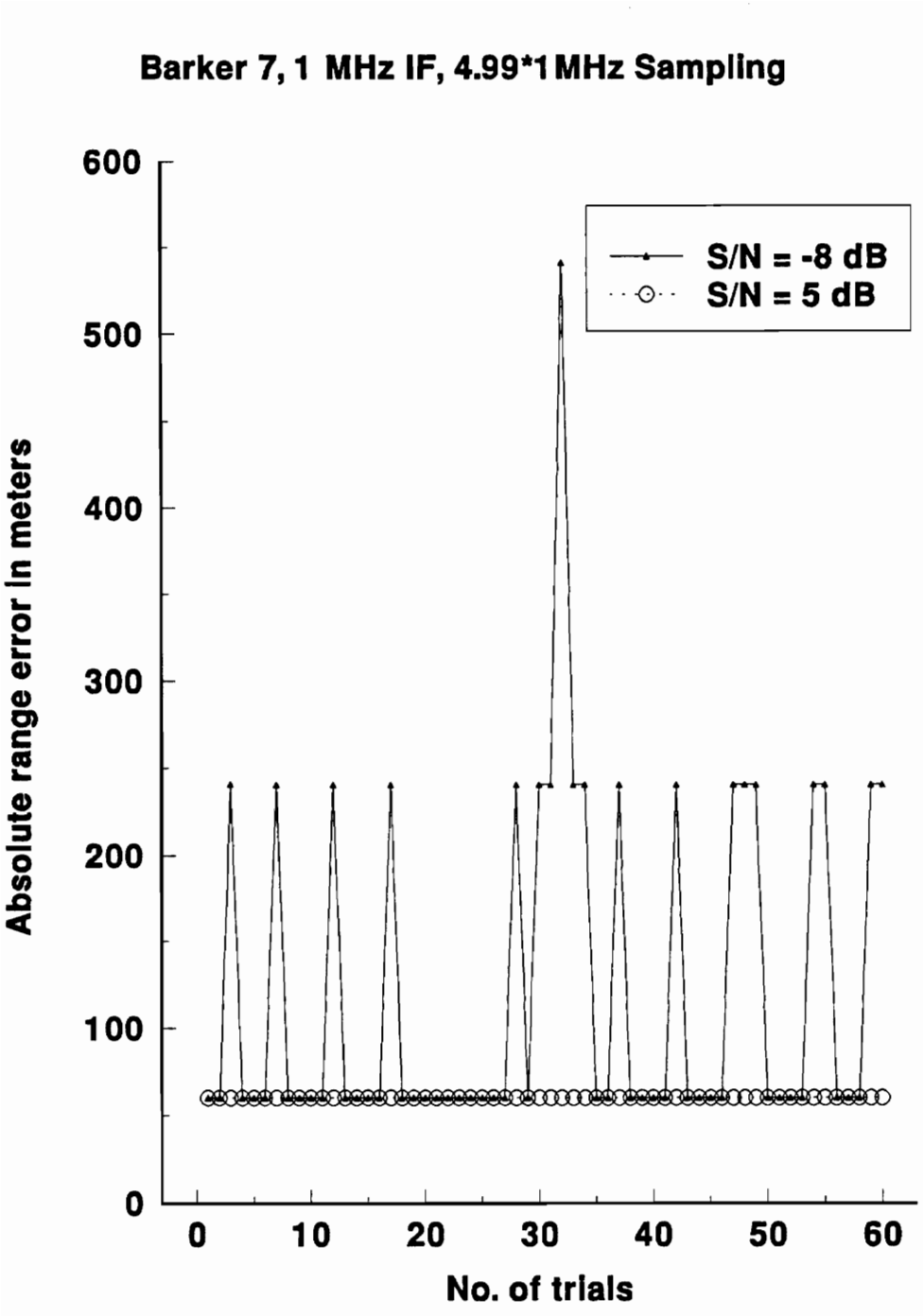


Figure 6.24: Effect of Non Integer Multiple Sampling (5.01* 1 MHz)

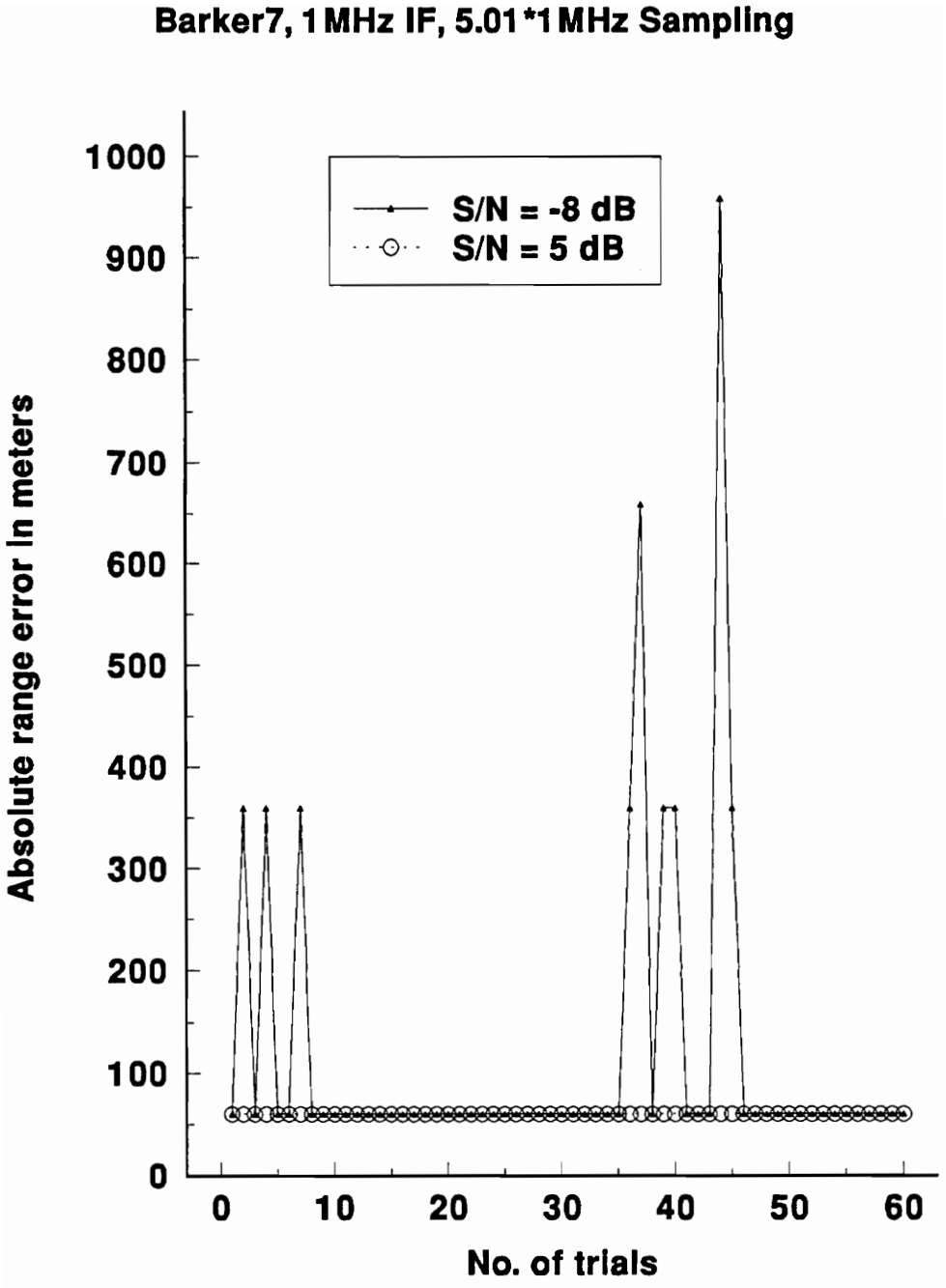


Figure 6.25: Effect of Non Integer Multiple Sampling (9.99* 1 MHz)

Chapter 7

Conclusion

7.1 Summary

This thesis investigates the feasibility of a binary phase shift keyed receiver with an IF correlator for position location applications. The issue that had to be resolved was, how to measure the time of arrival of a signal with a very high degree of accuracy. A time measurement precision greater than 1% of the bit period can be achieved by using an analog IF correlator (in conjunction with the digital bit by bit correlator after the data demodulator) and performing a sample by sample correlation.

The performance of this modified binary phase shift keyed receiver is dependent on the selection of an appropriate intermediate frequency, sampling rate, signal to noise ratio, orbital altitude of the navigation satellite and placing a bound on the drift from the selected IF (non integer multiple sampling).

By selecting the following parameters :

1. 1 MHz as the IF.
2. Five times the IF as the sampling rate.
3. A IF signal to noise of +5 dB.

4. Selecting the altitude to keep the effect of doppler to +/- 4 kHz.

5. Placing an upper and lower bound of +/- 1 kHz on the drift of the IF.

we can achieve an average absolute range error of 60 meters. This is an improvement by a factor of 10 over the 625 meter inherent receiver range error. The other factors [3] that contribute to the above mentioned range error are in predicting the position of the satellite in its orbit (20 meters to 50 meters), clock bias (10 meters to 50 meters), modeling the ionosphere (30 meters to 60 meters), modeling the troposphere (10 meters to 30 meters) and miscellaneous errors (50 meters). If we total all the errors the worst case absolute range error is of the order of 300 meters.

7.2 Navigation System Details

The proposed navigation system will be using low earth orbit satellites as a navigational aid. The low earth orbit satellites will be transmitting a data packet at regular intervals of time. The data packet will have a Barker sequence header. This header is used for detecting the arrival of the data packet at the receiver and also for recording the time of arrival of the signal at the receiver.The receiver uses this recorded time of arrival to measure the time of travel and computes the range to the satellite. The information in the data packet allows the receiver to compute the position of the satellite. By measuring the ranges to four different satellites and computing their orbital position, the receiver can use the algorithm used in section 4.4 to compute its own coordinates.

The total number of bits that make up the data packet will be less than 10,000 bits. At 4800 bits per second it will take 2.1 seconds to transmit the data packet. Thus, we can have 15 to 20 transmission per minute. The average speed of a vehicle is 60 miles per hour. The receiver will be receiving a new packet every 4 or 3 seconds. In 4 (3) seconds the vehicle can travel only 4 (3) miles. So the reading obtained from successive transmissions should place the vehicle in a 4 (3) mile radius of the past position. If there is a large variation from this value we can successfully discount it as an error.

The satellites have to be modified to be usable as a navigational aid. An additional buffer of 10,000 bits has to be added. This buffer should be accessible from the ground control station. The contents to be transmitted will be uploaded into this buffer by the ground control station. Additional circuitry has to be provided to enable the satellite to transmit the contents of this buffer 15 to 20 times per minute. The contents of the buffer should be transmitted in a fixed slot of the satellite transmit frame. This helps in reducing the complexity of the receiver. In case of variable slot transmission the receiver has to listen to the synchronization burst sent by the satellite, find out the correct slot, and get the data. The satellite also needs additional circuitry to determine the exact time of transmission of the signal depending on the slot selected for transmission. The final modification is that the IF has to be set to 1MHz.

7.3 Limitations

Section 7.1 showed that the worst case range error is 300 meters. This system cannot be used for applications requiring a very high positional accuracy, like bombing. This system cannot be used for city traffic navigation also. Another disadvantage is that the accuracy of the system cannot be improved by averaging. This system has been developed for vehicular applications. Since the roads can be winding, averaging of positions will generally give higher errors. Vehicles may also go up and down the same street or round a block thereby giving higher errors on averaging.

7.4 Future Work

The feasibility of this system has been tested only through software simulations. The system has to be implemented in hardware and its feasibility verified. Another area of research is looking for ways to represent samples without modifying the correlation properties of the sequence. The design of the antenna system for this navigation system will also be a challenging task.

7.5 Conclusion

The software simulations prove that the inherent range error of a binary phase shift keyed receiver can be reduced from 625 meters to around 60 meters if an analog IFcorrelator is used, if an IF of 1 MHz is used, an IF sampling rate of 5 time the IF is selected, an IF signal to noise ratio of 5 dB is maintained, the altitude of the satellite is selected to

keep the Doppler shift below 4 kHz, and designing the system so that the frequency variation does not exceed 1 kHZ. Thus, a Binary Phase Shift Keyed Receiver with an Analog IF Sample by Sample Correlator is suitable for position location.

References

1. L. Tetley and D. Calcutt, **Electronic Aids to Navigation**, Macmillan India Ltd., 1986.

2. G. J. Sonnenberg, **Radar and Electronic Navigation**, University Press, Cambridge, 1988.

3. David Wells, **Guide To GPS Positioning**, Canadian GPS Associates, 1986.

4. Tom Logsdon, **The Navstar Global Positioning System**, Van Nostrand Reinhold, New York, 1992.

5. Thomas A. Stansell Jr., "The Navy Navigation Satellite System: Description and Status", Navigation, Journal of The Institute of Navigation, Volume 15, Number 3, pages 229 - 243, Fall 1968.

6. Thomas A. Stansell Jr.,"Transit, The Navy Navigation Satellite System, Navigation", Journal of The Institute of Navigation, Volume 18, Number 1, pages 93 - 109, Spring 1971.

7. T. B. Merkel, "Military Application of the TRANSIT Satellite Navigation System in the P-3C ASW Aircraft", Navigation, Journal of The Institute of Navigation, Volume 20, Number 3, pages 245 - 251, Fall 1973.

8. Wilbur L. Pritchard, Henri G. Suyderhoud, and Robert A. Nelson, **Satellite Communication Systems Engineering**, Second edition, Prentice Hall, Englewood Cliffs, New Jersey , 1993.

9. Simo H. Laurila, **Electronic Surveying And Navigation**, John Wiley & Sons, 1976.

10. T. Jones, "NAVSTAR Global Positioning System: Status And Update", Proceedings of the fifth International Geodetic Symposium on Satellite Positioning,Volume 1, pages 28 - 52, Las Cruces, New Mexico, March 1989.

11. M. W. Gouldman, B. R. Herman, and D. L. Weedon, "Evaluation of GPS Production Ephemeris and Clock Quality", Proceedings of the fifth International Geodetic Symposium on Satellite Positioning,Volume 1, pages 210 - 222, Las Cruces, New Mexico, March 1989.

12. R. Bowen, P. L. Swanson, F. B. Win, N. W. Rhodus, and W. A. Feess, "Global Positioning System Operational Control System Accuracies", The Institute of Navigation: Global Positioning System, Volume 3, pages 241 - 257, 1986.

13. N. Ashby, "Relativistic Effects in GPS", Proceedings of the International Association of Geodesy Symposium of the XIX General Assembly of IUGG, Volume 1, pages 41 - 50, Vancouver, Canada, August 1987.

14. A. G. Evans, "Comparision of GPS Pseudo-Range and Biased Doppler Range Measurement to Demonstrate Signal Multipath Effects", Proceedings of the Fourth International Geodetic Symposium on Satellite Positioning, Volume 1, pages 573 - 587, Austin, Texas, April 1986.

15. James J. Spilker, Jr. **Digital Communications by Satellite**, Prentice Hall, Englewood Cliffs, New Jersey, 1977.

16. James J. Spilker Jr., "GPS Signal Structure and Performance Characteristics", Global Positioning System, The Institute of Navigation, Volume I, pages 29 - 54, 1980.

17. George Kamas and Sandra L. Howe, **Time and Frequency User's Manual**, United States National Bureau of Standards Special Publication, November 1979.

18. Byron E. Blair, **Time and Frequency: Theory and Fundamentals**, US Department of Commerce / National Bureau of Standards Publication, May 1974.

19. P. S. Noe and K. A. Myers, "A Position Fixing Algorithm for the Low - Cost GPS Receiver", IEEE Transactions on Aerospace and Electronic Systems, Volume AES - 12, Number 2, pages 245 - 298, March 1976.

20. V. N. Fadeeva, **Computational Methods of Linear Algebra**, New York, 1959.

21. G. C. Weiffenbach, "Tropospheric and Ionospheric Propagation Effects on Satellite Radio Doppler Geodesy", **Electromagnetic Distance Measurement**, University of Toronto Press, 1967.

22. H. D. Block, "An Easily Implemented algorithm for Tropospheric Range Correction", Journal of Geophysical Research, pages 1825 - 1828, April 1978.

23. Ivan I. Mueller, **Introduction to Satellite Geodesy**, Frederick Ungar Publishing Company, New York, 1965.

24. William W. Kaula, **Theory of Satellite Geodesy: Applications of Satellites to Geodesy**, Blaisdell Publishing Company, 1966.

25. Peter Vanicek and Edward Krakiwsky, **Geodesy: The Concepts**, Second Edition, North Holland, 1986.

26. Herbert Taub and Donald Schilling, **Principles of Communication Systems**, McGraw - Hill Book Company, 1987.

27. Fred E. Nathanson, Patrick Reilly, and Marvin Cohen, **Radar Design Principles**, McGraw Hill, 1991.

28. Jerry L. Eaves and Edward Reedy, **Principles of Modern Radar**, Van Nostrand Reinhold Company, New York, 1987.

29. Special Issue on SAW Convolvers and Correlators, IEEE Transactions on Sonics and Ultrasonics, Volume Su - 32, September 1985.

30. K. A. Ingebrigtsen, "The Schottky Diode Acoustoelectric Memory and Correlator: A Novel Programmable Signal Processor", Proceedings of IEEE, Volume 64, May 1976.

31. William W. Wu, **Elements of Digital Satellite Communication**: Volume I, Computer Science Press, 1984.

32. J. Maury and F. Styles, "Development of Optimal Frame Synchronization Codes For Goddard Space Flight Center PCM Telemetry Standards", Proceedings of the 1963 National Telemetering Conference.

33. J. Lindner, "Binary sequences up to Length 40 with Best Possible Autocorrelation Function, West Germany, 1975.

34. R. C. Dixon, **Spread Spectrum Systems**, John Wiley & Sons, 1976.

Vita

John Vareed Thommana was born on January 25, 1966 in Trichur, India. He graduated with a Bachelor of Engineering degree in Electronics And Communication from Manipal Institute of Technology, India, in 1987. He worked for four years with the Testing Department of the Tata Electric Companies, Bombay, India. He started work on his Masters Degree in Electrical Engineering at Virginia Polytechnic Institute And State University in the fall of 1991. John has accepted an employment offer from Hughes Network Systems, Germantown, Maryland, where he expects to commence work from January 1994.