1989

Global Positioning System information retrieval methodology

Larry Duane Synstelien
Iowa State University

Global Positioning System information retrieval methodology

by

Larry Duane Synstelien

A Thesis Submitted to the

Graduate Faculty in Partial Fulfillment of the

Requirements for the Degree of

MASTER OF SCIENCE

Department: Electrical Engineering and Computer Engineering
Major: Electrical Engineering

Iowa State University
Ames, Iowa

1989

TABLE OF CONTENTS

ABSTRACT vi

ACKNOWLEDGEMENTS viii

Page

CHAPTER 1 INTRODUCTION 1

CHAPTER 2 BACKGROUND INFORMATION 2
GPS Navigation Theory 3
Satellite and Receiver Geometry 5
Receiver Position Calculation 6
Kalman Filtering 9

CHAPTER 3 GPS TRANSMITTER 11
50 Hz Data 13
Coarse Acquisition (C/A) Code 14
Precision (P) Code 15
Mathematical Description 17
Frequency Spectrums 18

CHAPTER 4 GPS RECEIVER 20
RF Section 21
Digital Signal Processing (DSP) Section 23
Analog to Digital Conversion 23
Processing Algorithm 24
FFT Principles 24
Resolution 26
Bandwidth 28
Noise Effects 29
Bit Sync Error Effects 31
GPS Signal Acquisition 34
GPS Signal Tracking 36

CHAPTER 5 CONCLUSIONS 38

BIBLIOGRAPHY 40

APPENDIX I - GPS FACT SHEET 41

APPENDIX II - GPS RECEIVER BLOCK DIAGRAM 43

INDEX OF FIGURES

Figure		Page
Figure 2.1:	NAVSTAR System Concept	3
Figure 2.2:	GPS Satellite Constellation	4
Figure 2.3:	GPS Satellite to User Geometry	5
Figure 2.4:	GPS Pseudo Range to User Vectors	6
Figure 2.5:	GPS Position Vectors with Atmosphere and Clock Errors	7
Figure 3.1:	GPS Satellite Transmitter Block Diagram	12
Figure 3.2:	C/A Code Generator Block Diagram	15
Figure 3.3:	P Code Generator Block Diagram	17
Figure 3.4:	GPS L1 Signal Power Spectral Density	18
Figure 3.5:	GPS L2 Signal Power Spectral Density	19
Figure 4.1:	RF Section Block Diagram	22
Figure 4.2:	DSP Section Block Diagram	23
Figure 4.3:	FFT Block Diagram	25
Figure 4.4:	32 Point vs 512 Point FFT	27
Figure 4.5:	Resolution vs FFT Points at Various Sampling Frequencies	27
Figure 4.6:	Signal at Sample Point and 50% between a Sample Point	28
Figure 4.7:	Gain vs Sample Point Position	29
Figure 4.8:	Signal With and Without Noise	30
Figure 4.9:	Spectrum of Noisy Signal	30

Figure 4.10: Carrier with 50 Hz Data Bit Shift Shown in the Time Domain 32

Figure 4.11: Carrier with 50 Hz Data Bit Shift and Zero Bit Sync Error 33

Figure 4.12: Carrier with 50 Hz Data Bit Shift and 25% Bit Sync Error 33

Figure 4.13: Carrier with 50 Hz Data Bit Shift and 50% Bit Sync Error 34

Figure 4.14: Cross-Correlation Function 35

INDEX OF TABLES

Table **Page**

Table 2.1: Position Information from Satellites 9

ABSTRACT

Ever since the beginning of time, man has searched for better navigational aids. The NAVSTAR Global Positioning System (GPS) represents the culmination of years of research and development. The system utilizes state of the art satellite communication enabling all weather worldwide navigation never before possible. The system provides position accuracies within 9 meters; velocity information within 0.1 m/sec; time data within 100 nanoseconds.

With GPS still in the infancy stages, the potential applications remain limitless. Many James Bond type scenarios become very realistic -- a display in every car showing exactly where the car is and an electronic map showing possible courses. The application of GPS is limited only by one's own imagination.

This thesis explores the three GPS areas: 1) system concept; 2) signal structure; and 3) Digital Signal Processing (DSP) techniques. The GPS information presented allows the reader to become familiar with the NAVSTAR system concept and the application of a DSP technique in a GPS receiver design. By capitalizing on the rapid electronics

evolution, smaller, lighter and more powerful receivers are possible.

ACKNOWLEDGEMENTS

I would like to thank the many people who have helped and guided me in developing this thesis. The advice and information from A. J. Lenze, C. A. Popeck, and J. R. Bader, Rockwell International engineers, contributed to the success of the thesis.

I would also like to thank M. J. Synstelien (my wife) for her patience, support, and many hours of proof reading. Thanks also to Dr. T. Smay of ISU my major professor. He has supported and guided me through the graduate process.

I am particularly indebted to Dr. E. G. Anderson of NDSU for his guidance and help through both my undergraduate and graduate studies. His knowledge, wisdom, and insight added to the realization of this thesis.

A special note of appreciation to my parents for their inspiration and encouragement throughout my education. From young "engineering experiments" to present day endeavors they continually support my ventures.

CHAPTER 1

INTRODUCTION

This thesis discusses the development of the Global Positioning System (GPS), the structure of the GPS signal and the process of receiving GPS signals.

Chapter 2 introduces background information covering concepts and history of the Global Positioning System (GPS). A basic knowledge of these topics will facilitate understanding of the following chapters.

Chapter 3 discusses the GPS signal transmitted from the satellites. Knowing how the GPS signal is generated and what its individual components are aids in the receiving process analysis.

Chapter 4 analyzes the process of receiving GPS signals. Computer simulation programs were designed and developed to model a GPS satellite and a GPS receiver. By using simulation techniques various receiver topologies may be analyzed and optimized.

Chapter 5 discusses the conclusions drawn from the simulation and research performed.

CHAPTER 2

BACKGROUND INFORMATION

The Global Positioning System (GPS) with all-weather, three-dimensional accuracies ranging from meters to sub-meters, brings worldwide navigating to a new all time high plateau. Many years of research and development involving various branches of the United States Government and commercial contractors have culminated in the GPS program called NAVSTAR.

The infancy stages of GPS began in the early 1960s with the Navy's TRANSIT Navigation system developed for the Polaris submarine fleet. Following TRANSIT, both the Navy and Air Force developed their own programs called TIMATION and 621B respectively. Refer to reference one. As a result of taking the best concepts from both systems, the NAVSTAR Global Positioning System (GPS) was born.

The NAVSTAR system consists of the control, user, and space segment. Figure 2.1 depicts the NAVSTAR system concept. The control segment provides a method of uploading information to the space vehicles (satellites). Upload stations are located throughout the world to enable strategic communication with the satellites. The user segment consists of all the GPS receivers -- land, sea, or air. The space segment consists of all the satellites.

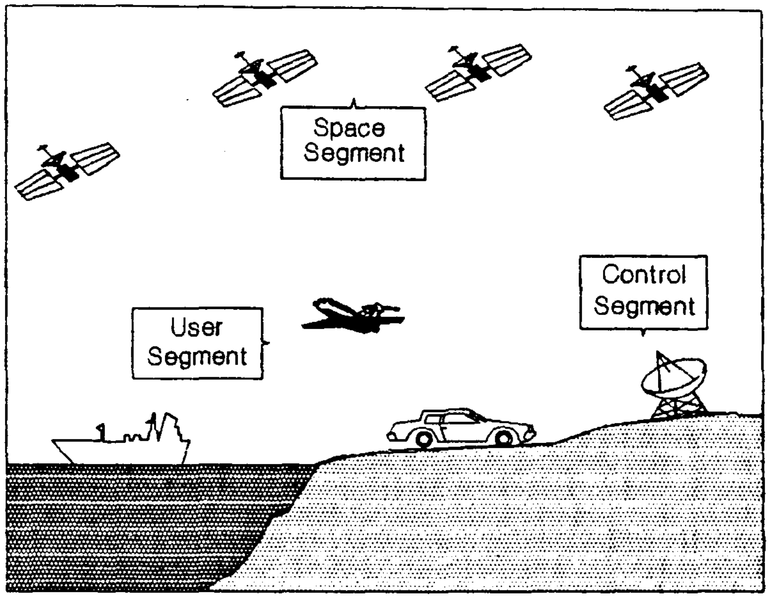

Figure 2.1: NAVSTAR System Concept

In the 1970s the first NAVSTAR satellites were launched for test purposes. Due to space shuttle launch delays the current satellite constellation consists of a limited number of working satellites, with plans for an entire operational constellation by the early 1990s.

GPS Navigation Theory

The GPS navigation theory is based on orbiting satellites continually transmitting their position and time. This allows receivers to derive their own position and time. A planned constellation of twenty-four satellites orbiting asynchronously around the earth will provide all weather, worldwide, three dimensional navigational information. Figure 2.2 depicts the proposed satellite constellation.

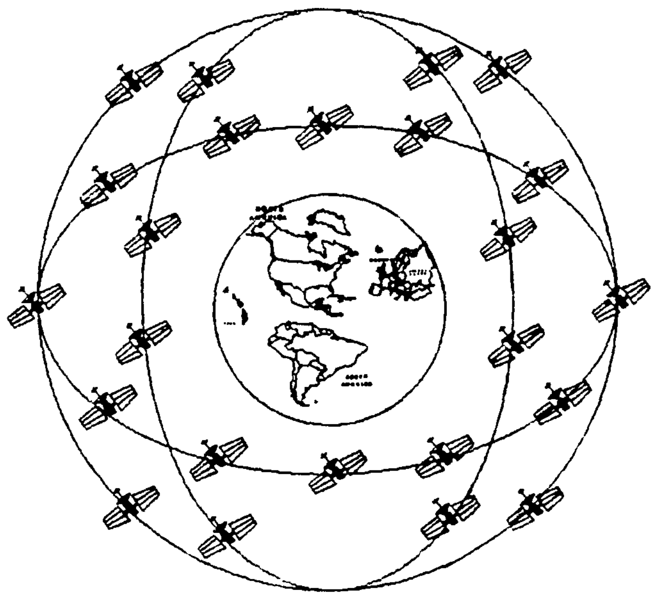

Figure 2.2: GPS Satellite Constellation

Each satellite broadcasts an Ultra High Frequency (UHF) signal telling its specific position, message transmission time, and information regarding the entire satellite constellation. Each satellite's signal contains a unique identifying code. After acquiring the signals from the satellites, a receiver may derive its position and time. Using the speed of light as constant and calculating the time delay between when the message is sent and received, the receiver determines the distance from the satellites.

Satellite and Receiver Geometry The first step in calculating the receiver's position involves determining the range between the receiver and the satellites. The process can be thought of empirically as the intersection of three spheres described as follows: 1) one satellite creates a sphere; 2) the second satellite's sphere intersects with the first, forming a circle; 3) the circle intersects with the third satellite's sphere producing two points, one being unrealistic, leaving one point indicating current position. See Figure 2.3 for a graphical representation. A fourth satellite allows correction for the receiver's internal clock bias.

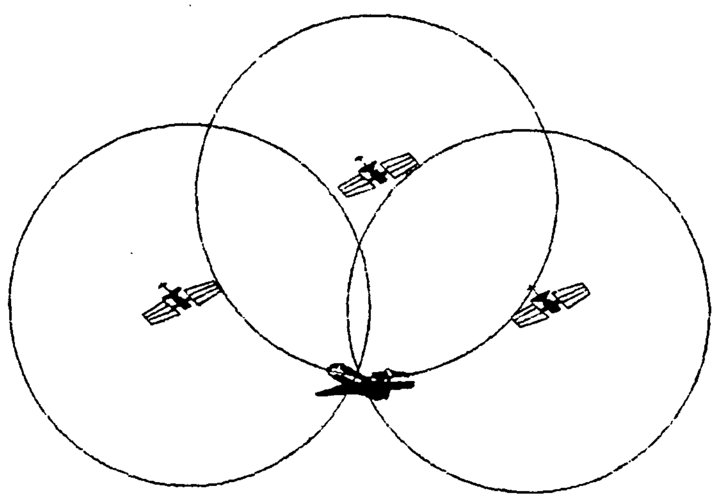

Figure 2.3: GPS Satellite to User Geometry

Receiver Position Calculation A more analytical approach to determining a three dimensional position from rotating satellites approximately 20,000 Km above the earth involves solving four nonhomogeneous equations with four unknowns.

The four equations evolve from calculating the ranges between four satellites and the receiver. A single Pseudo-Range (PR) equals the difference in time from transmission to reception multiplied by the speed of light. Figure 2.4 graphically depicts the pseudo range to user geometry.

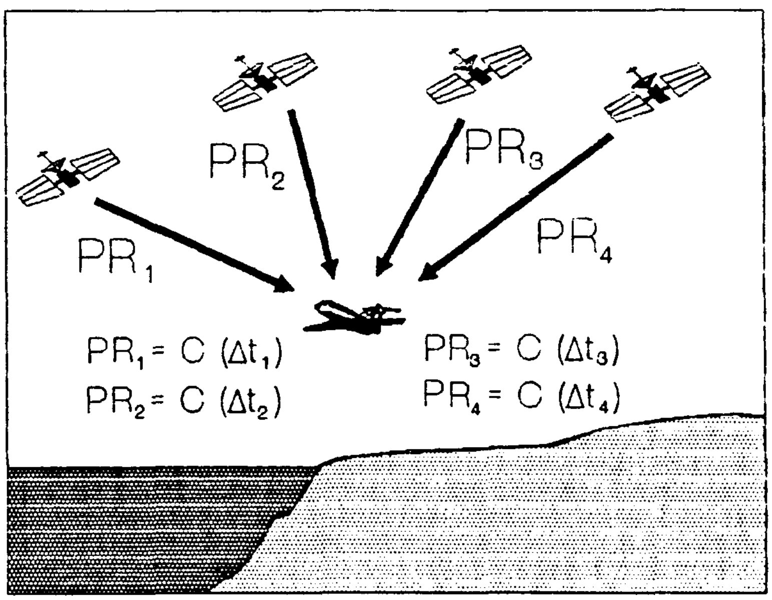

Figure 2.4: GPS Pseudo Range to User Vectors

The following Equation 2.1 details the pseudo range calculations. Refer to reference two.

$$PR_i = C\,(t_{RX(i)} - t_{TX(i)}) \qquad 2.1$$

Where: C = Speed of Light
i = Satellite Number (e.g., 1,2,3,4....)
t_{RX} = Time Satellite Message Received
t_{TX} = Time Satellite Message Sent

The equation may be further expanded by taking into account atmosphere, satellite and user clock errors. Figure 2.5 pictorially illustrates the vectors describing the entire system.

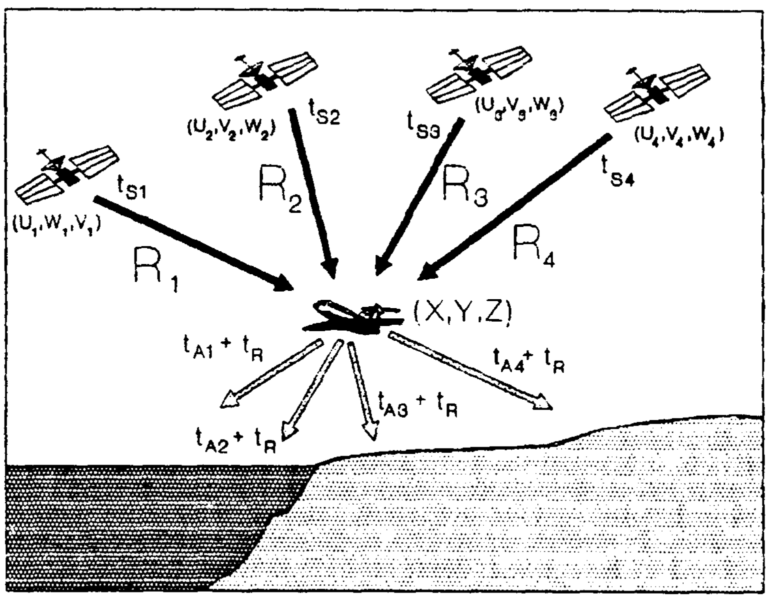

Figure 2.5: GPS Position Vectors with Atmosphere and Clock Errors

Equation 2.2 mathematically describes the pseudo range in terms of true range and delays caused by the receiver's clock, the satellites' clocks and the atmosphere.

$$PR_i = R_i + C(t_{A(i)} + t_{R(i)} - t_{S(i)}) \qquad 2.2$$

Where: R_i = True Range Between Satellite and Receiver
t_A = Time Delay Caused by the Atmosphere
t_R = Time Delay Caused by the Receiver's Clock
t_S = Time Delay Caused by the Satellite's Clock

To solve for the true range (R_i), let a common coordinate system be used -- Earth-Center-Earth-Fixed (ECEF). Denote the receiver's position by (X,Y,Z) and the various satellites' positions by (U_{si},W_{si},V_{si}) where i equals the respective satellite. The ephemeris data provide the satellite's position (U_{si},W_{si},V_{si}) and clock error (t_S). The atmosphere error (t_A) may be estimated by comparing the pseudo-ranges at the two carrier frequencies L_1 and L_2. This leaves four unknowns X, Y, Z and t_R with the following four equations:

$$PR_1 = ((U_1-X)^2+(W_1-Y)^2+(V_1-Z)^2)^{1/2} + C(t_{A(1)}+t_{R(1)}-t_{S(1)}) \qquad 2.3$$
$$PR_2 = ((U_2-X)^2+(W_2-Y)^2+(V_2-Z)^2)^{1/2} + C(t_{A(2)}+t_{R(2)}-t_{S(2)}) \qquad 2.4$$
$$PR_3 = ((U_3-X)^2+(W_3-Y)^2+(V_3-Z)^2)^{1/2} + C(t_{A(3)}+t_{R(3)}-t_{S(3)}) \qquad 2.5$$
$$PR_4 = ((U_4-X)^2+(W_4-Y)^2+(V_4-Z)^2)^{1/2} + C(t_{A(4)}+t_{R(4)}-t_{S(4)}) \qquad 2.6$$

Where: PR = Pseudo Range between Satellite and Receiver
U,V,W = Satellite Position
X,Y,Z = Receiver Position

The first three satellites provide a dimension in the navigation solution with the fourth satellite eliminating any receiver clock errors. The following Table 2.1

describes the position information available with different number of satellites.

Table 2.1: Position Information from Satellites

# Satellites	Position Information
1	1 Dimension
2	2 Dimensions
3	3 Dimensions
4	" " & Clock Corrections

Various approaches from simple algebraic manipulation to a more advanced Kalman filter technique may be used to solve the equations. Recently, Kalman filter techniques have gained great popularity.

Kalman Filtering

The Kalman filter, often referred to as a best guess estimator technique, was first introduced in R. E. Kalman's paper entitled "A New Approach to Linear Filtering and Prediction Problems" March 1960. Refer to reference three. The basic concept of a filter weighting was defined by Wiener in the 1940s. Kalman applied Wiener's work and developed a recursive approach that had practical application. The Kalman filter is typically applied today in a computer algorithm which allows the optimal processing of discrete data samples.

The filter consists of four fundamental steps: 1) calculate Kalman gain (value used to minimize the mean square error) given a prior estimate and error; 2) update the estimate with a new measurement; 3) compute the error covariance for the updated measurement; and 4) project ahead, determining a new estimate and error. The Kalman filter sequences through all four steps and then repeats. This recursive nature is ideally suited for implementation as a computer-based algorithm. Reference four discusses and details computer based applications.

With the Kalman filter approach, wide shifts in the measurements cause minor changes in the actual solution; also, new measurements may be added to the solution. For example, Inertial Navigation System (INS) data may be added to the estimated GPS solution by adding another state to the Kalman filter.

CHAPTER 3

GPS TRANSMITTER

The GPS signal transmitted by the satellites consists of four primary parts: 1) Carriers L_1 (1.575 GHz) and L_2 (1.227 GHz); 2) 50 Hz data; 3) Coarse Acquisition (C/A) Code (1.023 MHz); and 4) Precision (P) Code (10.23 MHz). The "50 Hz data" is a 50 Hz bit stream containing information from the satellites. The "C/A Code" and "P Code" are satellite unique Pseudo Random codes that identify each GPS satellite. The 50 Hz data, C/A code and P code modulate the L_1 carrier while only the P code modulates the L_2 carrier. Reference five defines and controls the GPS interface. A GPS satellite transmitter block diagram shown in Figure 3.1 illustrates the process of generating the GPS L_1 and L_2 signals.

The satellites transmit on two different carrier frequencies L_1 and L_2 to enhance the correction of media transmission errors. Due to the ionosphere affecting the two frequencies differently, comparing results between the two carriers allows for ionospheric correction.

The 50 Hz information allows the satellites to provide timely information to the receivers (i.e., satellite position, health, clock errors, almanac data). The C/A code allows easy acquisition while the P code provides more "Precise" information and improved Anti-Jamming characteristics. Both codes are considered to be "Pseudo Random" bit streams. They appear truly random; however, they are not because they have a periodic pattern. The C/A code repeats every one msec and the P code repeats every seven days.

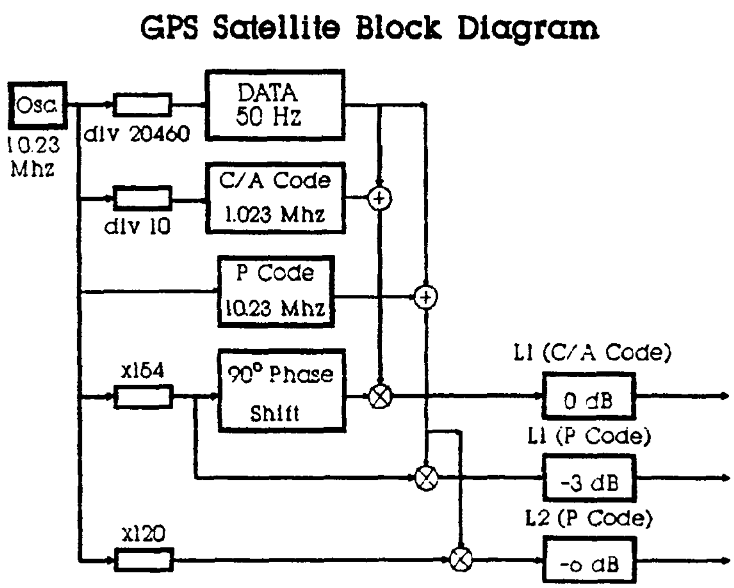

Figure 3.1: GPS Satellite Transmitter Block Diagram

The following sections detail the GPS signal characteristics.

50 Hz Data

The 50 Hz data phase modulates the C/A and P code on the L_1 carrier and the P code on the L_2 carrier. The data provide a means of transferring information, updated by the control segment, from the satellites to the receivers. The 50 Hz data provide the following information: 1) handover word used to switch from C/A to P code; 2) unique satellite position and time (ephemeris data) information; and 3) satellite constellation information regarding the positions and health of all the current satellites (Almanac data). Reference six details the GPS navigational message. The data are monitored and updated by a world-wide network of control stations.

All the data are transmitted in frames. Each frame has 5 subframes; each consisting of 1500 bits. A bit period of 20 msec yields a 50 Hz rate, hence the name 50 Hz data. The bits follow a NonReturn-to-Zero (NRZ) format.

Subframes begin with a Telemetry word and Handover word. The first subframe provides satellite clock and atmosphere information. Subframes two and three have ephemeris data describing the satellites unique orbit. Special control segment messages are sent on subframe four. Subframe five contains $1/25^{th}$ the information describing the entire satellite constellation (Almanac data). In order to receive the entire almanac data, subframe five must be decoded 25 times.

The 50 Hz data allow the receiver to calculate the range to a given satellite (i.e., Pseudo Range), determine precise time, and to systematically search for additional satellites. The clock data and ephemeris information enables the pseudo range calculation. The almanac data determine which satellites to search for and the health of all the satellites.

Coarse Acquisition (C/A) Code

Each satellite modulates its L_1 carrier with a unique 1023-bit code called the "C/A Code". The code is the modulo-2 sum of two unique 1023-bit Pseudo Random codes generated by two 10-bit shift registers. The different satellite codes are created by varying the tap points on the shift register. Figure 3.2 shows a C/A code generator block diagram.

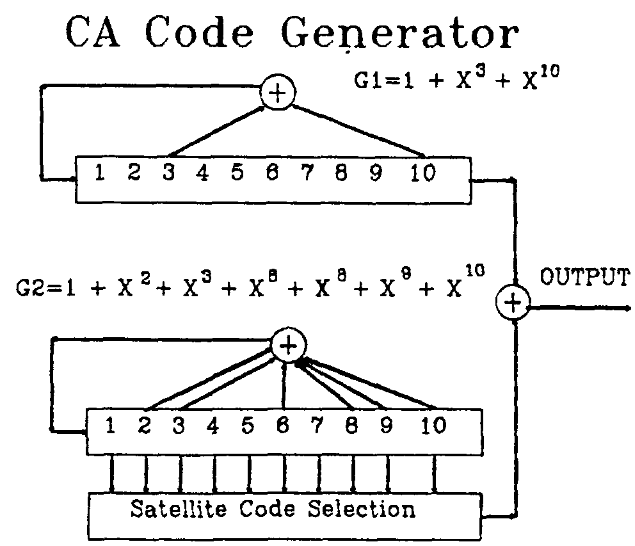

Figure 3.2: C/A Code Generator Block Diagram

The following formula describes C/A code:

$$G_i(t) = G_1(t)G_{2i}(t) \qquad 3.1$$

Where: $G_1 = X^{10} + X^3 + 1$
$G_2 = X^{10} + X^9 + X^8 + X^6 + X^3 + X^2 + 1$
$G_{2i} = G_2$ (delayed by mod-2 summing two outputs)

The C/A code bit stream is multiplied with L_1 shifted by 90°. The bit stream's clock rate is 1.023 MHz. When multiplied with the L_1 signal, it spreads the composite signal +/- 1.023 MHz from L_1.

<u>Precision (P) Code</u>

The 10.23 MHz "Precision" (P) code used for precise navigation repeats every 7 days. P code provides slightly

better accuracy and improved jamming resistance over C/A code. P code modulates both L_1 and L_2 at 10.23 MHz. The actual P code would run for slightly over 38 weeks without repeating. The code is subdivided into 37 non-overlapping sections with each satellite being assigned a unique section. The control segment creates an exact seven day cycle by resetting the code every Saturday at midnight. Transmitting P code on both L_1 and L_2 allows receivers to correct for ionospheric errors by comparing the data between L_1 and L_2.

The P code data pattern P_i is generated by the modulo-2 sum of two codes X_1 and X_{2i}. X_1 is the modulo-2 sum of X_{1A} and X_{1B} generated by two 12 bit shift registers. The X_{2i} is produced in similar manner as the X_1 sequence; however, the sequence is delayed by a selected number of chips (i.e., i equal 1 to 37) which produce 37 unique identifying codes.

The following P code generator block diagram shows the scheme for generating P code.

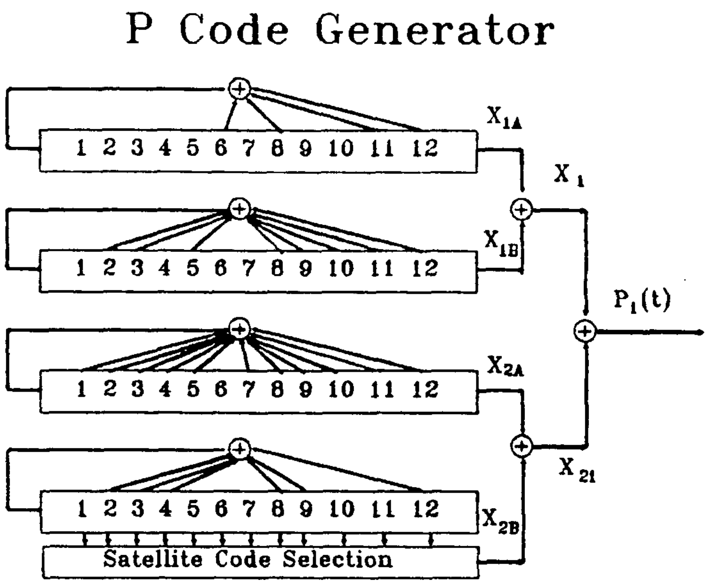

Figure 3.3: P Code Generator Block Diagram

The following formula describes the P code generation:

$$P_i(t) = X_1(t)X_{2i}(t) \qquad 3.2$$

Where: $X_1 = (X_{1A})(X_{1B})$

$X_{1A} = X^{12}+X^{11}+X^{8}+X^{6}+1$

$X_{1B} = X^{12}+X^{11}+X^{10}+X^{9}+X^{8}+X^{5}+X^{3}+X^{2}+X^{1}+1$

$X_{2i} = (X_{2A})(X_{2B})$

$X_{2A} = X^{12}+X^{11}+X^{10}+X^{9}+X^{8}+X^{7}+X^{5}+X^{4}+X^{3}+X^{2}+X^{1}+1$

$X_{2B} = X^{12}+X^{9}+X^{8}+X^{4}+X^{3}+X^{2}+1$

Mathematical Description

Mathematically the combined 50 Hz data, C/A Code, and P Code transmitted on L_1 and L_2 may be described by the following expressions:

$$L_1 = \underbrace{AP_i(t)D_i(t)\cos w_1 t}_{\text{P Code}} + \underbrace{2AG_i(t)D_i(t)\sin w_1 t}_{\text{C/A Code}} \quad 3.3$$

$$L_2 = \underbrace{AP_i(t)D_i(t)\cos w_2 t}_{\text{P Code}} \quad 3.4$$

Where: L_1 = GPS Satellite Signal Transmitted on L1
L_2 = GPS Satellite Signal Transmitted on L1
A = Amplitude (note C/A code approx 2 x P code)
P_i = Precision (P) code of satellite i
G_i = Gold or C/A code of satellite i
D_i = 50 Hz Data of satellite i
i = Indicates satellite number

Frequency Spectrums

Figures 3.4 and 3.5 illustrate the frequency spectrum of L_1 and L_2 respectively.

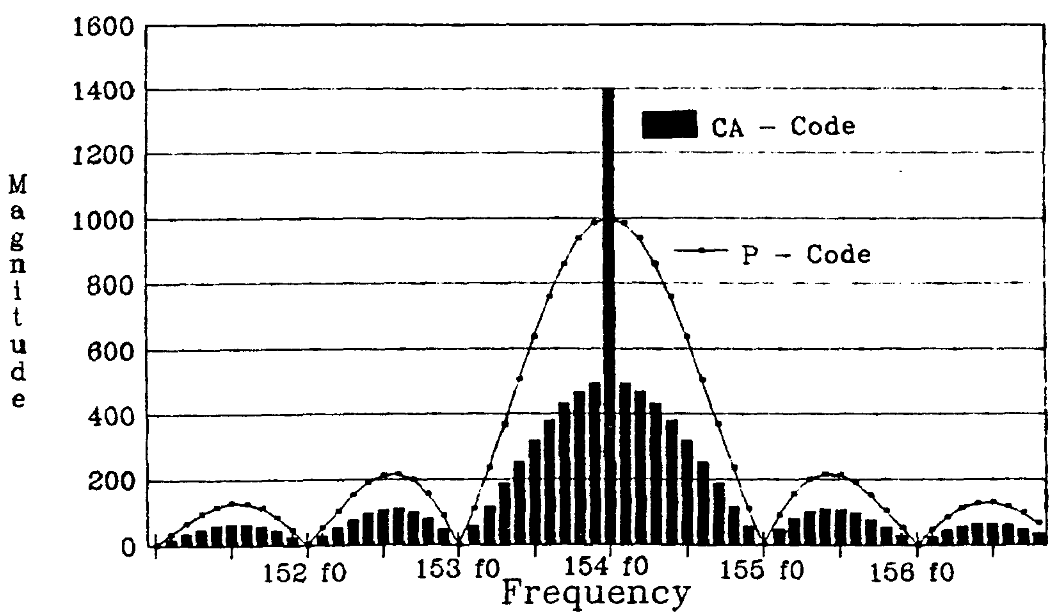

Figure 3.4: GPS L1 Signal Power Spectral Density

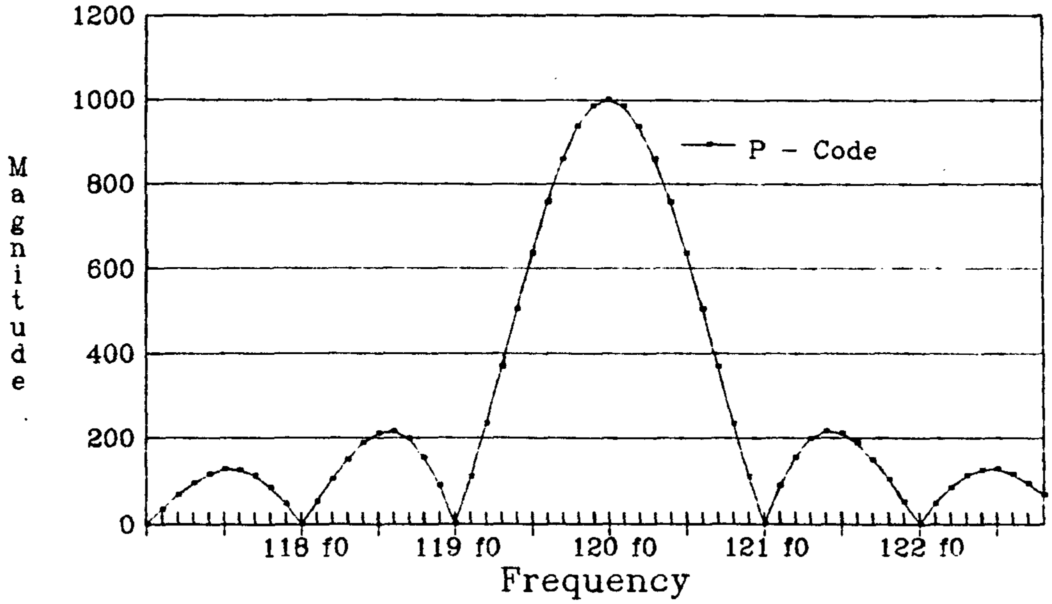

Figure 3.5: GPS L2 Signal Power Spectral Density

CHAPTER 4

GPS RECEIVER

The GPS receiver section explores retrieving information from the GPS signals transmitted by the satellites. The receiver's design objectives emphasized utilizing Digital Signal Processing (DSP) techniques. The techniques are currently possible with the widespread availability of high speed DSP chips.

Computer simulations modeling a GPS transmitter and receiver were written and analyzed. The routines were written with Microsoft C 5.1 and hosted on a Zenith '386 work-station.

The computer simulation enables the investigation of the receiver's acquisition and tracking performance. The GPS signal appears to the receiver as a low level (-163 dBw), typically below thermal noise, Pseudo Random signal. The transmitter simulation implements an algorithm to simulate the satellite's signal containing L_1 carrier, C/A code, 50 Hz data, and noise information.

The C/A code generator and 50 Hz data algorithm replicated the shift register and mixer method described in GPS Signal Characteristics Section. A Gauss Markov noise generator was used to degrade the transmitted signal by a broad band noise closely resembling that found in actual real world conditions.

The receiver design consists of three primary sections: 1) Radio Frequency (RF); 2) Digital Signal Processing (DSP); and 3) User Interface. Appendix II contains a simplified receiver block diagram. The modeling and analysis emphasizes the DSP algorithms necessary to acquire and track GPS signals.

RF Section

The RF section starts at the antenna and ends with the beginning of the DSP section. The RF section provides the DSP section with a usable signal.

As discussed previously in Chapter 3, the GPS signals are transmitted on two carrier frequencies (1.575 & 1.227 Ghz). The RF section converts the signals down to a frequency usable by the DSP section. The doppler frequency was used for the simulation. The final carrier shift from the nominal frequency was assumed to be doppler.

The following block Diagram 4.1 represents the RF section simulated.

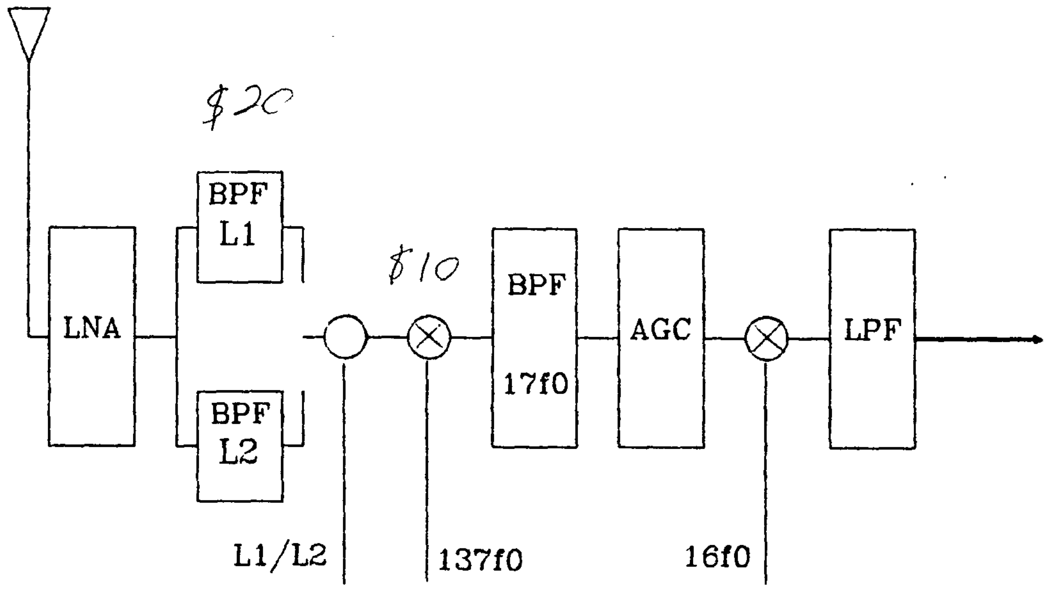

Figure 4.1: RF Section Block Diagram

The antenna provides gain at L_1 and L_2. The broadband signal from the antennas passes into a Low Noise Amplifier (LNA) to provide gain. The LNA amplifies the broadband signal. The signal then passes through a Band Pass Filter (BPF) for either L_1 or L_2 depending on the desired carrier.

The first mixer stage multiplies the signal by 137 f_0 converting the signal down to 17 f_0 for both L_1 and L_2. The second mixer stage multiplies the signal by 16 f_0 leaving the signal down converted to an IF of f_0 plus any doppler.

The signal is then passed to the DSP section where the simulation concentrated on decoding the 50 Hz data and the doppler information.

Digital Signal Processing (DSP) Section

The DSP section retrieves the 50 Hz data and doppler information from the down converted signal. The DSP section consists of two primary functions: 1) Analog to Digital (A/D) conversion and 2) processing the digital samples. The signal from the RF section is converted to digital samples. The samples are then processed to retrieve the 50 Hz data and the doppler. The following block diagram 4.2 illustrates the DSP section.

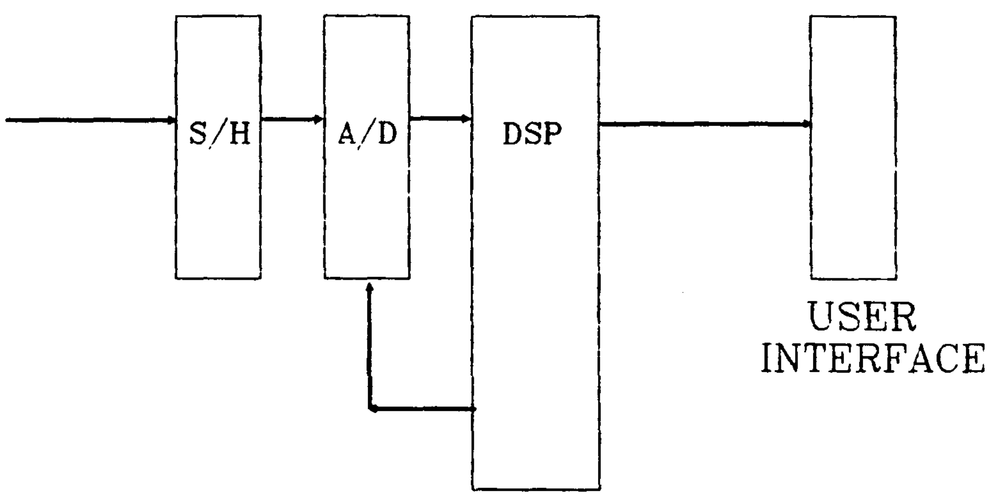

Figure 4.2: DSP Section Block Diagram

Analog to Digital Conversion The analog to digital conversion process samples the incoming analog signal and converts it to a digital sample. The analog signal is sampled and then held steady while the digital conversion takes place. The process must be capable of handling the rate and timing constraints of the processing algorithm.

The sample and hold must be able to track the incoming signal properly and when commanded hold the signal until the digital conversion process is completed. The digital conversion process supplies the processing algorithm with the samples when needed.

Processing Algorithm A Fast Fourier Transform algorithm was chosen to process the digital samples for the following reasons: 1) allows wide frequency spectrum analysis; 2) easily implemented as a computer algorithm; and 3) adaptive to varying degrees of resolution and processing time. The following sections discuss FFT principles and results with varying GPS signals (i.e., Bit sync error and noise).

FFT Principles Acquiring a GPS signal involves mixing an internally generated code with an incoming signal. The resultant power output is proportional to how close the signals are correlated. An FFT provides a convenient method for monitoring the magnitude, frequency and phase information. This information enables the acquiring and tracking of GPS signals.

An FFT may be thought of as a group of parallel filters with each output detector monitoring a particular frequency range. The block diagram in Figure 4.3 depicts this conceptual approach to an FFT. The input filters are evenly distributed across the desired frequency. The output detectors for each of the filters provide phase and magnitude information.

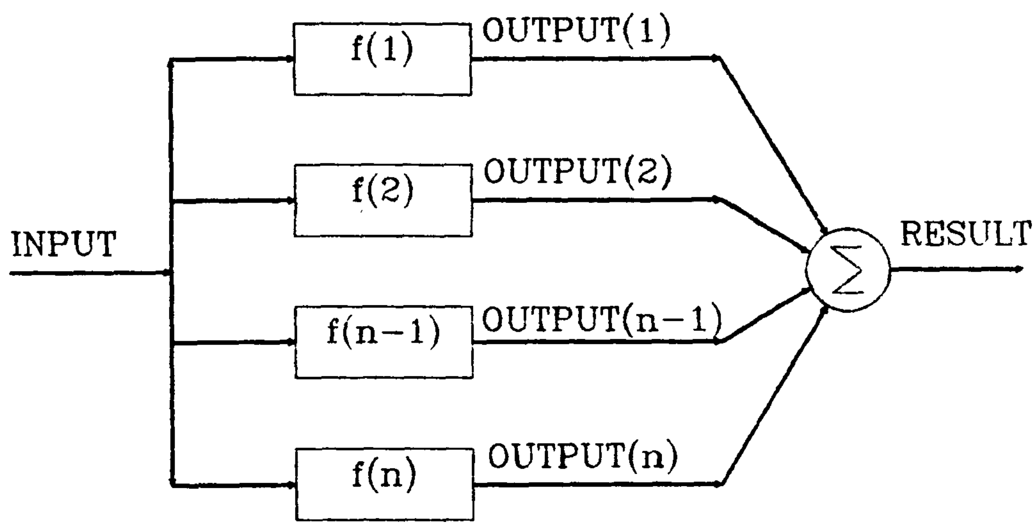

Figure 4.3: FFT Block Diagram

The total frequency spectrum containing meaningful data follows the Nyquist sampling theorem -- sampling rate must be at least twice the highest desired frequency. The sampling frequency and FFT size (number of points) determines the frequency resolution between points. The FFT's resolution equals the sampling frequency divided by the FFT size. The following formula mathematically describe this relationship.

$$\text{Resolution} = \frac{f_s}{\#\text{FFT Pts}} \qquad 4.3$$

Where: f_s = Sampling Frequency
#FFT Pts = FFT size (Number of FFT Points)

A few general observations may be made. As the sampling frequency increases, the total observable frequency increases; however, the frequency separation between FFT points increases thereby degrading the resolution. As the number of FFT points increase, the resolution improves; however, computational processing requirements also increase. Considering these fundamental relationships several tradeoffs may be made. For example, on initial acquisition the resolution may not be as important as covering a large frequency spectrum as fast as possible. After acquisition, better resolution may improve the accuracy and solution.

Resolution As the number of FFT points increases, the frequency resolution improves. The following two figures illustrate this relationship. Figure 4.4 shows the resolution attained with a 32-point FFT versus a 512-point FFT while Figure 4.5 compares resolution with the number of FFT points at different sampling frequencies.

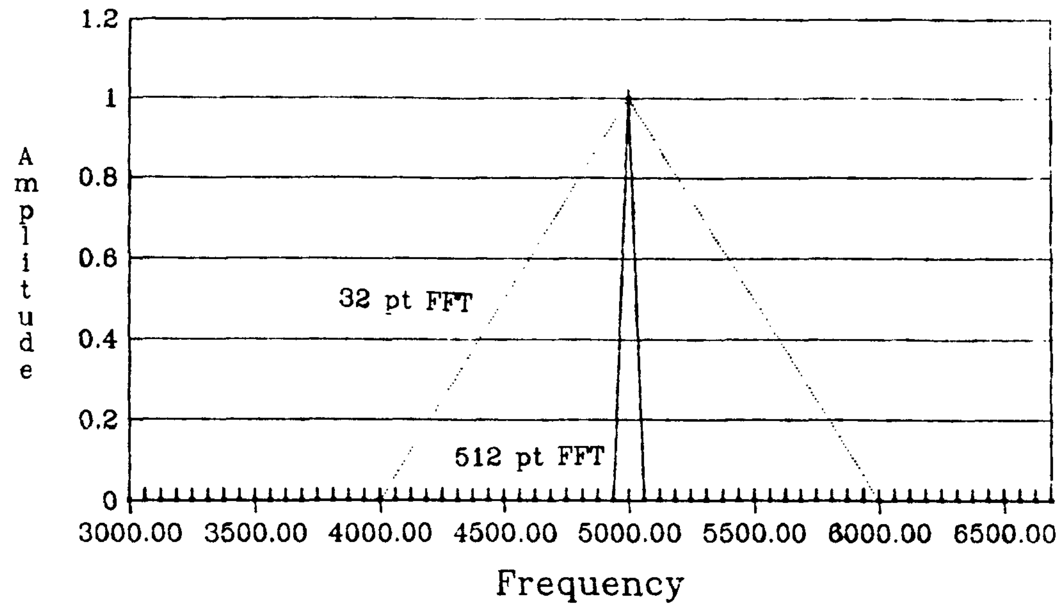

Figure 4.4: 32 Point vs 512 Point FFT

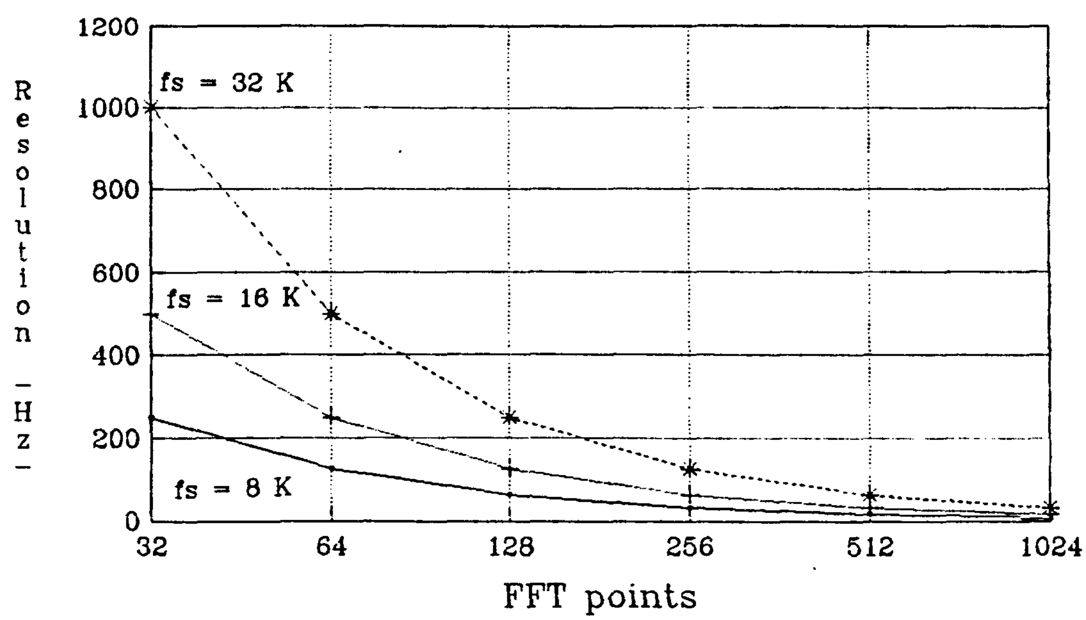

Figure 4.5: Resolution vs FFT Points at Various Sampling Frequencies

Bandwidth The FFT input filters have individual bandwidths. The resolution describes the frequency between FFT points. The gain, however, is not constant between the points. As the frequency changes, the gain changes producing a filter bandwidth.

An example illustrating the input filter bandwidth involves varying the input signal while keeping the FFT parameters constant. Figure 4.6 illustrates the results. The maximum gain occurs exactly on the FFT point with the minimum gain occurring halfway between the FFT points.

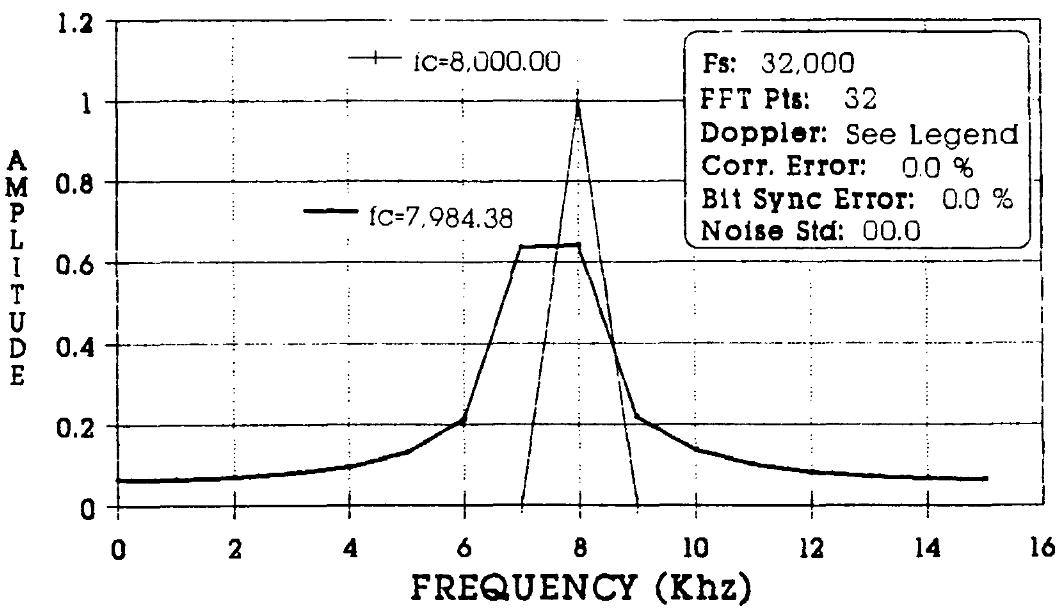

Figure 4.6: Signal at Sample Point and 50% between a Sample Point

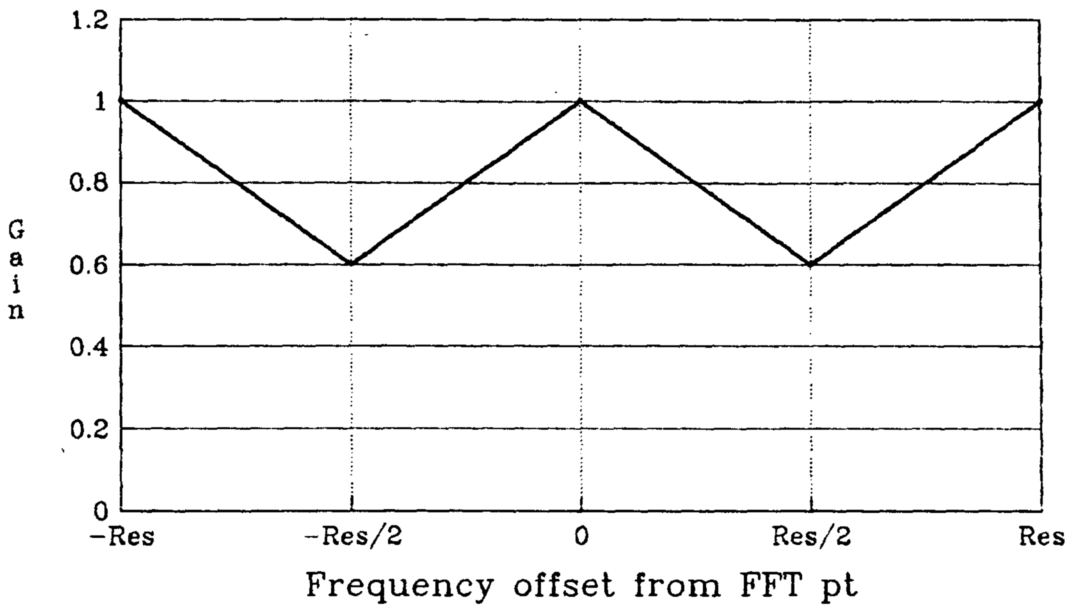

Figure 4.7: Gain vs Sample Point Position

Noise Effects When dealing with GPS signals, noise effects must be considered. Since typically the desired signal is below the thermal noise, there must be enough processing gain and filtering to isolate the signal from the noise. One way of reducing the noise effects is by summing the FFT results.

Noise found with GPS signals may be modeled with a Gausian distribution function. Figure 4.8 illustrates the GPS signal with and without noise.

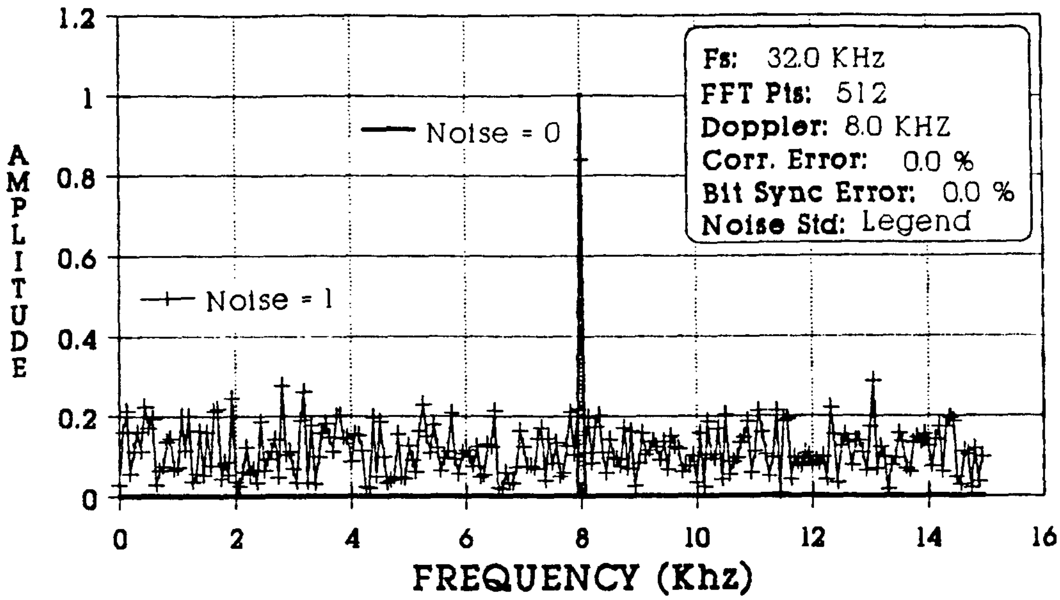

Figure 4.8: Signal With and Without Noise

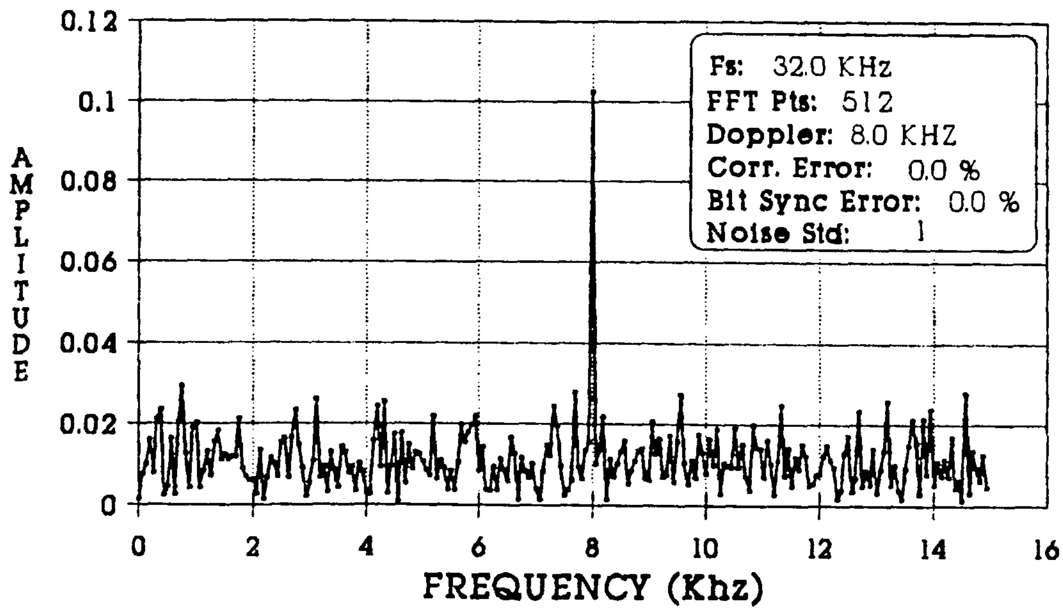

Figure 4.9: Spectrum of Noisy Signal

Figure 4.9 shows the spectrum of a noisy signal and the result of summing previous data. The noise, being random, cancels out over time.

A slight variation of the noise reduction method stated above involves weighting all signals considered noise. By setting a minimum threshold and assigning all the magnitudes falling below this threshold a small or zero value, the noise values will cancel out faster.

Bit Sync Error Effects Bit sync error refers to the offset between when a new data bit actually begins and when the system thinks the bit begins. A 180° carrier phase shift indicates the start of a new data bit. The detection of such a phase shift enhances data decoding. At the very least, knowing how the FFT handles a bit boundary provides useful information.

Without any bit sync error, the FFT produces the standard output expected. Introducing a phase shift and using samples on either side of the shift in an FFT calculation yields interesting results. Figure 4.10 illustrates the 180° phase shift.

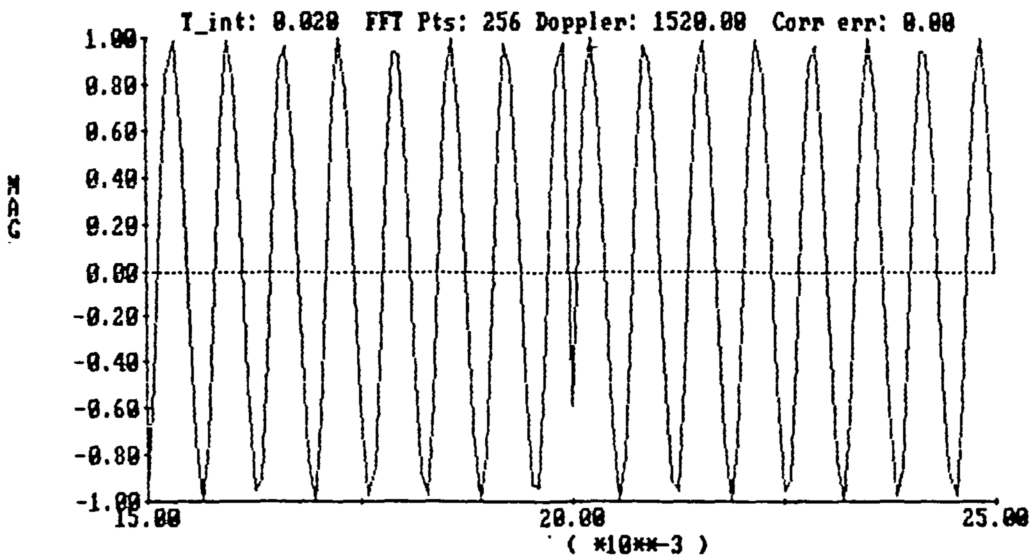

Figure 4.10: Carrier with 50 Hz Data Bit Shift
Shown in the Time Domain

As the bit sync error approaches 50%, (i.e., half the FFT points are before and half are after the phase shift), the output magnitude becomes less. Figures 4.11, 4.12 and 4.13 illustrate the FFT's results with 0%, 25% and 50% bit sync error respectively.

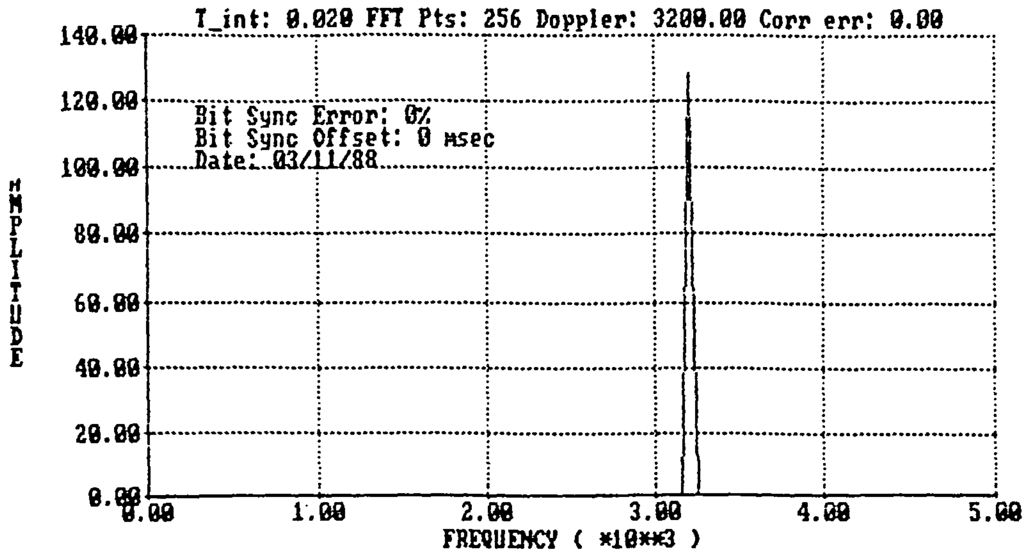

Figure 4.11: Carrier with 50 Hz Data Bit Shift and Zero Bit Sync Error

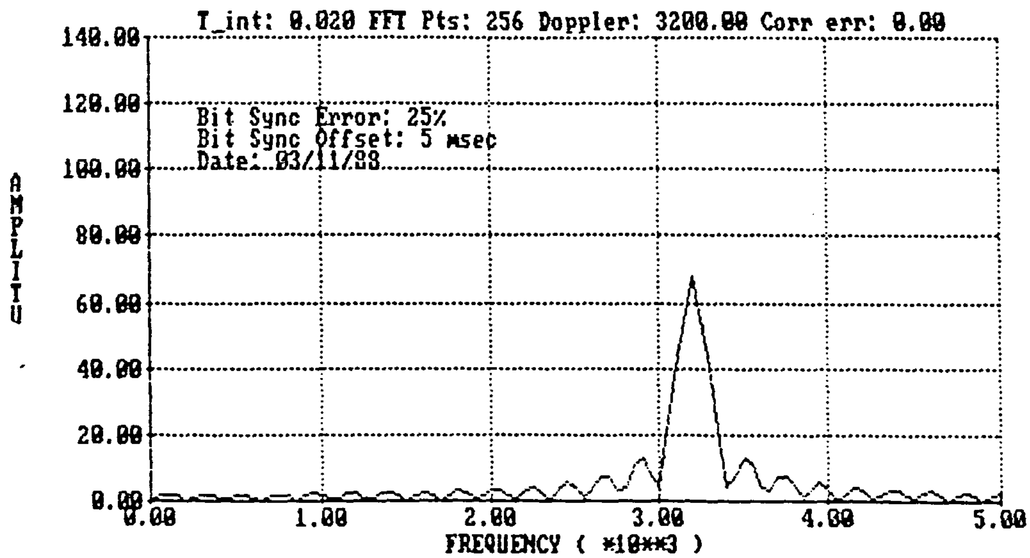

Figure 4.12: Carrier with 50 Hz Data Bit Shift and 25% Bit Sync Error

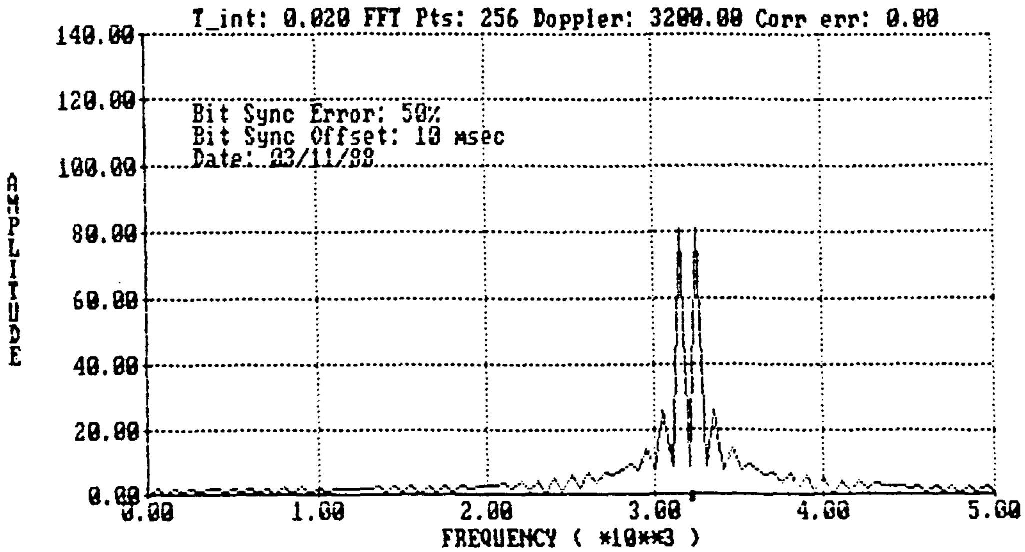

Figure 4.13: Carrier with 50 Hz Data Bit Shift and 50% Bit Sync Error

GPS Signal Acquisition

Given the GPS signal structure presented earlier, the goal is now for the receiver to acquire and track signals from different satellites. By despreading the GPS signal, it's possible to detect and track different satellites. Despreading the signal may be accomplished by matching an internally generated code with that of the received signal.

The process of mixing the internally generated code with the received signal is typically referred to as the correlation process. The codes are independent which means the process is actually a cross correlation rather than an auto correlation process. Figure 4.14 illustrates how the output signal varies with how close the codes match - the closer correlated the codes, the larger the correlation output.

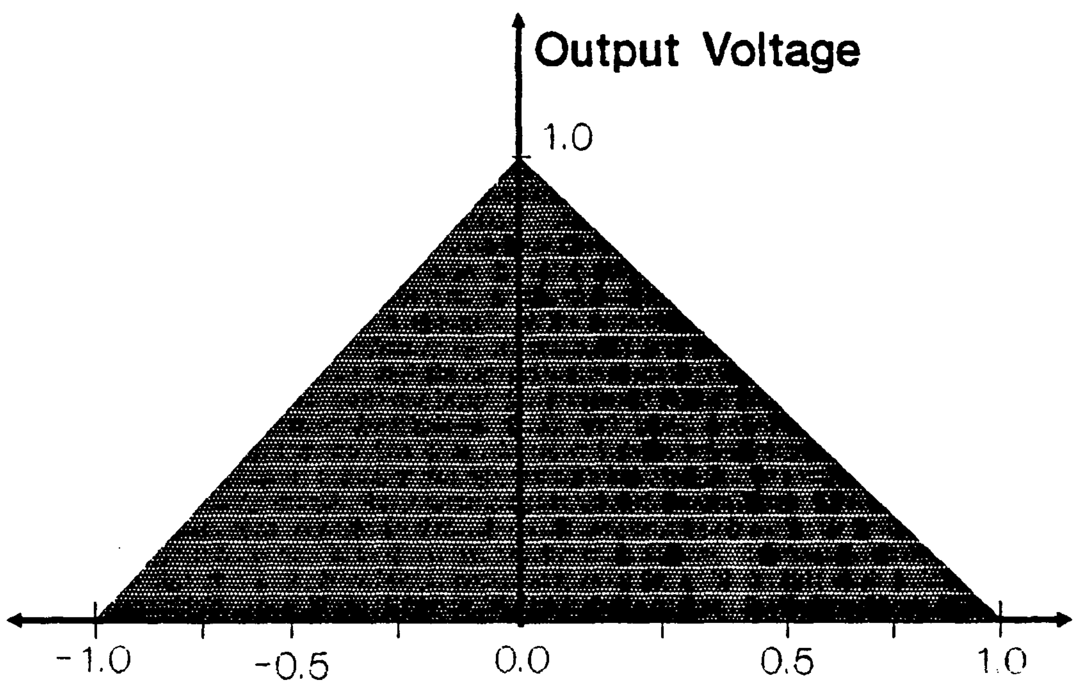

Figure 4.14: Cross-Correlation Function

By slewing the receivers C/A or P code back and forth while monitoring the cross correlation output, the two codes may be aligned. Matching the codes allows the processing of doppler and 50 Hz data information. The doppler information is derived from the frequency shift necessary to match the receiver's internal code with the received signal necessary for correlation. The frequency shift varies with respect to the nominal center code frequencies of 1.023 Mhz or 10.23

Mhz. With the codes aligned, the carrier phase may be monitored. A carrier phase change indicates the beginning of a new data bit. By monitoring the phase changes and 20 msec periods, the 50 Hz data may be decoded.

GPS Signal Tracking

After acquisition, the objective is to continually track the signal. This tracking loop must take into account the continually changing satellite and receiver dynamics. There are many different tracking algorithms. These algorithms typically involve monitoring the cross correlation output, tracking the carrier phase, or combining both.

The cross correlation output provides information on how closely the codes are matched. The closer the codes are aligned, the higher the output. Optimizing the power output by aligning the code may be thought of as code tracking or code lock.

The carrier phase provides a precise method of tracking the signal. Using a Phase Lock Loop (PLL) analogous to the Frequency Lock Loop (FLL) (which tracks phase versus frequency), slight variations in phase may be detected and corrected for. As the carrier's phase shifts slightly, the code may be slewed one way or another. Tracking the carrier phase may be thought of as carrier lock.

A combination of both code and carrier lock may be used. Code lock typically provides for approximate information while the carrier lock furnishes more precise data. Frequently, the control loop receives both code and carrier information depending on the dynamics.

CHAPTER 5

CONCLUSIONS

The GPS signal transmitted by the orbiting satellites resembles Pseudo Random noise, below that of thermal noise, when detected by a receiver. The receiver decodes the received signal and derives position, velocity and time information. Utilizing Digital Signal Processing (DSP) techniques the process of reliably and economically receiving GPS signals may be greatly improved.

A computer simulation program was written and tested to demonstrate recovering data from a GPS signal using DSP techniques. The algorithm implements a Fast Fourier Transform technique (FFT) to recover the 50 Hz data and doppler information from a GPS signal. Simulations were run with varying environmental and system conditions (i.e., FFT points, noise, doppler).

The simulation results indicated that the 50 Hz data and doppler information could be derived and tracked. Applying this technique to a receiver design would greatly improve the reliability and flexibility of its design compared with conventional approaches.

The Global Positioning System represents the most advanced navigational system available in the world.

Utilizing a network of satellites, the system will provide unprecedented all weather worldwide coverage. As the system becomes fully operational in the early 1990s military and civilian applications will expand.

BIBLIOGRAPHY

1. R. J. Milliken and C. J. Zoller. "Principle of Operation of NAVSTAR and System Characteristics." Institute of Navigation, 1 (1980): 3-14.

2. J. J. Spilker, Jr. "GPS Signal Structure and Performance Characteristics." Institute of Navigation, 1 (1980): 29-54.

3. R. E. Kalman. "A New Approach to Linear Filtering and Prediction Problems." Trans. of the ASME-J. of Basic Engr. Vol #1, (March 1960):35-45.

4. R. G. Brown. Introduction to Random Signal Analysis and Kalman Filtering. New York: Wiley, Inc., 1983.

5. "The GPS Interface Control Document." Prepared by Rockwell International Corporation, Seal Beach, California, September 1975.

6. A. J. Van Dierendonck, S. S. Russell, E. R. Kopitzke and Birnbaum. "The GPS Navigation Message." Institute of Navigation, 1 (1980): 55-73.

Other References:

7. Kai P., Yiu, Crawford, Richard and Ralph Eachenbach. "A Low-Cost GPS Receiver for Land Navigation." Institute of Navigation, 2 (1984): 44-60.

8. W. H. Hayt, Jr., and J. E. Kemmerly. Engineering Circuit Analysis. New York: McGraw-Hill, Inc., 1978.

9. H. L. Krauss, C. W. Bostian, and F. H. Raab. Solid State Radio Engineering. New York: Wiley, Inc., 1980.

APPENDIX I - GPS FACT SHEET

Doppler Shift:

```
   Due to 1 SV +2,600 nsec/sec
   "       "   -2,600 nsec/sec
   -------------------------------
     Total.......... 7,500 Hz

   Note:  Assumes Stationary user
```

P Code:

```
   Nickname:   Blue Code
   Restart:    7 days (initiated midnight each Saturday)
   Frequency:  10.23 MHz
   Chip:       97.75 nsec
   Resolution: 29.33 meters/chip
```

C/A Code:

```
   Nickname:   Gold Code
   Epoch:      1 msec
   Frequency:  1.023 MHz
   C/A Chip:   977.52 nsec
   Resolution: 293.3 meters/chip
```

Data:

```
   Epoch:      12.5 min
   Frequency:  50 bps
   Period:     20 msec
   Bit Format: NonReturn-to-Zero (NRZ)
   Subframe:   6 sec (300 bits)
   Frame:      5 Subframes = 30 sec (1500 bits)
               #1 - TLM, HOW, Clock info, Atmosphere info
               #2 - "       ",.Ephemeris data
               #3 - "                          " & AODE
               #4 - "       ", Special Messages
               #5 - "       ", Partial Almanac data
   Almanac:    requires 25 subframe #5's (12.5 min)
   TLM:        Telemetry word (Start of Header)
   HOW:        HandOver Word changes every 6 seconds
   X1 Epoch:   1.5 seconds
   Z:          Counts X1 Epochs, max value 403,199
               (Z = 4*(HOW)
```

Miscellaneous:
f_0 = 10.23 Mhz

L_1 Characteristics:
C/A code: -160 dBW min
P code: -163 dBW min
Frequency: 154 x f_0 = 1575.42 MHz

L_2 Characteristics:
C/A code: n/a
P code: -166 dBW min
Frequency: 120 x f_0 = 1227.60 MHz

GPS Satellites:
Total: 24 (3 spares)
Orbit: Asynchronous (12 hour rotation)
Altitude: Approx. 19,652 Km (10,611 nm)
Observable: 6 to 11 satellites visible at one time

APPENDIX II - GPS RECEIVER BLOCK DIAGRAM