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Department of Electrical and Electronic Engineering
University of Nottingham

Develop a GPS/GNSS receiver: Design of Correlators for GNSS Receivers Based on VHDL

Author	Yaowen Hu(20495331)
Supervisor	Dr Paul Blunt
Moderator	Dr Sindy Phang
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Chapter 1

Introduction

In an era where precise positioning, navigation, and timing have become fundamental requirements for numerous applications, the *Global Navigation Satellite System* (GNSS) has emerged as a transformative technology. *Global Positioning System*, commonly known as GPS, has revolutionized the way we navigate, communicate, and interact with our surroundings. As the demand for accurate and reliable GNSS positioning continues to grow, there is an increasing need to explore innovative methods to develop advanced GNSS receivers capable of handling diverse and challenging environments.

The aim of this project is to design and develop a GPS/GNSS receiver, focusing on the critical component of correlators, which form the backbone of any GNSS receiver. Correlators play a vital role in the tracking part of the GNSS positioning process, making them a key element in the overall receiver architecture.

1.1 Background

The GNSS has become an integral part of modern life, transforming how we navigate, communicate, and interact with the world around us. As the demand for accurate and reliable positioning information continues to grow, there is a constant need for advancements in GNSS receiver technology. The receiver's tracking module, responsible for extracting precise positioning data from satellite signals, plays a critical role in ensuring the accuracy and robustness of the overall GNSS positioning process.

- **Increasing Reliance on GNSS:** In recent years, there has been a substantial increase in the reliance on GNSS technology across various sectors and industries. From commercial transportation and aviation to precision agriculture, emergency response, and scientific research, GNSS has become a ubiquitous tool in countless applications. The accurate positioning and timing information provided by GNSS have not only improved operational efficiency but have also enabled the development of innovative services and solutions.
- **Importance of the Tracking Module:** The tracking module is a vital component of any GNSS receiver, responsible for acquiring and locking onto the weak satellite signals and maintaining their synchronization. Efficient tracking algorithms can increase SNR (*Signal-to-Noise-Ratio*) which are essential for accurate and real-time positioning, especially in dynamic environments where satellite signals may be temporarily obscured or weakened. Optimizing the tracking module's performance is crucial to enhancing the overall receiver's sensitivity, accuracy, and responsiveness to varying environmental conditions.
- **Opportunities for Hardware Optimization:** As the demand for high-performance GNSS receivers increases, there are opportunities to explore hardware optimization techniques to improve tracking capabilities. Implementing the tracking module using VHDL (*Very High-Speed Integrated Circuit Hardware Description Language*) offers advantages such as parallel processing and hardware acceleration, allowing for real-time tracking and reduced power consumption. The utilization of VHDL enables the development of customized *Application-Specific Integrated Circuits* (ASICs) or *Field-Programmable Gate Arrays* (FPGAs) tailored to the tracking function, leading to more efficient and specialized GNSS receivers.

1.2 Aims and Objectives

1.2.1 Aims

The project has three aims: first, to design a tracking processor for GNSS receivers using VHDL; second, to verify the results using MATLAB; and third, to learn about GNSS signal acquisition and tracking by reading papers, books, etc.

1.2.2 Objectives

- Literature survey on GNSS signal processing and tracking
- Be familiar with the principles of correlation functions, correlators, VHDL and Vivado
- Write a literature review
- Create and verify a set of correlators model in MATLAB
- Write the RTL (*Register Transfer Level*) code of the correlator in VHDL
- Write the testbench code of the correlator in VHDL
- Instance several times (e.g. three times) of the correlator VHDL code to implement the tracking part of the GNSS receiver
- Write the testbench code of the project
- Compare the results from VHDL with those from MATLAB
- Record and analyse the VHDL results against the MATLAB results
- Complete the final dissertation

1.3 Description of the work

I will design the correlators of the receiver using VHDL. I plan to design a set of correlators in an FPGA. The correlators can be used to capture GNSS signals to allow subsequent

devices to perform ranging and positioning. My front-end device will acquire the GNSS signal and transmit it to me. During the acquisition process I can receive at least one GNSS signal. I will extract the ranging code from it and compare it with the ranging code generated by the receiver, i.e. using a correlator.

Chapter 2

Literature Review

The literature review chapter serves as a critical foundation for this project, offering an in-depth exploration of existing research, developments, and advances in the field of GNSS receivers, with a particular focus on the tracking module. This chapter aims to identify the key theories, methodologies, and technologies that have shaped the evolution of GNSS tracking and provide valuable information for the design and development of the FPGA-based GNSS tracking module.

2.1 GPS/GNSS

GPS/GNSS consists of a constellation of satellites orbiting the Earth, transmitting continuous signals containing precise timing and positioning information. Each GNSS satellite is equipped with atomic clocks, ensuring high accuracy in the signals it emits. The GNSS constellation comprises multiple satellites, typically in *Medium Earth Orbit* (MEO) [1], providing global coverage to ensure that a sufficient number of satellites are visible from any point on Earth at any given time.

2.1.1 Functioning of GNSS

A GNSS receiver on the ground intercepts signals from multiple satellites in the constellation. By analysing the timing and phase information in these signals, the receiver can calculate the distance between itself and each satellite. By triangulating the dis-

tances from multiple satellites, the receiver can determine its precise three-dimensional position (latitude, longitude, and altitude). Additionally, the receiver can synchronize its internal clock with the highly accurate satellite atomic clocks, providing precise timing information.

2.1.2 Key Components of GNSS

GNSS commonly consists of these four components: satellites, GNSS receivers, control segment, and user segment [2].

Satellites: The heart of GNSS is the constellation of satellites orbiting the Earth. Each satellite broadcasts signals carrying unique identification information and precise timing data.

GNSS Receivers: GNSS receivers are devices that intercept and process the satellite signals to calculate the user's position, velocity, and time. These receivers can be integrated into various devices, such as smartphones, car navigation systems, aviation equipment, and scientific instruments.

Control Segment: The control segment consists of ground-based monitoring stations and control centres responsible for monitoring the health of the satellites, maintaining their orbits, and ensuring accurate timing information.

User Segment: The user segment encompasses the GNSS receivers used by individuals, industries, and organizations to access positioning, navigation, and timing services.

2.1.3 Applications of GNSS

The applications of GNSS are diverse and far-reaching, permeating nearly every aspect of modern life. Some key applications include [3]:

- **Navigation:** GNSS enables precise and real-time navigation for land, sea, and air transportation, making it a critical component of navigation systems in vehicles, ships, and aircraft.
- **Surveying and Mapping:** GNSS is widely used in geodetic surveying, mapping, and

cartography to obtain accurate geographic data for urban planning, construction, and land management.

- **Precision Agriculture:** GNSS-based systems optimize agricultural processes by providing precise positioning for automated machinery, crop monitoring, and targeted application of resources like fertilizers and pesticides.
- **Emergency and Disaster Response:** GNSS aids emergency services in locating and coordinating responses during disasters, enabling efficient search-and-rescue operations.
- **Timing and Synchronization:** GNSS provides highly accurate timing information, essential for the synchronization of critical infrastructure, such as power grids, telecommunication networks, and financial systems.
- **Scientific Research:** GNSS data is used in scientific research, including the study of tectonic movements, sea level changes, atmospheric monitoring, and climate research.

In conclusion, GPS/GNSS has transformed the way we navigate and interact with our environment. By leveraging signals from a constellation of satellites, GNSS provides precise positioning, navigation, and timing services, powering applications across diverse sectors and enriching various aspects of modern life. As technology continues to evolve, GNSS is expected to play an increasingly critical role in shaping our interconnected world.

2.1.4 Why Choose GPS/GNSS

On 4th September 2019, a lecture[4] was given at the "*International Colloquium on Scientific and Fundamental Aspects of GNSS*". Spacecraft mission design, astrodynamics, space navigation, software development, and space politics are among the areas of competence of the author, Joel Parker, a flight dynamics engineer at NASA Goddard Space Flight Center. The "*Transiting Exoplanet Survey Satellite*" (TESS) project, which started in 2017, seeks to find planets in the habitable zones of other stars. He actively participates in the flight dynamics team for this mission.

The presentation provides a comprehensive overview of the history and scope of GPS/GNSS, as well as its potential future applications in lunar exploration and beyond.

Numerous flight examples are presented to illustrate the indispensable role of GPS in the space sector. This underscores the critical importance of GNSS technology in space missions. The author then delves into new areas of GPS application, specifically focussing on lunar exploration. The concept of a GNSS receiver designed for the Artemis Project is introduced.

The report concludes with a summary of key development directions:

- Studying GNSS improvements and capabilities for use on the moon
- Internal and external cooperation with the user and supplier communities via the ICG (*International Committee on GNSS*), to guarantee signal quality and data availability
- Making use of tried-and-true antenna and receiver technology to solve technical problems
- Making flight demonstrations as moon exploration efforts are stepped up internationally
- Using operational programs to optimize the advantages of exploration and science

This presentation illustrates the success of GNSS applications and demonstrates their importance. This is one of the reasons why I chose this topic. It shows a high level of professionalism and will undoubtedly prove valuable for your MSc. project, particularly in providing a thorough introduction to the background of GPS/GNSS and its ongoing development.

2.1.5 GNSS Signal Plan

In complex engineering projects and system development, clear and effective communication between various subsystems and components is essential for successful integration

and operation. The *Interface Control Document* (ICD) of GNSS provides the basic information of the system, such as intermediate frequency, modulation scheme, code frequency, etc.

After reviewing the interface control documents of some systems, we have summarized the parameters of each system in Table 2.1.

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Table 2.1: Specifications of Systems

Specifications	GPS	GLONASS	Galileo	BeiDou
Frequency band	L1: 1575.42 MHz L2: 1227.6 MHz L5: 1176.45 MHz	L1: 1602MHz L2: 1246MHz (14 channels)	E1: 1575.420MHz E6: 1278.750MHz E5a: 1176.450MHz E5b: 1207.140MHz	B1c : 1575.42MHz B2a: 1176.45MHz B2b: 1207.14MHz B1I: 1561.098MHz B3I: 1268.52MHz
Band width	Block IIR, IIRM, and IIF: 20.46 MHz GPS III, GPS IIIF, and subsequent: 30.69 MHz	L1: 7.875MHz(562.5 kHz each) L2: 6.125MHz(437.5 kHz each)	E1: 24.552MHz E6: 40.920MHz E5a: 20.460MHz E5b: 20.460MHz	B1c: 32.736MHz B2a: 20.46MHz B2b: 20.46MHz B1I: 4.092MHz B3I: 20.46MHz
Modulation scheme	BPSK	Modulo-2 addition CDMA	E1: CBOC E5: AltBOC E6: BOC	B1c: QMBOC(6, 1, 4/33) Others: BPSK
Antenna polarization		RHCP*		
Chip rate	L1 C/A & P: 1.023MHz L2 CL & CM: 511.5 kHz L5 data & channel: 10.23 MHz	L1 C/A: 0.511MHz L1 P: 5.11MHz L2 C/A: 0.511MHz L2 P: 5.11MHz	E1 ranging Code: 1.023MHz E6: 5.115MHz E5: 10.230MHz	B1c ranging code: 1.023MHz B2a ranging code: 10.23MHz B2b ranging code: 10.23MHz B1I ranging code: 2.046MHz B3I ranging code: 10.23MHz

Note: *RHCP: *Right Hand Circularly Polarized*

Given that the GPS L1 system was the first to be deployed[5], it possesses a relatively straightforward structure. Based on the GPS L1 ICD[6], we can summarize the signal plan of GPS L1 in table 2.2.

Table 2.2: Specifications of GPS L1

Specifications	GPS		
	C/A	L1C	
Centre Frequency	1575.42MHz	1575.42 MHz	
Frequency Band	L1	L1	
Access Technique	CDMA	CDMA	
Signal Component	Data	Data	Pilot
Modulation	BPSK	TMBOC(6,1,1/11)	
Code Frequency	1.023 MHz	1.023 MHz	
Primary PRN Code Length	1023	10230	
Code Family	Gold Codes	Weil Codes	
Data Rate	50 bps/50 sps	50 bps/100 sps	N/A

As a result, the GPS L1 signal has been selected as the primary target signal for this project. Furthermore, it is important to note that the L5 signal has ten times the bandwidth of L1. Thus, in the event that the utilization of the L5 signal becomes necessary, the adjustments required for its implementation would be minimal.

2.2 Tracking Process

2.2.1 Book from P. D. Groves[7]

This book offers a thorough textbook on navigation systems, which make use of GNSS, *Intelligent Navigation Systems* (INS), and other sensors to deliver precise *positioning, navigation, and timing* (PNT) data. Paul D. Groves and Kayton M. Ned, two renowned authorities in the subject of navigation systems, are the esteemed authors behind this work.

Professor of satellite navigation at University College London, Paul D. Groves' research focuses on navigation algorithms and technology. Kayton M. Ned, on the other hand, was an expert in navigation and control systems for aerospace applications and was a former Stanford University professor of aeronautics and astronautics. With their wealth of knowledge and experience, they are qualified to write a thorough and reliable textbook on navigation systems.

The basics of GNSS systems are described in Section 8.1, which will provide us a foundational understanding. It explains how to find the receiver's distance from the satellite.

The user equipment in Chapter 9 refers to the receiver. It describes how GNSS receivers are made. An antenna, reception hardware, range processor, and navigation processor are all components of a GNSS receiver. The tracking component of the ranging processor is the main focus of my work. This chapter makes note of the six correlators that make up a basic receiver design and the frequent use of additional correlators to quicken signal collection. There is also a comprehensive flowchart of the capture procedure available.

In general, as this book is a textbook, it provides a very authoritative and accurate introduction to GNSS-related technologies. It is reliable and thought-provoking.

2.2.2 Book from E. D. Kaplan and C. Hegarty[3]

Elliott D. Kaplan has made significant contributions to the development and understanding of GNSS technology. Christopher J. Hegarty is also a prominent figure in the GNSS community. He has extensive experience with GPS and other satellite navigation systems. They have been associated with the MITRE Corporation and contributed to the advancement of GNSS technology and its applications.

The book delves into the fundamental principles underlying GNSS technology, including GPS, GLONASS, Galileo, BeiDou, and others. It explores the concepts of satellite orbits, signal structure, receiver design, and various positioning techniques used in GNSS applications.

Chapters 3 to 7 provide a systematic introduction to the various navigation systems, including GPS, GLONASS, Galileo, BeiDou, etc. It is of great help for the background part of the project. Chapter 8 details the design of the receiver and introduces the antenna, RF front-end, acquisition and tracking respectively, as well as the design of the loop filter. This part was extremely helpful to my understanding. It describes the working principle and the GNSS process through numerous mathematical equations.

2.2.3 Paper from J. C. Juang, Y. H. Chen et al.[8]

The paper titled "*Design and implementation of an adaptive code discriminator in a DSP/FPGA-based Galileo receiver*" is authored by Jyh Ching Juang, Yu Hsuan Chen, Tsai Ling Kao, and Yung Fu Tsai from National Cheng Kung University.

The coded tracking loop and its related discriminator play a significant role in the tracking performance of their work on the GNSS receiver design. The authors suggested a plan that was put into practice on a DSP/FPGA board to improve tracking performance. The GIOVE-A signal was used for testing in experiments, and the outcomes showed the benefits of their suggested code tracking architecture and discriminator design.

The paper presents a well-defined design methodology for an adaptive coding discriminator, which was subsequently implemented and thoroughly tested. This design approach is framed as an optimization problem leading to the development of two discriminators. Notably, the adaptive *noncoherent multi-correlator* (NMC) discriminator showcased improvements in transient response and tracking error.

Throughout the article, detailed mathematical principles of capture, tracking, and other processes are elaborated, along with a description of the correlator's design ideas. Numerous test results for correlators based on the new approach are provided, making this paper a valuable reference for my MSc project.

2.2.4 Paper from O. Jakubov, P. Kovar et al.[9]

To develop advanced GNSS signal processing algorithms, such as multi-constellation, multi-frequency, and multi-antenna navigation, a flexible and re-programmable *software-*

defined radio (SDR) solution is essential. To achieve this goal, the researchers have introduced various receiver architectures. Their chosen approach involves constructing an RF front-end with an FPGA universal correlator, mounted on an ExpressCard directly connected to a PC. This setup allows GNSS researchers and engineers to write signal processing algorithms (e.g., tracking, acquisition, and localization) in a Linux application programming interface. The unique hardware configuration enables easy modification of the RF front-end via a PC program, providing the flexibility to increase the number of RF channels, correlators, or antennas by attaching more ExpressCards to the PC, thus enhancing computational capability.

Utilizing the SDR platform, they have successfully implemented a GNSS receiver, offering significant advantages, including low cost, high software customization, and the potential for straightforward upgrades in computational power. The article also discusses a generic FPGA-based GNSS receiver, allowing a comparison of the different approaches' advantages and disadvantages.

The outcome of their work is the prototype of the Witch Navigator receiver. They have conducted successful tests on Galileo E5, E1b, and E1c signals with the correlator and the RF front-end. Moreover, they have fully addressed the communication between the FPGA and the PC, developing and testing all the corresponding controllers and drivers.

The article provides a comprehensive analysis of the design principles for receivers based on FPGAs, and the SDR platform enables the validation of the FPGA platform through MATLAB simulations. This combination of approaches facilitates the development of advanced and adaptable GNSS signal processing algorithms for future navigation systems.

2.3 FPGA Technique

FPGA is a type of integrated circuit that allows users to configure its hardware functionality after manufacturing. Unlike ASICs, which are designed for specific tasks and cannot be reconfigured, FPGAs offer flexibility and programmability. This characteristic makes FPGAs suitable for a wide range of applications [10], including digital signal processing,

communication systems, image and video processing, and in this case, GNSS receiver design.

Here are the advantages of using FPGA in the project [11]:

- **Hardware Customization:** FPGAs allow customization of hardware functionality, tailoring specific algorithms and designs for the GNSS tracking module. This flexibility optimizes hardware resources, resulting in a specialized and efficient GNSS receiver.
- **Real-Time Processing:** FPGAs excel in parallel processing, enabling real-time data processing with low latency. This is crucial for continuous and accurate GNSS positioning, especially in dynamic environments with intermittent satellite signals.
- **Power Efficiency:** FPGA designs can be optimized for high performance with low power consumption. This is essential for battery-operated GNSS devices, extending battery life and improving overall device usability.
- **Rapid Prototyping and Iteration:** FPGA development allows quick prototyping and iterative design refinement. Changes can be implemented and tested rapidly, speeding up development and performance improvements.
- **Adaptability and Future Upgrades:** The programmable nature of FPGAs allows easy updates and future upgrades. GNSS algorithms can be incorporated without hardware changes as technology advances.
- **Cost-Effectiveness:** FPGAs offer a cost-effective solution for custom hardware design compared to ASICs. They are suitable for smaller-scale projects or research without requiring expensive fabrication.

In summary, the choice of FPGA to design the GPS receiver is a no-brainer.

Chapter 3

Methodology

The methodology chapter is a pivotal component of this research, unveiling the systematic approach taken to address the specific goals and inquiries of the project. Within this chapter, an in-depth description of the research design, data collection methodologies, and analytical techniques deployed is meticulously presented. By offering a transparent and methodical account of the research process, this chapter safeguards the robustness and integrity of the study's outcomes.

3.1 Tracking

A complete GPS/GNSS work process includes acquisition, tracking and navigation. My project is mainly focused on the tracking stage.

After the acquisition phase, where the receiver identifies and locks onto the satellite signals, the tracking phase begins. During this phase, the receiver closely monitors the received signals and tracks their variations to accurately determine the user's position, velocity, and timing information. This involves maintaining a stable lock on the satellite signals despite various challenges, such as signal degradation due to atmospheric conditions, obstructions, and interference.

The following figure 3.1 shows the basic architecture of the tracking module. The signal is received by the RF front-end and is filtered and fed to the ranging processor. At the same time, the NCO (*Numerically Controlled Oscillator*) generates a GPS L1 IF

carrier and a carrier for the C/A (*Coarse Acquisition*) code. The GPS signal is first modulated to IF and then multiplied with the C/A code and finally integrated. Using the principle of the cross-correlation function, the C/A carrier frequency is continuously adjusted to synchronize with the C/A code in the GPS signal. And finally, complete the tracking[12].

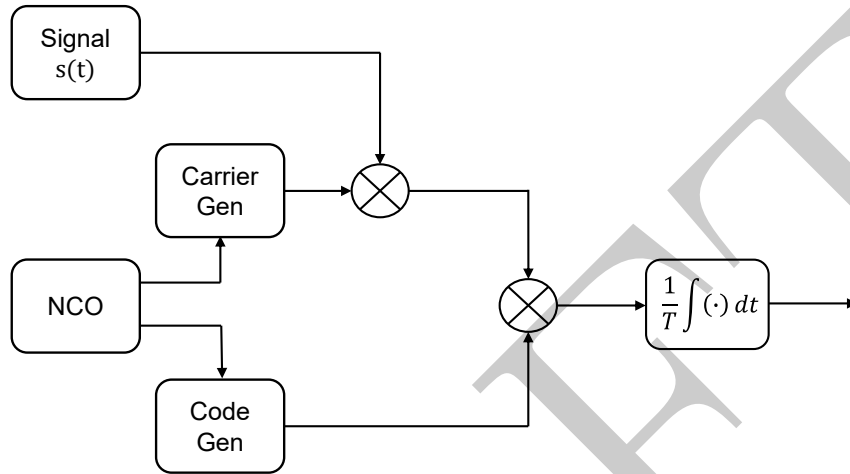


Figure 3.1: Tracking Module Architecture

3.1.1 NCO

In digital communications, it is often necessary to modulate and shift baseband signals (often IF) to high frequencies for transmission because the wavelengths of the high-frequency signals are better matched to the available antenna sizes. In order to modulate, we need to generate a carrier for the high-frequency signal, which is often a sine or cosine signal. Therefore, a module is required to generate the carrier at the desired frequency consistently and accurately.

Using hardware, we have three ways to generate such signals: direct form oscillator, NCO, and CORDIC algorithm. After comparing, we learnt that using the CORDIC takes up the least amount of resources in FPGAs[13], however, using the NCO is the simplest solution. In this project, we have designed an NCO module in FPGA to generate different frequency carriers.

The NCO is a signal generator that produces a specified frequency. It can generate square wave signals, i.e. PWM signals with a duty cycle of 50%, as well as sinusoidal

cosine signals and so on[14]. It is often used in conjunction with a DAC (*Digital-to-analog Converter*) so that an analogue signal of a specified frequency can be output. In general, the NCO consists of two parts, the *Phase Accumulator* (PA) and the *Look-up Table* (LUT)[15]. Their architecture is shown in figure 3.2.

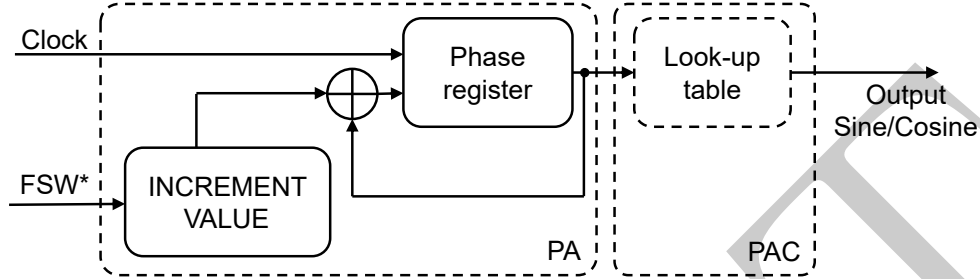


Figure 3.2: NCO Architecture
Note: *FSW: *Frequency Setting Word*

Phase Accumulator

The phase accumulator will complete an accumulation in each clock cycle according to the set increment value. In other words, the accumulator outputs the address of the look-up table so that the look-up table generates the correct sine-cosine signal[16]. By setting the increment value, the look-up table is made to sample in a controlled manner.

Here, we assume that the bit width of the accumulator is 32 bits. The ratio of the incremental 32-bit value to the fixed 4,294,967,296 accumulator overflow value determines how often the overflow occurs. This controls the triggering of the NCO output waveform. The equation is as follows,

$$F_{out} = (\text{increment value}) \times \frac{F_{clock}}{2^{Accum\ width}} \quad (3.1)$$

For example, if the clock is 99.375MHz and the NCO is required to generate a 1.023MHz signal with a register bit width of 32 bits, then the increment value 44,213,852 needs to be written to FSW.

Phase-to-Amplitude Converter

By using the look-up table, we can convert the phase value into an outputable sine-cosine signal. In other words, the look-up table is actually a *Phase-to-Amplitude Converter* (PAC). The easiest way to build it is to use *Read-only Memory* (ROM)[17], create the amplitude data in advance using software such as MATLAB, and then import it into a memory file or directly into the VHDL code.

3.1.2 Code Generator

3.1.3 Correlator

Cross-Correlation

3.1.4 Doppler

3.2 Verification

3.2.1 Behavioural Simulation

3.2.2 Post-Synthesis Functional Simulation

3.2.3 Post-Implementation Functional Simulation

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