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

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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 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), providing global coverage to ensure that a sufficient number of satellites are visible from any point on Earth at any given time.

1.2.1 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 distances 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.

1.2.2 Key Components of GNSS/GPS

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.

1.2.3 Applications of GNSS/GPS

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

- **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, GNSS/GPS 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.

1.3 FPGA

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, 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:

- **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.

1.4 Aims and Objectives

1.4.1 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.

1.4.2 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

1.5 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 the existing research, developments, and advancements 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 insights for the design and development of the FPGA-based GNSS tracking module.

2.1 Interface Control Document[1–6]

In complex engineering projects and systems 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, I have summarised the parameters of each system in Tbl. 2.1.

Table 2.1: Specifications of Systems

Specifications	GPS	Glonass	Galileo	BeiDou
Frequenc 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 system was the first to be deployed, it possesses a relatively straightforward structure. As a result, the GPS L1 signal has been selected as the primary target signal for this project. Furthermore, it is important to highlight that the L5 signal exhibits 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 Book from P. D. Groves[7]

This book presents a comprehensive textbook that covers navigation systems, encompassing GNSS, *Inertial Navigation Systems* (INS), and other sensors to deliver precise *positioning, navigation, and timing* (PNT) information. The esteemed authors behind this work are Paul D. Groves and Kayton M. Ned, both recognized experts in the field of navigation systems.

Paul D. Groves holds the position of a professor of satellite navigation at the University College London, where his research focuses on advanced navigation algorithms and technologies. On the other hand, Kayton M. Ned, a former professor of aeronautics and astronautics at Stanford University, specialized in navigation and control systems for aerospace applications. With their extensive experience and expertise, they are well-suited to provide a comprehensive and authoritative textbook on navigation systems.

Section 8.1 describes the fundamentals of GNSS systems which will help us to have a basic understanding. It tells us how to get the distance between the satellite and the receiver.

User equipment in chapter 9 refers to the receiver. It describes the design of GNSS receivers. An GNSS receiver contains an antenna, a receiver hardware, a ranging processor, and a navigation processor. My work focuses on the tracking part of the ranging processor. This chapter points out that a common typical receiver design contains six correlators and that more than six correlators are often used in order to speed up signal capture. A complete capture flowchart is also provided to clearly describe the capture process.

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

2.3 Book from E. D. Kaplan and C. Hegarty[8]

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 a great help for the background part of the project. In Chapter 8, it 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 GNSS working principle and process through numerous mathematical equations.

2.4 Paper from J. C. Juang, Y. H. Chen et al.[9]

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.

In their work on GNSS receiver design, the tracking performance heavily relies on the coded tracking loop and the associated discriminator. To enhance the tracking performance, the authors proposed a scheme that was implemented on a digital signal processor/field-programmable gate array board. Experiments were conducted using the

GIOVE-A signal for testing, and the results demonstrated the advantages of their proposed 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.

2.5 Paper from O. Jakubov, P. Kovar et al.[10]

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 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 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.

2.6 Presentation Sildes from J. Parker[11]

This presentation was delivered at the "*International Colloquium on Scientific and Fundamental Aspects of GNSS*" on 4th Sep. 2019. The author, Joel Parker, is a flight dynamics engineer at NASA Goddard Space Flight Center, with expertise in spacecraft mission design, astrodynamics, space navigation, software development, and space policy. He actively contributes to the flight dynamics team for the "*Transiting Exoplanet Survey Satellite*" (TESS) mission, which aims to search for planets in the habitable zones of other stars and commenced in 2017.

The presentation provides a comprehensive overview of the history and scope of GNSS/GPS, 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 focusing 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:

- Research into GNSS capabilities and enhancements for lunar applications.
- Collaboration with the user and supplier community, both internally and through the ICG (*International Committee on GNSS*), to ensure signal performance and

availability of relevant data.

- Utilizing proven receiver and antenna technologies to address technical challenges.
- Conducting flight demonstrations in the global expansion of lunar exploration activities.
- Working with operational programs to maximize the benefits of science and exploration.

The presentation showcases a high level of professionalism and will undoubtedly prove valuable for your MSc project, particularly in providing a thorough introduction to the background of GNSS/GPS and its ongoing development.

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