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Analysis and Design of an Imaging Ultra-Wideband Frequency Modulated Continuous Wave Primary Radar System operating in S, C, X and Ku Band

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ANALYSIS AND DESIGN OF AN IMAGING ULTRA-WIDEBAND FREQUENCY MODULATED CONTINUOUS WAVE PRIMARY RADAR SYSTEM OPERATING IN S, C, X AND KU BAND

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A bottomless curse, a bottomless sea.
Accepting of all that there is and can be.

Hidetaka Miyazaki

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Abstract

Research and development of modern radar systems has recently become the center of attention through the rise of various new applications. This results in more demanding requirements for radar systems such as high frequency agility, high range resolution and high radar range at the same time while generating low-noise radar images with a high amount of details. This multi dimensional optimization problem can be translated to specific research challenges. Accordingly, future radar systems require a high system bandwidth, high frequency chirp bandwidth while transmitting a frequency chirp at a low center frequency, high linearity and with low phase noise.

The presented work discusses the research and design process, from a custom signal generator ASIC to the final UWB FMCW imaging primary radar system. This is achieved from the ground up and does not use any previously available radar-specific components.

First, a novel consideration of non-linearities within an UWB FMCW primary radar transceiver is derived. This analysis identifies the critical spurious attenuation components of the down-conversion mixer to avoid ghost targets in the distance spectrum.

The commonly known topology of a cross-coupled LC tank oscillator is improved regarding its tuning range capability. Based on this research, a state-of-the-art UWB VCO ASIC achieving a record relative continuous frequency chirp bandwidth at a low center frequency combined with a very low phase noise is presented.

Furthermore, existing tuning range expansion techniques are studied and an innovative tuning range expansion concept is derived. Based on this concept a novel signal generator ASIC is presented, greatly increasing the tuning range of the single oscillator covering a frequency range from 3.1 GHz to 22.5 GHz while maintaining superior frequency chirp bandwidth and phase noise performance. The record figures of merit for both systems, the single VCO ASIC with 215 dB and the expanded signal generator ASIC with 217 dB confirm the validity of the derived concepts.

The signal generator ASIC is then employed in a closed-loop UWB frequency synthesizer. The analysis and design of the required loop filter is emphasized considering the targeted high bandwidth. A UWB receiver and further supporting systems like the transmit power amplifier, digital control system and power supply system are presented. A power supply noise filtering system is adapted and designed for the noise sensitive RF components and its influence on the resulting phase noise is investigated.

Finally, a compact and low weight FMCW primary radar is built. The typical EIRP of the designed system is 30.2 dBm and the typical power consumption amounts to 6.7 W while transmitting and receiving.

This researched and designed novel imaging UWB FMCW primary radar system operates in the S, C, X and Ku frequency bands. Guided by the identified research challenges, the presented radar achieves a superior combination of a very high relative system bandwidth of 143 %, a very high relative frequency chirp bandwidth of 79 %, a low center frequency of 10.85 GHz and a low typical phase noise of −105 dBc/Hz at 1 MHz offset.

Non-imaging radar measurements show the achieved very high range resolution of 2 cm for distant radar targets. Subsequently, the radar is expanded to an imaging SAR measuring various radar images of complex open field measurement scenarios illuminating a downrange of more than 100 m and a crossrange of 50 m. The SAR is further expanded towards a PolSAR system utilizing polarimetry. This system is deployed for a measurement series to monitor the effects of environmental factors on vegetation in a forest.

The superior performance enables the radar system to dissolve the existing compromise between a high range resolution and a high radar range. Both desired performance parameters are achieved at the same time without degrading the resulting phase noise and therefore allows low-noise radar images.

Furthermore, the presented primary radar offers an extremely high frequency flexibility allowing it to adapt to respective frequency restrictions and to operate as multi band, multi application system. Consequently, the presented concept can replace several narrowband and application specific radar systems with only one single radar front end. This reduces the overall cost, size, complexity and power consumption of future radar systems while enabling new fields of applications.

Zusammenfassung

Aufgrund zunehmender Anwendungsfelder ist die Forschung und der Entwurf moderner Radarsysteme in den Mittelpunkt der Aufmerksamkeit gerückt. Daraus ergeben sich umfassende Anforderungen an neuartige Radarsysteme wie hohe Frequenzflexibilität, hohe Entfernungsauflösung und eine hohe Radarreichweite bei gleichzeitiger Erzeugung rauscharmer Radarbilder mit hohem Detailgrad. Dieses mehrdimensionale Optimierungsproblem lässt sich in konkrete Forschungsschwerpunkte übersetzen. So benötigen zukünftige Radarsysteme eine hohe Systembandbreite, eine hohe Frequenzrampenbandbreite bei gleichzeitiger Übertragung einer Frequenzrampe mit niedriger Mittenfrequenz, einer hohen Linearität und geringem Phasenrauschen.

Die vorgestellte Arbeit beschreibt den Forschungs- und Entwurfsprozess von einem Signalgenerator-ASIC bis hin zu einem fertigen bildgebenden UWB-FMCW-Primärradarsystem. Das System wurde von Grund auf neu entworfen und verwendet keine zuvor verfügbaren radarspezifischen Komponenten. Zunächst wird eine neuartige Untersuchung von Nichtlinearitäten in einem UWB-FMCW-Primärradar Sender-Empfänger vorgestellt. Diese Analyse identifiziert die kritische Nebenwellenunterdrückungen des Mischers, um Geisterziele im Entfernungsspektrum zu unterdrücken.

Die bekannte Topologie eines kreuzgekoppelten LC-Oszillators wird im Hinblick auf seine Abstimmbereichsbandbreite verbessert. Basierend auf dieser Forschung wird ein hochmoderner UWB-VCO-ASIC entworfen, der eine rekordhohe relative Frequenzrampenbandbreite bei einer niedrigen Mittenfrequenz in Kombination mit einem sehr geringen Phasenrauschen erreicht.

Darüber hinaus werden etablierte Techniken zur Erweiterung des Abstimmbereichs untersucht und ein innovatives Konzept zur Erweiterung des Abstimmbereichs abgeleitet. Auf der Grundlage dieses Konzepts wird ein neuartiger Signalgenerator-ASIC vorgestellt, der den Abstimmbereich des Einzeloszillators erheblich vergrößert und einen Frequenzbereich von 3,1 GHz bis 22,5 GHz abdeckt, wobei die hervorragende Frequenzrampenbandbreite und das niedrige Phasenrauschen beibehalten wird. Die *figure of merit* Rekordwerte für beide Systeme, den VCO-ASIC mit 215 dB und den erweiterten Signalgenerator-ASIC mit 217 dB, bestätigen die Gültigkeit der abgeleiteten Konzepte.

Der Signalgenerator-ASIC wird anschließend in einem UWB-Frequenzsynthesizer mit geschlossenem Regelkreis implementiert. Die Analyse und das Design des erforderlichen Schleifenfilters werden unter Berücksichtigung der angestrebten

hohen Bandbreite besonders vertieft. Ein UWB-Empfänger und weitere Systeme wie der Sendeleistungsverstärker, das digitale Steuerungssystem und das Stromversorgungssystem werden vorgestellt. Für die rauschempfindlichen HF-Komponenten wird ein Rauschfiltersystem für die Stromversorgung angepasst sowie entworfen und dessen Einfluss auf das resultierende Phasenrauschen wird untersucht.

Schließlich wird ein kompaktes und leichtes FMCW-Primärradar gebaut. Das typische EIRP des entworfenen Systems beträgt 30,2 dBm und die typische Leistungsaufnahme beträgt 6,7 W beim Senden und Empfangen.

Dieses erforschte und entworfene neuartige bildgebende UWB-FMCW-Primärradarsystem arbeitet in den S, C, X und Ku Frequenzbändern. Geführt von den identifizierten Forschungsschwerpunkten, erreicht das vorgestellte Radar eine ausgezeichnete Kombination mit einer sehr hohen relativen Systembandbreite von 143 %, einer sehr hohen relativen Frequenzrampenbandbreite von 79 %, einer niedrigen Mittenfrequenz von 10,85 GHz und einem niedrigen typischen Phasenrauschen von -105 dBc/Hz bei 1 MHz Offset.

Die nicht-bildgebenden Radarmessungen zeigen die erreichte sehr hohe Entfernungsauflösung von 2 cm für weit entfernte Radarziele. Anschließend wird das Radar zu einem bildgebenden SAR erweitert, das verschiedene Radarbilder von komplexen Messszenarien im offenen Feld mit einer Reichweite von mehr als 100 m und einer Breite von 50 m misst. Das SAR wird weiter zu einem PolSAR-System ausgebaut, das Polarimetrie verwendet. Dieses System wird für eine Messreihe zur Überwachung der Auswirkungen von Umweltfaktoren auf die Vegetation in einem Wald eingesetzt.

Die neuartige und herausragende Leistung ermöglicht es dem Radarsystem, den bestehenden Kompromiss zwischen einer hohen Entfernungsauflösung und einer hohen Radarreichweite aufzulösen. Beide gewünschte Leistungsparameter werden gleichzeitig erreicht, ohne das resultierende Phasenrauschen zu verschlechtern und rauscharme Radarbilder beizubehalten.

Darüber hinaus bietet das vorgestellte Primärradar eine extrem hohe Frequenzflexibilität, die es erlaubt, sich den jeweiligen Frequenzbandregulierungen anzupassen und als Multi-Band- und Multi-Applikations-System eingesetzt zu werden. Folglich kann das vorgestellte Konzept mehrere schmalbandige und anwendungsspezifische Radarsysteme mit nur einem einzigen Radar-Frontend ersetzen. Dies reduziert die Gesamtkosten, Größe, Komplexität und den Stromverbrauch zukünftiger Radarsysteme und ermöglicht gleichzeitig neue Anwendungsbereiche.

Contents

1. Introduction

1.1. Motivation and Objectives

In the year 1886 the German physicist Heinrich Hertz was able to produce electromagnetic waves experimentally and proved their existence. He showed that metallic obstacles can reflect electromagnetic waves and thus the fundamental concept of a radio detection and ranging (Radar) system was discovered, more than a century ago.

The German radio frequency engineer and physicist Christian Hülsemeyer performed the first experiments using electromagnetic waves for detection in 1904 and is considered the inventor of radar. He discovered that the property of metallic surfaces to reflect electromagnetic waves can be used to detect distant objects. His telemobiloscope was the first prototype of a functioning radar system and followed the basic principles of a modern pulsed radar. For his first demonstration, Hülsemeyer deployed his telemobiliscope below the *Dombrücke* in Cologne covering a range of 3 km looking into the open water. A bell connected to the receiver system signaled incoming ships even when they were not yet visible due to difficult weather conditions. An panoramic view display was able to indicate the angle of arrival, but the distance of the obstacle could not yet be measured. Even though Hülsemeyer's development and its wide-ranging field of application did not receive any recognition at first, it sparked a century long era of radar research and design that continues today.

For many decades, many groups of researchers dealt with the discovery of Hülsemeyer, without any significant new findings. However, with the arms build-up in the early 1930s predating the second world war, radar research and development was intensified in many countries especially in Germany and the United Kingdom. The first modern radar system was presented in 1935 by the *Gesellschaft für elektroakustische und mechanische Apparate mbH* (GEMA) and designated as *Funkmessgerät*. This primary radar system allowed the detection and localization of aircrafts or naval ships and provided a technological advantage in the early years of the war.

In 1939 the English air defense developed an urgently needed radar system, that could distinguish between friend or foe. The system developed by Frederic Calland Williams and Bertram Vivian Bowden was later described as Identification Friend or Foe (IFF) and was the first ever successfully demonstrated secondary radar system.

In the aftermath of the Second World War, research in the field of radar systems was forbidden in Germany and therefore other countries took over with new theories and concepts. In the year 1951 the USA developed the synthetic aperture radar (SAR) system which is classified as imaging radar system providing a two dimensional presentation of the measured terrain. Such systems can be used for remote sensing and are often installed in aircrafts.

In the following years, the capabilities of radar systems advanced significantly driven by a wide range of industrial and civil applications. At the end of the 1970s first proximity and distance warning systems were developed for the automotive sector. Since the year 1990, space programs in various countries used radar technology for measuring the earth and other planets.

During the Second World War, radar operators discovered that weather was causing echoes on their respective measurements, masking potential radar targets. This led to the development of weather radar systems with great influence on our modern live. In recent years, weather radar systems became continuously more important. Research in this radar type intensified following the world-wide increase in extreme weather conditions caused by the climate change. Also radar based environmental observation systems are becoming more and more important to help fight the effects of climate change.

During the recent rise of computer technology, the capabilities of previously analog signal based radar systems were more and more enhanced. Now, radar systems are strongly interconnected with modern society enabling a wide range of applications, including meteorological monitoring, aircraft and ship navigation, terrestrial traffic control, geological or forestry environmental observations, surveillance systems and the automotive, medical and consumer electronic sectors. This is why the research for higher resolution, higher effective range and more portability with less resource use became continuously important over the last decade.

For example, an increasing number of applications use ultra-wideband (UWB) front end systems and the advantages of a high bandwidth. frequency-modulated continuous wave (FMCW) primary radar systems benefit directly from a high frequency chirp bandwidth. The range resolution, describing the minimal distance between two equal targets so that they can still be separated, and therefore the amount of information a FMCW primary radar can provide depends on the bandwidth of the frequency chirp which is transmitted by the system. Synthesizing a continuous frequency chirp with a very high bandwidth will result in a more detailed radar image and therefore provides enhanced detection capabilities.

Especially the modern automotive sector and the rise of autonomous driving proves to be an increasingly growing sector, pushing radar system development to new limits. In addition to the need for high range resolution, modern radar systems require a very high frequency agility and flexibility. A high frequency agility allows the system to inherently adapt the utilized center frequency to the respective frequency restrictions of the country in which the front end would be deployed. Furthermore, modern cars, aircrafts or other comparably complex systems use a wide range of different radar systems with their respective applications and frequency specifications. A frequency agile system with an UWB tuning range can replace a set of narrowband systems that cover different applications and therefore substantially reduces the required resources, size and complexity. In order to increase security and safety for autonomous driving, the radar systems require a combination of a very high radar range and high range resolution for precise measurement at high distances. Additionally, the provided radar image has to have as little noise as possible.

Consequently, modern radar systems face a multi-dimensional optimization problem. The objectives are generally valid for modern radar systems and can be summarized as follows.

- **Frequency Flexibility** - A high frequency flexibility and agility allows the radar system to be adapted to the respective application in regard to frequency regulation or radar target radar cross-section (RCS) frequency sensitivity. One frequency synthesizer with very high frequency flexibility can cover multiple frequency bands for different applications at the same time. This reduces the required resources, size and power consumption of the system while replacing multiple narrowband radar front ends.
- **Range Resolution** - A high range resolution allows the radar system to distinguish objects which are close to each other as separate radar targets which would otherwise merge to one target. Therefore, a high range resolution increases the precision and level of detail a radar system can detect and enables new applications.
- **Radar Range** - A high radar range allows the radar system to receive reflected electromagnetic waves from objects at great distance. This additionally widens the field of applications.
- **Low Noise Radar Image** - The measured radar image summarizes the reflection of all illuminated obstacles in a certain area and depicts them on a two-dimensional image representing a bird's eye view of the measured terrain. Noise within the radar image would increase the level of uncertainty whether the depicted target is a real reflecting obstacle or noise in the measured base band signal. Therefore, a low noise radar image is highly desirable.

To achieve a superior combination of these four identified main objectives and solve this multi-dimensional optimization problem of modern radar systems represents the main goal and the research question focus of the radar system presented in this thesis.

1.2. Scope of Thesis, Funding and Previously Published Original Work

This thesis is concerned with fundamental scientific research in the area of UWB primary radar systems and performs a feasibility study of the derived concepts. Commercial use, a specific application or the design of a finalized commercial product is explicitly not targeted. Instead this work follows the proof-of-concept philosophy.

Study, research, design, fabrication and measurement results of the primary radar system or any described subsystems are produced with the goal to prove the previously theoretically derived concepts and to show their impact on the final performance of a primary radar system. Consequently, the presented work and designed primary radar system classify as TRL 3 following the European technological readiness level classification [HOR15].

The presented imaging FMCW UWB primary radar system is novel in its emphasis on a very high and continuous tuning range in combination with low phase noise, while transmitting at a relatively low chirp center frequency. Through its modular, transparent and holistic design it serves as flexible learning platform recognizing the influence of the derived and utilized concepts and allowing to be shaped for the desired use-case scenario. The study and design of an UWB frequency synthesizer based on the designed signal generator application specific integrated circuit (ASIC) and utilized within the designed radar is the core of this work's advancement regarding state-of-the-art. The researched and designed radar serves as an implementation example and performance evaluation platform of the designed ASIC.

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1.3. Content and Structure

A structural overview of this thesis is depicted in Fig. 1.1 showing central transmitting and receiving hardware component milestones for the proof-of-concept.

This work does not use any previously available radar-specific components. Consequently, a deep understanding in various fields related to the research, design and measurement of the final radar was required. This includes advanced knowledge in radio frequency (RF) ASIC design combined with focus on analog and digital system design, implementation and testing as well as signal processing and filtering, circuit board design and fabrication, hardware description and software programming language, non-imaging and imaging radar design, polarimetric SAR understanding and finally knowledge about primary radar image processing and measurement.

In order to study and design a working state-of-the-art novel radar which achieves a previously unmatched combination of high range resolution, high radar range, high frequency agility and low phase noise, this thesis describes and overcomes major obstacles not only in the RF ASIC circuit design but also in the system design domain.

First, chapter 2 introduces the underlying concepts and fundamental definitions. The various radar classifications are described and the presented radar is categorized. Furthermore, the influence of the propagation channel on the radar performance is derived.

The FMCW time of flight principle for primary radar systems is presented and a mathematical model of a narrowband radar with ideal components is given. Subsequently, this model is expanded considering non-linearities within an UWB transceiver system and specific recommendations for the reduction of the influence to the base band signal is proposed. Additionally, this chapter describes the range resolution for FMCW radar systems and a means to measure it from a single radar target. Finally, four radar performance parameters are derived from the formulated main objectives to guide the design process of the radar system.

In chapter 3 the voltage-controlled oscillator (VCO) and UWB signal generator ASIC research, design, fabrication and evaluation is described. First the utilized semiconductor technology is introduced. Subsequently, the derived novel tuning range expansion concept is presented and compared with commonly used tuning range expansion techniques. The design of a UWB VCO ASIC is described compared with recent state-of-the-art systems.

Expanding on the single VCO ASIC, a complex signal generator ASIC utilizing the presented tuning range expansion concept is described. The fully self-biased signal generator ASIC expands the tuning range of the single VCO, features an on-chip prescaler by four allowing the ASIC to cooperate with low-cost off-the-shelf components and has an on-chip broadband output power amplifier.

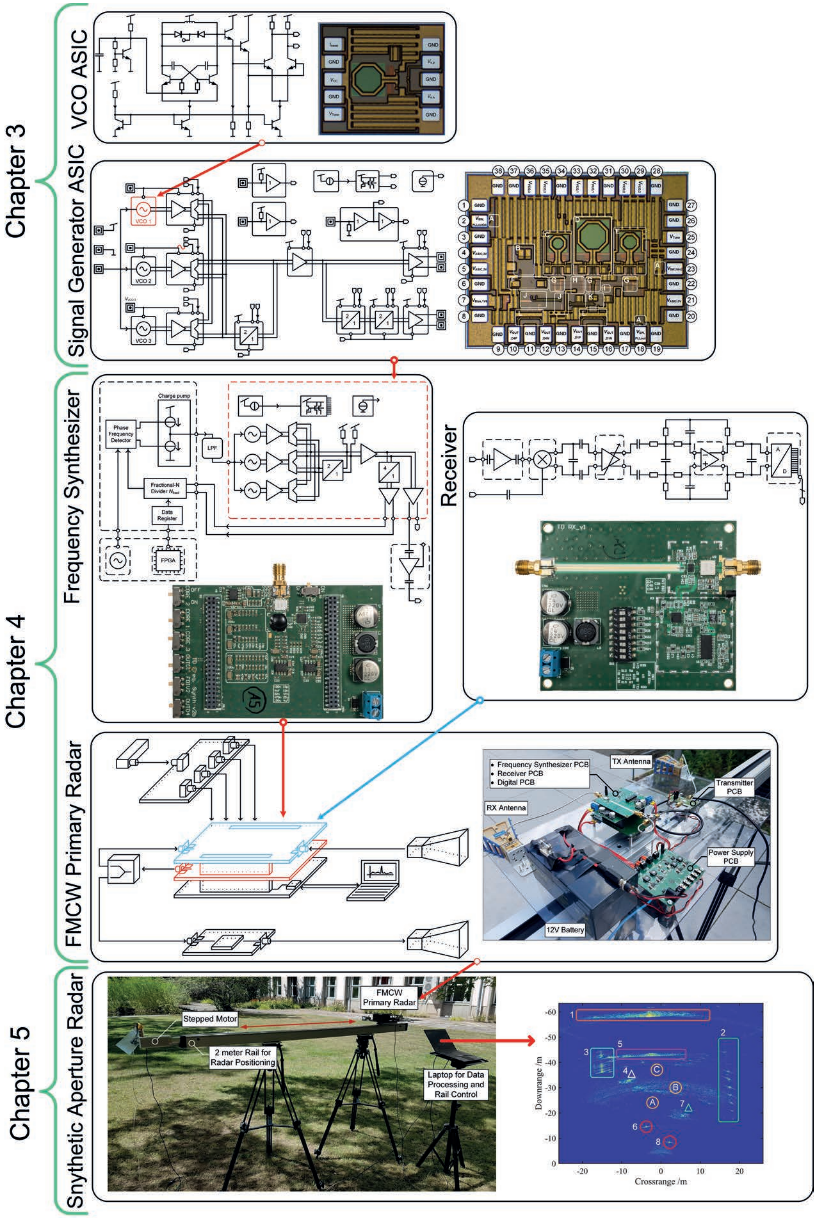

Figure 1.1.: Overview of the milestones for the designed prove of concept hardware of the system studied in this thesis.

The record figure of merits (FoM) for both, the single VCO ASIC and the expanded signal generator ASIC are compared to other state-of-the-art systems, showing the novel performance of the designed ASICs.

Chapter 4 describes the research and design of all required primary radar subsystems and the assembly of the final FMCW primary radar system.

The presented signal generator ASIC is employed into a designed charge pump phase-locked loop (CP-PLL) forming the closed-loop UWB frequency synthesizer presented in section 4.2. The study and design of the third order loop filter is emphasized considering the very high bandwidth of the synthesizer. Additionally, a filter subsystem for the power supply noise of the sensitive frequency synthesizer RF components is presented. The design of the final frequency synthesizer circuit board is described and supported by corresponding measurements.

Subsequently, an UWB receiver is presented in section 4.3. The design considers the identified specific requirements in regard to non-linearities when utilized within an UWB FMCW radar system. Furthermore, power supply line noise filtering for the sensitive receiver RF components is achieved by an additionally derived subsystem. Respective measurement results are presented.

Furthermore, the transmit signal path is presented and modeled in section 4.4. The design of a field-programmable gate array (FPGA) based digital control subsystem for radar configuration is described in section 4.5. In order to supply the primary radar system with only one voltage source a power supply circuit board subsystem is designed in section 4.6.

Finally, section 4.7 describes the assembly of the two different primary radar revisions. The first revision incorporates all presented subsystems on an acrylic plate for simple measurement and debugging of every subsystem. The second revision includes all subsystems in a small, low weight and weather-proof box mounted an a metal rail with the respective transmit and receive antennas at each rail side.

Chapter 5 describes the measurement results of the studied and designed UWB FMCW primary radar system.

First the respective configurations for each measurement are presented in section 5.1. Then non-imaging laboratory and open field measurements are presented in section 5.2. Practical range resolution measurements with closely placed objects structures as radar system targets are performed.

Subsequently, the non-imaging radar system is expanded into an imaging radar using a metallic rail with a stepper motor for precise positioning of the radar system along the aperture. Thereby, a SAR is formed and measured in section 5.3. The resulting radar images accurately depict the complex open field measurement scenarios allowing clear localization and identification of various radar targets. Also the SAR system is expanded with polarimetry by using two receive and transmit antennas with different polarization planes respectively.

Finally, the PolSAR system is used for a measurement series described in section 5.3.6, studying the effects of environmental factors on vegetation in the forest of *Tharandt*. For this, the designed PolSAR system was embedded into a weather proof housing, mounted on a tower overseeing the open field measurement scenario and independently performed hourly radar image measurements over a period of multiple months.

Chapter 6 presents the conclusion and outlook of this thesis.