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PERFORMANCE EVALUATION OF AN OPEN SOURCE SDR-BASED ADS-B RECEIVER

Master's Thesis

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VÕIMEKUSE HINDAMINE VABAVARALISEL TARKVARARAADIOL PÕHINEVAL ADS-B VASTUVÕTJAL

Magistritöö

Juhendaja: Yannick Le Moullec
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Author’s declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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# Abstract

Automatic Dependent Surveillance Broadcast (ADS-B) is a relatively novel air traffic surveillance system that is increasingly used around the world to improve the situational awareness that is usually achievable by traditional secondary surveillance radars. ADS-B uses a combination of satellite-based GPS technology and onboard sensors to create ADS-B messages that contain information such as aircraft identification, surface and airborne positions, velocities, etc. Such messages are broadcasted frequently and automatically, which provides better situational awareness to pilots and air traffic controllers. The extended information provided by ADS-B enables efficient navigation, thereby improving safety and reducing fuel consumption.

The fact that ADS-B messages are not encrypted has triggered a sizeable interest in the industry, academic, and amateur sectors and communities for building ADS-B receivers for commercial, research, teaching, and hobby purposes. Such ADS-B receivers are sometimes built using open-source hardware and software. Nuand is such a company that commercializes open-source FPGA-based software defined radios (SDR) and that has released a free-of-charge open-source ADS-B receiver for its SDR boards.

This thesis analyzes the performance of Nuand's ADS-B receiver implemented on an FPGA-based bladeRF x115 SDR board. First, a system-level analysis of the ADS-B receiver design has been performed for exposing its main blocks. Next, experiments with four different antennas, without and with three different amplifiers (and combinations thereof) have been conducted from different locations. It was observed that the characteristics of the amplifiers play a significant role in performance improvement in terms of achievable range and amount of received ADS-B messages. The experimental results also show that, with the best combination of antenna and amplifier available for this thesis, the maximum range is 210 km.

This thesis is written in English and is 55 pages long, including 6 chapters, 40 figures and 10 tables.

Annotatsioon

Võimekuse hindamine vabavaralisel tarkvararaadiol põhineval ADS-B vastuvõtjal

Automaatse sõltuva seire üldteavitus (ADS-B) on suhteliselt uus lennuliikluse jälgimise süsteem, mida maailmas järjest rohkem kasutatakse olukorratuvastuseks traditsiooniliste sekundaarradarite asemel. ADS-B kasutab kombinatsiooni satelliitidel põhinevast GPS tehnoloogiast ja pardasensoritest, mille abil luuakse ADS-B sõnumid, mis sisaldavad õhusõiduki identifikaatorit, asukohta maal ja õhus, kiirusi, jne. Selliseid raadiosõnumeid saadetakse perioodiliselt automaatselt välja, mis tagab parema olukorratunnetuse pilootidele ja lennujuhtidele. Täiendav informatsioon, mida jagatakse ADS-B kaudu, võimaldab efektiivset navigeerimist ja seetõttu parendab ohutust ja vähendab kütusekulu.

Fakt, et ADS-B sõnumid ei ole krüpteeritud, on tekitanud märkimisväärse huvi tööstusele, akadeemilisele ja amatöörsektorile ehitamaks ADS-B vastuvõtjaid kommertsiaalseks, teaduslikuks, õppe- ja hobikasutuseks. Sellised ADS-B vastuvõtjad on mõnikord realiseeritud vabavaralise riist- ja tarkvara baasil. Nuand on üks firma, mis müüb vabavaralisi FPGA-l põhinevaid tarkvararaadioid (SDR) ja on välja andnud tasuta vabavaralise ADS-B vastuvõtja oma SDRi moodulitele.

Käesolev diplomitöö analüüsib Nuandi vastuvõtja võimekust, mis baseerub bladeRF x115 SDR moodulil. Esmalt on teostatud süsteemi tasemel analüüs ADS-B vastuvõtjale selle põhiplokke lahti seletades. Järgnevalt on viidud läbi eksperimendid nelja erineva antenniga, ilma ja kolme erineva võimendiga (ja nende kombinatsioonid) erinevates asukohtades. On tuvastatud, et võimendite omadused mängivad olulist rolli töövõime parendamisel ADS-B sõnumite saabumiskauguse ja nende hulga osas. Eksperimentide tulemused näitavad, et parima kombinatsiooniga töö jaoks kättesaadavast antennist ja võimendist, on maksimaalne töökaugus 210 km.

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 55 leheküljel, 6 peatükki, 40 joonist, 10 tabelit.

List of abbreviations and terms

AA	Aircraft Address
ADS-B	Automatic Dependent Surveillance-Broadcast
ADS-C	Automatic Dependent Surveillance-Contract
ADS-R	Automatic Dependent Surveillance-Report
AMP	Amplifier
ANT	Antenna
ARNS	Aeronautical Radio Navigation Service
ATC	Air Traffic Controller
ATM	Air Traffic Management
CA	Capability
CRC	Cyclic Redundancy Check
dB	Decibel
DF	Downlink Format
DIY	Do-It-Yourself
FAA	Federal Aviation Administration
FE	Front End
FFT	Fast Fourier Transform
FIFO	First In First Out
FPGA	Field Programmable Gate Array
GSM	Global System for Mobiles
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
LNA	Low Noise Amplifier
LTE	Long-Term Evolution
MF	Message Field
MHz	Mega Hertz
Next Gen	Next Generation
PI	Parity

PLL	Phase Locked Loop
PPM	Pulse Position Modulation
RF	Radio Frequency
RTL	Register Transfer Level
SAW	Surface Acoustic Wave Filter
SDR	Software Defined Radio
SRAM	Static Random-Access Memory
SSR	Secondary Surveillance Radars
TC	Type Code
VHDL	Vhsic Hardware Description Language
VNA	Vector Network Analyzer

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1 Introduction

This chapter gives a brief introduction to the modern and older airplane tracking systems and software defined radio. Furthermore, the problem statement is formulated, followed by the thesis outline.

1.1 Context

Commuting from one corner of the world to another one has never been as easy as it is today. There are several driving factors behind this, such as globalization, tourism, modern technology, etc. Every passing day, cities are modernizing, connecting, growing and therefore traveling from one place to another is inevitable. Air transport is the main source of traveling in the present time. Therefore, the number of airports and airplane are increasing day by day and this is leading towards busy air traffic routes.

For example, a 150%-200 % increase in air traffic was predicated for 2006 – 2025 in year 2006 [1]. 3.8 billion air travelers travelled in 2016 and it is expected that this number will increase up to 7.2 billion according to the International Air Transport Association (IATA) [2]. Due to this fact, enhanced air traffic management systems are being deployed by airport management into their daily operations. The number of flights taking off or landing to an airport has been increasing rapidly. Therefore, airport management organizations have been constantly and increasingly adapting and implementing air traffic management (ATM) systems which are so sophisticated that they even generate alerts when aircraft gets too close to each other in the sky [1].

The USA have established the next generation (Next Gen) program to improve safety, capacity and resiliency of the aviation air transportation system [3]. Similarly, the European Union have decided to develop the Single European Sky Air Traffic Management Research (SESAR) project, in order to unify the management of the European airspace under a single agency [4]. SESAR was established in 2007 to increase ATM system performance and to build the European intelligent air transport system [4].

A major part of both the Next Gen and SESAR systems is the Automatic Dependent Surveillance-Broadcast (ADS-B) system [5].

ADS-B is a relatively new way to monitor the air traffic. As the name indicates, it is a system that automatically broadcasts information about the aircrafts position, heading, speed, etc. from the aircrafts sensors, in contrast to the traditional interrogate-reply system. The ADS-B “Out” signal is received by ground stations and relayed to the air traffic controllers (ATC)’s facilities; it can also, be received directly by other aircrafts with ADS-B “In” capabilities.

In 2006 the first aircrafts were equipped with ADS-B and from 2020 all aircrafts flying in the USA and Europe will have to be equipped with the ADS-B system. The standard is also being adopted in other parts of the world [6].

The ADS-B system builds on top of some of the old interrogation-reply systems. The ADS-B systems incorporate old data-link systems to communicate, like the civilian Mode-S data-link [6].

The ADS-B system operates on the frequency range 1087.7 – 1092.3 MHz. This allocated frequency range is nothing but a smaller part of the larger frequency spectrum that has been allocated to the aeronautical mobile radio service (AMRS) and the aeronautical radio navigation service (ARNS). One of major feature of ADS-B is that signals can be received and decoded freely. For instance “FlightAware”, “FlightRadar24” and “OpenSky Networks” are crowd sourced distributed networks receivers websites to track air traffic based on ADS-B [7][8][9].

Software defined radio (SDR) are a suitable platform for implementing ADS-B receivers. An SDR can be defined as a radio communication system implemented by the means of software. A software-based transceiver can be implemented on programmable or configurable [10]. Many SDR platforms are built around a field programmable gate array (FPGA) in combination with programmable RF circuitry. FPGAs offer both flexibility (the most common types being based on SRAM memory are reprogrammable) and computational power (fine-grain hardware parallelism suitable for digital signal processing).

1.2 Problem Statement

Although commercial SDR-based ADS-B receivers are available in the market, like RTL-SDR or RTL dongle, "NooElec NESDR Mini 2+ 0.5PPM TCXO-based RTL-SDR USB" and "FlightAware pro stick" [11][12][13], they are usually not open-source, and thus not well suited for research and teaching purposes since such activities require having access to the internal details of the architecture and the possibility to modify it.

One exception to the above situation is the ADS-B hardware decoder [14]provided by Nuand for its FPGA-based bladeRF SDR series [15]. The fact that this receiver is open source and targeted at mid-range SDRs makes it attractive for research and teaching purposes. Nevertheless, it remains to be seen how well it performs in different conditions.

The purpose of this MSc thesis is thus to implement and evaluate the performance (in terms of coverage) of the open source ADS-B receiver provided by Nuand in different locations and with different antennas and amplifiers.

To do so, the following thesis goals have been defined:

1. Get an understanding of the ADS-B principles;

2. Analyze the design of Nuand's open source ADS-B receiver;

3. Implement and experiment with Nuand's open source ADS-B receiver on the bladeRF x115 board;

4. Analyze the results and share the gained insight;

1.3 Thesis Structure

This thesis is organized in six chapters, a chapter-wise description is explained briefly as follows.

- Chapter 1 introduces the context of the work, formulates the problem statement and presents the thesis structure.
- In Chapter 2, an overview of secondary surveillance radar (SSR) and ADS-B are presented. Furthermore, the ADS-B message format and related modulation scheme (PPM) are discussed with examples.

- Chapter 3 explains the concepts of the radio receiver components used in this work.
- In chapter 4, the experimental setup, and the specific amplifier and antennas are discussed in detail.
- Chapter 5 presents the results gathered during the experiments.
- Chapter 6 concludes the thesis by summarizing the findings, limitations, and proposing a few suggestions and recommendations for future work.

2 Overview of secondary control radars and ADS-B

2.1 Secondary surveillance radars (SSR)

ADS-B technology is progressively replacing the current secondary surveillance radars (SSR) and has drastically improved the cockpit situational awareness.

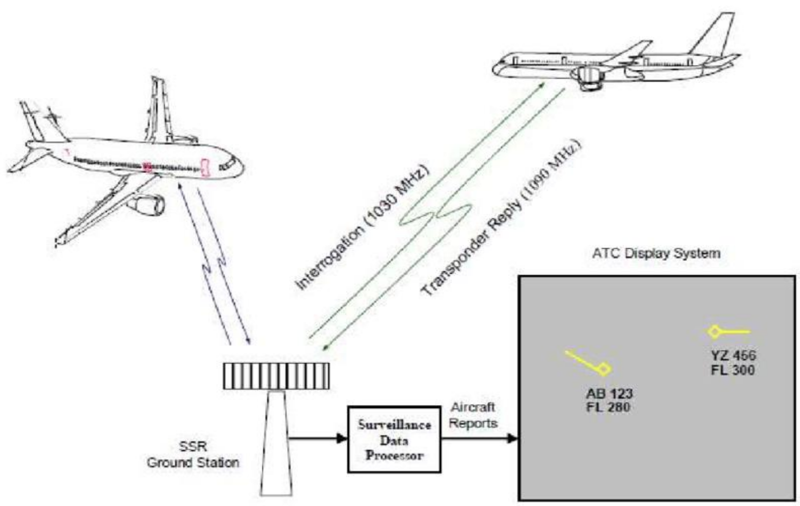


Figure 2.1: Illustration secondary surveillance radars [16]

As illustrated in Figure 2.1 for many years the ATC have been based on e.g. radars which tracks aircrafts within their area, radio systems where the pilot communicate with the air controller, and similar systems. Such systems provide information about the aircrafts to the ATC. SSR is based on interrogation protocols, where the different surveillance systems interrogate the aircrafts about their position, heading etc., to which the aircraft reply with the requested information through a transponder. SSR uses transponder replies and receives ground interrogating signal [17].

2.2 Automatic Dependent Surveillance

Automatic Dependent Surveillance (ADS, not to be confused with ADS-B) is a central component of the NextGen ATC program. In its generic form, ADS is a technology, which when implemented on an aircraft, provides data automatically. This data is mainly consisted of the data obtained from on-board navigation and from the global positioning systems (GPS). This data is based on various modules that include, among others, plane identification and positioning [18].

The technology that ADS uses through which the aircraft updates and broadcasts its information itself is far more advanced that the traditional SSR technology being used in ATC. This is because the information is both more complete and more rapidly shared due to the use of satellite navigation for the determination of position, enabling the aircraft to be tracked [19].

2.3 Forms of ADS

Several forms of ADS are currently in use, including:

- ADS-C
- ADC-R
- ADS-B

2.3.1 Automatic Dependent Surveillance-Contract (ADS-C)

ADS-C and ADS-B are like each other when it comes to functionality. But the main difference lies in ADS-C's way of transmitting which is completely based on a contract, i.e. demand contract, periodic contract, event contract and emergency contract, between a ground system and an aircraft. This technology is expected to find its most likely applications in sparsely trafficked transcontinental and transoceanic crossings [20].

2.3.2 Automatic Dependent Surveillance-Rebroadcast (ADS-R)

ADS-R can be defined as a datalink translate function used to compensate two separate frequencies (1090 MHZ (1090 MHZ (Mode-S extended squitter) and 978MHz (Universal Access Transceiver (UAT), used only in the USA and for altitudes below 18000 ft) [21]. The

ADS-R transform and reformat the signal received through ADS-B “In” from one frequency to another frequency. This system enables aircraft to receive signals regardless of the operating frequency of the other aircraft, it can be either 1090 MHz or the other frequency [22].

2.3.3 Automatic Dependent Surveillance-Broadcast (ADS-B)

ADS-B makes an aircraft visible and hence enhances its safety. This visibility is real time and is transmitted to ATC and other aircrafts that are equipped with ADS-B. It transmits the data containing position, velocity, etc., of the aircraft every second. This data can also be downloaded and recorded for the sake of post flight analysis.

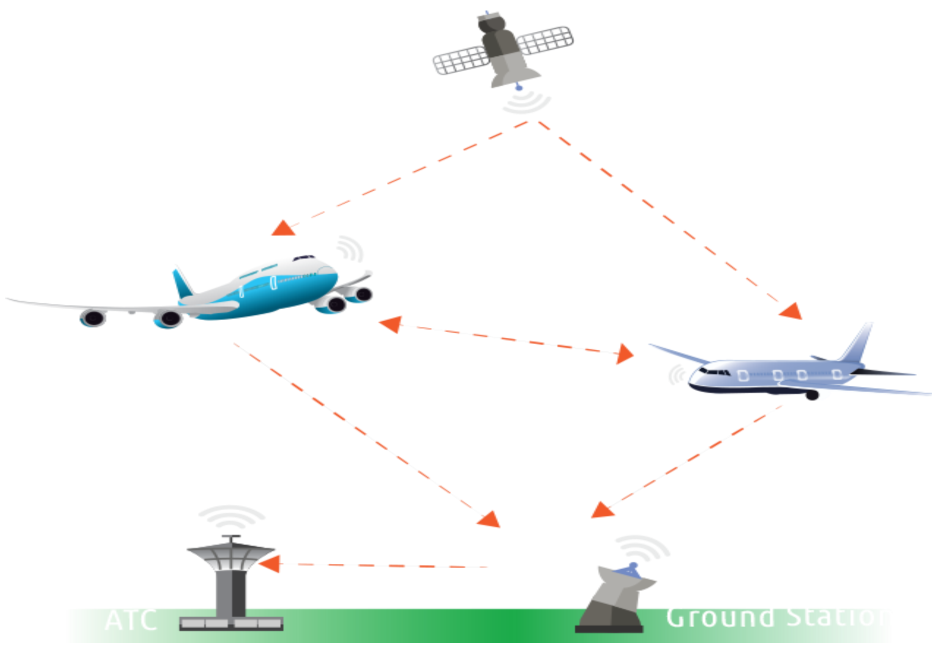


Figure 2.2: Illustration of the ADS-B principle [23]. Aircraft broadcast their information (itself collected from onboard sensors, GPS receivers, etc.) to ground stations and to other aircraft. The ADS-B signal received by the ground station is forwarded to the ATM system.

ADS-B as shown in Figure 2.2 has become the main application of the ADS principle since it is applied on aircraft or surface vehicle that broadcasts position, altitude, vector and other information for use by other aircraft, vehicles, and by ground facilities. Access to ADS-B information is free and free for all.

The ADS-B signals have various applications. They can be used for the purpose of surveillance, (ADS-B "Out") or can be used by other aircraft regarding the information about the surrounding traffic (ADS-B "In") and avoid collisions. For the purpose of transmission of ADS-B messages on the 1090 MHz center frequency, mode transponder Mode S Extended Squitter is used.

Outside of the USA, the center frequency of operation for the transmission of data used by on-board transponders is 1090 MHz. For the successful reception of these signals, the receiver should also be set at said frequency. This frequency of 1090 MHz belongs to the L-band of the frequency spectrum. Electromagnetic signal with such high frequencies is not reflected by the ionosphere and are distributed straightly into the environment. For the reception of these signal, it must be ensured that there is no obstacle between the aircraft and the receiving antennas. The antennas must be installed at the highest height possible having free space in all directions. This is done because, the greater the height of the aircraft is, the greater distance there is between the aircraft and the receiver and the probability of successful reception is practically decreased. For example, the signal from an aircraft which is at an altitude of 30,000 feet (10 km) may be received up to 277 km [24]. For this purpose, sensitive receiver and antenna are required.

2.4 ADS-B "Out" and "ADS-B" In

ADS-B mode has two main modes, i.e. ADS-B "Out" and ADS-B "In".

Since, ADS-B "Out" has its applications in the tracking of aircraft, it is more needed by ATC for managing its traffic. The data it provides includes aircraft's position, velocity and altitude which is provided at the rate of every one second. This transmission is successively received by ATC and other nearby aircrafts. This data is equivalent to a radar display. It is expected that most of the aircraft will equipped with ADS-B out by 2020 [22].

ADS-B "In" works other the way around to ADS-B "Out". ADS-B "In" allows the aircraft to receive signals from other aircrafts and ADS-B ground stations.

2.5 ADS-B Message

An ADS-B data is transmitted two times in a second at 1090 MHz frequency. An ADS-B message consists of a preamble and a data block, totaling an equivalent of 120 bits. The preamble makes it possible to detect the start of an ADS-B transmission and make synchronization. The preambles field consists of the equivalent of 8 bits. After the preamble comes a data block which is Pulse Position Modulated (PPM) and contains a total of 112 bits. The complete ADS-B message format is as shown in Table 2.1.

In the book [25], the authors explain the ADS-B message format in a very detailed way; most of the information presented in this section refers to this book.

Table 2.1: The 120 bits composing an ADS-B message

8 Bits	5 Bits	3 Bits	24 Bits	56 Bits	24 Bits
Preamble	Downlink Format	Capability	ICAO address	Message Field	Check Sum

2.5.1 Downlink Format (DF)

ADS-B message's data block starts with the downlink format (DF). There are three different types of DF values, as shown in Table 2.2. The downlink format tells what type of messages are transmitted from an aircraft, either "17" (Mode-S), "18" (not Mode-S), or "19" (reserved for military purposes). The first 5 bits of the data block are allocated to DF.

Table 2.2. Downlink format messages type

Value	Transmission device
17	Mode-S
18	Not Mode-S
19	Military Application

2.5.2 Capability (CA)

The next three bits of an ADS-B message's data block indicates the capability field, which corresponds to whether the aircraft is airborne or on the ground.

2.5.3 ICAO address (AA)

Each ADS-B message contains the aircraft identity which can be identified by using ICAO address. The ICAO address is unique for each aircraft assigned by International Civil Aviation Organization (ICAO): an organization which manage International civil aviation matters [26]. ICAO address can be decoded by using query tool called "World Aircraft Database" [27]. In the ADS-B message's data block, the 24 bits (9th to 32th bits) hold this aircraft ID.

2.5.4 Message Field (MF)

The actual message content is located in this part of an ADS-B message's data block, which consist of 56 bits and is called message field. The first five bits of the message field are called "Type Code" and corresponds to the identification of the information contained by an ADS-B message [25].

Table 2.3 Type code represented by the first 5 bits of the message field [25].

Type Code (TC)	Content
1-4	Aircraft ID
5-8	Surface position
9-18	Aircraft position
19	Aircraft velocity
20-22	Aircraft Height
23-27	Reserve
28	Aircraft status
29	Target state
31	Aircraft operation status

2.5.5 Parity (PI)

The last 24 bits are parity bits. They are used for cyclic redundancy check to verify the correctness of the received message.

2.6 Example of a received ADS-B message

In Table 2.4 a received ADS-B message is shown. As can be seen the received raw message is in hexadecimal format. The shown message is an Identification message as can be seen in

TC field which has a value binary value “10000”, which is equal to “1” in decimal. As shown in table 2.3 this type code corresponds to aircraft ID.

Table 2.4. Example of received ADS-B message

DF	CA	ICAO	TC	DATA	PI
8D 51102C 20 2D40B6E37820 E35315					
10001	101	101000100010000000101100	10000	101101010000000101101101110001101111000000100000	111000110101001100010101

2.6.1 Pulse Position Modulation

ADS-B messages are transmitted after modulating with carrier frequency by using Pulse Position Modulation (PPM) technique. In the PPM modulation scheme, the width and amplitude of a reference signal remains constant and the position of a reference signal is varied according the information signal [28].

PPM encodes the bits by pulse position, and for ADS-B a logical 0 can be defined as a transition from low to high and a logical 1 as a high to low transition as shown in Figure 2.3. Figure 2.4 illustrates the PPM signal for the sequence “0101”.

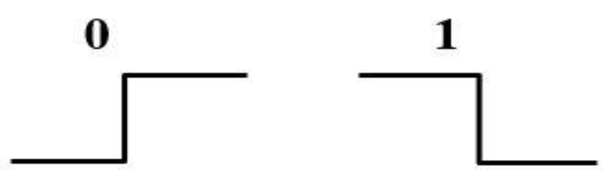


Figure 2.3: Illustration of bits in PPM. A transition from low to high denotes logical 0 and a transition from high to low denotes a logical 1.

Figure 2.4: PPM signal the sequence “0101”.

The PPM signal is multiplied with the carrier wave when a signal is transmitted, this way of transmitting a signal is also called amplitude-shift-keying (ASK).

2.1 Selected examples of academic works on ADS-B

In [29], the author discussed the basic advantages and disadvantages of ADS-B. Their scenarios were simulated in MATLAB and data was collected from Federal Aviation Administration (FAA) and International GNSS Service (IGS). In his work he proved that the accuracy of ADS-B is higher than existing conventional radar system.

In [30], the authors collected the data from one airport by using ADS-B and investigated anomalies in the data and quantified the associated possible risks. A dropout is considered when the update rate exceeds three seconds. Dropouts are of different durations and have a different level of risk depending on how much time ADS-B is unavailable as the surveillance system. Altitude deviation refers to the deviation between barometric and geometric altitude. Deviation ranges from 25 feet to 600 feet have been observed, author considered it as degradation of safety in future when more Unmanned Aircraft Systems (UAS) will flying around.

In [31], a feasibility study was conducted to show that ADS-B is capable of supporting space flight operations by examining ADS-B-related system issues and technical issues individually. A potential ADS-B space-oriented message set is proposed to be exclusively transmitted from space vehicles to other traffic and ATC. Simulations were performed to test the functionality of the message set, and sensitivity of three ADS-B system parameters, which are message update rate, data latency, and state vector accuracy.

In [32], the authors built and launched a demonstrator to receive ADS-B signals from low earth orbit nano-satellites. Their design builds around an FPGA-based highly-sensitive ADS-B SDR receiver payload. Their results show that ADS-B signals can be received in space and retransmitted to a terrestrial station from 700+ km altitudes.

The above selected works illustrate that not only ADS-B offers better situational awareness, but that ADS-B signals can potentially be received over long distances, also when using an SDR approach.

However, before implementing and evaluating Nuand’s ADS-B receiver performance, the basic elements used for building the receiver in this thesis are described in the next chapter.

3 Receiver

In radio communication a device which intercepts electromagnetic signal and converts it into usable information is known as receiver. The last two decades have seen the emergence of so-called SDRs which provide increased flexibility as compared to traditional fixed hardware-based receivers.

3.1 SDR

An SDR can be defined as software-based design paradigm for radio communication system. It is a programable transceiver where different radio components like amplifiers, filters, mixers, modulators/demodulators are implemented by means of software [33]. This software based transceiver provides the ability to implement several communication protocol without changing the hardware [10].

A personal computer that has an SDR system normally consists of an analog to digital converter preceded by some form of RF front end or with a sound card. Significant amount of signal processing that was first being done by a special purpose hardware are handed over to general-purpose processor, although there is still the possibility to execute whole or part of compute intensive functions on FPGA. Such type of design produces a radio that can handle different radio modulation schemes and protocols and can receive and transmit accordingly, solely on the basis of the software programmed. Their key application lies in the utility for the military and cell phone services. Both of these are required to serve a much wider variety of changing radio protocols in real time.

3.2 BladeRF x115

The last decade has witnessed the emergence of relatively low-cost SDRs which are popular among radio amateurs, researchers, and students. Table 3.1 gives an overview of some SDRs available on the market [10] (the last row has been added by the author).

Table 3.1: Different SDRs available on the market [10]. The last row has been added by the thesis' author.

	Programmability	Flexability	Portability	Computing power	Energy-efficiency	Soft core	FPGA	Cost (USD)
Imagine-based	✓	×	×	Medium	Low	Imagine stream processor	N/A	N/A
USRP X300	✓	✓	×	High	Low	PC	Xilinx Kintex-7	≈ 4–5K
KUAR	✓	×	×	Medium	Low	Pc + 2 x Power PC cores	Xilinx Virtex 2	N/A
LimeSDR	✓	✓	×	High	Low	PC	Intel Cyclone 4	≈300
Ziria	✓	✓	×	High	Low	PC	Depends on App	N/A
Sora	✓	✓	×	High	Low	PC	Xilinx Virtex-5	≈900
SODA	✓	✓	✓	High	High	ARM Cortex-M3	N/A	N/A
Iris	✓	✓	✓	High	High	Dual-core ARM Cortex-A9	Xilinx Kintex-4	≈1.2K
Atomix	✓	✓	✓	High	Medium	TI 6670 DSP	N/A	≈200
Airblue	✓	✓	✓	High	High	N/A	Intel Cyclone 4	≈1.3K
PSoC 5LP	✓	×	✓	Low	High	ARM Cortex-M3	N/A	N/A
Zynq-based	✓	✓	✓	High	High	Dual-core ARM Cortex-A9	Xilinx Kintex-4	≈1.2K
bladeRF x115	✓	✓	✓	High		PC	Intel Cyclone IV	≈650

The bladeRF x115, produced by Nuand, is an example thereof which is available at Thomas Johann Seebeck Department of Electronics. It is similar to the LimeSDR listed in Table 3.1, the main differences being the RF front-end chip of the bladeRF x115 not being able to tune below 300 MHz.

A photograph of the board is shown in Figure 3.1. One key aspect of Nuand is that both their hardware design and firmware are open-source, making it a suitable platform for research and teaching activities.

Another advantage of the bladeRF x115 is that it comes with a relatively larger 115 kilo element (KLE) Cyclone IV FPGA [14]. This FPGA provides additional room for implementing e.g. hardware accelerators and signal processing chains. These signal processing chains include e.g. FFTs, decoders, transmit modulators/filters, and receive acquisition correlators for burst modems.

Figure 3.1: Photograph of Nuand bladeRF x115 SDR board. The board builds around a Cyclone IV FPGA (in the middle), LMS6002D radio front-end (right, under the metallic shield), and Cypress FX3 USB 3.0 interface (left) [34].

When it comes to the specifications, the bladeRF x115 can tune from 300 MHz to 3.8 GHz out of the box, without having any need for extra boards. The board can be placed into its immediate use through various open-source software such as GNU Radio. Due to the inherent flexibility in its hardware and software, it can be made to different uses. For example, it can be configured to operate as a custom RF modem, a GSM and LTE picocell, a GPS receiver, an ATSC transmitter, or a combination Bluetooth/Wi-Fi client, without the need for any expansion cards. Of interest for this thesis, it can also operate as an ADS-B receiver.

3.3 Antenna

An antenna is used to receive and/or transmit electromagnetic waves. It has a metallic structure which basically enables it to transmit and receive the electromagnetic signals. They come in various shapes and sizes based on the type of their requirements.

The antenna is considered as an important component of radio communication. In transmission mode, an electric current is provided to the antenna terminal and electromagnetic energy radiates from antenna. On other hand in receiver mode, the antenna receives electromagnetic signal and converts it into electric current, which is then typically fed into an amplifier.

Antennas are characterized by S-parameters which indicate the input-output relationship between its ports (terminals). For example, S12 represents the power transferred from Port 2 to Port 1 and S21 represents the power transferred from Port 1 to Port 2. The most often considered parameter is S11, which indicates how much power is reflected from the antenna (also known as the reflection coefficient or return loss). When S11 = 0 dB, all the power is reflected from the antenna, i.e. no energy is radiated [35].

3.4 Amplifier

An amplifier is an electronic circuit which is used to amplify weak electronic signals. It can increase the power of the signal in terms of voltage or current. It is a two-port electronic circuit which amplifies the applied signal by using injected power from the power supply. An amplifier can be standalone circuitry or embedded with other components. The relationship between input and output is expressed in terms of gain. Amplifiers are classified into several classes like such as Class A, Class B, Class AB [36].

They have wide applications in electronics and radio technology. In radio communication power amplifier and low noise amplifiers are used to strengthen weak radio signals.

3.5 LNA

A LNA, also known as a low noise amplifier, is a significant parts of the radio receiver circuit and can even be considered to be the most important one; this is due to the fact that any kind of additive noise during the amplification of the received signal could result in the loss of the intercepted information [37]. To minimize the loss due to interference, LNAs are designed to be close to the receiving device. As their name suggests, they do add up a minimum amount of noise in the amplified signal, but this noise is just enough to not distort the information in any way. Any more noise, if added, would result in the loss of information.

The applications of LNA are widespread. For example, they are found in radio communication systems, different medical instruments and various types of electronic test equipment.

3.6 SAW Filter

A surface acoustic wave filter converts an electric signal to an acoustic wave. For this, a piezoelectric substrate is used, such as quartz, to produce the required output signal [38]. There are several types of SAW filters available, mainly based on their operations [39]. The most common type is called a band-pass filter. This filter is widely used in radio systems and different types provide different advantages. For example, some provide small shape, some have low insertion loss, and some operates on high frequency.

The next chapter presents the specifics of the antennas, amplifiers and experiments used to evaluate the performance of Nuand's open-source ADS-B receiver.

4 Experimental setup

4.1 Diagrams

Figure 4.1 shows the diagram of the initial experimental setup. The radio signal from the environment is captured through an antenna which is connected to the NUAND x115 bladeRF SDR board (described in Chapter 3) via a coaxial cable. The radio signal is then digitized and digitally processed in the SDR board (wherein Nuand's open-source ADS-B decoder has been implemented on FPGA). Finally, the decoded signal is transmitted to the computer to by using a USB 3.0 cable. In this first experimental setup, there is no amplifier between the antenna and the SDR board.

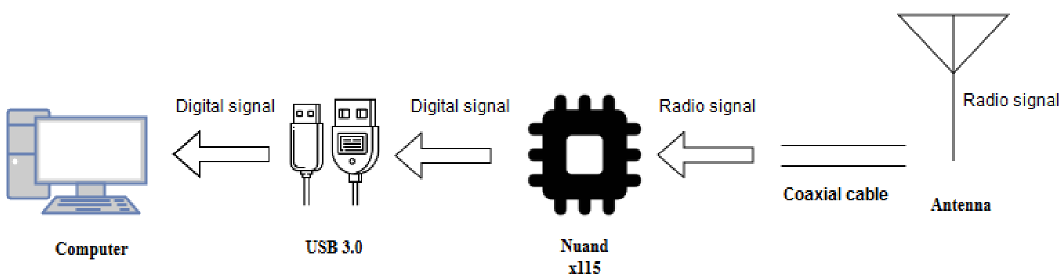


Figure 4.1: Diagram of the first experimental setup without amplifier between the antenna and Nuand x115 bladeRF SDR board. Nuand's open-source ADS-B decoder is implemented on the FPGA fitted on the SDR board.

Figure 4.2 shows the second experimental setup where an additional building block, an amplifier, was added. For receiving and decoding ADS-B signals, such amplifiers are typically a combination of band-pass filter (that rejects unwanted frequencies) and low noise amplifier (LNA) that amplifies the received (often weak) radio signal while limiting the added noise. The amplified signal is then transmitted to the Nuand x115 bladeRF SDR board, where it is processed, as described for the first experimental setup.

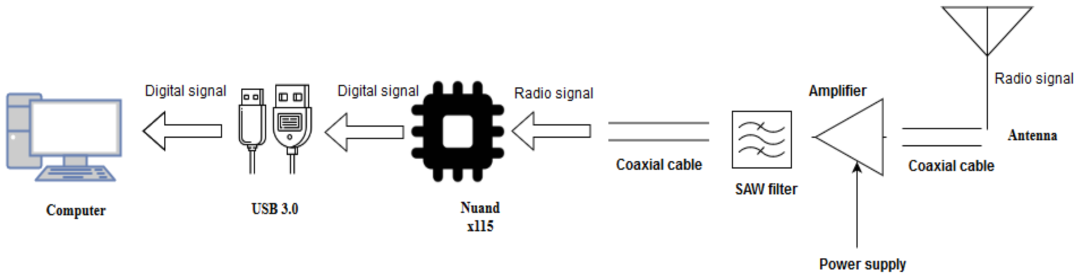


Figure 4.2: Diagram of the second experimental setup with an amplifier between the antenna and Nuand'x115 bladeRF SDR board. As for the first experimental setup, Nuand's open-source ADS-B decoder is implemented on the FPGA fitted on the SDR board.

4.2 Amplifiers used in the second experimental setup

While no amplifiers were used in the first experimental setup, three different types of amplifiers were selected for second experimental setup. These are introduced in what follows.

4.2.1 AMP1 (DIY Wide band Amplifier LNA-1400)

The first amplifier is a do-it-yourself (DIY) unit which consists of a wide band LNA without any filter. In Figure 4.3 the frequency response of AMP1 is shown; as can be seen it has 17 dB gain at 1090 MHz frequency. But this amplifier has no filter within which is expected to result in possibly degraded results.

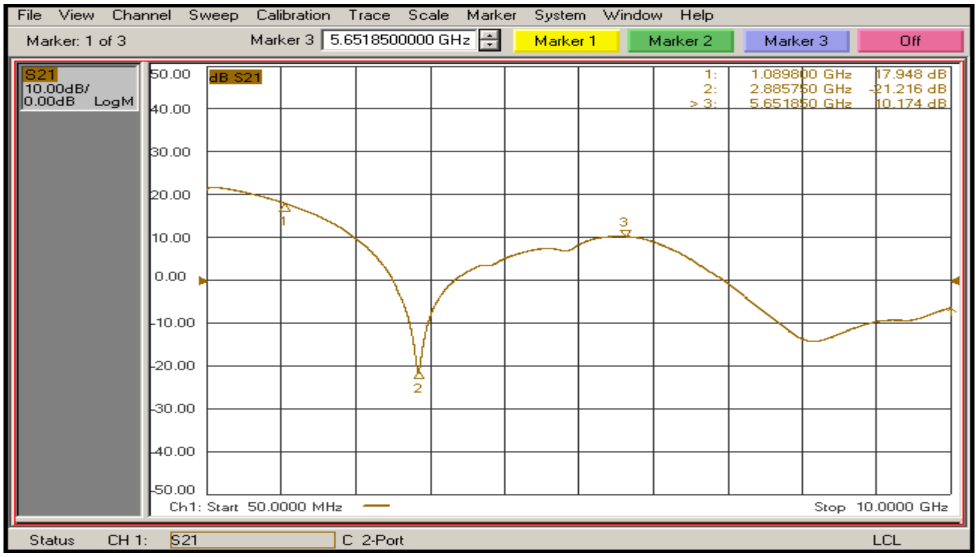


Figure 4.3: Frequency response of AMP1 (DIY Wide band Amplifier LNA-1400), based on measurements done in one of T.J. Seebeck Department of Electronics' lab by using a vector network analyzer (VNA). As can be seen, the amplifier is designed for wideband frequencies.

4.2.2 AMP2 (UPTRONICS HAB-FPA1090SAW)

What is referred to as AMP2 is manufactured by UPTRONICS; the reference is HAB-FPA1090SAW. A photograph thereof is shown in Figure 4.4. As can be seen in Figure 4.4, this unit contains an LNA (in black rectangular box) followed by a surface acoustic wave (SAW) filter (in red circle), which is a band pass filter [40].

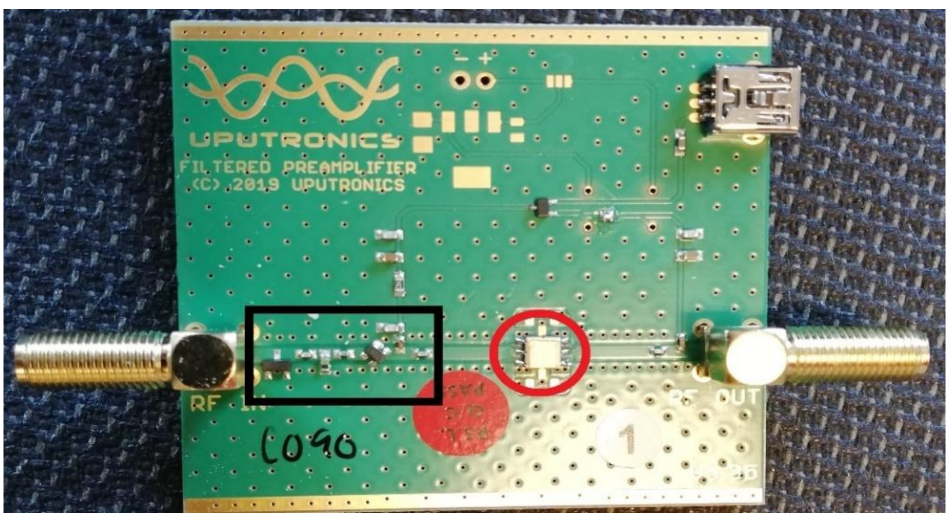


Figure 4.4: Photograph of AMP2 (UPTRONICS HAB-FPA1090SAW) including SAW filter and LNA [40]. The black box delimitates the LNA and the red circle indicates the SAW filer.

This unit is specifically tuned for ADS-B frequencies (1090MHz) and can be powered by either by a USB header or via bias-tee. The main characteristics of the unit are listed in Table 4.1, based on the values provided in the product's description datasheet [41]. In addition, its frequency response (measured in one of T. J. Seebeck Department of Electronics) is shown in Figure 4.5.

Table 4.1: Main characteristics of AMP2 (UPUTRONICS HAB-FPA1090SAW), based on [41].

Parameter	**Value**
Gain	Min 15 dB
Noise Figure (NF)	0.75 dB
Supply voltage	+5 V
Current consumption (at 5V)	Approx. 56 mA

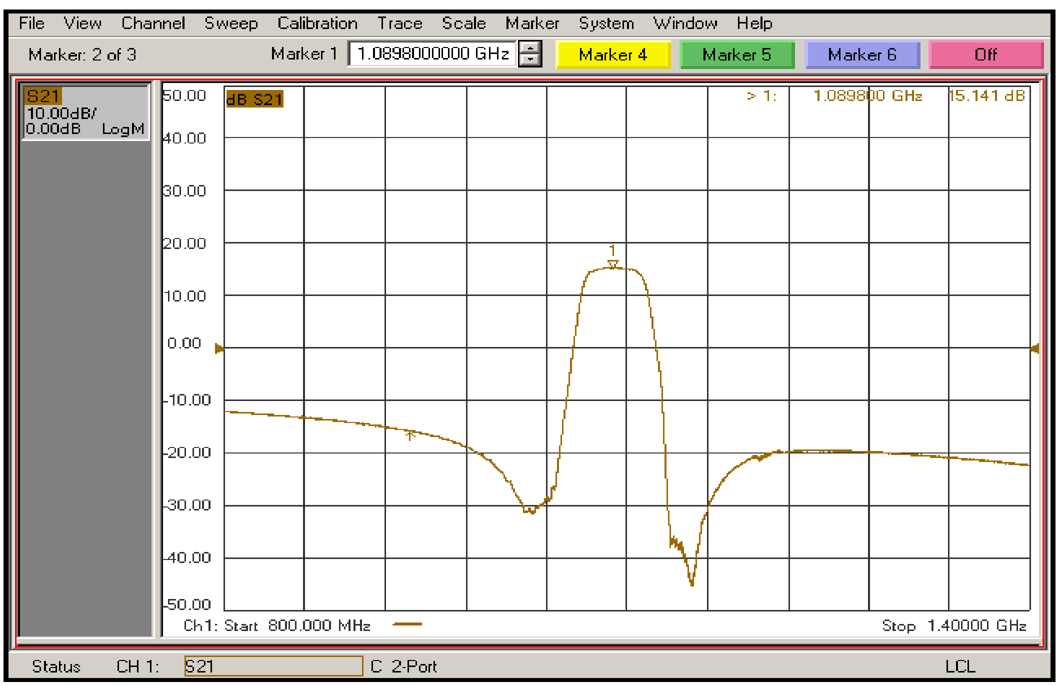


Figure 4.5: Frequency response of AMP2 (UPUTRONICS HAB-FPA1090SAW), based on measurements done in one of T. J. Seebeck Department of Electronics' lab by using a vector network analyzer (VNA). As can be observed, the amplifier is tuned for 1090 MHz, i.e., the frequency of ADS-B.

4.2.3 AMP3 (Akozon ADS-B RFFE)

Referred to as AMP3, this unit is sold either as a no-name device or as Akozon ADS-B RFFE. a photograph is shown in Figure 4.6. It consists of a two LNAs and two-stage filters (especially designed for ADS-B known as SAW filters). The SAW filters (shown in red circles) as can be seen in the red circle attenuate out-of-band signals and only allows 1090 MHz signals. It has 38 dB gain according to datasheet [42]. Its main characteristics, based on the information printed on the unit itself, are listed in Table 4.2.

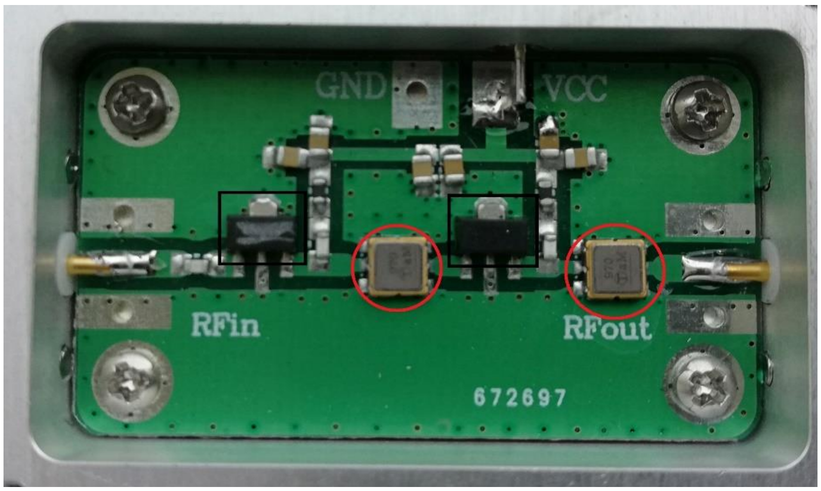


Figure 4.6: Akozon ADS-B RFFE amplifier. It consists of a two-stage LNA (black boxes) and two-stage filter (red circles) [42].

Table 4.2: Main characteristics of AMP3 (Akozon ADS-B RFFE), based on the information provided on the unit itself.

Parameter	**Value**
Gain	Min 38 dB
Frequency	1090 MHz (+/- 15 MHz)
Voltage	+ 5 V

Figure 4.7: Frequency response of AMP3 (Akozon ADS-B RFFE) based on measurements done in one of T. J. Seebeck Department of Electronics' lab by using a vector network analyzer (VNA). As can be seen, the amplifier is tuned for 1090 MHz, i.e., the frequency of ADS-B.

Figure 4.7 shows the frequency response of AMP3 which was measured in T. J. Seebeck Department of Electronics' lab by using a VNA. It can be noticed this amplifier has a measure 30.167 dB gain, which is lower as compare to the 38 dB, indicated on the unit.

4.3 Antennas

Four antennas were chosen to conduct the experiments (both with and without the amplifiers). These four antennas are different in shapes and sizes. Before starting the experiments, the antenna's characteristics have been measured in one of T. J. Seebeck Department of Electronics' lab by using a vector network analyzer (VNA).

4.3.1 ANT1 (Quarter Wave Antenna)

The first antenna, ANT1, is a DIY quarter wave antenna; as its name indicates it transmits and receives quarter wavelength of a frequency. Quarter wave antenna, known as Marconi antenna, was invented by Guglielmo Marconi [43][44].

As shown in Figure 4.8, the quarter wave antenna used in this work consists of four radials to maximize the ground conductivity.

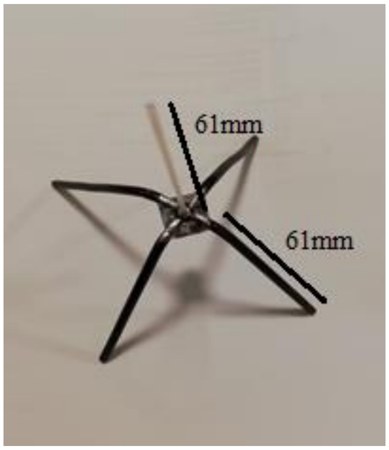


Figure 4.8: ANT1 (quarter wave antenna) used for the experiments.

The top part of the antenna is 61mm longer and the radials are also 61mm long, connected with a feed point at 45°, as shown in Figure 4.8.

The S11 parameter (see Section 3) has been obtained via VNA and is illustrated in Figure 4.9. As can been seen, S11 (return loss) is -17.53 dB at 1090 MHz, as Marker 1 indicates in Figure 4.9. Although S11 is even better at 1115 MHz (Marker 4), ANT1 is still deemed as a candidate for ADS-B reception.

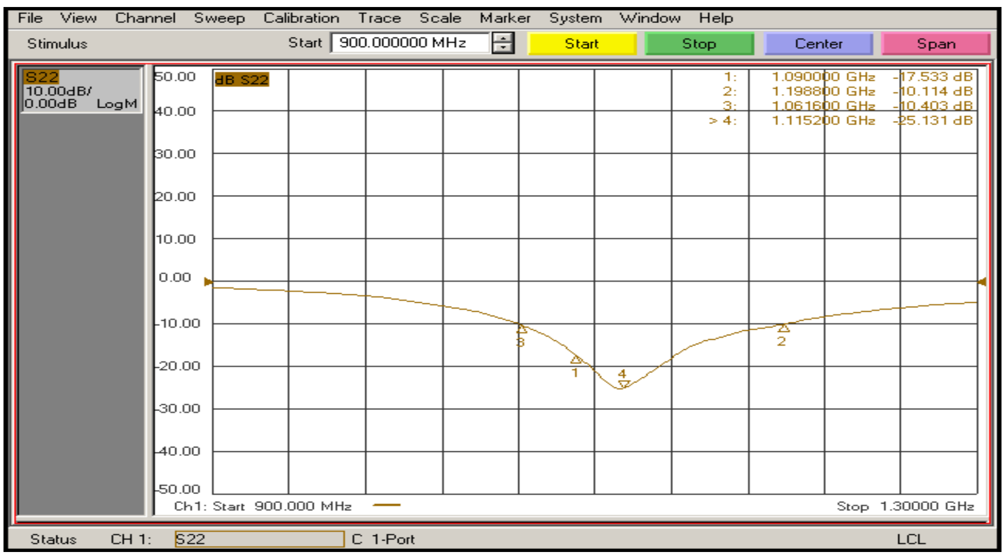


Figure 4.9: S11 parameters of ANT1 (DIY quarter wave antenna). S11 (return loss) value is -17.53 dB at 1090 MHz (Marker 1); ANT1 is deemed as a suitable candidate for ADS-B reception.

4.3.2 ANT2 (Flower pot antenna)

The second antenna, ANT2, is a DIY flower pot antenna, i.e. a vertical half wave center fed antenna which has a resonant choke at the bottom. Such antennas can be either single band or dual band; in this work, a single-band antenna is used as shown in Figure 4.10. Its coax inner length and extended length is 61mm.

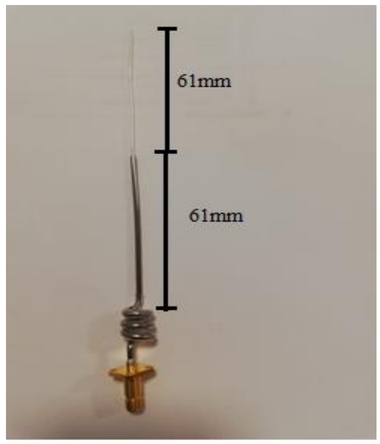


Figure 4.10: ANT2 (DIY flower pot antenna). Its coax inner length and extended length are both 61 mm.

Its S11 parameter, obtained via VNA is illustrated in Figure 4.11. As can been seen, S11 (return loss) is -38.845 dB at 1090 MHz, as Marker 1 indicates. This is the lowest S11 value for ANT2, which thus appears as a very good candidate for ADS-B reception.

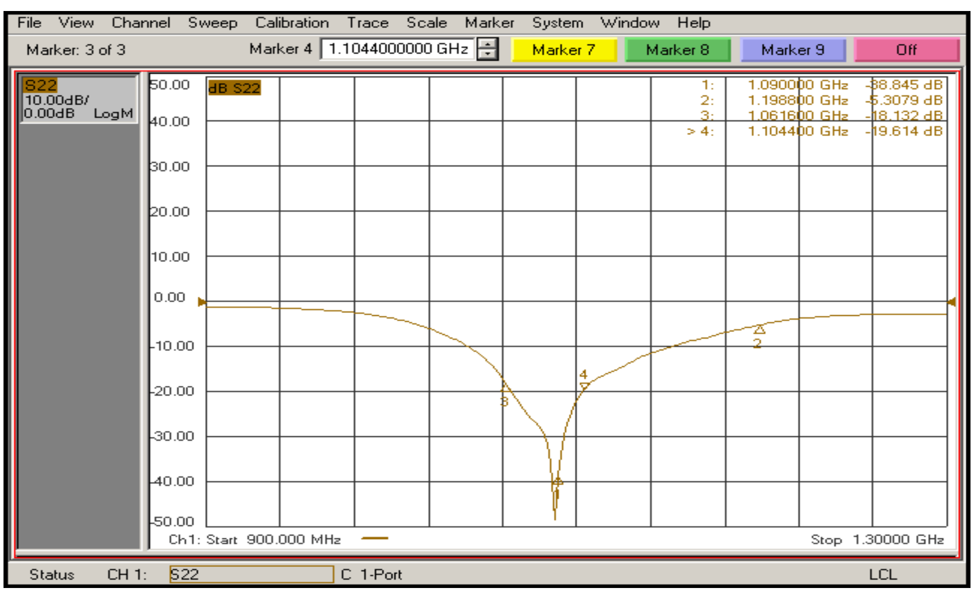


Figure 4.11: S11 parameters of ANT2 (DIY flower pot antenna). The lowest value (-38.845 dB) is obtained at 1090 MHz, making it a good candidate for ADS-B reception.

4.3.3 ANT3 (WA5VJB Log-Periodic antenna)

Log-periodic antennas have a large bandwidth which depends on the size of its structure. The so-called log-periodic array consists of several dipole elements but not all are operational at one frequency [45]. The third antenna used in this work (ANT3) is a log-periodic antenna produced by a radio amateur referred to as WA5VJB. The particular model range is 850 - 6500 MHz, i.e. including ADS-B at 1090 MHz. The announced typical forward gain is 6 dBi [46].

Figure 4.12 shows that the higher frequency end is considered as a feed and the low frequency end as a load [47].

Figure 4.12: ANT3 (WA5VJB Log-Periodic antenna). Its frequency range is 850 - 6500 MHz, i.e. including ADS-B at 1090 MHz.

As shown in Figure 4.13, ANT3's S11 parameter at 1090 MHz (Marker 1) is -12.175 dB. While this is not as good as ANT1, and is definitely less good than ANT2, this value still makes ANT3 a candidate for ADS-B reception.

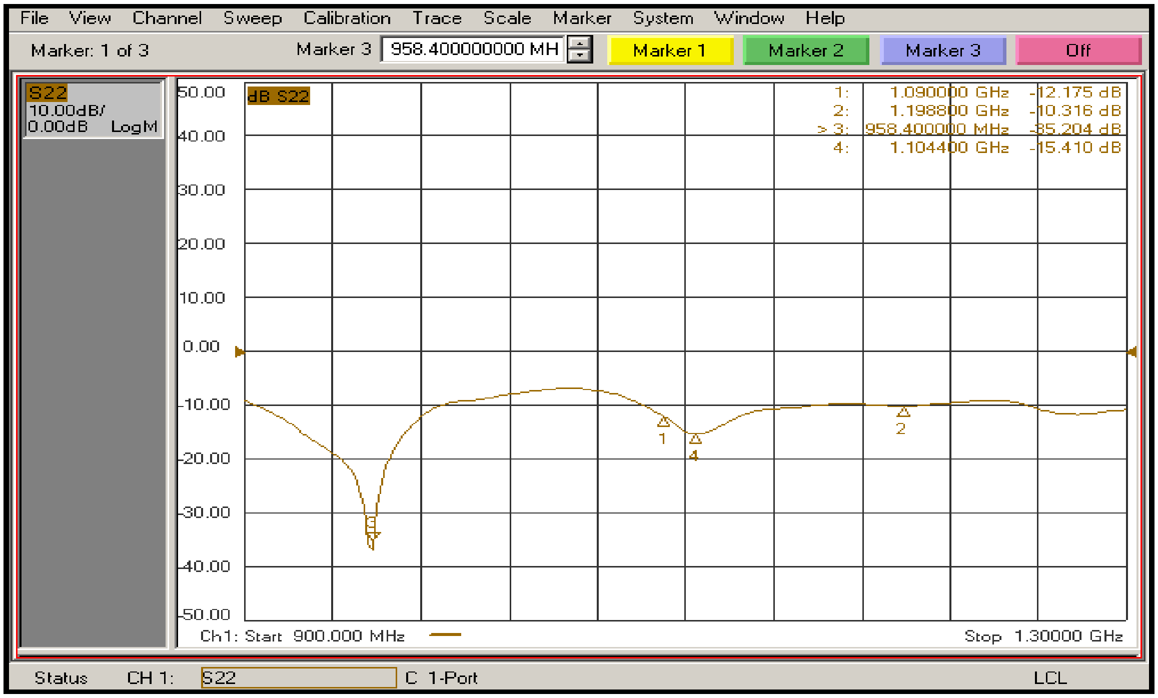


Figure 4.13: S11 parameters of ANT3 (WA5VJB Log-Periodic antenna). At 1090 MHz, S11 value is -12.175 dB, making is a candidate for ADS-B reception.

4.3.4 ANT4 (DIY Collinear Antenna)

Finally, the fourth antenna used in this work is a DIY collinear antenna. Array elements are arranged co-axially in such a collinear antenna or in other words dipole antennas are stacked on top of each other [48]. Sometimes they are also called COCO antenna. In Figure 4.14, the DIY collinear antenna used in this work can be seen with 72mm longer dipole antenna.

Figure 4.14: DIY collinear antenna with 72 mm longer diepole.

The S11 parameters of ANT4 can be seen in Figure 4.15. At 1090 MHz, the value is -11.110 dB, i.e. the lowest among the four antennas used in this work. Nevertheless, such a value does not preclude at all using ANT4 for ADS-B reception.

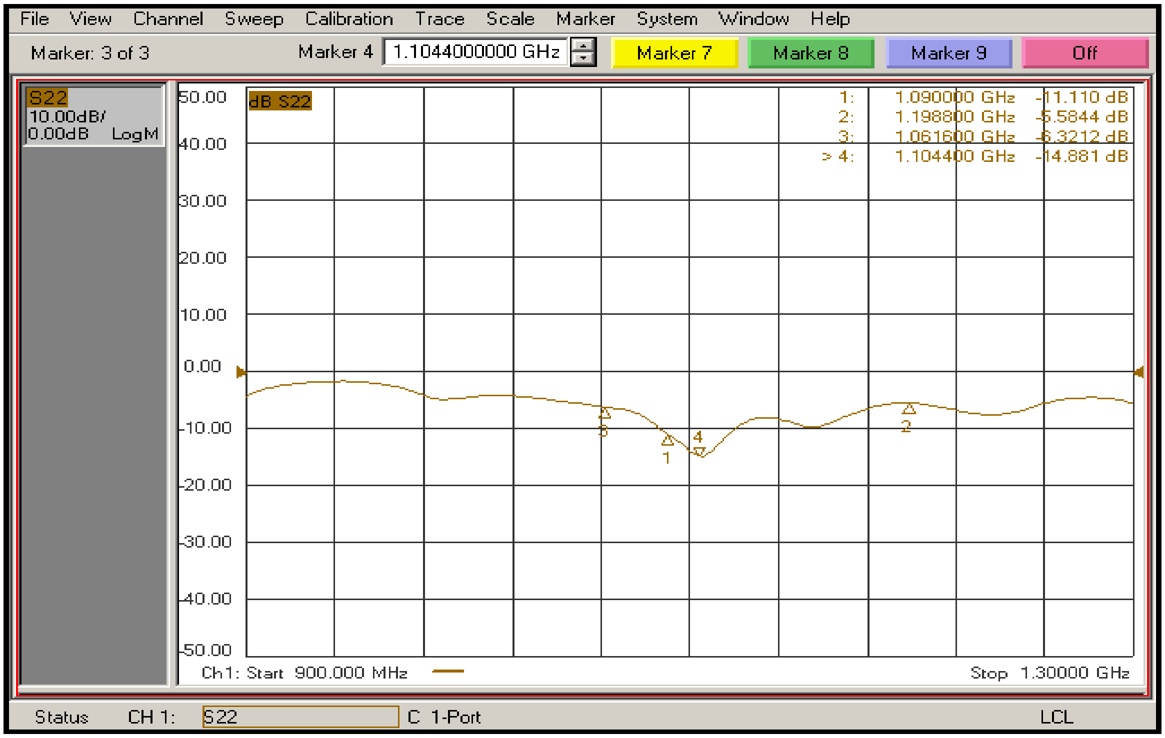


Figure 4.15: S11 parameters of ANT4 (DIY collinear antenna). At 1090 MHz, the value is -11.110 dB, making ANT4 a candidate for ADS-B reception.

4.4 NUAND's ADS-B open-source design

SDR as its name suggests, can tuned for the range of frequencies from narrow band to wide band through software or reconfigurable hardware such as FPGA. As mentioned in Section 3.2, in this thesis a Nuand x115 bladeRF board is used. The ADS-B open source design is provided by Nuand [49] and implemented on the FPGA of the board.

This section gives an overview of the design, including a top-level view of the four ADS-B blocks in the receive path and some details about each of them. In this thesis, Nuand's ADS-B open source design has been synthesized using Intel Quartus Prime 17.1 [50]. The screenshots in what follows are obtained thanks to the register transfer level (RTL) viewer of said tool.

Figure 4.16 shows the four main blocks of Nuand ADS-B receiver synthesized for the x115 bladeRF SDR board.

The main four blocks related to ADS-B (where [111..00]) correspond to the 112 bits of the ADS-B message's data block. There are 8 such lines, which suggests that some decoding is taking place in parallel (reflected by "NUM_DECODERS. positive.= 8" in adsb_decoder.vhd)

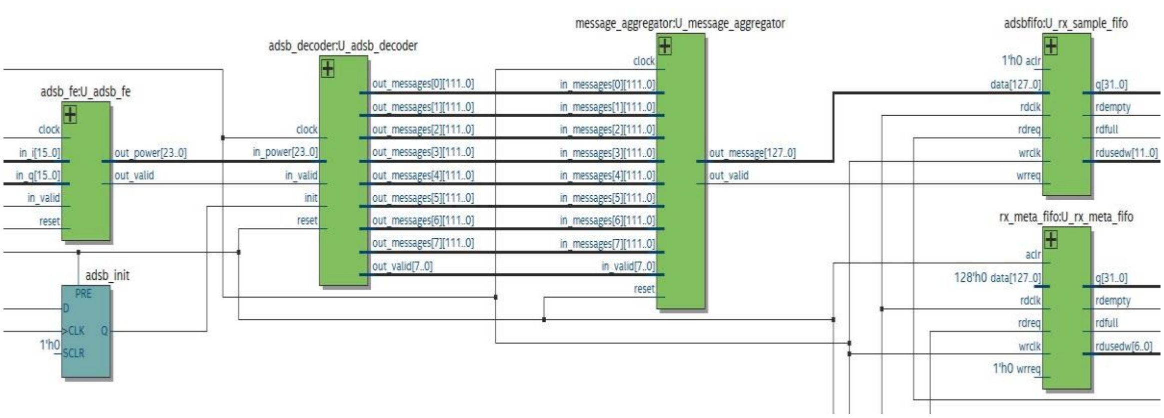


Figure 4.16: Main blocks of Nuand's ADS-B receiver synthesized for the x115 bladeRF SDR board.

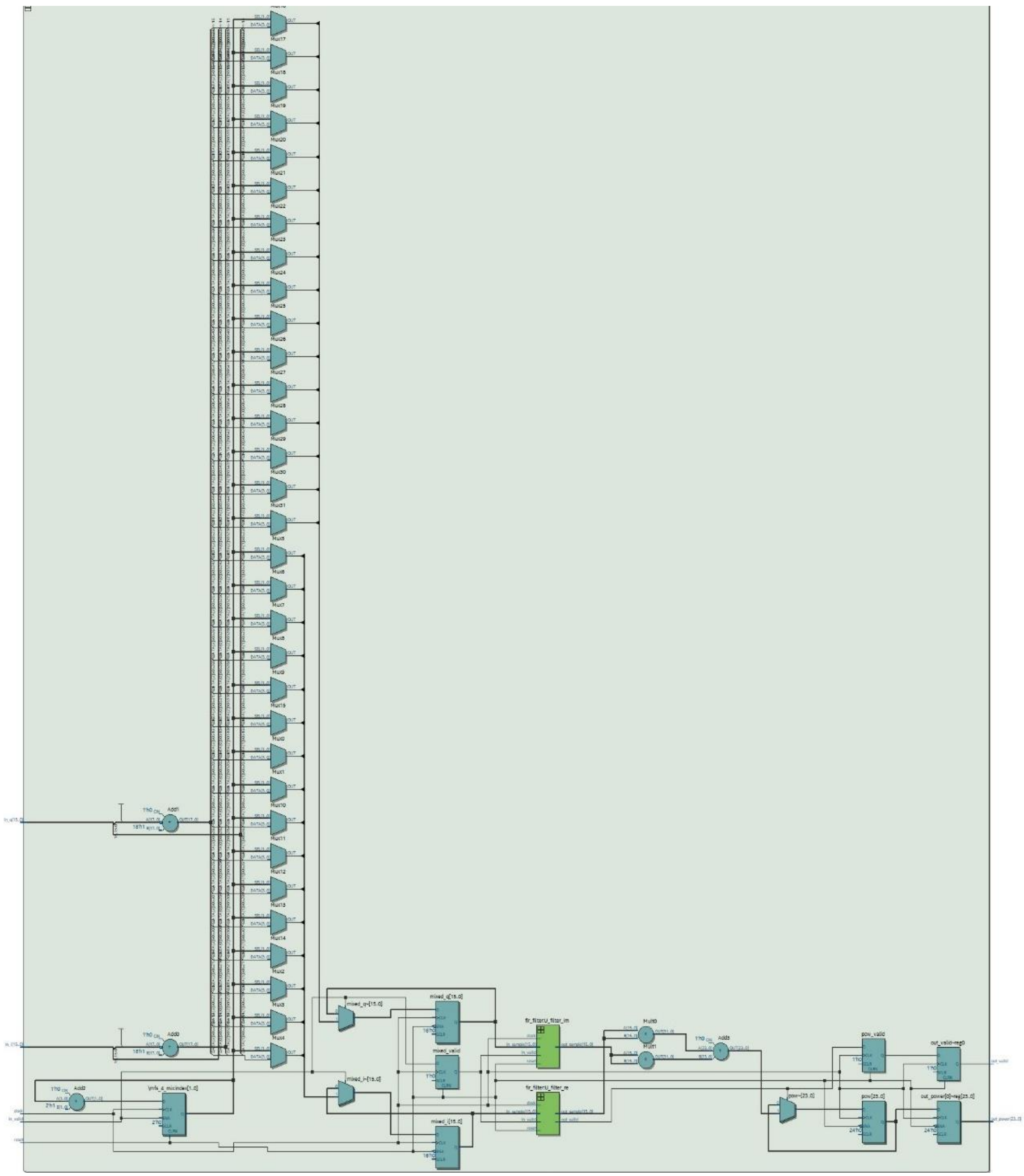


Figure 4.17: Overview of the first block adsb_fe, i.e. the front-end block.

The first block, “adsb_fe” (where fe stands for front end) is shown Figure 4.17. The source file is adsb_fe.vhd. This block does some preprocessing with the I and Q components of the signal, then some filtering, and then computes the power of the signal. This is then fed to the next block.

The second block “adsb_decoder” is shown in Figure 4.18. The source file is adsb_decoder.vhd.

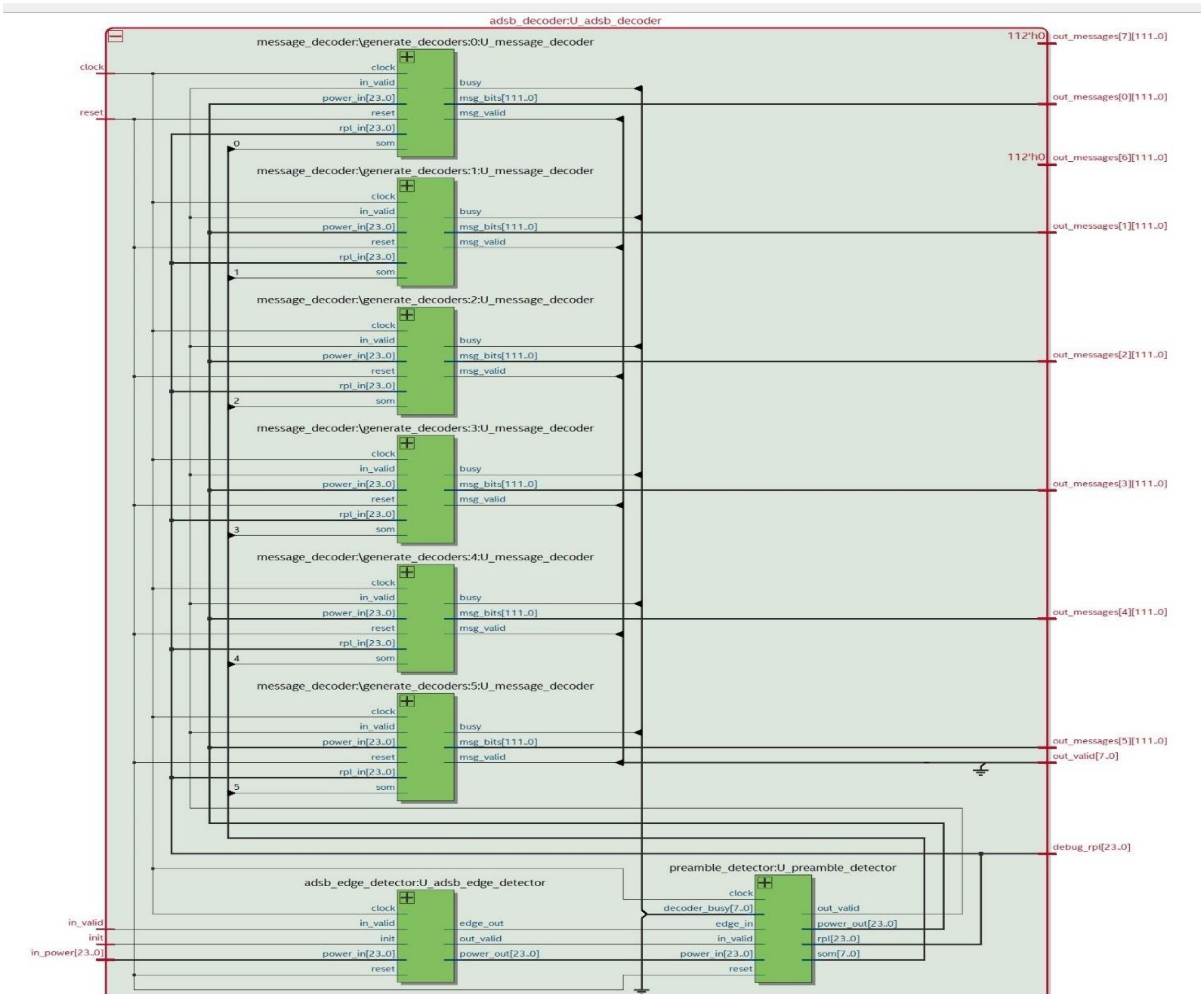


Figure 4.18: Overview of the second block, adsb_decoder, i.e. the ADS-B decoder.

This block firstly performs edge detection, i.e. it detects symbols (i.e. whether there were transitions from low to high and vice-versa (recall that a logical ‘0’ is encoded by a low to high transition and vice-versa)). This is followed by a preamble detector, i.e. to verify that the first elements in the received signal correspond to an ADS-B message (see Section 2.5 for the expected waveform). This is followed by the actual decoders (Decoders 6 and 7 are not shown, but their outputs are visible). When going inside each decoder, it can also be seen that the CRC check block are included therein.

The third block “message_aggregator” is shown in Figure 4.19. The source file is message_aggregator.vhd.

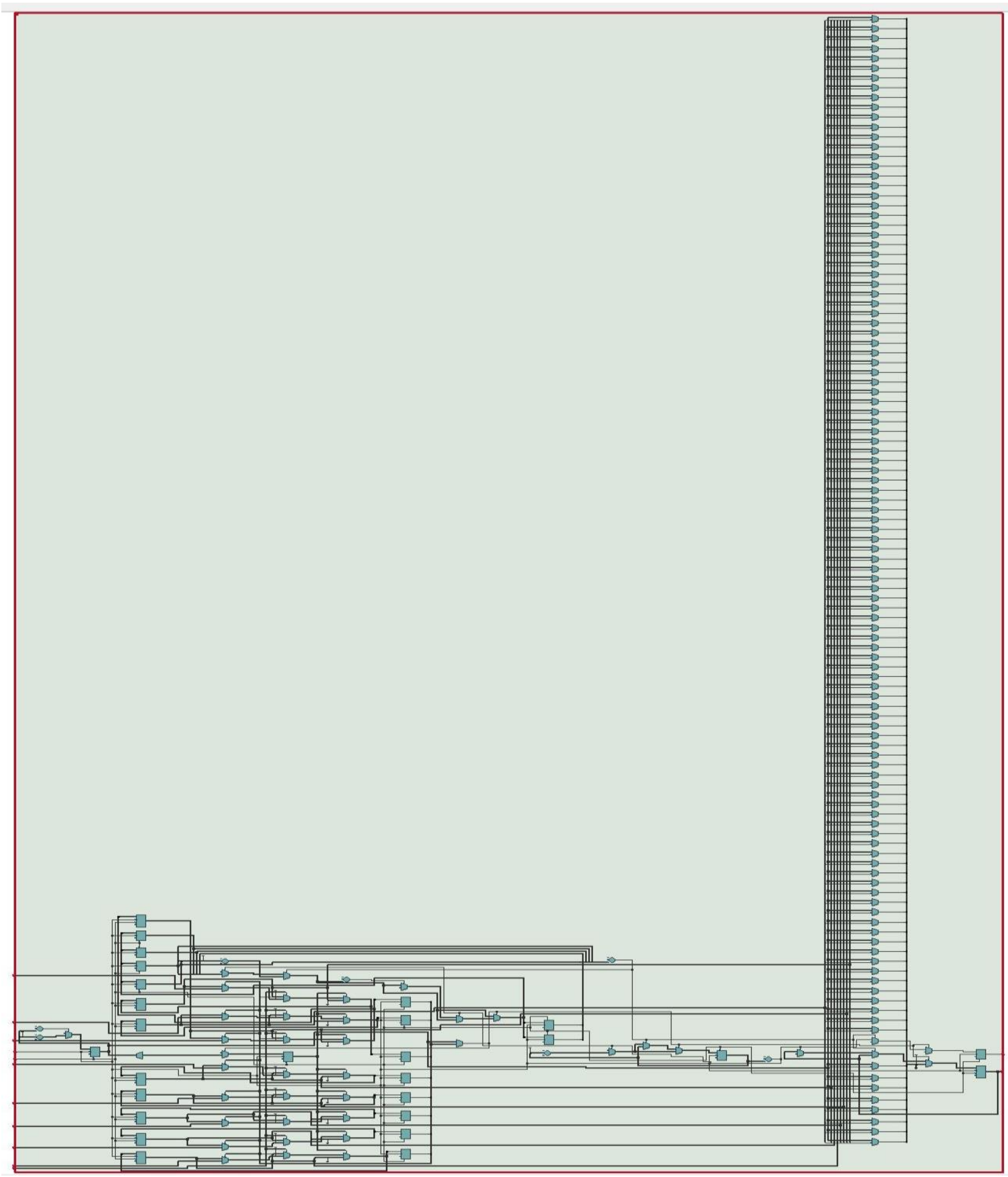


Figure 4.19: Overview of the third block, message_aggregator, that serializes the outputs of the 8 individual decoders.

This block serializes the outputs from the 8 decoders in a round robin style. The output is 128 bits and not 112 bits. This is because 16 bits are prepended as indicated in the VHDL source code by out_message <= holding(idx).msg & x"0001". This is needed to interface with the next block. There was no information about the code and deep analysis of the FPGA design was out of the scope of this thesis.

The fourth block is a FIFO for temporary storage, as shown in Figure 4.20.

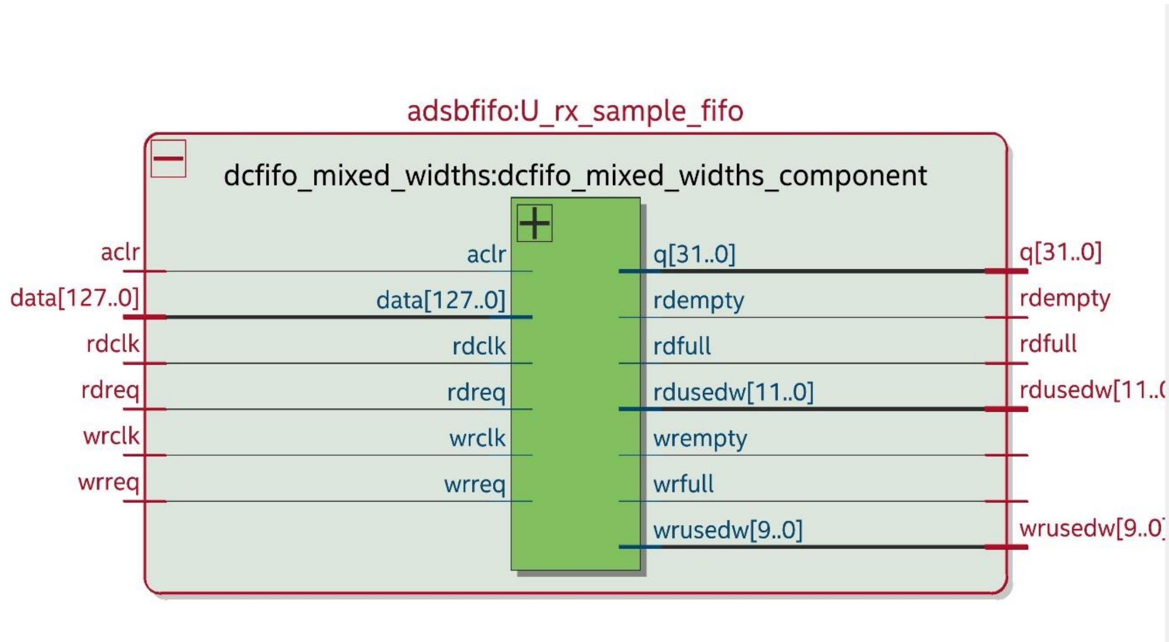


Figure 4.20: Overview of the fourth block, FIFO, for temporary storage.

Note that the output is on 32 bits only (for compatibility with the next block in the base design (i.e., FX3 which is the USB interface)). So, each ADS-B message needs 128/32 = 4 reads to be transferred.

Since no documentation is provided with the source-code, a deeper analysis of the FPGA design was left out of the scope of this thesis since this would require retro-engineering hundreds of lines of VHDL code.

4.4.1 FPGA synthesis results

Nuand’s ADS-B open source FPGA design was synthesized by using Intel Quartus Prime Lite Edition software tool. FPGA synthesis results are shown in Table 4.3. From Table 4.3 it can be seen, that the logical elements consume 25% of the available resources. On other hand only 5% of the memory resources and 10 multipliers (2%) are utilized. All in all, the design can be considered as relatively small, at least for the FPGA fitted on the bladeRF x115 board.

Table 4.3: FPGA synthesis results for the bladeRF x115 board

Quartus Prime Version	**17.1.1 Internal Build 593 SJ Lite Edition**
Revision Name	ADS-B
Top-level Entity Name	bladerf
Family	Cyclone IV E
Device	EP4CE115F23C8
Total logic elements	28,598 / 114,480 (25 %)
Total registers	17457
Total pins	139 / 281 (49 %)
Total virtual pins	0
Total memory bits	214,392 / 3,981,312 (5 %)
Embedded Multiplier 9-bit elements	10 / 532 (2 %)
Total PLLs	2 / 4 (50 %)

4.4.2 FPGA Chip Planner

In Figure 4.21, a screenshot of the FPGA Chip Planner is shown. It can be seen how the resources are distributed and utilized at the physical level.

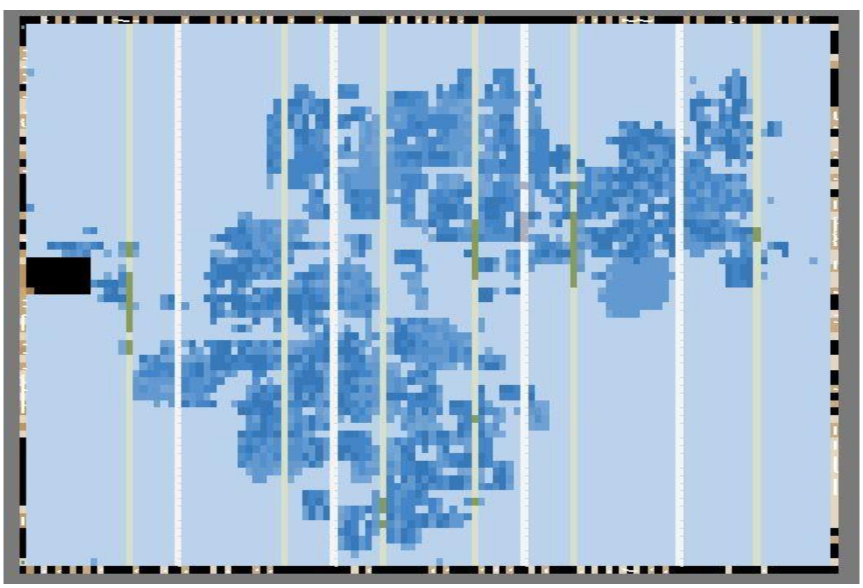


Figure 4.21: Screenshot of the FPGA Chip Planner when Nuand's ADSB receiver design is implemented on the bladeRF x115's FPGA.

4.5 Experiment locations

Initially, two places were discussed to perform the experiments. The first one was one of the laboratories of T. J. Seebeck Department of Electronics, the second one was an apartment on the edge of TalTech campus on “Akadeemia Tee 5” street.

4.5.1 Laboratory of T. J. Seebeck Department of Electronics

This laboratory is located on the 2nd floor of Building U02 of TalTech and is surrounded by other buildings and infrastructure. Experiments were conducted next to the window and the antenna direction was East-ward.

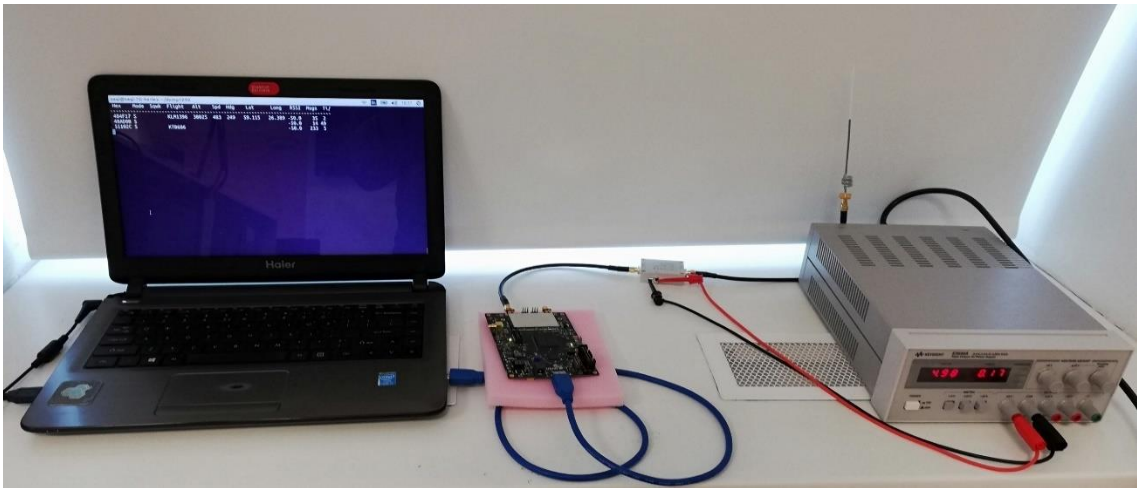


Figure 4.22: Experimental setup in a laboratory located on the 2nd floor of Building U02 of TalTech university.

Unfortunately, the East-ward direction does not offer a clear line of sight towards the aircraft flying in the surroundings, and the other three directions are completed obstructed.

4.5.2 Apartment on Akadeemia Tee 5

This place is situated next to TalTech university and it has no obstructions like huge buildings or vegetations. It is situated on the 1st floor and the setup was placed near the window, while it was facing north, as shown in Figure 4.23.

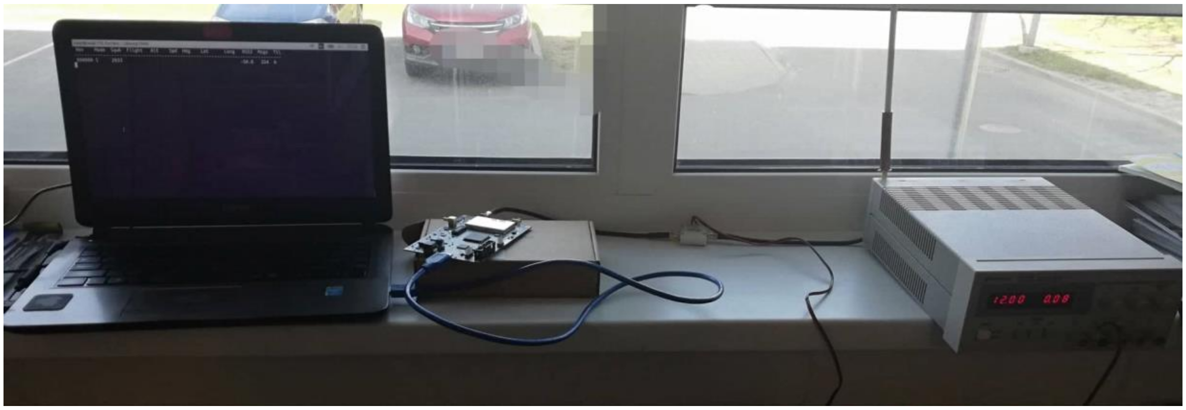


Figure 4.23: Experimental setup in an apartment on Akadeemia tee 5 facing the north side.

5 Results

This chapter presents the experimental results conducted with Nuand's open-source ADS-B receiver implemented on the bladeRF x115 SDR board. Results are presented for two locations (laboratory on TalTech campus and apartment on Akadeemia tee) without and with amplifiers, different antennas, and combinations thereof.

5.1 Results from the laboratory location

The first experiments were done in T. J. Seebeck Department of Electronics laboratory of TalTech. No amplifier was used in first experiments. All antennas were used to conduct the experiments.

5.1.1 Results from the laboratory without any amplifier

All antennas were used to perform the experiments, each antenna result has been plotted with different color as can be seen in Figure 5.1. As expected, using antennas only and no amplifier results in very limited ranges. It can be seen that ANT 1 (Quarter Wave Antenna, red dot) has a slightly better coverage (around 6 km), whereas the other antennas achieved only 3 km range.

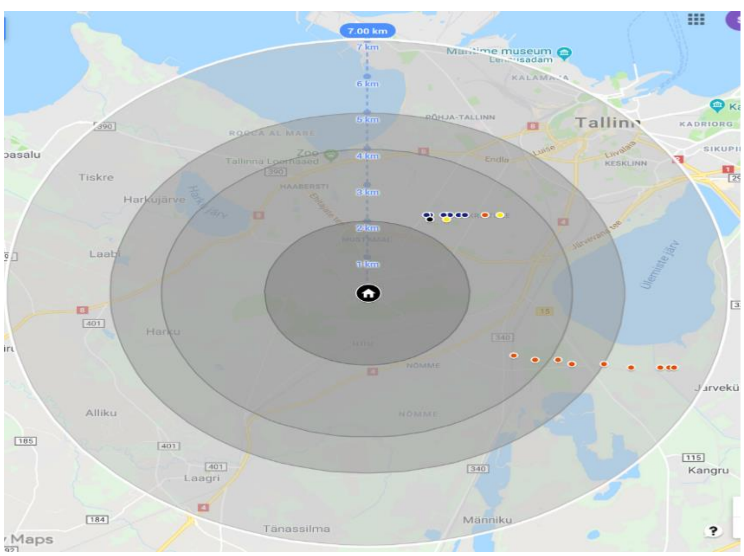


Figure 5.1: Received ADS-B messages and ranges with Nuand's open-source ADS-B receiver implemented on the bladeRF x115 SDR board from the laboratory location without any amplifier and four different antennas: ANT1 (Quarter Wave Antenna, red dots), ANT2 (Flower pot antenna, yellow dots), ANT3 (WA5VJB Log-periodic antenna, black dots), ANT4 (DIY Collinear antenna, blue).

5.1.2 Results from the laboratory with AMP1

Figure 5.2 shows the results of the experiment with AMP1 (wideband amplifier, as discussed in Chapter 4). AMP1 has a 17.95 dB gain. As can be seen in Figure 5.2, the performance with all antennas was improved with the amplifier and the coverage area increased to around 30 km with the ANT1 (Quarter Wave Antenna, red dot) antenna. All decoded ADS-B messages were received from the east side.

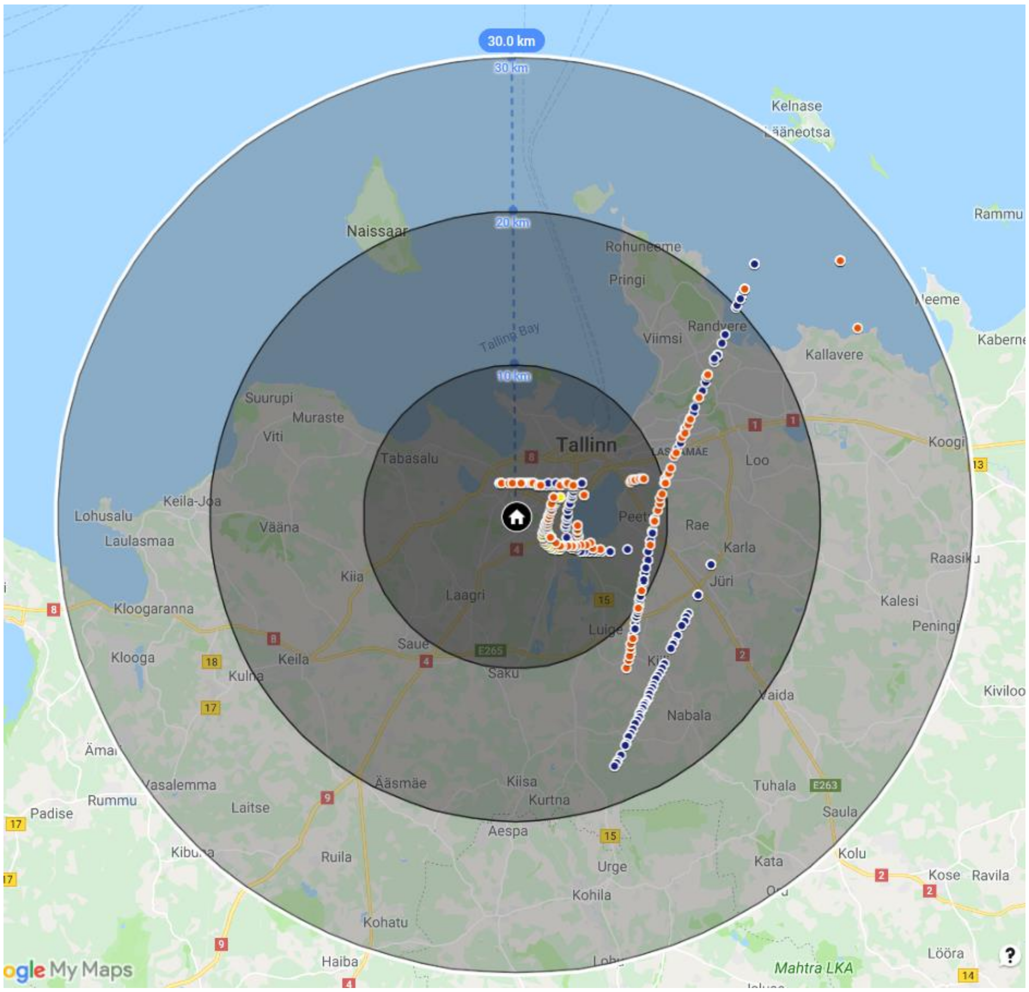


Figure 5.2: Received ADS-B messages and ranges with Nuand's open-source ADS-B receiver implemented on the bladeRF x115 SDR board from the laboratory location with AMP1 (wideband amplifier) and four different antennas: ANT1 (Quarter Wave Antenna, red dots), ANT2 (Flower pot Antenna, yellow dots), ANT3 (WA5VJB Log-periodic antenna, black dots), ANT4 (DIY Collinear antenna, blue).

5.1.3 Results from the laboratory with AMP2

Next AMP2 (UPUTRONICS HAB-FPA1090SAW) was used to conduct experiments in the laboratory and the resulting plot can be seen in Figure 5.3. This amplifier has a 15 dB gain and as can be seen, the performance was slightly improved as compared to the AMP1. Figure 5.3 shows that with AMP2, ANT1 (Quarter Wave Antenna, red dot) and ANT4 (DIY Collinear Antenna, blue dot) antennas have better performance over the other antenna, with a range of about up to 40 km. With AMP2, ANT3 (WA5VJB Log-Periodic antenna, black dots) antenna has poor results, the range does not exceed 10 km.

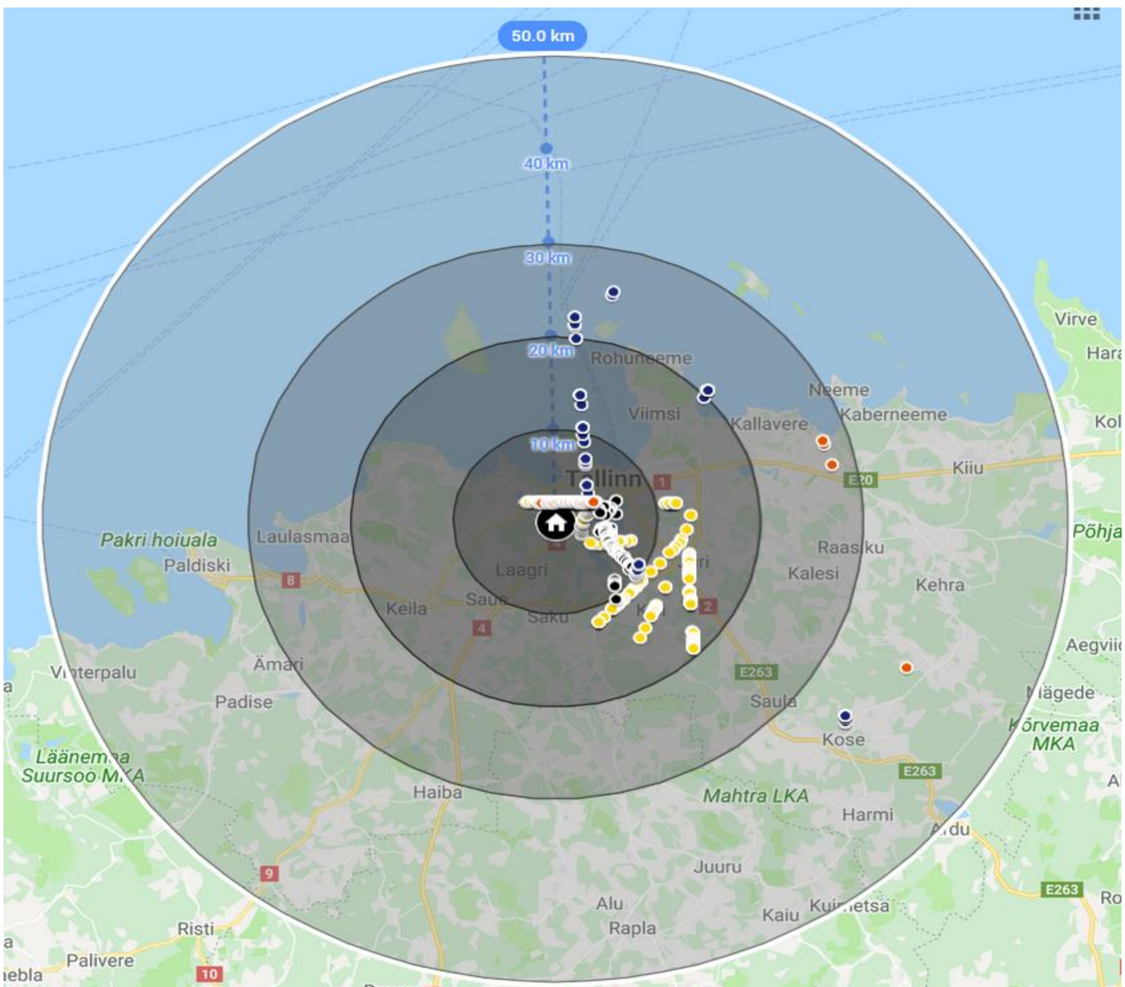


Figure 5.3: Received ADS-B messages and ranges with Nuand's open-source ADS-B receiver implemented on the bladeRF x115 SDR board from the laboratory location with AMP2 (UPUTRONICS HAB-FPA1090SAW) and four different antennas: ANT1 (Quarter Wave Antenna, red dots), ANT2 (Flower pot antenna, yellow dots), ANT3 (WA5VJB Log-periodic antenna, black dots), ANT4 (DIY Collinear antenna, blue dots).

5.1.4 Results from the laboratory with AMP3

The next experiments in the laboratory were done with AMP3 (Akozon ADS-B RFFE). AMP3 has maximum gain of 31db and two filters to suppress noise as explained in Chapter 3. Therefore, it shows better performance over the other two amplifiers, as can be seen in Figure 5.4. As can be observed, the overall performance of all antennas is improved; the best results are obtained with ANT3 (WA5VJB Log-periodic Antenna, black dots) with which the range reaches up to ca. 160 km. It is also observed that almost all captured messages are received from one side (west).

Figure 5.4: Received ADS-B messages and ranges with Nuand's open-source ADS-B receiver implemented on the bladeRF x115 SDR board from the laboratory location with AMP3 (Akozon ADS-B RFFE) and four different antennas: ANT1 (Quarter Wave Antenna, red dots), ANT2 (Flower pot antenna, yellow dots), ANT3 (WA5VJB Log-periodic antenna, black dots), ANT4 (DIY Collinear antenna, blue dots).

5.2 Results from Akadeemia Tee 5

The next experiments were conducted from an apartment located on at Akadeemia Tee 5. Here better performance is expected because there is more clear line of sight. The experiments order is the same as for the experiments from the laboratory, first without any amplifier and afterwards with AMP1, AMP2 and AMP3, respectively.

5.2.1 Results from Akdeemia Tee 5 without amplifier

In the first experiment no amplifier was used, and all antennas were used one after another. Figure 5.5 shows the resulting coverage area of all antennas without amplifier at Akademia tee 5. As can be seen, performance is not very good, as expected. The best coverage area lies only around 4 km as shown in Figure 5.5.

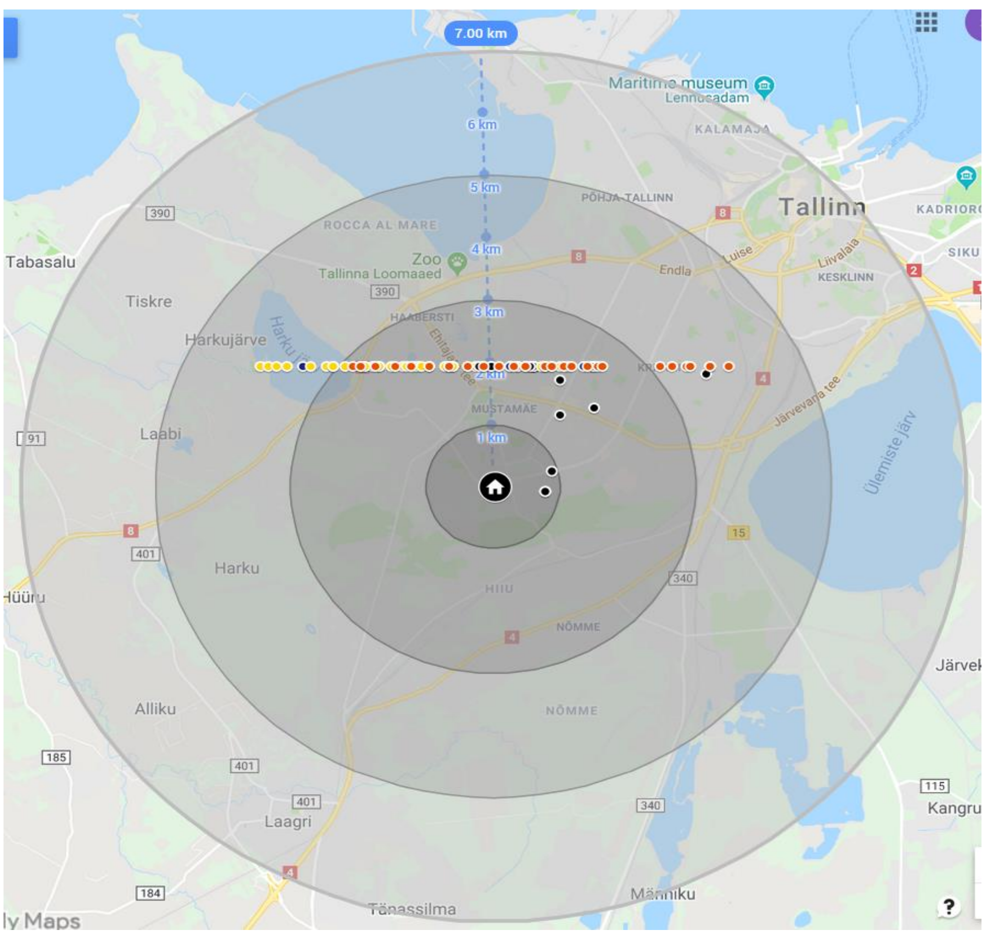


Figure 5.5: Received ADS-B messages and ranges with Nuand's open-source ADS-B receiver implemented on the bladeRF x115 SDR board from the apartment located on Akademia Tee 5 without any amplifier and four different antennas: ANT1 (Quarter Wave Antenna, red dots), ANT2 (Flower pot antenna, yellow dots), ANT3 (WA5VJB Log-periodic antenna, black dots), ANT4 (DIY Collinear antenna, blue dots).

5.2.2 Results from Akadeemia Tee 5 with AMP1

In this experiment, AMP1 (wideband amplifier) was used. The resultant plot shown in Figure 5.6. It can be seen that the coverage increased slightly as compared to the previous experiment mentioned in Section 5.2.1. As can be seen in Figure 5.6, with AMP1 only one antenna ANT4 (collinear, blue dots) was able to receive signals (range up to 5 km). It seems that noise was amplified and due to that the ADS-B decoder was not able to decode message completely.

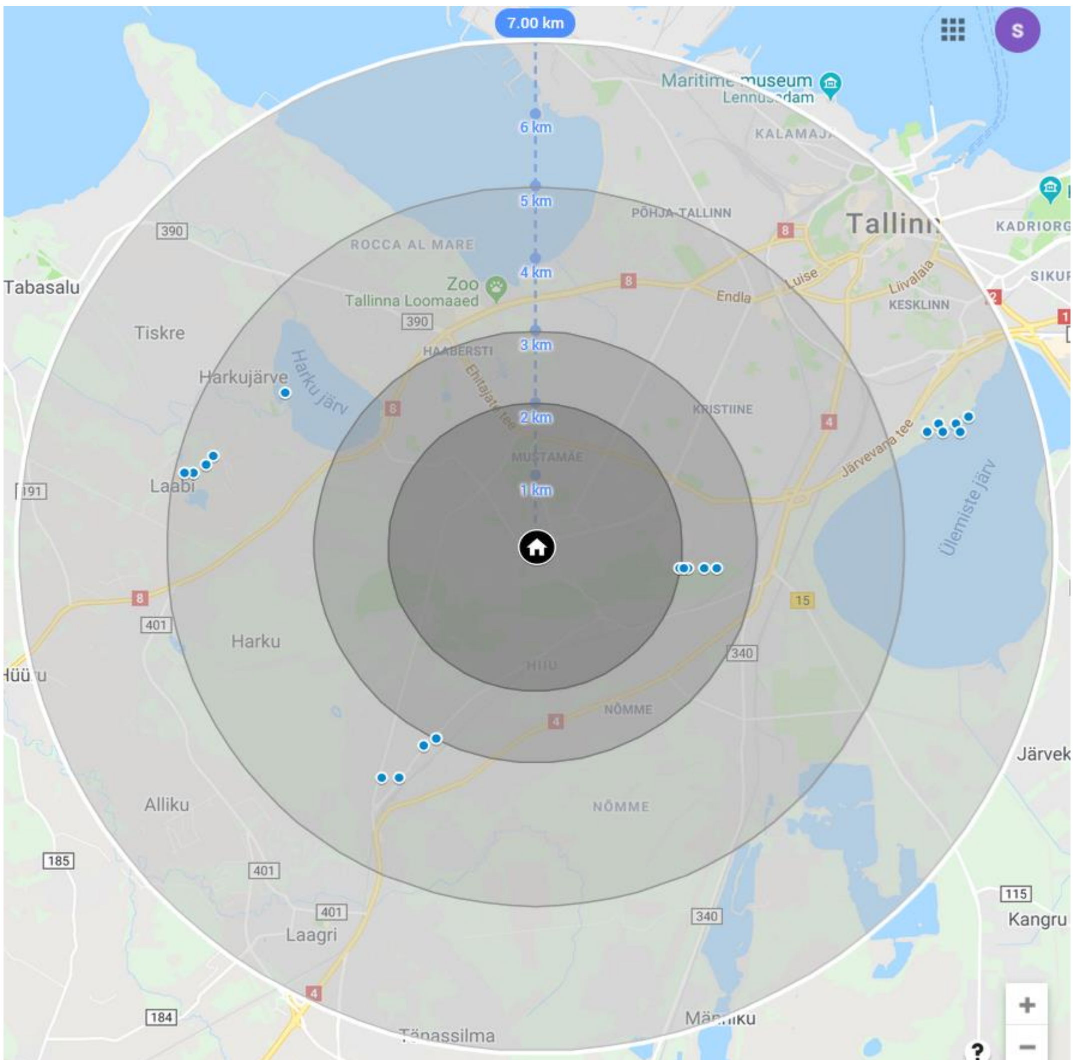


Figure 5.6: Received ADS-B messages and ranges with Nuand's open-source ADS-B receiver implemented on the bladeRF x115 SDR board from the apartment located on Akadeemia Tee 5 with AMP1 (wideband amplifier) and four different antennas. ADS-B messages could be received only with ANT4 (DIY Collinear antenna, blue dots).

5.2.3 Results from Akadeemia Tee 5 with AMP2

AMP2 (UPUTRONICS HAB-FPA1090SAW) was used in these experiments. AMP2 has an LNA with one SAW filter as mentioned in Chapter 4. As can be seen in Figure 5.7, the performance with all antennas is improved as compared to the first experiments (Section 5.2.1) but not much as compared to the results with AMP1. One point needs to be noticed, the coverage area is in all directions (contrary to previous results which were all East-wards) although the antenna was facing the North direction. One possible reason can be the line of sight, because this second location (Akadeemia Tee 5) has a better line of sight without any obstructions. The coverage reached around 50km.

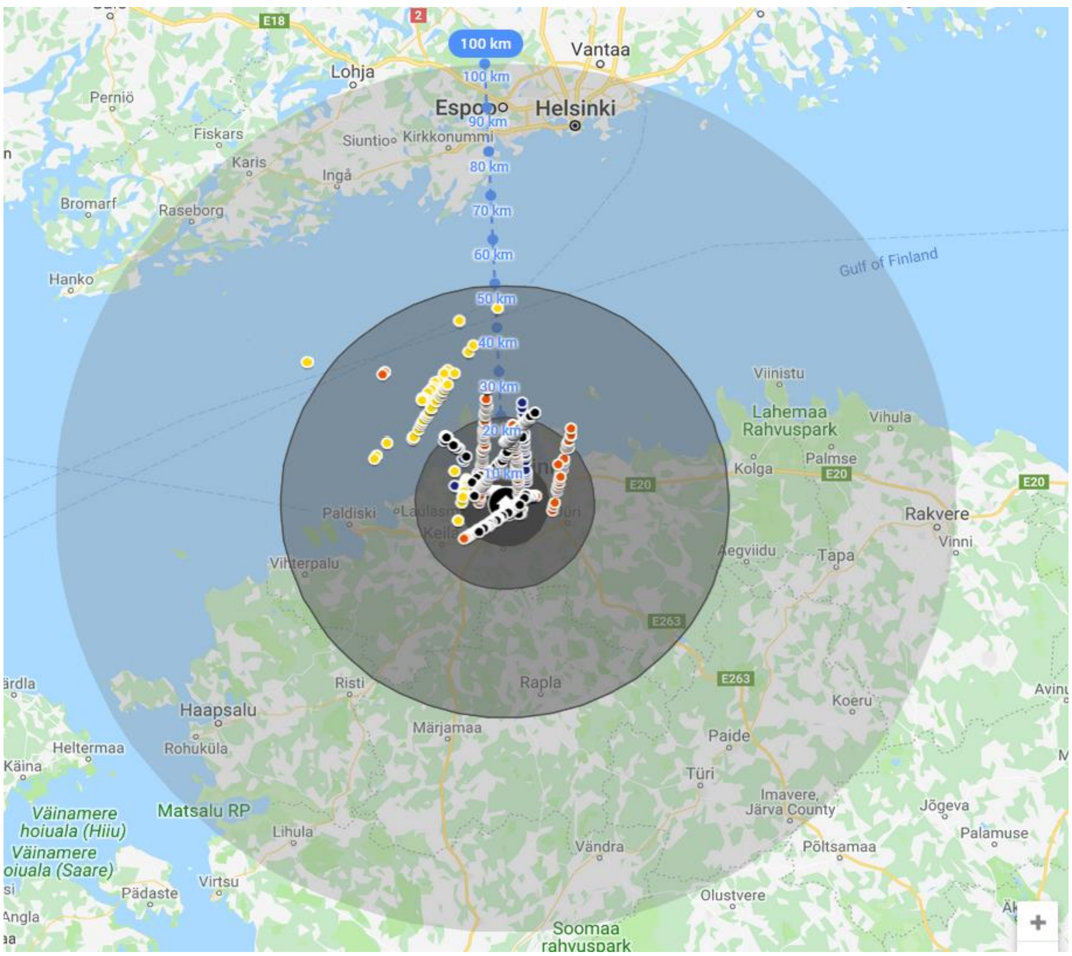


Figure 5.7: Received ADS-B messages and ranges with Nuand's open-source ADS-B receiver implemented on the bladeRF x115 SDR board from the apartment located on Akadeemia Tee 5 with AMP2 (UPUTRONICS HAB-FPA1090SAW) and four different antennas: ANT1 (Quarter wave antenna, red dots), ANT2 (Flower pot antenna, yellow dots), ANT3 (WA5VJB Log-periodic antenna, black dots), ANT4 (DIY Collinear antenna, blue dots).

5.2.4 Results from Akadeemia Tee 5 with AMP3

For these experiments AMP3 was used. Two LNAs and two SAW filters are embedded in this amplifier, as described earlier in Chapter 4. This amplifier shows overall better performance with all antennas (range up to ca. 210 km) and signals from all directions were intercepted.

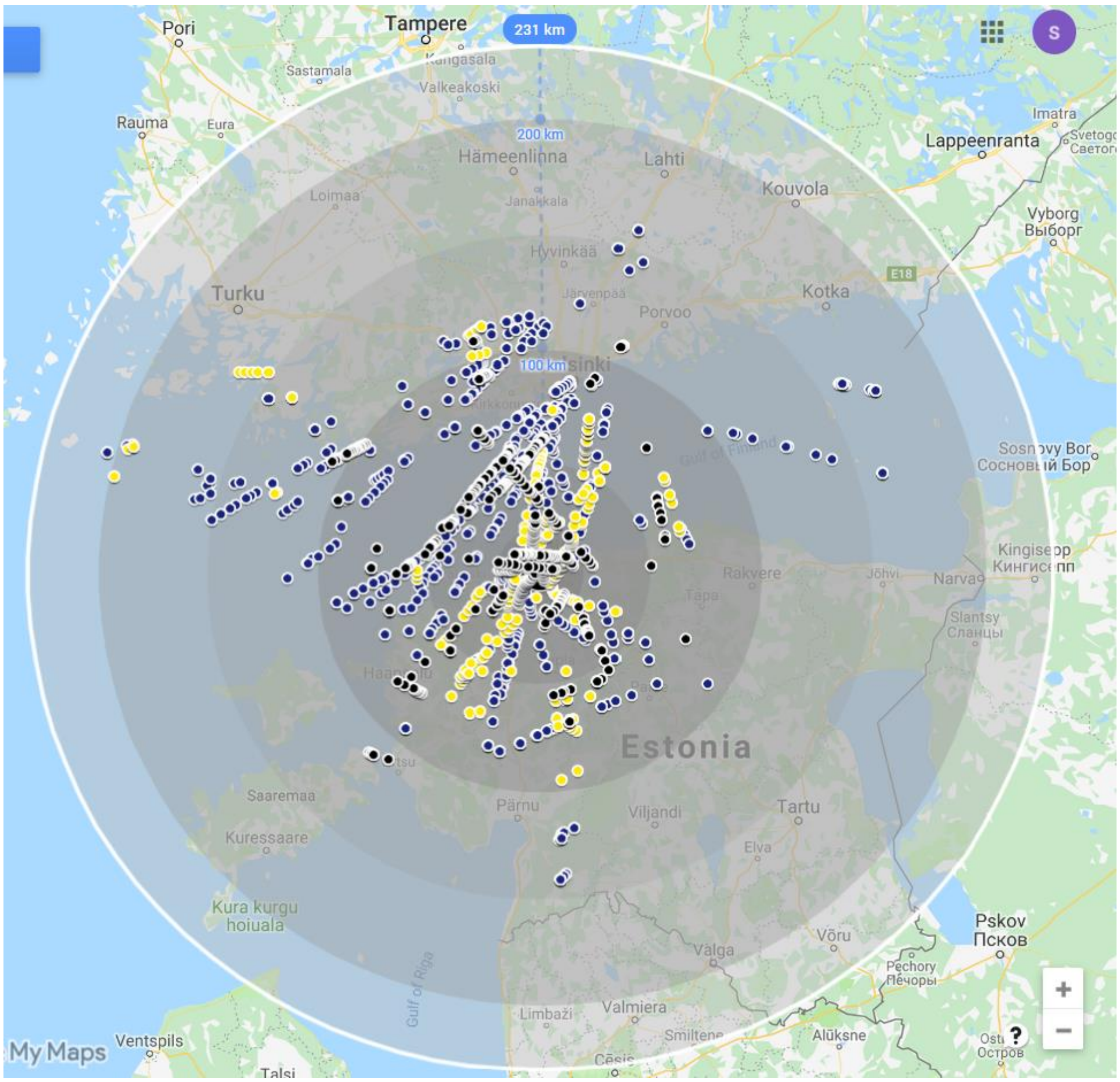
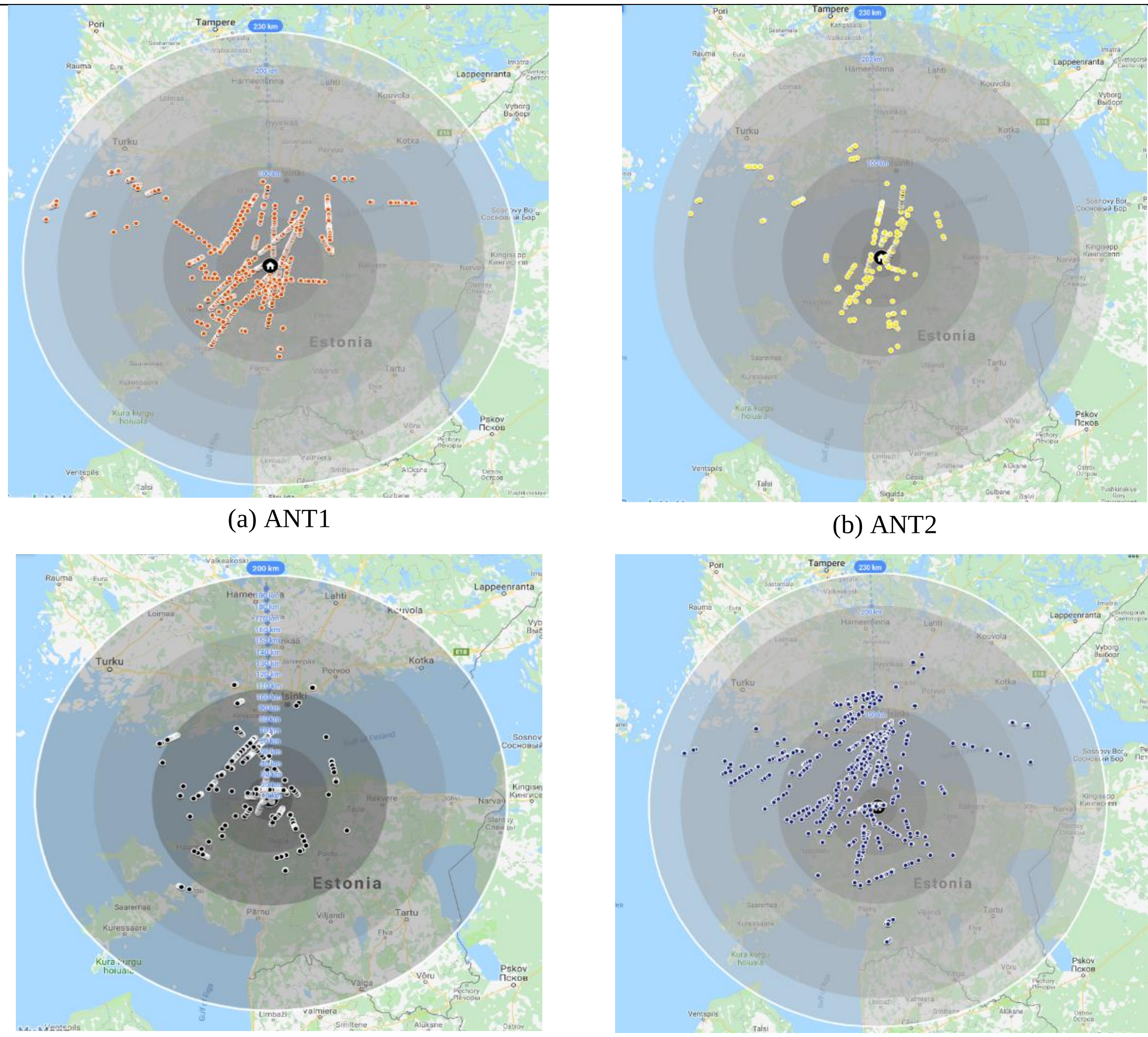


Figure 5.8: Received ADS-B messages and ranges with Nuand's open-source ADS-B receiver implemented on the bladeRF x115 SDR board from the apartment located on Akadeemia Tee 5 with AMP3 (Akozon ADS-B RFFE) and four different antennas: ANT1 (Quarter wave antenna, red dots), ANT2 (Flower pot antenna, yellow dots), ANT3 (WA5VJB Log-periodic antenna, black dots), ANT4 (DIY Collinear antenna, blue dots).

5.2.5 Results from Akadeemia Tee 5 with AMP3 with individual antennas

In Figure 5.13 the results with all four antennas with AMP3 (described in Section 5.2.4) are shown. The coverage with all antennas increased significantly when used with AMP3. It is also noted that the number of received messages also increased.



(a) ANT1 (b) ANT2 (c) ANT3 (d) ANT4

Figure 5.9: Comparison of the results obtained from the apartment location on Akadeemia Tee 5 with AMP3 (Akozon ADS-B RFFE) and the four antennas. (a): ANT1 (Quarter wave antenna), (b): ANT2 (Flower pot antenna), (c): ANT3 (WA5VJB Log-periodic antenna), (d): ANT4 (DIY collinear antenna).

Table 5.1 and Table 5.2 shows the comparative view of all antennas with each amplifier at both places. As can be seen, the overall performance at the second location (Akadeemia Tee 5) was better than from the laboratory. More results for each type of antenna can be found in Appendix A.

Table 5.1: ADS-B range obtained in the experiments performed in the laboratory at Taltech.

	ANT1 (Quarter Wave Antenna)	**ANT2** (Flowerpot Antenna)	**ANT3** (WA5VJB Log-periodic Antenna)	**ANT4** (Collinear Antenna)
No AMP	3.14 km	3.33 km	2.35 km	2.88 km
AMP1 (wideband amplifier)	21.3 km	5.02 km		22.8 km
AMP2 (UPUTRONICS HAB-FPA1090SAW)	27.6 km	19.2 km	10.1 km	35.5 km
AMP3 (Akozon ADS-B RFFE)	74.1 km	57.7 km	163 km	34.1 km

Table 5.2: ADS-B range obtained in the experiments performed at Akadeemia tee 5.

	ANT1 (Quarter Wave Antenna)	**ANT2** (Flowerpot Antenna	**ANT3** (WA5VJB Log-periodic Antenna)	**ANT4** (Collinear Antenna)
No AMP	3.95 km	3.97 km	3.51 km	3.72 km
AMP1 (wideband amplifier)	----------	6.14 km	----------	-----------
AMP2 (wideband amplifier)	44.4 km	55.3 km	20.8 km	24.1 km
AMP3 (Akozon ADS-B RFFE)	210 km	199 km	109 km	201 km

6 Summary and perspectives

Air traffic is increasing with every passing day. Therefore, air traffic management system should be step-up ahead to fulfill the requirements of congested airspace. In this regard, ATC is adopting the ADS-B system placed in aircraft that periodically broadcasts information about their velocity, position, and other aircraft information. Consequently, the overall situational awareness of ATC and pilots is significantly improved.

In this thesis, the performance of Nuand's ADS-B receiver implemented on an FPGA-based bladeRF x115 SDR board has been studied. First, this thesis gave an overview of the ADS-B system. Experiments with four different antennas, without and with three different amplifiers (and combinations thereof) have been conducted from two different locations.

In the first experiments (without amplifiers), the range was only around 4 to 5 km at both places. The range was extended to between 20 to 45 km by using AMP1 and AMP2 at both places. It was also noticed that AMP1 amplifier did not perform well because it is a wideband amplifier with no filter for the ADS-B frequency within. Therefore, it appears that it was amplifying other frequencies too, especially at second place of experiments.

AMP3 (Akozon ADS-B RFFE) has a 30 dB gain and it improved the range of antennas significantly at both locations; at second place (Akadeemia tee 5) results were very good (range up to 210 km).

As mentioned before, the received signals were only intercepted from one side from the laboratory location. This is due to the fact it has no clear line of sight and not too many flights passing on that route. On the other hand, signals received during the experiments at the second place (Akadeemia tee 5) were from all directions.

Based on the experiments results described in Chapter 5 it is concluded that Nuand x115 bladeRF can be used as an ADS-B receiver for educational purposes with proper amplifier (LNA and filter) and antenna. It was noticed that amplifier plays a significant role in the overall performance improvement. By using an amplifier with a 30 dB gain, the coverage area increased up to 210 km, which is not far from 277 km, a distance mentioned in [24].

As shown in Section 5.2, line of sight is another important factor that needs to be considered since it improved signal reception quality significantly.

The obtained results are encouraging and open some perspectives.

First of all, further testing should be performed by installing the antenna on the roof top as this is expected to improve the quality of the received signals and thus of the coverage area.

Furthermore, since no documentation is provided with the source-code, a deeper, but time-consuming, analysis of the FPGA design needs to be done to identify optimization possibilities, whether in terms of implementation aspects (resource utilization, execution time, power, and energy consumption) or in terms of signal processing (ADS-B decoding itself).

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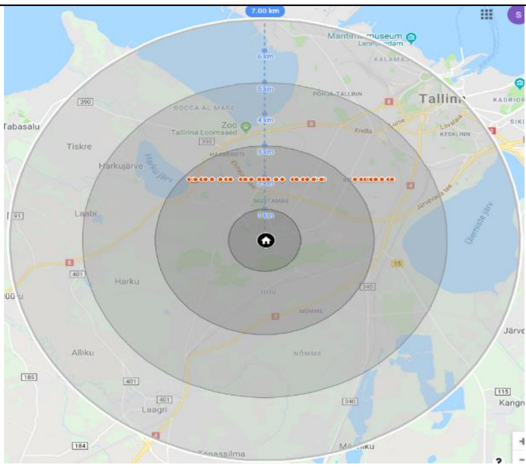
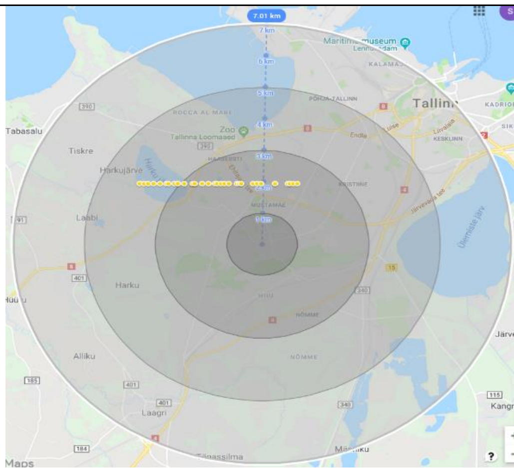
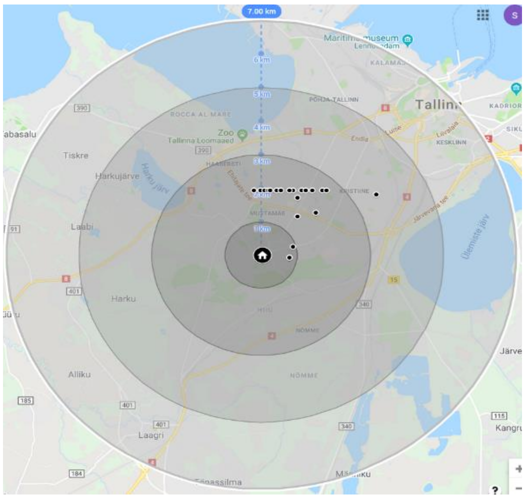
Appendix A – Selected individual results



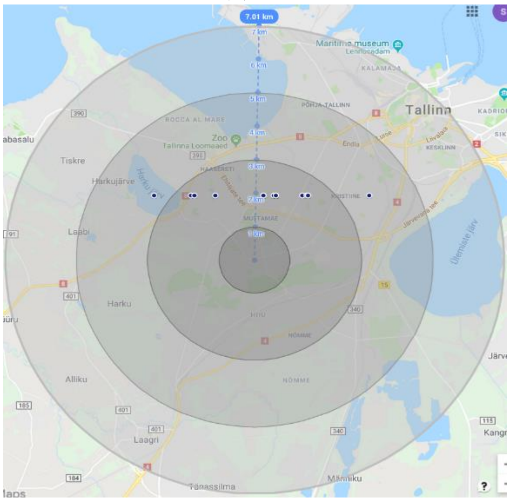
(a) ANT1



(b) ANT2

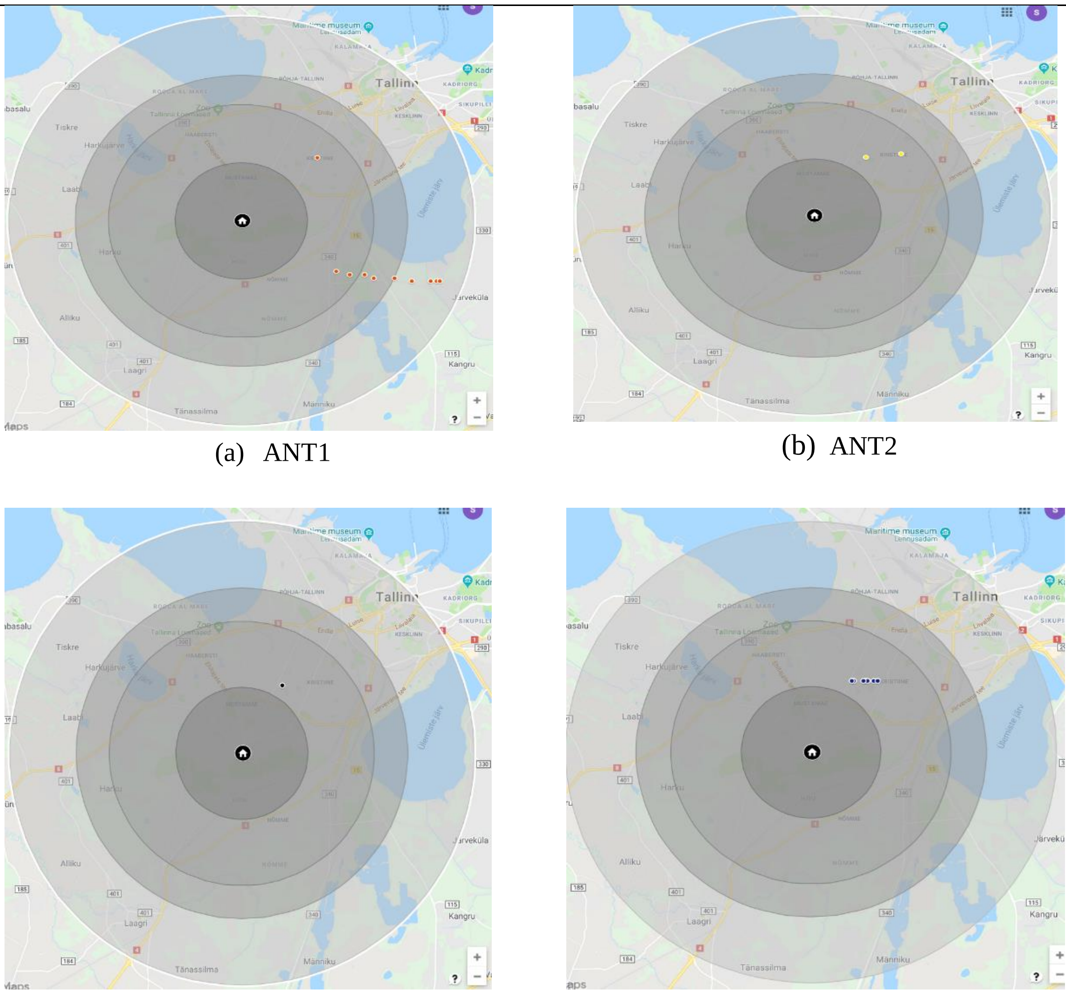


(c) ANT3



(d) ANT4

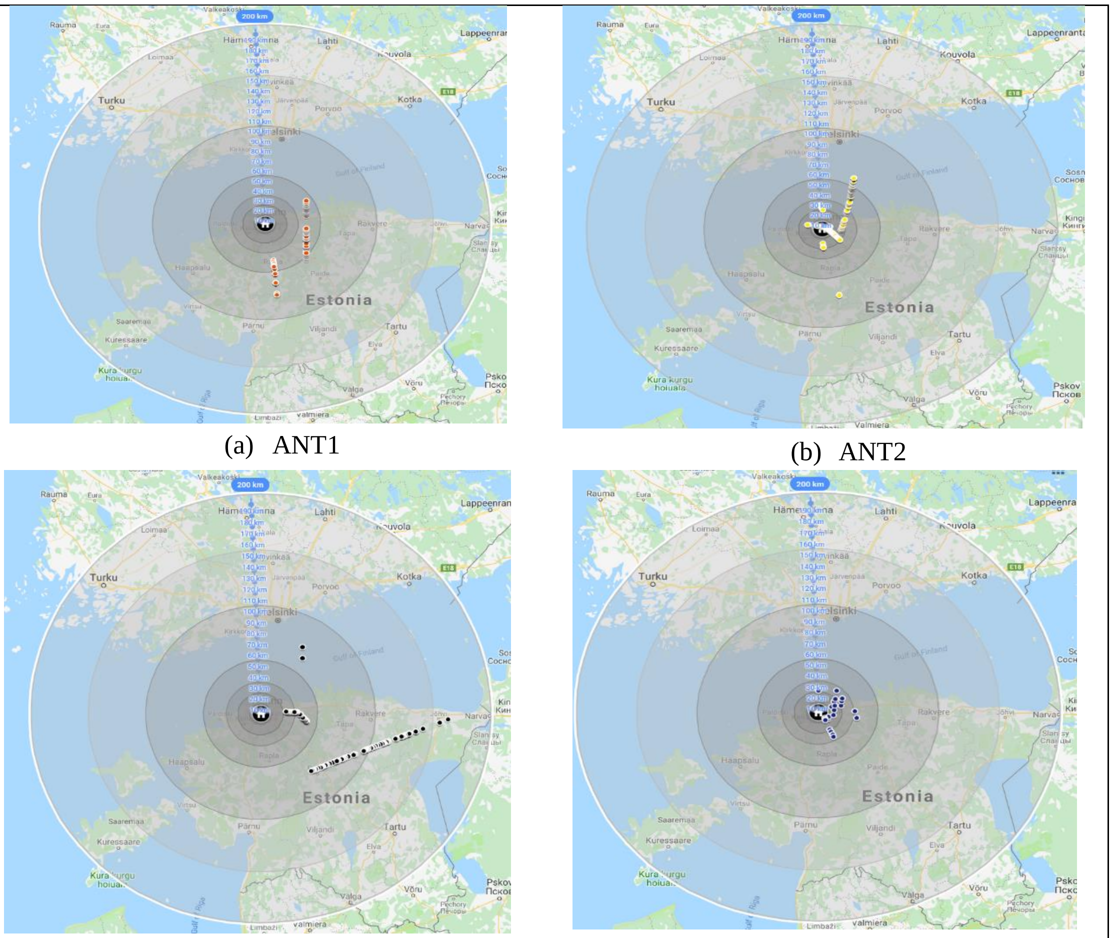
Figure A.1: Received ADS-B messages and ranges with Nuand's open-source ADS-B receiver implemented on the bladeRF x115 SDR board from the apartment located on Akademia Tee 5 without any amplifier and four different antennas: ANT1 (Quarter wave antenna, red dots), ANT2 (Flower pot antenna, yellow dots), ANT3 (WA5VJB Log-periodic antenna, black dots), ANT4 (DIY Collinear antenna, blue dots).



(a) ANT1 (b) ANT2

(c) ANT3 (d) ANT4

Figure A.2: Received ADS-B messages and ranges with Nuand's open-source ADS-B receiver implemented on the bladeRF x115 SDR board from the laboratory location without any amplifier and four different antennas: ANT1 (Quarter Wave Antenna, red dots), ANT2 (Flower pot antenna, yellow dots), ANT3 (WA5VJB Log-Periodic antenna, black dots), ANT4 (DIY Collinear Antenna, blue).



(a) ANT1 (b) ANT2

(c) ANT3 (d) ANT4

Figure A.2: Received ADS-B messages and ranges with Nuand's open-source ADS-B receiver implemented on the bladeRF x115 SDR board from the laboratory location with AMP3 (Akozon ADS-B RFFE) and four different antennas: ANT1 (Quarter Wave Antenna, red dots), ANT2 (Flower pot Antenna, yellow dots), ANT3 (WA5VJB Log-periodic Antenna, black dots), ANT4 (DIY Collinear Antenna, blue dots).