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Receiver design for propagation measurements for global HF communications

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Abstract

This thesis investigates the feasibility of designing low-cost multiband receiver for High Frequency (HF) propagation measurements using the Weak Signal Propagation Reporter (WSPR) protocol. Previous research utilizing the Red Pitaya Software-Defined Radio (SDR) platform motivated further investigation whether more affordable SDR platforms could provide comparable performance.

The proposed receiver system was implemented using KiwiSDR and WEB-888 together with a MLA-30 active loop antenna. The experimental measurement was conducted over a 24-hour period, receiving on multiple bands simultaneously under identical conditions and reporting them to WSPRnet.org. Performance was evaluated using metrics including received Signal-to-Noise Ratio (SNR) and number of received stations.

The results show that both SDR-platforms, the Web-888 and KiwiSDR, perform similarly to the reference platform, Red Pitaya. Based on these findings and the fulfilled evaluation criteria, the proposed SDR platforms can be considered as more cost-effective receiver designs for propagation measurements for global HF communications.

Keywords

SDR, WSPR, HF propagation measurments, multiband receiver station, active loop antenna

Sammanfattning

Detta examensarbete utreder möjligheten att utveckla kostnadseffektiva flerbandsmottagare för mätning av HF-utbredning med hjälp av protokollet Weak Signal Propagation Reporter. Arbetet bygger vidare på tidigare examensarbete där SDR-plattformen Red Pitaya användes, med målet att undersöka om det finns fler kostnadseffektiva SDR-plattformar som kan bidra med jämförbara resultat.

Det föreslagna mottagarsystemet som implementerades bestod av en KiwiSDR, WEB-888 och en MLA-30 aktiv loop antenn. Experimentets testperiod varade 24 timmar, där signaler mottogs över flera band samtidigt under identiska förhållanden och rapporterades automatiskt till WSPRnet.org. Prestandan utvärderades utifrån parametrar såsom signalens signal-to-noise ratio (SNR) och antal mottagna stationer.

Resultatet påvisar att de båda föreslagna SDR-mottagarna, Web-888 och KiwiSDR, presterar liknande så som referensmottagaren Red Pitaya gör. Baserat på resultaten och de uppfyllda utvärderingskriterierna, kan de föreslagna SDR-mottagarna betraktas som mer kostnadseffektiva mottagardesigner för utbredningsmätningar inom global HF-kommunikation.

Nyckelord

SDR, WSPR, HF-utbredningsmätningar, flerbandsmottagarstation, aktiv loopantenn

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Stockholm, June 2026
Harry Karlsson

AI Usage Declaration

Generative AI tools were used during this thesis project. ChatGPT (OpenAI) was used for language improvement, grammar correction and supporting with academic phrasing. Claude AI (Anthropic) was used for generating python code for data visualization used in this thesis.

Contents

1 Introduction **1**
1.1 Background . . . 3
1.1.1 Weak Signal Propagation Reporter (WSPR) . . . 3
1.1.1.1 WSPR protocol . . . 3
1.1.1.2 WSPRnet database . . . 3
1.1.2 Software Defined Radio . . . 6
1.1.3 Previous Work . . . 6
1.2 Problem Definition . . . 7
1.2.1 Research question . . . 7
1.2.2 Hypothesis statement . . . 7
1.2.3 Criteria of the stations . . . 8
1.2.4 Performance Metrics . . . 8
1.3 Related work . . . 8

2 Method **11**
2.1 Research Process . . . 11
2.2 Experimental design . . . 12
2.3 Reliability and validity of the method . . . 13
2.3.1 Reliability of method . . . 13
2.3.2 Validity of method . . . 13
2.4 Data Evaluation and Analysis . . . 14

3 Evaluated SDR Platforms **15**
3.1 Red Pitaya . . . 15
3.2 KiwiSDR . . . 15
3.3 WEB-888 . . . 17
3.4 Comparison of Platform Specifications . . . 18

4 Experiment **19**
4.1 System Architecture . . . 19
4.2 Equipment . . . 20
4.3 Setup . . . 21
4.3.1 Indoor . . . 21
4.3.2 Outdoor . . . 22
4.4 Measurement Procedure . . . 22
4.4.1 Location . . . 22
4.4.2 Measurement Period . . . 22
4.4.3 Reporting and Data Handling . . . 23
4.5 Data processing and calculations . . . 23

5 Results and Analysis **25**
5.1 SNR comparison . . . 25
5.1.1 Test 1 - KiwiSDR and Red Pitaya . . . 26
5.1.2 Test 2 - Web-888 and Red Pitaya . . . 28
5.2 Number of spots . . . 29
5.2.1 Test 1 - KiwiSDR and Red Pitaya . . . 30
5.2.2 Test 2 - Web-888 and Red Pitaya . . . 31
5.3 Analysis . . . 33
5.3.1 KiwiSDR vs Red Pitaya . . . 33
5.3.2 Web-888 vs Red Pitaya . . . 33

6 Conclusion **34**
6.1 Conclusions . . . 34
6.2 Discussion . . . 35
6.2.1 Performance . . . 35
6.2.2 Deployment . . . 36
6.2.3 Limitations . . . 37
6.3 Future work . . . 37

References **39**

List of Figures

1.1 WSPRnet database example of KiwiSDR reception[8] 4

2.1 Research Process 11

3.1 Red Pitaya Receiver 15
3.2 KiwiSDR Receiver 16
3.3 Web-888 Receiver 17

4.1 System Architecture 19
4.2 SDR setup - indoor 21
4.3 Antenna setup - outdoor 22

5.1 SNR relative to Red Pitaya 26
5.2 SNR average KiwiSDR and Red Pitaya 27
5.3 SNR relative to Red Pitaya 28
5.4 SNR average Web-888 and Red Pitaya 29
5.5 Spotcount 31
5.6 Spotcount Web-888 and Red Pitaya 32

List of Tables

1.1 Information available in the WSPRnet database 5

3.1 SDR Comparison 18

4.1 Equipment used in the experimental setup 20
4.2 Receiver call name 23

5.1 Spot count per WSPR-band for KiwiSDR and Red Pitaya . . . 30
5.2 Spot count per WSPR-band for Web-888 and Red Pitaya . . . 31

List of acronyms and abbreviations

ADC	Analog-to-Digital Converter
FPGA	Field-Programmable Gate Array
GPS	Global Positioning System
HF	High Frequency
RF	Radio Frequency
SDR	Software-Defined Radio
SNR	Signal-to-Noise Ratio
UTC	Coordinated Universal Time
WSPR	Weak Signal Propagation Reporter

Chapter 1

Introduction

The High Frequency (HF) band refers to frequencies between 3 and 30 MHz, corresponding to wavelengths from approximately 100 to 10 meters [1, Sec. 2]. HF radio signals primarily propagate through three modes: Line-of-sight, ground-wave and sky-wave propagation [1, Sec. 2]. However, the propagation mode of primary interest in this work is sky-wave propagation, as it enables beyond-the-horizon, long-distance global communication independent of terrestrial technology.

Higher frequency bands generally require line-of-sight paths or satellite relays [2, p.115]. In contrast, HF signals can enable over-the-horizon communications through ionospheric refraction.

Historically, portions of the HF bands have been allocated to amateur radio operators, for the purpose of research and experimentation [3, p.2990]. Following the discovery of ionospheric refraction in 1920s, it became evident that long-distance HF propagation is highly variable [3, p.990-2991] and as a result, significant efforts have been devoted to understanding, predicting, and continuously monitoring the ionospheric behavior in order to improve the reliability of HF communication links.

Sky-wave propagation in the HF bands is highly dependent on the state of the ionosphere. Furthermore, the ionosphere itself is strongly influenced by solar activity, since solar radiation (particularly during solar flares) induces ionization. Ionization is the process in which electrons are removed from neutral atoms or molecules, resulting in positively charged ions and free electrons [4, Sec 1.1].

The freely moving electrons are the key component in HF radio propagation, as they interact with the electromagnetic waves and cause them to be refracted back toward the Earth. The greater the electron density, the higher the frequencies can be reflected.

However, the ionosphere is divided into several regions: D, E, F1 and F2. These layers are ordered by increasing altitude and collectively spanning approximately 50 to over 500 km above the Earth's surface [4, Sec 1.1].

The D region is the lowest layer of the ionosphere and primarily causes attenuation of HF signals, thereby determining the lowest usable frequency (LUF) and is only present during solar radiation. Above the D region lies the E region, which is located at a higher altitude and contains a higher electron density. As a result, it has the properties of refracting the HF signals, during periods of high solar activity. The F region, which is divided into F1 and F2 regions during daytime, is the most important region since it is present throughout the day and its high altitude allows beyond the horizon communication and determines the maximum usable frequency (MUF)[4, Sec 2.2].

Due to the variability of ionosphere with time of day, season, and the solar cycle, the LUF and MUF are continuously changing. This creates a clear need for real-time monitoring of HF propagation to determine which frequency bands are usable at any given moment. Consequently, this thesis is motivated by the aim to contributing with proposals of affordable, suitable and reliable equipment to the beacon network by providing updated propagation data.

Previous work in this area has been conducted by Lennart Benedikt Sturm [5], who designed and evaluated a multiband receiver system for HF propagation measurements using the Weak Signal Propagation Reporter (WSPR) mode implemented on a Red Pitaya 122.88-16 Software-Defined Radio (SDR) platform [6], which is considered as a relatively expensive receiver.

Building upon his work, the aim of this thesis is to further investigate the performance of more cost-effective SDR platforms. In particular, this study focuses on evaluating whether lower-cost alternatives can achieve comparable or improved performance in terms of WSPR signal reception.

1.1 Background

1.1.1 Weak Signal Propagation Reporter (WSPR)

WSPR is a digital communication protocol designed to study radio propagation conditions in HF bands. The very low-power transmitted signals can be decoded at extremely low signal-to-noise ratios, and the decoded information is automatically reported to a global database, enabling real-time monitoring of HF propagation conditions.

1.1.1.1 WSPR protocol

The protocol is structured into three components: callsign, locator, and power. This means it includes the callsign of the transmitting station, the Maidenhead locator indicating its geographical position, and the transmit power expressed in dB. The entire message is encoded into 50 bits (28 bits for the callsign, 15 bits for the four-character Maidenhead locator, and 7 bits for the power level) [7].

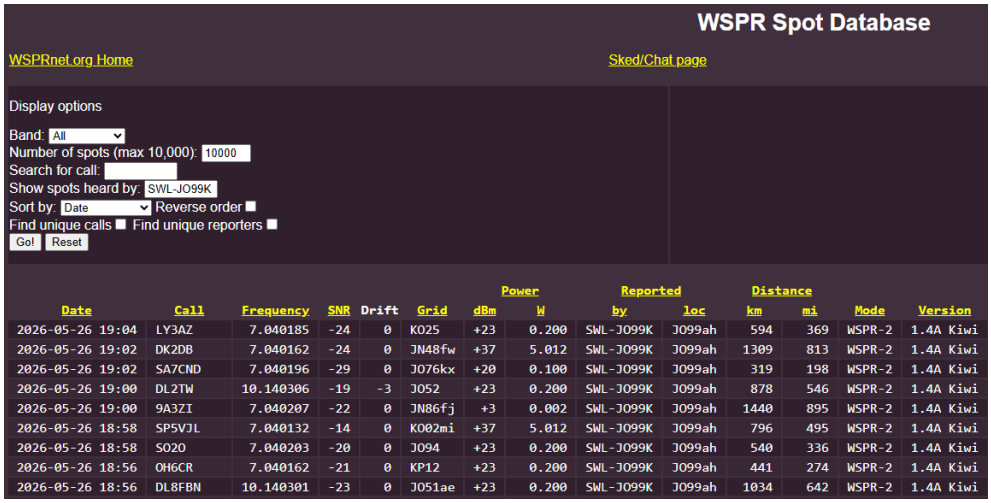
WSPR applies forward error correction (FEC) using a long constraint convolutional code with a constraint length of 32 and a coding rate of 1/2[7]. After encoding and synchronization symbol insertion, the message expands to 162 channel symbols.

The transmission speed is extremely low due to a symbol rate of 1.46 baud, and together with the 4-frequency shift keying (4-FSK) modulation, the occupied bandwidth becomes very narrow, approximately 6 Hz [7]. This combination enables WSPR signals to be decoded even when signal to noise ratio as low as -30 dB. Thus, each transmission cycle spans roughly two minutes, with all transmissions precisely synchronized to UTC.

1.1.1.2 WSPRnet database

The decoded information is automatically uploaded to WSPRnet.org[8], which supports large-scale monitoring of HF band skywave propagation. This data collection is carried out for research purposes and a useful framework to validate and compare results from different equipments receiving WSPR. In this thesis, the WSPRnet database serves as the primary source of measurement data, enabling SNR comparisons and comparisons of the number

of received signals between the different SDR platforms under identical propagation conditions.



WSPR Spot Database

WSPRnet.org Home Sked/Chat page

Display options

Band: All
Number of spots (max 10,000): 10000
Search for call:
Show spots heard by: SWL-JO99K
Sort by: Date Reverse order
Find unique calls Find unique reporters
Go! Reset

						Power		Reported		Distance			
Date	Call	Frequency	SNR	Drift	Grid	dBm	W	by	loc	km	mi	Mode	Version
2026-05-26 19:04	LY3AZ	7.040185	-24	0	KO25	+23	0.200	SWL-JO99K	JO99ah	594	369	WSPR-2	1.4A Kiwi
2026-05-26 19:02	DK2DB	7.040162	-24	0	JN48fw	+37	5.012	SWL-JO99K	JO99ah	1309	813	WSPR-2	1.4A Kiwi
2026-05-26 19:02	SA7CND	7.040196	-29	0	JO76kx	+20	0.100	SWL-JO99K	JO99ah	319	198	WSPR-2	1.4A Kiwi
2026-05-26 19:00	DL2TW	10.140306	-19	-3	JO52	+23	0.200	SWL-JO99K	JO99ah	878	546	WSPR-2	1.4A Kiwi
2026-05-26 19:00	9A3ZI	7.040207	-22	0	JN86fj	+3	0.002	SWL-JO99K	JO99ah	1440	895	WSPR-2	1.4A Kiwi
2026-05-26 18:58	SP5VJL	7.040132	-14	0	KO02mi	+37	5.012	SWL-JO99K	JO99ah	796	495	WSPR-2	1.4A Kiwi
2026-05-26 18:58	SO2O	7.040203	-20	0	JO94	+23	0.200	SWL-JO99K	JO99ah	540	336	WSPR-2	1.4A Kiwi
2026-05-26 18:56	OH6CR	7.040162	-21	0	KP12	+23	0.200	SWL-JO99K	JO99ah	441	274	WSPR-2	1.4A Kiwi
2026-05-26 18:56	DL8FBN	10.140301	-23	0	JO51ae	+23	0.200	SWL-JO99K	JO99ah	1034	642	WSPR-2	1.4A Kiwi

Figure 1.1: WSPRnet database example of KiwiSDR reception[8]

Figure 1.1 presents an example of the information available in the WSPRnet database. Each reception report contains parameters related to the received WSPR transmission, including transmitter and receiver identifiers, operating frequency, Signal-to-Noise Ratio (SNR), transmission location, and estimated propagation distance [8]. Table 1.1 summarizes the available database fields and highlights which parameters are utilized in this thesis.

Table 1.1: Information available in the WSPRnet database

Parameter	**Description**	**Used**
UTC Time	Time of reception (UTC)	Yes
Frequency	Received frequency of the WSPR signal	Yes
Transmitter Callsign	Identifier of the transmitting station	Yes
Receiver Callsign	Identifier of the receiving station	Yes
Grid	Location of transmission station	Yes
SNR	Signal-to-noise ratio of the received signal	Yes
Distance	Estimated propagation distance between stations	No
Power	Transmitter output power	No
Drift	Measured frequency drift of the signal	No
Mode	Transmission mode (e.g. WSPR-2)	Yes
Software Version	Software used for decoding and reporting	No

The selected parameters, such as UTC time, frequency, callsigns, grid locator, SNR and mode, form the basis for the pairwise comparison between receivers and enable evaluation of both SNR and number of received signals performance.

1.1.2 Software Defined Radio

The origins of Software Defined radio (SDR) can be traced back to the early 1990s, when Joe Mitola the 3rd first proposed the SDR concept [9]. SDR devices operate on an architecture based on an integration of hardware and software components, where software contributes the majority of the functionality [10, Sec. 2.1]. Traditionally, radio systems are implemented using analog electronic components such as filters, amplifiers, mixers, modulators, demodulators, and detectors. In a Software Defined Radio (SDR), many of these physical components are replaced by digital processing. The incoming analog signal is first converted into a digital signal using an analog-to-digital converter (ADC). The digitized signal is then processed in programmable hardware such as a Field-Programmable Gate Array (FPGA). Operations such as filtering and frequency translation are then performed digitally. The processed data can later be transferred through the CPU external applications for further analysis, visualization, or audio output.

The advantage of a Software Defined Radio (SDR) compared to a traditional hardware-based radio lies in its flexibility and reduced dependence on dedicated hardware components. Conventional radios rely on analog circuitry designed for specific frequency ranges and modulation schemes, which makes them less flexible and more constrained by their physical design. In some applications, such as wireless communication systems, multiple hardware components or chipsets may be required to support different standards (e.g., Bluetooth or LTE) [9]. In contrast, SDR systems utilize a common hardware platform, typically consisting of an FPGA and a CPU, where different functionalities and communication standards are implemented in software. Moreover, this flexibility is particularly important for WSPR-signals, where narrow-band filtering and precise frequency tuning are required.

1.1.3 Previous Work

This thesis builds upon previous work by Lennart Benedikt Sturm [5]. In that work, a multiband receiver system for HF propagation monitoring was designed and evaluated using the Red Pitaya 122.88-16 SDR platform [11]. The system utilized software developed by Pavel Demin [6] together with an active loop antenna [12].

The results demonstrated the feasibility of simultaneous multiband WSPR reception for ionospheric propagation studies. In particular, the system

showed positive results in low-noise outdoor environment as well as industrial outdoor environment, while indoor reception resulted in reduced performance [5, Sec. 4]. The system's portability enabled flexible deployment at different locations, making it suitable as a mobile WSPR receiver station.

Despite the promising results and portability that Red Pitaya achieves, the system is significantly a higher cost. This serves as the main motivation for the present thesis, which investigates whether lower-cost SDR hardware can achieve comparable performance while maintaining simultaneous multiband WSPR reception.

1.2 Problem Definition

1.2.1 Research question

This thesis evaluates two pre-selected SDR platforms, KiwiSDR 2 [13] and Web-888 [14], as potential low-cost alternatives to the Red Pitaya 122.88-16 [11] based receiver used by Sturm [5].

The research questions investigated in this thesis are:

- How do the KiwiSDR 2 and Web-888 platforms compare to the Red-Pitaya-based receiver used by Sturm [5] in terms of cost-effectiveness and multiband WSPR reception performance?
- To what extent can the KiwiSDR 2 and Web-888 perform reliable multiband WSPR reception under identical operating conditions as Red Pitaya.

To address these questions, a system is developed with a configuration as similar as possible to that of Sturm [5].

1.2.2 Hypothesis statement

The hypothesis of this thesis is that the pre-selected SDR platforms KiwiSDR 2 [13] and WEB-888 [14], can provide multiband WSPR reception performance comparable to that of the Red Pitaya while offering a more cost-effective receiver solution.

It is expected that both platforms will satisfy the defined system requirements,

including simultaneous multiband WSPR reception and automated reporting to the WSPR network.

1.2.3 Criteria of the stations

The criteria are largely based on those defined in Sturm's thesis [5]:

- The system should be portable and support mobile operation, in the sense that it should be able to be moved by one person in a simple way.
- The system should be capable of receiving WSPR signals on at least 4 bands simultaneously and uploading the information to WSPRnet database [8].
- A more cost-effective SDR platform than the Red Pitaya 122.88-16 [11] used by Sturm [5].

1.2.4 Performance Metrics

And to clarify the information that will be shared to the WSPRnet database is following:

- Signal-to-Noise ratio (SNR - defined as the signal power divided by the noise power[2])
- Number of receptions

1.3 Related work

The earlier thesis project by Sturms [5], which focuses on building a multiband receiving station for WSPR signals, provides valuable insight into how to establish a compact and functional WSPR receiving system using an active small active loop antenna and a SDR based on the Red Pitaya 122.88-16 platform. This work confirms that a multiband-WSPR receiver works, and will be a reference for the present thesis.

This research article investigates how different antenna configurations impact the SNR within HF communication [15]. It is relevant for understanding the selection of an antenna that is both portable and capable of covering HF frequency bands while maintaining high performance. Furthermore, the paper presents that selection of antenna impacts sensitivity when evaluating SNR,

which is an important aspect to remember for this thesis.

The article provides a comprehensive review of techniques for selecting the optimal operating frequency for HF communication systems, including historical, present technics and future research directions [3]. This work emphasizes the need of dynamic HF-communication systems, which underscore the need to monitor the ionospheric conditions across multiple frequency bands. It motivates therefore the demand of dynamic propagation monitoring.

Goodman's article provides an overview of factors that influence the variability of the ionosphere [16]. Events such as solar flares and space whether variations significantly affect ionospheric conditions. This emphasizes the need for continuous monitoring of ionospheric behavior to maintain stable communication performance. This perspective is highly relevant to the present thesis, as WSPR-based measurements rely on the same propagation mechanisms and are similarly affected by space weather dynamics. Therefore, Goodman's analysis supports the importance of multiband HF observations for both research and system evaluation.

However, despite previous work demonstrating feasability, limited work appears to compare low-cost SDR alternatives under identical WSPR measurment conditions.

Chapter 2

Method

2.1 Research Process

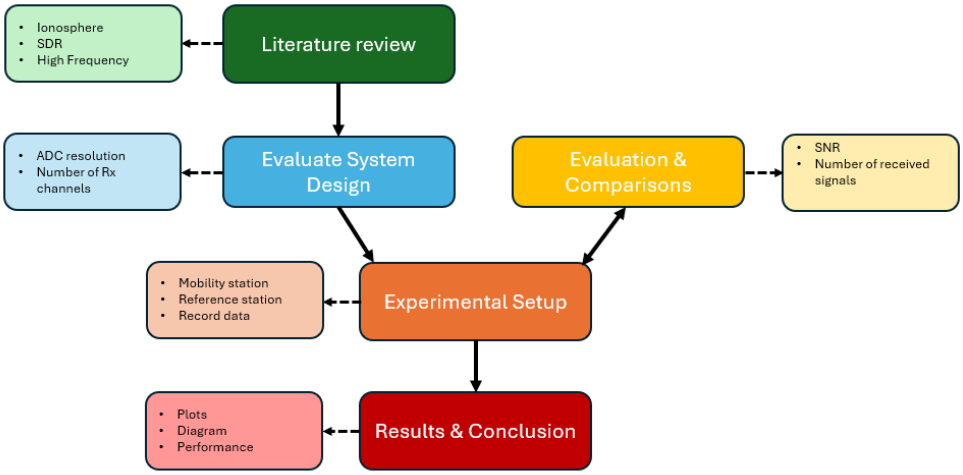


Figure 2.1: Research Process

Since this thesis builds upon the work of Sturm [5], it is relevant to follow the similar research structure in order to enable direct performance comparisons. The research process illustrated in Figure 2.1 is therefore inspired by and based on his research process.

The methodology consists of the following steps:

- **Literature review** is the first state with the purpose to achieve a

background knowledge in the research area, understanding the HF-communication, SDR technology and the WSPR-system. This is essential both for understanding the problem in detail and for evaluating the SDR platforms.

- **Evaluate system design** is based on the knowledge gained from the literature review. This means, relevant and promising equipment is evaluated with the intention of meeting the system requirements or achieving improved performance.
- **Experimental Setup** stage includes antenna placement and SDR configuration. Each measurement is performed as a pairwise comparison between one of the pre-selected SDR platforms and the reference receiver, Red Pitaya. Both receivers share the same antenna through a RF splitter, ensuring identical propagation conditions for all comparisons.
- **Evaluation & Comparisons** are performed using data collected from the SDR systems during the measurements. Each low-cost SDR platform is compared pairwise with the Red Pitaya [11], which serves as the reference platform in this study.
- **Results & conclusions** are presented in the final step, where the results are based on the defined requirements in Section 1.2.3.

2.2 Experimental design

The experiment is based on pairwise comparisons between the pre-selected SDR platforms and the reference receiver Red Pitaya [6] used by Sturm [5]. For each comparison, both receivers are connected to the same antenna through a splitter, ensuring that identical signals are received under the same propagation conditions. This setup eliminates variations that could otherwise arise if the receivers were tested separately, as any changes in propagation conditions affect both systems equally.

To reproduce the experimental conditions as closely as possible to those used by Sturm [5], the same antenna type is employed, which is an active loop antenna [12]. Each measurement is conducted over a 24-hour period to capture both day- and nighttime propagation conditions, as the ionosphere can change significantly over the course of a day.

During each experiment, received WSPR signals are automatically reported to WSPRnet database [8]. After the measurement period, the reported data are downloaded from WSPR Live [17] as CSV files. To obtain the data, each platform have to have their unique receiver call, to separate data from each other. To obtain the data, each platform must use a unique receiver call-sign to ensure that the datasets can be separated.

2.3 Reliability and validity of the method

2.3.1 Reliability of method

All collected data from the KiwiSDR and the Web-888 are analyzed in pairwise comparisons against the Red Pitaya, with all receivers connected to the same antenna through an RF splitter. This configuration ensures that both SDR platforms receive identical RF input under the same propagation conditions while avoiding additional splitter losses that would arise from including more receivers. This enables a fair and controlled comparison of receiver performance.

2.3.2 Validity of method

Several factors may influence the validity of the comparison:

HF propagation varies continuously due to changes in the ionosphere, time of day, and noise. To minimize these effects, each SDR platform and the Red Pitaya were connected to the same antenna via an RF splitter, ensuring identical RF input and comparable propagation conditions.

Another potential issue is signal degradation introduced by the splitter, since the antenna signal is divided between multiple receivers. Initial tests with all three SDRs connected simultaneously showed noticeably reduced performance on one of the receivers. To avoid this problem, all measurements were therefore performed as pairwise comparisons using the same splitter configuration, ensuring identical conditions for each test.

The measurements were performed over a 24-hour period to capture both daytime and nighttime propagation conditions. A limitation of the method is that the experiment was conducted at a single location and during a

restricted time window, meaning the results may not represent all possible HF propagation scenarios.

Based on these considerations, the method is considered valid for comparing the relative performance of the tested SDR platforms under the defined experimental conditions.

2.4 Data Evaluation and Analysis

For this thesis, the graphs and diagrams presented follow the same approach as in Sturm [5]. Inspired by his work, Python-based data analysis tools are used, specifically the packages **pandas** [18] and **matplotlib** [19], to process the collected data and extract relevant performance metrics from the reported data.

Chapter 3

Evaluated SDR Platforms

3.1 Red Pitaya

The configuration of the Red Pitaya is identical to the setup described in Sturms work [5, Sec 1.1.6]. Since the SDR-platform has been validated as a reliable and well-performing SDR receiver, it is used as the reference platform against the pre-selected SDRs.

Figure 3.1: Red Pitaya Receiver

3.2 KiwiSDR

The KiwiSDR is a SDR-platform designed for remote HF-signal reception and web-based access. The receiver reception range is from 10 kHz-30 Mhz [13],

which is required to cover all HF bands and enabling WSPR signal reception.

The platform is using a 14-bit Analog-to-Digital Converter (ADC) operating at 66.6 MHz together with a FPGA -based signal processing [13]. The digital down conversion (DDC) divides the HF spectrum into multiple independent receiving channels. This enables simultaneous multiband receptions and makes the platform suitable for this comparison.

The main advantage of the KiwiSDR is the integrated web user interface together with network connection, enabling remote deployment and continuously reporting data to WSPRnet database. The second advantage is the possibility of using Global Positioning System (GPS) synchronized ADC clock, which can adjust the clock frequency precisely so it matches the Coordinated Universal Time (UTC). This is particularly important in WSPR reception, since it is time-synchronized.

Figure 3.2: KiwiSDR Receiver

3.3 WEB-888

The WEB-888 is a SDR platform with a design similar to the KiwiSDR, intended for remote HF-signal reception and web-based accessed. The spectrum coverage of reception is 1 kHz to 62 MHz [14], to cover all WSPR bands.

This platform is using a 16-bit ADC operating at 122.88 MHz together with a FPGA-based signal processing [14]. In the signal processing the DDC is dividing the HF spectrum in to multiple different independent receiving channels, enabling multiband reception simultaneously.

The WEB-888 uses a similar integrated web user interface as the KiwiSDR platform, but using there own servers. It increases the simplicity of deployment and continuously reporting data to WSPRnet database. Moreover, the WEB-888 also have the option of using GPS synchronized ADC clock to increase reception performance.

Figure 3.3: Web-888 Receiver

3.4 Comparison of Platform Specifications

The three SDR platforms differ in several hardware and functional characteristics that may influence their performance in multiband WSPR reception. To provide context for the subsequent analysis, Table 3.1 summarizes the key specifications of the Red Pitaya, KiwiSDR, and Web-888, highlighting differences in ADC resolution, channel availability, timing capabilities, and system integration.

Table 3.1: SDR Comparison

Characteristics	**Red Pitaya**	**KiwiSDR**	**Web-888**
ADC resolution	16-bits	14-bits	16-bits
Rx channels	16	8	13
GPS ADC clock	No	Yes	Yes
Integrated Web UI	No	Yes	Yes
Standalone	Yes	No	No
Price (Euro)	935,50	347	352

Chapter 4

Experiment

4.1 System Architecture

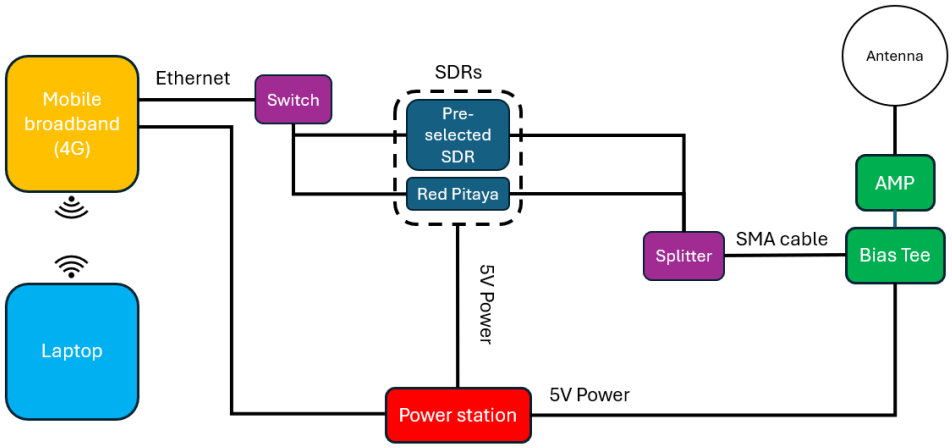


Figure 4.1: System Architecture

Figure 4.1 illustrates the system architecture used in the experimental receiver setup. The pre-selected SDR for each measurement shares the same antenna and the Radio Frequency (RF) splitter configuration, ensuring identical reception conditions during the measurement period. Both the selected SDR - either the KiwiSDR or the Web-888 - and the Red Pitaya are connected to the same Ethernet switch. The switch is in turn connected to a 4G mobile broadband providing internet access for data upload and communication with external servers.

The pre-selected SDR can be remotely monitored and configured from a laptop connected to the local network via Wi-Fi. In contrast, the Red Pitaya cannot be remotely controlled in this setup and operates autonomously once configured.

4.2 Equipment

The experimental setup consists of several hardware components required for receiving and reporting WSPR signals. To ensure that the experiment can be reproduced, the main equipment used during the measurements is listed in Table 4.1. The table includes the receiver platforms, antenna system, signal distribution components, and network equipment used in the experimental setup and can be seen physically in Figure 4.2.

Table 4.1: Equipment used in the experimental setup

Component	Model	Purpose
HF antenna	MLA-30 Plus active loop antenna	HF signal reception
Reference SDR	Red Pitaya 122.88-16	Reference receiver
SDR platform 1	KiwiSDR 2	Receiver under evaluation
SDR platform 2	WEB-888	Receiver under evaluation
RF splitter	Mini-Circuits ZSFC -3-1+	Signal distribution
Router	TP-Link Archer MR600	Network connection
Laptop	Lenovo Yoga 7	Configuration and monitoring

4.3 Setup

4.3.1 Indoor

Figure 4.2: SDR setup - indoor

The SDRs are connected to the antenna via a splitter from the bias tee, which will slightly affect the impedance between the antenna and the SDRs, although this is considered as a limited impact on performance in terms of performance degradation. All units are connected via Ethernet to a 4G mobile broadband router with inbuilt switch. This setup allows the SDRs to be controlled remotely from another location, while still remaining within the same local network, as all systems operate on local servers. The SDR setup can be seen in Figure 4.2

4.3.2 Outdoor

The tests were located in Tumba, which is considered as a suburban low-noise environment and was performed from 25th of May at 13:00 UTC to May 27th 15:30 UTC. The height of the antenna is approximately 1.5 meters and is mounted on a tree stick. The antenna setup can be seen in Figure 4.3.

Figure 4.3: Antenna setup - outdoor

4.4 Measurement Procedure

Due to instability observed when connecting all three receivers simultaneously, each SDR platform was evaluated in a separate pairwise test together with the Red Pitaya.

4.4.1 Location

The measurement was performed in a small village called Tumba south of Stockholm.

4.4.2 Measurement Period

The two identical tests was conducted on separate dates:

- **Test 1** - KiwiSDR and Red Pitaya, Start Date: 2026-05-25 13:00, End Date: 2026-05-26 13:00
- **Test 2** - Web-888 and Red Pitaya, Start Date: 2026-05-26 15:30, End Date: 2026-05-27 15:30

4.4.3 Reporting and Data Handling

To keep track of the data reported to WSPRnet database [8] and to separate the measurements for each platform, every SDR was configured to report under a unique receiver call name, as listed in Table 4.2.

SDR	Call name
Red Pitaya	SWL-JO99R
KiwiSDR	SWL-JO99K
Web-888	SWL-JO99W

Table 4.2: Receiver call name

4.5 Data processing and calculations

The collected WSPR data was processed to extract performance metrics for comparing the SDR platforms. The analysis was based on two main metrics:

Signal-to-Noise Ratio (SNR) comparison and the number of received WSPR spots.

For the SNR comparison, only matched reception events were included. A matched event means that the same WSPR transmission was successfully decoded by both the evaluated SDR platform and the Red Pitaya reference receiver.

For each transmitting station, the mean SNR value was calculated from all matched reception events:

$$\overline{SNR} = \frac{1}{N} \sum_{i=1}^{N} SNR_i$$

where N is the number of matched reception events.

The SNR difference was calculated as:

$$\Delta SNR = SNR_{SDR} - SNR_{Red\ Pitaya}$$

where a positive value indicates that the evaluated SDR reported a higher SNR than the reference receiver.

For the time-based SNR graphs, the received events were grouped into 30-minute intervals and the average SNR was calculated for each interval to visualize changes during different propagation conditions.

The second metric was the number of received WSPR spots. Each successfully decoded WSPR transmission reported by the receiver was counted as one spot. The total number of spots was calculated by summing all received spots during the measurement period, separated by frequency band.

Chapter 5

Results and Analysis

5.1 SNR comparison

In Figure 5.1 and 5.3, it shows 40 transmitting stations ordered from left to right sorted by the reference receiver Red Pitaya. Each data point represents the mean SNR value from transmission events detected by all SDR platforms during identical WSPR time slots. This can mean that a given transmitter may have been heard, for example 10 times during identical 2 minute WSPR cycles, and only those perfectly matched reception events are included in the comparison.

The second graph in Figure 5.1 and 5.3 builds on the first graph, demonstrating the SNR difference for the KiwiSDR and the Web-888 relative to the Red Pitaya. It can be seen as how much stronger or weaker each receiver performed compared to the reference for the same set of matched transmission events.

In Figure 5.2 and 5.4, the graph represents the SNR-average of all received WSPR transmission events across all bands, computed in 30-minute intervals. This representation is inspired by Sturm's SNR comparison method [5, Chapter 4].

5.1.1 Test 1 - KiwiSDR and Red Pitaya

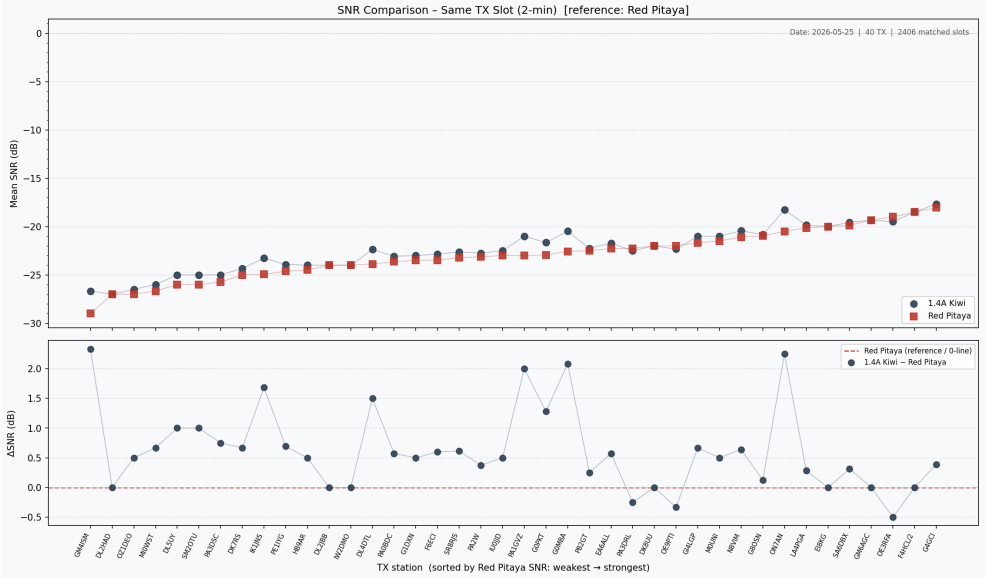


Figure 5.1: SNR relative to Red Pitaya

The trends in Figure 5.1 shows that the KiwiSDR achieves equal or higher SNR values than the Red Pitaya for almost all transmitters. The lower graph further illustrates that the KiwiSDR is reporting slightly higher SNR values for the majority of received stations. The performance difference is from approximately +2.5 dB to –0.5 dB relative to the reference line, which represents the Red Pitaya.

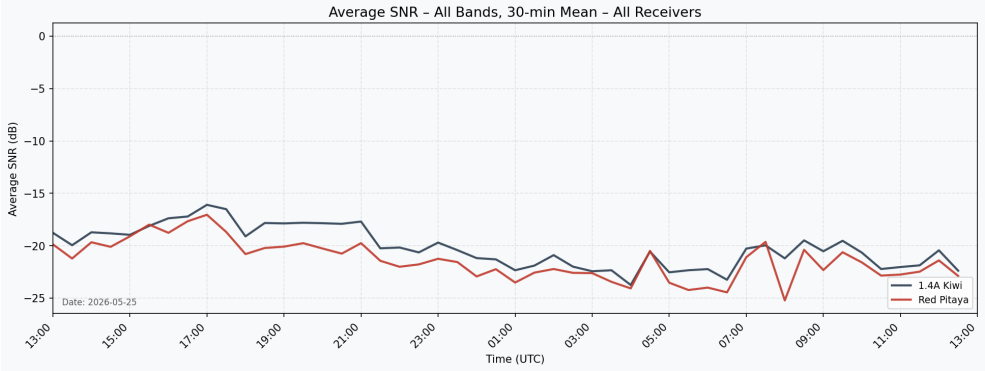


Figure 5.2: SNR average KiwiSDR and Red Pitaya

The graph in Figure 5.2 demonstrates that, for nearly the full 24 hour measurement, the KiwiSDR consistently reports higher SNR value. It can also be observed that both SDRs, reports higher SNR values during the afternoon and reduced values during nighttime and morning hours.

5.1.2 Test 2 - Web-888 and Red Pitaya

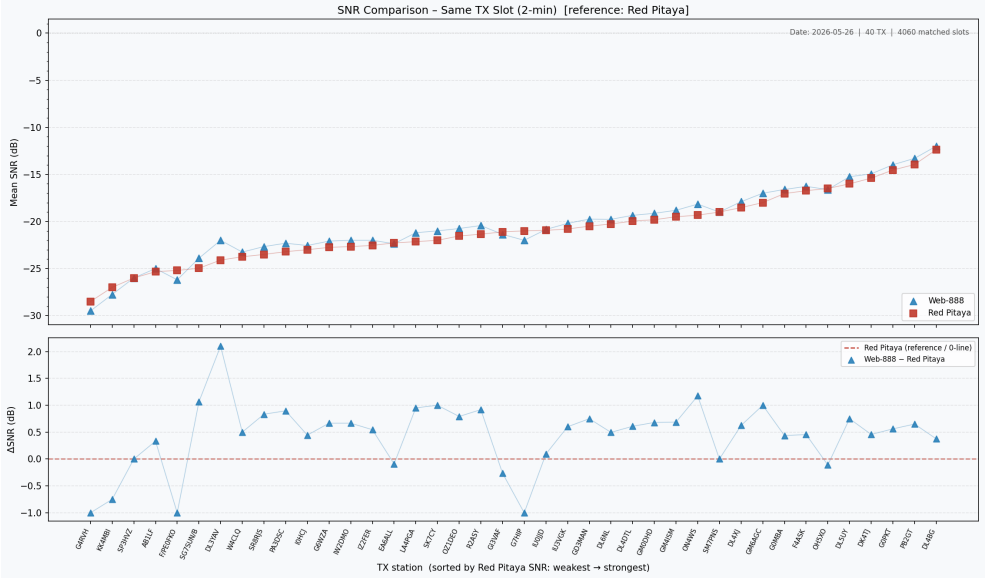


Figure 5.3: SNR relative to Red Pitaya

The trends in Figure 5.3 show that the Web-888 achieves higher SNR values or the same as the Red Pitaya for the majority of transmitters, indicating a slightly stronger received signal levels. The lower graph shows that the Web-888 receives signals with higher SNR for several stations, in some cases up to +2 dB, while a few stations exhibit slightly lower values, down to approximately –1 dB.

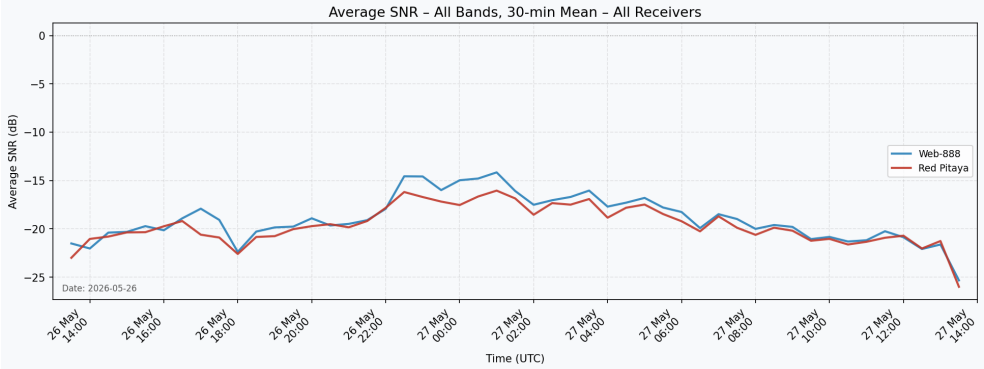


Figure 5.4: SNR average Web-888 and Red Pitaya

The graph in Figure 5.4 visualize that both the Web-888 and Red Pitaya follow the same overall SNR trend throughout the measurement period, although the Web-888 achieves slightly higher SNR values in some periods. The elevated SNR levels observed for both receivers during the night may be related to the typically lower noise floor during nighttime hours.

5.2 Number of spots

The Table 5.1 and 5.2 lists the total number of received spots per WSPR-band. This means that if a transmitting station sends, for example , 40 WSPR signals during the measurement period, all 40 successfully decoded receptions are counted and added to the corresponding band in the table.

The Figure 5.5 and 5.6 visualizes the number of received spots distributed over time. This enables an analysis of receiver performance during both night and daytime propagation conditions.

5.2.1 Test 1 - KiwiSDR and Red Pitaya

Band	KiwiSDR	Red Pitaya
3 MHz (80m)	1	1
5 MHz (60m)	1	17
7 MHz (40m)	787	715
10 MHz (30m)	1493	1392
14 MHz (20m)	1378	1107
18 MHz (17m)	-	9
21 MHz (15m)	-	20
24 MHz (12m)	-	2
28 MHz (10m)	196	2
TOTAL	**3856**	**3264**

Table 5.1: Spot count per WSPR-band for KiwiSDR and Red Pitaya

Table 5.1 shows that the KiwiSDR reported a total of 3856 spots whereas the Red Pitaya reported 3264 spots, which means that KiwiSDR recieved 18 % more signals. Both receivers detected signals on multiple bands. However, the KiwiSDR reported on six different WSPR bands, while the Red Pitaya reported on all nine WSPR bands.

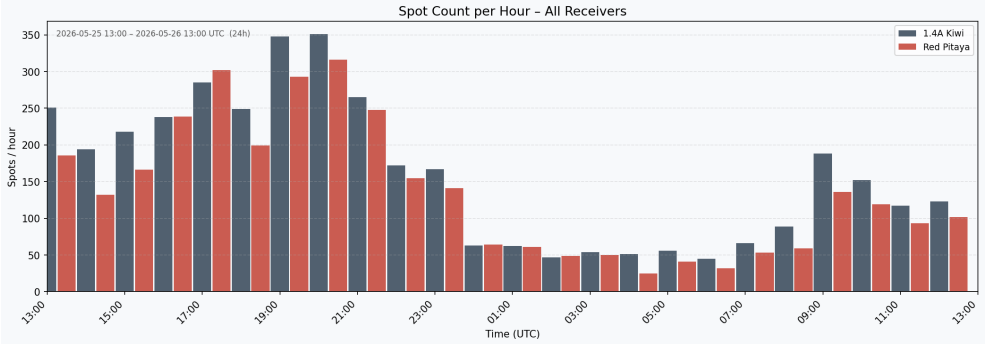


Figure 5.5: Spotcount

Figure 5.5 shows that the kiwiSDR reports a higher number of spots per hour during most of the measurement period. Both receivers experience increased traffic during the evening of 25 of May (Sunday) followed by significant reduction in spot count during the night and early morning hours.

5.2.2 Test 2 - Web-888 and Red Pitaya

Band	**Web-888**	**Red Pitaya**
3 MHz (80m)	2	27
5 MHz (60m)	52	134
7 MHz (40m)	2054	2080
10 MHz (30m)	2437	2200
14 MHz (20m)	1120	816
18 MHz (17m)	27	6
21 MHz (15m)	14	3
24 MHz (12m)	3	-
28 MHz (10m)	16	1
TOTAL	**5725**	**5267**

Table 5.2: Spot count per WSPR-band for Web-888 and Red Pitaya

Table 5.2 shows that the Web-888 received signals on all WSPR bands, whereas the Red Pitaya missed one band. The Web-888 also recorded a higher total number of spots (8,6 %). Across the individual bands, the Web-888

received more signals from 10 MHz up to 28 MHz, while the Red Pitaya had higher reception counts on the 7, 5 and 3 MHz bands.

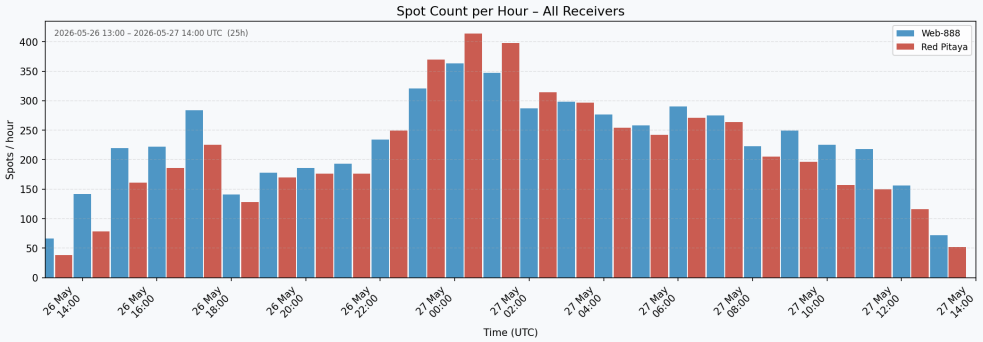


Figure 5.6: Spotcount Web-888 and Red Pitaya

Figure 5.6 shows that more spots are received during the nighttime than during the daytime hours. As mentioned earlier, a possible explanation is the generally lower noise floor at night. The figure also indicates that the web-888 receives more spots per hour than the Red Pitaya for most of the measurement period, except for a few hours around midnight where Red Pitaya reports a slightly higher spot count.

5.3 Analysis

The pre-selected SDR platforms, evaluated according to the criteria in Section 1.2.3, are analysed in comparison with the reference SDR-platform, Red Pitaya.

5.3.1 KiwiSDR vs Red Pitaya

1. Matches or exceeds the Red Pitaya in SNR for most transmitters.
2. Receives approximately 18 % more signals than the Red Pitaya during the measurement period.
3. Limited to six bands due to hardware constraints.

5.3.2 Web-888 vs Red Pitaya

1. Matches or exceeds the Red Pitaya in SNR for most transmitters.
2. Receives approximately 8,6 % more signals than the Red Pitaya during the measurement period.
3. Performs consistently across all nine WSPR bands with stable SNR levels.

Chapter 6

Conclusion

6.1 Conclusions

In this thesis, an investigation was conducted whether the pre-selected low-cost multiband WSPR receiver hardware can achieve performance comparable to the Red PitayaSDR-platform used in Sturms work [5].

In relation to the first research question, which concerns portability and support for mobile operation, both the Web-888 and the KiwiSDR were found to be portable and remotely controllable, allowing straightforward deployment provided that power, Ethernet connectivity, and an HF antenna are available. The proposed SDR-platforms are also simpler to operate than the Red Pitaya, due to their integrated web based user interfaces, which allow configuration without requiring direct backend access.

Regarding the second criterion of receiving signals on at least four WSPR bands simultaneously, both platforms met this requirement. In addition, the Web 888 achieved reception on all nine WSPR bands, whereas the KiwiSDR, due to receiver channel limitations, was restricted to seven bands and ultimately received signals on only six of them.

For the third research question, which concerns cost-effectiveness compared to the Red Pitaya, the Web-888 and KiwiSDR generally performed similarly or achieved improved performance in some cases. Both platforms received higher number of decoded signals, and in several cases achieved comparable or higher SNR levels relative to the Red Pitaya for the same transmitting stations. These results indicate that the investigated Web-888 and KiwiSDR are competitive

alternatives despite their lower cost.

Overall, both systems meets the definition of a low cost multiband WSPR receiver, as they are significantly more cost effective than the Red Pitaya while offering comparable performance in most scenarios. The main distinction is that the Red Pitaya support reception across all nine WSPR bands, whereas the KiwiSDR is limited to 7, in best case 8. Consequently, the Web-888 emerges as the most cost-effective multiband WSPR receiver in this study, while the KiwiSDR performs similarly but across fewer frequency bands.

The hypothesis statement is therefore supported, indicating that more cost-effective SDR platforms exist compared to the Red Pitaya while maintaining comparable reception performance. This increases accessibility for private users to establish their own receiver stations and contribute to the WSPR beacon network for propagation monitoring.

This thesis provides additional insight into the performance of low-cost multiband WSPR receivers, demonstrating that they can achieve comparable, and in some cases improved performance relative to more expensive SDR hardware solution.

6.2 Discussion

6.2.1 Performance

A positive outcome is that both platforms are able to receive signals on at least four bands simultaneously. Web-888 can receive signals on all nine WSPR bands simultaneously (See Table 5.2), whereas the KiwiSDR is limited to six bands (See Table 5.1). The difference may partly be explained by the FPGA architecture, since the Web-888 can process thirteen parallel channels, whereas the KiwiSDR limited to eight. Due to the design of KiwiSDR's integrated web interface, one of the channels must remain available for user access, meaning that only seven channels can be used for WSPR autoruns [13]. Although the same requirement applies to the Web-888, its larger channels capacity ensures that all nine WSPR bands can be covered without limitation.

Furthermore, the SNR comparison shows that both the Web-888 and the KiwiSDR can receive signals similarly to, and in many cases stronger than, the Red Pitaya. One possible explanation may be variations in

FPGA implementation efficiency for weaker signals. The KiwiSDR uses a 14-bit ADC , while the other platforms use 16-bit ADCs. Despite this lower resolution, the KiwiSDR still demonstrates strong performance when receiving weak signals. In this observation, the KiwiSDR illustrates that, in terms of SNR for received WSPR signals, a 14-bit ADC can achieve results comparable to those 16-bit ADC. It should be noted that reports showing unusually high SNR values must be interpreted with caution, as they may report higher values than it actually was.

Nevertheless, the total number of received WSPR signals offers a more reliable indicator of receiver performance and helps reduce the uncertainty associated with the possibility of inaccurate SNR values. As presented in Table 5.1 for Test 1, the KiwiSDR achieved 18 % more spots than the Red Pitaya and received significantly more on the higher frequency bands. It may indicate that the resources in the KiwiSDR are used more efficiently, allowing it to receive more signals despite being limited to six simultaneous WSPR bands. This is particularly evident at 28 MHz, where the KiwiSDR received 196 spots compared to only 2 for the Red Pitaya. An exception was the 5 MHz band, where the Red Pitaya achieved more, receiving 17 spots compared to only 1 for the KiwiSDR.

In Test 2, as shown in Table 5.2, the Web-888 decoded 8.6 % more spots during the measurement period. Although the trend of the Red Pitaya achieving higher spot counts on the lower frequency bands continues in Test 2, the Web-888 received more spots from 10 MHz and above, while the Red Pitaya performed better on the lower bands. This may indicate that the FPGA architecture of the Red Pitaya is slightly more optimized for lower-frequency operation.

6.2.2 Deployment

All three platforms can perform and be controlled remotely, but the KiwiSDR and Web-888 have an integrated web user-interface, which simplifies management of the platforms significantly and do not require external software. Moreover, both platforms operate as plug-and-play SDR systems, requiring only one antenna, an Ethernet connection, and a laptop to select frequencies of interest. Compared to the Red Pitaya solution, which requires backend configuration adjustments and does not provide a built-in waterfall display, an external software application must be used to visualize the RF

spectrum.

However, the splitter which was used in this system, may have a minor performance issue on one of the outputs, which makes the results somewhat uncertain. Earlier measurements showed this behavior, with one SDR repeatedly underperforming. Therefore a pairwise comparison is performed, to give the both pre-selected SDR platforms fair circumstances.

6.2.3 Limitations

A limitation of the study is that the RF splitter introduced performance degradation when more than two receivers were connected simultaneously. This prevented a direct three-way comparison within the same measurement period, and the evaluation was therefore carried out using pairwise tests, which ensured stable operation but required separate measurement periods for each SDR platform.

Longer measurement periods may also have introduced additional variability due to changing propagation conditions, weather, temporary noise sources, or fluctuations in band activity. Another limitation is that all measurements were conducted at a single location. Different environments could have produced different results.

Finally, the antenna and splitter may not have provided optimal impedance matching, which could have negatively affected the performance of the evaluated platforms.

6.3 Future work

Future work could be explore additional low-cost SDR platforms to identify even more cost-effective alternatives. However, a focused investigation into whether any of the receivers consistently report elevated SNR values would help rule out potential uncertainties and further strengthen the reliability of the results presented in this thesis.

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