Design of Sliding Correlator Channel Sounder for Ionospheric Channel Probing Based on Software Define Radio

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ABSTRACT

Observations of Ionosphere as a wireless channel using channel sounder method is needed to obtain the channel parameters characteristic. The Sliding Correlator Channel Sounder is known as a popular technique with low complexity and relatively low cost. Similar to the sliding correlator, Software Define Radio (SDR) device is one of the popular inexpensive platforms for implementing the system into the real world. Implementation of the sliding correlator channel sounder technique in the SDR platform will increase the ionosphere channel measurement system's advantages as an effort to obtain the dynamic of ionospheric channel characteristics. However, to guarantee the designed system able to works according to the SDR device specifications and meet the system performance targets, the optimization should be done. This paper discusses the design of a sliding correlator channel sounder system to observe the characteristics of ionosphere channels using SDR with consideration to the limitation of the hardware specification and the system performance target based on the recommendation of ionospheric channel characteristics ITU-R F.1487. Simulation and over-the-air test from the design results show that the expected system performance can be met and realized in a real-world implementation.

1. Introduction

Channel characteristics information, for instance, Delay Spread (T_m) and Doppler Spread (F_b), is needed to design the digital communication system. The channel quality that varies over time, especially for the ionospheric channel, should be well studied to optimize the design for its digital communication system (Maslin, 1987). Ionospheric channel (High-Frequency propagation) is known for its high temporal and spatial variation such that a certain area at a certain time has specific channel characteristics (McNamara, 1991). Experimental papers suggest the need verification as well as correction for the ionospheric channel characterization for designing a digital communication system for a specific area (Hervás et al., 2015; Jodalen, Lundborg, & Jacobsen, 2000), though the International Telecommunication Union (ITU) already published the recommendation of the digital communication system for the ionospheric channel implemented on recommendation letter ITU-R Rec. F.1487 of the year 2000. This leads to the need for an ionospheric channel characteristic observation system used for observing the characteristics with a simple and inexpensive system whose one of the factors needed that will determine the success of optimizing a digital communication design specifically in the form of ionospheric channel.

The sliding correlator is a popular technique that is used for wireless digital channel sounder systems. This sliding correlator approach is known for its simplicity yet lower hardware implementation cost compare with Vector Network Analyzer(VNA) (Salous, 2013). Furthermore, the Software Defined Radio (SDR) platform nowadays is more accessible to hobbyists and radio engineers thanks to its flexibility and reusability when the hardware subsystem is implemented in the software domain as a result of the rapidly evolving capabilities of digital electronics. The SDR platform is a modest choice as a tool to design and test in a real-world scenario at a lower expense (Sruthi, Abirami, Manikkoth, Gandhiraj, & Soman, 2013). The sliding correlator channel sounder applied on the SDR platform will benefit the needs of the affordable of

ionospheric channel observation. However, the system implementation on the SDR should be balanced between the SDR limitation and the sounder's overall performance (Sinha, Verma, & Kumar, 2016; Vachhani, 2015).

The channel sounder on the SDR platform has been implemented (Kurniawati, Hendrantoro, & Taufik, 2018; Mukti et al., 2014; Samayoa, Kock, Blume, & Ostermann, 2018). However, there are rooms to be investigated further on the technical design and the system performance based on ITU recommendation for ionospheric channel estimation, especially when dealing with the hardware limitations on available SDR. This paper investigates the design choices of a sliding correlator for a channel sounder implemented on an SDR platform used for ionosphere channel observation. The design is done by calculating system parameters based on the specifications of the SDR hardware to achieve the target performance of the channel sounder system, which refers to ITU-R F.1487 of the characteristics of the ionosphere channel. HackRF One SDR device is used along with the GNU Radio Companion software to the system implementation. The calculation through simulation as well as hardware in the loop testing was also conducted. With already known hardware specification, parameters of a sliding correlator are chosen to push the hardware capability. The chirp frequency (f_{chirp}) and a number of bits *(L)* are chosen to calculate time delay resolution and the number of *Pseudo Noise (PN)* based on the *Dynamic range (DR)* of the SDR. These parameters were optimized during the simulation and further tested in controlled environment at the laboratory. As for details, this paper describes the theory of the sliding correlator chosen for the channel sounder system in the 2nd chapter. In 3rd chapter, the proposed of the design system are describes following the simulation and experiment method explanations. In chapter 4, the result of the simulation and experiment is revealed and discussed. Finally, in the last chapter of this paper we conclude the findings and the possibility for the next step plan or experiment to sharpen the findings.

2. Literature Review

The sliding correlator technique is the main idea of a digital channel sounder that transmits the electromagnetic radiation in a pulse shaped fashion found on common pulsed radar system (Cox, 1972). This technique's susceptibility from interference, relatively high peak power, and missing the phase-shift footprint of the multipath signal can be minimized by using a Digital Spread Spectrum (DSS) approach (Pereira, Postolache and Girao, 2009). Principally, the technique sends an array of a semi-randomly bit sequence or Pseudo Noise (PN) mixed with a wide-band carrier signal to the ionospheric channel. On the receiver ends, this mixed-signal is then correlated with the replica of the sequence from the transmitter side, where the signal is down-converted at a lower frequency. This approach results in amplitude and phase information of the multipath signal on a spread spectrum traces (Pirkl & Durgin).
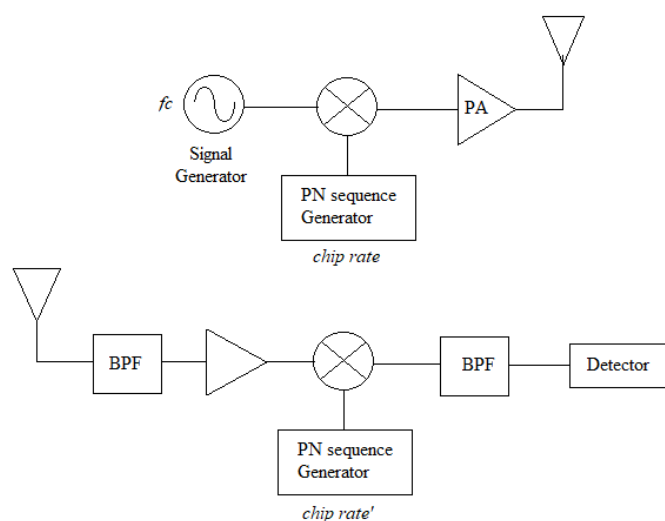

Figure 1. The sliding correlator channel sounder (Cox, 1972)

Figure 1 is a simplified diagram of a Sliding Correlator Channel Sounder. A sequence of bit PN is mixed with the carrier signal then is transmitted to the target channel to be observed. The received signals are calculated using the correlation function of the signal replica generated by the receiver, such that the time delay *(t_d)* value can be obtained as channel-specific parameters. Equation 1 is used for the cross-correlation process, resulting in a time delay *(t_d)* value.

$$R_{sr}(\Delta t, \tau) = E[s(t, \tau)r^*(t + \Delta t, \tau)] \dots\dots\dots 1)$$

Correlation value *(R_sr)* is where the received signal is correlated to transmitter signal replica, with *r* is the received signal as a function of time and delay, and *s* is a known transmitter signal replica. The R_{sr} value with the highest magnitude is an indicator of a strong correlation between signals in the time domain. The complex cross-correlation can be used to calculate the Power Spectral Density with complex Fourier as Equation 2, where the Fourier transform calculates the Doppler Shift of the received signals, with

$$S(f, \tau) = \int_{-\infty}^{\infty} R_{sr}(\Delta t, \tau)e^{-j2\pi f \Delta t}d\Delta t \dots\dots\dots 2)$$

Such that the performance of the sliding correlator i.e. the value of the maximum time delay (T_{max}) depends on the length of bit sequence and the chirp rate frequency (Eq. 3).

$$\tau_{max} = \frac{L}{f_{chirp}} \dots\dots\dots 3)$$

Whereas the channel performance i.e. Time Delay Resolution (T_{res}) depends on the chirp frequency value.

$$T_{res} = \frac{1}{f_{chirp}} \dots\dots\dots 4)$$

The sliding correlator's implementation uses the same or a lower clock frequency of the signal replica ($f_{chirp'}$) from the transmitter signal. The difference of the frequency is called *slide factor* (γ), which can be calculated from Equation 5.

$$\gamma = \frac{f_{chirp}}{f_{chirp} - f'_{chirp}} \dots\dots\dots 5)$$

Such that the value of the sliding factor γ determines the maximum of the Doppler Shift (f_{Dmax}), which can be expressed as

$$f_{D,max} = \frac{f_{chirp}}{2\gamma L} \dots\dots\dots 6)$$

With the value of *L*, f_{chirp} dan $f_{chirp'}$ for optimum performance of *channel sounder,* the value of *Dynamic Range* (DR) can be calculated by equation (7) as well as the *Gain Processing* (G_P) (8).

$$D_R \approx 16 \log_{10}(L) \dots\dots\dots 7)$$

$$G_p = 10\log_{10}\gamma \dots\dots\dots 8)$$

The DR and GP unit are decibel (*dB*) where the Dynamic Range (*DR*) value is the hardware specification or to be exact is the hardware limitation that should be considered when optimizing the system sensitivity as well as the Gain Process (*GP*) value that is used to calculate the link budget. To iterate the optimum parameter, the algorithm can be adopted in line with the optimum performance on specific hardware used (Pirkl & Durgin, 2008).

3. Research Method
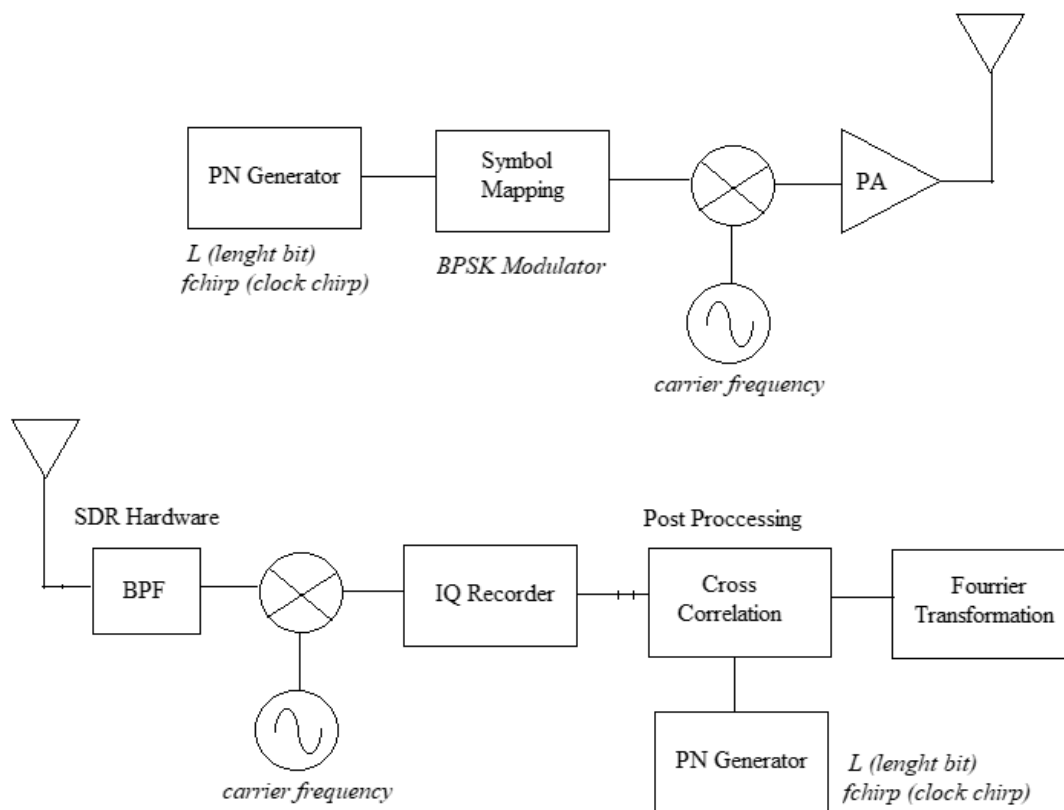
3.1. System Design

Figure 2. The proposed channel sounder sliding correlator

Figure 2 the proposed SDR-based channel sounder system. The target performances of the designed system are the resolution of maximum delay and the resolution of the Doppler shift, as shown in Table 1. Those values were based on the ITU-R F.1487 for the low latitude channel and at the worst channel condition.

Table 1. System performance target based on ITU R-Rec F.1478

System Parameter	Value
Doppler Shift resolution	1 Hz
Maximum Delay	10 milli second

The SDR device is HackRF One with the GNU Radio Companion as the software graphical user interface for simulation and control. Table 2 depicts the HackRF One specification for its internal hardware.

Table 2. The SDR technical specification

Parameter	Value
SDR Device	HackF one
Frequency spectrum	1 MHz to 6 GHz operating frequency
Bandwidth	up to 20 MHz
Power Output	50 mA at 3.3 V
ADC	8-bit quadrature samples (8-bit I and 8-bit Q)
Software	GNU Radio, SDR#, and more
Interface	Hi-Speed USB 2.0

Source: (Ossmann, 2016)

3.1.1.   Transmitter Implementation

Figure 3 shows the GNU Radio blocks to implement the transmitter system. It consists of a GLFSR Source block, Modulator Block (PSK Mode), Rational Resampler block, Multiply Constant, and a Sink block (Osmocom type). The GLFSR block is used to generate a Pseudo Noise (PN) bit sequence with a length of bit is L for one periodic sequence, with $L = 2^m - 1$. The PSK Modulator block maps the PN bit sequence symbols generated by the GLFSR block with the BPSK constellation. The Rational Resampler block fits the discreet signal's sample number as the Osmocom Sink block will output. The maximum sample number depends on the SDR digital to analog datasheet as well as the Multiply Constant block limits the amplitude to prevent the signal distortion when output to Osmocom Sink. The Osmocom Sink block itself plays as an interface to the transmitter antenna.
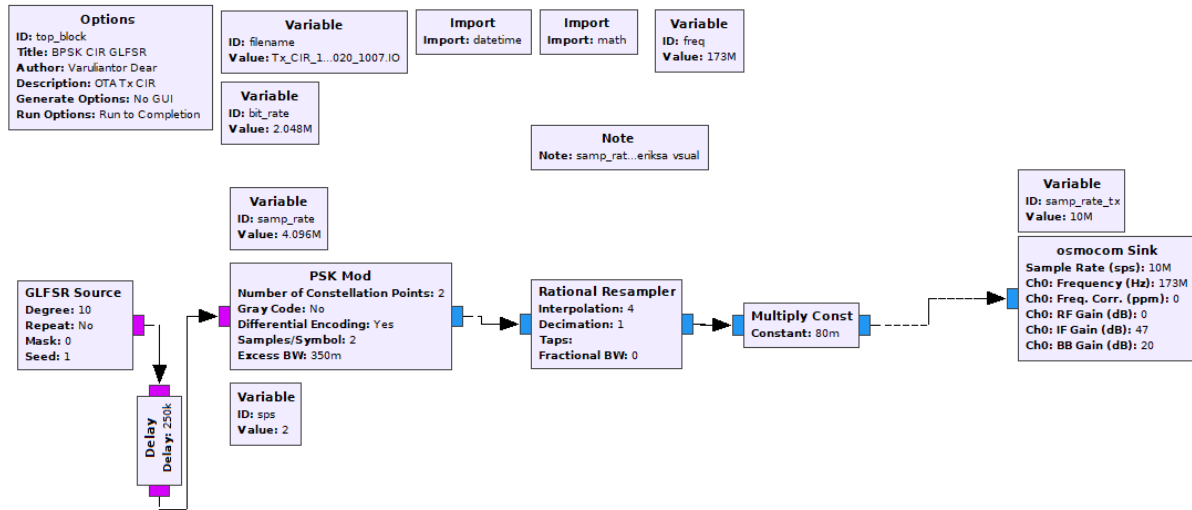

Figure 3. The transmitter implementation on GNU Radio (Dear, 2020)

To meet the pre-requirement of the design shown in Table 1, the chirp frequency and length of bit sequence L should first calculate. Beforehand, the time delay resolution value is chosen. The targeting maximum delay would be 10 milliseconds. The decision was to set the time delay resolution half of the maximum, which is 5 millisecond. Its results in the chirp frequency equal to 2 kHz, such that the length of bit sequence L can be calculated when refers to the Dynamic Range specification of the HackRF one SDR. Such that:

$$L_{max} = 10^{\left(\frac{DR}{16}\right)} \quad ....9)$$

with

$$DR = 20 \log_{10}(bit_{ADC}) \quad ....10)$$

The SDR peripheral has an 8-bit resolution (Table 2). Hence the maximum L value will be 1334 bit. However, note that the PN sequence is basically a shift register with modulo-2 fashion; hence the L value should be calculated as $L=2^m-1$. Practically a number of $L = 1023$ is then chosen. It leads to the calculation of time delay (Eq. 3) results in 5.12 millisecond, where this value is slightly higher than the actual target yet still acceptable. The chirp frequency (f_{chirp}) value depends on the hardware capability so that the bit rate value (R_b), sampling rate, and sample per symbol in the PSK modulator can be calculated (Eq. 11, Eq. 12, Eq. 13).

$$T_{chirp} = \frac{1}{f_{chirp}} \quad ....11)$$

Where T_{chirp} is the duration of the PN bit sequence. Based on (11), such that the bit period T_b calculated as

$$T_b = \frac{T_{chirp}}{N_{bit}}$$ ....12)

Based on (12) the bit rate is as follows

$$R_b = \frac{1}{Tb}$$ ....13)

By equation (12) and (13) value of L and the number of bit N, such the *bit rate* depends on f_{chirp} and L can be calculated (14).

$$R_b = L.f_{chirp}$$ ....14)

R_b is the *bit rate* and L is the length of *PN* bit sequence. For the value of R_b, finally, we can conclude that the sampling rate value on the SDR will be

$$Sampling\ Rate = sps.Rb$$ ....15)

with *sps* is the number of samples per symbol.
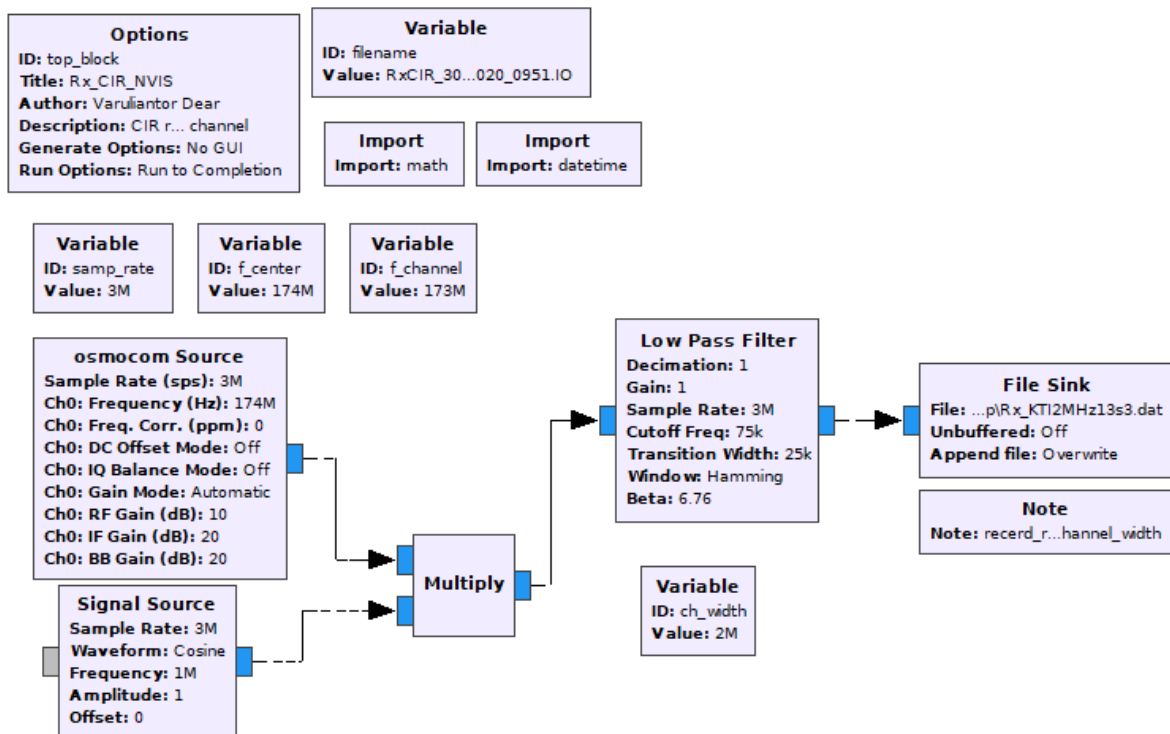
3.1.2   Receiver Implementation

Figure 4. Receiver implementation with GNU Radio software (Dear, 2020)

Figure 4 shows the GNU Radio blocks structure to implement a Receiver side. The Receiver consists of a Source block (Osmocom) being the Signal Source, Multiply block, Low Pass Filter block, and File Sink. The Osmocom and Signal Source block determine the mid-frequency in the assigned bandwidth as the SDR receive capability. The multiplication of the received signal and the signal generated from this source is a frequency translation process called heterodyne receiver to optimize the receive performance (Ossmann,

2016). For the experiment, the VHF frequency was used to test the design's laboratory scale, which is further explained in the 4th chapter.

The Multiply block outputs the signal at a certain bandwidth with a fixed sampling rate, which corresponds to the setting parameter on the Source block (Osmocom). Signal bandwidth should be fixed in order to ease the signal analysis at the baseband frequency at the lowest noise as possible, such that the LPF block is added to specifically restrict the lower frequency at 1 MHz bandwidth, and then the File Sink block records the output with *Decimation factorization* at 2 MHz sampling rate.

When it refers to equation 6, the Doppler Shift Resolution value depends on the γ value and the chirp frequency *(f_{chirp})*, which can be calculated in post processing method. However, the calculation of γ with a sense of f_{Dmax}, f_{chirp}, and length of *L* values can be expressed as:

$$\gamma = \frac{f_{chirp}}{2f_{Dmax}L} \quad\text{...16)}$$

Such that γ = 1 for *L* = 1024, f_{chirp} = 2000 Hz and f_{Dmax} = 0.9 Hz. Overall, the evaluation of the parameters both for the transmitter and the receiver side concludes the theoretical specification described in Table 3 whereas the maximum Time Delay value was still in the range of target specification, which is 10 milliseconds. On the other hand, the GP value should be evaluated on the run as a margin using the RF Power Amplifier and Low Noise Amplifier (LNA) in the system.

Table 3. Software define radio specification

Parameter	Nilai
Delay Resolution	5.10^{-4} second
Max Delay	0.512 second
Doppler resolution (γ =1)	0,9 Hz
DR	48 dB
GP (γ =1)	0 dB

Source: (Dear, 2020)

3.2. Simulation and Experiment of Transmitted Signal

3.2.1. Simulation

Figure 5 describes the simulation process, as the PN bit sequence with a length of *L* is generated by the PN Bit Generator at duration *(Tb)* of $2.94.10^5$ second refers to Equation 12. The bit sequence is then BPSK modulated and forwarded to a model that represents the multipath channel as in the real ionospheric channel. In this model, the signal experiences attenuation, multipath, and phase shift. The attenuation is modeled with the value of channel gain *(< 1)* as well as the multipath is modeled with two identical signals which have a random time of arrival with its arbitrary frequency shifts (BPSK mode). The models represent the activity of the ionospheric layer, which causes the variability of the channel. The velocity of the signal propagation can be derived from the Doppler frequency, where

$$I_{fs} = 1 \pm \frac{v}{c} \quad\text{...17)}$$

I_{fs} is the ratio coefficient of propagation velocity on the ionospheric channel *(v)* and propagation on free air *(c)*, 3.108 m/s. The ratio noted with negative or positive represents the frequency shift at a higher or lower side. The internal noise caused by the AWGN cable transmission is also taken into account. It adds overall SNR on the system that can be set on the Multipath block.
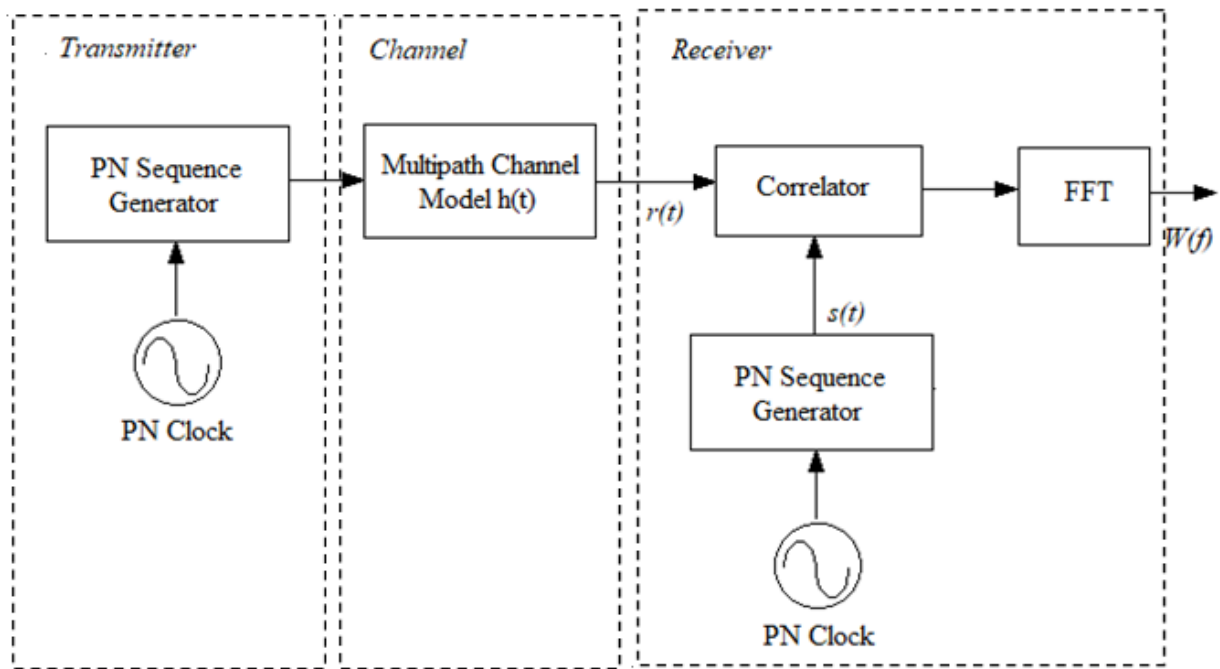
Figure 5. Simulation diagram block (Dear et. al, 2020)

The Correlator block calculates the correlation between the received signal and its replica on the transmitter side. Their cross-correlation basically is the time difference (lag) between them. When the 2 signals correlate with each other, it outputs the maximum peak correlation value. There will be two correlations in this experiment: the received signal from the ionospheric propagation channel (multipath block model) and the received signal from the free air propagation. Hence there are two peak values; with these peaks, the Doppler or the frequency shift can be calculated (Equation 2).

3.2.2. Signal Transmission Experiment
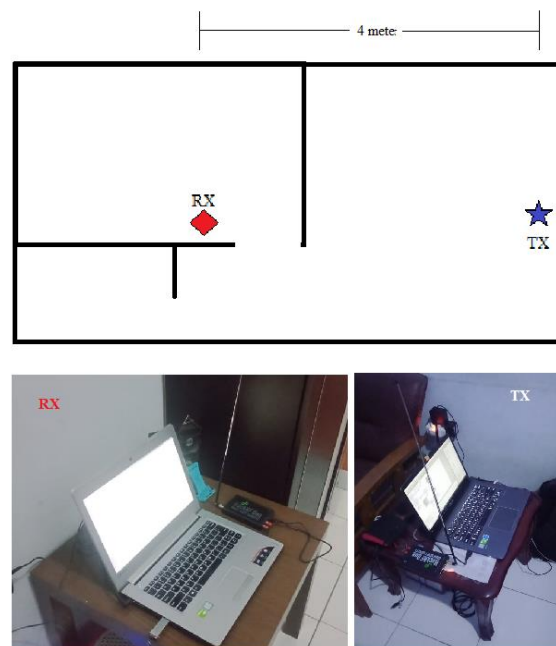
Figure 6. The Experiment layout and devices

The experiment layout can be seen in Figure 6. This set up is needed to demonstrate the implemented calculation and design system works as intended. To simplify the system experiment, the VHF frequencies were used with a smaller antenna dimension rather than real HF frequency, making it difficult to deploy such an antenna in a limited area. Note that no RF power amplifier was used in the experiment so that maximum RF power is around 1mW.

Table 4. The system specification for experiment

Paramater	Value
Transmitter	Hack RF One
Carrier Frequency	173 MHz
Sampling rate RF	10 Msps
Bit Rate	2048000 bit/sec
Antenna	Telescopic Monopole
Power	1 mW
Receiver	Hack RF One
Bandwith RF	3 MHz
Sampling rate RF	3 Msps
Samping Rate File Sink	2 Msps
Antenna	Telescopic Monopole
Post Processing Software	MATLAB
Sampling rate signal	2 MHz
FFT size (N_{FFT})	4096

To represent the characteristics of a multipath channel, two signals were transmitted manually. The time difference between the two signals was used to validate the time delay value of the cross-correlation process. The Doppler shift calculation is then derived from the output of the cross-correlation step. This correlation and Fourier transformation step were post-processed with MATLAB Software. Table 4 shows the system specifications in the experiment.

4. Result and Discussion

4.1. Simulation

The signal transmission and the received signal can be seen in Figure 7. The transmitted signal is a BPSK modulated frequency from the PN Generator and the received signal is a mix of 2 signals with different trajectories and random time of arrival. The received signal was attenuated and contained with transmission line noise (AWGN Noise).
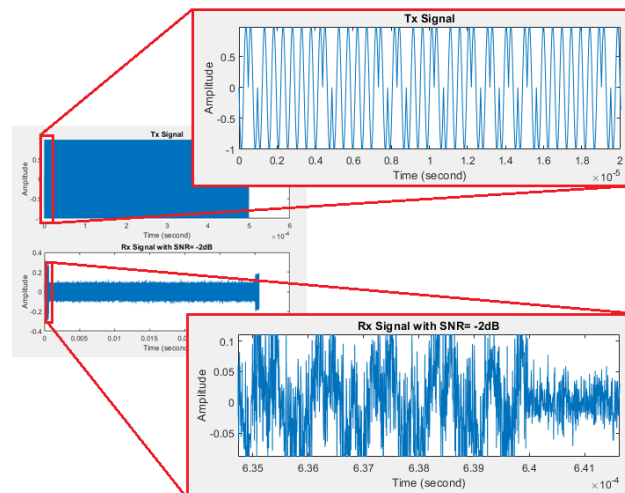

Figure 7. Signals plot of the transmitted and received from simulation

To emulate an asynchronous communication system, both the transmitted and received signals have different time duration and the receiver section was activated first before the transmission. The recording was extended to a certain duration to capture all the multipath signals (mimics real ionospheric channel). Figure 8 describes the correlation output of signals, as can be seen that there are 2 peaks of correlation values from the normalized amplitude of signals. The first peak shows the correlation at time of a 99.25 μs, whereas the second peak shows the correlation at 3.016 ms. The time difference between the two peaks is a Delay Shift value, which is 2.916 ms. The value represents the characteristic information of the channel investigated using the sliding correlator channel sounder.
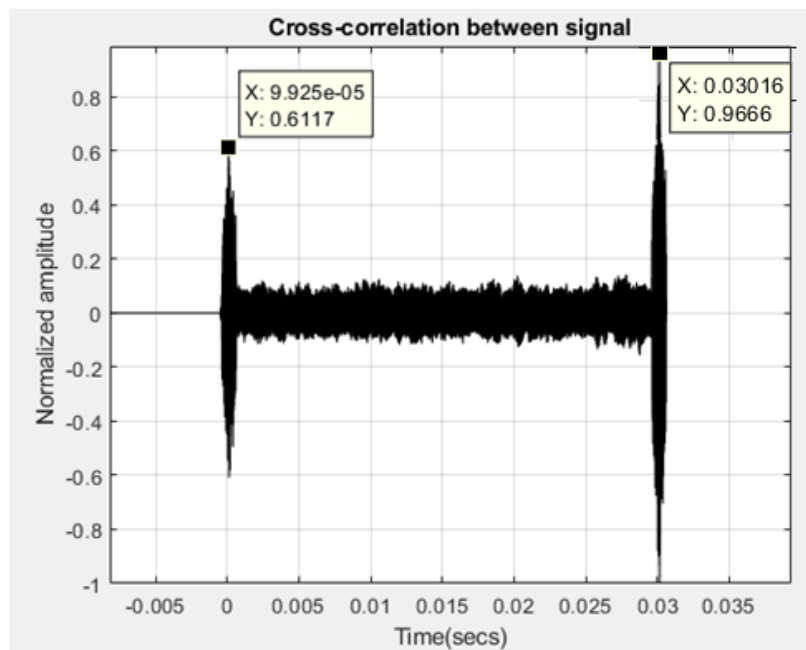
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Figure 8. Cross-correlation of the received signal and the PN signal replica

Table 5 presents the results of the experiment for various SNR values from -15dB to 0dB. The time difference between the first and the second peak is the time Delay Shift occurs in the channel. The results in Table 5 show that the time Delay Shift varies from 10 ms to 30 ms. This concludes that the parameters used for the sounder experiment are suitable for achieving the expected time Delay value.

Table 5. Cross-correlation result at varying SNR

SNR (dB)	Impulse 1 (second)	Impulse 2 (second)	Delay shift (second)
-15	0,000702	0,0107	0,009998
-14	0,000703	0,0307	0,029997
-13	0,000703	0,0307	0,029997
-12	0,000502	0,0205	0,019998
-11	0,000301	0,03029	0,029989
-10	0,000105	0,0201	0,019995
-9	0,0009	0,0209	0,02
-8	0,0006	0,03057	0,02997
-7	0,000101	0,0101	0,009999
-6	0,0007	0,0107	0,01
-5	0,000598	0,0206	0,020002
-4	0,000499	0,0205	0,020001
-3	0,000487	0,03049	0,030003
-2	0,000698	0,02067	0,019972
-1	0,00034	0,03029	0,02995
0	0,0006	0,0106	0,01

Furthermore, Figure 9 shows the Fourier transform of the correlated signals as a function of Power Spectral Density (PSD). It can be seen that the highest magnitude lies at frequency 1.699840 MHz. The transmitted signal frequency was 2.048 MHz; hence the frequency difference is 348.160 kHz, which denotes the frequency shifts value or the Doppler Shift parameter in the channel. This implies that the implemented parameters in the designed channel sounder are suitable for achieving the expected channel characteristic.
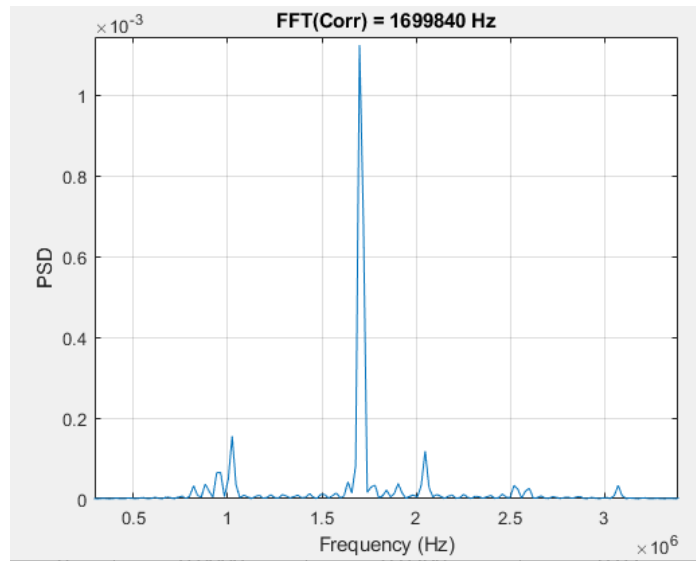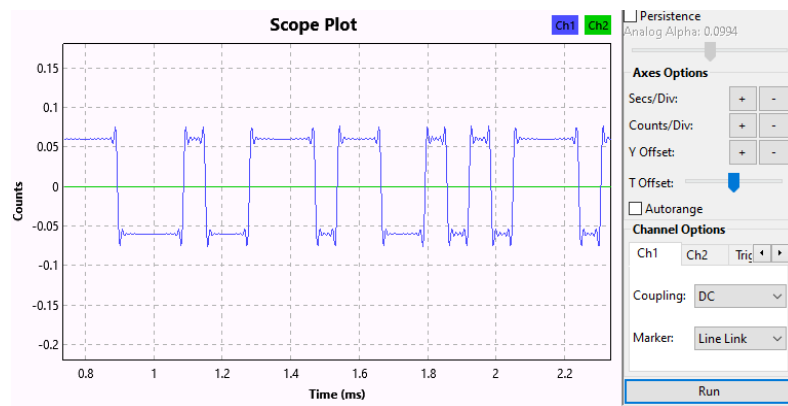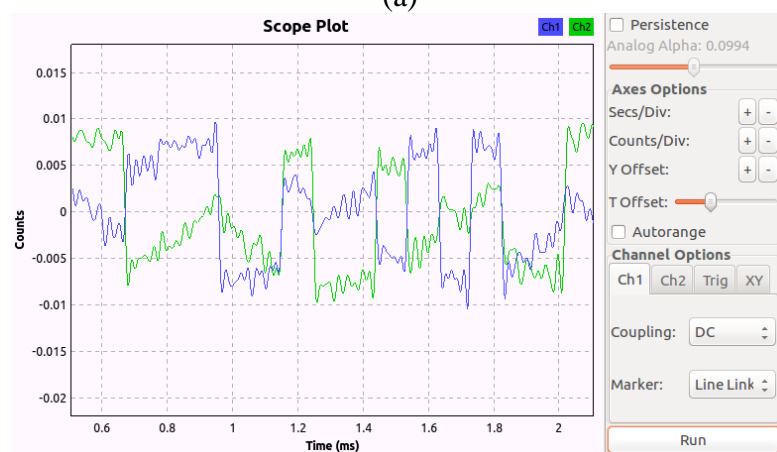

Figure 9. The simulated power spectral density

4.2. The Signal Transmission Experiment

(a)

(b)

Figure 10. GNU radio scope plot (a) Transmitted signal, and (b) Received signal

Figure 10 shows the capture of the transmitted signal and the received signal on the Scope plot block. The first plot (Figure 10 a.) is a pick out of a short duration of one signal transmission. In the experiment this signal was transmitted twice for the validation process when calculating the time delay of system design. The second plot (Figure 10 b.) is the In-Phase and Quadrature signal captured by the receiver.

Figure 11 shows the cross-correlation between signals where their first peak lies at 1.295 seconds, whereas the second peak is at 2.712 seconds; hence the time gap between the two signals is 1.5 second. This time gap is the confirmation of the time difference between two signals manually transmitted in the experiment. Each signal transmission was triggered manually such that the delay of around a second is reasonable.
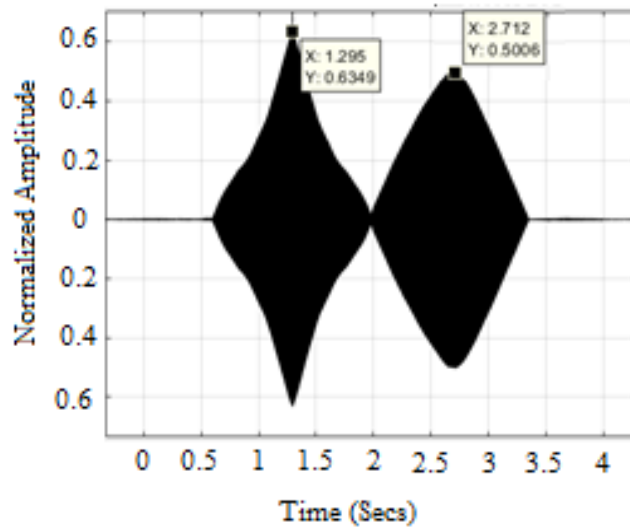

Figure 11. The cross-correlation of transmitted signal and received PN signal

Figure 12 depicts the Fourier transform of the correlated signal between transmitted and received signal as can be seen from the figure. The highest magnitude is at the frequency 2.048 MHz, the exact baseband frequency of the transmitted signal. This experiment shows zero frequency shift or zero Doppler shift since both transmitter and receiver are fixed and the channel used in the experiment is static. The experiment result concludes the design of the sliding correlator sounder is working as expected. However, further experiments should be done, especially the experiment in HF frequency for the real ionospheric channel.
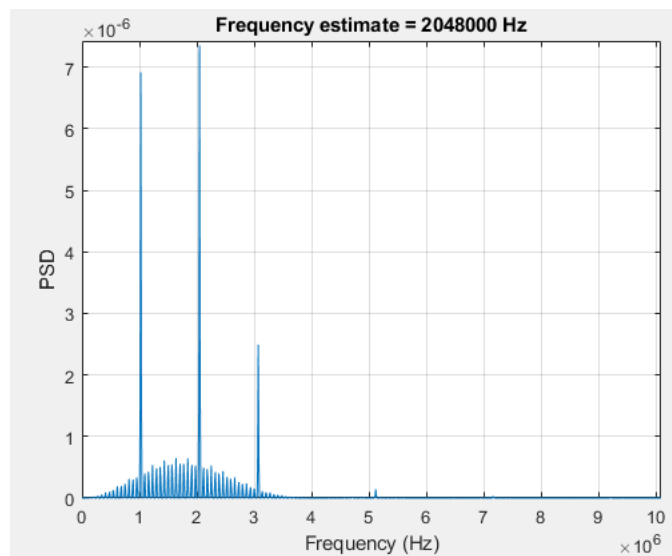

Figure 12. Power Spectral Density Calculation

5. Conclusion

The Design of the sliding correlator of channel sounder based on the SDR to measure the ionospheric channel was done by adjusting and compromising both the hardware specification and the achievable system performance. Firstly, the channel's time delay resolution should be stated from the known Dynamic Range value of the SDR hardware. Secondly, the chosen time delay resolution value should refer to the ITU channel recommendation (ITU-R F.1487) that was used to calculate f_{chirp} with equations 5 and 6. Thirdly, since the Dynamic Range is determined solely by the ADC resolution on the SDR, it implies that the parameter of maximum bit sequence (L) of PN codes should be calculated (equation 7 and 8). The simulation result shows that the performance of the designed channel sounder system is able to meet the expected system performance, which is Maximum Delay is 0.5 second and Doppler resolution is 0.9 Hz. Those values are better than the target performance system, which are 10 milliseconds for a maximum time delay and 1 Hz for Doppler resolution. The signal transmission experiment shows that the designed system can be implemented in real conditions. These results can be further improved with HF channel measurement with RF Power Amplifier implementation such that the Gain Processing is upscaled based on the designed system. In addition, the consideration of choosing the location of the transmitting and receiving stations needs to be studied properly to ensure that the propagation between stations is only a skywave propagation.

6. Acknowledgment

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