DETECTION OF AIRCRAFT FROM YOUR HOME

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ABSTRACT

The low cost and wide availability of software defined radios (SDRs) has made the detection of aircraft easily available to anyone. This project evaluated the performance of 3 SDRs, the SDRPlay, AIRSPY and RTL-SDR, at detecting aircraft by receiving and decoding aircraft ADS-B transmissions to obtain positional data and other information about specific aircraft. SDR performance factors such as signal-to-noise ratio, dynamic range, DC offset and 1/f noise were investigated for each of the SDRs. The SDRs were used to receive the ADS-B transmissions from aircraft in the area and ADS-B decoder software was used to decode the ADS-B signals to get the position of the aircraft which was then plotted onto a map using a plotter program. It was found that the AIRSPY had the best aircraft detection performance by being able to detect all the aircraft nearby and also being able to detect aircraft up to 171 km away.

INTRODUCTION

The rapid development and increasing availability of software defined radios (SDRs) in the recent years has led to their increasing use by the public for more advanced uses such as HAM radio, radio astronomy, spectrum surveillance and aircraft detection.

Aircraft detection using an SDR can be implemented either through a passive radar setup or receiving radio signals transmitted by equipment on board an aircraft. Passive radar involves measuring the reflection of radio signals that are already in the air off targets and comparing them to the original signal to derive information such as a target’s speed and range. Direct reception of radio signals transmitted by the aircraft is more straightforward and involves an SDR tuned to receive the frequency of the transmission of interest and possibly some software to decode the information contained in the signal.

Modern commercial aircraft carry a wide array of radio transmitting equipment on board for a variety of purposes ranging from navigational aids to flight safety. Some of these equipment that transmit radio signals include weather radar, radio altimeters, VHF communications, Traffic Collision Avoidance System (TCAS) transponder and Automatic Dependent Surveillance Broadcast (ADS-B) transponder. While the radio signals from all these transmission equipment can be received using an SDR, the broadcast signals from the ADS-B transponder of an aircraft are of particular interest for those interested in detecting aircraft using an SDR.

BACKGROUND INFORMATION

Automatic Dependent Surveillance Broadcast

The automatic dependent surveillance broadcast (ADS-B) system is a secondary radar system where a transponder on the aircraft communicates with a receiver on the ground. This is different from a primary radar system where both the transmitter and receiver are on the
ground and detects the reflection of radio waves off an aircraft. ADS-B has a much longer operational range than primary radar systems and is particularly useful when an aircraft is flying outside the operational range of primary radar systems.

ADS-B consists of a base station on the ground and a transponder on an aircraft. The transponder on the aircraft is connected to sensors on the aircraft such as the GPS, airspeed sensors and altimeters.

The ADS-B transponder on the aircraft periodically sends out ADS-B broadcasts at a frequency of 1090MHz every second or so. Each broadcast is made of an ADS-B packet that contains information about the aircraft such as its position in latitude and longitude, altitude, heading and speed. The aircraft will also transmit a 24 bit identification number that is unique to each aircraft. This ID number is used to identify the flight and individual aircraft [1].

ADS-B transponders on commercial aircraft are also capable of transmitting Mode S signals. Mode S is a form of secondary surveillance radar that involves two-way communication between a transponder on board an aircraft and a base station on the ground. The base will station send an interrogation ping at a frequency of 1030 MHz consisting of one 8uS long pulse followed by a 21uS long pulse. When the aircraft’s transponder receives this interrogation ping, it will respond by transmitting a data packet containing information about its current altitude and an ID number at a frequency of 1090 MHz. Unlike ADS-B, Mode S transponders do not transmit continuously but instead wait for an interrogation ping. In addition, Mode S only transmits the aircraft’s altitude while ADS-B also transmits information about the aircraft’s position.

Software Defined Radio

A software defined radio (SDR) is a device that plugs into a computer and enables it to receive radio signals. While there are many different SDRs available on the market, their general design is similar.

![SDR Block Diagram](image)

Figure 1: SDR Block Diagram [2]

Figure 1 shows a block diagram of an SDR. The radio signal is received by an antenna and passed to a band-pass filter which is set to let only a certain range of frequencies through. An SDR usually has a few hardware band-pass filters that can be selected to cater to different ranges of frequencies. The filters are software-selectable depending on the frequency or frequencies of interest. The signal from the filter is then passed to the gain stage to amplify it. The gain stage normally consists of a low-noise amplifier (LNA) to boost the incoming signal while minimising the addition of noise. This allows weaker signals to be detected by the SDR.
Some SDRs have a limiter before the gain stage to limit the power of the input signal. This is to prevent the LNA from being overloaded if the input signal is too strong, which will result in spurious signals being introduced into the signal. On some SDRs, the gain of the LNA can be manually controlled while others use automatic gain control to set the gain of the LNA. The amplified signal is passed to the mixer where it is combined with the signal from the local oscillator tuned to the target frequency. This produces an Intermediate Frequency (IF) which goes to the analog-digital-converter (ADC) that converts the continuous analog signal into discrete digital levels. The digital signal is sent to the computer as the In-phase and Quadrature components of the received waveform [3].

**Software**

An SDR is controlled using a computer running appropriate interface software. While there are many free programs available to control SDRs, the software SDR# is the most popular and widely used. SDR# [4] supports multiple SDRs like the RTL-SDR, AIRSPY, HackRF and SDRPlay and also accepts input from the computer’s sound card. SDR# displays the frequency domain power spectrum of the signals received and a waterfall diagram showing the short history of the intensity of the various signals received. SDR# provides a few common demodulation techniques such as narrow and wideband FM and AM. Various SDR settings like LNA gain, IF frequency and bandwidth can be controlled using SDR#. SDR# also provides a recording function that enables received signals to be recorded as a .WAV file.

**PROJECT AIM**

The aim of this project is to compare the performance of the SDRPlay, AIRSPY and RTL-SDR at receiving the ADS-B transmissions from aircraft to find out which is the best receiver to use for the detection of aircraft from home.

**METHODOLOGY**

The SDRs tested are the SDRPlay, AIRSPY and RTL-SDR. Each SDR is connected to an antenna tuned to 1280 MHz and placed at a window with direct line-of-sight to aircrafts taking off and landing at Changi International Airport. The SDR under test is connected to a computer and tuned to the ADS-B transmission frequency of 1090 MHz. The received signals are viewed using SDR# and evaluated for any noise or spurious signals.

An ADS-B decoder program is utilised to decode and extract information about an aircraft’s position, speed, altitude and identity from the received ADS-B signals. The information output from the decoder is sent to a plotter program that displays the position of aircraft detected onto a map of the relevant region. The plotter program used is a free software called ADSBScope [5]. As there is no universal ADS-B decoder program that is compatible with all the SDRs being tested, a different decoder program, is used for each of the SDRs. The outputs however, are compatible with ADSBScope.
The performance of an SDR as an aircraft detector can be measured by its range and how many aircrafts it is able to detect. As a comparison, data is taken from the website flightradar24.com and compared to the ADS-B data received by the SDR. Flightradar24.com displays the number of planes in an area and their location on a map of the region in almost real time using flight data collected from ADS-B transmissions from aircraft. Additionally, it utilises a network of multiple receivers to perform multilateration based upon the time-difference of arrival of Mode S signal at various receivers to localize aircraft such as military planes which do not transmit ADS-B but other modes like A, C or S which helps to give viewers a more accurate picture of all the aircraft that are in the area. Comparing the aircraft detected using the SDR and those displayed on flightradar24, the performance of the SDR can be measured based on its range and number of aircraft detected. Care was taken to ensure that the aircraft shown on flightradar24 used for comparison were detected using their ADS-B transmissions as indicated by the designation WSSS-1 under the radar type used to detect them rather than T-MLAT which indicates that the aircraft was detected by multilateration of their Mode S signals.

**SDR PERFORMANCE**

**SDRPlay**

The SDRPlay is a SDR utilising the Mirics MSI3101 SDR chip which comprises of the MSI001 tuner and MSI2500 ADC and USB Bridge. It has a frequency coverage from 0.1MHz to 2GHz and a dynamic range of 67dB along with a 12-bit ADC [6]. The SDRPlay comes in a plastic housing which helps to insulate the circuits from sudden ambient temperature changes which may impair the performance of the on board oscillator. However, the plastic casing does not provide good shielding against external RF interference and noise.

The image below shows the output from the SDRPlay when it is tuned to the ADS-B frequency of 1090 MHz using SDR#.
From figure 3, it can be seen that the noise floor is elevated around the center of the tuned frequency range from around -75dBFS at the edges to around -37dBFS near the center. This indicates that the SDRPlay suffers from elevated noise levels near the center of its tuned frequency range, leading to a poor signal-to-noise ratio (SNR) when tuned to frequencies near the center of the tuned range. The sharp peak at the center of the tuned range shows that the SDRPlay suffers from the classic SDR problem of DC offset, characterised by a persistent peak exactly at the center of the tuned frequency range regardless of what the frequency the SDR is tuned to [7].

As received ADS-B signals are relatively weak, setting the ADS-B frequency of 1090MHz at the centre of the SDRPlay’s tuned range will result in some if not most of the ADS-B signals being lost due to the poor SNR of the region around the center of the tuned frequency range. Thus the SDRPlay is tuned in such way that 1090MHz is nearer the ends of its tuned frequency range where the noise floor is much lower, enabling weak ADS-B signals highlighted by the red box in figure 3 to be picked up over the background noise. The ADS-B signals show up as faint white dashes against the deep blue background.

Due to the unavailability of an ADS-B signal decoder for the SDRPlay, the ADS-B signals received by the SDRPlay were unable to be decoded and displayed on ADSBScope.

**AIRSPY**

The AIRSPY is an SDR based on the R820T2 tuner chip and a Cortex M4F processor. It has a frequency range from 24-1800MHz and a large dynamic range of 80dB [8]. The AIRSPY comes in a metal casing which provides better shielding from external sources of interference or noise as compared to the SDRPlay and RTL-SDR which both have plastic cases. The AIRSPY also has a bias-tee to power active antennas and external LNAs that can be switched on or off via software control.

The image below shows the output from the AIRSPY when it is tuned to the ADS-B frequency of 1090 MHz using SDR#. 
From figure 4 it can be seen that the AIRSPY has a noise floor of around -78dBFS. This noise floor is more or less consistent throughout the entire bandwidth that it is tuned to and there is no spurious noise or overloading. It can also be observed that there is an absence of any DC offset at the center of the tuned range as there is no sharp peak at the center of the tuned range of frequencies shown in the image. There is also a lack of 1/f noise in the AIRSPY’s output as seen by the absence of a sloping peak region in the center of the tuned frequency range and described on the AIRSPY website [9]. The received ADS-B signals appear as small white dashes highlighted by the red box in figure 4. The AIRSPY has a good signal-to-noise ratio as highlighted by the ADS-B signals showing up clearly as white lines contrasted against a deep blue background.

The ADS-B decoder software for the AIRSPY is called ADSBSpy and comes together with the SDR# software. Running ADSBSpy together with ADSBScope gives the following image of the detected planes in the area.

As shown in figure 5, the AIRSPY has received ADS-B transmissions from 3 different planes highlighted by the coloured boxes.
A screen capture of flightradar24 taken a while later (figure 6) shows the corresponding aircraft having moved some distance along their flight path. The same aircraft are denoted by the same colour across figure 5 and 6. The aircraft in the red, green and orange coloured boxes are aircraft whose ADS-B transmissions have been detected by the AIRSPY and information from flightradar24 show that they were all airborne.

There is an additional group of aircraft, highlighted in the yellow box, shown by flightradar24, that the AIRSPY did not detect. Data from flightradar24 shows that these aircraft were on the ground. It is likely that the AIRSPY was unable to receive the ADS-B signal from these aircraft as there was no clear line of sight between them and the AIRSPY due to the aircraft being on the ground.

After running the AIRSPY together with the ADS-B decoder for an extended period of time, it was observed that the maximum range at which the AIRSPY could receive the ADS-B signal from an aircraft was 171km. It was also noticed that the AIRSPY seemed to only be able to detect aircraft toward the east and southeast of the airport. This directional sensitivity could be attributed to the placement of the antenna at the south-eastern part of Singapore near the southern end of the airport. This would result in the antenna only having a clear-line-of-sight of aircraft in the east and south-east directions. Low-flying aircraft taking off or coming in to land towards the north would have tall buildings in the way that would block the ADS-B signal from the AIRSPY’s antenna, thus reducing the chance of the AIRSPY detecting them. However, if aircraft north of the airport were flying high enough, the ADS-B signal would not be obscured by any buildings and the AIRSPY would be able to receive it. For example, during the extended test period, the AIRSPY was able to detect and receive the ADS-B transmissions from aircraft flying at 15000 feet over Malaysia even up to the town of Kluang which is approximately 130km from the location of the antenna.

**RTL-SDR**

The RTL-SDR dongle is a very popular low-cost SDR based on the RTL2832U DVB-T and COFDM demodulator chip and either the R820T2 or the less common E4000 tuner chip. The dongles with the R820T2 chip have a frequency range of 24-1766MHz and a dynamic range of around 45dB [10], much less than the SDRPlay and the AIRSPY. Unlike the other 2 SDRs which have a 12-bit ADC, the ADC inside the RTL-SDR is only 8-bits [11]. This results in it having a much lower precision in sampling the input signal. The RTL-SDR comes in a plastic case with no shielding over the RF sections of the circuit board. This lack of shielding causes
it to be more susceptible to picking up interference and noise from the surroundings as the unshielded PCB traces can act as tiny antennas that can pick up stray signals in the air. The image below shows the output from the RTL-SDR when it is tuned to the ADS-B frequency of 1090 MHz using SDR#.

![RTL-SDR output at 1090MHz](image)

**Figure 7: RTL-SDR output at 1090MHz**

From figure 7, the absence of a sharp peak and elevated noise floor at the center of the tuned frequency range highlights that the RTL-SDR does not suffer from problems of DC offset and 1/f noise. However, the noise floor of the RTL-SDR is around -47dbFS which is much higher than the noise floor of the SDRPlay and AIRSPY. Furthermore, the intensity plot for the waterfall diagram is yellow for the noise as compared to the deep blue colour for the noise floors of the other 2 SDRs. The higher noise floor will drown out weaker signals that have a power below that of the noise floor. This will affect its ability to detect aircraft that are far away as the ADS-B transmissions would be rather weak by the time they are picked up by the RTL-SDR. The ADS-B signals show up on the waterfall diagram in figure 7 as faint red lines highlighted by the red box against the yellow background. The elevated noise floor has resulted in a much lower SNR than the other 2 SDRs which impedes the RTL-SDR’s ability to pick up ADS-B signals from aircraft that are far away as it is unable to distinguish the very weak signals from background noise.

The ADS-B decoder software for the RTL-SDR is called RTL1090 which can be downloaded separately from SDR# free of charge. Running RTL1090 together with ADSBScope gives the following image of the detected planes in the area.

![ADSBScope output using RTL-SDR as receiver](image)

**Figure 8: ADSBScope output using RTL-SDR as receiver**
From figure 8, it can be seen that the RTL-SDR has detected two aircraft in the air highlighted by the coloured boxes. It has also detected the ADS-B transmissions from a few aircraft that are on the ground below the aircraft in the orange box. As they are on the ground, ADSBScope marks them with a dot rather than a plane icon on the map. A screen capture of flightradar24 taken at the same time as the ADSBScope readings shows all the aircraft in the area.

![Figure 9: flightradar24 showing all the aircraft in the area](image)

The aircraft are highlighted in figure 9 by coloured boxes. The aircraft in the green and orange coloured boxes are aircraft whose ADS-B transmissions have been detected by the RTL-SDR. The colour of the boxes shows corresponding aircraft across figure 8 and 9. The individual flight details from flightradar24 show that the 2 aircraft detected by the RTL-SDR were all airborne. The group of stationary aircraft detected by the RTL-SDR are shown as a small yellow cluster of plane icons below the aircraft highlighted by the orange box. In addition, the 2 aircraft highlighted in red boxes in figure 9 were airborne aircraft displayed on flightradar24 which did not show up on ADSBScope, indicating that their ADS-B transmissions were not received by the RTL-SDR.

After running the RTL-SDR with the ADS-B decoder for an extended period of time, the maximum range at which it could receive the ADS-B transmissions form aircraft was found to be 112km towards the southeast. The RTL-SDR was generally better able to detect aircraft towards the East and Southeast. This is due to the position of the antenna at the southeast side of Singapore, providing line-of-sight view towards the east and southeast. Towards the north, there were tall buildings which blocked the ADS-B signal from aircraft at the north and combined with the higher noise floor of the RTL-SDR drowning out the very weak ADS-B signals, resulted in the RTL-SDR being unable to detect those aircraft.

**LIMITATIONS AND IMPROVEMENTS**

One limitation is the location of the receiver’s antenna. There were tall buildings towards the North and West of the antenna which blocked signals coming from these directions. This limited the ability of the SDRs to detect aircraft in these directions as their ADS-B transmissions were blocked by the buildings. This problem can be solved by placing the antenna at a tall and unobstructed place, possibly a hill top or a building’s roof to enable it to have a clear 360 degree of the sky.
Due to a limitation in resources, the data for the different SDRs was collected at different times. This number of aircraft in the sky was not kept constant and this could have affected the performance of the SDRs. A much better way would have been to run the different SDRs together on different computers to simultaneously collect data. This would ensure a fairer comparison of their performance.

CONCLUSION

In conclusion, the performance of 3 SDRs at receiving the ADS-B transmissions of aircraft was evaluated. Of the 3 SDRs only AIRPSY and RTL-SDR could actually be used together with a decoder to display the position of aircraft on a map.

It was found that the maximum detection range of the AIRSPY was 171km while the RTL-SDR had a maximum range of 112km. The AIRSPY was also able to detect all the airborne aircraft in the area while the RTL-SDR failed to detect 2 out of a total of 4 aircraft that were airborne. However, the RTL-SDR was able to detect a few aircraft that were on the ground while the AIRPSY was unable to do so.

Thus it can be concluded that for the purpose of detecting airborne aircraft by receiving their ADS-B transmissions, using the AIRSPY is a much better choice.

FUTURE WORKS

As of the time of writing, there is no freely available ADS-B decoder program for the SDRPlay. An ADS-B decoder program could be written for the SDRPlay using a programming language like Python to enable the evaluation of the performance of the SDRPlay’s performance for detecting aircraft.

This research project only investigated the performance of 3 SDRs at detecting aircraft. To make the study more comprehensive, the performance of more SDRs could be tested. Some SDRs that could potentially be tested include the BladeRf, HackRF Blue and the USRP. These SDRs can be tuned to higher maximum frequencies than the SDRPlay, AIRSPY and RTL-SDR and it will be of great interest to investigate the effect that a larger operational frequency range will have on their ability to receive ADS-B signals from aircraft. They also have different implementation schemes for the band-pass filter stage which may affect their reception performance.

Apart from receiving and decoding ADS-B signals to derive an aircraft’s position, another method of detecting aircraft that can be explored would be to use multilateration based on receiving the Mode S signals from an aircraft like the alternative aircraft detection method used by flightradar24. This would involve the use of several receivers in several locations that are kilometres apart and time synchronised perhaps to the GPS satellite clock. The time-difference-of-arrival of the Mode S signals at the various receivers can be used to triangulate the position of the aircraft. An advantage that this system has over ADS-B is that it can be used to correctly detect military aircraft which do not broadcast ADS-B signals but do transmit pings on the same frequency as Mode S and aircraft that are transmitting false position information in their ADS-B packets.

Passive radar can also be investigated as a means of detecting aircraft. Passive radar works by receiving the reflections of radio signals that are already in the air off targets such as aircraft
to derive their position and speed. As passive radar does not rely on an aircraft transmitting signals, it is capable of detecting aircraft that are not operating any active transponders. However, as a passive radar system relies on transmitters that cannot be controlled, there are many challenges to extracting reflected radio signals off targets from other unwanted signals such as direct path interference and ground clutter reflections.

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