Development of a Terrestrial-Based ADS-B Receiver Using a Novel Software Defined Radio Platform

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***Abstract*—In recent years, ADS-B (Automatic Dependent Surveillance-Broadcast) has become a new air traffic surveillance technology. The aircraft identifies it position using satellite navigation and transmits it on a regular basis, allowing it to be tracked. This technology is utilized to enhance a variety of aspects for both pilots and air traffic controllers, such as collision avoidance and situational awareness. To reduce the complexity and value of the ADS-B system installation, the system is developed with the help of Software Defined Radio. This wireless communication technology is used to increase flexibility and improve the performance of the system. This project is about developing a Terrestrial-based ADS-B receiver utilizing a novel highly integrated SDR platform, particularly the Totem Motherboard SDR, and GNU Radio as a software development framework. The ultimate goal of this work is to validate the efficiency of the developed Ground-based ADS-B receiver as the first step for designing a Nanosatellite's SDR payload that acts as a receiver of ADS-B messages transmitted by the aircraft using Totem SDR from Alèn Space as an SDR platform.**

***Index Terms*—SDR, ADS-B, ATC, Totem SDR, GNU Radio**

I. Introduction

The necessity of safety in the aviation world cannot be negligent. This factor is strongly linked to the role of Air Traffic Control (ATC) in operating navigation systems and facilities for tracking aircraft positions, such as using Primary Surveillance Radar (PSR) technology. However, increasing air traffic each year creates new challenges for Air Traffic Control (ATC) in monitoring air traffic. Then, the quality of ATC services must be enhanced.

The Federal Aviation Administration (FAA) created the NextGen technology known as Automatic Dependent Surveillance Broadcast (ADS-B) [1]. It is a surveillance technology used on aircraft for air traffic control that uses GPS and satellites and is more efficient and cost-effective than traditional radar at airports. ADS-B operates by receiving ADS-B messages transmitted by aircraft at a frequency of 1090MHz. However, not all the Earth's surface is currently covered by ADS-B and RADAR detection. The placement of Ground Stations, which cannot be installed in the middle of the ocean or in remote areas, limits ADS-B and RADAR coverage. To address this issue, one potential solution is to use satellite communication [1].

Figure 9 illustrates how PSR works by emitting RF pulses, which are reflected back to radar if they strike the surface of an object (aircraft). The radar will use the reflection time to determine the object's distance.

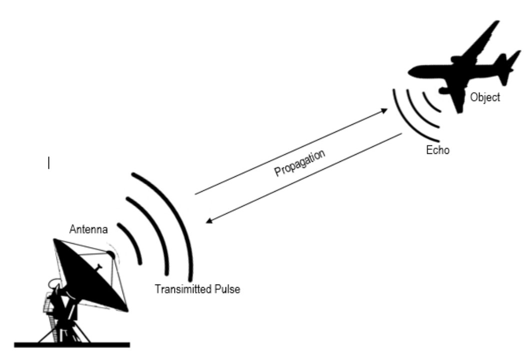

Fig. 1. Primary Surveillance Radar (PSR)

Based on previous studies, Terrestrial-based ADS-B receivers are increasingly deployed, but the coverage is limited to a few kilometers. Therefore, space-based surveillance will provide enhanced Air Traffic Services and global coverage.

In [1], The author implements a prototype design for a nanosatellite that acts as a receiver of ADS-B messages transmitted by aircraft at a working frequency of 1090MHz, with RTL-SDR RTL2832U as the receiver and Raspberry Pi 3 Model B as On-Board Data Handling (OBDH).

In [2], the author discusses the design and implementation of a multichannel ADS-B receiver as an approach to solving the known issues for satellite-based aircraft surveillance by using an SDR platform based on a field programmable gate array (FPGA) like GSDR.

In [3] [4], the authors present a resume of the world's first in-orbit demonstration of a space-based ADS-B system. The outcomes of this in-orbit demonstration have proven that 1090ES ADS-B surveillance is technically feasible and will pave the way for future advancements toward global satellite-based air traffic surveillance. The primary goal of a space-based ADS-B system is to increase air traffic surveillance, particularly on remote, polar and oceanic areas that are not yet covered by ground-based surveillance.

The work reported in this paper demonstrates the implementation of a Terrestrial-based ADS-B receiver using a novel SDR platform. The purpose of developing this project is not only to receive ADS-B signals by a terrestrial receiver, but we consider this work as a first step to develop a nanosatellite SDR payload where we will test the ADS-B system as a radio application. Consequently, we chose the "Totem Motherboard SDR" from Alèn Space(spain) as an SDR platform based on a field programmable gate array (FPGA) to acquire and decode the ADS-B signal. Certainly, the principal advantage of this SDR payload is its flexibility and re-programmability. That means all programs can be uploaded in flight as soon as they have been developed and tested on the ground.

This document is organized as follows. Section II contains a technical overview of SDR, GNU radio, and the ADS-B Protocol. Section III goes through the system's design and execution. Section IV analyzes the Results and Discussions. Finally, in section V, the conclusion and perspectives are provided.

II. Technical description

A. Software Defined Radio

Software Defined Radio (SDR) is one of the most important and latest technologies for modern wireless communication that performs all signal processing and modification in software rather than hardware. This means that a hardware design can accommodate a wide range of communication requirements, including different frequencies, modulation/demodulation schemes, and data rates.

TABLE I
COMPARATIVE STUDY OF SOME SDR DEVICES

Name	Frequency range	Max Bandwidth	RX/TX	Sampling rate	Host interfaces	Processing system/FPGA
RTL-SDR	0.5-1766MHz	max of 2.4 MHz	1/0	2.4-3.2 MHz	USB	
HackRF one	70MHz-6GHz	20 MHz	1/1	8-20 MSPS	USB 2.0	LPC4330 microcontroller
BladeRF 2.0 micro	47MHz–6GHz	56 MHz	2/2	61.44 MSPS	USB 3.0 Super speed	Altera Cyclone V
LimeSDR mini	10MHz–3.5 GHz	30.72 MHz	2/2	30.72 MSPS	USB 3.0	Altera MAX 10
USRP E310	70MHz-6GHz	Up to 56 MHZ	2/2	25-50 MSPS	Ethernet USB	ARM Cortex A9 / Xilinx Zynq 7020
AstroSDR	70 MHz-6 GHz	56 MHz-25 MHz	3/1	61.44 MSPS, 30.72 MSPS	UART Ethernet	ARM Cortex A9 / Xilinx Zynq 7045
Totem SDR	70MHz-6GHz	Up to 56 MHz	3/2	30 MSPS	CAN Ethernet UART JTAG I2C	ARM Cortex A9 / Xilinx Zynq 7020

The comparison study shown in Table. I provides the information about some SDR devices. We notice that there are differences between SDRs in terms of frequency range, bandwidth, Rx/Tx ports, and other features. For example, The RTL-SDR dongle is the least efficient of the cited SDRs, but it is the most widely used and least expensive. Furthermore, various SDR platforms, such as Totem SDR, GomSpace SDR and AstroSDR, are specifically dedicated to use in small satellites due to their performance and their capability to be designed for sub-missions.

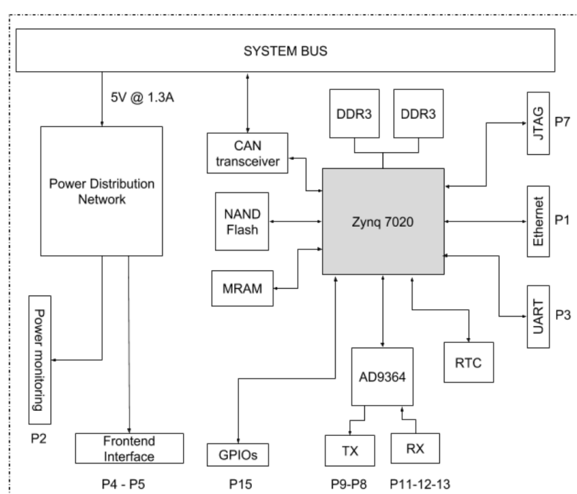

Fig. 2. TOTEM-Motherboard block diagram [5].

As shown in Fig. 2, The Totem SDR is physically divided into two parts. The first part is the processing system, which is based on the Xilinx 7020 Zynq System on Chip (SoC) and includes both ARM processors and an FPGA, the second part is an RF transceiver with a wide frequency ranges (AD9364) and has two TX differential RF interfaces and three RX differential RF ports [5].

B. GNU Radio

GNU Radio is an open-source toolkit for developing software radios that do all signal processing in software. It offers a signal-processing block library that may be used to do a number of tasks [6]. Filters, channel codes, synchronization components, equalizers, demodulators, vocoders, decoders, and many other elements are available in GNU Radio. These components may be simply linked to control how data flows in the SDR [7].

C. ADS-B Message

Before an ADS-B transmission can be decoded, the various elements of the message must be identified. In Fig. 3, we present the general structure of The ADS-B encapsulated frame.

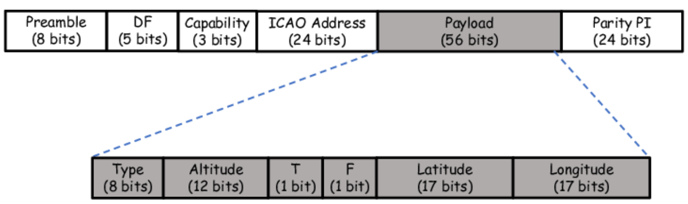

Fig. 3. ADS-B Frame format

The initial section of the message is known as the preamble, and it is composed of the first 8 bits of any message and is used to identify the beginning of a communication. As shown in Table. II, Bits 1-5 of the message are the downlink format, which defines what sort of communication is being received. The downlink format of ADS-B messages is 17 or, 10001 in binary. Bits 6-8 specify the information that the aircraft's transmitter is capable of conveying. Bits 9-32 specify the aircraft's particular address, called the International Civil Aviation Organization (ICAO) 24-bit address. This address is unique to each transponder and enables the message to determine which aircraft is broadcasting. The real ADS-B data is represented by 56 bits (33-88). The final 24 bits provide a parity check to guarantee that received messages are neither corrupted nor erroneous [8].

TABLE II
ADS-B PACKETS FORMAT [9]

nBits	Bits	Abbr	Content
5	1-5	DF	Downlink Format
3	6-8	CA	Capability (Additional Identifier)
24	9-32	ICAO	ICAO aircraft address
56	33-88	DATA	data
24	89-112	PI	Parity/Interrogator ID

III. Design and Implementation of ADS-B Receiver

This chapter goes into further detail regarding the used components, the Radio Frequency requirements and the system design. In this project, the Totem SDR serves as a receiver of ADS-B data collected from airplanes.

A. Used components:

The following components are utilized for ADS-B data reception and analysis:

- TOTEM-Motherboard SDR
- L Band Antenna & 1090 MHz
- GNU Radio

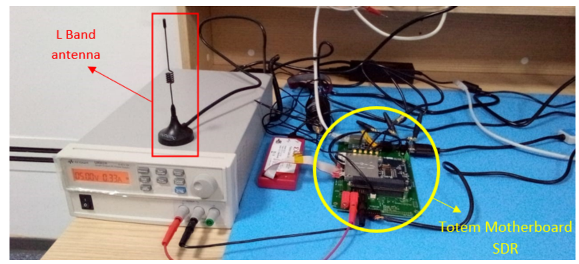

Fig. 4. Hardware setup: A Totem SDR One equipped with a 1090 MHz antenna

In the hardware setup as shown in Fig. 4, the Rx port of the totem SDR is connected to an L band antenna (1.09 GHz). The Ethernet port is connected to the network through an Ethernet cable, which can be connected to the host computer that exists in the same LAN using the SSH communication.

B. RF Requirements

The ADS-B receiver operates at a center frequency of 1090MHz, which is within the frequency range of the Totem SDR. Fig. 5 represents the software libraries and interfaces of the ADS-B receiver. The receiver needs to run an implementation of the IIO interface to get access to the baseband IQ data buffers and to tune the AD9364 transceivers.

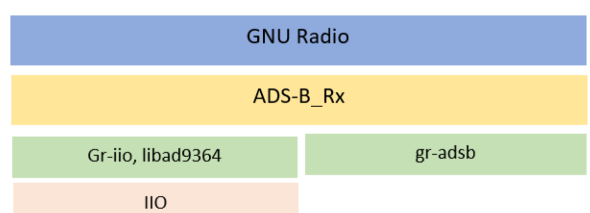

Fig. 5. Required software libraries and interfaces

For the signal processing tool, GNU Radio is selected to acquire and decode the ADS-B signal. For the IIO interface, a GNU Radio implementation of the libiio library, called gr-iio, is used. An out-of-tree (OOT) module gr-adsb is selected as a basis for the baseband processing of the ADS-B messages [10].

C. ADS-B receiver implementation

In order to acquire and decode ADS-B frames, we developed a GNU Radio block diagram as shown in Fig. 6. This diagram is based on two OOT modules gr-soapy and gr-adsb for processing ADS-B messages in GNU Radio. Firstly, we provide a SoapySDR module(gr-soapy) to interface with the TOTEM SDR, which acts as a thin layer between the SoapySDR API and low-level libiio calls. This means that we connect with the AD9364 radio transceiver using the Soapy source block. In this block, the necessary parameters are set as:

- The IP address of Totem SDR is 10.42.0.100
- The center frequency is set to 1.09 GHz;
- The sample rate of 2 million samples per second;
- The bandwidth of 2 MHz centered at 1.09 GHz;
- The overall gain value is 70 dB.

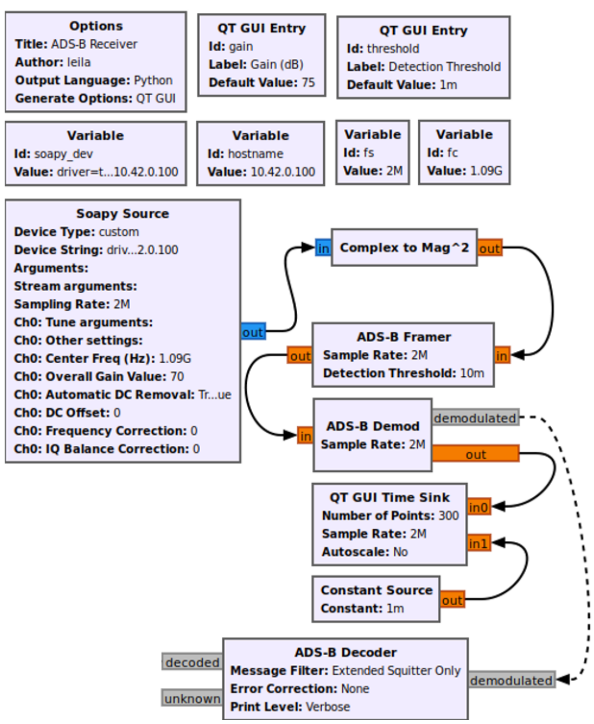

Fig. 6. ADS-B GNU Radio Flowgraph

Secondly, we add a GNU Radio out-of-tree (OOT) module gr-adsb to demodulate and decode ADS-B messages using the blocks ADS-B Framer, ADS-B Demod and ADS-B Decoder. Therefore, The DF17 preamble detection is handled by the ADS-B Framer detector block in gr-adsb. The magnitude data is detected by specifying a detection threshold. This means any magnitude value above than the set threshold is read as high, while anything below is viewed as low. The Framer conducts no additional demodulation and instead compares the PPM modulated version of the 16-bit Mode-S preamble with the sample stream. If a matching pattern is identified, GNU Radio's tagging system marks the beginning of the prospective ADS-B messages in the data stream. The ADS-B demodulator uses the stated threshold value to determine the High and Low amplitudes by taking data blocks of 224 PPM samples (at base sample rate) and demodulating them into 112-bit Mode-S DF 17 conform binary sequences at the presumed message locations as they were tagged by the Framer. Finally, an ADS-B decoder will receive the modulated signal and display it either in "verbose" or "brief" outputs. [10].

IV. Results and Discussions

After running the GNU Radio program, aircraft information such as ICAO, Call sign, altitude, speed, latitude, longitude, and other information are successfully displayed. The aircraft and its information can be detected as long as it stays within the limits of the antenna detection area. Consequently, we conclude that the coverage area provided by the proposed receiver is limited typically to a few hundreds of kilometers.

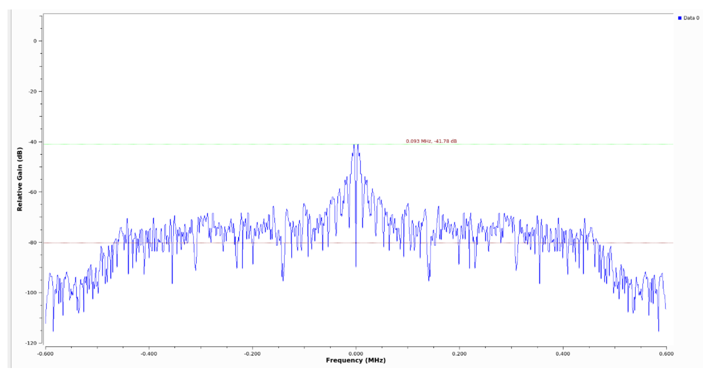

Fig. 7. Frequency Domain Signal of ADS-B Receiver

Furthermore, if you are in an area with little aircraft traffic, it is recommended that you run the model for a longer period of time in order to collect some useful data. By inspecting the spectrum analyzer, you can determine whether there is any useful data. A typical ADS-B frequency an time spectrum are shown respectively in the Fig. 7 and the Fig. 8.

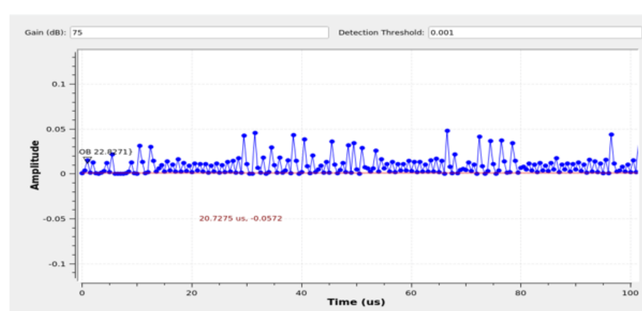

Fig. 8. Time Domain Signal of ADS-B Receiver

The data is shown by selecting one of two modes: "Brief" mode or "Verbose" mode. In Brief mode, all ADS-B frames from captured aircraft are presented without tracking the aircraft until it disappears from the antenna area. The Fig. 9 shows the "Brief" mode results found during the running of the previously mentioned GNU Radio program. In the "Verbose" mode, the ADS-B data of the aircraft acquired first remain displayed throughout the passage of this aircraft in the detection zone.

Time	ICAO	Callsign	Alt ft	Climb ft/m	Speed kt	Hdng deg	Latitude deg	Longitude deg	Msgs
12:59:13	4d21c5	SZN404	39000	0	449	-124	33.7588348	-6.8939770	54
12:59:12	02006e			-2112	398	-109			1
12:59:12	020095	RAM229	18900	-2752	348	-124	33.8412424	-6.7273521	81
12:59:12	484b6e	TRA749L	20400	-1792	346	-123	33.7914276	-6.7828245	80
12:59:12	4ca708	RYR1459	41025	0	416	-124	33.8045127	-6.8554115	30
12:59:12	3424d4	VLG70JZ	31000	0	433	-124	33.5545807	-7.1517072	111
12:59:12	020127	MAC266C	18675	-2304	380	-123	33.7804871	-6.7882616	97
12:59:12	020072	RAM795Z	22800	-2176	430	-127	33.8556976	-6.7084425	50
12:59:12	3944e1	AFR1576	37000	0	435	-124	33.8001833	-6.9514275	36

Fig. 9. " BRIEF" output of received ADS-B Data

```
[INFO] ------------------------------------------------------------------
[INFO] Datetime: 2022-07-20 16:11:46.496947 UTC
[INFO] SNR: 25.20 dB
[INFO] Downlink Format (DF): 17 Extended Squitter
[INFO] Capability (CA): 5 Level 2 or Above Transponder, Can Set CA 7, In Air
[INFO] Address Announced (AA): 396449
[INFO] Callsign: AFR781
[INFO] Type Code (TC): 11 Airborne Position
[INFO] Surveillance Status (SS): 0 No Condition Information
[INFO] Time: 0 Not Synced to 0.2s UTC Epoch
[INFO] Latitude: 33.83723889367055 N
[INFO] Longitude: -6.877613067626953 E
[INFO] Altitude: 39000 ft
[DEBUG] DF: 24 Unknown DF
[INFO] ------------------------------------------------------------------
[INFO] Datetime: 2022-07-20 16:11:46.571441 UTC
[INFO] SNR: 19.33 dB
[INFO] Downlink Format (DF): 17 Extended Squitter
[INFO] CRC: Passed
[INFO] ------------------------------------------------------------------
[INFO] Datetime: 2022-07-20 16:11:46.571441 UTC
[INFO] SNR: 19.33 dB
[INFO] Downlink Format (DF): 17 Extended Squitter
[INFO] Capability (CA): 5 Level 2 or Above Transponder, Can Set CA 7, In Air
[INFO] Address Announced (AA): 396449
[INFO] Callsign: AFR781
[INFO] Type Code (TC): 19 Airborne Velocity
[INFO] Subtype (ST): 1 Ground Velocity
[INFO] Intent Change (IC): 0 No Change in Intent
[INFO] Speed: 450 kt
[INFO] Heading: -125 deg (SW)
[INFO] Climb: 0 ft/min
[INFO] Climb Source: 1 Barometric Source
[DEBUG] DF: 31 Unknown DF
[INFO] ------------------------------------------------------------------
```

Fig. 10. "Verbose" Output of Received ADS-B data

Fig. 11. Graphical View of Flight "AFR781" in FlightRadar24

The Fig. 10 presents the ADS-B frame of the aircraft "AFR781" displayed in Verbose mode, in the other hand, we observed that the same aircraft detected by our system has been captured by the world's popular flight tracker application "FlightRadar24" as shown in Fig. 11.

V. Conclusion and Future Work

The work presented in this paper demonstrates the development of a terrestrial-based ADS-B receiver using a new software-defined radio platform, namely Totem SDR from Alen Space. However, due to the limited coverage area of the proposed receiver. Space-based ADS-B receivers are an adequate solution for global surveillance of air traffic movements because only the satellites can provide global coverage.
In the future, this work will be implemented as a space application for Nanosatellite's payload, considering the parameters between a ground station implemented in Rabat, Morocco, and a nanosatellite in orbit.

Acknowledgment

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