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AIS-Based Vessel Monitoring System Using *Software-Defined Radio*

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ABSTRACT

This study implements a low-cost Software Defined Radio (SDR)-based receiver system for the Automatic Identification System (AIS) operating at frequencies of 161.975 MHz and 162.025 MHz using a 44 cm V-dipole antenna with a 90° angle. Spectrum analysis is performed using Airspy to identify AIS signal characteristics in real time within the frequency domain, with measured Signal-to-Noise Ratio (SNR) values of 21.3 dB for AIS 1 and 21.4 dB for AIS 2. The signal decoding process is carried out by AIS-catcher, which handles GMSK demodulation and efficiently extracts AIS message payloads. The decoded data is then visualized using OpenCPN in the form of a digital map to monitor vessel positions and movements in real time. SDRangel is utilized as a supporting platform for signal observation, SDR device configuration, and additional analysis of reception quality. System performance evaluation demonstrates stable capability in receiving and decoding AIS signals with a satisfactory success rate, although it is still affected by interference and propagation conditions. GNU Radio is used in a limited capacity as a signal processing environment for filtering and basic parameter adjustment. The results confirm that low-cost SDR is an effective, flexible, and economical solution for implementing AIS monitoring systems at the research and basic application levels.

Keywords: AIS Signal, RTL-SDR, NMEA Data, VHF Communication

ABSTRAK

Penelitian ini bertujuan untuk mengimplementasikan dan mengevaluasi sistem penerima Automatic Identification System (AIS) berbasis Software Defined Radio (SDR) berbiaya rendah dalam membaca dan memantau sinyal AIS secara real-time. Sistem dioperasikan pada frekuensi 161,975 MHz dan 162,025 MHz menggunakan antena V-dipole sepanjang 44 cm dengan sudut 90°. Analisis spektrum dilakukan menggunakan Airspy untuk mengidentifikasi karakteristik sinyal pada domain frekuensi, dengan hasil Signal-to-Noise Ratio (SNR) sebesar 21,3 dB pada kanal AIS 1 dan 21,4 dB pada kanal AIS 2. Proses dekode dilakukan menggunakan AIS-catcher yang mendukung demodulasi GMSK dan ekstraksi payload pesan secara efisien. Data hasil dekode divisualisasikan melalui OpenCPN dalam bentuk peta digital untuk memantau posisi kapal. SDRangel digunakan untuk konfigurasi perangkat dan analisis kualitas sinyal, sementara GNU Radio dimanfaatkan untuk filtering dan penyesuaian parameter dasar. Hasil pengujian menunjukkan bahwa sistem mampu menerima dan mendekode sinyal AIS secara stabil, meskipun masih dipengaruhi oleh interferensi dan kondisi propagasi. Dengan demikian, SDR berbiaya rendah terbukti efektif, fleksibel, dan ekonomis untuk aplikasi pemantauan AIS.

Kata kunci: Sinyal AIS, RTL-SDR, data NMEA, komunikasi VHF

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1. INTRODUCTION

Safety and efficiency in navigation are important aspects in the modern maritime world. As sea transportation activities increase, the need for accurate and real-time ship monitoring systems becomes increasingly urgent. One of the technologies widely used to support this need is the Automatic Identification System (AIS). AIS plays a very important role nowadays where there is an increasing demand for safety, efficiency, and sustainability of global navigation in maritime monitoring[1].

The implementation of AIS not only assists navigation but also plays an important role in monitoring sea traffic, collision prevention, and supporting the analysis of ship movements in certain water areas. AIS utilizes position data from GPS sent in the National Marine Electronics Association (NMEA) format to support communication between maritime devices[2]. The AIS system is used by ships to automatically exchange navigation information, such as location and speed, via Very High Frequency (VHF). This signal can be received using RTL-SDR and then processed into real-time ship monitoring data[3].

However, the quality and availability of AIS data are often affected by several factors, such as signal propagation conditions, ship traffic density, and receiver device limitations[4].

To optimize signal reception, the use of a Low Noise Amplifier (LNA) in the AIS system functions to amplify weak signals received by the antenna before being processed by Software Defined Radio (SDR) software, thereby improving reception quality and the success of data decoding processes[5].

Indonesia is an archipelagic country with a very vast maritime area, approximately 7.81 million km^2 dominated by waters, thus having a strategic position in the maritime sector[6]. Along with the development of radio technology, SDR software devices, especially RTL-SDR, have become an economical solution. This device is flexible, relatively low cost, and can be integrated with open-source platforms such as GNU Radio for implementing communication systems and signal processing, including in applications for receiving ship AIS data[7], [8]. The results of decoding AIS messages can visualize ship movements in the form of digital maps used for maritime traffic analysis. The integration of AIS data processing into visualization systems allows interactive monitoring of ship positions through a Geographic Information System (GIS)-based dashboard, thus supporting the development of more effective sea navigation monitoring and analysis systems[9], [10].

AIS works by utilizing radio waves as a means of data exchange between devices. This system uses the VHF band at maritime frequencies 161.975 MHz and 162.025 MHz, where the 161.975 MHz channel is used for simplex communication that is one-way, specifically for sending information from stations to ships[11].

The use of SDR in maritime communication systems carries potential security risks that need to be considered, thus requiring a threat modeling approach to identify and analyze vulnerabilities that may occur in the implementation of SDR-based systems in the maritime environment[12]. IMO mandates that all ships include cyber risk analysis and protection in the Safety Management System (SMS) starting January 1, 2021, to enhance ship and marine environment security through the implementation of the ISM Code (IMO, 2017)[13].

AIS is used to transmit ship navigation data such as position, speed, and identity periodically to support monitoring and navigation safety. The integration of AIS with RTL-SDR devices, external antennas, and LNAs can improve the performance of ship monitoring systems, while the SDR approach allows the development of low-cost systems that can still effectively perform monitoring functions[14], [15].

The Software-Defined Radio (SDR)-based approach in the Automatic Identification System (AIS) becomes important because it allows the implementation of a flexible RF receiver through digital signal processing, so parameters such as operating frequency, bandwidth, gain, and demodulation schemes can be configured dynamically. Compared to conventional AIS devices that have fixed hardware, SDR offers advantages in terms of reconfigurability, cost efficiency, and the ability to integrate with various signal processing platforms.

The main contribution of this research is the implementation of a low-cost SDR-based AIS receiver system optimized through the configuration of front-end and baseband parameters, including the use of a V-Dipole antenna, LNA, as well as adjustments to sampling rate, bandwidth filter, and gain to improve signal quality. In addition, this research integrates several software, namely SDRangel for acquisition and spectrum monitoring, GNU Radio for signal processing (filtering and resampling), and AIS-catcher for GMSK demodulation and AIS data decoding. Performance evaluation is carried out quantitatively using Signal-to-Noise Ratio (SNR) parameters and decoding success rate, as well as analyzed against the influence of environmental conditions and propagation. Compared to previous research that tended to focus on simulation or proprietary devices, this research emphasizes real-time SDR-based implementation with configu

2. RESEARCH METHOD

In this study, the researcher goes through several structured and interconnected stages, starting from the preparation phase to the comprehensive system design. Each stage is designed to ensure the research process runs systematically and produces outputs that align with the established objectives. This research specifically focuses on the design and testing of an AIS signal receiver system based on SDR, thus requiring a clear and directed methodological approach.

The first stage carried out is a literature study, aimed at collecting and understanding various references related to AIS concepts, SDR technology, as well as relevant signal reception and processing methods. Through this literature study, the researcher obtains the theoretical foundation and technical references that serve as the basis for system design. Subsequently, the research stages continue according to the planned flow, which can be seen in the following research flow block diagram as an overview of the entire process carried out.

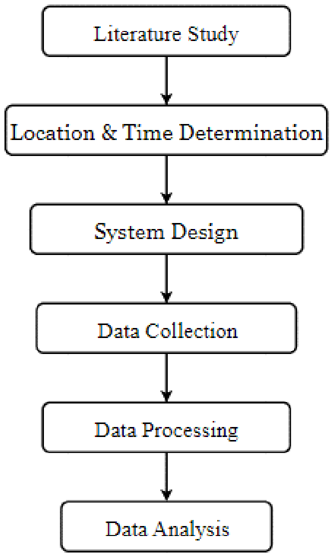


Figure 1. Research Flow Block Diagram.

2.1. Literature Study

This literature study was conducted to compile and develop information by collecting various references. This stage is carried out so that the researcher has basic knowledge to design and implement the system applied in the research to be conducted. The sources collected by the researcher related to this study include books, journals, and articles about AIS signals on ships, starting from the process of receiving and processing ship AIS signals so that they can be processed into digital maps.

2.2. Location and Time Determination

The selection of this location is based on the consideration that the AIS system utilizes line-of-sight communication on VHF frequencies, so signal reception is greatly influenced by antenna height, geographical conditions, and the distance of the ship to the receiver location.

The density of ship traffic tends to increase during port operating hours from morning to afternoon.This is how to start a subsection. The paragraph is indented 0.5 inch, justified, single column. The paragraph should consist of more than a sentence.

Figure 2. Research Location Point.

The research was conducted in Tlk. Bayur, South Padang, Padang City, West Sumatra, Indonesia, at the geographic coordinates −0.999852 (S) and 100.386536 (E). Data collection was carried out over three days with a time range from 07:00 to 01:00 WIB the following day.

2.3. System Design

The device specifications and system configuration are designed to ensure optimal performance and reproducibility. The system uses a VHF V-Dipole antenna (element length 44 cm, angle 90°) connected via RG-58 coaxial cable, and is amplified using an SPF5189Z LNA (50–4000 MHz, +5 V). The receiver uses RTL-SDR V3 (RTL2832U) configured at AIS frequencies 161.975 MHz and 162.025 MHz with a sampling rate of 1 MS/s. The signal is filtered using a bandwidth of about 25 kHz with a transition width of 5 kHz, and the gain (RF gain) is set in the range of 40–49.6 dB. Furthermore, the sampling rate is adjusted to about 48 kS/s to match the AIS symbol rate of 9.6 kbaud with 5 samples per symbol.

The data acquisition process is conducted under good to overcast weather conditions, with the antenna installed at an altitude of about 3 meters above sea level in an open area without significant obstacles. These parameters support stable signal reception and allow the system to optimally decode AIS signals and be replicated under similar conditions.

The AIS reception system designed in this study has an architecture composed of several hardware and open-source software components that are integrated with each other.

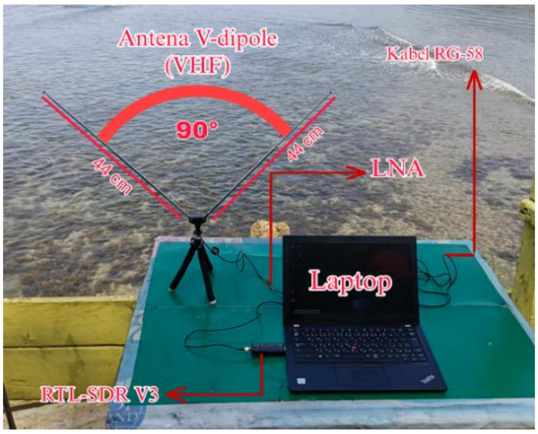


Figure 3. AIS Signal Reception System Design.

The antenna used in this study is a V-dipole antenna with each element having a length of 44 cm. The determination of the antenna length is based on the calculation of the wavelength of the AIS signal operating at a frequency of around 162 MHz, using the equation λ = c/f, with the calculation as follows:

$$\lambda = \frac{c}{f}$$

$$\lambda = \frac{3 \times 10^8}{162 \times 10^6} = 1.85 \text{ m}$$

$$L = \frac{1}{2}\lambda = 0.925 \text{ m}$$

$$L_{\text{elemen}} = \frac{L}{2} = 46.25 \text{ cm}$$

Where c is the speed of light (3×10^8 m/s) and f is the frequency (Hz). Based on these calculations, the wavelength (λ) obtained is approximately ±1.85 m, so the half-wave antenna length (½λ) is about 0.925 m or ±46.25 cm for each element. The realized antenna element length of 44 cm is close to this theoretical value, thus still within a good resonance range. The difference between the theoretical and realized values can be influenced by practical factors, such as the antenna material characteristics, the 90° V-dipole angle configuration, and the measurement environmental conditions, but overall the antenna is still able to receive AIS signals well.

Table 1. Hardware and Software

NO	System Configuration	
	Hardware	**Software**
1	VHF Antenna	AIS-catcher
2	LNA	OpenCPN
3	RG-58 Cable	Airspy
4	RTL-SDR	SDR Angel
5	Laptop	GNU Radio

After the system was designed, the data collection process was carried out by capturing AIS signals at frequencies 161.975 MHz and 162.025 MHz. Data was collected in real-time from ships around the research location. By utilizing the User Datagram Protocol (UDP), the distribution of NMEA data between the AIS catcher and OpenCPN can be done quickly and efficiently within a local network environment.

2.4. UDP AIS-catcher Configuration to OpenCPN Via Local Host

Table 2 presents the data communication configuration parameters between the AIS catcher and OpenCPN used in the AIS signal reception system based on a local network. This configuration includes the type of data protocol used, the destination IP address, and the communication port involved in the data transmission process of the decoded results.

Table 2. Configuration Parameter

Options	Connections
Data Protocol	NMEA 0183
Address	127.0.0.1
DataPort	10110

Based on Table 2 the system uses the NMEA 0183 protocol as the standard data format for AIS information exchange. The IP address 127.0.0.1 indicates that communication is conducted through localhost, so the data transmission process occurs internally within a single device. In addition, the use of port 10110 serves as a communication channel to send AIS data from the AIS catcher to OpenCPN, allowing the received data to be directly processed and visualized.

2.5. Data Collection

Data collection in this study was carried out by utilizing an SDR-based AIS receiver system. AIS signals were received through a VHF antenna and processed using RTL-SDR equipment to obtain raw data that would be used in the next stage.

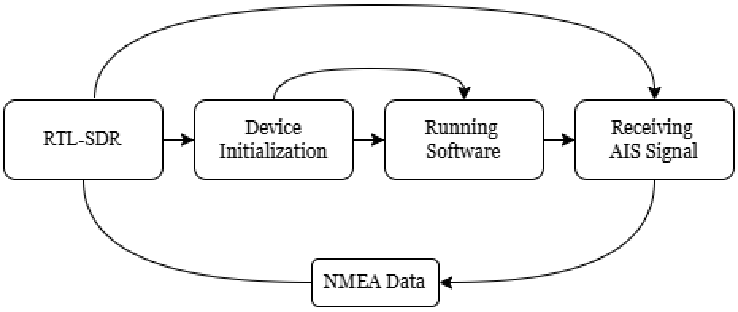


Figure 4. Data Acquisition Block Diagram

The output signal is data in NMEA format that needs to be further processed with additional supporting software.

2.6. Data Processing

Data in NMEA format received by the RTL-SDR through the AIS-catcher software needs to be decoded and processed into a digital map using OpenCPN software. This stage also includes integrating the data into the mapping system to produce a spatial representation of ship movements that is close to real-time conditions.

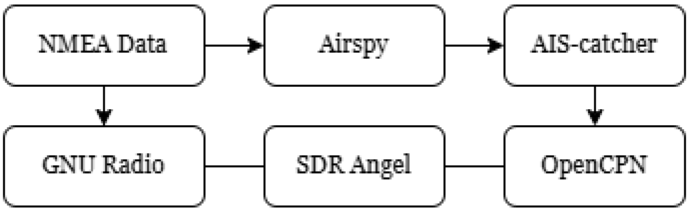


Figure 5. Data Processing Block Diagram

The block diagram shows the data processing flow of AIS starting from the reception of NMEA data to processing.

3. RESULTS AND DISCUSSION

The following are the results and discussion of this study, which include the analysis of the AIS signal reception process, ranging from the characteristics of the received signal, spectrum quality, to factors affecting reception performance. In addition, the results of the AIS signal decoding process using several SDR-based software are also discussed, including the evaluation of output parameters such as NMEA data, ship identification, and the accuracy of the obtained position information.

To improve the quality of analysis, system performance assessment was conducted in a measurable manner based on the SNR parameter, the number of AIS messages successfully decoded, and the stability of the received signal.

3.1. AIS Signal Reception with Airspy

On the Airspy display, the frequency being monitored (VFO) is at 161.975 MHz, which is one of the AIS 1 channels.

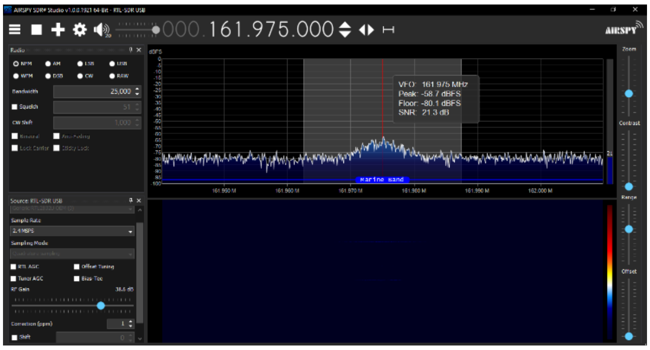


Figure 6. AIS Spectrum at 161.975 MHz

Narrowband Frequency Modulation (NFM) mode is used in the process of observing Automatic Identification System (AIS) signals in the frequency domain to monitor their presence and spectral characteristics. Signal acquisition is carried out using an SDR device with a sample rate of 2.4 MS/s, allowing for a wider and more detailed capture of the spectrum in the VHF band. NFM is chosen because it has a narrow bandwidth suitable for the AIS channel (±25 kHz), making the signal visualization clearer and more focused. However, the decoding process is not performed using NFM, but rather through GMSK demodulation as the main modulation scheme in the AIS system.

The received signal has a peak value of approximately -58.7 dBFS, while the noise floor is around -80.1 dBFS. The difference between the two results in a Signal-to-Noise Ratio (SNR) of 21.3 dB, indicating that the signal quality is quite good and suitable for the decoding process.

On the Airspy display, the frequency being monitored (VFO) is at 162.025 MHz, which is one of the AIS 2 channels.

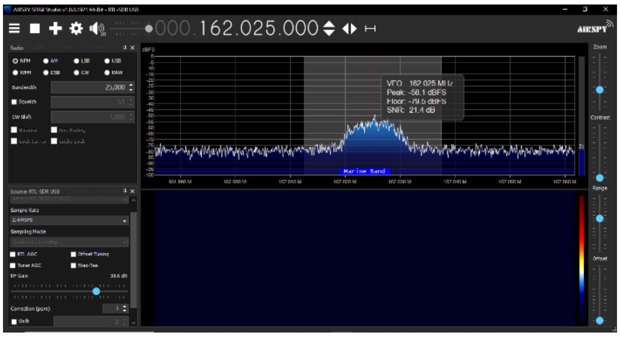


Figure 7. AIS Spectrum at 162.025 MHz

The received signal has a peak value of approximately -58.1 dBFS, while the noise floor is around -79.5 dBFS. The difference between the two results in an SNR value of 21.4 dB, indicating that the signal quality is quite good and suitable for the decoding process.

Measurement results recorded an SNR value of 21.3 dB on AIS channel 1 and 21.4 dB on AIS channel 2, indicating that the signal conditions were sufficiently good for the demodulation process. Comparative analysis was also carried out between system conditions without using an LNA and those using it, where there was an increase in signal strength and consistency of the obtained NMEA data. Performance evaluation was conducted based on the measured parameters, namely SNR value, decoding success rate, and stability of the received signal. The results showed that the system was able to maintain stable decoding performance with an SNR value above 20 dB, as well as having a high decoding success rate in open environment conditions. Thus, the proposed system demonstrates stable performance and can be applied for AIS-based monitoring.

3.2. AIS Signal Decoding (NMEA Stream)

The system successfully acquired AIS signals on the VHF frequency band using SDR. The received radio signal was processed into a baseband stream and then decoded into NMEA format. The system is connected between the AIS-catcher Software and the OpenCPN Software through localhost.

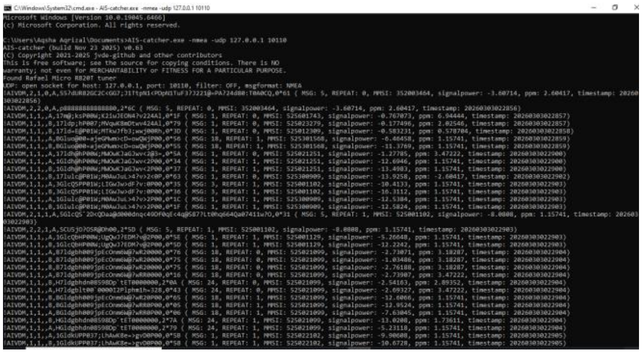


Figure 8. Real-time NMEA Stream

The process of receiving NMEA data occurs in real-time as data is sent from the ship's AIS source; the use of UDP in this system also allows the system to be lighter on hardware.

3.3. AIS Signal Transformation Process to Digital Map

The decoded AIS results are processed to extract navigation parameters such as coordinates (latitude and longitude), SOG, and COG, then mapped using OpenCPN so that they can be visualized as the ship's position on a digital map.

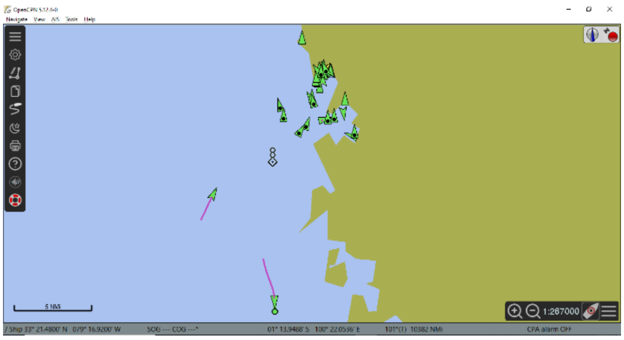
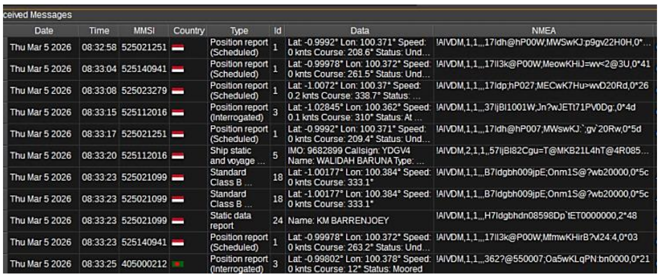


Figure 9. AIS Conversion to Digital Map Through OpenCPN

The implementation results through OpenCPN connected with decoding on AIS-catcher show that the system is capable of updating positions sequentially according to the AIS transmission interval, thus supporting real-time movement representation.

3.4. Decoding Results Using SDR Angel

Figure 10 shows the ship data and status successfully read using SDRangel at frequencies 161.975 MHz and 162.025 MHz.



ceived Messages

Date	Time	MMSI	Country	Type	Id	Data	NMEA
Thu Mar 5 2026	08:32:58	525021251		Position report (Scheduled)	1	Lat: -0.9992° Lon: 100.371° Speed: 0 knts Course: 208.6° Status: Und…	!AIVDM,1,1,,,17Idh@hP00W;MWSwKJ:p9gv22H0H,0*…
Thu Mar 5 2026	08:33:04	525140941		Position report (Scheduled)	1	Lat: -0.99978° Lon: 100.372° Speed: 0 knts Course: 261.5° Status: Und…	!AIVDM,1,1,,,17Il3k@P00W;MeowKHiJ=wv<2@3U,0*41
Thu Mar 5 2026	08:33:08	525023279		Position report (Scheduled)	1	Lat: -1.0072° Lon: 100.37° Speed: 0.2 knts Course: 338.7° Status: …	!AIVDM,1,1,,,17Idp;hP027;MECwK7Hu>wvD20Rd,0*26
Thu Mar 5 2026	08:33:15	525112016		Position report (Interrogated)	3	Lat: -1.02845° Lon: 100.362° Speed: 0.1 knts Course: 310° Status: At …	!AIVDM,1,1,,,37IjBI1001W;Jn?wJETt71PV0Dg:,0*4d
Thu Mar 5 2026	08:33:17	525021251		Position report (Scheduled)	1	Lat: -0.9992° Lon: 100.371° Speed: 0 knts Course: 209.4° Status: Und…	!AIVDM,1,1,,,17Idh@hP007;MWswKJ:`;gv`20Rw,0*5d
Thu Mar 5 2026	08:33:20	525112016		Ship static and voyage …	5	IMO: 9682899 Callsign: YDGV4 Name: WALIDAH BARUNA Type: …	!AIVDM,2,1,1,,57IjBI82Cgu=T@MKB21L4hT@4R085…
Thu Mar 5 2026	08:33:23	525021099		Standard Class B …	18	Lat: -1.00177° Lon: 100.384° Speed: 0 knts Course: 333.1°	!AIVDM,1,1,,,B7Idgbh009jpE;Onm1S@?wb20000,0*5c
Thu Mar 5 2026	08:33:23	525021099		Standard Class B …	18	Lat: -1.00177° Lon: 100.384° Speed: 0 knts Course: 333.1°	!AIVDM,1,1,,,B7Idgbh009jpE;Onm1S@?wb20000,0*5c
Thu Mar 5 2026	08:33:23	525021099		Static data report	24	Name: KM BARRENJOEY	!AIVDM,1,1,,,H7Idgbhdn08598Dp`tET0000000,2*48
Thu Mar 5 2026	08:33:23	525140941		Position report (Scheduled)	1	Lat: -0.99978° Lon: 100.372° Speed: 0 knts Course: 263.2° Status: Und…	!AIVDM,1,1,,,17Il3k@P00W;MfmwKHirB?v24:4,0*03
Thu Mar 5 2026	08:33:25	405000212		Position report (Interrogated)	3	Lat: -0.99802° Lon: 100.378° Speed: 0 knts Course: 12° Status: Moored	!AIVDM,1,1,,,362?@550007;Oa5wKLqPN:bn0000,0*21

Figure 10. Ship data read on SDR Angel

Figure 10 presents information from the decoded AIS signal displayed in a structured table form. The parameters shown include date and time as markers of data reception time, Maritime Mobile Service Identity (MMSI) as the ship's unique identity, and country indicating the ship's registration origin. In addition, the type and id columns represent the AIS message type and message identification, while the NMEA column contains raw data in the standard format used for maritime navigation device communication.

This information enables the process of identification, tracking, and analysis of ship movements in real-time. With the successful decoding of NMEA data, the SDR-based system demonstrates the capability to accurately reconstruct ship navigation information for maritime purposes.

3.5. Decoding Results Using GNU Radio

Figure 11. Block diagram of the system using GNU Radio which includes acquisition stages, signal processing, GMSK demodulation, and data decoding.

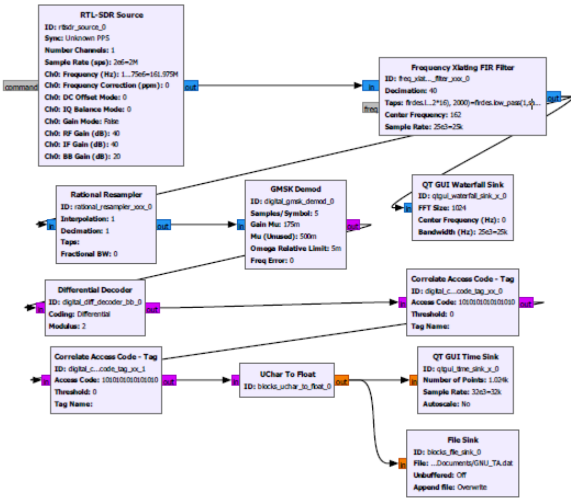


Figure 11. Block Diagram of AIS Reception Through GNU Radio

Figure 11 is the GNU Radio block diagram in the figure showing the complete flow of reception and processing of AIS signals based on SDR. The process begins with the RTL-SDR Source block configured at the AIS channel operating frequency, which is 162.025 MHz, with a sampling rate of 1 MS/s. The gain parameter is set using an RF gain of 40 dB to increase reception sensitivity to weak signals.

The received RF signal is then processed using a Frequency Xlating FIR Filter with a center frequency offset adjusted to translate the signal to baseband. This filter is designed with a bandwidth of about 25 kHz and a transition width of 5 kHz to limit the AIS signal spectrum and reduce interference outside the channel. The filter coefficients use a low-pass FIR based on windowing (for example, a Hamming window) to maintain frequency response stability.

Next, the signal is passed to the Rational Resampler block with an interpolation ratio of 48 and decimation of 500, resulting in a new sampling rate suitable for demodulation needs. This adjustment is made to obtain an optimal number of samples per symbol relative to the AIS symbol rate of 9.6 kbps.

The demodulation stage is carried out using the GMSK Demod block with parameters of samples per symbol set to 5, gain_mu set to 175m, mu unused set to 500m, and omega_relative_limit set to 5m. This configuration allows the timing tracking and symbol recovery processes to run stably under signal conditions affected by noise and fading.

The output from the demodulator is then processed by the Differential Decoder to restore the original binary data from the differential encoding scheme used in the AIS system. Next, the Correlate Access Code – Tag block is used to detect the AIS preamble with a standard bit pattern as the frame start marker, enabling accurate data synchronization with the digital_c...code_tag_xx_0 ID and Access Code 1010101010101010.

The decoded data is then converted using the UChar to Float block for signal visualization purposes. The signal representation is displayed on the QT GUI Time Sink for time-domain analysis, as well as the QT GUI Waterfall Sink for real-time frequency spectrum observation with a sample rate of 25kHz. Additionally, the output data is stored via the File Sink in binary format for further decoding into NMEA data.

Overall, the parameter configuration in this flowgraph is designed to match the characteristics of AIS signals in the VHF band, resulting in a receiver system capable of performing signal demodulation and decoding optimally, stably, and reproducibly in similar implementations.

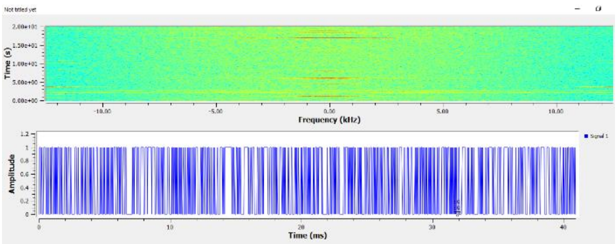


Figure 12. Frequency spectrum of the AIS Signal

Figure 12 AIS signal in the frequency domain (top) and time domain (bottom) shows the frequency spectrum representing the energy distribution of the signal, while the time graph displays the bit stream resulting from GMSK demodulation.

The figure shows the visualization results of the AIS signal obtained using GNU Radio, consisting of two main domains, namely the frequency domain (waterfall) and the time domain (time signal). At the top is displayed the waterfall spectrum with the horizontal axis showing frequency (kHz) and the vertical axis showing time (s), while the color intensity represents the signal strength.

In the waterfall display, there is a concentration of signal energy around the center frequency (baseband), marked by a lighter color compared to the surrounding area. This pattern indicates the presence of an AIS signal modulated using GMSK with a narrow bandwidth, generally around ±25 kHz from the center frequency. The relatively stable color variation indicates that the signal is received continuously, although there are small fluctuations that can be caused by noise, interference, or propagation effects such as fading.

At the bottom is displayed the signal in the time domain using QT GUI Time Sink, with the horizontal axis showing time (ms) and the vertical axis showing amplitude. The visible signal consists of digital pulses that change discretely, which are the output results of the process.

4. CONCLUSION

Based on the research results, the SDR-based AIS system has been proven to be implemented as a low-cost AIS receiver solution with adequate functionality. However, the performance of AIS signal reception is greatly influenced by propagation factors, such as the distance between the transmitter and receiver, antenna height, and the presence of physical obstacles like buildings and vegetation. Additionally, the multipath fading phenomenon also contributes to the degradation of the received signal quality.

The application of an LNA in the receiver chain shows an improvement in signal quality by reducing the noise contribution at the initial amplification stage. This impacts the improvement of signal quality parameters, allowing the demodulation and decoding of AIS data in NMEA format to be carried out more reliably. Thus, the received data can be accurately visualized and mapped by AIS processing software.

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