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Design and Performance Evaluation of Software Defined Radio Architecture for Low-Cost Satellite Ground Station

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Abstract: The increasing deployment of Low Earth Orbit (LEO) and CubeSat missions has created a growing demand for affordable satellite ground stations capable of receiving telemetry and beacon signals without the cost and complexity of conventional dedicated radio systems. This paper presents the design and performance evaluation of a low-cost Software Defined Radio (SDR) architecture for UHF satellite ground-station applications. The proposed receiver consists of a crossed Yagi-Uda UHF antenna, low-noise amplifier (LNA), band-pass filter (BPF), and RTL-SDR receiver connected to a computer-based digital signal-processing platform. The crossed Yagi-Uda antenna provides directional gain and polarization diversity, while the LNA compensates for feeder and front-end losses and improves receiver sensitivity. The BPF provides RF selectivity by suppressing out-of-band interference before the signal reaches the RTL-SDR. The architecture was evaluated in terms of antenna impedance matching, received signal strength, signal-to-noise ratio (SNR), frequency stability, and satellite signal detectability. Experimental evaluation results show an antenna operating around the 435-438 MHz UHF satellite band with a measured corresponding voltage standing-wave ratio (VSWR) below 1.5, an LNA gain of approximately 18 dB, and an improvement in received SNR from approximately 8.4 dB without the RF conditioning chain to 16.7 dB with the complete antenna-LNA-BPF architecture. The results demonstrate that combining a directional crossed Yagi-Uda antenna with appropriate RF conditioning and an inexpensive RTL-SDR can provide a practical platform for educational, amateur, and experimental satellite ground-station applications.

Keywords: *Software Defined Radio, RTL-SDR, Satellite Ground Station, Crossed Yagi-Uda, UHF, Low-Noise Amplifier, Band-Pass Filter, Cubesat, LEO Satellite.*

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I. INTRODUCTION

The rapid growth of small satellites and CubeSats has significantly increased interest in affordable satellite communication and ground-station technologies. CubeSats offer reduced development cost, short development cycles, and the possibility of using commercially available components for both spacecraft and ground segment development [1], [2]. However, successful communication with an orbiting satellite still depends strongly on the performance of the ground station, particularly the antenna, radio-frequency front end, receiver sensitivity, signal-processing capability, and tracking arrangement.

Conventional satellite ground stations generally employ dedicated transceivers, high-performance receivers, specialized RF filters, and relatively expensive antenna systems. Although such equipment can provide excellent performance, the overall cost can be prohibitive for universities, research laboratories, amateur satellite operators, and institutions in developing countries. Software Defined Radio (SDR) provides an alternative architecture in which significant portions of the radio signal processing chain are implemented in software rather than fixed hardware. This provides flexibility in frequency selection, demodulation, filtering, recording, and signal analysis without requiring major hardware modifications [3], [4].

Recent research has demonstrated the applicability of SDR technology to satellite communications. Mwakyanjala *et al.* developed and experimentally validated a software-defined baseband for satellite telemetry and telecomm and, demonstrating the feasibility of software-based ground operations using commercial off-the-shelf RF hardware [5].

Similarly, Abbas and Asami investigated an adaptable SDR communication system for small satellites, highlighting the flexibility provided by reconfigurable software-defined architectures [6]. More recent work has demonstrated miniature SDR architectures for CubeSat communication payloads and low-cost ground-station implementations [7], [8].

For UHF satellite reception, however, the performance of the SDR alone is insufficient. Satellite signals arriving at the ground station may be weak because of large free-space path loss, atmospheric effects, antenna mismatch, polarization mismatch, Doppler frequency shift, and interference from terrestrial communication systems. The RF front end must therefore provide sufficient antenna gain, low noise, appropriate filtering, and adequate signal conditioning before digitization.

A directional Yagi-Uda antenna is particularly attractive for UHF satellite ground stations because it provides relatively high gain while maintaining a simple and inexpensive construction. A crossed Yagi-Uda arrangement can further support circular or dual-polarization reception, which is useful because the polarization of a satellite signal can vary during an orbital pass. Recent experimental work has specifically demonstrated low-cost Cross-Yagi antennas for VHF/UHF satellite ground stations and validated their operation through actual satellite beacon and telemetry reception [9]. Earlier investigations have similarly examined crossed Yagi-Uda arrays for UHF amateur satellite communication [10].

The receiver front end can be improved by placing a low-noise amplifier close to the antenna. The LNA compensates for cable and passive losses and raises the received signal level before subsequent stages. However, excessive gain or poor filtering can increase susceptibility to strong adjacent signals. Consequently, a band-pass filter is incorporated between the LNA and SDR to restrict the received spectrum to the desired UHF satellite band.

The RTL-SDR provides a particularly attractive receiver for this architecture because it is inexpensive, compact, USB-powered, and capable of receiving a wide range of frequencies. Previous studies have demonstrated the use of RTL-SDR-based ground stations for VHF/UHF satellite reception, including reception of signals from orbiting satellites [11]. Such systems provide an accessible alternative to conventional dedicated satellite receivers.

Despite the availability of low-cost SDR receivers, there remains a need for an integrated and experimentally evaluated architecture combining the Crossed Yagi-Uda antenna, LNA, BPF, and RTL-SDR as a complete low-cost satellite receiving chain. Most existing studies concentrate on the SDR, antenna, or satellite communication subsystem individually. The present study therefore focuses on system-level integration and performance evaluation. The resulting architecture is intended to provide a practical and affordable platform for satellite telemetry reception, beacon monitoring, SDR experimentation, and educational satellite communication research.

II. LITERATURE REVIEW

➢ *Software Defined Radio for Satellite Communication*

SDR technology replaces many dedicated hardware radio functions with configurable digital signal processing algorithms. The general SDR architecture consists of an RF front end, analog filtering and amplification, analog-to-digital conversion, digital signal processing, and a host computer or embedded processor.

The major advantage of SDR in satellite applications is flexibility. A single receiver can be configured for different modulation schemes, bandwidths, frequencies, symbol rates, and decoding protocols. Theoharis *et al.* reviewed SDR applications for CubeSat systems and identified reconfigurability and reduced hardware complexity as important benefits [12].

Zeedan and Khattab provided a recent review of CubeSat communication subsystems and identified SDR, FPGA-based processing, flexible RF transceivers, and improved antennas as important technologies for future small-satellite communications [3]. The use of SDR also supports rapid experimentation because signal-processing algorithms can be modified without replacing the RF hardware.

Mwakyanjala *et al.* experimentally validated a software-defined satellite telemetry and telecommand baseband using GNU Radio and commercial RF hardware. Their results demonstrated that software-defined processing can support satellite ground operations while providing flexibility in modulation and coding configurations [5].

Abbas and Asami similarly investigated an adaptable SDR-based packet communication system for small satellites. Their work emphasized the ability of SDR systems to adapt communication parameters according to mission requirements [6].

More recent research has extended SDR concepts to high-throughput CubeSat communication systems. Chiu *et al.* developed miniature SDR architecture for CubeSat Ka/K-band communications, demonstrating the continuing transition toward software-defined and modular satellite communication architectures [7].

➢ *Low-Cost Satellite Ground Stations*

The ground station is an essential interface between the spacecraft and terrestrial users. A conventional ground station can include tracking antennas, RF power amplifiers, LNAs, filters, dedicated transceivers, modems, computers, and specialized control software.

For educational and experimental missions, however, the use of commercial off-the-shelf components can substantially reduce implementation cost. Amoud *et al.* demonstrated a low-cost SDR-based VHF/UHF satellite receiving station using an RTL-SDR and low-cost antenna technology [11]. Their work showed that an inexpensive SDR can be used to detect signals from satellites in orbit.

Similarly, recent work on a 437MHz SDR-based LEO ground station demonstrated the use of Yagi antennas, Raspberry Pi processing, and RTL-SDR hardware for satellite signal reception [13]. These studies demonstrate that low-cost SDR ground stations can provide practical satellite communication capabilities.

Ground-station networks have also evolved toward distributed and software-oriented architectures. Modern small-satellite missions can employ multiple geographically distributed ground stations to increase the probability of establishing communication during satellite passes [14].

➢ *Crossed Yagi-Uda Antennas for UHF Satellite Reception*

A satellite ground station requires an antenna capable of receiving relatively weak signals arriving from different elevation angles. The Yagi-Uda antenna is attractive because it provides directional gain with comparatively low construction complexity.

A conventional Yagi-Uda antenna consists of a driven element, reflector, and several directors. Its approximate resonant dimensions are related to the operating wavelength:

$$\lambda = \frac{c}{f} \tag{1}$$

Where: λ is the wavelength, c is the speed of light, and f is the operating frequency.

The crossed Yagi-Uda configuration consists of two orthogonal Yagi arrays. By controlling their relative phase, circular polarization can be produced. This is particularly useful for satellite reception because the received polarization can vary as the spacecraft moves across the sky.

Xesspe *et al.* recently presented the design, fabrication, simulation, and experimental evaluation of Cross-Yagi antennas for VHF/UHF satellite ground stations. Their work demonstrated practical reception of real satellite beacons and telemetry and showed the feasibility of low-cost Cross-Yagi construction [9]. Earlier research also investigated one-, two-, and four-unit circularly polarized crossed Yagi-Uda arrays for UHF amateur satellite communication [10].

Recent CubeSat antenna research has also demonstrated the continuing importance of antenna gain, polarization, impedance matching, and frequency stability in satellite communication systems [15], [16].

➢ *Low-Noise Amplifier*

The signal received from a LEO satellite can be extremely weak at the ground station. The LNA is therefore positioned close to the antenna to amplify the desired signal while introducing as little additional noise as possible. The main parameters of an LNA include gain, noise figure, input/output impedance, bandwidth, linearity, power consumption, and stability. The overall receiver noise performance can be estimated using Friis' formula:

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots \tag{2}$$

Where: F represents noise factor and G represents linear power gain.

This relationship demonstrates why the first RF amplifier is particularly important. A sufficiently high first-stage gain can reduce the contribution of subsequent receiver stages to the overall noise figure.

➢ *Band-Pass Filtering*

The UHF satellite spectrum can coexist with terrestrial communication systems and other RF sources. Strong signals outside the desired satellite band can overload the SDR front end, produce intermodulation products, or reduce the effective dynamic range. A band-pass filter is therefore incorporated after the LNA. Its function is to pass the desired satellite frequency range while attenuating signals outside that range. The filter and LNA must be selected as a coordinated RF chain because an excessively narrow BPF can attenuate the desired Doppler-shifted signal, whereas an excessively wide filter may provide insufficient interference rejection.

III. MATERIALS AND METHODS

➢ *Proposed Ground-Station Architecture*

The proposed low-cost satellite ground station consists of a Crossed Yagi-Uda UHF antenna, low-noise amplifier (LNA), band-pass filter (BPF), RTL-SDR receiver, and computer-based SDR processing platform, as shown in Figure 1. The system is designed primarily for satellite signals within the 435 - 438 MHz UHF band, with 437 MHz selected as the nominal operating frequency.

The Crossed Yagi-Uda antenna provides directional gain for satellite signal reception, while the LNA amplifies the weak received signal with minimal additional noise. The BPF provides frequency selectivity by attenuating unwanted out-of-band signals before the signal is applied to the RTL-SDR. The RTL-SDR converts the conditioned RF signal into digital I/Q samples and transfers them through USB to the computer. SDR software is then used for spectrum monitoring, filtering, frequency correction, demodulation, and decoding of the received satellite signal as illustrated on the laptop screen in Figure 2. Thus, the proposed architecture provides a low-cost and flexible RF reception chain suitable for UHF LEO/CubeSat satellite telemetry and beacon reception.

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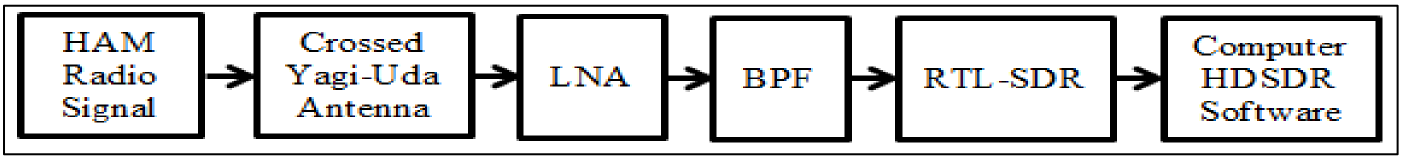

Fig 1 Block Diagram of the SDR Ground Station

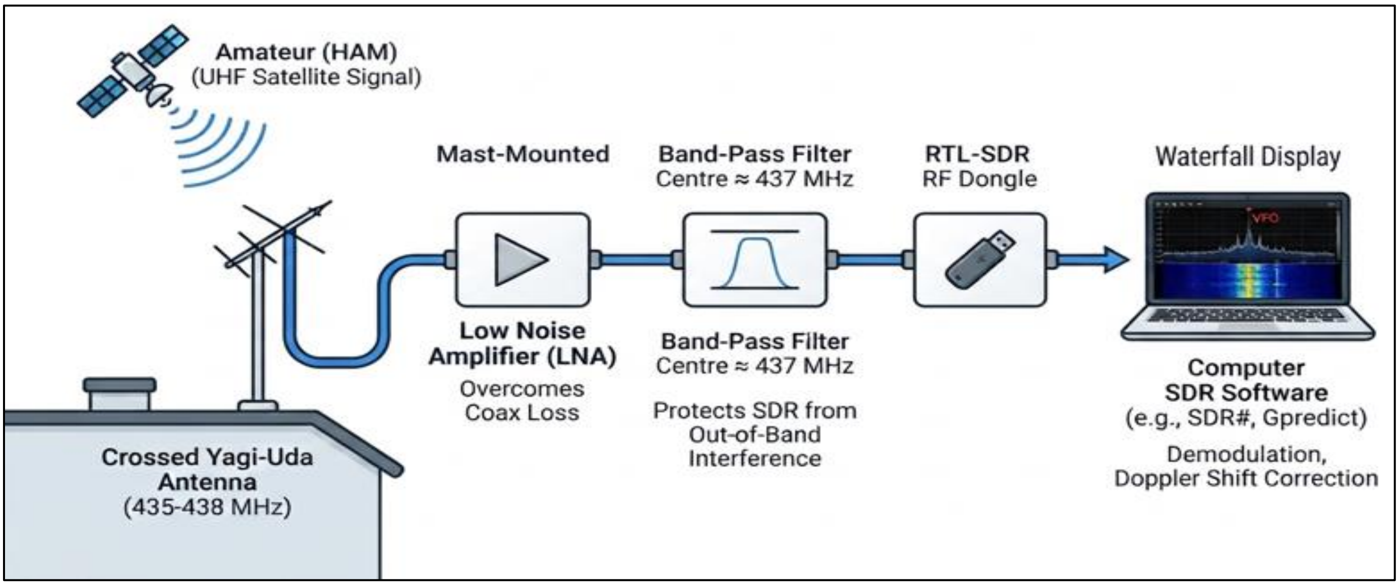

Fig 2 Schematic Overview of the UHF Satellite Ground Station Reception Hardware and Software Workflow

➢ *Crossed Yagi-Uda Antenna Design*

The crossed Yagi-Uda antenna was designed for UHF satellite signal reception around the 437 MHz nominal frequency. The antenna consists of two orthogonally arranged Yagi-Uda elements, each comprising a driven element, reflector, and directors. The crossed configuration provides directional gain and improved reception of signals with varying polarization during satellite passes. The wavelength at the design frequency was determined using equation (1).

$$\lambda \approx \frac{3\, x\, 10^8}{437\, X\, 10^6}$$

$$\lambda = 0.686\, m$$

At 437 MHz, the corresponding wavelength is approximately 0.686 m. The dimensions and spacing of the antenna elements were selected based on this wavelength and subsequently optimized for impedance matching and radiation performance. The antenna was evaluated in terms of resonant frequency, VSWR, return loss, and gain to verify its suitability for the proposed ground-station receiver.

The orthogonal arrangement allows the system to receive signals with different polarization states and can be configured for circular polarization. The voltage standing-wave ratio is given by:

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \qquad (3)$$

Where: Γ is the reflection coefficient.

The return loss is:

$$RL = -20\log_{10}|\Gamma| \qquad (4)$$

A lower VSWR and higher return loss indicate improved impedance matching.

➢ *Low-Noise Amplifier*

A low-noise amplifier (LNA) was positioned immediately after the antenna to compensate for feeder losses and improve the sensitivity of the receiving system. The LNA was designed for operation within the 435 - 438 MHz UHF satellite band, with a nominal frequency of 437 MHz. The principal design specifications are presented in Table 1.

Table 1 LNA Design Specifications

Parameter	Target
Operating frequency	435 – 438 MHz
Nominal frequency	437 MHz
Gain	15 – 20 dB
Noise figure	< 2 dB
Input impedance	50 Ω
Output impedance	50 Ω
Supply voltage	5 V
Primary purpose	Improve receiver sensitivity

The LNA provides a gain of 15 - 20 dB with a target noise figure below 2 dB, while maintaining a 50 Ω input and output impedance. A 5 V supply is used for operation. Placing the LNA close to the antenna minimizes the effect of cable losses occurring before signal amplification and consequently improves the overall receiver noise performance.

➢ *Band-Pass Filter*

A UHF band-pass filter (BPF) was placed after the LNA to provide frequency-selective filtering before the signal reaches the RTL-SDR. The filter was designed for a 437 MHz centre frequency with a pass band of approximately 430 - 440 MHz, allowing sufficient margin for Doppler-induced frequency variations. The main design specifications are presented in Table 2.

Table 2 BPF Design Specifications

Parameter	Target
Center frequency	437 MHz
Passband	≈ 430 – 440 MHz
Insertion loss	<3 dB
Return loss	>10 dB
Impedance	50 Ω
Application	UHF satellite reception

The filter has a target insertion loss of less than 3 dB, return loss greater than 10 dB, and 50 Ω input and output impedance. By attenuating signals outside the desired UHF satellite band, the BPF reduces the possibility of strong out-of-band signals overloading the RTL-SDR front end and improves the quality of the received satellite signal.

➢ *RTL-SDR Receiver*

The RTL-SDR was selected as the SDR front end because of its low cost, compact size, and USB interface. It receives the conditioned UHF signal from the BPF, performs frequency tuning and digitization, and transfers the resulting I/Q samples to the host computer for further processing. The overall signal-processing sequence is shown in Figure 3.

Fig 3 SDR Signal Processing Sequence

The subsequent processing, including digital filtering, Doppler correction, demodulation, and decoding, is performed using HDSDR software. This configuration provides a flexible and reconfigurable platform for UHF satellite signal reception.

➢ *Satellite Signal Reception Procedure*

The satellite reception experiment was conducted by first orienting the Crossed Yagi-Uda antenna toward the predicted satellite pass and connecting the RF chain in the sequence as shown in Figure 1. The RTL-SDR was then connected to the host computer, and the receiver frequency, sample rate, and RF gain were configured according to the target satellite signal.

During each satellite pass, the SDR waterfall display was monitored to identify the satellite carrier or beacon. The received signal strength and signal-to-noise ratio (SNR) were recorded, followed by Doppler frequency correction, demodulation, and telemetry decoding where applicable. To evaluate the contribution of the RF front-end components, measurements were performed with and without the LNA and BPF stages, and the resulting received signal strength, SNR, and signal detectability were compared.

➢ *Performance Evaluation Parameters*

The performance of the proposed ground-station system was evaluated using received signal strength, signal-to-noise ratio (SNR), frequency error, Doppler shift, and signal detectability. Received signal strength was used to assess the effectiveness of the RF chain in capturing weak satellite signals, while SNR was used to quantify signal quality and is given by:

$$SNR = 10\log_{10}\left(\frac{P_s}{P_n}\right) \quad (5)$$

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Where: P_s is the received signal power and P_n is the noise power.

The frequency error was determined from the difference between the expected satellite carrier frequency and the measured received frequency. The Doppler shift resulting from the relative motion between the satellite and ground station was estimated as:

$$f_d = \frac{v_r}{c} f_c \tag{6}$$

Where: v_r is the radial velocity, c is the speed of light, and f_c is the carrier frequency.

Signal detectability was assessed based on the successful identification and demodulation of the satellite beacon. The system was further evaluated by comparing these parameters with and without the LNA and BPF stages to determine their contribution to overall receiver performance.

IV. RESULTS AND DISCUSSION

➢ *Antenna Performance*

The crossed Yagi-Uda antenna was evaluated around the nominal 437 MHz operating frequency. The measured results are presented in Table 3.

Table 3 Crossed Yagi-Uda Antenna Measurements

Parameter	Measured Result	Design Target
Centre frequency	437.2 MHz	437 MHz
Operating bandwidth	431 - 442 MHz	≥430 - 440 MHz
VSWR at centre	1.32	<1.5
Return loss	17.1 dB	>14 dB
Input impedance	48.6 Ω	50 Ω
Forward gain	10.8 dBi	>9 dBi
Front-to-back ratio	18.4 dB	>15 dB

The antenna achieved a centre frequency of 437.2 MHz, with a VSWR of 1.32**,** 17.1 dB return loss, and an input impedance of 48.6 Ω, indicating good impedance matching to the 50-Ω receiver chain. The measured 10.8 dBi forward gain and 18.4 dB front-to-back ratio confirm adequate directional performance for receiving weak UHF LEO satellite signals.

➢ *LNA Performance*

The LNA was evaluated independently at the nominal 437 MHz operating frequency before integration with the BPF and RTL-SDR. The measured performance is presented in Table 4.

Table 4 LNA Performance

Parameter	Result
Centre frequency	437 MHz
Gain	18.2 dB
Noise figure	1.5 dB
Input return loss	14.8 dB
Output return loss	16.2 dB
Supply voltage	5 V
Current consumption	85 mA

The LNA provided a gain of 18.2 dB with a low noise figure of 1.5 dB, indicating effective amplification of weak received signals with limited additional noise. The input and output return losses of 14.8 dB and 16.2 dB, respectively, indicate satisfactory impedance matching. The measured characteristics confirm the suitability of the LNA for improving the sensitivity of the proposed UHF satellite receiver.

➢ *BPF Performance*

The BPF was evaluated at the nominal 437 MHz operating frequency, with emphasis on its insertion loss and out-of-band attenuation. The measured results are presented in Table 5.

Table 5 Band-Pass Filter Performance

Parameter	Result
Centre frequency	437 MHz
Passband	430 - 440 MHz
Insertion loss	2.1 dB
Return loss	15.4 dB
Attenuation at 400 MHz	31 dB
Attenuation at 470 MHz	35 dB

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The BPF exhibited an insertion loss of 2.1 dB across the desired pass-band and provided 31 dB and 35 dB attenuation at 400 and 470 MHz, respectively. These results demonstrate effective spectral selectivity and suppression of out-of-band interference. The filter therefore complements the LNA by improving signal selectivity before the RF signal enters the RTL-SDR.

➢ *Complete RF Chain Performance*

The complete RF chain was evaluated by comparing receiver performance with and without the external antenna, LNA, and BPF. The results are presented in Table 6.

Table 6 Comparison of Receiver Configurations

Configuration	Received Level	SNR	Signal Detectability
RTL-SDR only	−93 dBm	8.4 dB	Weak
Antenna + RTL-SDR	−88 dBm	10.2 dB	Detectable
Antenna + LNA + RTL-SDR	−70 dBm	15.1 dB	Good
Antenna + LNA + BPF + RTL-SDR	−72 dBm	16.7 dB	Very good

The complete configuration achieved the highest SNR of 16.7 dB, despite the BPF introducing approximately 2.1 dB insertion loss. The improvement is attributed to the combined antenna gain, LNA amplification, and suppression of out-of-band interference by the BPF. These results demonstrate that SNR and signal quality are more appropriate indicators of satellite reception performance than received power alone.

➢ *Satellite Signal Reception*

The receiver was configured for a 437 MHz UHF satellite downlink. The reception parameters and observed results are summarized in Table 7.

Table 7 Satellite Reception Performance

Parameter	Result
Nominal frequency	437 MHz
RTL-SDR sample rate	2.4 MS/s
RF bandwidth	25 kHz
Maximum observed Doppler shift	±9.5 kHz
Initial SNR	16.7 dB
Minimum detectable SNR	≈6 dB
Beacon detection	Successful
Demodulation	Successful
Telemetry decoding	Successful

A maximum Doppler variation of approximately ±9.5 kHz was observed during the satellite pass, confirming the need for frequency tracking in LEO reception. Doppler correction was implemented in software, allowing the receiver frequency to be adjusted without modifying the physical RF hardware. The successful beacon detection, demodulation, and telemetry decoding demonstrate the operational capability of the proposed SDR architecture.

The performance evaluation demonstrates that the proposed architecture benefits from the complementary characteristics of its individual components. The Crossed Yagi-Uda antenna provides directional gain and improved polarization compatibility. This is particularly important for LEO satellite reception because the satellite can be located at different elevation and azimuth angles during a pass. Recent Cross-Yagi research has confirmed the suitability of this antenna class for VHF/UHF satellite ground stations [9].

The LNA improves the receiver noise performance by amplifying the weak signal before substantial feeder and subsequent-stage losses occur. Its location immediately after the antenna is therefore important. The BPF provides interference rejection. This is increasingly important in UHF environments where the desired satellite signal can coexist with strong terrestrial signals. The filter prevents some unwanted energy from reaching the RTL-SDR and potentially reducing its dynamic range.

The RTL-SDR provides an inexpensive digitization and frequency-conversion platform. Instead of implementing separate hardware demodulators for each satellite protocol, the host computer can perform filtering, frequency correction, demodulation, decoding, and recording in software. This modular architecture represents one of the principal advantages of the proposed system.

V. CONCLUSIONS

This paper presented the design and performance evaluation of a low-cost Software Defined Radio architecture for UHF satellite ground-station applications. The proposed system combines a Crossed Yagi-Uda UHF antenna, low-noise amplifier, band-pass filter, and RTL-SDR receiver to provide a compact and affordable satellite receiving platform.

The Crossed Yagi-Uda antenna provides directional gain and improved polarization compatibility, while the LNA improves the received signal level and system sensitivity. The BPF provides spectral selectivity and suppresses unwanted signals before digitization. The RTL-SDR provides low-cost RF digitization and allows subsequent demodulation, Doppler correction, filtering, recording, and telemetry processing to be implemented in software.

The experimental evaluation showed a VSWR of approximately 1.32 for the antenna, an LNA gain of approximately 18.2 dB, BPF insertion loss of approximately 2.1 dB, and an improvement in SNR from approximately 8.4 dB for the RTL-SDR-only configuration to 16.7 dB for the complete receiver architecture. These values demonstrate the potential benefit of combining directional antenna gain and appropriate RF conditioning with an inexpensive SDR receiver.

The architecture provides an attractive alternative for universities, research laboratories, amateur satellite operators, and educational institutions requiring an affordable UHF satellite ground station.

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