

Low-cost Satellite Receiver System using RTL-SDR Technology for Weather Monitoring

Nor Azlan Mohd Aris^{1*}, Mawarni Mohamed Yunus¹, Muhammad Aiman Mohd Zarawi¹, Wan Irfan Syahmeey Wan Zaini², Muhammad Faiz Aiman Rezuan¹ and Afiq Shahrulnizam¹

¹Faculty Technology dan Kejuruteraan Elektronik dan Computer, University Technical Malaysia Melaka, Jalan Hang Tuah Jaya, Durian Tunggal, Melaka, Malaysia

²Quadro Technology Sdn Bhd, Puchong, Selangor

*Corresponding Author

DOI: <https://dx.doi.org/10.47772/IJRISS.2025.909000755>

Received: 26 September 2025; Accepted: 02 October 2025; Published: 29 October 2025

ABSTRACT

This paper presents the development of a low-cost satellite receiver system using RTL-SDR technology for capturing NOAA weather satellite signals. The system integrates a cross-dipole antenna and a Low-Noise Amplifier (LNA) to enhance signal reception in the 137-138 MHz frequency range. Software components include SDR# for signal processing and WXtoImg for image generation from Automatic Picture Transmission (APT) signals. Results demonstrate effective signal reception with high Signal-to-Noise Ratios (SNR) and wide antenna coverage, enabling real-time imaging of weather phenomena. The system demonstrates potential applications in meteorology, disaster management, and climate research, offering accessible tools for real-time weather monitoring and analysis. By addressing the barriers of cost and accessibility, it serves as a model for expanding weather-monitoring capabilities, particularly in regions with limited infrastructure. Future improvements aim to optimize antenna design and software capabilities for broader deployment in remote and underserved areas.

Keywords: Weather, Meteorological Satellite, SDR

INTRODUCTION

Satellite technology has become a cornerstone of modern weather monitoring and prediction, providing indispensable data for meteorological analysis on a global scale (Mitra, 2023). The data and imagery from these satellites enable scientists to forecast a wide range of weather phenomena, including temperature, atmospheric pressure, humidity, storm development, and cyclone trajectories (Li et al., 2024; Mitra, 2023). This predictive capability is vital for government agencies in their daily operations and plays a crucial role in safeguarding lives, property, and critical infrastructure from severe weather events.

Moreover, weather satellite imagery plays a pivotal role in advancing climate change studies. For instance, monitoring ocean temperatures using satellite data serves as a critical indicator of marine ecosystem health and stability (Kazemi Garajeh et al., 2024). Additionally, observing fluctuations in atmospheric heat retention enables researchers to gain insights into the effects of rising greenhouse gas emissions, which are a key factor contributing to global climate change (Santer et al., 2017). Furthermore, integrating weather variables into short-term electric load forecasting models has shown to enhance the accuracy of predictions, demonstrating the practical applications of weather data beyond meteorology (Janicki, 2017). While these applications highlight the critical role of satellite data, realizing their full potential requires timely and direct access to imagery and measurements, which is a challenge that persists in many parts of the world.

In practice, real-time access to weather satellite imagery is often constrained by high equipment costs and the need for specialized expertise. Despite their widespread use, access to weather satellite image data in real-time

is limited due to several factors, such as the expensive development cost for a retrieval system and a lack of expertise to decipher the complex information within the data (Ardizzone et al., 2018; Sambasivam et al., 2020; Vidal et al., 2024). Researchers, environmentalists, and climate study enthusiasts can access near real-time satellite data sets through web portals of space agencies for analysis and prediction. However, the unavailability of high-speed internet, particularly in areas without access to fiber optic connections, presents a significant obstacle in obtaining timely weather information. This creates a disparity in weather data accessibility and limits the ability of individuals and communities to make informed decisions based on satellite weather patterns (Burleigh et al., 2019).

To address these limitations, there is a growing need for low-cost, accessible satellite receiving solutions (Rivera et al., 2023; Singh et al., 2022). Recent advancements in Software-Defined Radio (SDR) technology, specifically with devices like the Realtek Software Defined Radio (RTL-SDR), have presented a promising alternative to traditional, bulky, and expensive radio equipment (Jendo, 2019; Sugadev et al., 2022). These affordable and versatile devices enable the reception of signals from weather satellites, such as those from the National Oceanic and Atmospheric Administration (NOAA) series, which transmit continuous Automatic Picture Transmission (APT) signals containing vital weather images.

This study is motivated by the need to democratize access to meteorological information by developing a low-cost weather ground station using RTL-SDR technology. The aim is to create a portable, user-friendly system that can receive and process real-time weather images, thereby enhancing the accessibility and affordability of satellite-based weather data reception (Bosquez et al., 2016; Jendo, 2019; Quiroz-Olivares et al., 2019; Sugadev et al., 2022). While the development of low-cost satellite receivers has been explored globally, such systems are not yet widely adopted in Malaysia. This project presents a pioneering effort to develop and validate a functional, affordable ground station for real-time weather monitoring within a local academic setting.

METHODOLOGY

The system's architecture, as depicted in Figure 1, is a two-part framework comprising hardware and software components. The hardware components (antenna, low-noise amplifier (LNA), and RTL-SDR) receive and convert the satellite signal, which is then processed by a chain of software (SDR# and WXtoImg) to generate the final weather image. Gpredict is used for satellite tracking. To realize this architecture, both hardware and software elements were designed and integrated to ensure that each stage, from signal capture to image generation, operates efficiently.

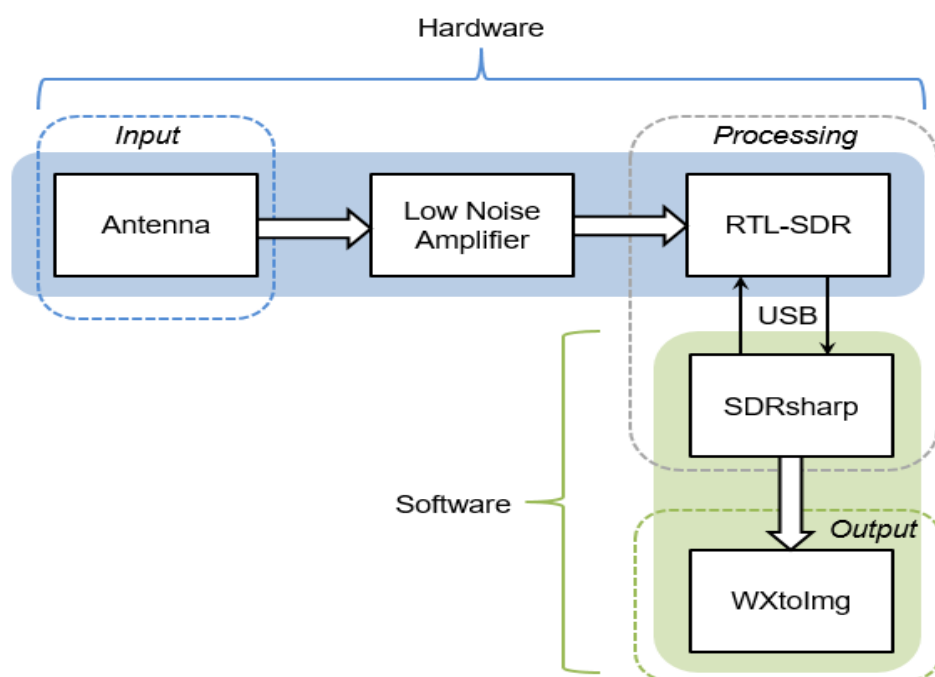


Figure 1. Architectural overview of the low-cost satellite ground station.

The following subsections detail the development of the hardware and software components. The hardware chain is responsible for receiving and converting the raw satellite signal, while the software chain handles the processing, decoding, and visualization of the data. This integrated workflow ensures a complete process from data capture to the final weather image output.

Hardware Development

The hardware components of this low-cost ground station include a Realtek Software-Defined Radio (RTL-SDR), a Low-Noise Amplifier (LNA), a custom-built cross-dipole antenna, and a laptop. The RTL-SDR dongle acts as a versatile receiver, capturing the satellite signals and interfacing with the software on the laptop. An LNA is integrated into the system to boost the weak satellite signals, which are susceptible to degradation over long distances. This component is essential for preserving the signal's quality before it reaches the RTL-SDR, as it directly impacts the overall Signal-to-Noise Ratio (SNR) and the clarity of the final decoded image.

A cross-dipole antenna was chosen for its effective reception of the circularly polarized APT signals from NOAA satellites, which transmit within the 137-138 MHz frequency band. The antenna's design was first simulated and optimized using CST Studio Suite to ensure optimal performance, as shown in Figure 2.

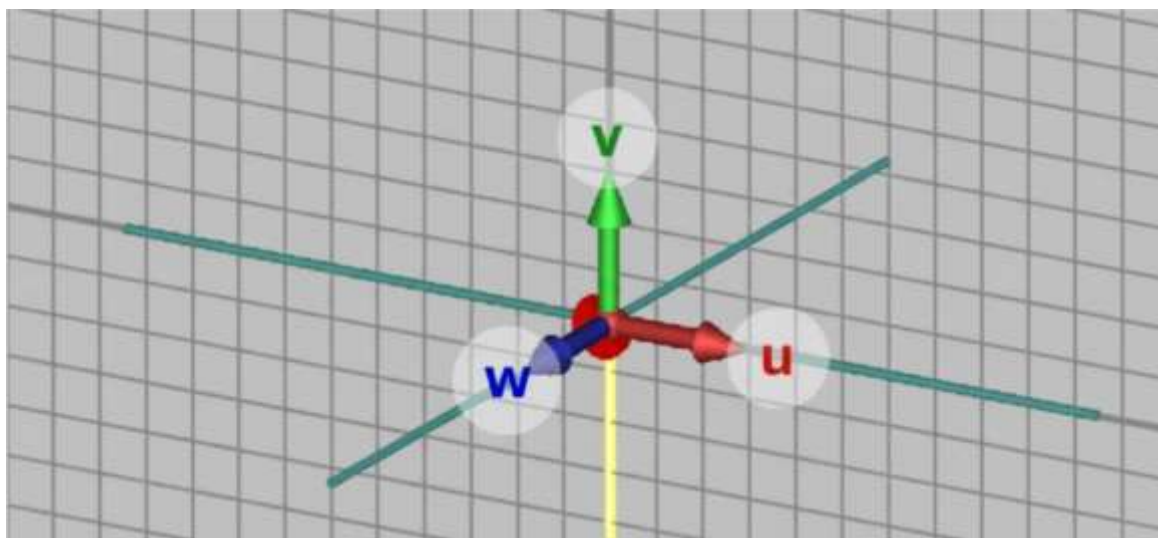


Figure 2. Cross-dipole antenna design simulation in CST Studio Suite

Following the simulation, the antenna was physically constructed using four copper rods arranged perpendicular to each other, forming a cross shape. These rods are connected via coaxial cable loops and mounted on a PVC support structure for stability. This setup, depicted in Figure 3, allows for stable and reliable signal reception.

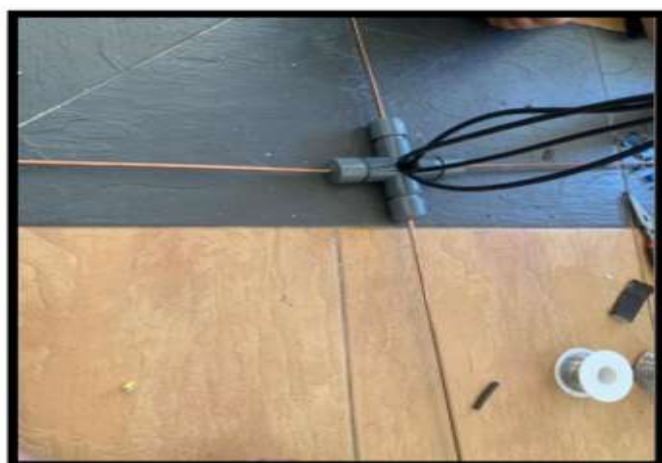


Figure 3. Construction of the cross-dipole antenna, showing the copper rods and PVC mounting

Software Development

The software components are essential for processing the raw data received by the hardware. SDRSharp (SDR#) is utilized for signal demodulation and tuning. This software configures the RTL-SDR and processes the raw radio signals into a demodulated audio stream, as illustrated by the tuned spectrum in Figure 4. For satellite tracking, Gpredict provides real-time orbital data such as the satellite's azimuth and elevation, which is crucial for aiming the antenna correctly.

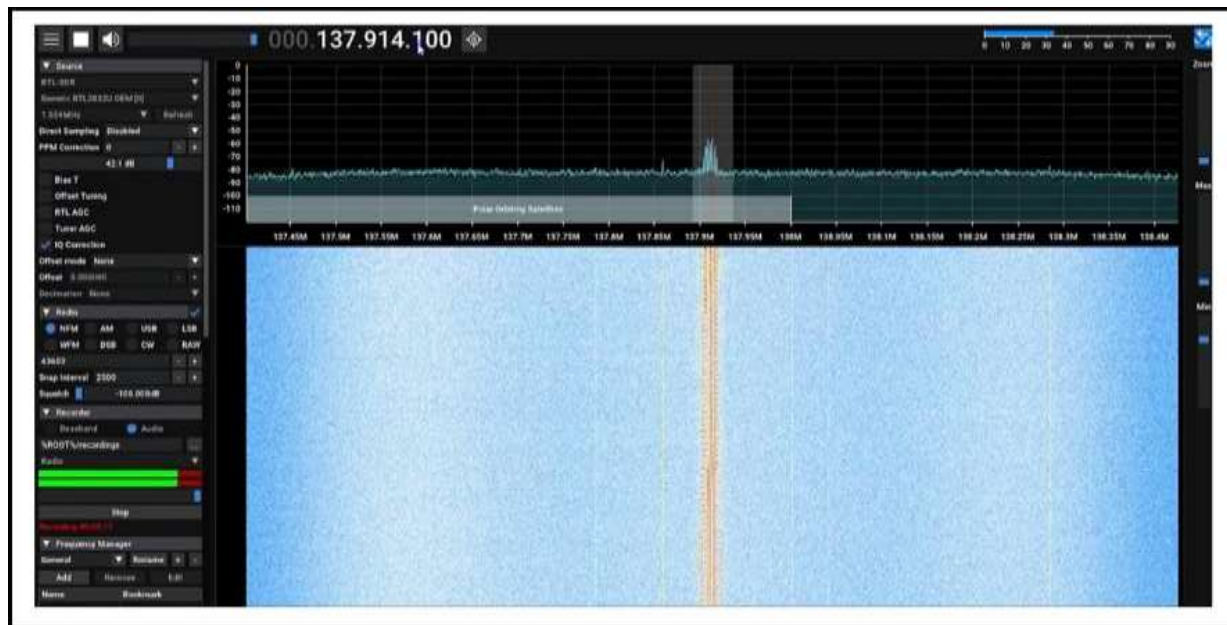


Figure 4. SDR# software interface tuned to the NOAA APT frequency, showing the signal spectrum and waterfall display

Finally, WXtoImg processes the audio output from SDR# to decode the APT signal and generate the final weather images. The recording and decomposition process within WXtoImg is shown in Figure 5. This software suite creates a seamless pipeline from raw signal to a usable weather image.

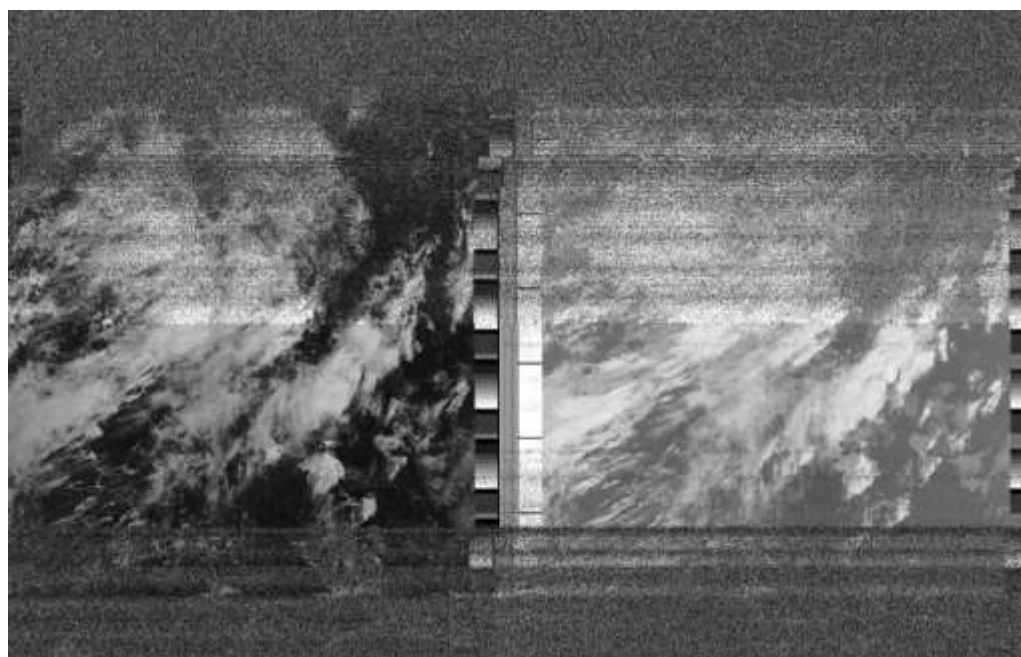


Figure 5. The process of recording and decoding an APT signal in WXtoImg, from the raw recording (left) to the decomposed image (right)

Experimental Setup

The complete system was deployed for live signal reception and testing on the rooftop of the Faculty of Electronic and Computer Technology and Engineering (FTKEK) building, at the University Technical Malaysia Melaka (UTeM) main campus, providing a clear line of sight critical for optimal satellite communication. This practical implementation at a local university demonstrates the system's viability for educational and research applications in the region. The field setup, including the antenna and data acquisition equipment, is shown in Figure 6.



Figure 6. Satellite ground station system set up for a field test

RESULTS AND DISCUSSION

This section presents a detailed analysis and discussion of the performance of the developed satellite ground station, focusing on the key metrics of its hardware, and the quality of the resulting APT images. To evaluate the performance of the developed system, measurements focused on two key aspects: (1) the antenna and LNA performance, which directly influence signal quality, and (2) the accuracy and clarity of the decoded images.

Antenna and LNA Testing Results

As depicted in Figure 7, the S11 parameter analysis of the cross-dipole antenna showed an impedance bandwidth (with a return loss ≤ -10 dB) of 16.2 MHz, covering frequencies from 130 to 147.2 MHz. This bandwidth corresponds to approximately 11.8% relative to the central frequency of 137.6 MHz, meeting the criteria for receiving NOAA APT signals effectively. The return loss at -40.086 dB indicates that over 99.64% of the power is absorbed by the antenna, with less than 1% being reflected. Such a high return loss value signifies a well-matched impedance, which is essential for achieving optimal antenna performance.

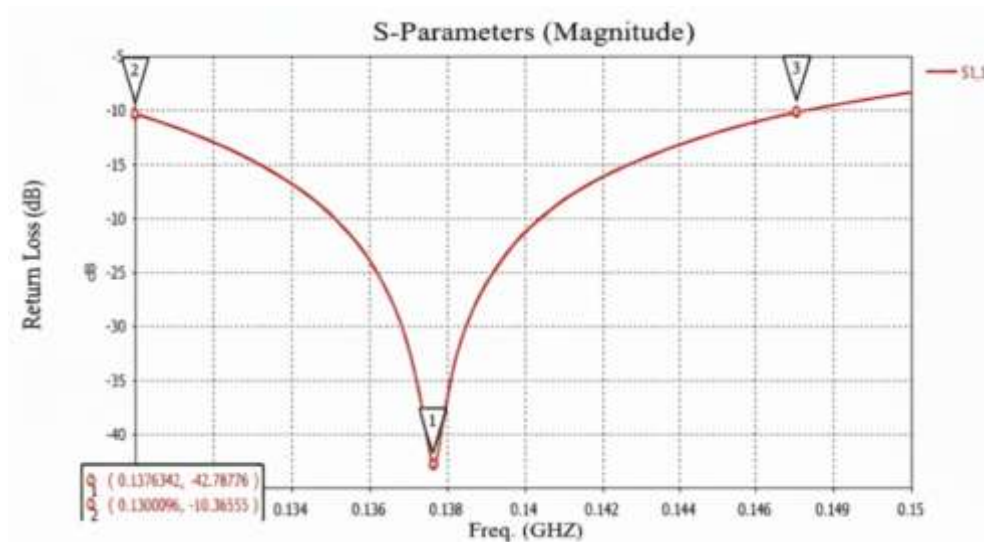


Figure 7. Simulated S11 return loss of the custom-designed cross-dipole antenna

The radiation pattern illustrated in Figure 8 shows the antenna's main lobe gain of 2.12 dBi and relatively wide beamwidth of 78.7°. This wide coverage area would be useful for monitoring satellites across the sky without needing accurate pointing or mechanical tracking. Hence, this simplifies the system, reduces cost, and makes it more accessible for amateurs.

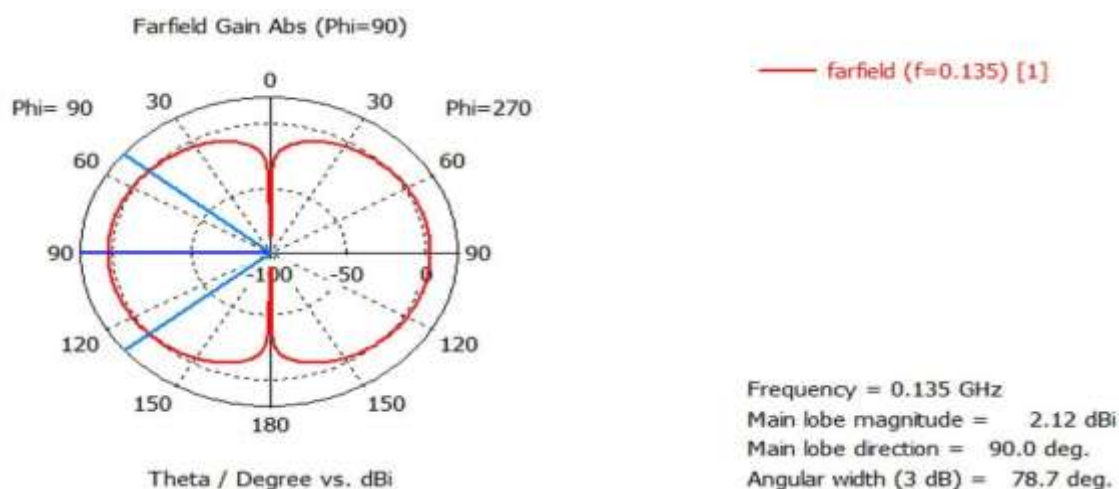


Figure 8. Simulated vertical plane radiation pattern of the cross-dipole antenna at 137 MHz, illustrating its main lobe gain and wide beamwidth, which simplifies satellite tracking

LNA noise characteristics were then evaluated with RF gain optimized to 11 dB on RTL-SDR. Table 1 presents the Signal-to-Noise Ratio (SNR) measurements at specified frequencies. The high average SNR of 27.78 dB as tabulated in Table 1 is a direct result of the effective integration of the LNA with the antenna. This robust SNR performance is critical, as it ensures that the raw signal is strong enough for accurate decoding by the software, leading to the clear, high-quality images as presented in Figures 9 and 10. This result validates the design choice to include an LNA for a reliable and high-performance system, demonstrating the effectiveness of the LNA in maintaining high signal clarity across the NOAA frequency band.

Table 1. Signal-to-Noise Ratio (SNR) measurements of the received signal,

Frequency (MHz)	Psignal (dBm)	Pnoise (dBm)	SNR (dB)
137.1	-97.2354	-133.7854	36.5500
137.3	-109.8391	-132.7845	22.9454
137.5	-99.9903	-134.0973	34.1070
137.6	-110.7829	-133.9987	23.2158
137.7	-110.0078	-130.7862	20.7796
137.8	-106.9876	-132.9888	26.0012
137.9	-99.9978	-130.8933	30.8995
			27.78

Acquisition Results

The analysis of weather images observed by the receiver system was performed on June 18 and 20, 2023, at 10:40 AM and 11:24 AM local time, respectively. Figures 9 and 10 show imagery captured by a NOAA satellite using multiple infrared channels as described in the setup. The successful real-time acquisition of weather images from NOAA-19 and NOAA-18 satellites on two separate dates validates the system's operational capability. This method allows direct reception of weather satellite images on the screen without reliance on central communication networks.

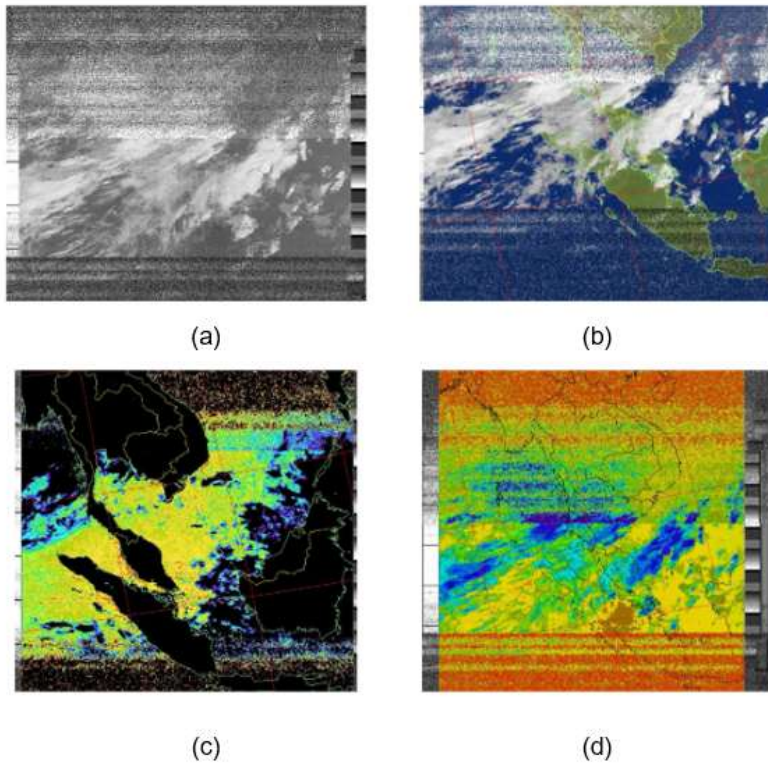


Figure 9. NOAA-19 satellite images captured on June 18, 2023. Image (a) shows the raw recording, (b) is the High-Level Cloud (HVC) image, (c) highlights sea surface temperatures, and (d) displays the thermal image.

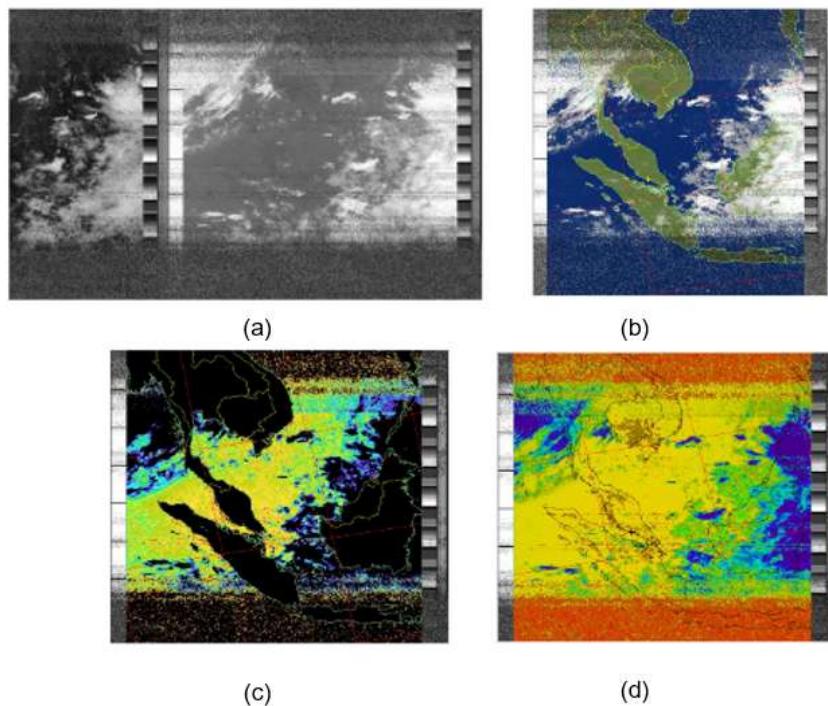


Figure 10. NOAA-18 satellite images captured on June 20, 2023. Image (a) shows the raw recording, (b) is the High-Level Cloud (HVC) image, (c) highlights sea surface temperatures, and (d) displays the thermal image.

The processed images demonstrate the system's ability to generate meaningful meteorological data. Different hues and tones in the High-Level Cloud (HVC) false-color image differentiate between different types of clouds at lower altitudes and high-level clouds, typically composed of ice crystals and occurring at higher altitudes. Meteorologists and researchers can use such images to track weather systems, evaluate cloud patterns, and understand atmospheric conditions crucial for climate monitoring and weather forecasting. For instance, the ability to distinguish high-level clouds in near real-time (as seen in Figures 9b and 10b) is particularly valuable

for local aviation and maritime warnings in the Strait of Malacca, as these cloud types are often associated with developing convective systems and potential turbulence.

Darker or bluer colors in thermal images signify colder temperatures, while brighter or redder colors indicate warmer temperatures. This facilitates the identification of warm and cold fronts, identifies potential precipitation locations, and tracks variations in atmospheric heat. Similarly, color tones in sea surface images provide researchers with valuable information on ocean temperatures, aiding in the study of climate change effects on marine ecosystems. The captured images of the Malaysian peninsula and surrounding sea surfaces (Figures 9 and 10) directly demonstrate the system's capability for localized weather monitoring. This capability can be leveraged for various applications such as agricultural planning, local disaster preparedness, and climate research specific to the Southeast Asian region. Specifically, the sea surface temperature data (Figures 9c and 10c) can serve as a direct input for local climate models or provide agricultural stakeholders with data on microclimates, influencing planting and harvesting decisions. This transforms the system from a technical demonstration into a practical tool for regional decision-making.

System Performance, Limitations, and Operational Considerations

While our results show the system works well, a practical perspective requires acknowledging its performance context and operational limitations. At the heart of our system is the RTL-SDR, a device that delivers remarkable capability for its cost. Although a direct benchmark against high-end commercial receivers was beyond this project's scope, our achieved SNR values and image clarity align well with findings from similar low-cost stations documented in the literature (e.g., Ardizzone et al., 2018; Bosquez et al., 2016; Quiroz-Olivares et al., 2019). This shows that the RTL-SDR is a solid, budget-friendly option for educational purposes and non-critical monitoring, especially when budgets are tight.

That said, taking the system from a prototype to something that can be used reliably in the field brings up some real challenges. The system's performance can be affected by signal interference, especially in urban areas with significant radio frequency (RF) noise. This makes careful antenna placement, with a clear line of sight to the sky and away from electronic noise, essential for success. While the antenna's wide beamwidth is forgiving, significant antenna misalignment can still degrade signals from satellites at low elevations.

Beyond the physical setup, making the system truly accessible for non-technical users presents further challenges. The current software process, which requires navigating multiple applications, demands a certain level of technical skill. For the system to be adopted more widely, this workflow needs to be simplified. Finally, ensuring long-term reliability involves practical maintenance, such as weatherproofing the antenna against tropical conditions and maintaining the computer hardware, all of which are vital for sustained, autonomous operation.

CONCLUSION

This work addresses the challenge of making real-time weather satellite imagery accessible to a wider audience by developing an affordable and portable RTL-SDR-based ground station. The results confirm that such a system can reliably capture and decode NOAA signals. The project successfully captured and decoded NOAA satellite signals with affordable hardware and open-source software like WXtoImg and SDR#. An optimized antenna design and integrated LNA improved signal reception, evidenced by SNR performance and radiation pattern analysis. The system generates real-time weather images, aiding agriculture, disaster management, and climate research. It supports early warning systems and informed decision-making. Future improvements in antenna design and software could enhance performance and usability in remote areas, benefiting educational institutions and amateur radio operators. With further refinements, similar systems could empower local communities, educators, and researchers to engage directly with meteorological data, strengthening resilience to extreme weather events.

ACKNOWLEDGEMENT

The authors are grateful to the Faculty Technology dan Kejuruteraan Elektronik dan Computer (FTKEK), Centre

for Research and Innovation Management (CRIM) and University Technical Malaysia Melaka (UTeM) for the opportunity, support and resources.

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