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# Hardware Prototyping of Real Time Weather Satellite Tracking System

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***Abstract: This project presents the design and implementation of an automated antenna tracking system for capturing real-time weather images transmitted by polar-orbiting satellites, particularly the National Oceanic and Atmospheric Administration (NOAA) satellite series. The system employs satellite orbital prediction data to automatically control the azimuth and elevation positioning of a directional antenna, ensuring reliable signal reception during satellite passes. It combines mechanical antenna movement, embedded system control, sensor-based feedback, and a software-defined radio receiver using the RTL-SDR v3 platform. The main aim of this work is to develop a dual-axis antenna tracking mechanism by integrating satellite prediction software with a hardware rotator system. The proposed solution is designed to be portable, affordable, and suitable for educational and research applications, especially for students, researchers, and hobbyists interested in Earth observation and amateur radio communication. By replacing expensive commercial antenna rotators with a microcontroller-based control system, the project encourages practical learning through hands-on experimentation. Furthermore, the study examines several practical challenges involved in satellite signal reception, including Doppler shift effects, signal-to-noise ratio (SNR), antenna alignment precision, hardware implementation, and software-based signal processing and interpretation.***

***Keywords: Antenna Tracking System; NOAA; Derived Detail Image; Average Morphological Similarity indices; Textural indices; Classification***

## I. INTRODUCTION

Weather satellites operated by the National Oceanic and Atmospheric Administration (NOAA) continuously broadcast Automatic Picture Transmission (APT) signals containing real-time meteorological image data. Fig. 1 illustrates the trajectory of a polar-orbiting satellite. Since these satellites travel in near-polar orbits, they remain visible to a ground station for only a short duration during each pass. Therefore, precise antenna tracking is essential to maintain strong signal reception and obtain high-quality weather images. Conventional satellite tracking systems are often costly and technically complex, which limits their accessibility for educational and experimental purposes [1]. The present work addresses these challenges by developing a low-cost and automated antenna tracking system using easily available components. The proposed system determines the real-time satellite position from publicly available orbital and trajectory data, then automatically adjusts the antenna orientation to optimize signal reception quality. The received APT signals are subsequently processed and decoded into weather images using freely available software tools, as illustrated in Fig. 2. The figure displays three software windows operating simultaneously: one window shows the Software-Defined Radio (SDR) receiver capturing satellite signals, another displays the antenna rotator control along with satellite trajectory prediction and tracking information, while the third window processes and decodes the received signals into real-time weather images transmitted by polar-orbiting satellites.

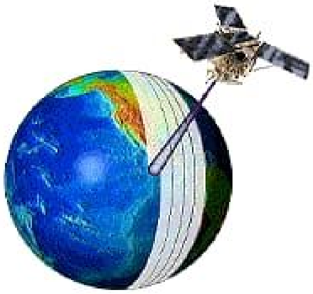
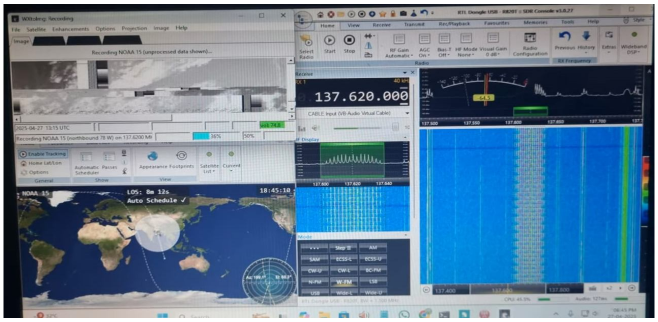


Fig. 1- Polar orbiting satellite trajectory



Recording NOAA 15 (unprocessed data shown)...
2025-04-27 13:15 UTC
Recording NOAA 15 (northbound 78 W) on 137.6200 MH
LOS: 8m 12s
Auto Schedule ✓
137.620.000
CABLE Input (VB-Audio Virtual Cable)

Fig. 2- Software interterfacing

Rest of the paper is organized as follows. In section II, the proposed methodology is described in detail. Experimental results are reported in section III, discussion and conclusion of this work are summarized in section IV and section V respectively.

## II. METHODOLOGY

The proposed system operates on the principle of a dual-axis control mechanism. It consists of two motorized axes positioned perpendicular to each other at an angle of 90°, as illustrated in Fig. 3. These two axes enable azimuth and elevation movements, allowing the antenna to accurately align toward the desired satellite direction. Two 12 V DC geared motors with a rotational speed of 0.6 RPM are employed to drive the antenna rotator mechanism.

Fig. 4 illustrates the perpendicular drilling arrangement used for mounting the motors onto a metal enclosure to ensure structural rigidity and stability. Proper motor selection and mechanical design are critical aspects of the system because unwanted movements such as backlash or jitter can negatively affect the tracking accuracy. Excessive mechanical play may interfere with the control mechanism and potentially lead to instability in the antenna tracking system.

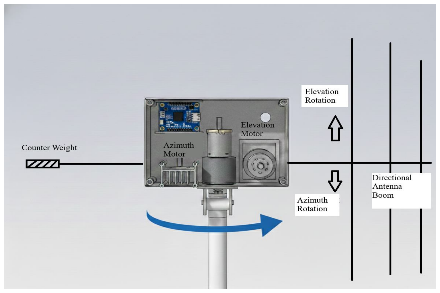


Fig. 3- Schematic of Mechanical Model

Fig. 4- Motor Assembly

The DC motors used in the antenna rotator are driven by two H-bridge motor driver circuits. In this project, the L298N Motor Driver Module based driver is selected due to its wide availability and support for PWM control, which enables smooth and controlled motor rotation. To determine the antenna's orientation and directional position, a three-axis accelerometer and three-axis magnetometer sensor, the LSM303DLHC, is mounted along the antenna boom. Proper calibration and alignment of the sensor with the antenna axis are essential for achieving accurate position measurements. The sensor communicates through the I2C interface and provides 16-bit digital output data, allowing precise orientation sensing. To minimize measurement errors, the sensor wiring is shielded and positioned away from magnetic, ferromagnetic, and electrically noisy environments, as shown in Fig. 5. The core control unit of the antenna rotator is based on an AVR microcontroller platform. Both the Arduino Nano and Arduino Uno R3 are used during the testing and final implementation stages. These microcontrollers were selected because of their popularity, extensive open-source community support, and availability of software libraries that simplify development.

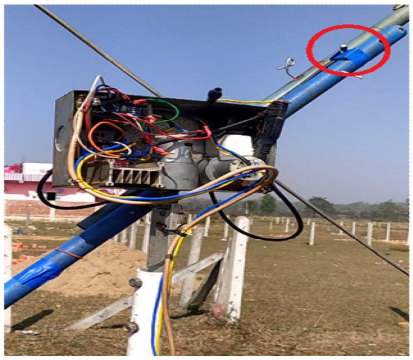


Fig. 5- Sensor Mounting

### *A. Rotator Circuit assembly*

The overall system configuration is illustrated in the block diagram shown in Fig. 6, where the major components of the antenna rotator system are represented. At the core of the system is the AVR-based microcontroller, which functions as the primary control unit of the antenna tracking mechanism. The MEMS-based orientation sensor is connected to the microcontroller through shielded I2C communication lines to ensure reliable data transmission with minimal interference. The microcontroller processes the positional data obtained from the three-axis magnetometer and accelerometer sensor and executes the control algorithms required for antenna positioning. Based on these calculations, rotation control signals are sent to the dual H-bridge motor driver, specifically the L298N Motor Driver Module, which drives the DC motors responsible for antenna movement. PWM signals with dead-time control are applied to the motors to achieve smooth and stable rotation, allowing accurate positioning of the antenna assembly in both azimuth and elevation directions. The antenna rotator receives rotation commands in the form of azimuth (AZ) and elevation (EL) coordinates from a computer running the Gpredict satellite orbit prediction program. The software continuously calculates the satellite trajectory and communicates the required positioning data to the microcontroller for real-time antenna tracking.

Since the system is highly sensitive to electrical noise, particular attention is given to minimizing electromagnetic interference generated by the motor drive circuitry, which could otherwise affect antenna reception performance. To reduce such disturbances, shielded wiring and careful cable management techniques are implemented throughout the system after extensive testing and optimization.

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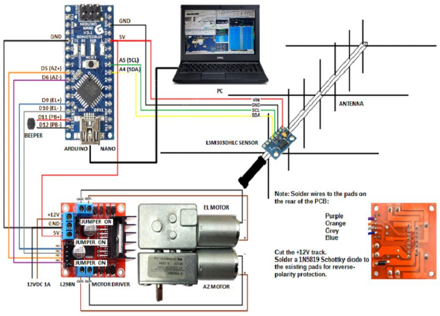


Fig. 6- Circuit Diagram of Rotator

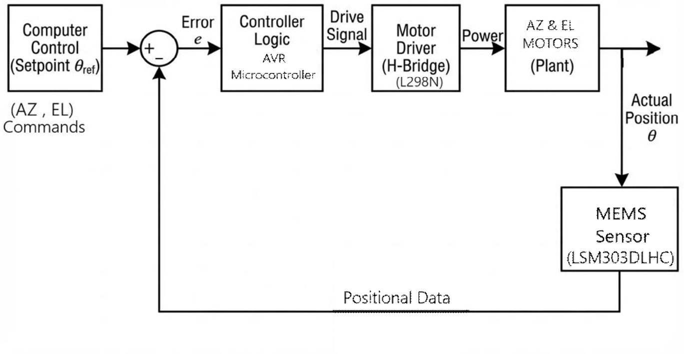


Fig. 7- Schematic diagram of the Control System of the rotator

The control circuit of the rotator system is shown in Fig. 7. The commands were taken from the controlling software as AZ and EL data as well as sent back to the computer from the rotator as well (Amset Easycom 2 Protocol). The control logic in the rotator is then read and processed the target and actual data for rotation signal generation for the azimuth and elevation motors.

Communication and Protocol

The system interacts with external Tracking Software (e.g., G-predict,orbitron or other tracking software) in our case “G-Predict” via the AMSAT EasyComm II protocol.

- PC to MCU: Commands are sent as ASCII strings: AZ[val] EL[val].
- MCU to PC: The MCU returns current status: AZ[curr] EL[curr].

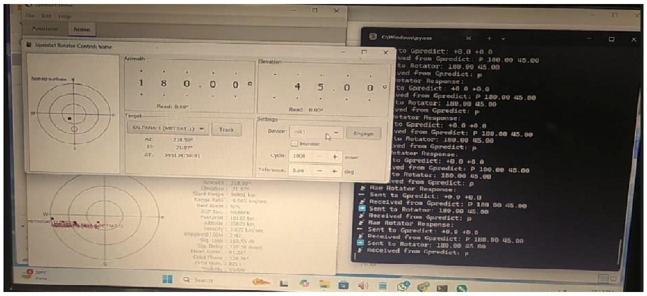
The MCU processes these strings using a simple Serial Parser, converting the ASCII values into floating-point Setpoints for the control loop.

### *B. Rotator interface on PC*

The microcontroller communicates with the computer through a USB interface, as illustrated in Fig. 8. A computer running Windows 11 is used to operate the antenna rotator control software as well as the satellite signal decoding applications. Once connected, the rotator appears on the computer as a serial COM port, enabling communication between the computer and the microcontroller through serial communication at a baud rate of 9600 bps.

To establish coordination between the antenna rotator and the satellite tracking software, a custom Python program was developed. This program interfaces with the rotator through the serial USB connection while simultaneously communicating with the satellite prediction software using SSH-based data transfer. In this project, Gpredict is utilized as the primary satellite tracking and orbit prediction software. By using updated Keplerian orbital data, the software continuously generates real-time satellite positional information and transmits tracking data through a host address and communication port. The custom Python application, shown running in the terminal window on the right side of Fig. 8, acts as an intermediary between the tracking software and the hardware rotator, ensuring reliable antenna control and synchronization during satellite passes. In addition to Gpredict, other open-source satellite tracking programs such as Orbitron can also be integrated into the system.

The open-source nature of these community-driven software projects greatly simplifies system integration and customization. It also provides an excellent educational platform for experimenting with satellite communication technologies, allowing users to learn about hardware-software interaction, signal tracking, and antenna control in a practical and engaging manner.



```
to Gpredict: +0.0 +0.0
ved from Gpredict: P 180.00 45.00
to Rotator: 180.00 45.00
ved from Gpredict: p
otator Response:
to Gpredict: +0.0 +0.0
ved from Gpredict: P 180.00 45.00
to Rotator: 180.00 45.00
ved from Gpredict: p
otator Response:
to Gpredict: +0.0 +0.0
ved from Gpredict: P 180.00 45.00
to Rotator: 180.00 45.00
ved from Gpredict: p
otator Response:
to Gpredict: +0.0 +0.0
ved from Gpredict: P 180.00 45.00
to Rotator: 180.00 45.00
ved from Gpredict: p
Raw Rotator Response:
Sent to Gpredict: +0.0 +0.0
Received from Gpredict: P 180.00 45.00
Sent to Rotator: 180.00 45.00
Received from Gpredict: p
Raw Rotator Response:
Sent to Gpredict: +0.0 +0.0
Received from Gpredict: P 180.00 45.00
Sent to Rotator: 180.00 45.00
Received from Gpredict: p
```

Fig.8- Rotator interfaceing

### C. *Sensor calibration and testing*

Sensor calibration and testing are performed after the fitting and assembly processes. For sensor calibration, a 3-axis movement jig as shown in Fig. 9 is developed to provide stable movement along all three axes. Using this setup, the MEMS sensor (LSM303DLHC) is calibrated, and the calibration data is stored in the EEPROM of the AVR microcontroller. The jig enables precise movement while displaying the changing calibrated data flow as the sensor moves, ensuring that the measured data is accurately recorded and saved. In addition, the magnetic declination of the installation location is programmed into the system to compensate for magnetometer measurements and improve calibration accuracy.

Since the “scrcnet rotator mk1” [1] was designed to perform calibration and control operations, it carries out these functions in a similar manner. The program also supports an external buzzer to assist during calibration. Whenever new calibration data is written, the buzzer connected to the microcontroller produces a sound, indicating that the data is being received and stored successfully.

Calibration is performed for all 12 directions in the 3D plane. This step is highly important because incorrect calibration may cause the rotator to behave improperly, resulting in malfunction or oscillation.

The AVR program also includes additional features. Through the serial monitor window, users can send commands to interact with the rotator, perform sensor-data calibration, and store the calibrated values in the EEPROM. It is also necessary to save the magnetic declination angle of the user’s location using the serial commands described below:

Enter two integers AZ and EL in degrees separated by a space to manually control the rotator. e.g. 270 45<Enter> Note: AZ here works in either 0~180~360 or -180~0~180 degree format.

- r - Reset. Prints the calibration data. Resets the rotator to the home position and resets the windup value.
- b - Debug mode. Prints the raw sensor data: Mx, My, Mz, Gx, Gy and Gz.
- c - Calibrate mode. Displays the calibration data only when it changes.
- d - Demo mode. Tracks linearly through the following AZ/EL points in a cycle: 0/0, 90/90, 0/180, 90/90 0/0, -90/90, -180/0, -90/90, 0/0
- m - Monitor mode. Prints current AZ and EL, set points for AZ and EL, the AZ windup angle, the AZ windup state, the AZ and EL error.

Fig. 9- Axis Movement Jig

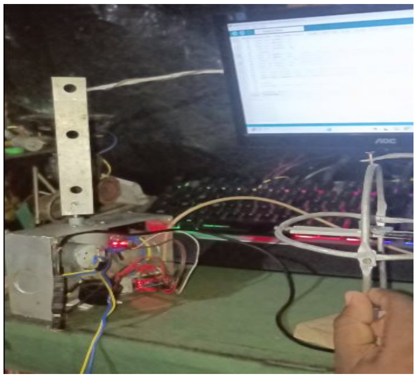


Fig. 10- Sensor Calibration

- a - Abort Calibrate, Monitor or Demo mode
- e - Enter Magnetic Declination. e.g. e11.7<Enter>. It is positive for East or negative for West.
- s - Save Magnetic Declination and Calibration Data.
- h – Help
- p – Pause

The Fig. 10 shows the calibration process of the sensor, where the fixture rotates the sensor while the data is recorded and monitored through the serial monitor window. Slow and steady movement is essential for achieving accurate sensor calibration. After all calibration values are saved, the rotor’s movement direction is tested manually by moving the sensor and observing the response. Once satisfactory results are obtained, the rotator is fully assembled and prepared for operation through computer commands.

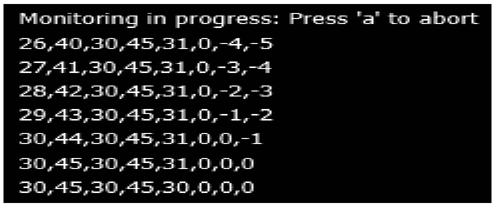
The rotator is then moved outdoors and tested with the antenna and counterweight attached to ensure complete rotational movement along all rotor axes, as shown in Fig. 11. In this stage, the demo program is executed to verify the full-degree rotational capability of the rotator and to evaluate software features such as anti-windup protection, which prevents wire entanglement. The tests also ensure that the rotation speed and tracking position are functioning correctly.

The serial monitor window shown in Fig. 4.4 displays several parameters in sequence, including:

- Current AZ (Azimuth)
- Current EL (Elevation)
- Targeted AZ
- Targeted EL
- AZ windup angle
- Windup state
- Error AZ
- Error EL

During testing, the speed, response time, and unwanted oscillations of the system are adjusted through the program. Parameters such as alpha and beta values, along with the motor PWM dead-time gain, are tuned to achieve smooth, precise, and fast movement of the rotator.

Fig. 11- Testing Rotator with Associated load



```
Monitoring in progress: Press 'a' to abort
26,40,30,45,31,0,-4,-5
27,41,30,45,31,0,-3,-4
28,42,30,45,31,0,-2,-3
29,43,30,45,31,0,-1,-2
30,44,30,45,31,0,0,-1
30,45,30,45,31,0,0,0
30,45,30,45,30,0,0,0
```

Fig. 12- Serial Monitor Data

### *D. Antenna and RF data reception*

In this project, we aimed to track satellites in Low Earth Orbit (LEO). Since several of these satellites operate in the VHF band around 137 MHz, a directional Yagi–Uda antenna was also designed and constructed for signal reception. The antenna consists of three elements and provides an approximate gain of 7.5 dB. Antenna specification is given below:

- Frequency f: 137 MHz
- Wavelength λ: 2 m 188 mm
- Element diameter: 7.3 mm…21.9 mm ( min.: 0.003λ , max.: 0.01λ )
- Approx. antenna gain: 7.3 dBi
- Bandwidth by VSWR less than 2: 10 MHz (approx.)
- Reflector length R: 1 m 130 mm
- Dipole length V: 1 m 24 mm
- Dipole-reflector distance S1: 376 mm
- Director length D: 930 mm
- Dipole-director distance S2: 300 mm
- Minimum boom length Bl: 698 mm

Open source tools such as *yagi_uda_antenna_DL6WU.php* were used to calculate the design parameters for the Yagi–Uda antenna. Although the antenna is intended only for signal reception (RX), it provides a beamwidth of approximately 68°–70° in the E-plane and 135°–150° in the H-plane, as shown in Fig. 13. The antenna boom is made of non-conductive PVC material, and a counterweight is attached at the opposite end to balance the antenna along the motor axis. This balancing improves the stability of the elevation motor during rotation. Since the antenna elements are approximately 6 mm in diameter, the antenna achieves a relatively wide bandwidth, allowing reception of signals from nearby frequency bands if required. The dipole element of the Yagi–Uda antenna is terminated with an SMA-type coaxial connector. An RG-174 coaxial cable, terminated with SMA male-to-female connectors, is used to connect the antenna to the Software Defined Radio (SDR), as shown in Fig. 14.

The coaxial cable is approximately 1.5 meters long, providing greater mechanical flexibility for the rotating system. RG-174 coaxial cable supports wideband reception up to 6 GHz, making it suitable for RX applications. In this setup, the RG-174 cable introduces minimal signal loss and is adequate for the intended operation.

Fig. 13- 3 element YAGI-UDA antenna

Fig. 14- RG174 type of coax cable

### *E. Software Defined Radio (SDR)*

In this study, RTL-SDR Blog V3 Receiver (SDR) [2] is utilised. The RTL-SDR Blog V3, a wideband receiver built on the RTL2832U ADC and the R820T2 tuner chipset, makes up the front end.

- Frequency Stability: The system features a 1 PPM Temperature Compensated Crystal Oscillator (TCXO), which is essential for maintaining stable frequency lock on the 137 MHz band and minimizing thermal drift.
- Thermal Management: The aluminum enclosure functions as a passive heat sink, helping to reduce internal noise and prevent PLL (Phase-Locked Loop) unlocking during extended satellite passes.
- RF Shielding: An improved 4-layer PCB design minimizes clock spurs and electromagnetic interference (EMI), resulting in better signal quality and stability.

The block diagram of the RTL-SDR is shown in Fig. 15. Through the USB interface, the radio can be connected to and controlled by software. A wide range of software applications are available for receiving radio signals with advanced graphical interfaces and control features. In this project, SDR Console V3 (SDRplay) was used because of its open-source nature and powerful control capabilities, making it well suited for the system requirements.

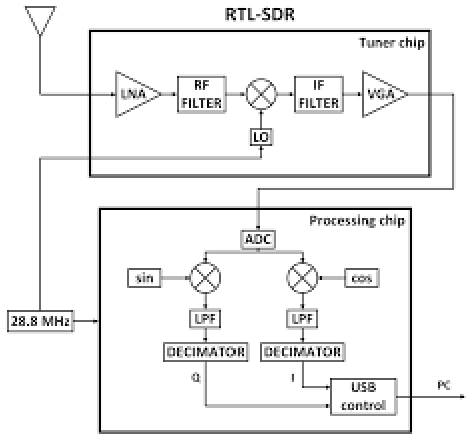


Fig. 15- Block diagram of SDR

### *F. Signal Characteristics and Modulation from LEO satellites*

The NOAA APT signal uses a complex modulation scheme for image transmission.

Carrier Frequencies:

- 137.100 MHz for NOAA-19
- 137.620 MHz for NOAA-15
- 137.9125 MHz for NOAA-18

As of 2026, NOAA-18 has been decommissioned due to its age and equipment malfunctions. However, during the course of this project, numerous satellite images were successfully received from all three satellites.

Modulation Type:

The image information is transmitted using a 2400 Hz AM subcarrier, which is then frequency modulated (FM) onto the main 137 MHz carrier signal (FM/AM).

Bandwidth:

An Intermediate Frequency (IF) bandwidth of approximately 34–40 kHz is required to capture the complete sidebands of the subcarrier without signal clipping.

In addition to NOAA satellites, the Russian METEOR-M series satellites can also be received using the system. These satellites transmit LRPT (Low Resolution Picture Transmission) signals.

- Meteor-M N2-3: Active, typically operating on 137.100 MHz
- Meteor-M N2-4: Active, typically operating on 137.900 MHz

Modulation Scheme:

The METEOR-M satellites use QPSK or OQPSK (Offset Quadrature Phase Shift Keying) modulation.

Symbol Rate:

The transmission symbol rate is typically 72,000 symbols per second (72k) or 80,000 symbols per second (80k).

### *G. Software Implementation and Audio Pipeline*

SDR Console V3 is available for Windows operating systems running on x86-based systems and is widely used in observatories by both amateur and professional radio enthusiasts. Its ease of installation, user-friendly interface, and powerful control capabilities make it a suitable choice for this project. The software includes advanced features such as automatic recording schedules, power-saving modes, and both RX and TX control options.

In this system, SDR Console V3 functions as the primary Digital Signal Processing (DSP) engine. It receives data from the SDR hardware and provides various forms of demodulated signal data to the computer.

The software interface is configured as follows:

- Mode Selection: The receiver is configured in WFM (Wide FM) mode to accommodate the approximately 36 kHz signal deviation of the satellite transmission.
- Gain Control: Manual gain control is adjusted within the range of approximately 32–40 dB to optimize dynamic range and prevent ADC saturation or clipping.
- Doppler Correction: By using the built-in Satellite Tracker, the software compensates for Doppler shift in real time by automatically adjusting the VFO (Variable Frequency Oscillator) frequency as the satellite approaches and moves away from the ground station. The software interface running on the PC is shown in Fig. 16.
- APT Audio Processing: The received APT-format audio data is further processed and decoded for image generation.

Audio Routing Through a Virtual Pipeline

To transfer the processed audio to the decoding software [3] without loss of signal quality, a Virtual Audio Cable (VAC) is used. In the Windows operating system, the software *VB-Audio Cable* is utilized to create a digital audio bridge between the SDR output and the decoder input software.

- Sample Rate: The audio stream is standardized at either 48,000 Hz or 11,025 Hz using 16-bit PCM format to meet the requirements of the decoding algorithm.
- Signal Path: [SDR Console Output → VB-Audio Cable → WXtoImg Input]

Real-Time Decoding with WXtoImg

WXtoImg [4] performs the final satellite image reconstruction, as shown in Fig. 8.1. It is an open-source application available for Windows operating systems. The audio data is routed through the virtual audio cable setup, and with updated Kepler orbital data, WXtoImg can perform real-time recording and decoding of satellite transmissions. The software also includes an automatic scheduler along with several image-processing and filtering features. Additionally, it stores raw image data for further analysis and processing.

- Synchronization: The software detects Sync A and Sync B pulses located at the beginning of each scan line in order to correctly align the 2080-pixel-wide image frames.
- Telemetry Processing: In real time, the software interprets telemetry wedges to calibrate grayscale values for both the visible-light and infrared image channels.
- Image Enhancement: Post-processing features include slant correction to compensate for geometry distortions caused by PC clock timing inaccuracies, along with false-color overlays based on thermal image data.

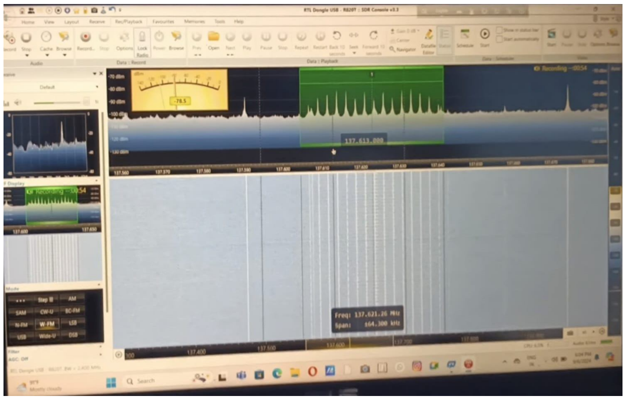


Fig. 16- SDR console V3 software interface

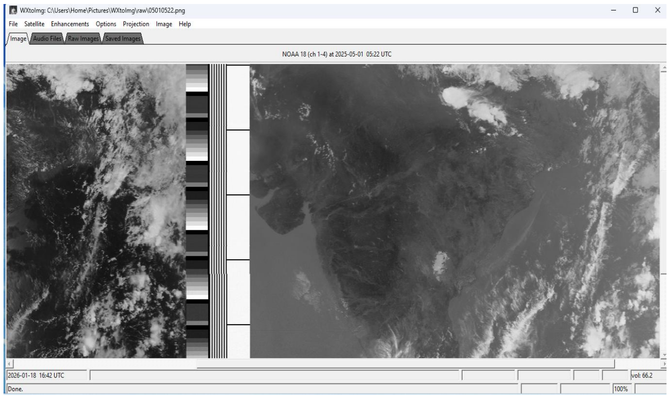


Fig. 17- WX to IMG software interface

## III.PROJECT IN OPERATION

The hardware prototype of proposed Real Time Weather Satellite Tracking System is shown in Fig. 18. The antenna rotator is installed in an open location free from surrounding obstructions. The satellite tracking software provides the predicted satellite pass time in advance. Before operation, all power connections and peripheral interfaces between the rotator and the computer are properly connected. Since the rotator calibration is a one-time process and the calibration data is permanently stored in the EEPROM, recalibration is not required during regular operation. Once initialized, the rotator is ready to receive commands directly from the computer.

All required software applications are launched and prepared for monitoring and control. The tracking software establishes communication with the rotator and automatically positions it toward the satellite's rising horizon. The VHF Yagi–Uda antenna receives the satellite signals, which are transferred through the coaxial cable to the Software Defined Radio (SDR). The SDR is connected to the computer and operated using SDR Console V3 software. After tuning to the appropriate satellite frequency and enabling Doppler correction, the system is ready to receive the APT signal transmission from the satellite.

During testing, NOAA-18 was successfully tracked on 01 May 2025 at 11:06:34 AM IST (05:22 UTC) from a laboratory location at coordinates 22°27′N, 86°58′E, India. The satellite pass reached an estimated maximum elevation of approximately 64 degrees. As the satellite moved across the horizon, the rotator continuously and smoothly tracked its movement. The entire 64-degree satellite pass lasted for approximately 12 minutes.

Fig. 18- Rotator set up for weather Block diagram of SDR

The captured image data is carefully processed and stored in a folder. Free open-source software and internet access can then be used to upload the images online, allowing anyone to view weather images of our continent. This project demonstrates the development of a system that tracks satellites and receives and processes real-time satellite data using open-source resources available on the internet. The results are shown in Fig. 19.

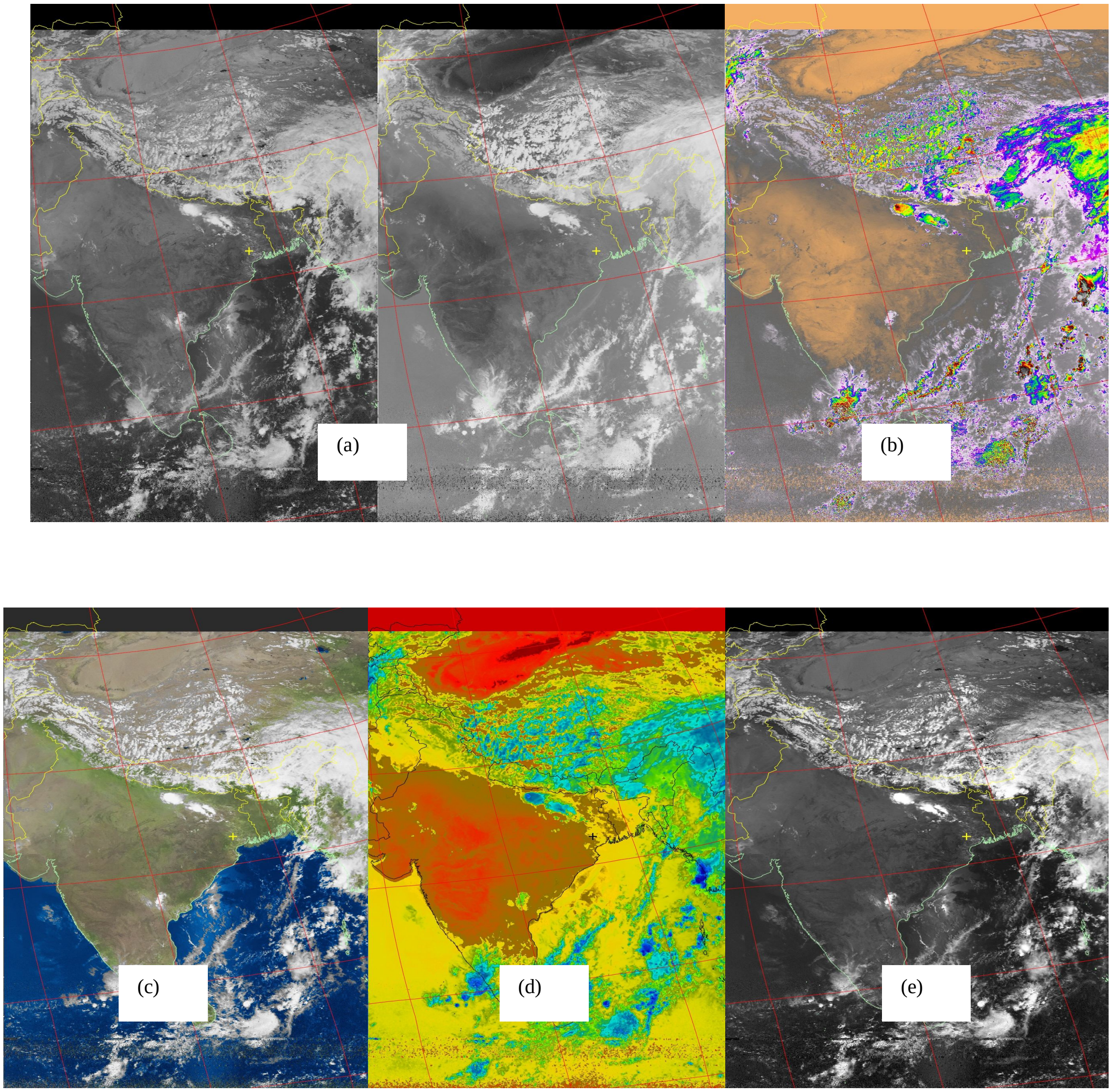


Fig. 19- Some of the results; (a) Enhance Image; (b) Rain Mapping; (c) Cloud Formation; (d) Temperature; (e) Grey Image

## IV. CONCLUSIONS

The project successfully demonstrates a real-time satellite tracking and data reception prototype as a low-cost and practical alternative to commercial systems. It has strong value for education, research, and amateur radio applications.

The implemented calibration, filtering, and motor control algorithms enhance system stability, reliability, and tracking accuracy. The project also highlights the effective integration of embedded control systems, sensor processing, and electromechanical actuation. Overall, the system offers an efficient and affordable satellite antenna tracking solution for educational and amateur hobby applications. In future we can integration of advanced AI and machine learning algorithms for automatic satellite prediction and signal optimization.

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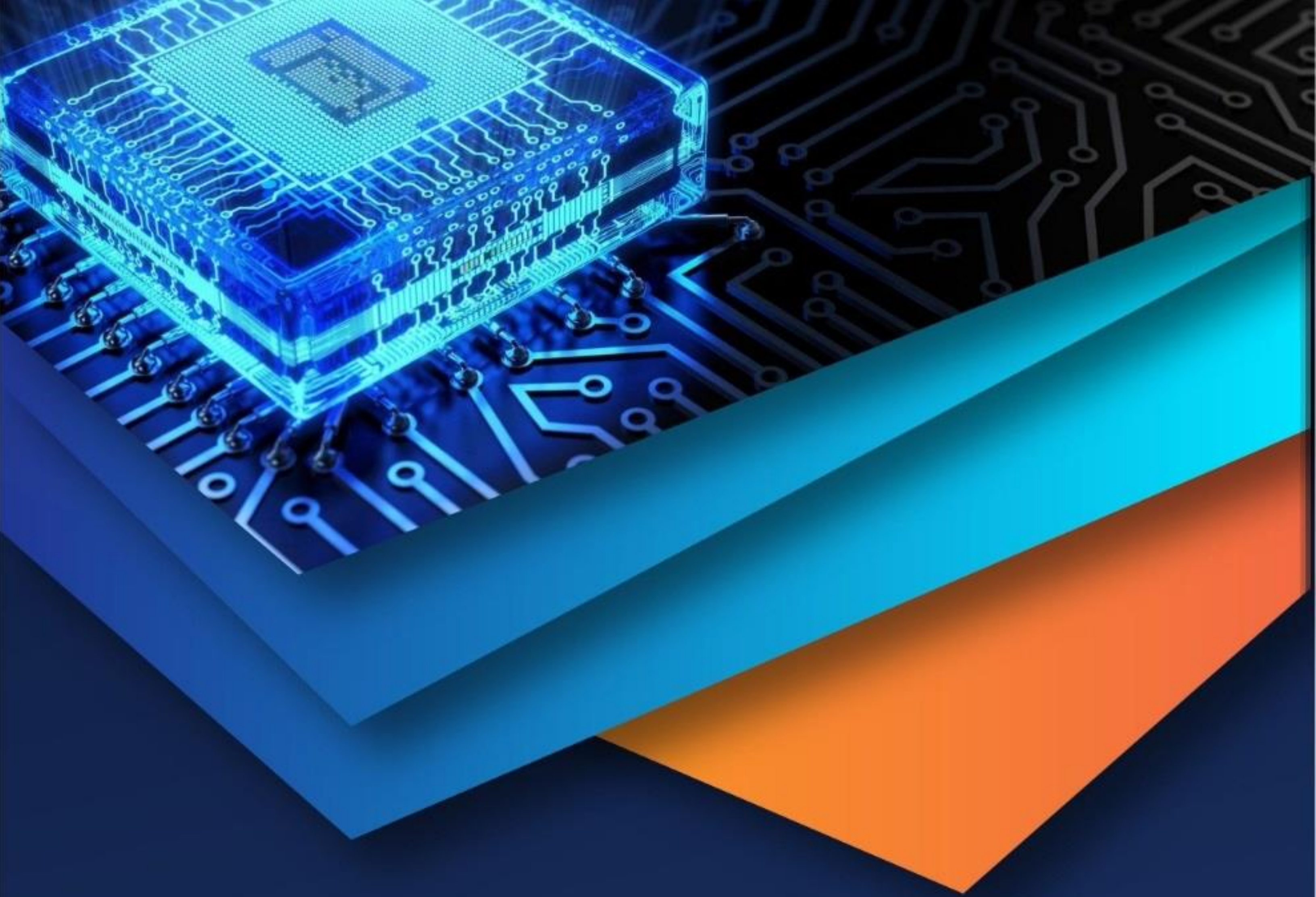

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