

Dual-mode Antenna Tracking System for Rocket Launch Applications

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Abstract—Rocket launches are complex events that require tracking antennas to maintain a communication link. This study introduces a hybrid tracking strategy that combines manual and program modes by utilizing a predetermined trajectory of the rocket. Automatic switching between tracking modes ensures ongoing monitoring, even during unexpected trajectory changes with the monopulse approach. The dual parabolic antenna arrangement enables this switching. The system estimates the monopulse ratio from the signal strength of each antenna, allowing automatic program tracking to shift to manual mode when reception concerns arise. Performance evaluations included manual, programmable, and dual-mode tests. The system responded to human input and automatically aligned the antenna with slight elevation errors during the initial phase. Adjusting the initial elevation reduced the error. The mode transition was examined by measuring the antenna radiation patterns and monopulse ratio. The system's performance was evaluated in rocket launches, with the rocket trajectory input into the graphical user interface. The antenna exhibited an azimuthal movement of up to 10 °, and the ratio fluctuation values remained within the antenna's field of view. After 8.8 seconds, the mode switched from program to manual, indicating that the functioning of the system's functioning was stable.

Keywords: *manual, program mode, rssi, rocket, tracking antenna*

I. INTRODUCTION

Rocket launches are complex and dynamic events in which, for operational and safety reasons, it is critical to track the rocket's flight path [1]. Tracking antennas play a pivotal role throughout the entire journey from launch to the final destination. Starting from the launch, the tracking antenna diligently maintains its beam axis aligned with the moving target, such as the rocket [2]. This continuous tracking maintains the communication link with the rocket, ensuring uninterrupted data transmission and reception, and minimizing the risk of signal loss and data corruption. Additionally, tracking antennas are instrumental in monitoring the rocket's trajectory and ensuring it remains on its intended course [3].

Existing tracking antenna systems for rockets can be classified into three types: manual mode [4], [5], monopulse [6], [7], Global Position System (GPS)-based [8]–[10], and received power signals [11], [12]. They are also mostly employed in UAVs and satellite systems [13]–[17]. Although effective, these systems have limitations for rockets. Manual mode requires regular operator modifications to keep the antenna aligned with the rocket [18]. Although this method provides direct control, it can be error-prone, especially during high-speed rocket travel. Furthermore, it is incapable of handling the intricacies of fast-moving rockets or elaborate movements during launches and flights.

On the one hand, GPS offers accuracy. However, when a rocket surpasses the operational limits of the GPS, its module is capable of autonomously detecting this condition as a potential hazard and then ceasing its functionality. Therefore, during the ascent phase of a sounding rocket, the GPS experiences a highly dynamic and high-acceleration environment, making it unsuitable as a tracking system for the rocket due to its limitations [19].

Monopulse tracking is a high-precision and real-time tracking method [20]. This method utilizes information from the sum and difference channels to obtain the angle of the target. The received power signal method compares each received power level to determine the angle information and decides to aim the antenna in the direction of the target. In cases of low Signal-to-Noise-Ratio (SNR), these methods may not accurately point to the target and may have a certain deviation in the target angle owing to limitations in detection accuracy and the relative motion of the target [21]. This characteristic results in narrow angular coverage, and when the angular velocity of the antenna is low, it can lead to target tracking loss.

To address the limitations of existing rocket tracking methods, this study proposes a hybrid strategy that blends two dual-tracking methods: manual and program mode. This strategy combines the flexibility of manual mode with the automation of program tracking, allowing the antenna to achieve automatic alignment. The rocket flight

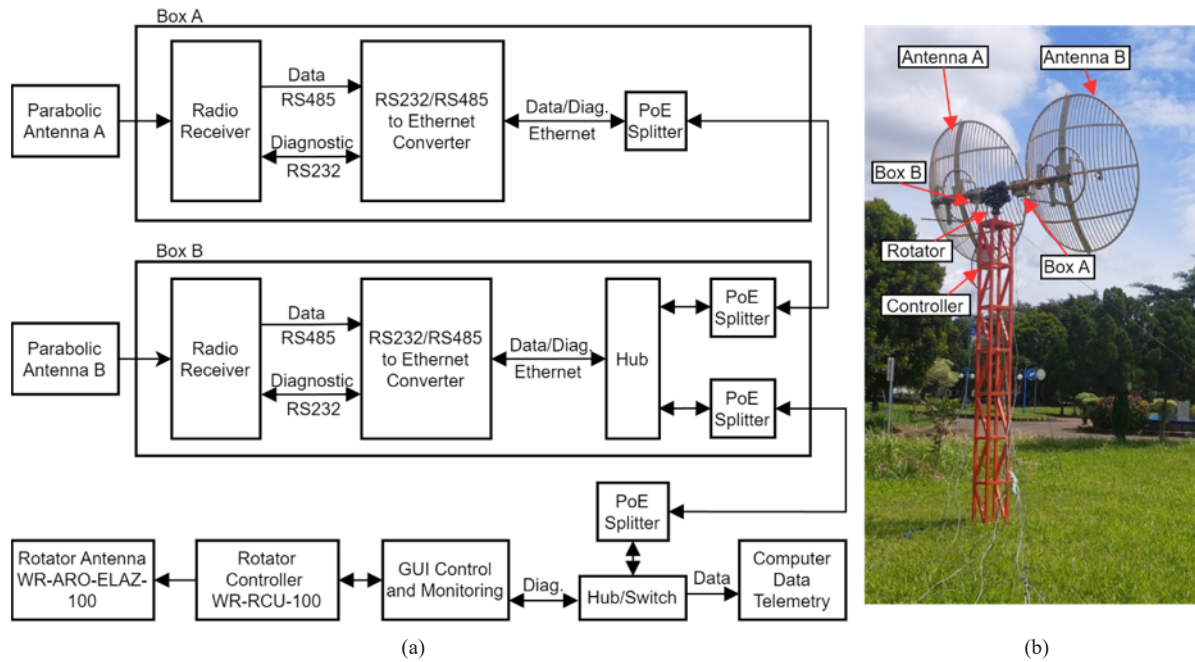


Figure 1. Antenna tracking system: (a). Block diagram; (b). Antenna system on the tower

trajectory, particularly that of a sounding rocket, consists of three phases: boost, midcourse, and reentry [22]. This trajectory is predetermined and can, therefore, be used as input for the program track. This method allows for more efficient tracking of fast-moving rockets while also improving the tracking antenna's capability to handle complex movements during launch and flight.

The program track may lack flexibility when coping with unanticipated trajectory changes, leading to the antenna losing sight of the rocket. To overcome this, the monopulse method is used to automatically switch from programmable to manual mode when necessary due to unanticipated trajectory changes, and operators can intervene and make real-time adjustments to ensure ongoing tracking. This strategy enables operators to use the antenna in the best possible way for the individual situation by combining manual and programmed modes, rather than relying solely on manual or programmable mode. This feature improves the versatility and resilience of tracking antenna systems.

A dual-parabolic antenna is employed to make automatic switching possible. A parabolic antenna is used for its high gain, directional accuracy, and ability to maintain communication over long distances [23]. Additionally, two parabolic antennas improve the angular coverage of the tracking system. Next, the received signal strength from each antenna is measured, and the monopulse ratio is calculated to decide between switching modes. It also measures the number of bytes received over time. If reception problems develop during the flight, this information is used to perform an automatic transition from program tracking to manual mode.

II. METHOD

The developed dual-mode antenna tracking system

employs two adjacent parabolic antennas (A and B) connected to boxes (A and B). Figure 1(a) illustrates the block diagram of the system, showing both boxes containing radio receivers connected to an Ethernet converter that enables both radios to connect to the Local Area Network (LAN). Through this network, the radios and the controller can be monitored and controlled via a Graphical User Interface (GUI). The antennas, boxes, rotator, and controller are mounted on the antenna tower, as shown in Figure 1(b). The antenna tracking system consists of two modes: manual and programmable. This system automatically switches from programmable to manual mode in case of data reception problems by monitoring and comparing the radio receiver's diagnostic data (RSSI and received bytes) measurement features. Both radio's diagnostic and telemetry data are then transmitted to the computer GUI program using the Ethernet communication protocol. Ethernet was chosen due to its suitability for long distances and high data transfer rates.

The GUI program has three functions: receiving and processing diagnostic data, performing tracking processing, and controlling the antenna controller. Two tracking modes are utilized: manual and program mode. In manual mode, the antenna is aligned manually using the arrow buttons on the computer and GUI. In contrast, program mode utilizes the predetermined trajectory and calculates the antenna angle data to align both the azimuth and elevation of the antenna. In general, the system development process is divided into two stages: the assembly of hardware such as antennas, radios, and Ethernet communication, and the development of the GUI program. The GUI program is developed using Visual Studio C# applications. The GUI design interface is shown in Figure 2, divided into three sections: controller, diagnostic, and tracking.

The diagnostic section controls the Ethernet connection for data reception from both radios and displays the

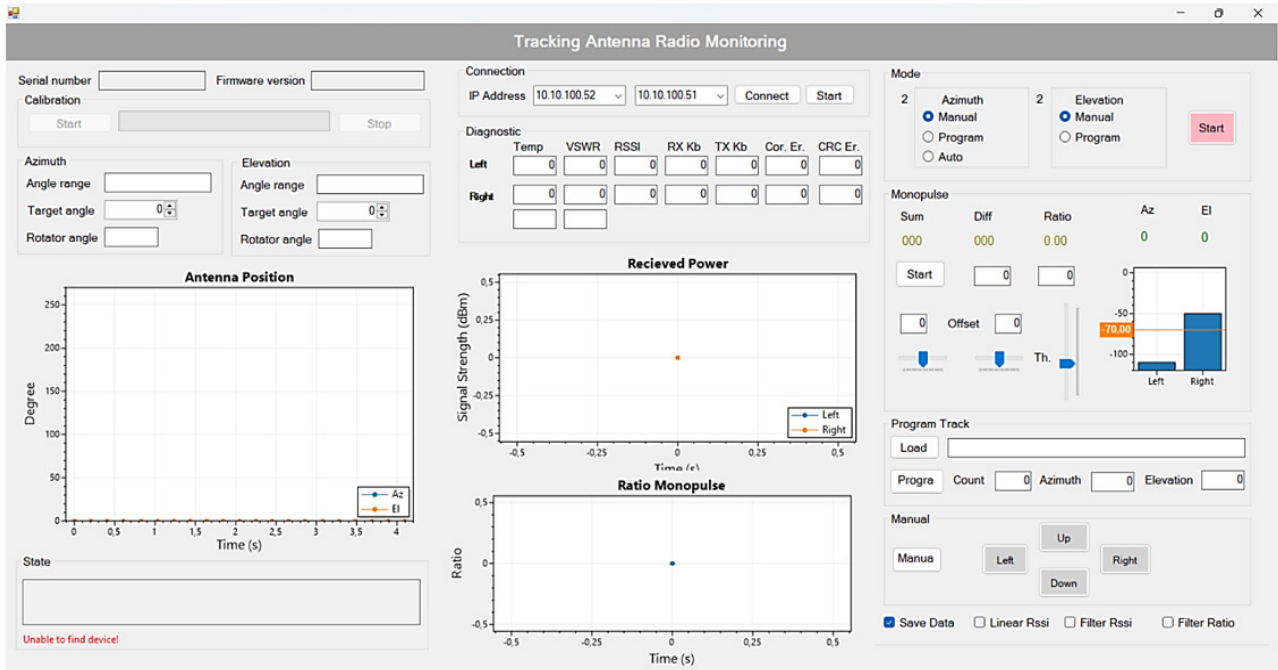


Figure 2. Graphical user interface of antenna tracking

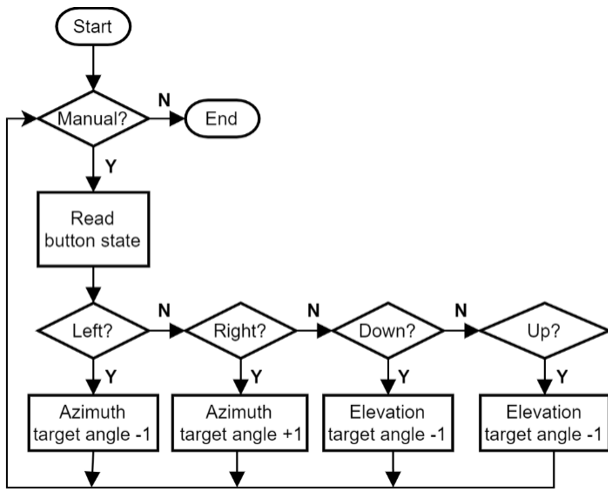


Figure 3. Flowchart of manual control

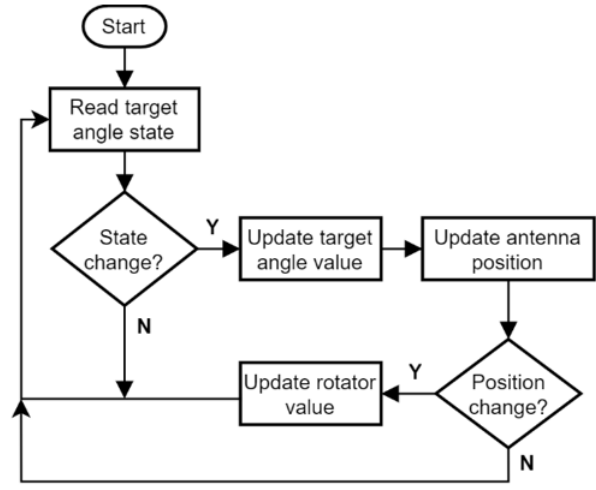


Figure 4. Flowchart of controller

received data graphically. The tracking sections control the tracking mode for azimuth and elevation, save data, and manage the settings for manual and program tracking. In the manual section, four buttons (left, right, up, and down) can be clicked to adjust the movement of the antenna rotator. Program track section has a button to load trajectory data in comma-separated value (CSV) file format.

A. Manual Mode

The manual mode is implemented using keyboard controls and a GUI button, allowing users to intuitively adjust the antenna's position and orientation in real-time. Figure 3 shows the flowchart of the manual program implemented in the GUI. When the manual mode is selected, the GUI reads the state of the keyboard and the GUI button. Then, the value of the rotator target angle will

be adjusted according to the pressed button. The rotator controller automatically detects the change in the target angle, which then rotates to the angle value. This process is illustrated in Figure 4. The GUI provides users with visual feedback in the controller section, displaying the current position and orientation of the antenna.

B. Program Mode

The programmable mode utilizes predetermined rocket trajectories to generate azimuth and elevation angles to rotate the antennas. Figure 5 shows the flowchart of programmable mode, in which the process starts by loading the trajectory data, calculating the angle data, and rotating the antenna. The generation of azimuth and elevation angle data requires that the antenna coordinates () and launch coordinates (ϕ_a , λ_a , h_a) be known. Then, the

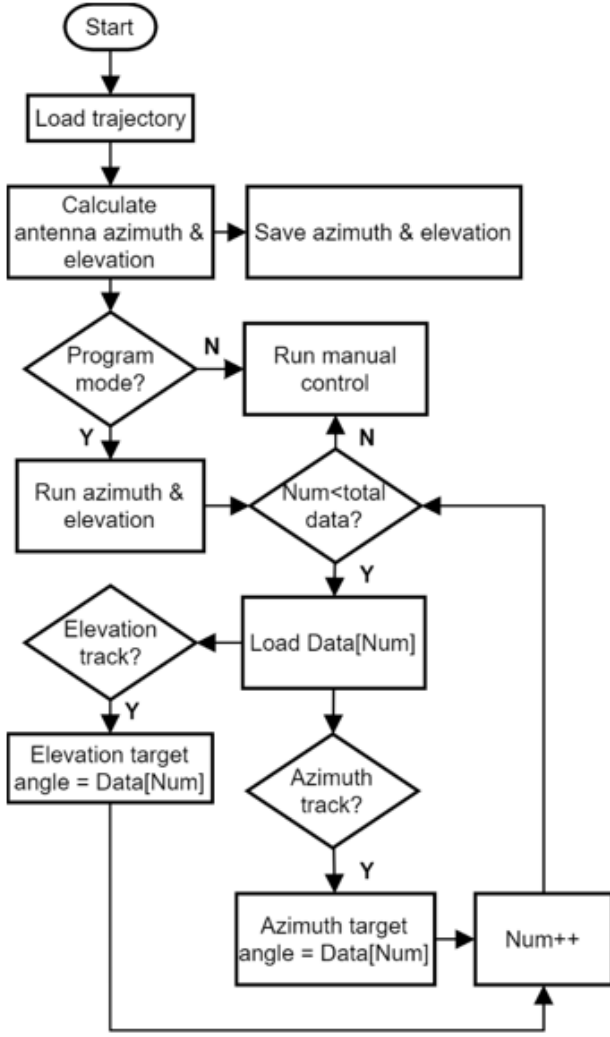


Figure 5. Flowchart of controller

calculation is done as follows: First, the rocket trajectory (X_t , Y_t , Z_t) is converted to the East-North-Up (ENU) coordinate and rotated to rocket launch azimuth (θ) using the rotation matrix as follows:

$$\begin{bmatrix} E_t \\ N_t \\ U_t \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}. \quad (1)$$

Then, the ENU data is converted to Earth-Center-Earth-Fixed (ECEF) coordinates, with the origin of the ENU system being the launch point (ϕ_p , λ_p , h_p) [24]:

$$\begin{bmatrix} X_p \\ Y_p \\ Z_p \end{bmatrix} = \begin{bmatrix} (N + h_p) \cos \phi_p \cos \lambda_p \\ (N + h_p) \cos \phi_p \sin \lambda_p \\ [N(1 - e^2) + h_p] \sin \phi_p \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix} = \begin{bmatrix} -\sin \lambda_p & -\sin \phi_p \cos \lambda_p & \cos \phi_p \cos \lambda_p \\ \cos \lambda_p & -\sin \phi_p \sin \lambda_p & \cos \phi_p \sin \lambda_p \\ 0 & \cos \phi_p & \sin \phi_p \end{bmatrix} \begin{bmatrix} E_t \\ N_t \\ U_t \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} X_{ECEF} \\ Y_{ECEF} \\ Z_{ECEF} \end{bmatrix} = \begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix} + \begin{bmatrix} X_p \\ Y_p \\ Z_p \end{bmatrix}, \quad (4)$$

where N and e are WGS84 geodetic properties. Then, the antenna position (ϕ_a , λ_a , h_a) is converted to ECEF coordinates (Y_a , Y_a , Z_a) using equation (2) by replacing only the latitude, longitude, and altitude values. Thus, the range vectors from the antenna position to each trajectory point in the ECEF can be calculated and transformed back to the ENU coordinates, with the origin of the ENU system changing to the antenna position:

$$\begin{bmatrix} d_x \\ d_y \\ d_z \end{bmatrix} = \begin{bmatrix} X_{ECEF} - X_a \\ Y_{ECEF} - Y_a \\ Z_{ECEF} - Z_a \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} R_E \\ R_N \\ R_U \end{bmatrix} = \begin{bmatrix} -\sin \lambda_a & \cos \lambda_a & 0 \\ -\sin \phi_a \cos \lambda_a & -\sin \phi_a \sin \lambda_a & \cos \phi_a \\ \cos \phi_a \cos \lambda_a & \cos \phi_a \sin \lambda_a & \sin \phi_a \end{bmatrix} \begin{bmatrix} d_x \\ d_y \\ d_z \end{bmatrix} \quad (6)$$

Using these vectors, the elevation and azimuth of the antenna can be calculated as:

$$Az = \tan^{-1} \left(\frac{R_E}{R_N} \right) \quad (7)$$

$$El = \sin^{-1} \left(\frac{R_U}{\sqrt{R_E^2 + R_N^2 + R_U^2}} \right). \quad (8)$$

The angle data is then saved and used when the program track begins. Each angle data point is used to update the target angle value of the rotator, allowing the system to autonomously follow the programmed trajectories. The process of rotating the antenna is the same as manual control, with the number of the antenna movements corresponding to the number of calculated angle data points.

C. Modes Switching

The radio receivers used have diagnostic features that allow them to monitor parameters such as the received signal strength indicator (RSSI) and number of bytes received. Real-time data collection of diagnostic data from the radio receiver is performed using the request-reply method through Ethernet. The GUI sends data bytes requesting the parameters. Then, the radio receivers respond by sending the parameters back. The GUI then checks the header of the replied data byte. If it is the correct header, then the data are processed. It should be noted that the radio receiver has a 20-millisecond inter-command delay; thus, the request-reply rate must have a value greater than that in order for the request to not overlap [25]. Considering the speed of Ethernet and this inter-command period, a rate of 100 milliseconds is used for data collection.

Diagnostic parameters, specifically RSSI, are employed to detect angle deviations by converting to power and calculating the monopulse ratio. It should be noted that

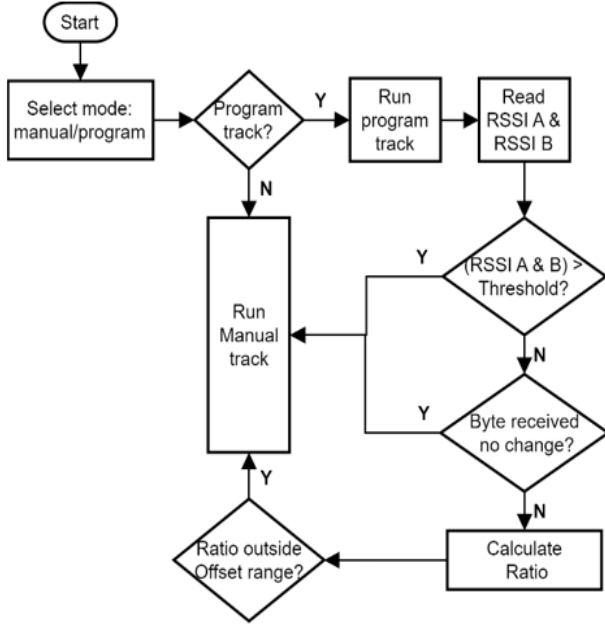


Figure 6. Flowchart of mode switching

because the two antennas are placed horizontally, only the azimuth deviations are considered. When a problem is detected, the GUI automatically switches its mode from program to manual mode. This process is depicted in Figure 6, which shows three condition that can switch the mode. That is, when both RSSI values are above the threshold value, the number of bytes received does not changing, or the monopulse ratio is outside the offset range value. This offset range functions as an indicator, signifying that the antenna is either off-tracking or on-tracking. This monopulse ratio is expressed as [26]:

$$Ratio = \frac{power\ A - power\ B}{power\ A + power\ B} \quad (9)$$

$$Power\ (mW) = 10^{\frac{RSSI}{10}} \quad (10)$$

D. System Testing

The system is evaluated to assess its functionality and performance. The evaluation conducted consists of a diagnostic monitoring test, manual mode test, programmable mode test, and switching mode test. The diagnostic monitoring test is conducted by assessing data collection time through Ethernet and monitoring received parameters of both radios. The system's ability to monitor and report receiver health will be assessed. Manual mode is tested by operating the rotator through the keyboard button. During this test, user input is saved as a certain value and later compared with the antenna position to ensure the manual mode functions correctly and accurately, moving the antenna as intended.

Programmable mode is tested by using a predicted rocket trajectory, as shown in Figure 7. This trajectory has a maximum range of 25.75 km, an altitude of 7.6 km, and a flight time of 82.1 seconds. Because the data points have

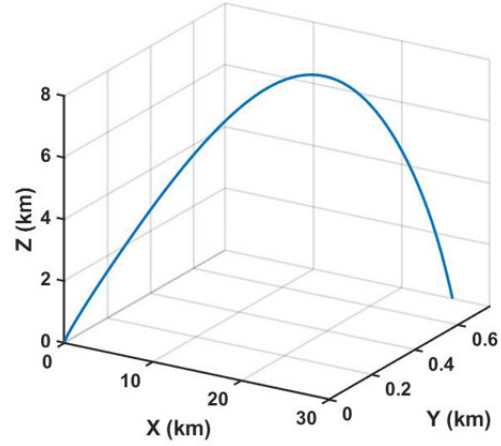


Figure 7. Rocket trajectory

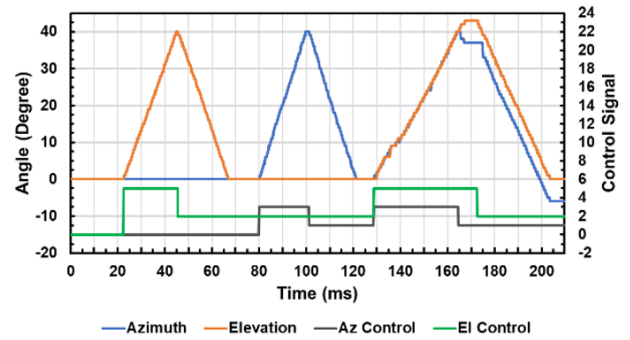


Figure 8. Manual mode test result

100 millisecond intervals, a 10 Hz rate will be used for program control. The trajectory data will be loaded, and the angle data will be generated. Antenna system coordinates and launch coordinates used in this test are $(-7.643628^\circ, 107.685612^\circ)$ and $(-7.644735^\circ, 107.684212^\circ)$. The distance from the antenna system to the launch pad is 197.4 meters. The rocket has a launch azimuth of 249 degrees. Tracking accuracy is assessed by comparing the tracked antenna position with corresponding position, and tracking errors will be calculated.

The switching mode test involves collecting RSSI from different angles to find the monopulse ratio that is used for the offset. After that, the program will be activated using the same trajectory, and an evaluation is conducted of the system's ability to switch the mode to manual mode when one condition is satisfied. The monopulse ratio and the modes will be compared for analysis the system's ability to switch.

III. RESULTS AND DISCUSSIONS

A. Manual Mode Performance

The experimental results of the manual mode test are presented in Figure 8. The test involved the user input as a control signal, which was used to manipulate the position of the antenna. The response of the antenna was measured in terms of the angle in azimuth and elevation. During the initial 20 milliseconds of the test, there was no user input, thus the control signal remained at 0. Consequently,

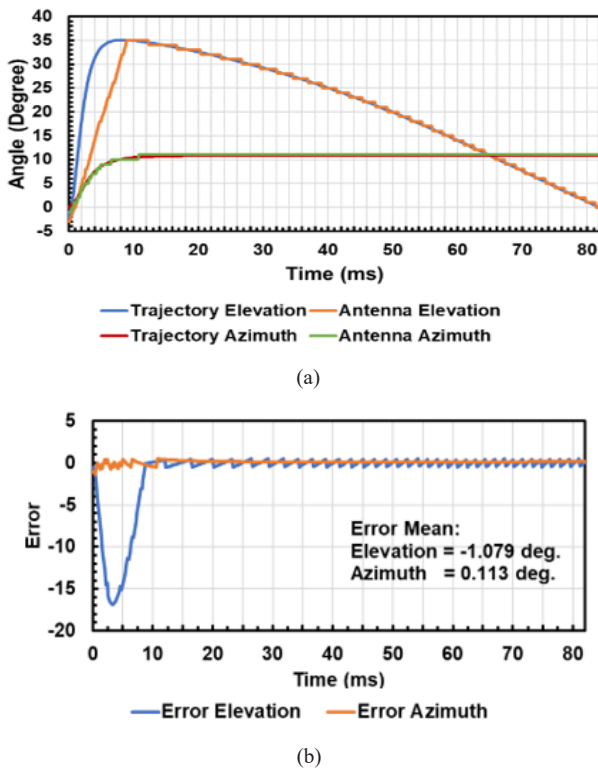


Figure 9. Result of program control test: (a). Antenna angle, (b). Error

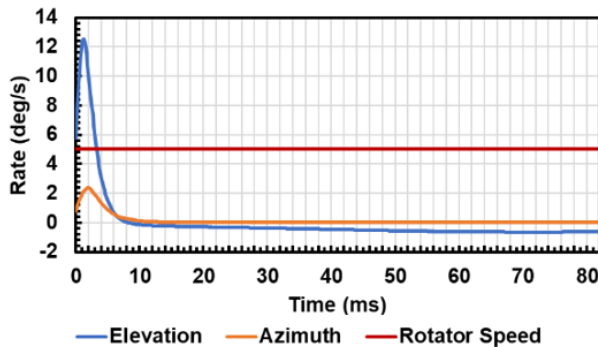


Figure 10. Rate of change in azimuth and elevation

both azimuth and elevation positions of the antenna remained at 0 degrees. Then, the antenna was adjusted to move upwards, with a control signal value of 3. At 80 milliseconds, the antenna began moving towards the right, as indicated by a control signal value of 4. Once the antenna reached a 30-degree angle, it changed direction and started moving towards the left. Following this, both the azimuth and elevation position of the antenna were adjusted to move upwards and towards the right with a control signal value of 3 and 1. The graph depicting these results clearly demonstrates that the manual mode system is functioning correctly. The antenna accurately moves in the intended direction as the user input dictates.

B. Programmable Mode Performance

The program mode's trajectory is then evaluated using the trajectory shown in Figure 7. The CSV file with the trajectory data is imported into the program. The

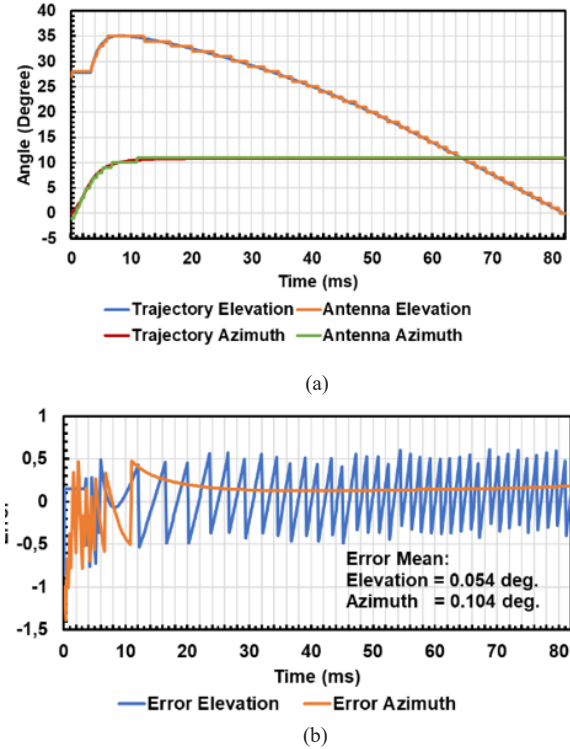


Figure 11. Result of adjustment: (a). Antenna angle, (b). Error

experimental results are shown in Figure 9, demonstrating the antenna's ability to move along the trajectory in both azimuth and elevation. The antenna's elevation movement was a considerable inaccuracy that happened in the first 10 seconds, but the error was reduced after that. This error is due to the rotator's rotational velocity exceeding its upper limit. The data in Figure 10 represents the rate of change in elevation and azimuth velocities as calculated by trajectory calculations. The point of maxima changes at the azimuthal angle is seen at the value of 2 degrees. The aforementioned number stays below the stated rotator speed limitation of 5 degrees per second. Meanwhile, the elevation change in the first 10 seconds exceeds the rotor's maximum speed. The observed phenomena cause antenna displacements in elevations, making it impossible to effectively track the specified trajectory elevation values.

In order to address this issue, a potential solution is to adjust the initial elevation position of the antenna to a higher value. By doing so, the rate of change in elevation of the antenna becomes smaller and remains below the speed of the rotator. Consequently, the rotor is able to effectively track the trajectory movement. The selection of this initial position is based on the elevation value of the trajectory when the rate of change in velocity of the elevations is equal to the rotation speed. It is worth noting that increasing the initial elevation position does not interfere with the reception of data, as the distance between the antenna and the rocket at the launch positions remains relatively close. This adjustment is reflected in the data presented in Figure 11, which illustrates a noticeable reduction in the average error elevation of the antenna.

The variability of the error happened because the rotator resolution is 1 degree. It made the rotator could

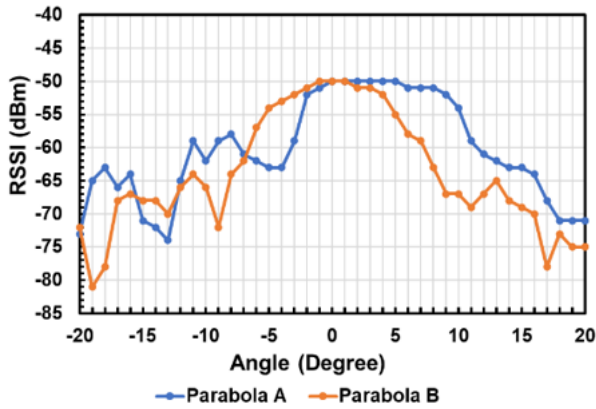


Figure 12. Antennas radiation pattern

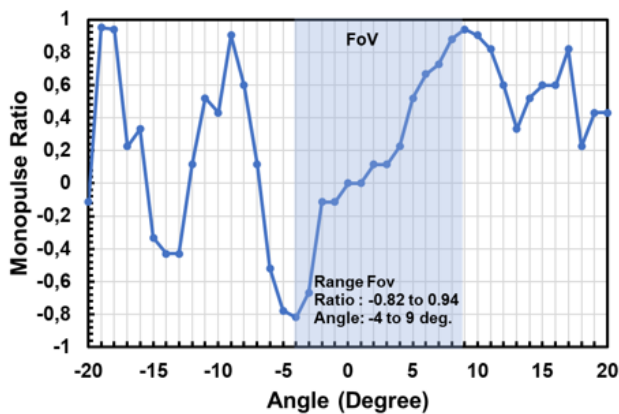


Figure 13. Measured monopulse ratio

not follow the trajectory change smoothly. Nevertheless, the antenna used has a 5.3 degree beamwidth [27]. So that the reception of the data can still be maintained during the launch. This is because the error is still within the range of the antenna's beamwidth.

C. Mode Switching Performance

Next, an assessment was conducted to evaluate the system's ability to transition between modes autonomously. Before further analysis, it's crucial to perform measurements of the antenna radiation patterns. The experimental procedure involved placing the transmitter at a distance of 100 meters from the antenna. Subsequently, both radios measured the received signal strength. The angular radiation patterns, spanning a range of 40 degrees from -20 to 20 degrees, are depicted in Figure 12. Furthermore, it's important to note that the radiation patterns exhibit slight variations in their respective beamwidths. These observed dissimilarities can be attributed to the influence of the array, which introduces an asymmetry in the radiation pattern [28].

Following this, the monopulse ratio was computed using equations 9 and 10. The results of this computation are illustrated in Figure 13, showing the antenna system's field of view ranging from -4 to 9 degrees with a ratio of -0.82 to 0.94. A positive angle is assigned when the rocket moves to the right, while a negative angle is assigned



Figure 14. Launch of RX200TC-03 rocket

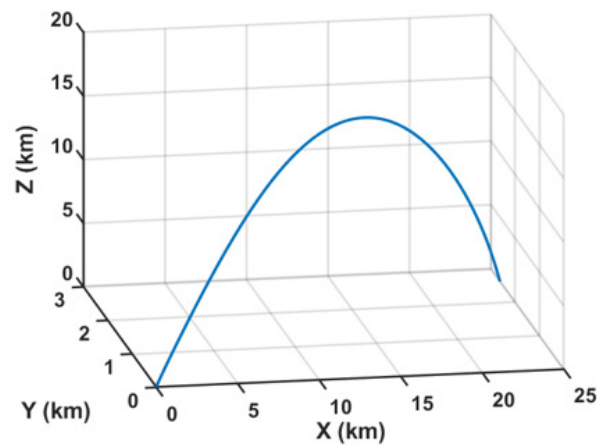


Figure 15. Trajectory of RX200TC-03 rocket

when it moves to the left. Alternatively, a larger ratio corresponds to a leftward movement of the target, while a smaller ratio indicates a rightward movement. This field of view is used as a standard to determine whether the antenna is on-tracking. If the monopulse ratio falls within the field of view (FoV) region, it signifies that the antenna is not tracking. The region selection process involves choosing a region that eliminates ambiguity [29].

Subsequently, the system's performance was assessed through its application in the RX200TC-03 rocket launch, as shown in Figure 14. The coordinates of both the antenna and the launch point coincide at $(-7.643952^\circ, 107.685404^\circ)$ and $(-7.644858^\circ, 107.684100^\circ)$, respectively. The rocket's trajectory matches that depicted in Figure 15, which has a range of 25 km, an altitude of 16.3 km, and a launch azimuth of 247 degrees. At launch initiation, the rocket's flight path is input into the GUI for use in the antenna mode program. The program mode begins with the rocket's launch, ensuring that the initial data of the program aligns with the launch starting point.

The recorded RSSI data and monopulse ratio during the launch event are shown in Figure 16. The presented data covers up to the 65th second of the flight time. The

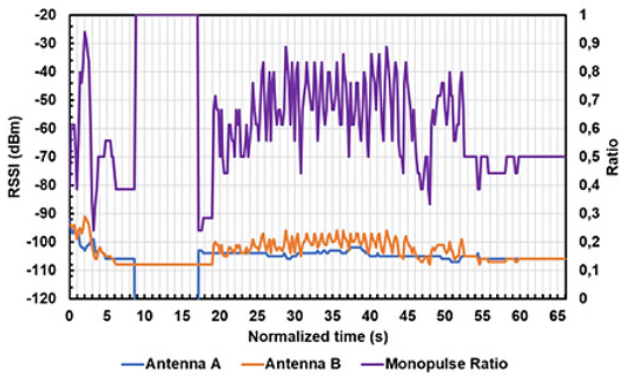


Figure 16. Measured RSSI and ratio during the launch

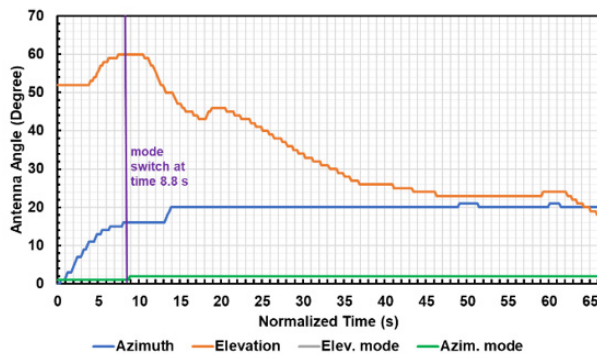


Figure 17. Antenna angle and control mode during launch

figure shows that in the early stage of the rocket flight, the monopulse ratio increased, indicating the rocket was on the right side of the antenna system. Subsequently, when the antenna moved programmatically to the right, the rocket was on the left side of the antenna. At 8.8 seconds, the monopulse ratio falls outside the offset range, which is a value greater than 0.94. This satisfies one of the switching mode conditions, causing the system to switch to manual mode.

Figure 17 illustrates the exact position of the azimuth, the antenna's elevation, and the corresponding mode employed during the launch process. Before 8.8 seconds of the flight time, the antenna system moved programmatically in the azimuth up to 16 degrees in accordance with its trajectory. In the early stage of the flight, the antenna elevation was constant at 52 degrees. This constant value represents the initial position calculated by the program to overcome the speed limitation of the rotator, as explained previously. Subsequently, the elevation angle increased in accordance with its trajectory. At 8.8 seconds, the mode switched automatically from program mode to manual mode, as mentioned before. This allowed the user to take control and move the antenna intuitively.

IV. CONCLUSION

A dual-control antenna tracking system has been developed and evaluated. All systems can function appropriately. Tests on real rocket launches, specifically RX200TC-03, also show that the system is capable of directing the antenna based on the trajectory and that the

transition mode can autonomously switch from program mode to manual mode.

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