Design of a remotely accessible satellite tracking system

Rushil Kisoon[1], *Khehla* Gumede[1], *J.* Fernandes[2] and *Riaan* Stopforth[2]

[1]Scientific Multidisciplinary Advanced Research Technologies (SMART) Lab, University of KwaZulu-Natal, South Africa
[2]Advanced Mechatronics Technology Center, Nelson Mandela University, South Africa

Abstract. The growing number of objects in orbits has led to an increase in space monitoring. While large-scale tracking system exist, enthusiasts often use basic methods for satellite monitoring. To eliminate the need for physical access to tracking stations, the remote accessible satellite tracking system is proposed and implemented in this paper. The proposed system will track satellites and receive transmissions. A Raspberry Pi was used for control of the device, and a satellite tracking software – Gpredict – was used for calculating coordinates for rotation. Test results showed that the system could operate within 5 degrees of the intended target. Radio transmissions and slow-scan images could be received and recorded.

1 Introduction and research background

Since the launch of Sputnik 1 in 1957, tracking objects in orbit has been a critical aspect of space research. Early methods depended on visual confirmation via telescopes, but modern technology now employs radar, optical sensors, and surveillance satellites to automatically detect and document space objects. This data is stored in databases like Space-Track and CelesTrak [1], Making this information publicly accessible helps guide future launches while keeping the skies safe. South Africa is in a geographically significant location on Earth. This position in the southern hemisphere makes it ideal for observing satellites within their first few hours of launch [2]. Various space agencies have taken an interest in South Africa as many orbital paths pass over the area.

The primary aim of this research is to develop a system capable of tracking and receiving signals from satellites, featuring a user interface (UI) that can be remotely accessed for control. The research objectives include:

- Identifying suitable tracking methods and potential improvements.
- Developing a mechanical rotator system.
- Researching software design and UI development.
- Developing a remotely accessible UI with tracking and radio reception software.

* Corresponding author: stopforth.research@gmail.com and 217016308@stu.ukzn.ac.za

An iterative approach was employed to design and develop the satellite tracking system, divided into mechanical, electronic, and software subsystems. Necessary components were procured and fabricated, and the mechatronic system was tested and refined to meet initial parameters. Experimental testing involved using two smartphones, mobile applications such as Commander Compass Go and Phyphox [3], and multiple devices to ensure data accuracy. Data was tabulated and visualized to illustrate results, and radio recordings were decoded to assess the quality of slow-scan images. The performance and effectiveness of the system were analysed to determine if the research's aims and objectives were achieved.

1.1 Literature review

The Space Fence, developed by Lockheed Martin for the United States Space Force, tracks over 25,000 objects in low Earth orbit using S-band radar. Operational since March 2020, its primary system is in the Marshall Islands, with selected data available through platforms like http://www.space-track.org and http://www.celestrak.com. This system represents a significant advancement in space surveillance, enhancing the ability to monitor and manage space debris [4].

The French-based GRAVES radar surveillance system assists the European Space Agency in tracking debris and satellites using bistatic Doppler radar. Operational since 2005 and upgraded in 2017, GRAVES broadcasts over a large area of Europe, requiring users to have specific receiving equipment, including an antenna and a Software Defined Radio (SDR). This system significantly contributes to European efforts in space situational awareness and debris management [5] [6].

The NyanSat challenge was developed to engage individuals in satellite tracking by enabling them to build their own ground stations. Created in partnership with the US Air Force and Defence Digital Service, this initiative provides participants with a kit that includes an antenna PCB and encourages them to add components like servo motors and antennas. This hands-on approach not only fosters education and interest in space technology but also contributes to grassroots satellite tracking efforts [7].

Dan White presented the SatNOGS rotator and controller at the 2018 Conference on Small Satellites. This system features an aluminium extrusion-based frame designed for versatility, allowing various antenna types to be mounted. It uses gears, DC motors, and 3D-printed parts to control azimuth and elevation. SatNOGS promotes community-driven satellite tracking and data sharing, enhancing collaboration among enthusiasts [8].

The SATRAN rotator is a small, Wi-Fi-controlled satellite antenna rotator that can be ordered as a kit, complete with 3D-printable parts [9]. This device allows users to track satellites via an app, which updates coordinates based on the smartphone's GPS. Its universal mounting base supports various antenna types, making satellite tracking more accessible and user-friendly [9].

Lastly, an IEEE publication by Reza Chalak Qazani et al. details the creation of an antenna rotator using an ABB IRB 6600 industrial robot. With 6-degrees-of-freedom (DoF) for precise motion control, the team utilized MATLAB and Simulink to command the robot, incorporating an inertial measurement unit (IMU) for accurate orientation feedback. This innovative application of robotics in satellite communication showcases the potential for automation to enhance tracking capabilities [10].

2 System design

2.1 Mechanical design

Table 1 outlines the requirements for the system design.

Table 1: Design specifications.

Aspect	Description
Movement	360° azimuth rotation, 90° elevation rotation.
Cost	The frame is made of aluminium extrusions, which are cost-effective due to their lightweight nature, reducing material costs and shipping expenses while minimizing assembly labour.
Electronics	The plate of 300 mm x 300 mm shall be positioned at the base of the frame to accommodate the electronic components and ensure proper wiring.
Manufacturability	Maximum use of off-the-shelf components.

Fig. 1 shows complete mechanical system.

Fig. 1. Completed mechanical system.

The tracking system's mechanical structure features a frame made from aluminium extrusions, forming independent enclosures for the azimuth and elevation mechanisms. The drive mechanism includes an RS-390 12V DC wiper motor and a combination of a 40-tooth pinion spur gear and a 60-tooth spur gear, resulting in a combined gear ratio of 1.5 for increased torque and reduced revolutions per minute (RPM). Sections of the gear shaft were turned to various diameters to facilitate mounting the bearings, gear, and coupling. This careful profiling, starting at 7 mm for the motor coupling and stepping up to 15 mm for the gear, ensures optimal fit and stability for enhanced performance. The azimuth and elevation axes utilize 38 mm aluminium tubes which extends from side to side of the frame, secured by fabricated steel stands and bearing blocks. Custom mounts at the end of the aluminium tube attach the telescope and antenna to the elevation axis. Hole reducers adapt M6 bolts to M12-sized bearing block holes, ensuring secure connections. The system integrates precise components for accurate and reliable tracking.

2.2 Electronic integration

The satellite tracking mechanism required automation and control. A microcontroller was needed to manage the operation of various systems, with suitable sensors providing the necessary data. In this section, we explore the design of the electronic system for a remotely accessible satellite tracking system.

2.2.1 Specifications

Table 2 details the electronic requirements for the system. To get the electronic system operational, a flowchart was created.

Table 2: Electronic integration requirements.

Aspect	**Requirement**
Control computer	Allow for remote access, control serial devices, and support a UI.
Microcontroller	Control motor drivers, serial devices, and sensors.
SDR	Software controlled radio tuning.
Global Positioning System (GPS)	Provide latitude and longitude.
IMU	Orientation feedback with 6 DoF.
Motors	Accurately move each axis.

2.2.2 Electronics system design

In this section, the subsystems and their interconnections, along with all the components used to design this system, are discussed.

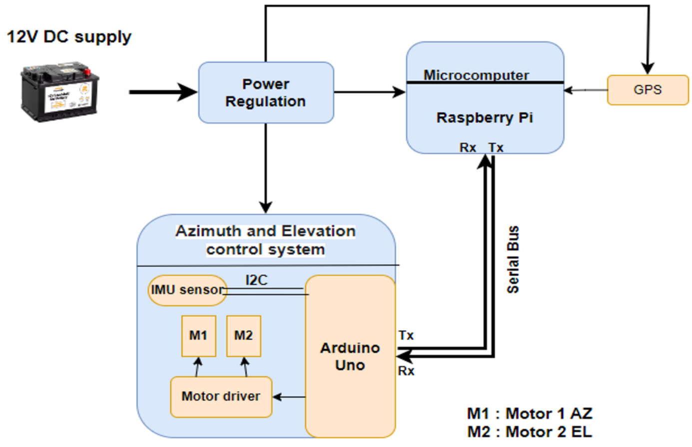

Fig. 2. System block diagram.

A device was required to process the information from the two-line element (TLE) data, allow remote access to the system, and enable interfacing between the SDR and the microcontroller. In this paper, a Raspberry Pi 4B was chosen for this purpose. A radio receiver was required to obtain the transmissions broadcasted from various satellites, and the RTL-SDR V3 was chosen since it is compatible with the Raspberry Pi 4B and is ideal for receiving broadcasts from satellites across all frequency ranges **[11]**. The geographical location of the satellite tracker needs to be known to calculate the new orbital paths from updated TLE data. By utilizing a GPS sensor, precise longitude and latitude values can be obtained. An IMU sensor is used to determine the orientation of the tracking system, The LSM303DLHC IMU sensor was used in this application.

Motors with significant torque were required to rotate the axes and maintain a position, so a wiper motor was used. The worm gears in the wiper motor provide significant torque while preventing the output shaft from rotating when the motor is not powered. The azimuth and elevation control system will receive azimuth and elevation angle from the Raspberry Pi system via serial communication. The Arduino system will then check the current orientation from the IMU sensor. The unit will then drive the motors until the system reaches the required orientation.

The power regulation system was designed to utilize voltage regulators and current limiters to manage the voltage and current for each subsystem and sensors. Since the Raspberry Pi, Arduino Uno, IMU sensor, and GPS sensor all require a 5V DC power supply, a voltage regulator was necessary to convert the 12V DC input to 5V DC.

2.2.3 Software process and controls

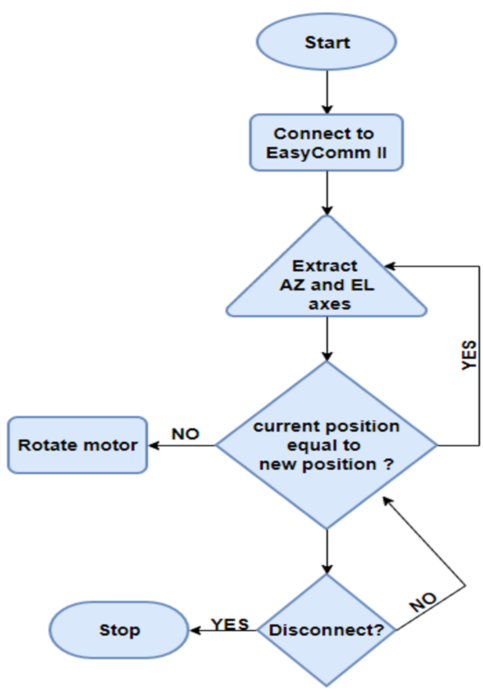

Fig.3. Controls process

EasyComm II is a protocol that allows control and feedback from a custom rotator system [12]. Once implemented, rotator control software such as Gpredict, will be able to recognise the rotator as an EasyComm II compatible device and take control of the system [13]. A method was required to get the two systems working. The team from SARCNET created a rotator controller using an Arduino [14]. Their software was modified to suit the current hardware configuration of the system. It implements the EasyCommII protocol, allowing the Arduino and subsequent hardware are recognised as a controllable rotator device when connected to a computer. A PID ramp-up and ramp-down speed control was used for the position tracking.

2.3 Software design

To enable users to easily access the satellite tracking system remotely, a TrackGUI desktop application was designed using Python library Tkinter. Figure 4 displays the desktop application, which integrates popular satellite tracking software such as Gpredict, SSTV, radio tuner, GPS, and image tracking, all within a single window. With just a single click on the icon, the corresponding software is launched. On startup the TrackGUI software processes various background tasks such as opening ports, to allow communication between devices.

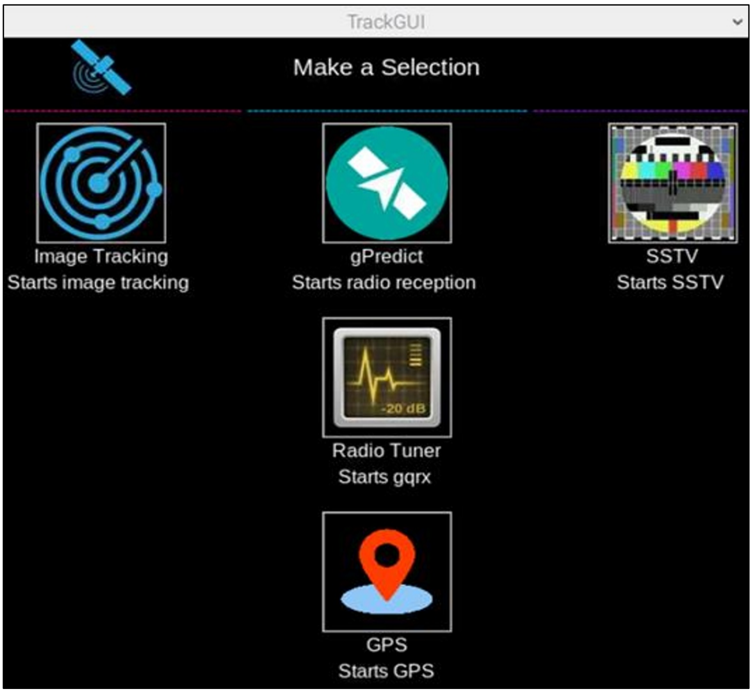

Fig.4. TrackGUI program.

Traditionally, remotely accessing a computer would have involved setting up a firewall and port forwarding, but RealVNC does this easily since it is built into the Raspberry Pi OS [15]. Fortunately, due to an agreement between the Raspberry Pi Foundation and RealVNC, this service is offered for free, when used non-commercially [4]. Via use of the RealVNC app, the Raspberry Pi can be accessed via a mobile device or a PC allowing quick access to the desktop.

Gpredict is the most comprehensive software available to monitor and track satellites. The automatic TLE updates allow satellite passes to remain accurate. Once the base station was set up, the informative GUI visualised the selected satellite paths on a world map. By utilising the algorithms such as SGP4 and SDP4 to model the orbits of satellites around earth, these are used to predict the satellite positions based on TLE sets [5]. The GQRX radio tuner was installed, as it has the most comprehensive feature set as well as driver support for the RTL-SDR dongle. It has a remote-control feature, allowing other software, like Gpredict, to change the frequency automatically [16].

Hamlib is a library used to control both radios and rotators [17]. The Hamlib Application Programming Interface (API) is an intermediary software layer that interfaces with many radios and rotators. Rotctl is a Hamlib rotator control daemon [17]. It sends and receives commands between the software and rotator hardware. Details such as the azimuth and elevation can be sent to the rotator, with positional information from the IMU being sent back [17]. Many off-the-shelf rotators from Yaesu and Celestron have native support for interfacing with Hamlib. The current rotator system utilises non-standard hardware, so a custom protocol is required to facilitate device communication.

The GPS sensor is connected to the Raspberry Pi using the serial pins on the general-purpose input-output (GPIO) header. Using serial commands, the position of the GPS can be obtained for use as the ground station coordinates. Certain satellite transmissions contain SSTV broadcasts. An image is transmitted using frequency modulation. Once the audio is received, it can be decoded by a utility such as *QSSTV*. Depending on the image complexity, a transmission can be from a few seconds to minutes for a single frame.

3 Testing

Quantifiable results are needed to verify the system, components and processes used. These investigations aim to assess the suitability and performance of various aspects within the system. With there being a range of features to test, each item had its own methodology.

3.1 System orientation test

The movement of the azimuth and elevation axes was tested to determine their accuracy. The system was moved to various positions, and recordings were taken to verify the orientations. The rotator axis that was being tested was set to 0°. The phone was secured to the antenna bracket and oriented to EL 0° using the app "Sensor Kinetics" to verify that the EL angle is 0° (the phone sensor is oriented such that the elevation value is 0° when held upwards; when placed flat, it displays a value of -90°). A command was then sent to the Arduino to move the axis to various degrees. Fig. 5 shows the results obtained when the command to move the elevation axes from position 0° to 15° and from 7° to 15° is sent to the orientation control system.

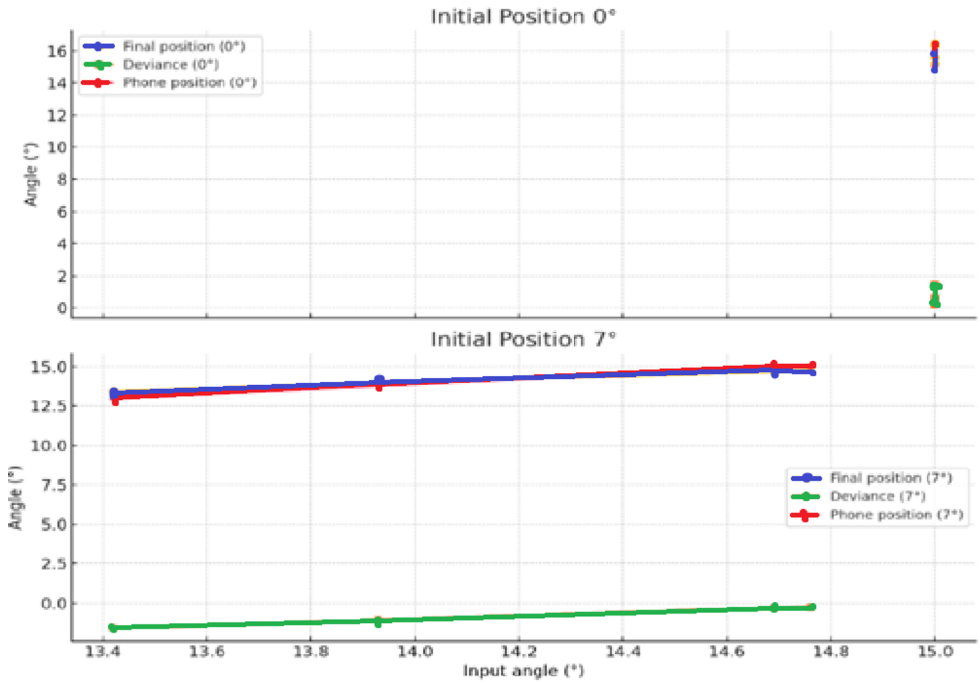

Fig. 5. Orientation test analysis.

The test was repeated for different angles for both azimuth and evaluated the system's motion, revealing specific trends. When the elevation axis moves from 0°, it tends to overshoot the target value, whereas it undershoots when moving from larger angle to smaller angle. This behaviour is consistent for larger movement angles. The azimuth axis, influenced by a uniform mass, shows increasing overshoot as the starting value approaches the target, applicable to all increments tested.

Comparison between the phone sensor and IMU indicated accuracy, though the phone sensor's precision is lower. Most results were within the ±2-degree accuracy of the IMU. Some outliers were due to mechanical backlash, where the axis stops only when gear teeth mesh perfectly. External forces like gravity, inertia, and momentum significantly impact motion mechanics. Despite these challenges, the system can accurately rotate 360° in azimuth and 90° in elevation.

3.2 Satellite tracking test

Satellites that broadcast signals, such as Meteor M2 and NOAA 19, were selected for this test. During the testing, the overhead satellite was NOAA 19, and it was selected on Gpredict for tracking, the system then moved to track the satellite accordingly. Fig.6 shows the relationship of the expected values of the satellite from Gpredict versus the actual values obtained from the system.

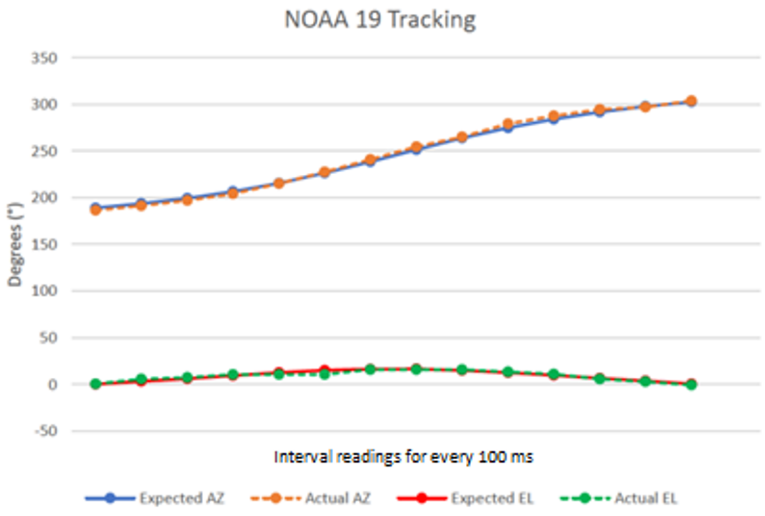

Fig. 6. NOAA 19 satellite tracking results.

Fig. 7 shows the relationship of the expected values of the satellite from Gpredict versus the actual values obtained from the system.

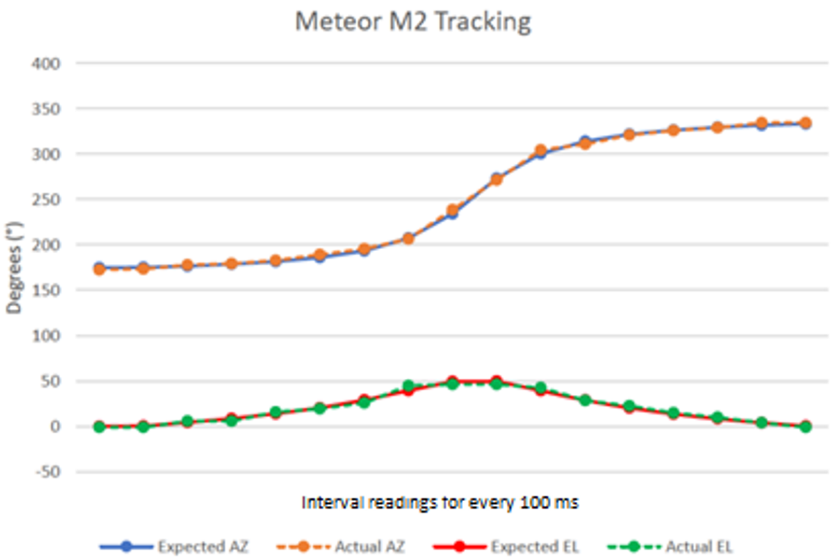

Fig. 7. Meteor M2 tracking results.

The analysis reveals notable insights into the tracking capability of the system. In the azimuth direction, the actual values closely matched the expected values for both Meteor M2 and NOAA 19 satellites, indicating consistent and accurate tracking performance. However, slight deviations were observed in elevation tracking, with some actual values differing from the expected ones. This discrepancy may be attributed to challenges such as stall torque hindering smooth upward motion, as noted in the elevation trend analysis. Despite these deviations, the system demonstrated overall effectiveness in tracking the selected satellites, with the majority of actual values falling within an acceptable range of deviation from the expected values. These results underscore the system's capability to reliably track satellite positions overhead, highlighting areas for potential improvement in elevation tracking precision while affirming the system's overall suitability for its intended purpose of satellite tracking and signal reception.

3.2.1 SSTV test

An ISS SSTV transmission was recorded and the audio transmission was recorded and decoded. An example is shown in Figure 8.

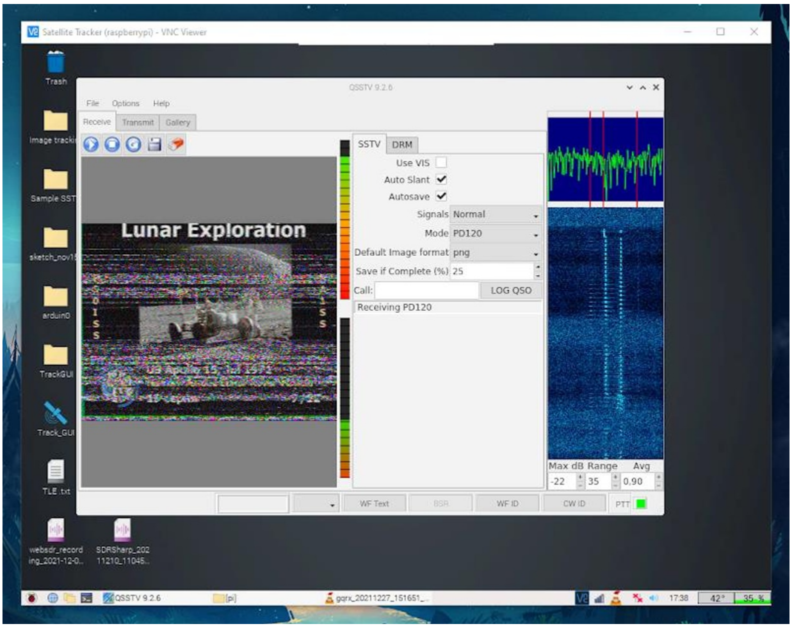

Fig. 8. ISS SSTV decoding.

Although the image is visible, there was fuzziness around the middle and bottom, resulting from electrical interference or signal obstruction from clouds.

3.2.2 Frequency ID test

Using the STRF program, frequency identification was performed. Quadrature signal (QI) recordings were taken for a period of 10 minutes to generate .bin files. The recording was processed and visualised by MATLAB function rfplot. Frequency analysis was performed by MATLAB function rfffit.

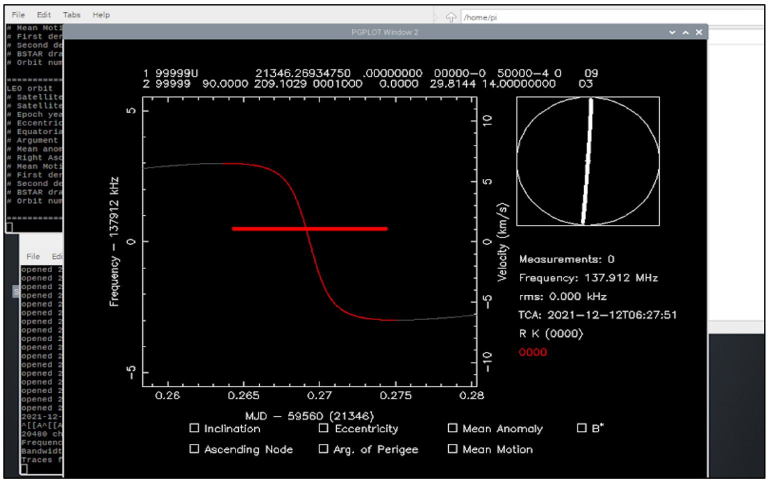

Fig. 9. Frequency analyses, using rffit.

This process, similar to the Doppler Estimation for Passive RF Sensing Method in Space Domain Awareness, confirmed a valid broadcast from NOAA 18 at 137.900 MHz. Despite the success, the CPU-intensive nature of QI data analysis on a Raspberry Pi and the congestion from multiple satellites in the line of sight presented significant challenges.

3.2.3 Discussion

Similar antenna rotator systems are compared in Table 3.

Table 3: System comparison.

	Current System	SatNOGS v3	SATRAN v1
Tracking	Yes	Yes	Yes
Accuracy	5°	1°	1.8°
Telescope Mount	Yes	No	No
Material	Aluminium	3D printed + Aluminium	3D printed
Power Source	12 V battery	DC 48V adaptor	DC 9V adaptor
Remote access	VNC	Website	Android App
Controller	Raspberry Pi	Raspberry Pi + Custom PCB	Custom PCB
Frequency ID	Yes	No	No
SSTV	Yes	Yes	Yes
Frame Size (H x W x L)	660 mm x 330mm x 330 mm	280 mm x 140 mm x 140 mm	180 mm x 150 mm x 150 mm
Cost	US$1 195	US$ 500	US$ 172

The designed system is larger than others but offers unmatched stability and strength due to its all-metal construction, including the ability to support a telescope something other systems lack. Unlike the SatNOGS and SATRAN systems, which use 3D-printed parts that reduce rigidity and introduce points of failure, this system integrates a robust structure. Additionally, a software system was developed to form a user interface, allowing the integrated components to receive radio signals and rotate to track selected satellites. Numerous modifications and improvements were made throughout the system to ensure optimal functionality. allowing for the following:

- The system integrates hardware and electronic components to track satellites and receive their radio transmissions.
- A remotely accessible graphical user interface for various tracking tools, with an admin and user access hierarchy.

4 Conclusion

Creating a remotely accessible satellite tracking system was the motivation behind this research. Various hardware and software systems were researched and selected to develop an optimized solution for the task at hand. Verification of device functionality was performed before software integration to facilitate communication. After resolving numerous network issues, the Raspberry Pi became remotely accessible using RealVNC. TrackGUI was created to allow users to log in and easily access and operate commonly used tracking and monitoring functions. The capability to receive radio transmissions was incorporated using the RTL-SDR. An SSTV and frequency identification utility were included. Testing of various systems is detailed in Section 3. Results confirmed that the subsystems work well and effectively achieve the specified aims and objectives.

We would like to express my sincere gratitude to RS Components, Eskom TESP, Horne Technologies, and Steltron for their invaluable support throughout this research. Their resources and commitment have greatly contributed to the success of this research. We are particularly thankful for the collaborative spirit and encouragement from all the teams involved. This research would not have been possible without your generous support.

References

1. "CelesTrak," Satellite Catalog (SATCAT), (2022). [Online]. Available https://celestrak.com/satcat/search.php [Accessed 25 May 2022].
2. "Astronomical Society of South Africa," Observing satellites, 2022. [Online]. Available: https://assa.saao.ac.za/how-to-observe/satellites/. [Accessed 25 May 2022].
3. K. Healy, Data visualization: a practical introduction, Princeton University Press, 2018.
4. "Space Fence Surveillance System," Lockheed Martin, 2022. [Online]. Available: https://www.lockheedmartin.com/en-us/products/space-fence.html. [Accessed 27 May 2022].
5. "Using the GRAVES Radar to Listen to Reflections from Meteors, Planes and," RTL-SDR, 2017. [Online]. Available: https://www.rtl-sdr.com/using-the-graves-radar-to-listen-to-reflections-from-meteors-planes-and-spacecraft/. [Accessed 12 May 2024].

6. Jouad, Antoine and Barka, Andr, “Massively parallel implementation of FETI-2LM methods for the simulation of the sparse receiving array evolution of the GRAVES radar system for space surveillance and tracking,” *IEEE Access,* vol. 7, no. IEEE, pp. 128968--128979, 2019.
7. nyan-sat, “nyan-sat,” nyan-sat.com, 2020. [Online]. Available: https://nyan-sat.com/. [Accessed 11 May 2024].
8. L. S. Foundation, “SatNOGS: Satellite Networked Open Ground Station,” [Online]. Available: https://satnogs.org. [Accessed 12 June 2024].
9. SATRAN, “ SATRAN Antenna Rotator,” SATRAN, 2021. [Online]. Available: https://www.satran.io/. [Accessed 9 May 2024].
10. Chalak Qazani, Mohammadreza and Asadi, Houshyar and Mohamed, Shady and Nahavandi, Saeid and Winter, Joseph and Rosario, Keith, “A Real-Time Motion Control Tracking Mechanism for Satellite Tracking Antenna Using Serial Robot,” no. Deakin University, 2021.
11. Danymol, R and Ajitha, T and Gandhiraj, R, “Real-time communication system design using RTL-SDR and Raspberry Pi,” in *2013 International Conference on Advanced Computing and Communication Systems*, IEEE, 2013, pp. 1--5.
12. Alam, Md Mahbubul and Islam, Md Monjurul and Mansoor, Ahmad Tamim, “Fully automated satellite tracking system for directional antenna,” BRAC University, 2018.
13. C. Jackson, “EASYCOMM II Standard,” 2021. [Online]. Available: https://www.mustbeart.com/software/easycomm.txt. [Accessed 27 May 2022].
14. “Mini Satellite-Antenna Rotator Mk1,” School Amateur Radio Club Network, 2018. [Online]. Available: https://www.sarcnet.org/rotator-mk1.html. [Accessed 27 May 2022].
15. J. W. Jolles, “Broad-scale applications of the Raspberry Pi: A review and guide for biologists,” *Methods in Ecology and Evolution,* vol. 12, no. 9, pp. 1562--1579, (2021).
16. M. Campus, “Design and development of low cost ground receiving station for LEO satellite operations,” *International Journal of Pure and Applied Mathematics,* vol. 119, no. 12, pp. 2921--2933, 2018.
17. “Hamlib,” Ham Radio Control Library , 2021. [Online]. Available: https://github.com/Hamlib/Hamlib/wiki. [Accessed 26 August 2021].
18. J. T. Richelson, “The future of space reconnaissance,” *Scientific American,* vol. 264, no. 1, pp. 38--445, (1991).
19. B. Fang, “Satellite-to-satellite tracking orbit determination,” *Journal of Guidance and Control,* vol. 2, no. 1, pp. 57--64, (1979).
20. N. L. Johnson, “US space surveillance,” *Advances in Space Research,* vol. 13, no. 8, pp. 5--20, 1993.
21. C. Jackson, “EASYCOMM II Standard,” 2021. [Online]. Available: https://www.mustbeart.com/software/easycomm.txt. [Accessed 27 May 2022].