Advancing Ground Station Capabilities: A Web-based Application with GNU Radio for Seamless Satellite Tracking and Communication

Adriana Rivera ARIVERA35@MINERS.UTEP.EDU
UTEP Aerospace Center, 500 W. University Ave, El Paso, TX 79968 USA

Keren Lozoya Flores KAFLORESHERNANDEZ@MINERS.UTEP.EDU
UTEP Aerospace Center, 500 W. University Ave, El Paso, TX 79968 USA

Joel Quintana JQUINTANA@UTEP.EDU
UTEP Aerospace Center, 500 W. University Ave, El Paso, TX 79968 USA

Abstract

The authors present a web-based satellite tracking application for the automated tracking of two student-designed CubeSat satellites scheduled for launch in 2024 operating in the UHF and S-band frequency bands. Satellite signals are captured and processed by integrating GNU Radio with the Ettus Research USRP x300 SDR hardware. The application uses GNU Radio's signal processing capabilities to implement the DVB-S2 communication standard and the QPSK modulation scheme, ensuring compatibility and efficient communication with the tracked satellites. Challenges such as Doppler shift compensation, signal demodulation, and synchronization are addressed, enabling reliable and accurate satellite tracking. Integrating open-source software and libraries, such as GPredict, facilitates precise satellite position prediction, automated tracking, and communication scheduling. The application showcases the potential of open-source tools in revolutionizing satellite tracking and analysis. Overall, this work aims to improve satellite communication, space exploration, and scientific research in the upcoming era of satellite deployment.

1. Introduction

1.1. CubeSats

CubeSats are a class of nanosatellites whose basic unit (“U”) is a 10 cm edge that typically weighs less than 1.33 kg. Initially developed for educational purposes, CubeSats have since evolved to be used in a variety of sectors including industry and government agencies [1]. This surge in popularity can be attributed to their affordability, simplicity, and rapid development timeline, making them accessible to a broader audience. SleeperSat-1 is a CubeSat mission by the University of Texas at El Paso’s Aerospace Center scheduled to be launched in 2024 that proposes a concept for developing rapid deployment modular satellites with an emphasis on digital engineering principles and techniques. As part of the mission, the Aerospace Center is developing an in-house satellite ground station to track and communicate with satellites operating in UHF and S-Band frequency ranges within a single web application. This consolidated approach streamlines satellite monitoring and facilitates seamless communication, marking a significant advancement in CubeSat mission control and operations.

1.2. Importance of Ground Stations for Successful CubeSat Missions

CubeSats, due to their miniature size and resource limitations, face unique challenges when it comes to their communication systems. The primary issue lies in the limited physical space available on these nanosatellites, which restricts the placement of essential communication equipment, antennas, and solar panels [2].This spatial confinement not only complicates the effective positioning of communication hardware but also severely constrains the allocation of solar panels. As a result, CubeSats grapple with a constant scarcity of power resources, forcing strict management to fulfill all mission tasks, including data collection, processing, and transmission. Moreover, the compact size of CubeSats presents an additional challenge in maintaining proper attitude control. Without the robust propulsion system commonly found on larger satellites, CubeSats must contend with the task of adjusting their orientation to optimize two critical aspects: aligning solar panels with the sun to maximize power generation and pointing communication antennas toward Earth for data transmission. To overcome these innate obstacles in CubeSat communication systems, the support of ground stations becomes paramount. Ground stations enable real-time satellite tracking, the transmission of data to Earth, and the relay of commands to the spacecraft. Ground station reliability is central to mission success, as unreliable communication can lead to mission failure and the loss of valuable scientific data [3]. Statistics show that approximately one-third of CubeSat missions that ended in failure were unable to establish contact with their satellites after launch. This inability to communicate results in a mission's inability to collect scientific data, execute critical commands, or make necessary adjustments during the mission's progression [5]. Therefore, ground stations are essential components, without which CubeSat missions face significant challenges in achieving their objectives and advancing scientific research in space exploration.

2. System Architecture and Design

2.1. Objectives

Having established the unique communication hurdles CubeSats present and in light of the upcoming mission, our focus is ensuring mission success. To accomplish this, we propose a robust ground station system in the form of an integrated web application with the following objectives:

- Live Tracking of Satellites: The web application provides a real-time tracking interface, allowing users to monitor the precise locations and orbits of CubeSat satellites.
- Scheduling Real-time Communication: Our web application schedules and manages real-time communication with CubeSat satellites. Acting as the intermediary between the mission control team and the satellites, it employs GNU Radio and the USRP X300 SDR receiver to decode UHF and S-Band signals seamlessly.
- Satellite Data Display: To provide a comprehensive view of mission-critical data, the application offers a satellite data display module. Users can access telemetry data, satellite positions, and other vital information in real-time, supporting informed decision-making.
- Log Keeping and Analysis: The web application maintains detailed logs of all commands sent and data received from CubeSats. These logs serve as a valuable resource for mission analysis and post-mission evaluations.
- Academic Learning and Ground Station as a Service: An essential aspect of our proposal is the utilization of the ground station as a service, emphasizing its educational value. By operating and managing this ground station web application, students can gain valuable skills and insights that are highly relevant in an academic setting.

In summary, our proposed single web application seamlessly integrates critical ground station functions, addressing the mission's technical requirements while fostering academic growth through practical learning experiences for students.

2.2. Software and Hardware Components

With the objectives of our system now established, the following section provides a comprehensive overview of the software and hardware components that will comprise the foundational infrastructure of our CubeSat mission's ground station web application.

2.2.1 SOFTWARE COMPONENTS

- Ground Station Computer (Linux OS): The ground station computer operates on a Linux OS, providing a stable and secure environment for executing critical software components. It serves as the foundation for all ground station operations.
- GNU Radio: GNU Radio enables advanced signal processing, modulation, and demodulation. It is essential for decoding UHF and S-Band signals and ensuring efficient satellite communication.
- GPredict: The backend of our web application is based on GPredict, enhancing satellite tracking capabilities and Doppler shift correction. GPredict's source code provides accurate predictions of satellite orbits, aiding real-time tracking and mission planning [6].
- Server: The server component of our web application ensures seamless data storage, retrieval, and communication. It acts as a central hub for managing mission-critical information and facilitating user interaction.

2.2.2 HARDWARE COMPONENTS

- UHF Cross Polarized Yagi-Uda Antennas: Used to receive and transmit UHF signals. They are crucial for maintaining contact with CubeSat satellites.
- S-Band Parabolic Reflector Antenna: The S-Band parabolic reflector antenna enables high-data-rate communication with CubeSat satellites, enhancing data transmission capabilities.
- Azimuth and Elevation Rotor Controller: Allows for precise control of antenna azimuth and elevation angles, ensuring accurate satellite tracking and communication.

- USRP x300 Software-Defined Radio (SDR): SDR technology is instrumental in decoding UHF and S-Band signals, supporting efficient and reliable satellite communication.

The seamless integration of these software and hardware components empowers our ground station web application, enabling real-time tracking, seamless communication scheduling, and effective data management. This robust technical infrastructure is the cornerstone of our CubeSat mission's success.

Figure 1: S-Band and UHF antennas on ground station roof

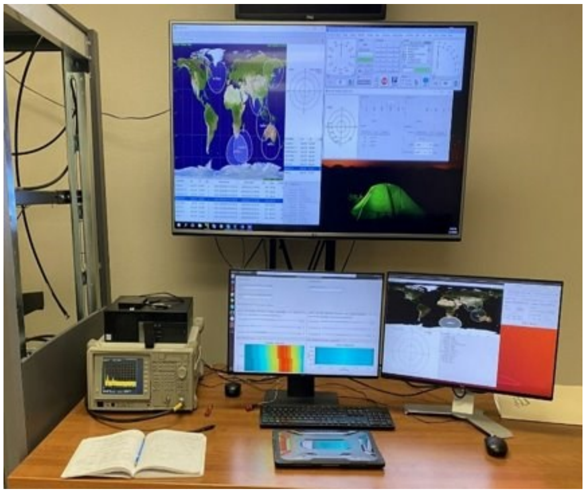

Figure 2: Ground station inside setup

2.4. Communication Specifications

In the context of developing our ground station system, the configuration of the SleeperSat-1's communication system is important as it directly impacts the design and functionality of our system. It is composed of:

- UHF Transceiver (Half-Duplex): The CubeSat is equipped with a UHF transceiver operating in half-duplex mode.
- Deployable UHF Antenna: Accompanying the UHF transceiver is a deployable UHF antenna. This antenna enhances signal transmission and reception capabilities, allowing the CubeSat to maintain contact with ground stations throughout its mission.
- S-Band Transceiver (Full-Duplex): The CubeSat also features an S-Band transceiver operating in full-duplex mode.
- Patch S-Band Antenna

In addition to these hardware components, the CubeSat employs the following protocols and modulation scheme:

- AX.25 Packet Protocol: AX.25 is used to encapsulate and transmit data packets, offering reliability and efficiency in data transmission.
- ESTTC Protocol: Developed by EnduroSat, the ESTTC (EnduroSat Standard Telemetry and Telecommand Communication) protocol enhances telemetry and telecommand functions, streamlining mission operations.
- Quadrature Phase Shift Keying (QPSK) is selected as the modulation scheme for efficient data encoding into radio signals.

This comprehensive communication configuration ensures the CubeSat's ability to transmit and receive data reliably, aligning with the mission's scientific objectives.

3. Development

3.1 Enabling satellite tracking capabilities

To add precise satellite tracking capabilities to our system we have adapted the computational components of GPredict, a renowned open-source software known for its exceptional satellite tracking functionality, into a back-end system. At the core of GPredict lies the use of Two-Line Elements (TLEs). These data sets contain critical information about the orbital parameters of Earth-orbiting objects, including CubeSats. TLEs encompass essential details such as satellite identification, epoch data, orbital inclination, eccentricity, mean motion, argument of perigee, right ascension of the ascending node, and mean anomaly [7]. To ensure tracking precision, our system automatically fetches TLEs from Celestrak once a day. When a user requests tracking of a specific satellite, our system queries the acquired TLE data, based on the catalog number of the desired satellite. This data is then seamlessly processed through the GPredict back-end, producing precise real-time calculations of the satellite's position. This real-time selection process ensures the accuracy of satellite tracking. Our adapted GPredict-based back-end integrates the Simplified General Perturbations 4 (SGP4) propagator, a mathematical model renowned for its ability to accurately predict the positions of objects in Earth's orbit. SGP4 meticulously processes TLE data, enabling precise calculations of the satellite's position and velocity at any given moment. This process considers various factors such as gravitational influences, perturbations, and atmospheric drag. Our adapted GPredict-based back-end produces an array of outputs:

- Latitude and Longitude: This feature provides accurate live geographical coordinates that are then used to plot the satellite's location on the map displayed in the GUI.
- Azimuth and Elevation: These real-time measurements offer precise angular positioning data to be passed on to the rotor controller to move the antennas to follow the trajectory of the satellite.
- Velocity: Calculations of the satellite's current speed in relation to the ground station.
- Next AOS (Acquisition of Signal) and LOS (Loss of Signal): Accurate predictions of when the satellite will become visible and within communication range so that we can schedule this communication window.
- Doppler Shift Correction: GPredict dynamically corrects Doppler shift by predicting the satellite's position and calculating the expected frequency shift based on its relative motion. The ground station's transmitter and receiver frequencies are then adjusted in real-time to compensate for the shift.

These comprehensive outputs, achieved through the adaptation of GPredict's algorithms, not only enable the meticulous tracking of the satellite but also facilitate optimized data communication.

```
AO-73

     Azimuth :  28.72°
   Elevation :  -9.44°
 Slant Range : 4226 km
  Range Rate : -4.881 km/sec
  Next Event : AOS: 2021/05/08 08:35:33
    SSP Loc. : NQ83KK
   Footprint : 5603 km
    Altitude : 669 km
    Velocity : 7.511 km/sec
Doppler@100M : 1628 Hz
   Sig. Loss : 144.92 dB
  Sig. Delay : 14.10 msec
 Mean Anom. : 107.49°
 Orbit Phase : 151.16°
  Orbit Num. : 40150
  Visibility : Daylight
```

Figure 3: Example of GPredict outputs

Figure 4: Graphical user interface

3.2 Scheduling communication based on future pass prediction

The GPredict-based back-end delivers a comprehensive set of data, including real-time latitude, longitude, azimuth, elevation, velocity, and Doppler shift correction information. This data can then be used to schedule communication. By precisely knowing the satellite's azimuth and elevation concerning our ground station, we can determine how to orient our antennas for optimal signal reception. These calculations are vital for maintaining a stable connection during the satellite pass. To automate antenna movement, we establish a serial link between the rotor controller and the ground station computer. Just before the calculated AOS time, we send the azimuth and elevation values for the satellite of interest to the rotor controller. This advance notice ensures that the antennas start moving in anticipation of the satellite's arrival within the communication range. By sending the calculated azimuth and elevation values to the rotor controller a little before the AOS time, our system proactively reorients the antennas, allowing them to smoothly track the satellite's trajectory. This precise movement ensures that communication with the satellite is established as soon as it enters our ground station's field of view. This automated approach minimizes the risk of signal loss during satellite passes, making our communication system highly reliable. It also optimizes our ability to collect and transmit data, supporting the success of our CubeSat mission.

3.2 Receiving and processing satellite signals

Software-defined radio (SDR) devices have made a massive contribution to communication systems by reducing the cost and development time for radio frequency (RF) designs [4]. SDRs opened the gate to programmers and enabled them to increase the capabilities of these easily manipulated systems. Our system leverages the capabilities of the USRP x300 SDR equipped with two 160 MHz daughterboards, providing support for various frequencies and signal types. This dual-daughterboard configuration enhances our ground station's adaptability, allowing it to handle a wide spectrum of frequencies relevant to CubeSat communications. Complementing the hardware, GNU Radio will be used in the background of our web application to process signals. GNU Radio’s python API allows for seamless integration and communication between the web application's back-end and the GNU Radio software. The processing of satellite signals will be the following:

- Signal Decoding: Once the signals are received by the USRP x300 and passed to GNU Radio, we will use custom-built signal processing scripts to decode the data. For example, in the case of telemetry data transmitted from the CubeSat, we will use decoding algorithms to extract information such as sensor readings, battery status, and mission-specific data.
- Error Correction: To ensure data integrity, error correction codes will be applied to correct any bit errors introduced during transmission. These codes enhance the reliability of the received data, especially in scenarios where signal quality may be compromised.
- Data Parsing: After decoding and error correction, the data will be parsed into meaningful information that can be further analyzed or displayed to the user through our web application. This step involves structuring the data according to predefined protocols, making it accessible for mission control and analysis.
- Real-time Display: Processed data will be displayed in real-time on our web application, providing users with up-to-the-minute information about the satellite's status, telemetry, and mission-specific metrics.

4. Conclusion and Future Work

In this paper, we have presented the development of a web-based satellite tracking application aimed at enhancing CubeSat mission control and operations. While CubeSats offer a cost-effective and accessible means for conducting scientific research and space exploration, they face unique challenges, especially in communication and ground station support. Our system leverages open-source tools and libraries, such as GPredict, GNU Radio, and USRP x300 SDR, to achieve live satellite tracking and real-time communication scheduling. Through the adaptation of GPredict's algorithms, we ensure precise satellite tracking, with features like latitude, longitude, azimuth, elevation. Furthermore, our system automates antenna movement based on future pass predictions, minimizing signal loss and optimizing data communication. The foremost future work involves the integration of signal processing into the web-based application. This includes developing custom signal processing scripts for decoding, error correction, and data parsing. Once implemented, this component will enable the application to receive and process satellite signals effectively, providing users with real-time telemetry data and mission-specific metrics.

References

[1] Villela, T., Costa, C. A., Brandão, A. M., Bueno, F. T., & Leonardi, R. (2019). Retrieved from https://www.hindawi.com/journals/ijae/2019/5063145/

[2] Caldwell, S. (2017). Small Spacecraft Technology State-of-the-Art Retrieved from https://www.nasa.gov/smallsat-institute/small-spacecraft-body-of-knowledge

[3] National Academies of Sciences. (2016). Achieving science with cubesats: Thinking inside the box. Retrieved from https://doi.org/10.17226/23503

[4] Maheshwarappa, M. R., & Bridges, C. P. (2014). Retrieved from https://ieeexplore.ieee.org/abstract/document/6880174/

[5] Swartwout, M. Retrieved from https://www.jossonline.com/storage/2014/12/0202-The-First-One-Hundred-Cubesats.pdf

[6] Gpredict. Retrieved from http://gpredict.oz9aec.net/

[7] Vallado, D., & Cefola, P. (2012). Retrieved from https://www.researchgate.net/profile/David-Vallado/publication/289774073_Two-line_element_sets_-_Practice_and_use/links/5698f55208aea14769431606/Two-line-element-sets-Practice-and-use.pdf?origin=publication_detail