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Research Article

Real-Time Telemetry Transmission for CubeSat Mission using KL AP – APRS

Mr. Chopparapu Hemanth Nag[1*], Mr. D. Surya Teja[2], Ms. N. Sushma[3], Mrs. P. Vijaya Santhi[4], Mrs. R. latha[5], Mr. Sarat K Kotamraju[6], Mrs. K. Chinnari Sri Kavya[7]
[1*] Student, Electronics and Communication Engineering, KL University, Vaddeswaram, Guntur, India-522502
[1*]Email: chhemanthnagnaidu@gmail.com
[2]Student, Electronics and Communication Engineering, KL University, Vaddeswaram, Guntur, India-522502
[3]Student, Electronics and Communication Engineering, KL University, Vaddeswaram, Guntur, India-522502
[4]Research scholar, ECE, Koneru Lakshmaiah Education Foundation, Guntur, India-522502
[5]Research scholar, ECE, Koneru Lakshmaiah Education Foundation, Guntur, India-522502
[6]Professor & Director (R&D, Placements Relations), ECE, Koneru Lakshmaiah Education Foundation, Guntur, India-522502
[7]Professor & Director (Alumni), ECE, Koneru Lakshmaiah Education Foundation, Guntur, India-522502

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ABSTRACT

This paper describes the design and implementation of a ground station to receive Automatic Packet Reporting System (APRS) signals from the KLAP transmitter module designed for the KLSAT 1U CubeSat. The KLAP module enables fast transmission of telemetry data using the APRS protocol, specifically operating in the AX.25 standard. The ground station includes the use of software to determine APRS signals, a Terminal Node Controller (TNC) integrated with the antenna for signal processing, and an increase in the operating frequency to 144.390 MHz (APRS frequency). The system works with the PINPOINT APRS application and APRS.fi, allowing continuous monitoring and analysis of telemetry data from CubeSats. The test demonstrated that the KLAP module provides reliable and efficient data transmission from space to ground, demonstrating the potential of APRS technology in the development of small satellite communications. The design ensures data integrity and low cost, making it suitable for small satellite missions. We conducted extensive practical tests to evaluate the performance of the KLAP module and ground station and demonstrated that the system can instantly and reliably identify and analyse telemetry data from CubeSats. The results highlight the effectiveness of APRS technology in improving small-scale radio communications, providing high-resolution and efficient field telemetry solutions. This study demonstrates the potential for APRS to be more widely used in satellite communications, especially in the field where limited use requires new methods of information transmission and resception.

Keywords: APRS; APRS tracker; Cube satellite; Telemetry data

1. INTRODUCTION

The rapid development of CubeSats (small satellites measuring 10x10x10 cm and weighing less than 1.0 kg) has had a major impact on satellite technology, especially for Low Earth Orbit (LEO) deployments. The CubeSat and microsatellite industry has grown exponentially over the past decade, spurring innovation and encouraging competitive research aimed at improving efficiency and effectiveness. Despite this progress, nanosatellite development and commercialization still face major challenges, such as power constraints, transponder size limitations, and the urgent need for onboard communication systems. To address these issues, new communication technologies are being explored, with recent efforts focusing on improving signal-to-noise ratio (SNR) and optimizing channel performance to provide reliable communication in the harsh conditions of low Earth (LEO).

This study focuses on the KLSAT mission, a CubeSat launched by the KL University as a high-altitude satellite and specifically focuses on the use of Automatic Packet Reporting System (APRS) technology for persistent transmission of telephony data. APRS is widely accepted in monitoring and is the best solution to improve the transmission of telemetry parameters such as temperature, pressure, and altitude. Traditional RF telemetry often requires costly infrastructure and higher power consumption. In contrast, APRS operates efficiently with low power and leverages the existing network of amateur radio stations, reducing operational costs.

LoRa based communication offers advantages in terms of low power consumption and long-range data transmission. However, LoRa's susceptibility to interference and its reliance on specific frequencies limit its effectiveness. Conversely, APRS benefits from pre-existing infrastructure and ensures enhanced data integrity through its automatic error correction and packet-based transmission mechanism.

This study uses AFSK modulation for transmission signals to improve the efficiency and reliability of data transmission from satellites to Earth. As shown in the accompanying table, the telemetry data recorded during the KLSAT mission demonstrates the satellite's ability to transmit important environmental and operational data back to earth. This research contributes to the expansion of nanosatellite communication technology by examining the complexity of these systems and improving existing systems to improve the number of data communications of APRS, thereby improving the overall capabilities of the CubeSat mission.

2. LITERATURE SURVEY

Yue et al., [1] LEO SCS has gained increasing popularity due to its advantages of seamless global coverage and low latency. However, there are many unsolved problems in using its full potential, including the security of LEO SCS. Due to the special location of the area, high mobility other characteristics of the world, the low-lying world will face serious security problems. Not only security attacks (such as eavesdropping and DoS) but also trust (such as collisions and SEU) can affect the security on LEO SCS. In LEO SCS, the problems are classified, their characteristics are noted, and suggestions are discussed. In response to these problems, we will introduce and summarize some solutions that can be divided into security and reliability improvement solutions. Therefore, we focus on ISAC-supported transmission security.

Zhan et al., [2] Satellite measurement and control systems play an important role in office operations. As a measurement and control technology, satellite measurement has matured and has the potential for development. However, deep exploration, measurement, and control systems still face many challenges that need to be solved. Based on future research, this paper presents the status of satellite measurement and control technology, reviews future technology trends, and discusses effective methods for satellite measurement and control. Deep exploration and satellite mega-constellations will provide the foundation of future satellite measurement and control panic. We believe that with the progress of science and technology, satellite measurement and control will promote the development of human aviation and the space industry.

Ivanushkin et al., [3] Satellite measurement and control systems play an important role in office operations. As a measurement and control technology, satellite measurement is growing and has the potential to develop. However, deep research, measurement, and control systems still face many problems that need to be solved. Measurement and control. We believe that with the progress of science and technology, satellite measurement and control will promote the development of the human aviation industry.

Squadrito et al., [4] This paper improves and refines the antenna extension. The electrical measurement model, axial ratio, and gain are in good agreement with the simulation results, clarifying the electromagnetic design. Mechanical and thermal tests verify that all the materials, screws and designs used in the skirting boards are necessary to obtain a design that meets the site needs. Four antennas (two RHCP and two LHCP) are used to implement the TT&C system. In this way, a quasi-isotropic refraction model is obtained. The antenna is designed to meet the requirements of the system, namely the beam width is greater than 40°3dB, the maximum gain exceeds 6dBi, and the axial ratio is less than 4dB in the entire 2.0-2.3GHz operating frequency band. In addition, the proposed antenna has a wide impedance bandwidth of 19.7%.

Saha et al., [5] In order to meet the increasing need for sending and receiving channels, data is widely used in telemetry/remote command processing, it is recommended to use HC compression for telemetry/remote command channel. A modified version of the CCSDS packet model will be used to account for compression and encryption. The recycling of world goods will be guaranteed by cheap goods and the world station. Thus, encryption really protects sensitive data. Different implementations of AES have been shown to provide different measures and security advantages in different systems.

Zeedan & Khattab, [6] Small satellite communications have recently entered a period of great interest due to the increasing commercial and public use and the impact of various innovations. The deployment costs make them promising to play an important role in global wireless communications with applications such as global photography and military space exploration. In addition, low Earth orbit (LEO) CubeSat constellations meet the increasing demand for low-cost, high-speed, flexible, and global coverage. However, this requires new solutions to solve the critical problem of high-data-cost, low-energy communications space. This presents a comprehensive review of the design, layout, and engineering of state-of-the-art CubeSat communications subsystems, with a special focus on frequency models.

Saeed et al., [7] Given the ever-increasing amount of information about location, research into new location markets has become attractive. An important area of space exploration is now the creation of miniaturized satellites called CubeSats, which are attractive because they are widely used and low-cost to build and deploy. The new space communication concept of CubeSats opens up many applications, such as remote sensing, space exploration, and remote communications. CubeSats also provides connectivity for the Internet of Things (IoT), creating a global network of institutions. This article provides an overview of various CubeSat missions and a comprehensive review of the topic from both academia and industry.

Un S, et al., [8] The research focuses on ways to communicate address information in the event of a disaster when the network connection is interrupted. The system works between the smartphone GPS and amateur radio equipment, enabling emergency alerts via APRS. According to the above test procedure, the test results are generated from GPS location data from the smartphone in offline mode (assuming that the smartphone does not have access to the network). The location difference between the MSO is the real APRS-IS map on the RSO side. Moreover, when APRSDroid is used on a smartphone, its location is also tracked and displayed in the apr.fi web application.

Theoharis et al., [9] This presents a brief review of space SDRs, focusing on designs related to CubeSats. Two different approaches have been proposed to build SDRs for mass and small space probes such as CubeSats. High-throughput SDR is also planned for CubeSat applications. The radio is equipped with an FPGA SoC, thus achieving the best SDR architecture. This design can achieve a data rate of 60 Mb/s; only 2.6 W during transmission and 0.4 W during reception. It is versatile, instantly reconfigurable, and can communicate at high data rates with low power consumption. The common platform addresses current communication limitations of CubeSats and demonstrates the potential to create swarms of CubeSats.

Quach et al., [10] The collaboration between MGSS and INSPIRE has opened up a new way to improve low-cost workplaces. Instead of seeing the development of the terminal as driving the development or upgrade of the ground, we look at FSW and GDS in a broader context as two interconnected systems. By following the rules and deciding on clean, connected elements, we can separate the modules without affecting their ability to work together. As a result, MGSS can provide INSPIRE with command interrupt and telemetry systems at a very low cost.

3. SYSTEM DESIGN

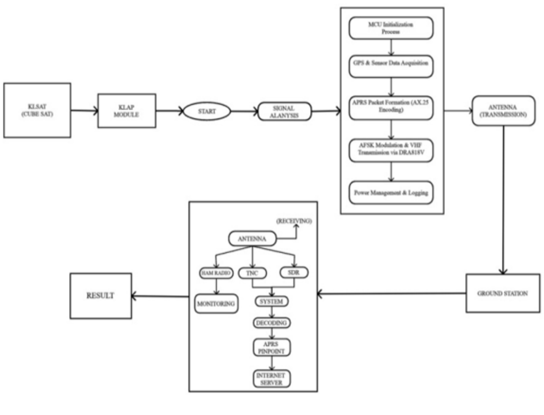

Fig 1: Automatic Packet Reporting System (APRS) Based Telemetry and Data Transmission for CubeSat Communication Systems.

Designed for real-time [11] telemetry of the KLSAT 1U CubeSat mission, the system consists of two main components: the KLAP payload telemetry module for APRS data transmission and the ground station for data reception and analysis. The KLAP modules use the AX.25 protocol to reliably transmit telemetry data in real-time via the Automatic Packet Reporting System (APRS). Ground stations effectively receive and decode these APRS signals, allowing continuous monitoring and analysis of CubeSat telemetry data. This design provides efficient and cost-effective communications for small satellite projects in Fig 1.

3.1 Space Module (Klap)

Fig 2: Architecture for APRS Data Transmission and Signal Processing of Cubesat data

Fig 2 shows that, The KLAP [12] module operates efficiently with the MCU at its core. Upon system boot, the MCU initializes essential components, including the clock, peripherals like GPS, sensors, and the DRA818V VHF radio module, and configures input/output (I/O) ports. Configuration parameters such as callsign, frequency, and transmit interval are loaded, likely from flash memory, as KLAP lacks EEPROM. The GPS module acquires satellite signals, with the MCU parsing the received NMEA data to extract latitude, longitude, and altitude. This position data is temporarily stored in the 32 KB RAM, which has double the capacity of the previous version, allowing more complex operations. If sensors are present, the MCU initializes them, reads real-time data through interfaces like I2C or SPI, and formats the sensor data to include it in the APRS packet. The MCU then constructs an APRS packet containing the source callsign, GPS position, sensor data, and other relevant information, encapsulating it in the AX.25 format. The larger 256 KB flash memory allows for more extensive or flexible packet structures. The packet is converted into a bitstream, modulated using AFSK (typically at 1200 baud), and transmitted via the DRA818V radio module, configured with the required frequency, power, and modulation scheme. The KLAP operates on a broad input voltage range (2.7V - 16V) and optimizes power consumption by entering low-power states after transmission or during idle periods, aided by the MCU's power management capabilities. The MCU also manages sleep cycles, waking up periodically based on a timer or external event to repeat the process.

Data like position and transmission logs can be stored in the expanded 256 KB flash memory, with telemetry data sent regularly or triggered by specific events. The system includes error detection using CRC, with retry logic for retransmission if a packet fails to be acknowledged. The MCU continuously monitors the status of all modules and can reset or reconfigure them if a fault is detected. Commands received over APRS can be used to remotely reconfigure the device. In case of a low [13] battery or a shutdown command, the device ensures that all data is safely stored, and modules are powered down correctly. KLAP improves upon its predecessor by double the available RAM, increased flash storage, and a higher frequency (48 MHz compared to 8 MHz). These enhancements allow for more efficient and faster operations, better power management, and increased flexibility in APRS packet construction and transmission, making Light KLAP a robust solution for lightweight, portable, and low-power APRS applications.

3.2 Ground Station

To configure a ground station for APRS beacon reception, start by installing the DIREWOLF software. Add a LOGDIR command at the end of the installation script to ensure that log files are logged. Now connect the VHF antenna to the Terminal Node Controller (TNC) and now connect [14] TNC to your system to decode the packets. Open the DIREWOLF application and connect to the virtual audio that will transmit the data packets in the form of an audio signal. Make sure you select the correct virtual audio cable in the application. This step should be performed in an open-air environment for optimal signal reception. Set the TNC to the frequency of 144.390 MHz, commonly used for APRS transmissions. Enable "record audio" to capture audio signals for decoding. Check the location by setting the same frequency on the HAM radio. This will ensure that the ground station is connected with a good signal. Once confirmed, open the PINPOINT APRS application and update the TNC, APRS-IS, and GPS settings as necessary. Start the I-Gate to facilitate the reception and transmission of APRS packets. To monitor the transmitted data, visit the APRS.fi website and enter the call sign (for example, "VU3DAC" for the KLAP balloon satellite). Set the location and SSID (Secondary Station Identification Number) as required. In the Raw Packets section, select Decode to view incoming APRS packets. As the balloon satellite moves, the beacons will be updated by the DIREWOLF application, the APRS.fi website and the TNC. This configuration allows ground stations to efficiently receive, identify, and track APRS transmissions, providing the necessary information for research.

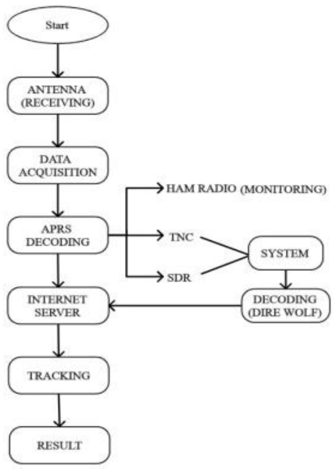

Fig 3: APRS-Based Ground Station for tracking CubeSat

This flowchart Fig 3 describes the general operation of a system designed to use the Automatic Packet Reporting System (APRS) for data capture, processing, and transmission. The process begins with data collection, where raw data is collected from various surroundings. The collected data is then subjected to signal analysis and processed to extract relevant information such as signal strength, frequency, or parameters. This optimized data then goes through the APRS [15] encoding stage and is converted to a special format compatible with the APRS protocol, such as AX.25 or AFSK (Audio Frequency Shift Keying). This process makes the data useful for transmission over the APRS network.

The encoded information is then controlled by the central system block that controls the process and ensures that all elements work together. The APRS data is sent to the receiver/ground station where it is received and processed by the TNC (Terminal Node Controller). The TNC is responsible for demodulating the received signal and converting it into a data format that can be analysed or used by the system. The system then performs the APRS decoding process to extract the original message from the encoded signal so that it can be understood and processed. The interrupt data is then sent to the Connect NM PNP, which can be responsible for network [16] management or plug-and-play operations, facilitating connections with other systems. Finally, data is sent to the APRS-FI/Internet server for storage, distribution, or further analysis, completing the loop. This detailed workflow ensures efficient and effective data processing from acquisition to final output while maintaining compliance with established APRS standards.

4. RESULTS AND DISCUSSIONS

Fig 4: Results of Real-Time APRS Telemetry and Tracking with Direwolf and APRS.fi Integration

This Fig 4 shows the configuration and results of a time tracking and telemetry system based on the Automatic Packet Reporting System (APRS) operating at a frequency of 144.390 MHz. uses other data packets and various software tools to receive, decode, and track data packets. The system [17] uses KLAP modules to send data over radio frequencies identified by Direwolf and tracked via APRS.fi. Each element of the image provides a unique insight into the capabilities of the APRS system, from instantaneous location to detailed phone information.

Map View of Real-Time Tracking:

This map view provides instant tracking of APRS equipment, allowing operators or researchers to track its location and [18] movement. This capability is important for applications such as weather balloon tracking, vehicle tracking, or other location telemetry.

Direwolf Decoding of APRS Data:

Direwolf's decoding [19] window is required to interpret raw APRS packets sent over radio frequency. Identifying the data provides information about the device's location and environment, ensuring that the data is immediately available for review and storage.

APRS.fi Packet Feed:

The APRS.fi feed allows for global monitoring and tracking of APRS data in real-time. By logging each transmission online, APRS.fi ensures that location and telemetry data are accessible beyond the immediate radio range, making it ideal for research requiring long-distance tracking or archival of data packets.

This setup combines Direwolf and APRS.fi to provide a comprehensive, real-time APRS monitoring and telemetry system. The KLAP module operates on the 144.390 MHz APRS frequency, continuously transmitting location and environmental information. Direwolf software decodes these packets locally, while APRS.fi stores and tracks them online. This integration [20] supports ground-based and Internet-based monitoring of APRS-enabled mobile or fixed devices, providing a comprehensive solution for research applications. In-field electricity usage and IoT-based location tracking allow researchers to instantly monitor, identify and collect information from a remote location.

To configure the space module, the transmitter module antenna is responsible for transmitting data packets as positioned data. To ensure accurate reception, the GPS must be locked by initiating an initial beacon, which signals the start of transmission. This beacon provides essential data parameters,

Table 1: Representation of latitude, longitude, and telemetry data

Latitude	Longitude	Telemetry
16.440522	80.622361	002TxC 39.50C 1001.99hPa 5.03V 04S
16.440524	80.622353	003TxC 39.30C 1002.25hPa 5.01V 04S
16.440491	80.622297	004TxC 40.10C 1001.69hPa 5.03V 07S

16.440489	80.622295	005TxC 41.50C 1002.65hPa 5.04V 07S
16.440518	80.622258	006TxC 41.50C 1002.89hPa 5.02V 08S
16.440442	80.622227	009TxC 43.50C 1002.76hPa 5.03V 11S
16.440425	80.622090	010TxC 42.80C 1002.29hPa 5.03V 11S
16.440480	80.622449	012TxC 42.30C 1004.58hPa 5.03V 07S

Table 1 represents data received by the KLSAT 1U CubeSat's KLAP transmitter module and contains latitude and longitude coordinates that describe the position of the satellite at different times. Each telemetry entry has a unique identifier (e.g. 002TxC) followed by environmental and operational information such as temperature (e.g. 39.5°C), barometric pressure (e.g. 1001.99hPa), voltage (e.g. 5.03V), and specified elapsed time (e.g. parameters come. , 04S). These measurements provide important information about the satellite's environmental conditions and electrical performance during its mission, helping to monitor and analyze its ongoing operations as it orbits the Earth.

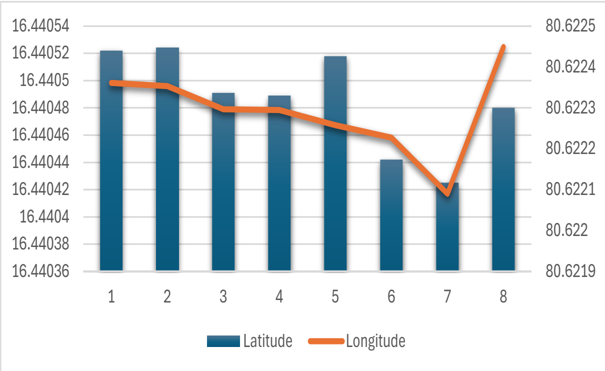

Fig 5: Analysis of geographical coordinate variation over time.

This Fig 5 shows how the latitude and longitude change over time to analyze satellite position and movement. The latitude remains very stable, with only low variations indicating minimal positional shifts. However, the longitude indicates that it gradually decreases before suddenly increasing at the last data point. This can be caused by factors such as trajectory drift, signal delay, or adjustments to the tracking system. These variations highlight the importance of improving the accuracy of APRS-based persecution, improving satellite telemetric systems, and optimizing communication protocols to ensure accurate and reliable locations.

Table 2: Representation of ISO time, altitude

ISO Time	Altitude
2023-09-16T04:50:22Z	37.5 m
2023-09-16T04:51:14Z	37.5 m
2023-09-16T04:52:07Z	46.9 m
2023-09-16T04:52:59Z	47.5 m
2023-09-16T04:53:52Z	58.2 m
2023-09-16T04:56:30Z	48.8 m
2023-09-16T04:57:32Z	59.7 m
2023-09-16T04:59:11Z	85.0m

The table 2 shows CubeSat altitude measurement timer uses the ISO 8601 time format to record the exact time of each measurement. The ISO timestamp (for example, 2023-09-16T04:50:22Z) indicates the time in Coordinated Universal Time (UTC) when the altitude was recorded. The altitude column shows the height of the satellite above the Earth's surface at a given time in meters (for example, 37.5 m). The data charts the CubeSat's ascent or descent over a short period of time, showing changes in altitude as it follows its orbital path.

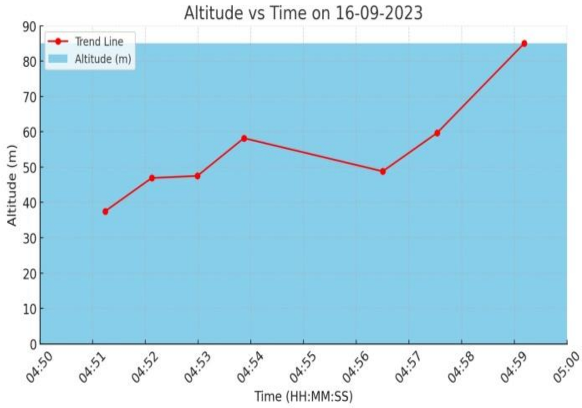

Fig 6: Analysis of altitude variation over time.

On 16-09-2023, the CubeSat's altitude increased from 37.5 meters to 85.0 meters, showing small fluctuations of about ±5 meters initially, likely due to wind or minor control adjustments. After reaching 60.0 meters, the altitude rose steadily, as shown by the red trend line. Measurements were recorded every 10 seconds, capturing the gradual ascent despite minor disturbances. These variations highlight the need to improve APRS-based persecution accuracy, enhance satellite telemetric systems, and optimize communication protocols for reliable tracking. Continuous advancements in tracking and control systems are essential for better performance and precision in future missions. Fig 6 shows the Analysis of altitude variation over time.

Received data from the module:

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:han,utime,isotime,source,heard,level,error,dti,name,symbol,latitude,longitude,speed,course,altitude,frequency,offset,tone,system,status,telemetry,comment
),1694839822,2023-09-16T04:50:22Z,VU2LWI-11,VU2LWI-11,107(50/20),0,/,VU2LWI-11,/O,16.440522,80.622361,1.0,78.0,37.5,,,,LightAPRS - TA2MUN and TA9OHC,,, 002TxC  39.50C 1001.99hPa  5.03V 04S
.ightAPRS-W 2.0
),1694839874,2023-09-16T04:51:14Z,VU2LWI-11,VU2LWI-11,105(50/20),0,/,VU2LWI-11,/O,16.440524,80.622353,0.0,78.0,37.5,,,,LightAPRS - TA2MUN and TA9OHC,,, 003TxC  39.30C 1002.25hPa  5.01V 04S
.ightAPRS-W 2.0
),1694839927,2023-09-16T04:52:07Z,VU2LWI-11,VU2LWI-11,101(48/20),0,/,VU2LWI-11,/O,16.440491,80.622297,2.0,78.0,46.9,,,,LightAPRS - TA2MUN and TA9OHC,,, 004TxC  40.10C 1001.69hPa  5.03V 07S
.ightAPRS-W 2.0
),1694839979,2023-09-16T04:52:59Z,VU2LWI-11,VU2LWI-11,102(50/19),0,/,VU2LWI-11,/O,16.440489,80.622295,0.0,78.0,47.5,,,,LightAPRS - TA2MUN and TA9OHC,,, 005TxC  41.50C 1002.65hPa  5.04V 07S
.ightAPRS-W 2.0
),1694840032,2023-09-16T04:53:52Z,VU2LWI-11,VU2LWI-11,96(44/18),0,/,VU2LWI-11,/O,16.440518,80.622258,0.0,78.0,58.2,,,,LightAPRS - TA2MUN and TA9OHC,,, 006TxC  40.50C 1002.89hPa  5.02V 08S
.ightAPRS-W 2.0
),1694840190,2023-09-16T04:56:30Z,VU2LWI-11,VU2LWI-11,100(46/19),0,/,VU2LWI-11,/O,16.440442,80.622095,1.0,88.0,48.8,,,,LightAPRS - TA2MUN and TA9OHC,,, 009TxC  43.50C 1002.76hPa  5.03V 11S
.ightAPRS-W 2.0
),1694840243,2023-09-16T04:57:23Z,VU2LWI-11,VU2LWI-11,101(48/18),0,/,VU2LWI-11,/O,16.440425,80.622090,1.0,88.0,59.7,,,,LightAPRS - TA2MUN and TA9OHC,,, 010TxC  42.80C 1002.92hPa  5.03V 11S
.ightAPRS-W 2.0
),1694840351,2023-09-16T04:59:11Z,VU2LWI-11,VU2LWI-11,101(47/18),0,/,VU2LWI-11,/O,16.440480,80.622449,8.0,108.0,85.0,,,,LightAPRS - TA2MUN and TA9OHC,,, 012TxC  42.30C 1004.50hPa  5.03V
)4S LightAPRS-W 2.0
),1694840470,2023-09-16T05:01:10Z,VU2LWI-11,VU2LWI-11,93(50/17),1,/,VU2LWI-11,/O,16.440434,80.622414,0.0,108.0,83.8,,,,LightAPRS - TA2MUN and TA9OHC,,, 013TxC  41.50C 1006.20hPa  5.02V 04S
.ightAPRS-W 2.0
),1694840576,2023-09-16T05:02:56Z,VU2LWI-11,VU2LWI-11,104(53/20),0,/,VU2LWI-11,/O,16.441180,80.622566,1.0,108.0,28.7,,,,LightAPRS - TA2MUN and TA9OHC,,, 015TxC  41.50C 1006.20hPa  5.02V
11S LightAPRS-W 2.0
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Fig 7: Tracking system data overview

This dataset collects important data from the satellite or high-altitude balloon called KLSAT, allowing us to track its movements and follow its flight. It records important information such as the location, speed, and altitude of the KLSAT, as well as the strength and quality of the signals it sends back. It also provides information about the body's overall health and possible errors. By carefully analyzing this information, we can better understand how KLSAT performs under different conditions and investigate any problems that may arise during its journey. This assessment is important to ensure the effectiveness of the mission and the reliability of the technology. Ultimately, this information plays a key role in fulfilling our mission and improving our understanding of the game engine**.** Fig 7 shows the tracking system data overview

5. CONCLUSION

This study successfully developed a real-time system for sending telemetry data from a 1U CubeSat using KLAP and APRS technology. By integrating the KLAP module with APRS for data transmission and setting up a ground station with DIREWOLF and APRS tracking tools, we achieved reliable CubeSat-to-ground communication. The KLAP module, with improved memory and power management features, effectively handled telemetry data transmission, including position information. The ground station setup was able to receive and analyze this data in real-time, showing that the system works well for tracking and monitoring satellite performance. The results highlight the benefits of using APRS technology for small satellite communications. The system proved to be both effective and cost-efficient, making it a good option for future CubeSat missions.

Future Improvements

Future developments in the 2U CubeSat mission could enhance the KLAP module's data processing speed and memory for faster data handling. Advanced communication protocols, such as inter-satellite links, can improve transmission. Upgrading ground stations will enable real-time analytics and automated alerts for better mission control.

Expanding multi-satellite communication will increase the data coverage, while stronger security measures, like encryption, will protect mission data. Cost-effective designs, such as modular hardware and efficient power management, will enhance sustainability.AI and machine learning can improve real-time data analysis, anomaly detection, and decision-making. Ensuring interoperability with other space systems will allow seamless integration with satellite networks, enabling joint missions.

Data Availability Statement

Data sharing does not apply to this article as no new data has been created or analyzed in this study.

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