

Full functional test, data management, machine learning and automatization of the Cubesat Control Centre: moving towards the operations phase of an educational ground

Original

Full functional test, data management, machine learning and automatization of the Cubesat Control Centre: moving towards the operations phase of an educational ground station / Abbate, G., Campioli, S., Cazacu, D.A., Demoro, D., Tomatis, A., Di Nardo, L., Corpino, S., Stesina, F.. - (2025), pp. 51-61. (2025 IAF Space Operations Symposium at the 76th International Astronautical Congress, IAC 2025 Sydney (Aus) 29 September - 3 October 2025) [10.52202/083086-0005].

Availability:

This version is available at: 11583/3016674 since: 2026-10-15T09:22:06Z

Publisher:

International Astronautical Federation

Published

DOI:10.52202/083086-0005

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

IAC-25,B6,1,7,x99866

Full functional test, data management, machine learning and automatization of the Cubesat Control Centre: moving towards the operations phase of an educational ground station.

Mr. Giorgio Abbate ^{a,†}, Ms. Serena Campioli ^a, Mr. Daniel Alexandru Cazacu ^b, Mr. Davide Demoro ^c, Mr. Andrea Tomatis ^d, Mr. Leonardo Di Nardo ^a, Prof. Sabrina Corpino ^a, Dr. Fabrizio Stesina ^a

^a *Department of Mechanical and Aerospace Engineering (DIMEAS), Politecnico di Torino, 10129 Turin, Italy.*
giorgio.abbate@studenti.polito.it; serena.campioli@polito.it; leonardo.dinardo@studenti.polito.it;
sabrina.corpino@polito.it; fabrizio.stesina@polito.it;

^b *Department of Applied Science and Technology (DISAT), Politecnico di Torino, 10129, Turin, Italy.*
danielalexandru.cazacu@studenti.polito.it;

^c *Department of Control and Computer Engineering (DAUIN), Politecnico di Torino, 10129, Turin, Italy.*
s284379@studenti.polito.it;

^d *Department of Mathematical Sciences (DISMA), Politecnico di Torino, 10129, Turin, Italy.*
s307104@studenti.polito.it;

[†] Corresponding Author.

Abstract

In recent years, the accessibility of CubeSat missions has significantly improved, yet operational autonomy remains a challenge for many university teams. The CubeSat Team Polito at Politecnico di Torino continues to address this by further developing its CubeSat Control Centre (C3), an in-house ground station designed for end-to-end satellite mission operations. Building on the previous phase, this work presents the latest advancements, focusing on the installation of the antenna system on the roof of Politecnico di Torino, full functional and performance testing, and the development towards an automated ground station. Following the successful integration of key RF subsystems, the installation of the antenna array marks a critical milestone in C3's evolution. Performance tests have been conducted to evaluate system efficiency, interference levels, and communication reliability under real operational conditions. Signal reception and tracking accuracy have been assessed using Software Defined Radios and calibrated test signals, ensuring optimal functionality. Additionally, considering the future difficulties in accessing the station during the satellite passes, the automation of the station becomes a priority to allow a continuous flow of data to the ground to continuously monitor the satellite. Moreover, in case of missing scientific data in some passes, the gaps will be covered using machine learning algorithms. While waiting for the launching of the team's satellite under development, ELECTRA, these operations and testing phases will be done using meteorological satellites in LEO operating in S-Band such as NOAA and METEOR. Beyond technical progress, the project remains a valuable educational tool, allowing students to gain hands-on experience in system integration, validation procedures, and ground station operations. Best practices for managing complex test campaigns and engaging students in hands-on experimental learning are also discussed. This paper builds on the lessons learned from the development of C3 for VHF, UHF and S-bands work and the new steps towards an autonomous system. This represents a step forward in establishing a fully continuously operational, student-driven ground station, reinforcing Politecnico di Torino's role in university-led space missions.

Abbreviations

ACE Advanced Composition Explorer
AIT&V Assembly, Integration, Testing and Verification
AM Amplitude Modulation
ARI Associazione Radioamatori Italiani
BER Bit Error Rate
BPSK Binary Phase Shift Keying
C3 Cubesat Control Centre
COTS Commercial off-the-shelf
CSV Comma Separated Values
DSCOVR Deep Space Climate Observatory
DSP Digital Signal Processing

ELECTRA Electron Layer Exploration using CubeSat for TEC Research and Analysis
EOF End of File
FM Frequency Modulation
FSK Frequency Shift Keying
GMSK Gaussian Minimum Shift Keying
GNSS Global Navigation Satellite System
GPS Global Positioning System
GSE Geocentric Solar Ecliptic
GSM Geocentric Solar Magnetospheric
GSaaS Ground Station as a Service
GUI Graphical User Interface
HPA High Power Amplifier

IMF	Interplanetary Magnetic Field
ISS	International Space Station
KISS	Keep It Simple, Stupid
LEO	Low Earth Orbit
LNA	Low Noise Amplifier
LSTM	Long Short-Term Memory
MCC	Mission Control Center
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Aerospace Defense Command
PoliTO	Polytechnic of Turin
PSK	Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RFT	Reduced Functional Test
RNN	Recurrent Neural Network
RSSI	Received Signal Strength Indicator
RX	Receive
SDR	Software Defined Radio
SI	Software Infrastructure
SNR	Signal to Noise Ratio
SSB	Single Side Band
STARLab	Systems and Technologies for Aerospace Research Laboratory
TCN	Temporal Convolutional Networks
TEC	Total Electron Content
TLE	Two Line Element
TS	Tracking Subsystem
TT&C	Telemetry, Tracking and Command
TX	Transmit
UHF	Ultra High Frequency
VHF	Very High Frequency
ZMQ	ZeroMQ

1 Introduction

The continuous advancement in miniaturization of space platforms, coupled with the accessibility of increasingly powerful yet cost-effective hardware, has positioned CubeSat, and small satellites in general, as a key enabler for research and investment [1], [2], [3]. Consequently, this exponentially increased numbers of satellites in Low Earth Orbit (LEO) has generated an equally pressing demand for ground segment infrastructure. In particular, the need for accessible, flexible, and autonomous ground stations has grown significantly

On this matter, the Cubesat PoliTO Team, a student-lead team at the Polytechnic University of Turin, addressed the demand for a local ground station to serve the university's satellites with the **Cubesat Control Centre**,

C3 for short. The team's heritage covers the full life-cycle of the satellite and includes the launch of **e-st@r-I** in 2012 during the Vega maiden flight, and **e-st@r-II** in 2016, as well as collaboration with local and international student teams. For these missions, ground operations relied on ground stations provided by local amateur radio associations such as ARI Bra. While such partnerships enabled successful satellite communication and represented an incredible learning opportunity for the students, on one hand the team wanted to take a step forward in the hands-on training by building, operating and maintain their very own ground station, on the other challenges in integration and logistics when using second-parties stations underscored the necessity for a dedicated independent ground station.

This paper presents the Cubesat Control Centre (C3) architecture and functionality as well as its role in supporting the upcoming Electron Layer Exploration using CubeSat for TEC Research and Analysis (ELECTRA) CubeSat mission. It then details the implementation of the automated scheduler within the operational system, followed by an overview of data recovery efforts leveraging machine learning techniques. Finally, the paper reports on recent validation activities and outlines the next steps, including comprehensive system-level testing to be performed once the ground station is fully assembled.

2 The CubeSat Control Centre (C3)

C3 is a modular educational ground station developed, tested and assembled entirely by students [4] [5]. Its primary objectives are to provide hands-on training in Radio Frequency (RF) and telecommunications and to enable reliable communication with the Polytechnic's satellites. The ground station has been designed with the *Keep It Simple, Stupid* (KISS) principles, ensuring usability even for non-professional operators with only basic system knowledge.



Fig. 1: Render of the C3 antennas and configuration

C3 supports satellite communication across radioamateur VHF, and UHF bands, as well as the reserved S-Band

used for space operations. The RF front-end includes the Software Defined Radio (SDR), amplifiers, transmission lines and antennas, all based on Commercial off-the-shelf (COTS) available on the market. This design choice ensures that the system is both maintainable and easily upgradable in case of malfunctions or technological advancements.

The ground station is capable of autonomous satellite tracking and downlink operations, while also supporting manual control for testing campaigns and calibration. The software [6], developed entirely in Python, manages scheduling, satellite tracking, rotor motor control, digital signal processing and data management. A conscious decision was made to minimize reliance on pre-existing software in order to reduce the computational load on the hardware and maximize the project's educational value. GNURADIO has been used for the Digital Signal Processing (DSP) and to develop the RF control panel Graphical User Interface (GUI).

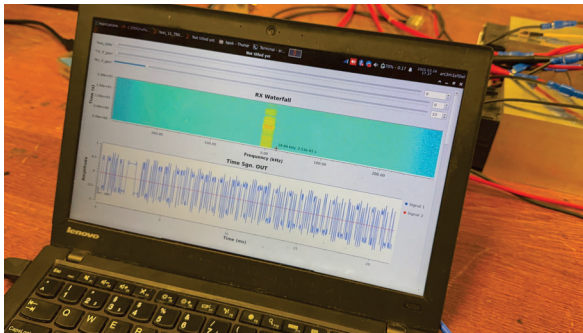


Fig. 2: Waterflow during a BPSK transmission

Currently, C3 supports a wide range of modulations, including AM, FM, SSB, FSK, PSK, QPSK, BPSK, GMSK, with additional ones under development. These capabilities enable both packet-based satellite communication and experimentation with voice modes on radioamateur satellites. Given its features, C3 emerges as the ideal candidate for managing the satellite operations of the ELECTRA mission. In preparation for the mission, several enhancements have been implemented into the ground station, including upgrades to the graphical user interface as well as the introduction of automation and scheduling measures to accommodate the high frequency of accesses, particularly during nighttime hours. Testing campaigns have a key role in the development of a ground station, ensuring a reliable system and a continuous operability.

3 The ELECTRA Mission

ELECTRA, acronym for *Electron Layer Exploration using CubeSat for TEC Research and Analysis*, is a 3U CubeSat currently under development by the Cubesat PoliTO Team. The mission aims to analyze the upper

F2 layer of the ionosphere and map the ionospheric Total Electron Content (TEC) in LEO using GNSS signals from GPS and GALILEO.

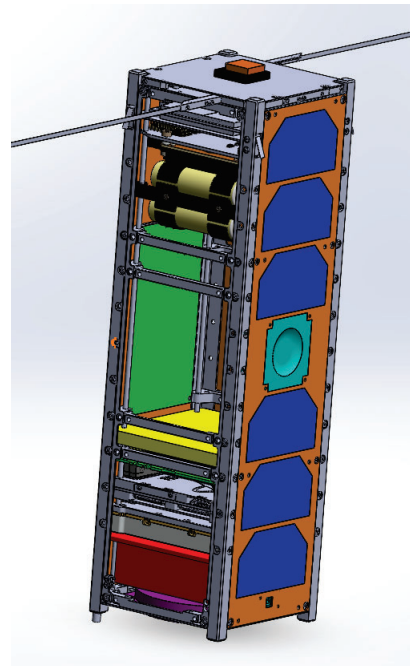


Fig. 3: The ELECTRA satellite

Due to the high data volume anticipated from the required sample rate and the number of GNSS signals to be processed, the mission design includes an S-Band transceiver with a dedicated patch antenna, enabling data downlink rates of up to 512 kbps. For redundancy, and to ensure communication in scenarios where satellite misalignment may compromise the S-Band link, a UHF transceiver with a turnstile antenna has also been incorporated in the design. Hence, the communication links are defined as follow: (i) Uplink: UHF (Telecommands); (ii) Downlink: UHF (Beacon), S-Band (Telemetry).

The adopted telecommunications strategy is based on a *Store & Forward* approach, where scientific data are collected, stored onboard, and downlink during the earliest available ground station contact.

All design choices of the ELECTRA Telemetry, Tracking and Command (TT&C) subsystem were made with a view to ensuring seamless integration with C3, thereby enabling efficient ground operations and supporting future scalability of the system. Given the high data rate expected by ELECTRA and the challenges identified through ITU recommendations and simulations results - such as high BER at low elevations, fade caused by rain and fog, particularly common in Turin - mitigation strategy have been adopted. These mitigation strategy include automation of mechanical and repetitive procedures such as satellite

tracking and downlink of scientific data, introducing a scheduling algorithm and the use of machine learning algorithms to recover corrupted packets.

4 Scheduler and Database

The occurrence of frequent nighttime passes necessitates the automation of tracking and downlink operations, particularly given that the operators involved are university students who, in addition to working in the CubeSat PoliTO Team, must adhere to tight schedules and academic commitments. This also reflects a key lesson learned from previous satellite missions conducted by the team, where the rapid execution of multiple tasks — such as identifying the satellite, selecting the appropriate telecommand interface, and receiving and decoding telemetry—is critical. In this context, one of the core functions of a ground station is its ability to operate autonomously, executing tasks according to predefined rules and operator needs. This autonomy ensures continuous support for satellite operations, even in absence of direct human supervision. Such operations must adapt to the available ground station resources while leveraging the flexibility of its hardware and software components. For this reason, the project was implemented on a high-performance Machine capable of handling scheduling, tracking, and data acquisition in parallel.

Given that the satellites in LEO have short and frequent yet arbitrary orbital periods, automation of the communication process is essential, especially during mission phases where downlink and data acquisition are dominant tasks.

4.1 Scheduling

For a given set of target satellites, the prediction of overpasses can be performed using an open source software such as GPREDICT, together with the Two Line Element (TLE) of the object provided by governmental agencies. The main task of the scheduling software is to calculate the rise and set times of each satellite pass and associate them with the corresponding downlink frequencies. This information forms the basis for the generation of pass-specific tracking commands.

4.2 Priority Management

Since satellite passes occur independently, conflicts may arise when passes overlap or coincide. These cases are handled using a priority scheme defined by the operator. Several strategies are possible, such as selecting the first satellite to pass and discarding simultaneous ones, or assigning each satellite a priority value to determine which pass is retained in case of overlap. In practice, priority values are ordered and stored in the scheduler, ensuring that conflicts are consistently resolved before commands are sent to the TT&C.

4.3 Scheduler implementation

Through a dedicated control interface, the ground station operator selects which satellites to track. The information is transmitted via ZeroMQ (ZMQ) [7] protocol and includes: (i) the *satellite identifier*; (ii) the *priority value*, set by the operator; (iii) the *tracking data*, time-position tuples derived from TLE propagation.

Upon receiving the aforementioned information, the tracking subsystem processes these data by segmenting them into discrete passes and constructing a time-ordered schedule of all the requested passes. Overlapping passes are then filtered based on the assigned priorities, ensuring a conflict-free schedule. Once the final schedule is determined, a summary is returned to the ground station. This summary specifies, for each pass, the start time, duration, and satellite identifier, enabling synchronization between tracking and listening processes.

4.4 Listening process implementation

Using the scheduler output, the recording process is executed via SDR. A scheduling-record method waits for the scheduler message, which contains the pass parameters (start time, duration, identifier), and is received with the ZMQ protocol. A mapping between satellite identifiers and downlink frequencies is maintained for future reference and consistency.

Upon polling the system time, when the scheduled one is reached, the SDR is triggered to begin recording by creating a subprocess [8] to run the implemented flowgraph as shown in Figure 7. A customly modified GNURADIO [9] program is employed, using OSMOCOM [10] functions to tune to the correct frequency and save the raw signal to a WAV file, to be further analyzed a posteriori. This method has been adapted to accept the target frequency as input argument and is terminated via a controlled OS PKILL call after the pass ends.

The use of the WAV file format provides robustness, as its chunk-based structure prevents corruption even in case of abrupt termination. The bit rate is set according to the expected satellite signal, ensuring data integrity and compatibility with downstream decoding (Appendix 7 provides implementation details).

4.5 Database

Long-term storage is managed through a dedicated directory structure, functioning as a lightweight database. Each recorded file is named according to a consistent convention, for example:

```
SatelliteName-Frequency-PassStartTime-Duration.wav
```

A log of all generated files is also maintained. Storing raw data in this format provides flexibility, allowing operators to reprocess signals with different decoding schemes or adapt to different modulation and encryption methods

- source : Data origin (ac = ACE, ds = DSCOVR)
2. satellite_pos.csv (satellite positions in GSE coordinates)
 - gse_x : X position (km)
 - gse_y : Y position (km)
 - gse_z : Z position (km)
 3. lables.csv
 - Dst values (indexed using the same period and timedelta multi-index)

Each position column is recorded separately for ACE (_ace) and DSCOVR (_dscovr), allowing analysis of how their positions within their orbits around L1 affect the quality and consistency of the solar wind measurements.

5.2 Data Pre-processing

Data pre-processing is necessary to combine all the dataset files into one single .csv file such that they can use it to train the aforementioned models. The implemented procedure is listed below:

1. The following columns were removed from "solar_wind.csv": theta_gse, phi_gse, bx_gsm, by_gsm, bz_gsm, theta_gsm, and phi_gsm. This step was necessary because these columns represent the same information as bx_gse, by_gse, and bz_gse, but in a different frame of reference. Keeping them would have slowed down the model and could have easily misled it into assigning different importance to variables that, in fact, describe the same physical quantities.
2. The Dst column from the file labels.csv was merged with the rest of the dataset. This step was necessary in order to perform model training.
3. The columns containing the satellite positions from satellite_pos.csv was added. Both this operation and the previous one were carried out by carefully aligning the timestamps of each record across the different tables.

5.3 XGBoost model

The first model considered is a XGBRegressor, part of the family of XGBoost models. XGBoost (Extreme Gradient Boosting) [12] is a high performance machine learning algorithm based on gradient boosting decision trees. It builds an ensemble of weak learners (usually decision trees) in a sequential way, where each new tree focuses on correcting the errors of the previous ones. XGBoost is widely used because it is fast, scalable, and accurate, with features like regularization to prevent overfitting, handling of missing values, and support for parallel and distributed computing. It is commonly applied

in classification, regression, and ranking tasks, often outperforming many other models in structured/tabular data problems. Its Regressor was used to predict the value of Dst based on past The dataset was divided into training and test sets with an 80:20 proportion. These sets contained all the previously mentioned columns except for period, timedelta, and Dst. This choice was made because, prior to training, the dataset had been ordered by period and timedelta, so those columns were not needed. Additionally, the model training was performed without shuffling. The column Dst has been removed because, as indicated by the dataset provider, it is only weakly related to the next Dst value (the target we want to predict). For the training the following parameters were used, ensuring the best configuration before overfitting:

Parameter	Value
n_estimators	100
learning_rate	0.05
max_depth	50
subsample	0.8
colsample_bytree	0.8
random_state	42

Table 1: XGBoost model parameters

Unfortunately this model performed badly on the test samples, returning a mean square error of **159.2**. This result is inadequate as the Dst values in our dataset have the distribution in Figure 5.

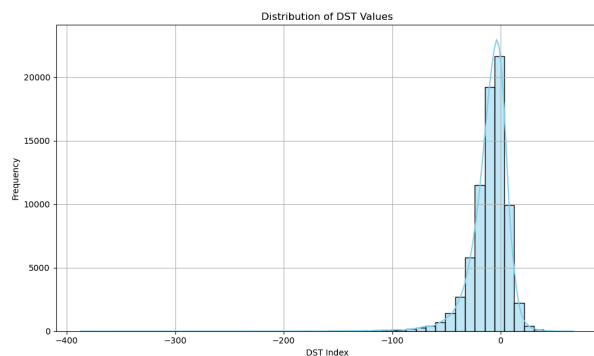


Fig. 5: Dst values distribution. From the NASA and NOAA Satellites Solar-Wind Dataset

The key issue that brought this conclusion is probably the high non linearity nature of the magnetospheric dynamics, that makes it extremely difficult for the regressor to extrapolate a meaningful function to fit the data. It is clear that a more complex model is needed to obtain better results.

5.4 TCN models

The next category of model considered are the Temporal Convolutional Networks (TCNs) [13], a class of neural network architectures designed for sequence modeling tasks, particularly time series forecasting. Unlike recurrent architectures such as RNNs and LSTMs, TCNs leverage one-dimensional causal convolutions with dilation to capture temporal dependencies over long horizons while allowing parallel training. The causal structure ensures that predictions at a given time step only depend on past observations, preserving the temporal ordering of the data. Dilated convolutions, in turn, allow the receptive field of the network to grow exponentially with depth, enabling efficient modeling of long-term dependencies without requiring excessively deep architectures. TCNs often achieve superior stability during training compared to recurrent models, while also providing competitive or improved forecasting accuracy. Due to their flexibility and efficiency, TCNs have been successfully applied in diverse domains such as demand forecasting, anomaly detection, and natural language processing. Unfortunately, challenge was faced that made it impossible to deploy these models efficiently. The issue was related to the structure of the data. Most TCNs (and, more generally, most time series models) require a complete dataset with homogeneously timed observations as input. This means that the frequency of measurements must remain perfectly constant over time. Achieving this property is particularly difficult with satellite data, including the datasets used in this study as dataset used contained unevenly spaced records and missing values. While such imperfections typically do not cause major issues during exploratory data analysis, they become problematic for TCNs, which strictly require complete and regularly spaced time series. To satisfy this requirement, only small portion of the dataset were fed to the algorithm. This limitation led to insufficient training data and, consequently, poor performance on the test set. The data recovery problem remains, for the time being, unsolved. On a positive note a much clearer understanding has been gained to address in the future these challenges. Two directions are suggested for future research and development: (i) conducting a deeper investigation into Temporal Convolutional Networks, which appear to be the most promising approach for this task; and (ii) developing a robust C3 communication system to enable high-quality data collection consistently structured for machine learning applications.

6 Testing and Validation

As already mentioned, testing campaigns play a key role on ensuring usability of the ground station, enabling continuous requirements validation of a system prone to *wear and tear* and in close contact with the adverse weather conditions of the Piedmont region, as well as

the atmospheric agents characteristic of an urban environment. Prior to the full functional test that will verify all system requirements, a multitude of small testing campaign have been performed to ensure that the newly integrated features and modules progressively added to the system operated as intended. The scheduler and the data recovery algorithms are no exception and will require extensive testing - some of which has been already done - before being integrated with the rest of C3. In the final phase of development and testing, two main validation steps are foreseen: the already completed Reduced Functional Test, and the upcoming Full Functional Test, through which the operability of the ground station will be formally certified, marking the beginning of the operational phase of the ground station.

6.1 Reduced Functional Test

The Reduced Functional Testing (RFT) was conducted in March 2025 at the CubeSat PoliTO Team's STARLab facility before the full assembly of C3 on the roof. This test aimed to verify core functionalities in a controlled, simulated environment, confirming the system's readiness for integration [14]. Notably, the RFT operated without the large high gain x-quad antennas, opting for a smaller dipole stile antenna. Instead, tracking was emulated using synthetic Two-Line Element (TLE) data, and the satellite was simulated via a Software Defined Radio (SDR) connected to a computer that transmitted images and alphanumeric data.

6.1.1 Objectives and Requirements Verified

The RFT targeted over 30 functional, operational, and interface requirements across subsystems, including Radio Frequency (RF), Tracking Subsystem (TS), SDR, Software Infrastructure (SI), and GNU Radio. Key objectives included:

- Verifying the switch's ability to toggle between transmit (Transmit (TX)) and receive (Receive (RX)) modes based on commands.
- Ensuring the TS could compute and propagate orbits, estimate visibility periods, and generate position control signals using TLE data from NORAD.
- Testing GNU Radio's interface with the BladeRF SDR for binary data transmission and reception.
- Validating software infrastructure for data handling, hardware configuration, and state machine control of relays.
- Confirming interfaces between components, such as remote communication between the User Computer and Tracking Computer.

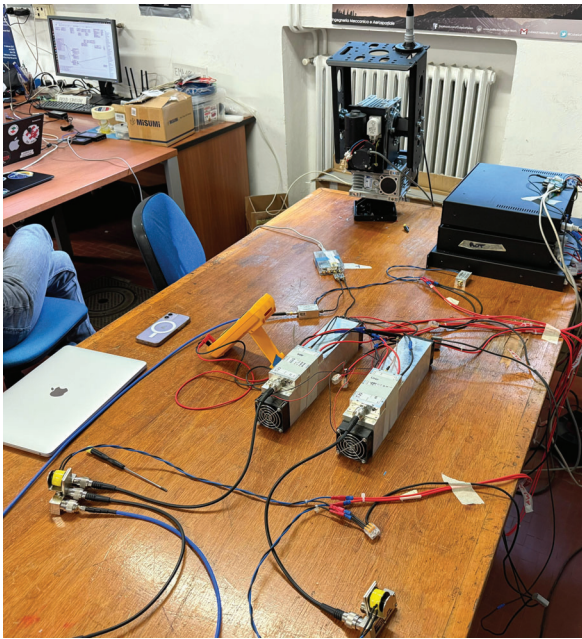


Fig. 6: C3 deployed during the RFT

6.1.2 Methodology and Setup

The test followed the Assembly, Integration, Testing, and Verification (AIT&V) philosophy, emphasizing safety and use of available instruments [15]. It was performed in the STARLab using ground support equipment like a compass, level, multimeter, and the SDR setup. The configuration emulated the full system:

- **Hardware:** Power supplies, HPAs (High Power Amplifiers), LNAs (Low Noise Amplifiers), RF switches, and the MD-01 rotator controller.
- **Software:** GPredict for tracking emulation and GNU Radio for communication, with custom scripts in Python for position control and data processing.
- **Satellite Emulation:** An SDR transmitted test data, simulating uplink and downlink scenarios in VHF and UHF bands.

The step-by-step procedure involved over 50 actions, starting with hardware assembly (e.g., connecting cables, WAGO connectors, and ground lines) and calibration of the rotator to zero azimuth and elevation. Software installation included libraries like Flask, Astropy, NumPy, and Skyfield on the Mission Control Center (MCC) computer. Testing then proceeded to:

- Orbit propagation and tracking simulation via a web interface (<http://127.0.0.1:5000>), where users selected satellites, loaded predictions, and initiated tracking.

- **Uplink/Downlink Tests:** For VHF and UHF, the system switched between TX/RX modes, transmitted data from TXData.bin, and received/demodulated signals, storing results for analysis.

Pass/fail criteria focused on successful data exchange, relay switching, and rotor movement. The test required a team of operators: an RF Tester (level 3 experience), two Software Testers (level 3), and a Verifier (level 3), ensuring compliance with procedures.

6.1.3 Outcomes

The RFT successfully verified the system's functional capabilities in a reduced setup, identifying minor issues in relay timing and software interfaces that were resolved. Data collection included metrics on tracking accuracy (via emulated positions) and communication reliability (e.g. packet reception rates). This paved the way for C3's assembly on the roof, confirming that the antenna control and communication subsystems could integrate seamlessly without real-world environmental variables [14].

6.2 Full Functional Test

With the RFT complete and C3 now assembled on the Politecnico di Torino roof, the full testing campaign is scheduled for late 2025. This phase will build on the RFT by incorporating the actual antenna system (including the X-Quad antennas for VHF/UHF, and the S-Band parabolic antennas) and real-world conditions, transitioning from emulation to a real life operational validation with live satellites.

6.2.1 Objectives

The full campaign aims to:

- Validate end-to-end antenna functionality, including precise pointing and tracking of real LEO satellites using actual NORAD IDs and TLE data.
- Assess communication performance, such as signal strength, data throughput, and error rates during real transmissions.
- Evaluate integration with the full infrastructure, including remote control, scheduling and data processing.
- Test robustness under environmental factors like weather, wind, and urban interference.
- Ensure compliance with all remaining requirements, focusing on performance metrics (e.g. tracking accuracy within 1–2 degrees, link budgets for RX/TX).

6.2.2 Methodology

The campaign will follow a phased approach:

1. **Preliminary Setup and Calibration:** Install and calibrate the antennas on the roof rotator. Use tools like GPredict and GNU Radio, aligning with real geographic coordinates. Verify power supplies, relays, and SDR interfaces under outdoor conditions.
2. **Antenna Tracking Tests:** Track real satellites (e.g., ISS or amateur CubeSats) using live TLE data updated weekly from NORAD. Compare antenna positions with predicted paths, assessing accuracy and response time.
3. **Communication Tests:** Establish links with test satellites for uplink commands and downlink telemetry. Transmit/receive binary data, images, and packets, measuring bit error rates and signal-to-noise ratios.
4. **Integration Tests:** Test seamless operation with MCC software, including remote access and automated state machine transitions for TX/RX switching.
5. **Environmental Tests:** Conduct operations in varied weather (rain, wind up to 50 km/h) and times (day/night) to evaluate performance degradation.

6.2.3 Equipment and Resources

- **Hardware:** Full antenna array, rotators (e.g., MD-01), transceivers, HPAs, LNAs, and weatherproof enclosures.
- **Software:** Enhanced versions of GPredict, GNU Radio, and custom Python scripts for real-time monitoring.
- **Data:** Live TLE from NORAD, satellite passes predicted via Skyfield.
- **Team:** Expanded to include roof safety operators, with levels 4–5 experience for RF and environmental handling.

6.3 Data Collection and Analysis

During the testing campaign, data will be collected systematically across all phases to evaluate the ground station's performance comprehensively. This involves real-time logging from hardware sensors, software interfaces, and communication tools, ensuring traceability and repeatability. Key performance metrics will be captured to quantify system behavior, drawing from established practices in CubeSat ground station validation, such as pass

quality assessment and anomaly detection in telemetry data. Data acquisition will utilize tools like GPredict for orbital tracking logs, GNU Radio for signal processing and I/Q sample recording, and custom Python scripts for aggregating sensor readings from the rotator (e.g., azimuth and elevation positions) and transceivers (e.g., RF power levels).

Specific Metrics to be Monitored

- **Tracking Accuracy:** Angular errors in azimuth and elevation (measured in degrees), calculated by comparing predicted satellite positions from propagated TLE data with actual antenna orientations via rotator feedback. Tolerance thresholds will be set at $< 2^\circ$ for acceptable performance, with real-time Doppler shift corrections evaluated for frequency alignment.
- **Communication Reliability:** Signal-to-noise ratio (SNR in dB), bit error rate (BER), packet error rate (PER, targeting $< 5\%$), and data throughput (bits per second). For uplink/downlink tests, received signal strength indicator (RSSI) and packet success rates ($> 95\%$) will be logged during live satellite passes, including assessments of link quality under varying elevation angles.
- **System Responsiveness and Robustness:** Latency in command execution (milliseconds), scheduling and priority algorithm reliability, system uptime (percentage during passes), power consumption (watts), and environmental resilience metrics, such as performance degradation due to wind, rain, or temperature fluctuations (e.g., vibration-induced pointing drift measured via accelerometers).
- **Pass Quality:** Overall satellite pass effectiveness, incorporating visibility duration, maximum elevation, and downlink volume (megabytes transferred), to optimize future operations and ground station scheduling.

Data will be stored in structured formats, such as CSV files for time-series logs and binary files for raw I/Q samples, on the Mission Control Center (MCC) computer. Post-test, analysis will employ Python libraries like Pandas for data cleaning and aggregation, Matplotlib and Cartopy for visualizations (e.g., plots of tracking error over time or geographic pass maps), and SciPy for statistical computations (mean, standard deviation, correlation analysis).

Advanced techniques, including machine learning models for anomaly detection in telemetry (e.g., using isolation forests or autoencoders to flag outliers in SNR or

BER), will be applied to identify subtle issues like interference or hardware drift. This analysis will highlight areas for improvement, such as software optimizations for faster relay switching or hardware adjustments for better antenna alignment, ensuring the C3 facility meets operational requirements for reliable GSaaS. Results will be documented in a verification report, cross-referenced with the requirements matrix to confirm compliance.

7 Conclusions

What initially began as a student-led initiative aimed at providing educational insights to the world of satellite telecommunications, C3 evolved in a modular multipurpose ground station, easily integrable with the missions developed by the CubeSat team and capable of communicating with any satellite in LEO. A milestone in completing the project prior to commissioning was the automation of the ground station, crucial for reducing operator workload and human error. To ensure continuous operability a robust and reliable scheduling system was implemented to C3. Recognizing that error reduced does not equate to complete error elimination, efforts was devoted to the recovery of downlink data subject to data loss and corruption. To address this issue, machine learning algorithms were employed, specifically XGDBOost and Temporal Convolutional Networks. While these algorithms demonstrated promising results, they showed limitations due to the irregular and incomplete nature of satellite telemetry datasets. The final phase of the development, which also marks the beginning of the operational phase, consists of the full functional test. This will be conducted immediately after assembly of the ground station on the Polytechnics attics. Applying insights gained from past test campaigns, the validation of the system aims to fully confirm the ground station's performance and reliability under real world conditions. With these advancements, C3 is therefore on the right track to become not only the primary control platform for the Polytechnic's satellites mission, but also as a valuable educational tool, offering hands-on experience with real satellite operations.

Appendix

Robustness of the wav file generation

The WAV audio file format is designed with a header-centric structure that makes it remarkably robust to improper termination of the writing process, which is exactly the case mentioned of killing abruptly the GNURADIO flow based on the OSMOCOM block, which in turns make the WAV still playable. The reason for this behavior is the placement and the content of the WAV header, which is placed at the very beginning. It contains all critical metadata needed for a player to interpret the subsequent raw audio samples, among which are Sample Rate, Bit depth, Number of channels, Audio format, Data chunk

size. When a GNU Radio flowgraph begins recording to a WAV file, one of its first actions is to write this complete header, populating the data chunk size field based on the expected length of the recording. Since the final length is unknown at the start, this value is often set to a placeholder (0xFFFFFFFF for "unknown" or a large estimate) or is updated periodically as the file grows. Upon killing the generation process, the data chunk size field doesn't get updated to the correct value, but despite this inconsistency, the file remains usable. The players and analyzers are designed to be fault tolerant, and read the file until they find the EOF byte sequence. So the WAV file behaves as a header followed by a raw dump of samples, that do not corrupt the previous data portion on abrupt truncation.

References

- [1] S. Corpino and F. Stesina. Inspection of the cis-lunar station using multi-purpose autonomous cubesats. *Acta Astronautica*, 175, 2020. doi: 10.1016/j.actaastro.2020.05.053.
- [2] F. Ingiosi, G. Ammirante, G. Taiano, A. Pennacchia, S. Corpino, F. Stesina, F. Branz, A. Caon, L. Lion, M. Imperatrice, F. Sansone, G. Girardi, M. Peruffo, J. Van den Eynde, C. Pirat, A. Francesconi, S. Campioli, A. D'Ortona, E. La Bella, L. Bartolucci, and L. Deva. The space rider observer cube (sroc) cubesat mission. In *Proceedings of the International Astronautical Congress (IAC)*, 2024. doi: 10.52202/078365-0023. Paper ID: 83289.
- [3] S. Campioli, F. Stesina, E. La Bella, S. Corpino, L. Niero, and C. My. Concurrent engineering to enhance autonomy for deep-space cubesat mission design. *IFAC-PapersOnLine*, 58(16):163–168, 2024. ISSN 2405-8963. doi: 10.1016/j.ifacol.2024.08.480.
- [4] G. M. Capez, S. Corpino, and F. Stesina. Design and verification of a cubesat ground station. Master's thesis, Polytechnic University of Turin, 2021. Available online. url: <https://webthesis.biblio.polito.it/17889/>.
- [5] S. Campioli, G. Abbate, S. Corpino, F. Stesina, F. Coppa, D. A. Cazacu, V. Frangipani, L. Di Nardo, A. Tomatis, and D. Demoro. Integration and testing campaign of an educational satellite ground station. In *Proceedings of the International Astronautical Congress (IAC)*, 2024. doi: 10.52202/0783630113.
- [6] Cubesat polito team. c3 software infrastructure, 2025. Available online. Url: <https://github.com/CubeSatTeam/C3>.
- [7] iMatrix Corporation. Zeromq (zmq) documentation, 2025. Url: <https://pyzmq.readthedocs.io/en/latest/>.
- [8] Python software foundation. subprocess — subprocess management — python 3.11.5 documentation, 2025. Available online. Url: <https://docs.python.org/3/library/subprocess.html>.
- [9] Gnu radio project. gnu radio documentation, 2025. Available online. Url: <https://www.gnuradio.org/doc/doxygen/>.

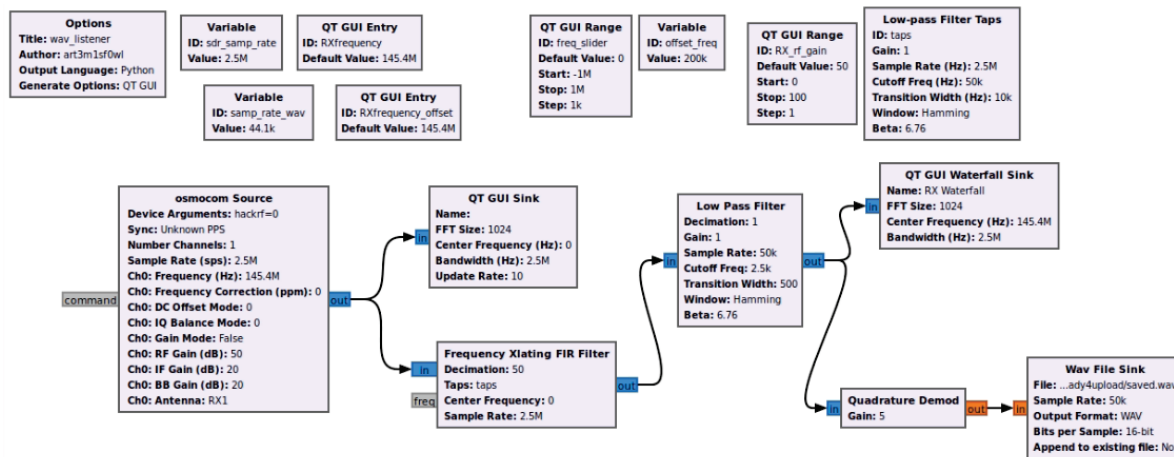


Fig. 7: GNURADIO flowgraph for WAV generation

- [10] Osmocom. Osmosdr - osmocom sdr framework, 2025. Available online. Url: <https://github.com/Nuand/gr-osmosdr>.
- [11] @arashnic. Nasa and noaa satellites solar-wind dataset, 2025. Available online. Url: <https://www.kaggle.com/datasets/arashnic/soalr-wind/>.
- [12] Xgboost developers. xgboost documentation, 2025. Available online. Url: <https://xgboost.readthedocs.io/en/stable/tutorials/model.html>.
- [13] Unit8. tcmodel — forecasting model, darts documentation, 2025. Available online. Url: https://unit8co.github.io/darts/generated_api/darts.models.forecasting.tcn_model.html.
- [14] L. Di Nardo, G. Abbate, D. Demoro, and D. A. Cazacu. Uhf/vhf & tracking rft – test specification and procedure. Test specification and procedure, CubeSat Team, Politecnico Di Torino, March 2025.
- [15] L. Di Nardo, G. Abbate, A. Pettinicchio, and F. Coppa. Assembly, integration and verification (aiv) plan of c3. Technical note, CubeSat Team, Politecnico Di Torino, January 2024.