An Academic Ground Station as a Service (GSaaS) Devoted to CubeSats

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***Abstract*— CubeSats have become important assets in space environment. The capabilities of these platforms enable building unprecedented missions to fulfil a variety of goals. Notwithstanding the reduced system complexity and cost, operations do not scale down with the size of the spacecraft. This can be seen as a negative side of CubeSat missions. As Politecnico [1], we prefer to look at it as an opportunity to train future operators through the management of systems with low-cost associated risk, resulting in already trained experts and an increased effectiveness of future full-scale operations. In this paper we present the design of a CubeSat Control Centre (C3), developed by BSc, MSc, and PhD students at Politecnico di Torino as an innovative ground station for supporting CubeSat Operations.**

***Index Terms*—Communications, Control Centre, CubeSats, Ground Segment, Operations, Tracking**

I. Introduction

Operations of CubeSats are crucial both for successful and for degraded and uncompleted missions, to provide information and flight heritage for future applications [02]. This statement is true for any stakeholder, integrator, CubeSat developers but it assumes a dramatic relevance for educational missions where most of the failures and anomalies occur falling in lack of contact opportunities [03] and operational tests [2]. For educational and small missions, the support of radio amateur and, more in general, of an amateur network of ground stations, especially for the critical phases of the mission (i.e., commissioning and payload activation and management) is the ideal solution [05]. Due to the reduced power, complexity, and budget available to amateur and academic stations, they typically involve a restricted number/kind of transceivers, limiting the communication capabilities to a restricted number of missions. This can be partially solved by adopting reconfigurable components capable of spanning over multiple bands, such as Software Defined Radio (SDRs), and by moving the Digital Signal Processing from hardware to software solutions (e.g., GNUradio). These criteria are adopted in the design process of the CubeSat Control Centre (C3), which claims capabilities beyond usual amateur ground stations. In terms of band coverage, this means adopting the most commonly operated bands in CubeSat missions. The VHF and UHF band are predominant by far among amateur missions and, in the last years, also the S-Band is wide-spreading among academic and non-professional operators. Looking at the latest trends [3], [4], the design of C3 includes the VHF/UHF amateur bands and the commercial S-band. The advantage of this outlook, especially if part of a network, consist in the spread distribution of hot spots offering a more frequent access to a great variety of S/Cs. All of this is achieved at low cost. Nevertheless, the most important benefit in developing a CubeSat control centre remains the exploitation of university facilities. In this perspective, the C3 project was created to offer students and nonprofessional operators opportunities to manage and control CubeSat missions with complete freedom. Being free to explore different design possibilities allows to extrapolate the better project according to available infrastructure and needs.

II. CUBESAT CONTROL CENTER RATRIONALE

The first step to get confident with the system of interest is to identify the conventional mission operations considering the ground station as a part of the space mission architecture. Figure 1 shows a typical mission architecture adapted to a CubeSat mission [5]. The architecture is the same for small and large satellites. The difference lays in the fact that the control centre and ground station of CubeSat Missions are more prone to be located on the same site. Nevertheless, this is not mandatory and, as we will see, C3 is designed both for remote and on-site mission control.

The C3 ground segment design, to achieve its full functionalities, envisages the following:

- **Communication System (CS)**: including both the physical components for generating and amplifying signals (i.e., the Front-End) and the Digital Signal Processing (DSP) needed for digital-to-analogue data conversion and vice versa (i.e., the Backend).
- **Tracking System (TS)**: involves orbit propagator, physical structure and mechanical/moving components used to point the antennas toward the satellite in a timely manner.
- **Software Infrastructure (SI)**: safely exchanging mission data between the C3 server and third-party systems, allowing real time operations from any location via internet connection.

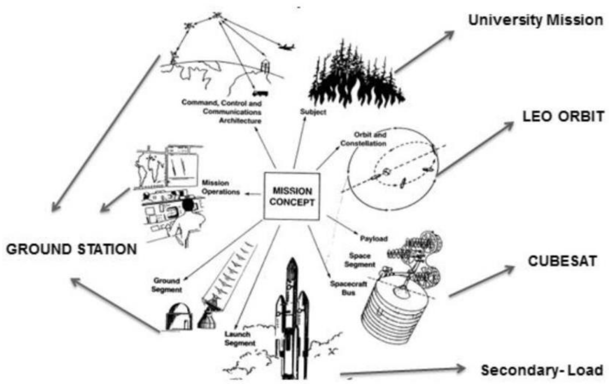

Figure 1: Traditional CubeSat Architecture, adapted from [1]

A. Abbreviations and Acronyms

C3: CubeSat Control Centre
CCSDS: Consultative Committee for Space Data System
CS: Communication System
ECSS: European Cooperation for Space Standardization
EM: Electro Magnetic
GS: Ground Station
KISS: Keep It Simple, Stupid
PKT: Packet
RF: Radio Frequency
S\c: Spacecraft
SDR: Software Defined Radio
SI: Software Infrastructure
TC: Telecommand
TLE: Two-Line Elements
TM: Telemetry
TS: Tracking System

B. Objective and Design Drivers

The project aims at developing a ground segment focused on CubeSat missions that brings an effective added value to students and non-professional operators who want to deepen their know-how on mission operations. The present project has interpreted this intent by formalising three different objectives:

- OBJ1: To develop and deploy a Control Centre devoted to CubeSats at Politecnico di Torino.
- OBJ2: To support CubeSats mission operations offering Ground Station as a Service (GSaaS).
- OBJ3: To develop a Ground Station at a lower cost than professionally driven ground segment for making its concept adoptable by students from other universities.

The process of system requirements definition foresees the analysis of the objectives, the identification of the constraints, the identification of the measurements of interest and the definition of system drivers. The latter point is reported hereafter. The drivers are then used to better identify the high-level project requirements:

Safety. The entire C3 system shall consider the following aspects, at system level:

- Electro-magnetic interference protection: protection of the UHF/VHF and S-band parabolic antenna from mutual and external electromagnetic interference.
- Operator safety: detection and isolation of the failure to protect the operators.

Safety critical functions/items must be identified and managed. Fault avoidance (high-quality parts and appropriate design margins), and fault tolerance (redundancy) approaches shall be implemented at least for safety-critical functions.

Reliability. Its aim is to minimize the probability of failures and their severity and criticality to achieve high reliability. To achieve this important goal, possible solutions could be fewer components, redundant components (whenever possible), low complexity components, components protection and distributing the capabilities of the architecture to lower criticality of faults.

Flexibility. It refers to the ability of the ground station to operate at various frequencies without sacrificing much performance. In other words, it refers to the capability to move to other frequency while replacing the minimum number of components. It also refers to the high resolution of rotators to move to higher frequencies, which require high pointing accuracy.

Simplicity. The ability of the design project to remain in the KISS approach.

Cost. To satisfy all requirements with a budget of about 20 k€, COTS components to minimize custom-made designs. This philosophy may lead to falling back on non-ad-hoc solutions, with a consequent increase in system complexity. A trade-off evaluation is therefore needed.

III. CubeSat Control Center Design Process

A. Functional Architecture and Product Tree

The architecture of the ground segment is derived through the application of the design methodology illustrated in Figure 2. The methodology schematization involves 8 main blocks, playing a key role in the creation of a good product, which we explain the present section.

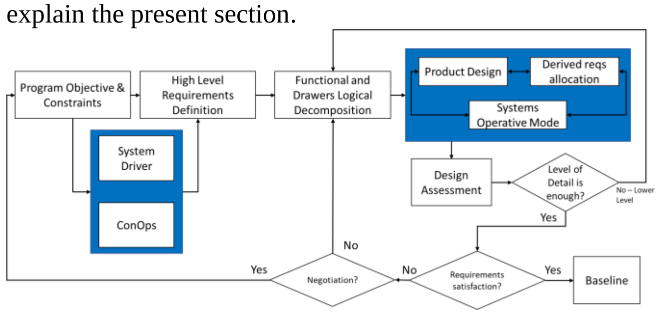

Figure 2: Design Methodology

1. **Program Objectives and Constraints**. The initial point of the design process is the definition of the programme objectives and constraints, deriving from the statement of work that highlights stakeholders' expectations in this research program.
2. **High level requirements definition**. A consistent portion of high-level requirements directly derives from the above-mentioned objectives. A second portion is instead derived

from the design drivers reported in the previous section. A third portion of requirements considers the constraints, as imposed by regulations, the operative environment, the logistics (e.g., test environment), to mention some. Moreover, Concepts of Operations (ConOps) cover important role for the system definition. The ConOps are then refined during the design loop (point 4 of this methodology) when the modes of operation of the platform are identified. During the design process the High-Level Requirements are derived from objectives, constraints, and drivers. As known, the process of requirements definition is recursive and iterative: the high-level requirements are the "parent" of the system requirements and lower subsystems, equipment, and components levels.

3. **Functional Analysis and Logical Decomposition**. High-level requirements are decomposed into lower-level requirements and allocated across the system. This decomposition and allocation process continues until a complete set of design-to-requirements is achieved. At each level of decomposition (system, subsystem, etc.), the total set of derived requirements must be validated against the parents' requirements before proceeding to the next level of decomposition. The traceability of requirements to the lowest level ensures that each requirement is necessary to meet the objectives. The Logical Decomposition is the process through which the functional and performance requirements are derived from the higher-level ones. Logical decomposition makes use of functional analysis to create a system architecture. Typical functional analysis techniques adopted in this project are: The Functional Tree decomposing the functions top-down; the Functional / Equipment Matrices linking each function to the piece of equipment which accomplishes that function; and the N2 diagram that allows to identify the interactions/interfaces among equipment. Functional tree helps to define functional requirements, F/E matrices and N2 diagrams lead to the definition of the interface requirements [2].
4. **Trade Studies and (Inner) Iterative Design Loop**. The defined logical decomposition brings to: 1) the **product definition**; 2) the **definition of operative modes**; and 3) the associated sets of **technical requirements**. The product definition passes through the product tree development and block diagrams definition to obtain the functional and then, physical architectures of the ground station. A physical block diagram is defined highlighting the number of components, and all the types of components connections. Moreover, technical budgets complete the product definition quantifying aspects such as the total mass of the platform, the volume occupation and the layout, the power consumption, and the handled data quantity. Operative modes of C3 are defined according to refined ConOps and the transition conditions are explained. State analysis is the main tool adopted to explain the operative modes transitions. Alternative architectures and updated ConOps are evaluated through detailed trade-off studies that result in the selection of a preferred alternative. Physical and configuration requirements are derived from the definition of the product, and operational requirements are obtained from the analysis of the operative modes.
5. **Design assessment**. The design solution is assessed to verify that the technical requirements are satisfied. The design verification at this level is achieved throughout a peer review.
6. **Details level.** If the product definition level is not sufficient, an additional design iteration is started. Otherwise, the baseline design can be traced.
7. **Requirements satisfaction.** It derives from the design assessment outputs that shall confirm if the requirements are satisfied through analysis and review of design. If the design is compliant with the requirements, the details of the baseline solution are identified and confirmed through the Design Review (DR).
8. **Negotiation of the requirements.** The design assessment is intended to highlight whether the requirements are satisfied by the proposed solution. If not, a major (outer) design iteration is started and a new, more detailed functional analysis and logical decomposition are performed.

B. *Functional Architecture and Product Tree*

The functional tree is a hierarchical representation of the functional architecture of C3. The functions have been derived from analysis of high-level requirements. For the ground station, the blocks describe the macro-functions with shallow details.

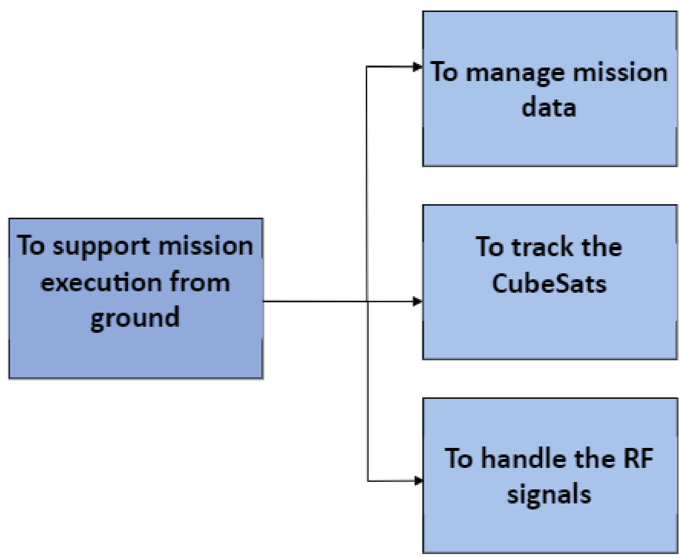

Figure 3: C3 Functional Tree (First Level)

The product architecture is obtained through development of functions/equipment (F/E) matrix at several levels of decomposition. Based on this, a trade-off analysis is conducted and reported in the next paragraph. From this it is possible to extrapolate a detailed definition of any component of C3, whose layout is reported in the further chapter, dedicated to the design of each composing system.

C. *Baseline Proposal Trade-Off*

Three possible proposals of ground architectures are evaluated to achieve the better configuration according to requirements and mission objectives. All the designs follow the KISS (Keep It Simple, Stupid) approach to make it as reliable as possible and reduce complexity:

- **Compact Architecture**: S-band and VHF/UHF-band together on the same rotator.
- **Large Architecture**: S-band, VHF/UHF-band on three different rotators.
- **Compact Single Feed Architecture**: S-band on one rotator. VHF/UHF-band on a different rotator.

In the definition of the system, a trade-off study consists of comparing the characteristics of each system element (figures of merit) for each candidate proposal architecture to determine the best solution that could better balances the choose criteria.

For the three proposal the figures of merit are the following:

- **Cost**: To satisfy all requirements with a budget of about 20 k€, in the realisation of a VHF/UHF/S-band GS, COTS components are considered for minimizing custom-made designs. This philosophy is a great incentive for the project because using these components could increase the complexity of the ground station but with a lower cost.
- **Radio Frequency (RF) Performance**: Evaluates parameters like full duplex operation, bandwidth, losses, gain, link budget, efficiency, error rate and other specific RF attributes.
- **Tracking Performance**: Evaluates parameters like angular resolution, rotating speed, vertical load, breaking and turning torque.
- **Ground Station Performance**: Evaluates global parameters like number of satellites with which the station can communicate at the same time, and the quality of the visibility window.
- **Architectural Reliability**: It aim is at scaling down the probability of failures and their severity and criticality to achieve high reliability. To achieve this important goal, possible solutions could be fewer components, redundant components (whenever possible), low complexity components, components protection and distributing the capabilities of the architecture to lower criticality of faults (separate rotators for example).
- **Footprint**: In order to install the antennas on a roof, this figure of merit is fundamental for the trade-off analysis.
- **Mass**: Overall weight of the components.
- **RF Flexibility**: It refers to the ability of the ground station to operate at various microwave frequencies without sacrificing much performance, and it refers to the capability to move to other frequency while replacing the minimum number of components.
- **Tracking Flexibility**: It refers to the high resolution of rotators to move to higher frequencies, which require high pointing accuracy.
- **Simplicity**: the ability of the design project to remain in the KISS approach.

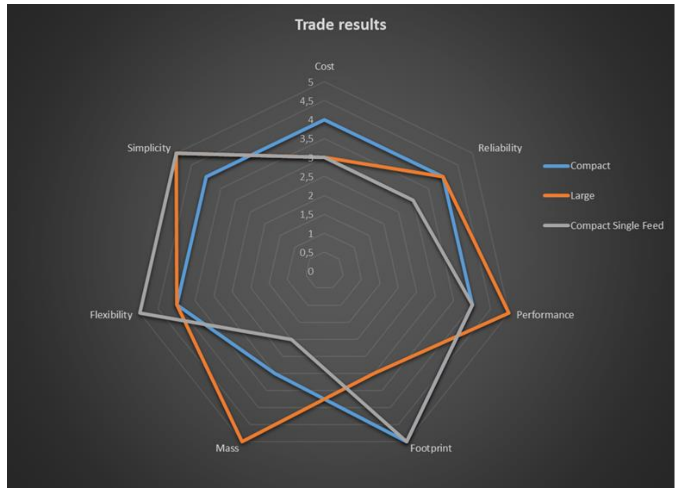

Figure 4 : Trade-off results

As seen in Figure 4, the best proposal for the project is the **Compact Architecture** with S-band and VHF/UHF-band on the same rotator.

IV. C3 Physical Layout

The physical overall architecture is composed of three major groups of components, each of them belonging to a specific system (i.e., Tracking System, Communication System, Software Infrastructure). Hereafter the physical layout of the overall architecture of C3 is introduced and in the further paragraphs is further treated.

The **Communication System (CS)**, as first, allows translating information from the wire medium to EM Waves capable of reaching the target satellite, defined in terms of frequency, encoding, modulation and polarization. The physical location of the single systems may be split. The antennas of the CS could be located on the rooftop of the Politecnico (i.e., the line components comprised between the antennas and the SDRs) to have a clear line of sight between the antennas and the spacecraft. Setting the whole CS Front-End (i.e., SDR, HPAs, LNAs, Multiplexer, TR-Switches, Phasing Harnesses and Network interface elements) as close as possible to the antennas is important to maintain the line-losses through coaxial cables as low as possible. On the other hand, the Back end (i.e., the BPS) could be in the Control Room, within the buildings of Politecnico.

The **Tracking System (TS)** is responsible for supporting/pointing the antenna to the target satellite while passing over the visibility cone of the ground station. The system is provided by two degrees of freedom, allowing rotation on the horizontal plane (for the Azimuth orientation) and on a vertical plane (for Elevation). In contrast to the CS system, the Tracking system will be entirely located on the roof, leaving the only control software running on the BPS and interacting with the control boxes via a web server deployed within a VPN.

The **Software Infrastructure (SI)** allows all the software components, both functional (e.g., Digital Signal Processing Software) and of configuration (e.g., web server for controlling the power supplies) to be controlled by a single operator. The Software Infrastructure handles safe remote access to the operators and provides the interface for exchanging mission data with third party systems (i.e., the users). These data are “tunnelled” through C3 to the user’s satellite.

A. *Communication System (CS)*

The main system of C3 is the Communication System, which is responsible for establishing and maintaining a communication link between the Ground Station and the target spacecraft in visibility so to permit the transmission of telecommands and the reception of telemetry and payload data in support of the mission execution. It is a digital communication system designed for transmission and reception of packetized data. To do so, it must be capable of adapting to channel variations, interfacing with the propagation medium, processing the baseband signals and converting them to and from an intermediate frequency, among other functions, all while respecting the applicable emission standards of the ITU [7] and CCSDS [6] regarding spurious emissions and interference. It is composed of two main subsystems, the RF Subsystem responsible for the communication link itself and the Thermal Control Subsystem, responsible for the thermal management and configuration of the RF Subsystem.

The RF Subsystem is composed of three units: the first is the *Antenna Unit*, which contains the antennas that are responsible for interfacing with the propagation medium, radiating the electromagnetic field confined, shaped, and guided by the waveguides. These radiating elements transmit and receive signals from and to the *RF Front-end Unit* (i.e., the individual communication lines), responsible for conditioning the analog signal, that is, amplifying, filtering, phasing and frequency converting it, so that it is compatible with the core of our system, the Software Defined Radio.

The *Baseband Processing Unit*, constituting the Backend of the Communication System, samples and quantizes the analog baseband signal into the digital baseband signal, performs frequency, phase, and frame synchronization, to decode and demodulate the data. In transmission, it encodes, modulates, shapes, and synthetizes the waveform that must be amplified by the RF front-end for transmission by the antennas. The Baseband Processing Unit is also responsible for structuring the Command Link Transmission Unit (CLTU), for relaying the telemetry and payload data to the remote user’s systems and store data for diagnostic.

The Communication System was designed to support VHF (144-146 MHz), UHF (430-440 MHz) and S-band (2.025-2.120/2.200-2.400 GHz) links but to be reconfigurable for other bands by changing the minimum number of components possible, such as the filters and amplifiers. For protection of the receiver and transmitter electronics, transmit and reject filters are used.

Another design principle of the Communication System is the support of high bitrate (>= 1 Mbps) full-duplex communication in S-band for simultaneous transfer of telecommands, telemetry and payload data between the spacecraft and the ground segment, maximizing the utilization of the visibility window of the ground station. In this way, a higher number of packets may be transferred, and the latency is reduced, as there is no need to wait for a telecommand being transmitted for telemetry to be correctly received. This is made possible by the usage of high-gain parabolic reflector antennas with waveguide feeds (>= 25 dBi for S-band and diplexers. In S-band, a waveguide diplexer offers high isolation between the TX and RX frequency bands (>= 50 dB) with very low insertion loss (<0.4 dB). Active self-interference cancellation with circulator-based approaches were considered but the cost of SIC circuits and dual-junction circulators that offered the required isolation and the cost of ultra-wideband antennas and circulators for wideband impedance matching between elements to prevent damage to the SDR was deemed not worth it. For the VHF/UHF links, only half-duplex operation is supported by the usage of a TR switch (coaxial relay) to alternate between transmission and reception. This is because most target spacecraft operate at low bitrates (< 19200 bps) with small bandwidths around kHz and at frequencies close to one another. Due to the colocation of the transmit and receive antennas, their low directivity (12 dBi gain for UHF, 10 dBi for VHF) and that the transmission is done at a high power (+47 dBm), the signal emitted by one antenna would be received by another and would not be sufficiently attenuated to prevent damage to the SDR. Instead of using a costly cavity filter, it was decided to go half-duplex and combine through a power splitter two antennas (which would have been the TX and RX antenna) to obtain an approximately 3 dB stacking gain (increasing the gains to 15 dBi for UHF and 13 dBi for VHF) and improve their directivity.

Regarding antenna polarization, it was decided to support both linear and circular polarizations for VHF/UHF. By default, through a phasing harness, RHCP polarization is standard and linear polarizations may be received with a 3 dB polarization loss. If LHCP is desired, the phasing harness must be manually changed. This was done to minimize the cost and avoid a complex polarization switching scheme while still supporting many satellites. The same holds for the S-band with its helix feed. The choice of one circular polarization as default was chosen because single reflections are automatically cancelled as they change sense of rotation but mostly because many spacecrafts do not have a precise axis control and thus the polarization mismatch may be very high if it is 90* offset from what would be expected with linearly polarized antennas. During propagation, rain and other effects can rotate the linear polarization and these effects are not significant if one of the antennas is circularly polarized. All electronics were chosen to be put as close as possible to the antennas to minimize cabling loss and improve the noise figure of the system and therefore they will all be enclosed by a weatherproof enclosure. Heat is dissipated by conduction through aluminum heatsinks that are cooled by forced air.

The SDR chosen is the Nuand bladeRF 2.0 micro, which uses the RF Agile Transceiver AD9361 and operates from 47 MHz up to 6 GHz, has two channels for transmission that share the same frequency synthesizer and two synchronous channels sharing the same oscillator for reception allowing for 2x2 MIMO applications or, in our case, multi-channel operation, low TX noise floor (< 150 dBm/Hz), low RX noise figure (< 3 dB), high linearity and 12-bit ADC/DAC resolution. Moreover, it supports a bandwidth of up to 56 MHz at a 61.44 Msps sampling rate which is more than enough to support most LEO applications. It has programmable digital filtering, analog filter blocks, automatic gain control, I/Q sampling and its PLL can be locked to an external reference. The AD931 includes an internal

LNA and an attenuator for its transmitter that allow for precise gain adjustments. Additionally, the SDR includes a Cyclone V 301 kLE FPGA that can either offload the digital processing from the Baseband Processing Server or be programmed to allow the SDR to operate standalone. The usage of such a SDR is also very advantageous for rapid prototyping as it has an API that allows it to be programmed by combining different functional blocks using MATLAB/Simulink or GNU Radio, reducing the turnaround time. Lastly, such a flexible SDR can be used for Fault Detection, Identification and Recovery, as it is capable of sampling and receiving signals from any part of the radio-frequency front-end when combined with an adequate power splitter or attenuator, making FDIR simpler.

Using two of such SDRs allowed the Communication System to be built on fully independent lines, one for each frequency band of interest, each one with its own amplifiers, filters, and antennas, maximizing its reliability; if one of the wideband amplifiers or SDR fails, it can be quickly substituted by the other. This principle of redundancy is present where it could be afforded, as the UHF/VHF lines have also cold-redundancy on the amplifiers, but the S-band does not. However, high reliability components in hermetically sealed enclosures with input protection, over-voltage protection and built-in voltage regulation were selected for S-band to reduce the probability of a critical failure or damage coming from a strong interferer. Their filters are waveguide-based and very robust.

B. Tracking System (TS)

The main purpose of the TS is to orient the ground antennas toward the CubeSats, while in the visibility periods. This means that the TS system aims at reducing the angular offset between the transmitted beam and the line of sight with the satellite, so to reduce any pointing loss and maintain an optimal configuration of the RF channel. To do so, it is essential to keep the pointing accuracy as high as possible, while relying on COTS components.

The pointing error loss can be calculated as it follows:

$$L_{pr} = -12\left(\frac{2e_p}{\theta}\right)^2$$

where θ is the beamwidth of the antenna and e is the angular error.

Typically, for VHF/UHF bands, Yagi antennas are used, having a beamwidth of about 30°. Parabolic dishes are often used in S-band, reducing its beamwidth to about 5°. Table 1 below show the pointing error loss for these beamwidths and an increasing angular error. In the rage considered by narrow beamwidth applications, the S-band pointing loss is not linear with the angular pointing error, as shown in Figure 5. The same is not valid for VHF/UHF Yagi antennas, whose gain is not weakened by the angular errors considered.

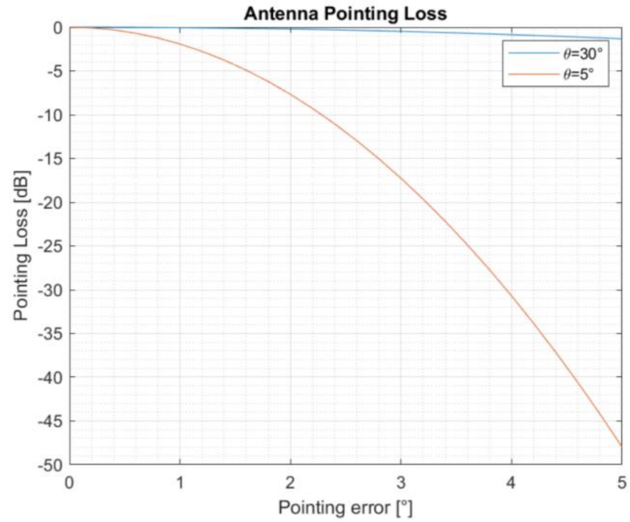

Figure 5: Antenna pointing loss

TABLE I
POINTING ERROR LOSS

e_p	L_{pr} ($\theta = 30°$)	L_{pr} ($\theta = 5°$)
0.1°	0 dB	-0.01 dB
1°	-0.05 dB	-1.92 dB
2°	-0.21 dB	-7.68 dB
3°	-0.48 dB	-17.28 dB

Seen the high difference that occurs between the pointing requirements for the antennas adopted, the stricter requirement is imposed. It thus becomes necessary to select a rotator that allow an accurate rotation of the antennas. This reflects on the sensor capability to measure the position of the shaft. In the radio amateur market, the rotators are typically divided in two categories:

- **Standard resolution rotators** (Accuracy: 1-5°)
- **High resolution rotators** (Accuracy 0.1-0.2°)

To fulfil these requirements, an inspection of radio amateur market is conducted to identify the main products categories and chose the perfect rotators for the C3 project. The selected rotator is the SPX-03/HR for all the VHF, UHF and S-band lines, which falls within the elicited requirement.

The structure unit is aimed at supporting the antennas in their work. The structure is defined to be composed by three main parts:

1. **Fixed structure**, i.e., the part of the structure that is fixed to the ground and sustains the whole mechanical load of the antennas and the rotator. It is also called "tower".
2. **Rotator**, which has both to sustain the mechanical load of the antennas and to move them thanks to the actuation of its two motors.
3. **Antenna Frame**, which is the part of structure that holds the antennas in position onto the rotator. The antennas are directly attached to this part of the structure through a rigid joint.

From this definition of the unit, it results that the structure has two main functions to carry out. The first is to sustain all the mechanical loads (both vertical and bending loads), the second is to orientate the antennas. The structure holding the antennas is mounted on top of a rotator. This is mounted on top of a raised pole, so to guarantee the less obstacles on the line of sight. The rotator is controlled by a hardware device connected by both control and power cables.

Figure 6: View of complete assembly of the structure

C. Software Infrastructure (SI)

The decomposition pattern is the base of our proposal, as any software component is packaged and deployed as a container, connected to the others via network sockets. In the current implementation, there are three principal subsystems:

1. Secure Remote Access Gateway
2. Digital Signal Process Service
3. Antenna Control Service

The first one consists of a Virtual Private Network (VPN) access gateway with a Public Key Infrastructure (PKI) authentication based on the OpenVPN software. This represents the main entrance point for the GS operators, as all communications and interactions with the station subsystems are managed in a controlled and secure way. The PKI infrastructure is self-hosted, and it uses EJBCA software. Our service model is based on the following pattern: a X.509 certificate is issued to every user, and represents the access token to the internal network, on which all services are exposed. Other subsystems (that will be referred to as "services" later on) are organized in "stacks", which are sets of containers connected via internal networks.

The second subsystem, the Antenna Control Service, is composed of three containers: the main one hosts an instance of GPredict [8], which is responsible for propagating the satellite orbit and calculating the relative position to the GS at a specified epoch. The position is then converted in azimuth and elevation parameters that are communicated to the antenna rotator via meta-commands. These are then transmitted to a "driver" container (HAMlib [9]) that translates them into real commands to be sent to the antenna rotator controller: the container in this case acts as adaptation layer. The operator interacts with the system (GPredict user interface) using a VNC [10] remote desktop session.

The third subsystem, the Digital Signal Process Service, contains three main components: the frontend, the modem, and the payload handler. The frontend module is composed of multiple instances of GNURadio that are responsible for processing the signal and controlling the SDR devices, making them accessible via network socket. This adaptation layer allows to decouple the SDR from the software modem. One of the benefits of this approach is the segregation of the signal acquisition from the signal processing module, meaning that the software modem can be modelled as a functional block, abstracting it from the SDR hardware device and its handling. Another positive aspect is the fact that the software modem (which is a CPU bound workload) can be run on high-performance host that doesn't need to be located near the SDR or the antenna system. The software modem component is another GNURadio instance, which implements all the signal processing logic, to act as a mid-level gateway to communicate to the satellite. At the end of the pipeline, we can find the last component of the system which is the payload handler block. Payload handler block implementation won't be part of this description, as it needs to be designed specifically for the communication protocol used by the specified satellite. Anyway, our design allows us to simply change that module on the fly, just running and stopping the right container, which will be implementing the specific protocol used by the target satellite. The other modules are in fact common for all satellites and are so designed to be sufficiently generic to not represent a limit in the protocols that the GS can handle.

V. Ground Station Performances

In the design process of C3, as results of the constraints evaluation and on the base of trade-off analyses, the budgets were defined, in terms of Mass, Electrical Power Consumption and Communication Links.

A. Mass Budget

TABLE II
C3 Mass Budget

	Mass (Kg)
S-band + UHF/VHF	104
Base	20
Tower	105
Total	**229**

The total weight of the station (antennas and rotators) is approximatively 230 Kg. This number is important to respect the security standard for the future installation on a roof (Table 2).

B. Power Budget

TABLE III
C3 Power Budget

Item	Number	Max Power Absorption (W)	*Power* (W)
Kuhne Power Supply 12V	1	320	320
Kuhne Power Supply 24V	1	320	320
PS-02	2	485	970
Sever	1	400	300
Total			**1910**

According to Table 3, the total consumption of the station in Watt is less than 2 kW. These characteristics are important for the management of the project, but also for the developing of the control centre that has the aim to manage and control the entire station and to communicate with the satellites.

C. *UHF/VHF Link Budget*

The VHF/UHF systems were statically designed to support a 100 kbps downlink (BER < 1E-6 @ EbN0 >= 9.6 dB) and 64 kbps uplink (BER < 1E-8 @ EbN0>= 12 dB) with a satellite using a crossed-dipole antenna (+2.1 dBi gain) capable of transmitting up to 2W/+33 dBm using RHCP polarization and uncoded BPSK/QPSK and a noisy receiver (T = 485 K) at 400 km altitude with a 8° elevation, resulting in a 1570 km slant range. A 3 dB link margin was used in the design for the downlink and 6 dB for the uplink considering 1 dB of ionospheric losses, 2 dB of atmospheric losses. Rain attenuation due to rain in Piemonte (Italy) according to ITU P837 targeting 99.9% availability is negligible. An antenna noise temperature of 290 K is considered for the satellite and 290 K for the ground station to account for a quiet receiving site outside of an urban environment [ITU P372].

D. *S-band Link Budget*

The S-band (2.025-2.120 GHz Downlink/2.200-2.400 GHz Uplink links were statically designed using a tabular method for the worst case communication at an elevation angle of 5° with LEO satellites at an altitude of 400 km, producing a maximum slant range of 1800 km and using digital modulations such as QPSK with CCSDS coding such as LDPC(16384, 8192) to support high data-rate downlinks (>= 1 Mbps, BER < 1E-6 @ EbN0 >= 1 dB) and high reliability uplink using LDPC(128,64) (64 kbps, BER < 1E-12 @ EbNo >= 5 dB) with satellites using patch antennas pointed at the ground station by the ADCS system. A 3 dB link margin was used in the design for the downlink and 6 dB for the uplink considering very low ionospheric losses plus attenuation due to rain in Piedmont according to ITU P837 targeting 99.9% availability. For the S-band spacecraft, COTS components such as a S-band RHCP Patch Antenna (7.5 dBi gain) and S-band Transmitter (2W/+33 dBm @ 2025-2110 MHz) and noisy receiver (T = 485 K) were considered. To share the patch antenna between the transmitter and receiver, a 1.0 dB microstrip or ceramic (SMD) diplexer insertion loss was considered. Spacecraft cabling loss is considered very low (0.2 dB) due to close placement of antenna and amplifiers. In the ground architecture, unlike the X-band approach, which immediately amplified and converted the signal near the antenna using waveguide filters, the S-band ground segment uses a helix feed with Type N connectors and a waveguide diplexer with SMA connectors and may have a considerable length of cabling between the amplifier and the antenna. Hence, up to 3 dB cabling loss can be accepted in transmission and reception. A 1 dB implementation loss is considered in both receivers. No external mixers were considered as the transmitters and receivers can directly synthetize the frequencies of interest. The antenna temperatures are 50 K for the clear sky conditions seen by the ground station at 5-degree elevation and 290 K for the spacecraft that sees the Earth.

The S-band link budget demonstrates that all the links have been closed under the worst-case conditions with 6 dB extra margin for the uplink and 1 dB of extra margin for the downlink. One can observe the cabling introduces losses in transmission and significantly increases the receiver's noise figure. If no coding was present, then it would not be possible to support the 1 Mbps bitrate without accepting a higher bit error rate. Pointing losses remain negligible but both spacecraft and ground station must use the same (circular) polarization for such bitrate to be achievable. Halving the bit rate would compensate for a possible 3 dB mismatch loss between a linearly polarized spacecraft and the RHCP ground segment or allow the orbit's altitude to be increased.

TABLE IV
C3 LINK BUDGET RESULT

	Uplink (dB)	Downlink (dB)	Result
UHF	18.61	5.73	Links are closed
VHF	25.86	13.23	Links are closed
S-band	12.29	4.84	Links are closed

E. *Ground Segment Cost Budget*

All the design follow the **KISS (Keep It Simple, Stupid)** approach in order to work best if systems are kept simple rather than made complicated; therefore, simplicity is a key goal in design, and unnecessary complexity will be avoided. To satisfy all requirements with a budget of about 20 k€, COTS components are considered to try to find, adapt and acquire items already available on the market while minimizing custom-made designs. This philosophy is a great incentive for the project because using these components could increase the complexity of the ground station but with a lower cost.

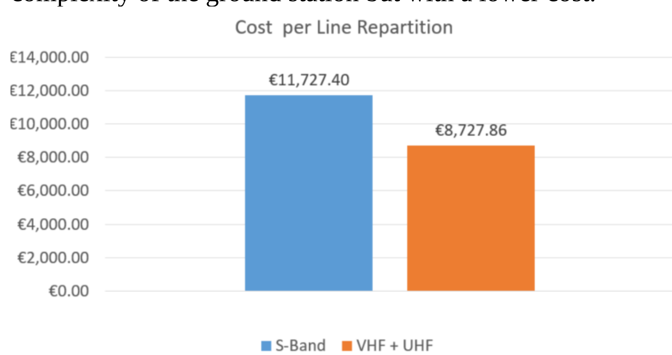

Figure 7: Cost Budget Diagram for Line

In conclusion, in respect of requirements and budget, the total cost of C3 is 20.455,26 €.

VI. CONCLUSION

To conclude, C3 is an enormous multi-year project undertaken by the CubeSat Team at Politecnico di Torino and many open points must be closed before it can become operational. Among them, we highlight:
1) Testing and verification must be completed; VHF, UHF, and S-band lines must be verified in transmission.

2) The precise position of the antennas on Politecnico di Torino's rooftop must be established, considering possible line-of-sight obstructions by buildings and objects.
4) Tracking and Communication Systems must be integrated for final acceptance tests.
Finally, two topics should be investigated in future developments: expansion of Fault Detection and Isolation capabilities to improve ground station reliability, and automation of the Communication System to reduce workloads and mission turn-around times.

REFERENCES

[1] CubeSatTeam. *About Us.* url: https://www.cubesatteam-polito.com/
(visited on 12/30/2020) (cit. on p. 1).
[2] F. Stesina, S. Corpino, "In orbit operations of an educational cubesat: The e-st@r-ii experience", International Review of Aerospace Engineering, Volume 13, Issue 2, Pages 40 – 50, 2020, DOI 10.15866/irease.v13i2.18317
[3] Busso A., Sousa M., Mascarello M., Stesina F., "A procedure to recover data of a cubesat mission at very low S/N ratio", In proceedings of 8th ESA International Workshop on Tracking, Telemetry and Command Systems for Space Applications, TTC 2019, Darmstadt, September 2019
[4] M. Langer, M. Weisgerber, J. Bouwmeester and A. Hoehn, "A reliability estimation tool for reducing infant mortality in Cubesat missions," 2017 IEEE Aerospace Conference, 2017, pp. 1-9, doi: 10.1109/AERO.2017.7943598.
[5] Stesina, F.; Corpino, S. Investigation of a CubeSat in Orbit Anomaly through Verification on Ground. Aerospace, Volume7, DOI: https://doi.org/10.3390/aerospace7040038
[6] B. Klofas, J. Anderson, "A survey of CubeSat Communication Systems 2009-2012", CubeSat Developers Workshop, April 2013
[7] NASA, "CubeSat Communications: State of the Art Survey", https//www.nasa.gov/smallsat-institute/sst-soa/communications#9.5.1
[8] Larson, W. J., & Wertz, J. R. (1992). Space mission analysis and design. Torrance, Calif: Microcosm.
[9] ITU, "Radio Regulations", 2020
[10] CCSDS, "401.0-B-29", March 2019
[11] GPredict, Official Web Site, http://gpredict.oz9aec.net/
[12] HamLib, Open Source GitHub Repository, https://hamlib.github.io/
[13] VNC Connect, VNC Official Web Site, https://www.realvnc.com/en/connect/download/viewer/