CubeCat-1

Communications System of a Nano-satellite

Sumit KARKI

Directed by:
Prof. Adriano CAMPS CARMONA

Supervised by:
Roger JOVÈ CASULLERAS

MASTER THESIS
UNIVERSITAT POLITÈCNICA DE CATALUNYA
MASTER OF RESEARCH IN INFORMATION AND COMMUNICATION TECHNOLOGIES

30 de juliol de 2013
Abstract

The CubeSat program provides a cost-effective solution to the educational institutions and private firms, around the world, willing to put their satellites in orbit, which are no bigger than a 10 cm cube, and weigh less than 1.33 kg. Benefitting from such program is a CubeSat from Universitat Politècnica de Catalunya, Cat-1, which aims to test various scientific payloads in a space environment. Like most of the satellites, a CubeSat requires a harmonious interactions among different subsystems to function properly.

The thesis focuses on one such subsystem, the communications subsystem, which is responsible for establishing a communication link between the CubeSat and the ground stations. The communication can take different form, from transmitting only the status of the satellite to transferring payloads data to earth or responding to the tele-commands uploaded from the ground station.

The report emphasises on the detailed design and test of the communications subsystem consisting of the RF front-end, the antenna and the electronic hardware. It also focuses on different experiments conducted to optimise the design. Furthermore, the work outlined in this thesis can be extended to future CubeSat projects.
Abstract

La iniciativa CubeSat ha permès obrir l’accés a l’espai a organismes educacionals i empreses privades, que necessiten posar en òrbita petites càrregues útils, que puguin cabre en un cub de 10cm i un pes inferior a 1.33kg. Emmarcat en aquesta iniciativa, la Universitat Politècnica de Catalunya ha posat en marxa el $3^{\text{Cat}} - 1$, amb la intenció de provar diferents càrregues útils dissenyades per diferents departaments a l’espai. Com qualsevol altre satèl·lit, un CubeSat necessita un bon funcionament dels diferents subsistemes per poder funcionar.

Aquesta tesi es focalitza en el subsistema de comunicacions, que és el responsable d’establir comunicació entre el satèl·lit i la estació de seguiment terrestre. La comunicació entre els dos pot anar des de transmetre únicament l’estat del satèl·lit fins a transmetre les dades dels experiments, o bé respondre als telecomandaments enviats des de l’estació terrestre.

El treball presentat emfatitza el disseny i test del subsistema de comunicacions, que consisteix en una interfície RF, l’antena i el hardware electrònic. Igualment, el document para especial atenció als tests realitzats per a validar i optimitzar el disseny del subsistema. Finalment, es preveu que el material presentat en aquesta Tesi pugui ser reutilitzat en futures missions de satèl·lits a la UPC.
Abstract

La iniciativa CubeSat ha abierto el acceso al espacio a organismos educacionales y empresas privadas que necesitan poner en órbita pequeñas cargas útiles, que puedan caber en un cubo de 10cm de lado con un peso inferior a 1.33kg. Dentro de esta iniciativa, la Universitat Politècnica de Catalunya ha puesto en marcha el $^3$Cat − 1, con la intención de probar distintas cargas útiles diseñadas en distintos departamentos en el espacio. Como cualquier otro satélite, un CubeSat necesita un correcto funcionamiento de los distintos subsistemas para poder funcionar.

Esta tesis se focaliza en el subsistema de comunicaciones, que es el responsable de establecer la comunicación entre el satélite y la estación de seguimiento terrestre. La comunicación entre la Tierra y el satélite puede ir desde una transmisión del estado del satélite hasta el envío de los datos de los experimentos embarcados, o bien responder a los telecomandos que se envían desde la estación terrestre.

El trabajo presentado enfatiza el diseño y test del subsistema de comunicaciones, que consiste en una interfície RF, la antena y el hardware electrónico. Igualmente, el documento presta especial atención a los tests realizados para validar y optimizar el diseño del subsistema. Finalmente, se prevé que el material presentado en esta Tesi pueda ser reutilizado en las próximas misiones de satélites de la UPC.
Acknowledgements

First and foremost, I would like to express my sincere gratitude to Dr. Adriano Camps, my thesis director, for giving me this wonderful opportunity to work in the CubeSat project. His dedication and tutelage in the project has whetted my curiosity and broadened my knowledge. I am also grateful to Roger Jové, my supervisor and project manager of 3Cat-1, for his perpetual support throughout the project duration.

I am deeply thankful for the support offered by the people working in the Antennas, RF and Microwave, and Remote Sensing group, namely to Alberto Alonso, Edgar Diaz, Juan Carlos Rodríguez Silva, and Raul Onrubia. I am also grateful to Albert Marton, laboratory technician, for his help in fabrication.

Last but not least, I want to thank all the current students involved with the CubeSat project for the help and support endowed upon me. I would also like to remark on the work done in the communications subsystem by the previous students, which was instrumental in kick-starting the project.
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<tr>
<td>ADCS</td>
<td>Attitude Determination and Control Subsystem</td>
</tr>
<tr>
<td>AM</td>
<td>Amplitude Modulation</td>
</tr>
<tr>
<td>ASK</td>
<td>Amplitude Shift Keying</td>
</tr>
<tr>
<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
</tr>
<tr>
<td>BC</td>
<td>Battery Charger</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>Cal Poly</td>
<td>California Polytechnic State University</td>
</tr>
<tr>
<td>CNAF</td>
<td>Cuadro Nacional de Atribución Frecuencias</td>
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<tr>
<td>COMMS</td>
<td>Communications Subsystem</td>
</tr>
<tr>
<td>COTS</td>
<td>Commercial off-the-shelf</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>EPS</td>
<td>Electrical Power Subsystem</td>
</tr>
<tr>
<td>FM</td>
<td>Frequency Modulation</td>
</tr>
<tr>
<td>FSM</td>
<td>Finite State Machines</td>
</tr>
<tr>
<td>GENSO</td>
<td>Global Educational Network for Satellite Operations</td>
</tr>
<tr>
<td>GS</td>
<td>Ground Station</td>
</tr>
<tr>
<td>IARU</td>
<td>International Amateur Radio Union</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>ISM</td>
<td>Industrial, Scientific and Medical</td>
</tr>
<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
</tr>
<tr>
<td>LHCP</td>
<td>Left Hand Circular Polarisation</td>
</tr>
<tr>
<td>LNA</td>
<td>Low Noise Amplifier</td>
</tr>
<tr>
<td>LV</td>
<td>Launch Vehicle</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro-Electro-Mechanical Systems</td>
</tr>
<tr>
<td>OBC</td>
<td>On-Board Computer</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>POLs</td>
<td>Points Of Loads</td>
</tr>
<tr>
<td>P-POD</td>
<td>Poly-Picosatellite Orbital Deployer</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RHCP</td>
<td>Right Hand Circular Polarisation</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>SPI</td>
<td>Serial Peripheral Interface</td>
</tr>
<tr>
<td>SSB</td>
<td>Single Side Band</td>
</tr>
<tr>
<td>SSDL</td>
<td>Space Systems Development Laboratory</td>
</tr>
<tr>
<td>TCS</td>
<td>Thermal Control Subsystem</td>
</tr>
<tr>
<td>TNC</td>
<td>Terminal Node Controllers</td>
</tr>
<tr>
<td>TVAC</td>
<td>Thermal Vacuum Chamber</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra High Frequency</td>
</tr>
<tr>
<td>UPC</td>
<td>Universitat Politècnica de Catalunya</td>
</tr>
<tr>
<td>URE</td>
<td>Union de Radioficionados Españoles</td>
</tr>
<tr>
<td>VNA</td>
<td>Vector Network Analyser</td>
</tr>
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Capítol 1

Introduction to CubeSat

This chapter provides a brief introduction to the CubeSat program, its standard and deployment mechanisms. It also presents an overview of the communications subsystem, justifies the choice of frequency band and explains the regulations at hand.

1.1 CubeSat

CubeSat is a cube of 10 cm weighing at most 1.33 kg, which can fly in space as a small nano-satellite. Such CubeSat is known as a ‘1U’ or 1 unit CubeSat, with ‘2U’ and ‘3U’ CubeSats also fast emerging. The CubeSat program began as a collaboration of Prof. Jordi Puig-Suari from California Polytechnic State University (Cal Poly), San Luis Obispo, and Prof. Bob Twiggs from Stanford University’s Space Systems Development Laboratory (SSDL). Their aim was to standardize the design of pico-satellites providing quick and cost-effective solutions, and to make space more accessible to educational institutions, private firms willing to put their scientific, private or government payloads in orbit [1]. Fig 1.1 shows a CubeSat prototype from Universitat Politècnica de Catalunya (UPC).

1.1.1 Background

Having started the CubeSat project in 1999, Profs. Jordi Puig-Suari and Bob Twiggs set about the standardization of CubeSat. Now, the CubeSat project caters to more
than 100 educational institutions and private firms with their design needs. One of the most challenging aspects of the program was to provide access to space for the small independent developers. With the Cal Poly’s Poly-Picosatellite Orbital Deployer (P-POD), it was possible to safely stack three standard ‘1U’ CubeSats and provide an interface between the CubeSat and the Launch Vehicle (LV). So, the CubeSat developers play an important role to ensure the safety of the whole mission as failure to adhere to the given specifications may lead to damages to the LV or even to the entire CubeSat program.

1.1.2 The CubeSat Specifications

The CubeSat program specifies the different requirements that CubeSat developers need to comply with. The detailed specifications are provided in [1]. The excerpts of the requirements relevant to the communications subsystem are presented below:

- All electronics should be disabled to avoid interference with the LV and the primary payloads.
- The deployable components of the CubeSat, like the antennas, should wait for a minimum of 30 minutes after the CubeSat’s deployment switch is activated from P-POD ejection.
Chapter 1: Introduction to CubeSat

- The RF transmitter greater than 1 mW should wait for a minimum of 30 minutes to transmit after P-POD ejection.

- CubeSat operators should obtain necessary licenses for the use of frequencies. At amateur frequency, a proof of frequency coordination by the International Amateur Radio Union (IARU) is required.

Testing requirements should be fulfilled in order to meet the launch vehicle requirements as well as that of the CubeSats and P-POD. In any case, the CubeSats need to undergo a random vibration test, thermal vacuum test and a visual inspection as well as survive qualification testing requirements of the LV and protoflight testing.

1.1.3 Launch Mechanism

The Cal Poly’s Poly Picosatellite Orbital Deployer (P-POD) is used to deploy the CubeSats. It acts as an interface between the Launch Vehicle (LV) and the CubeSat, and also protects the LV and the primary payload.

The P-POD is shown in Fig 1.2. The P-POD is a rectangular box capable of carrying three CubeSats with a spring mechanism, which springs open the door ejecting the CubeSats slid in the P-POD along a series of rail. A recent figure shows that 66 CubeSats have been launched so far from 2000 to 2012 AD [2].

![Image of P-POD and cross section]

**Figure 1.2:** Poly Picosatellite Orbital Deployer (P-POD) and its cross section [1]
1.2 Review of the CubeSat Communication Systems

The communications subsystem is one of the major subsystems in a CubeSat, without which it would be nothing more than a space debris. First, a brief overview of the radio spectrum is given, then the different transceiver configurations available in the market are discussed, and finally a brief comparison of the communications subsystem of different CubeSats is given.

1.2.1 Radio Spectrum: Frequency Bands and Licensing

The electromagnetic spectrum consists of all possible frequencies, which emit electromagnetic radiation. It ranges from very low frequencies used for radio communication to very high frequencies of gamma radiation. For the purpose of communication system, a range of electromagnetic spectrum called radio spectrum corresponding to the radio frequencies, lower than 300 GHz or a wavelength greater than 1 mm, is used.

The International Telecommunication Union (ITU) radio regulations designates the frequency band from 3 kHz to 300 GHz, as shown in Table 1.1.

For the CubeSat community, the frequency bands of interest are usually in the VHF and the UHF bands. Most of the CubeSats in orbit, so far, use the frequency band in UHF (see Table 1.5). The UHF band can be subdivided into different bands. Radar
Chapter 1: Introduction to CubeSat

### Taula 1.1: ITU Radio Bands

<table>
<thead>
<tr>
<th>Band Number</th>
<th>Symbols</th>
<th>Frequency Range</th>
<th>Wavelength Range</th>
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<tbody>
<tr>
<td>4</td>
<td>VLF</td>
<td>3 to 30 kHz</td>
<td>10 to 100 km</td>
</tr>
<tr>
<td>5</td>
<td>LF</td>
<td>30 to 300 kHz</td>
<td>1 to 10 km</td>
</tr>
<tr>
<td>6</td>
<td>MF</td>
<td>300 to 3000 kHz</td>
<td>100 to 1000 m</td>
</tr>
<tr>
<td>7</td>
<td>HF</td>
<td>3 to 30 MHz</td>
<td>10 to 100 m</td>
</tr>
<tr>
<td>8</td>
<td>VHF</td>
<td>30 to 300 MHz</td>
<td>1 to 10 m</td>
</tr>
<tr>
<td>9</td>
<td>UHF</td>
<td>300 to 3000 MHz</td>
<td>10 to 100 cm</td>
</tr>
<tr>
<td>10</td>
<td>SHF</td>
<td>3 to 30 GHz</td>
<td>1 to 10 cm</td>
</tr>
<tr>
<td>11</td>
<td>EHF</td>
<td>30 to 300 GHz</td>
<td>1 to 10 mm</td>
</tr>
<tr>
<td>12</td>
<td>THF</td>
<td>300 to 3000 GHz</td>
<td>0.1 to 1 mm</td>
</tr>
</tbody>
</table>

systems engineers use letter designations to describe the frequency band of operation. *IEEE Standard Letter Designations for Radar-Frequency Bands* designate a frequency band from 2 to 4 GHz as an S-band.

Another frequency band of interest to the CubeSat developers is the amateur radio bands. Amateur radio or ham radio is used for non-commercial private communication, whose radio frequency spectrum is allocated by ITU. Amateur radio services are overseen by the International Amateur Radio Union (IARU), which organises the countries in the world in different regions, and has as its members the national amateur radio societies. The different regions of the world are shown in Fig 1.4.

![Figura 1.4: IARU Regions](image)

IARU Region 1 consists of Europe, Africa, Middle East and Northern Asia, IARU Region 2 consists of the Americas and IARU Region 3 consists of Asia-Pacific. Therefore, Spain
Chapter 1: Introduction to CubeSat

falls in Region 1, and is represented by Union de Radioaficionados Españoles (URE), a national amateur radio association in Spain. Cuadro Nacional de Atribución de Frecuencias (CNAF) is the national body in Spain overlooking the entire frequency allocation in the country. CNAF allocates 25 kHz bandwidth for a frequency band of 430 - 440 MHz [4]. Also, it notes that the frequency band from 433.05 to 434.79 MHz falls in the ISM band, and any radio communication operations must tolerate the interferences generated by devices operating at that band.

1.2.2 Link Budget: Power and Bandwidth Requirements

A link budget gives the power requirement of a communication link, taking into account, all the gains and losses from the transmitter through the medium to the receiver in a communication chain.

A basic link budget equation, expressed in decibels, can be written as the logarithmic form of the Friis transmission equation, including the losses [5].

\[
P_r (\text{dBm}) = P_t (\text{dBm}) + \text{Gains (dB)} - \text{Losses (dB)}
= P_t (\text{dBm}) + G_T (\text{dB}) + G_R (\text{dB}) - L_{FS} (\text{dB}) - L_M (\text{dB})
\]

(1.1)

where,

- \( P_r \) = Received power
- \( P_t \) = Transmitted power
- \( G_T \) = Gain of the transmit antenna
- \( G_R \) = Gain of the receive antenna
- \( L_{FS} \) = Free space path loss
- \( L_M \) = Miscellaneous losses like polarization mismatch

If \( \lambda \) = wavelength, \( c \) = speed of light, \( f \) = frequency, and \( R \) = distance between the transmitter and the receiver, the free space path loss is:

\[
L_{FS} = \left( \frac{\lambda}{4\pi R} \right)^2 = \left( \frac{1}{4\pi R} \cdot \frac{c}{f} \right)^2
= 32.45 \text{ dB} + 20 \times \log[f(\text{MHz})] + 20 \times \log[R(\text{km})]
\]

(1.2)
If we consider a case for a CubeSat, revolving around the Earth at a maximum distance of 3000 km [6], operating at different frequencies in VHF and UHF, with a gain of transmit antenna 1 dB and a gain of 12 dBi (for VHF) and 16 dBi (for UHF) (normal for a Yagi-Uda antenna taken for ISIS ground station [7]) at a ground station ignoring the miscellaneous losses, the received power (for different transmit power) by using the equations 1.1 and 1.2 can be computed. The result is shown in Table 1.2.

**Taula 1.2:** Received power at different frequencies and transmit power

<table>
<thead>
<tr>
<th>Power (mW)</th>
<th>145 MHz</th>
<th>434 MHz</th>
<th>900 MHz</th>
<th>2.4 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 (19 dBm)</td>
<td>-113.18 dBm</td>
<td>-118.71 dBm</td>
<td>-125.17 dBm</td>
<td>-133.56 dBm</td>
</tr>
<tr>
<td>300 (24.7 dBm)</td>
<td>-107.44 dBm</td>
<td>-112.97 dBm</td>
<td>-119.43 dBm</td>
<td>-127.82 dBm</td>
</tr>
<tr>
<td>500 (26.9 dBm)</td>
<td>-105.23 dBm</td>
<td>-110.75 dBm</td>
<td>-117.21 dBm</td>
<td>-125.60 dBm</td>
</tr>
<tr>
<td>1000 (30 dBm)</td>
<td>-102.21 dBm</td>
<td>-107.74 dBm</td>
<td>-114.20 dBm</td>
<td>-122.59 dBm</td>
</tr>
<tr>
<td>2000 (33 dBm)</td>
<td>-99.20 dBm</td>
<td>-104.73 dBm</td>
<td>-111.19 dBm</td>
<td>-119.58 dBm</td>
</tr>
</tbody>
</table>

From Table 1.2, it can be seen that the highest power is received for a transmit power of 2 W at 145 MHz and the lowest for a 80 mW transmit power at 2.4 GHz. But received power is only one of the important factors - bandwidth plays an equally important role, which affects the data rate of the channel. The relation between power and bandwidth can be easily seen in the computation of Signal-to-Noise Ratio (SNR).

**Noise Computation**

The system effective noise temperature is a sum of the antenna noise sources consisting of the weighted average of all the external noise sources, and the internal noise introduced by the transmission lines and the preamplifier [8]. For a Yagi-Uda ground station antenna, the noise figure is taken as 0.9\( (F) \) at UHF [7]. The antenna noise temperature depends on the frequency of operation as well as the elevation of the satellite being observed. For sub-GHz operations and an elevation of 45°, we can assume the antenna noise temperature, \( T_a \) to be around 3 K for a cloudless atmosphere. Therefore, the system effective noise temperature, \( T_s \) for \( T_0 = 290K \) is,

\[
T_s = T_a + T_r
= T_a + T_0(F - 1)
= 3 + 290(10^{0.9/10} - 1)
= 69.78K
\]
Bandwidth Computation

Before the computation of SNR, the bandwidth needed to transmit data at a certain rate is computed. Using Shannon’s Capacity Theorem [9], it is possible to compute the rate of transmission through a channel having a certain bandwidth. The channel capacity is given by,

$$C = W \log_2 \left( 1 + \frac{P}{N_0W} \right) \text{ bits/s} \quad (1.3)$$

where,

- $W = \text{Bandwidth (Hz)}$
- $P = \text{Signal power}$
- $N_0 = \text{Noise power spectral density}$

The minimum bandwidth requirements for data rate, ranging from 1200 bps to 9600 bps, and a received power at -104.73 dBm (transmit power of 2W at 434 MHz) are computed. The results are shown in Table 1.3

<table>
<thead>
<tr>
<th>Data Rate (bps)</th>
<th>Minimum Bandwidth (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>62.87</td>
</tr>
<tr>
<td>2400</td>
<td>133.33</td>
</tr>
<tr>
<td>4800</td>
<td>283.86</td>
</tr>
<tr>
<td>9600</td>
<td>607.10</td>
</tr>
</tbody>
</table>

Table 1.3 shows the non-linear interdependence of data rate with the bandwidth. Obviously, the values in Table 1.3 are theoretical minimums for an AWGN non-fading channel, and do not take into account the effect of channel coding. Therefore, the bandwidth required will be much higher than the one computed in Table 1.3.

For amateur satellite operations, IARU allocates the frequency bands from 144 - 146 MHz, 435 - 438 MHz and 2400 - 2450 MHz [10]. And, within these bands, only about 25 KHz or less is allocated for a satellite [11]. Assuming that the maximum bandwidth
available to a satellite is 12.5 KHz, the SNR at 434 MHz is given in Table 1.4.

\[
\text{Noise Power, } P_n = kT_s W \\
= 1.23 \times 10^{-23} \times 69.78 \times 12.5 \times 10^3 \\
= -139.19 \text{ dBm}
\]

Table 1.4: SNR for different received power at 434 MHz

<table>
<thead>
<tr>
<th>Transmit Power (dBm)</th>
<th>Received Power (dBm)</th>
<th>SNR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>-118.71</td>
<td>20.48</td>
</tr>
<tr>
<td>24.7</td>
<td>-112.97</td>
<td>26.22</td>
</tr>
<tr>
<td>26.9</td>
<td>-110.75</td>
<td>28.44</td>
</tr>
<tr>
<td>30</td>
<td>-107.74</td>
<td>31.45</td>
</tr>
<tr>
<td>33</td>
<td>-104.73</td>
<td>34.46</td>
</tr>
</tbody>
</table>

From Table 1.4, it is apparent that even at a transmit power of 19 dBm, a decent enough SNR is obtained to allow some sort of communication. Normally, the beacon in a CubeSat can use minimal transmission power. With a bandwidth of 12.5 KHz, a data rate higher than 9600 bps can also be obtained.

1.2.3 Rationale Behind the Frequency Band Selection

From sections 1.2.1 and 1.2.2, we can compare the pros and cons of using different frequency bands, in particular the S-band (2.4 GHz), the UHF band (434 MHz) and the VHF band (145 MHz).

S-Band at 2.4 GHz

One of the most important advantages of operating at 2.4 GHz is that we do not need to use deployable antennas as small patch antennas can fit in the CubeSat. Operation at lower frequencies require longer antennas, which need to be wrapped around CubeSat, and eventually need to be deployed after being ejected from LV. Also, a higher data rate is possible as a higher bandwidth is available (ref. 1.2.2). However, the antennas used have high directivity, and need to be pointed towards earth for communication. Therefore, the CubeSat needs to have an advanced attitude control for reasonable downlink, straining on the power requirements. Also, transmission at this frequency will be intermittent. There are also far less ground stations capable of receiving at this frequency [12]. However,
parabolic reflector antennas can be used as ground station antennas to achieve a very high directivity.

**UHF (434 MHz) and VHF (145 MHz)**

At UHF and VHF, there is a higher transmission efficiency, and thus, low power transmission is possible. Advanced attitude control is not required as the antennas are more or less omnidirectional. However, it requires deployable antennas, complicating the design. Besides, all the ground-stations are compatible at these frequencies. But, it can only support lower data rate (up to around 9600 bps) compared to that at S-band. Still, this data rate is sufficient for less data-intensive CubeSats. Because of these reasons, most CubeSats have chosen to operate at UHF and VHF than at S-Band, as seen in Table 1.5.

### 1.2.4 Transceiver

The communications subsystem in the CubeSats can have a modified or unmodified Commercial off the shelf (COTS) transceiver or a custom-built one.

An unmodified COTS transceiver, perhaps, presents the most simplified design of the communication subsystem. Such transceivers should be able to send and receive serial data, and encapsulate and decapsulate them, while performing error checking and correction. However, the ground station might require an identical transceiver in order to communicate as the protocols are mostly proprietary and device-specific. One such transceiver, RFC 1100H, has been used in this project ([13], in Chinese).

A modified COTS transceiver may require conformation to the space requirements, and also to the CubeSat standard. Space environment presents a whole new difficulty to devices meant to operate in ground. Apart from the size and mass miniaturisation, the device must be able to effectively dissipate heat, a case most apparent in the amplifiers. A transceiver meant for space needs to transmit sufficient power so as for the ground station to receive. This generally means an increase in the transmit power. However, the power is limited in a CubeSat and so we require the use of highly efficient transceivers.

Some prefer to design the whole transceiver out of individual components or even at the transistor level. While a custom-built transceiver is a great way for students to learn RF design, they have been less successful because of the difficulties in the design [14]. Such
designs can be tailor-made to conform to the exact requirements of CubeSat. In this project, apart from the RFC1100H, all the rest of the circuits have been custom-built from individual components to incorporate the different requirements of the CubeSat.

### 1.2.5 Comparison of CubeSats

Table 1.5 shows the comparison of different CubeSats based on the transceivers, downlink frequencies, power, antenna etc. The table has been extracted from [14].

The CubeSats compared are mostly 1U in size operating at UHF (430-440 MHz) transmitting at 500 mW to 1000 mW using a dipole antenna. Most of the CubeSats have a beacon transmitter to transmit the satellite identifier and its health status, and a transceiver to transmit/receive data and control to/from the ground station. Also, the frequency band used are mostly in amateur band. At UHF, the antenna used is dipole while at S-band, patch antenna is also used.

The transceivers are mostly modified COTS or custom built from components like CC1100, a transceiver from Texas Instruments. Unmodified COTS like Microhard MHX-2400 are proprietary, and require a similar model in the ground station for communication.

### 1.3 Summary

Chapter 1 discussed briefly about the CubeSat program, and its standards and specifications. The communications subsystem was briefly discussed, mainly on the frequency band of choice, different regulations pertaining to the CubeSat, link budget and the transceivers. Finally, the chapter provided a brief overview of the existing CubeSats and their specifications.

Given the amount of interest in the UHF band from the CubeSat community, it can be concluded that operating a CubeSat in the band (434 MHz) seems logical and sufficient according to the specifications of the UPC CubeSat, called CubeCat-1. Chapter 2 will open up with the introduction of this CubeSat, on which this master thesis is based on.
<table>
<thead>
<tr>
<th>CubeSat</th>
<th>Size</th>
<th>Transmitter</th>
<th>Frequency</th>
<th>License</th>
<th>Power</th>
<th>Lifetime</th>
<th>Antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAU1 CubeSat</td>
<td>1U</td>
<td>Wood&amp;Douglas SX450</td>
<td>437.475 MHz</td>
<td>amateur</td>
<td>500 mW</td>
<td>3 mths</td>
<td>dipole</td>
</tr>
<tr>
<td>DTUsat-1</td>
<td>1U</td>
<td>RFMD RF2905</td>
<td>437.475 MHz</td>
<td>amateur</td>
<td>400 mW</td>
<td>0 days</td>
<td>canted turnstile</td>
</tr>
<tr>
<td>CanX-1</td>
<td>1U</td>
<td>Melexis</td>
<td>437.880 MHz</td>
<td>amateur</td>
<td>500 mW</td>
<td>0 days</td>
<td>crossed dipoles</td>
</tr>
<tr>
<td>Cute-1</td>
<td>1U</td>
<td>Maki Denki (Beacon)</td>
<td>436.8375 MHz</td>
<td>amateur</td>
<td>100 mW</td>
<td>65+ mths</td>
<td>dipole</td>
</tr>
<tr>
<td>QuakeSat-1</td>
<td>3U</td>
<td>Tekk KS-960</td>
<td>436.675 MHz</td>
<td>amateur</td>
<td>2 W</td>
<td>7 mths</td>
<td>turnstile</td>
</tr>
<tr>
<td>XI-IV</td>
<td>1U</td>
<td>Nishi RF Lab (Beacon)</td>
<td>437.490 MHz</td>
<td>amateur</td>
<td>80 mW</td>
<td>65+ mths</td>
<td>dipole</td>
</tr>
<tr>
<td>XI-V</td>
<td>1U</td>
<td>Nishi RF Lab (Beacon)</td>
<td>437.345 MHz</td>
<td>amateur</td>
<td>80 mW</td>
<td>36+ mths</td>
<td>dipole</td>
</tr>
<tr>
<td>UWE-1</td>
<td>1U</td>
<td>PR430</td>
<td>437.505 MHz</td>
<td>amateur</td>
<td>1 W</td>
<td>0.75 mths</td>
<td>end-fed dipole</td>
</tr>
<tr>
<td>Cute-1.7+APD</td>
<td>2U</td>
<td>Telemetry Beacon</td>
<td>437.385 MHz</td>
<td>amateur</td>
<td>100 mW</td>
<td>2.5 mths</td>
<td>dipole</td>
</tr>
<tr>
<td>GeneSat-1</td>
<td>3U+</td>
<td>Atmel AT48402 (Beacon)</td>
<td>437.067 MHz</td>
<td>amateur</td>
<td>500 mW</td>
<td>3 mths</td>
<td>dipole</td>
</tr>
<tr>
<td>CSTB1</td>
<td>1U</td>
<td>TI CC1000</td>
<td>400.0375 MHz</td>
<td>experimental</td>
<td>&lt;1 W</td>
<td>19+ mths</td>
<td>dipole</td>
</tr>
<tr>
<td>AeroCube-2</td>
<td>1U</td>
<td>TI CC1000</td>
<td>902-928 MHz</td>
<td>ISM</td>
<td>2 W</td>
<td>0.25 mths</td>
<td>patch</td>
</tr>
<tr>
<td>CP4</td>
<td>1U</td>
<td>TI CC1000</td>
<td>437.325 MHz</td>
<td>amateur</td>
<td>1 W</td>
<td>2 mths</td>
<td>dipole</td>
</tr>
<tr>
<td>Libertad-1</td>
<td>1U</td>
<td>Stensat</td>
<td>437.405 MHz</td>
<td>amateur</td>
<td>400 mW</td>
<td>1 mth</td>
<td>monopole</td>
</tr>
<tr>
<td>CAPE1</td>
<td>1U</td>
<td>TI CC1020</td>
<td>435.245 MHz</td>
<td>amateur</td>
<td>1 W</td>
<td>4 mths</td>
<td>dipole</td>
</tr>
<tr>
<td>CP3</td>
<td>1U</td>
<td>TI CC1000</td>
<td>436.845 MHz</td>
<td>experimenta</td>
<td>1 W</td>
<td>19+ mths</td>
<td>dipole</td>
</tr>
<tr>
<td>MAST</td>
<td>3U</td>
<td>Microhard MHX-2400</td>
<td>2.4 GHz</td>
<td>ISM</td>
<td>500 mW</td>
<td>0.75 mths</td>
<td>dipole</td>
</tr>
<tr>
<td>Delfi-C3</td>
<td>3U</td>
<td>Custom Beacon</td>
<td>145.87 MHz</td>
<td>amateur</td>
<td>400 mW</td>
<td>7+ mths</td>
<td>turnstile</td>
</tr>
<tr>
<td>Seeds-2</td>
<td>1U</td>
<td>Musashino (Beacon)</td>
<td>437.485 MHz</td>
<td>amateur</td>
<td>90 mW</td>
<td>7+ mths</td>
<td>monopole</td>
</tr>
<tr>
<td>CanX-2</td>
<td>3U</td>
<td>Custom S-band</td>
<td>2.2 GHz</td>
<td>space research</td>
<td>500 mW</td>
<td>7+ mths</td>
<td>patch</td>
</tr>
<tr>
<td>AAUSAT-II</td>
<td>1U</td>
<td>Holger Eckhardt (DF2FQ)</td>
<td>437.425 MHz</td>
<td>amateur</td>
<td>610 mW</td>
<td>7+ mths</td>
<td>dipole</td>
</tr>
<tr>
<td>Compass-1</td>
<td>1U</td>
<td>BC549 (Beacon)</td>
<td>437.275 MHz</td>
<td>amateur</td>
<td>200 mW</td>
<td>7+ mths</td>
<td>dipole</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Holger Eckhardt (Data)</td>
<td>437.405 MHz</td>
<td>amateur</td>
<td>300 mW</td>
<td>7+ mths</td>
<td>dipole</td>
</tr>
</tbody>
</table>
Capítol 2

CubeCat-1

CubeCat-1, originally named as UPCSat-1, is the first CubeSat initiative from Universitat Politècnica de Catalunya (UPC). The main purpose of CubeCat-1 is to design a CubeSat capable of performing numerous scientific experiments, and to give the students an opportunity to work in the entire development of a nano-satellite. The chapter focuses on CubeCat-1, its mission requirements, and the various subsystems integral to the CubeSat.

2.1 Introduction

CubeCat-1, named as $^{3}$Cat-1 from here onwards, is an education-oriented CubeSat developed under the initiative of Profs. Adriano Camps and Juan Ramos at UPC, Barcelona. The project has been an incentive to numerous students involved to make their dreams of building a satellite become true. The project aims to teach the students the different phases of a satellite mission, and make them aware of the various expertise needed to build a complete satellite. For this very reason, the project has benefitted from the proactive contributions from the students throughout its lifetime with the involvement of more than 20 students. The project involves students from different backgrounds, namely telecommunications, electronics and industrial engineering. Even though the objective of $^{3}$Cat-1 is mostly educational, it also has a scientific objective to test different concepts developed at UPC in a space environment like Celsat solar cells, Peltier cells etc. [15]
As with any spacecraft, a CubeSat works because of the interactions of its various subsystems. Some of the more critical subsystems like the power system, on-board computer and the communications subsystems have been given more emphasis, and undertaken sterner test to comply with the CubeSat standard [16].

The entire subsystems are listed below:

- Attitude Determination and Control Subsystem (ADCS)
- Electrical Power Subsystem (EPS)
- On-Board Computer (OBC)
- Communications Subsystem (COMMS)
- Structural Subsystem
- Thermal Control Subsystem (TCS)
- Payloads

The block diagram of ³Cat-1 with various subsystems is shown in Fig. 2.1.

**Figure 2.1:** Block diagram of ³Cat-1 with various subsystems
2.2 ³Cat-1 Subsystems

The CubeSat can only function properly with an appropriate interaction among different subsystems. Every subsystem has its own purpose, and is interdependent on the functionality of other subsystems. For example, the OBC is responsible for scheduling different tasks the CubeSat does but it can’t operate if the EPS doesn’t supply power. On the other hand, the communications subsystem is made as independent as possible. COMMS combines three different signals and transmits it to earth. If, by some chance, one or two of the three signals don’t get through, some information about the CubeSat can still be retrieved on earth.

2.2.1 Attitude Determination and Control Subsystem (ADCS)

The ADCS controls the CubeSat attitude in the space, and points it properly towards earth. The attitude determination and control becomes trickier with a small satellite because of the reduced mass of the satellite. The attitude of a satellite has to be determined and controlled because of the following reasons:

- **Thermal Stabilisation**: Thermal stability is needed in the satellite as overheating may occur if a single face is constantly heated by the Sun’s radiation.

- **Camera**: The camera needs to point towards earth in order to take a picture.

- **Communications**: The antennas need to be aligned appropriately so as to maximise the radiation towards earth.

There are different approaches available for the control. The control may be passive, or active or both depending on whether it has a permanent magnet or a coil acting as an actuator.

The block diagram showing the ADCS is shown in Fig 2.2. It basically consists of the passive control block and the active control block. The active control block consists of the sensors, the microcontroller and the coil. Only the active control block shall interact with the OBC for controlling the magnetic field in the coil to change the attitude of the CubeSat.
The different blocks of the ADCS will be explained below:

**Passive Control System**

The passive control system is composed of a magnet and the hysteresis rods ($\mu$-metal). This control ensures that the satellite axis rotation is reduced, stabilising its movement, thus, guaranteeing that the roll axis points towards earth as shown in Fig 2.3.

The magnet stabilises the roll axis rotation, and ensures that the axis is parallel to earth’s magnetic field. The hysteresis rods or the $\mu$-metals are added to the CubeSat frame in the axes perpendicular to the magnetic axis, as shown in Fig 2.4.

**Active Control System**

The active control of the CubeSat is performed by this system. Currently, the active control is needed in $^3$Cat-1 for taking pictures at right angle to earth. Once the axes
rotation is stabilised, and the roll axis is pointing towards the Earth, it is possible to initiate active control by changing other axes position. In \(^3\text{Cat-1}\), the current active control is able to control only the pitch axis.

Figura 2.5: Active Control Configuration

The magnetic field of the CubeSat can be changed by passing a current through the coil (Fig 2.5), which generates a magnetic field of its own.

**Sensors**

The different sensors used in the ADCS are the magnetometer, the accelerometer and the gyroscope. A magnetometer measures the strength and the direction of the magnetic fields. This gives a measurement of the satellite’s correct position relative to earth’s magnetic field. An accelerometer measures the acceleration of the device it is attached to, where for a perfectly circular orbit the readings from the accelerometer should be equal to zero. A gyroscope measures the orientation of the device around each axis given by yaw, \(\psi\), pitch, \(\theta\), and roll, \(\phi\). All these sensor readings are required by the microcontroller to find the attitude of the CubeSat. With these readings the microcontroller can change the attitude of the CubeSat by controlling the magnetic field of the coil by passing through it the necessary current.

**Microcontroller**

The microcontroller is responsible for communicating with the OBC when the active control is needed. The microcontroller then passes the current through the coil to change the overall magnetic field, so that the CubeSat aligns properly to take a picture. When the microcontroller gets the sensor values, it calculates the amount of magnetic field required to be induced to change the orientation of the CubeSat by a certain angle.
2.2.2 Electrical Power Subsystem (EPS)

The Electrical Power Subsystem (EPS) is one of the most important subsystems in a CubeSat. Without electrical power, no electrical system can operate. Therefore, the EPS is responsible for managing the power generated by the solar panels, storing the energy into the batteries, and distributing the regulated power supply throughout the CubeSat to components which need power through a common system bus.

The main functions of the EPS are:

- Supply continuous electrical power to different subsystems throughout the mission lifetime,
- Control, and distribute the regulated electrical power,
- Ensure protection and recovery against spikes, cuts and faults in the power supply,
- Handle peak power consumption taking into account the energy cycle,
- Maintain the batteries’ temperature above freezing to ensure efficient battery operation, and
- Provide constant telemetry indicating the 'health' of the CubeSat to the ground station

The EPS is currently being developed using COTS components, and tested rigorously for space survival in the testing facility at UPC NanoSat lab.

The block diagram of the EPS is shown in Fig 2.6.

The boost converter is responsible for taking care of all the voltage and current variations of the solar cells. It also gives a constant voltage to the EPS. Moreover, the EPS also has a Battery Charger (BC), and the Points of Loads (POLs) that are fed by the power generated by the solar cells through the boost converter. The BC is responsible for charging the batteries, and managing power during the shadow period and the sun period considering the battery cycles. The POLs supply a regulated duty-cycled voltage to each subsystem requiring power from the EPS. Besides, the microcontroller in the EPS is responsible for enabling all the POLs except that of the Battery Heaters, sending sensor data to the OBC, and telemetry data to the beacon.
Some of the functional blocks of the EPS will be explained below:

**Solar Cells**
The solar cells harvest solar energy from the sun, and are the only feasible way to generate power in most satellites, and Cat-1 is not an exception. Therefore, the solar panels need to be the outermost layer covering all the six sides of the CubeSat. However, not all the six faces of the CubeSat will have the same type of solar panels. One will be the CelSat solar panels developed at the Electronics Engineering Department of UPC, while the other ones are space qualified Spectrolab *Triangular Advanced Solar Cells (TASC)* solar panels [18].

The efficiency of solar cells impose a constraint on the whole system. The solar panels have, therefore, been chosen taking into account the efficiency-cost-mass, the lifetime degradation factor of the cells, the area occupied by the panels and also the radiation resistance [15].

**Batteries**
While the solar cells provide energy when the sun is visible, the energy needs to be stored in a battery for later use when there is a demand for power in the shadow period.
Therefore, the batteries act as a secondary source of energy in the CubeSat, the solar cells being the primary. It is extremely important to choose wisely the batteries proven to work in a space environment, and with a battery charge cycle long enough to withstand the mission’s lifetime.

**Battery Charger (BC)**

The BC is responsible for the management of the battery pack. It should constantly sense all the critical parameters of the battery health like voltage, current and temperature, so that the battery doesn’t get damaged in a space environment. Also, the BC is responsible for charging the battery pack while feeding the other subsystems directly from the power generated from the solar cells during the sunlit hours. The BC should also feed power from the batteries to the other subsystems when there is no power generated from the solar cells during the shadow hours.

**Points of Loads (POLs)**

The POLs convert the input voltage to the voltage required by a particular subsystem. The POLs should be able to handle the current consumption of the load, which is determined by an external inductor. Adhering to the design specification while fabricating the POLs is critical as non-compliance might damage a subsystem permanently. Also, the non-DC terms and ripples need to be rejected in the output. The POLs will be used not only in the EPS but also in other subsystems, so that they are close to the loads. The POLs for the battery heaters, the microcontroller and the OBC will be located in the EPS board, while all the rest will be located in the respective floors of the subsystems.

The POLs need to be duty-cycled for energy management throughout the CubeSat. One way to do it is by enabling the POL only when it’s needed. Except for the POLs of the battery heaters and the microcontroller, all the rest are enabled by the microcontroller based on the energy requirements of various subsystems and payloads.

**Microcontroller**

A microcontroller will be used to enable all the POLs of various subsystems depending on the energy cycle. Besides, it also sends the sensor data to the OBC. For this, the microcontroller will gather data from the batteries as well as the solar panels. The telemetry data including the battery health, and the CubeSat identifier will be sent directly to the beacon in the COMMS board to communicate with the ground station.
2.2.3 On-Board Computer (OBC)

The on-board computing is performed by PortuxG20 from Taskit [19] as shown in Fig 2.7. The OBC is responsible for payload and communications data processing, and interaction with other subsystems.

Even though industrial-qualified PortuxG20 has never been tested in the space before, it has been tested in the UPC NanoSat Lab testing facilities. It is a good compromise between performance and power consumption [20]. The board has numerous interfaces suited to a data-processing-intensive tasks. Also, the board comes pre-installed and pre-configured with a specific Linux distribution for embedded devices (Angstrom ¹). Having Linux as an operating system for embedded products is a huge advantage considering the amount of documentation, support through communities, tools, drivers and software libraries they have.

The OBC should contain a low power consumption microcontroller, powerful memory for data-intensive tasks, large flash memories to store payload data, real time clocks, bus interfaces (USART, I2C, SPI), and over-current and voltage protection. Portux is a single-board computer with a 400 MHz ARM9 CPU core and a 2 GB external micro SD card. The ARM architecture is a modern, widely used processor architecture for embedded devices [19].

¹http://www.angstrom-distribution.org/
Functions
The OBC is responsible for basically two operations: system control and payloads management. System control is concerned with energy management, handling of communications, and system state control. Payloads management schedules various tasks, manages different payload processes, and handles their data.

Power consumption
The power consumption of the OBC is a very critical factor. Even though the OBC handles the power consumption of each module, and stops or doesn’t initiate a process if there is no power available, it has to self-sustain its power demands.

Robustness and reliability
The OBC should be robust and perform reliably in a space environment, where an erroneous state may propagate through the system, and jeopardise the whole mission. The system should be able to detect errors, and correct them accordingly to return to a safe state, or reset to a default value if the errors persist. There are watchdog timers in the OBC, which resets the system should it hang. Besides, an external reset will power down the OBC at-least once a week to ensure reliable performance.

Software Architecture
The software architecture of the OBC is based on layers, as shown in Fig 2.8.

![System Core Layer Components](image)

**Figura 2.8: System Core Layer Components**

The high level module is being programmed in Prolog, a high-level general purpose logic programming language used for artificial intelligence. The language makes use of
different Finite State Machines (FSM), while the lower process manager layer is being programmed in C.

The system manager is responsible for overall system check, earth communication and power recovery. The system manager interacts with the energy manager to know if it has sufficient energy to run a task.

2.2.4 Communications Subsystem (COMMS)

The COMMS is one of the most important subsystems as it is responsible for communicating with the ground stations. The nature of communication depends on what kind of information is needed to be exchanged. For example, the data gathered by the scientific experiments in the CubeSat may need to be eventually transmitted to earth in some favourable conditions when there is enough power and ground station demands it. There is also a need to send a continuous stream of data to earth indicating the identifier and the health of the satellite. In $^3$Cat-1, the former is achieved through a main transceiver, which interacts directly with the OBC while the latter is performed with a beacon. Moreover, there is an alternative beacon, the Peltier beacon, used in the communications subsystem to send the data gathered through the Peltier cells experiment (see section 2.2.7). It also sends the identifier of the satellite and the status of the experiment. Only the main transceiver operates in half-duplex while the two beacons use simplex communication.

The block diagram of the COMMS is shown in Fig 3.1.

The three signals coming from the main transceiver and the two beacons are combined with a 3-way-0° power combiner. Afterwards, the combined signal is again separated with a 2-way-90° power splitter. This introduces a phase-shift of 90° between the split signals. This operation introduces a circular polarisation, which is widely used in the satellite missions, to improve the reception at a cost of 3-dB power loss [21].

Main transceiver

The main transceiver is responsible for establishing the main communication link between the CubeSat and the ground station. The main transceiver used is a RFC1100H [13]. It consists of a CC1100 transceiver chip from Texas Instruments, and is responsible for encapsulating the data received from the OBC with necessary error correction operations.
The data packets are then amplified to deliver a peak output power of 33 dBm. The OBC controls the transceiver, and sends commands to initiate or terminate communication. The payload data are also sent by the OBC to the transceiver.

**Beacons**

The main purpose of the beacon is to let the ground stations know that the satellite is alive and working properly. While a complete evaluation of the satellite status is not possible from the data received from the beacons, it can at-least indicate the health of the satellite, mainly the health of the batteries (voltage, current, irradiance and temperature). The beacon transmitter is independent of the OBC, and has to perform independently, regardless of the system failure. The main beacon is controlled by the EPS while the Peltier beacon is controlled by the Peltier cells, which are independent of all the other systems. This independence makes the COMMS robust during critical operations.

**Antenna Subsystem**

The antenna subsystem consists of all the passive elements starting from the power combiner to the actual antennas. As explained before, after having the signals combined and split to generate circular polarisation, the signals can’t be fed directly to the antennas as they are unbalanced. The antenna used is a turnstile\(^2\), which needs to be fed with a

\(^2\)two dipoles crossed orthogonally, and fed 90° out-of-phase
balanced network. Therefore, the baluns are used to feed the antennas. There are four arms of the antennas, each acting as a $\lambda/4$ monopole antenna. When two monopoles are fed from a same network, they act as a single dipole. One of the dipole antennas is placed perpendicular to the other dipole antenna, and they are fed $90^\circ$ apart to generate circular polarisation.

The COMMS is the main focus of this thesis, and will be described in details in Chapters 3 and 4.

### 2.2.5 Structural Subsystem

The structural subsystem is the CubeSat structure itself, which encloses all the other subsystems, with only the deployable units like antennas protruding out of it. The structure should be modular and sturdy enough to protect both the CubeSat and the LV while providing easy assembly of the different subsystems minimising the complexity and the cost of the design. The structure should be able to fit all the modular subsystems snugly. Yet, it should also be light enough so as to maximise the allowable weight of the other subsystems, and not to exceed the maximum allowable mass of a CubeSat.

The CubeSat specifications require that the structure should be a cube of 10 cm, with 3 mm clearance above and below the cube for mounting some external components. For easy ejection from the P-POD, the CubeSat must have four launch rails along the edges of the CubeSat. Also, the centre of mass of the CubeSat must correspond within ±2 cm of the geometric centre [1].

The structural subsystem should also have a kill switch, which, when pressed, should shut down the CubeSat. The structure should undergo harmonic and random vibration tests. The materials suggested for the structure are Aluminum 7075 or 6061, Stainless Steel, Titanium, Composites, and Honey Comb.

After careful consideration of the specifications, the ISIS 1U CubeSat structure was chosen [22]. The ISIS structure is shown in Fig 2.10. The ISIS structure has two kill-switches as demanded in some missions (like ESA Vega Maiden Flight). It also holds all the PCBs of the different subsystems through a frame connected to the whole structure for added robustness even though the structure is tedious to mount.
2.2.6 Thermal Control Subsystem (TCS)

The temperature variation in space can be a challenge to maintain in order to limit damages to the batteries and the electronic components. In 3Cat-1, the temperature variations have to be controlled from 273K to 320K [20]. Below 273K, there is a risk of freezing the batteries, which can be permanently damaged, and above 320K, the electronic components may not be able to operate properly. Therefore, a mechanism called thermal control in the TCS is required to maintain the temperature of the CubeSat.

The temperature of the CubeSat depends on the optical properties of the material used and the beta angle\(^3\) of the orbit. A wise selection of the materials and the angle can yield better thermal stability without any control. From the studies performed on the batteries temperature, it was found that the gold-covered surface of the solar panels with a beta angle of the orbit between 60° and 90° required no thermal control at all [20]. However, to improve the reliability of the system, a battery heater was added in the EPS to warm the battery should it fall to a dangerous low level.

2.2.7 Payloads

The 3Cat-1 mission boasts of being a payload-based CubeSat carrying out numerous scientific experiments and technology demonstrations. A brief description of various

\(^3\)angle between the satellite’s orbital plane and the sun orbit
payloads is given below [20]:

- **Wireless Power Transfer**: To test wireless power transfer phenomenon in space conditions; part of a PhD thesis on Satellite Formation Flying,

- **MEMS Monoatomic Oxygen Detector**: To study the presence of monoatomic oxygen in lower ionosphere; designed and manufactured at the Electronics Engineering Department at UPC,

- **CelSat Si Solar Panels**: To study the degradation of CelSat Si solar panels in space conditions; designed and manufactured also at the Electronics Engineering Department at UPC,

- **Graphene Transistor**: To study this new type of transistor in space conditions,

- **Geiger Counter**: To measure the beta radiation levels to correlate them with the results of previous experiments,

- **Digital CMOS Camera**: To obtain images of the Earth from space; equipped with a VGA camera and jpeg compression,

- **Peltier Cells**: To test the energy harvesting capability of the Peltier cells in space. It feeds a beacon to transmit data down to earth. This beacon signal is directly combined to the antenna subsystem, and

- **Photodiodes**: To determine the attitude as a coarse sun sensor; placed in the solar panels in the outer faces of the CubeSat

Besides these payloads, there are other components in various subsystems, which are not classified as space-qualified by the manufacturers, but which have passed the rigorous testing at UPC NanoSat Lab testing facilities. The COTS components in the radio transceiver, and the EPS will also prove their functionalities under the harsh space conditions.
2.3 Ground Station (GS)

Communications with earth are not possible without a ground station. A ground station is capable of communicating with the spacecrafts and satellites. UPC Campus Nord has already acquired a GS from ISIS [7], as shown in Fig 2.11.

The GS is fully compatible with the CubeSat project, and can operate in VHF, UHF and S-band. Besides, it is integrated in GENSO network, and also provides satellite tracking. It is equipped with two Terminal Node Controllers (TNC), which are used by radio-amateurs to communicate using AX.25 packet radio networks.

Some of the specifications of the GS is tabulated in Table 2.1.

<table>
<thead>
<tr>
<th>Specifications of ISIS Ground Station</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency Range</strong></td>
</tr>
<tr>
<td>VHF  144 - 146 MHz</td>
</tr>
<tr>
<td>UHF  430 - 450 MHz</td>
</tr>
<tr>
<td><strong>Modulation Supported</strong></td>
</tr>
<tr>
<td>SSB, AM, FM, CW</td>
</tr>
<tr>
<td><strong>Antenna Gain</strong></td>
</tr>
<tr>
<td>VHF  12 dBic, switchable RHCP - LHCP</td>
</tr>
<tr>
<td>UHF  16 dBic, switchable RHCP - LHCP</td>
</tr>
<tr>
<td><strong>LNA Noise Figure</strong></td>
</tr>
<tr>
<td>VHF  0.8 dB</td>
</tr>
<tr>
<td>UHF  0.9 dB</td>
</tr>
</tbody>
</table>

The GS is controlled by a PC rack. It has the following software installed to track and communicate with the satellites:
• **WiSP, WiSP DDE and Orbitron**: Tracks the satellite while the rotors of the antennas rotate

• **Warbler and Terminal**: Decodes sound and data received respectively

• **Ultra VNC Remote Desktop**: Controls the GS remotely

### 2.4 Testing Facilities

The testing of 3Cat-1 subsystems and the payloads is carried out in the UPC NanoSat Lab. The lab is equipped with a Thermal Vacuum Chamber (TVAC), a Sun Simulator and a Shake Table. Because of these equipments, it’s possible to test if all the subsystems comply with the space requirements.

The TVAC, shown in Fig. 2.12, can work at the pressure of $10^{-5}$ mBar, and can go down up to $-196^\circ$ C. The Sun Simulator, shown in Fig. 2.13, can provide light power equivalent to two Suns as in the top of the atmosphere [20]. It has a power rating of 4 kW, but only 2 kW is used.

The Shake Table (Fig. 2.14) is used to perform vibration test on all the components.
Chapter 2 discussed about 3Cat-1, a university CubeSat from UPC. Various subsystems and the payloads in 3Cat-1 were described in the chapter. The ground station and the testing facilities at UPC were also discussed.

A CubeSat mission’s success does not depend solely on a single subsystem. A CubeSat requires interaction among various subsystems working in conjunction. There are some critical subsystems like the OBC, the EPS and the COMMS, whose functionalities should be put to sterner, iterative testing to improve the chance of success of a CubeSat mission.
Capítol 3

Design of the Communications Subsystem

This chapter explains, in detail, the design of the entire communications subsystem, except that of the main transceiver RFC1100H. It also explains how the different signals are integrated and fed to the antennas. It starts with an overview of the entire subsystem, and delves into each component of the subsystem.

3.1 Design Overview

The Communications Subsystem is one of the most important subsystems in the CubeSat, without which any form of communication to the ground stations is not possible. The COMMS is built by using several COTS components, some of which are space-qualified. Rest of the components have been tested and qualified in the UPC NanoSat Lab for its compliance with the space standards.

The COMMS is responsible for communicating with the ground station. The ground station needs to download data gathered by the 3Cat-1 from the numerous experiments performed. Also, the status of the nano-satellite along with its identifier needs to be constantly transmitted to the Earth for any ground stations to track the CubeSat. The former is performed by the main transceiver while the latter is performed by a beacon. Moreover, in 3Cat-1, there is an extra beacon, which performs a similar function as the normal one, but it is a payload itself, powered by the Peltier cells, and totally independent
from the other subsystems, even the EPS. These signals are then combined using a 3-way-0° power combiner, and then split into a 2-way-90° to create the circular polarisation. These circularly polarised waves are then fed to the baluns and the antennas.

The block diagram of the COMMS is shown in Fig 3.1.

**Figura 3.1: Block Diagram of the Communications Subsystem (COMMS)**

The main transceiver unit, RFC 1100H, consists of a transceiver, CC1101\(^1\) from Texas Instruments, along with the other RF components such as amplifiers and matching circuits. The maximum output power is 33 dBm. The state machine of the transceiver CC1101 needs to be programmed in order to transmit/receive, which is done by the OBC. Besides, the power supply to the transceiver is duty-cycled through a Point of Load (POL), which considerably saves the energy consumption, and only turns on the transceiver when needed.

The beacon data, however, is fed by the EPS, independent of the OBC. It consists of the CubeSat identifier, and the status of the batteries. The voltage is boosted before being fed to the beacon, so that it can transmit at its full power. The Peltier beacon is controlled by the Peltier cells, and consists of the CubeSat identifier and the status of the Peltier cells. While the main transceiver is bidirectional, the beacons are unidirectional.

\(^1\)http://www.ti.com/product/cc1101
3.2 System Requirements

Every subsystem in a CubeSat has to comply with a specific set of standards so that the integration of the subsystems becomes easy. This section explains the various requirements imposed on the COMMS regarding the specifications of the PCB, the system bus, and the antenna deployment. All the boards were designed respecting these standards from the very first design.

3.2.1 PCB Requirements

The PCBs in ³Cat-1 should have the dimensions as shown in Fig 3.2. The PCBs based on this layout can be mounted in the ISIS CubeSat structure (ref. 2.2.5),

![Model PCB Layout in ³Cat-1](image)

**Figura 3.2:** Model PCB Layout in ³Cat-1

The material used in the PCB is FR-4. Even though the properties of this material vary from manufacturer to manufacturer, and from one lot to the other, some of the typical properties for a board from MG Chemicals are given in Table 3.1 [23].

²Relative Permittivity
Taula 3.1: PCB Specifications

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_r$</td>
<td>4.35 @ 500 MHz</td>
</tr>
<tr>
<td>$\tan\delta$</td>
<td>0.016 @ 500 MHz</td>
</tr>
<tr>
<td>Copper thickness</td>
<td>34.1 µm</td>
</tr>
<tr>
<td>Substrate thickness, $d$</td>
<td>1.60 mm</td>
</tr>
</tbody>
</table>

These specifications are required to define the transmission line width so as to have a given characteristic impedance. Microstrip technology is used to transport the RF signal throughout the circuit. As it happens, the PCB can be thought of as a microstrip, where a conducting strip of certain width is separated from the ground plane by a dielectric. Microstrip technology is a popular choice of planar transmission lines because of its ease of fabrication and integration with passive and active RF devices. However, the analysis of the microstrip is complicated due to the fact that the strip on top of the dielectric interacts with the air or vacuum (in space) while also interacting with the dielectric in the bottom. This non-homogeneity in the material interaction leads the electromagnetic waves in the air to travel somewhat differently from the ones in the dielectric. This behaviour is described by the effective dielectric constant, which is the dielectric constant of an equivalent homogenous medium that replaces the air and the dielectric regions of the microstrip [24].

The effective dielectric constant, $\epsilon_e$, is given by

$$\epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \frac{1}{\sqrt{1 + 12d/W}}$$  \hspace{1cm} (3.1)

The characteristic impedance, $Z_0$, of the microstrip line is given by

$$Z_0 = \begin{cases} \frac{60}{\sqrt{\epsilon_e}} \left( \frac{8d}{W} + \frac{W}{4d} \right) & \text{for } W/d \leq 1 \\ \frac{120\pi}{\sqrt{\epsilon_e}} \left( W/d + 1.393 + 0.667 \ln(W/d + 1.444) \right) & \text{for } W/d > 1 \end{cases}$$  \hspace{1cm} (3.2)

For a given $Z_0$ and $\epsilon_r$, the $W/d$ ratio is given by

$$\frac{W}{d} = \begin{cases} \frac{8e^A}{\epsilon_r^2 - 2} & \text{for } W/d < 2 \\ \frac{2}{\pi} \left[ B - 1 - \ln(2B - 1) + \frac{\epsilon_r - 1}{2\epsilon_r} \left\{ \ln(B - 1) + 0.39 - \frac{0.61}{\epsilon_r} \right\} \right] & \text{for } W/d > 2 \end{cases}$$  \hspace{1cm} (3.3)
where,
\[
A = \frac{Z_0}{60} \sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1} \left( 0.23 + \frac{0.11}{\varepsilon_r} \right)
\]
\[
B = \frac{377\pi}{2Z_0\sqrt{\varepsilon_r}}
\]

As an example, in our case, for \(\varepsilon_r = 4.6\), and \(d = 1.58\), we assume that \(W/d < 2\). From (3.4),

\[
A = 1.558
\]

From (3.3),

\[
\frac{W}{d} = 1.848
\]

\[
W = 1.848 \times 1.58 \text{ mm} = 2.92 \text{ mm}
\]

This transmission line width is used throughout the COMMS board to maintain a 50 \(\Omega\) line. However, not only the transmission line width, but also the transmission line length has an important effect on the characteristics of a transmission line. The transmission line length introduces a phase-shift given by (3.5).

\[
\phi = \beta \cdot l = \sqrt{\varepsilon_e} \cdot k_0 \cdot l = \sqrt{\varepsilon_r} \cdot \frac{\omega}{c} \cdot l
\]

A mismatch in the length of two transmission lines leading up to the same node introduces different phases at the node. However, at lower frequency, the effect is minimised. For example, computing \(\varepsilon_e\) from (3.1), at a frequency, \(f\) of 433 MHz, the phase difference induced by a 1 cm long line is only about 9°, while at 2.4 GHz, it is 55°. This gives the flexibility of being able to afford mismatch lines to best suit the layout in the COMMS board. Normally, if this is the case when the antennas are being fed with the waves coming at different phase shift, it affects the radiation pattern. But, in our case, circular polarisation is used, which negates the effect greatly.

The COMMS board is at the top floor of the structure, and it can undergo certain modifications. The most significant modification is the one performed to accommodate the camera peeping out of the CubeSat. To accommodate the camera would require drilling a whole of diameter 15 mm in the bottom right corner of the board.
Chapter 3: Design of the Communications Subsystem

The system bus also needs to be modified since having a full fledged 3×32 connector would hinder the antennas. Therefore, only a 2×8 connector was conceived as being sufficient for the signalling purpose in the COMMS board. The main transceiver unit is going to be attached underneath the COMMS board in such a way that the required signalling for the transceiver (like the SPI interface, power supply) is mapped out in the right-top of the board. The modified board can be seen in Fig 3.5.

3.2.2 System BUS Connector

The signals required to communicate with the COMMS are exchanged through the system bus. As mentioned before, the COMMS doesn’t utilise the full system bus but only requires a 2×8 connector to communicate with the rest of the CubeSat.

The physical system bus connected to the COMMS board is shown in Fig 3.3. The characters outside of the bus in Fig 3.3 is common to the system bus throughout the CubeSat, and are read column- and row-wise while the numbers inside the bus, indicated simply from 1 to 16, are used in the schematic and the layout throughout the COMMS board. The reader might notice the equivalence between these two conventions. For example, A3 is equivalent to BUS-6. The functions of the pins used are given in Table 3.2.

![FIGURA 3.3: System Bus Connector in the COMMS Board](image)

3.2.3 COM Connector

There’s also another connector, which is going to latch onto the main transceiver unit, RFC1101H. The physical connection, simply written as COM, is shown in Fig 3.4.

The pin assignment common to both COM and BUS connectors is given in Table 3.3.
### Table 3.2: System Bus Pin Assignment

<table>
<thead>
<tr>
<th>Pin</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>A5 (BUS-10)</td>
<td>GND</td>
</tr>
<tr>
<td>A4 (BUS-8)</td>
<td>SPI</td>
</tr>
<tr>
<td>B5 (BUS-9)</td>
<td>SPI</td>
</tr>
<tr>
<td>B4 (BUS-7)</td>
<td>SPI</td>
</tr>
<tr>
<td>A3 (BUS-6)</td>
<td>SPI</td>
</tr>
<tr>
<td>B2 (BUS-3)</td>
<td>POL Enable (RFC1100H)</td>
</tr>
<tr>
<td>B6 (BUS-11)</td>
<td>Boost Enable (Beacon)</td>
</tr>
<tr>
<td>A6 (BUS-12)</td>
<td>Beacon Data Input</td>
</tr>
<tr>
<td>A7 (BUS-14)</td>
<td>Data Peltier</td>
</tr>
<tr>
<td>A8 (BUS-16)</td>
<td>GND Peltier</td>
</tr>
<tr>
<td>B7 (BUS-13)</td>
<td>VCC Peltier</td>
</tr>
<tr>
<td>B8 (BUS-15)</td>
<td>Supply Voltage (EPS)</td>
</tr>
<tr>
<td>A1 (BUS-2)</td>
<td>Antenna Deployment Enable</td>
</tr>
</tbody>
</table>

### Figure 3.4: COM Connector in the COMMS Board

### Table 3.3: COM and System BUS Connector Pin Assignment

<table>
<thead>
<tr>
<th>COM Pin</th>
<th>System BUS Pin</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>2, 4, 17, 18</td>
<td>A5 (BUS-10)</td>
<td>GND</td>
</tr>
<tr>
<td>6</td>
<td>A4 (BUS-8)</td>
<td>SPI</td>
</tr>
<tr>
<td>7</td>
<td>B5 (BUS-9)</td>
<td>SPI</td>
</tr>
<tr>
<td>8</td>
<td>B4 (BUS-7)</td>
<td>SPI</td>
</tr>
<tr>
<td>11</td>
<td>A3 (BUS-6)</td>
<td>SPI</td>
</tr>
<tr>
<td>1, 3</td>
<td>x</td>
<td>VCC (5 V)</td>
</tr>
<tr>
<td>5</td>
<td>x</td>
<td>VCC (3.3 V)</td>
</tr>
</tbody>
</table>
Putting these two connectors along with the hole for the camera, the layout, as shown in Fig 3.5, is obtained.

![PCB Layout with Connectors in the COMMS Board](image)

**Figura 3.5: PCB Layout with Connectors in the COMMS Board**

### 3.3 Peltier Beacon

The Peltier beacon is an ASK transmitter capable of transmitting at 433.92 MHz. It transmits the CubeCat identifier, and the status of the Peltier cells to the ground stations. It is totally independent from the rest of the subsystems and it can communicate to the ground station even if the normal beacon and the main transceiver are not working. Hernan Corimaia has been working in the Peltier cells, and has designed the transmitter circuit. It was later integrated in the COMMS board.

The Peltier beacon is based on MAX7044 from Maxim IC. MAX 7044 is a VHF/UHF transmitter, which works from 300 MHz to 450 MHz, providing a maximum output power of 13 dBm at a data rate of upto 100 kbps [25]. The Peltier cells are responsible for generating the power, and feeding the transmitter with the required energy. The data is generated through a microcontroller present in the Peltier cells payload.
The schematic for the beacon is based on the evaluation kit provided with MAX7044 [26]. The schematic of the Peltier beacon, drawn in Eagle CAD\(^3\), is shown in Fig 3.6.

![Peltier Beacon Schematic](https://www.cadsoftusa.com/)

**Figura 3.6: Peltier Beacon Schematic**

The required components are listed in Table 3.4.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Qty</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>1</td>
<td>15pF (0603)</td>
</tr>
<tr>
<td>C2, C6</td>
<td>2</td>
<td>12pF (0603)</td>
</tr>
<tr>
<td>C4, C10</td>
<td>2</td>
<td>0.01µF (0603)</td>
</tr>
<tr>
<td>C11, C12</td>
<td>2</td>
<td>220pF (0603)</td>
</tr>
<tr>
<td>C14, C15</td>
<td>2</td>
<td>12pF (0603)</td>
</tr>
<tr>
<td>L1</td>
<td>1</td>
<td>27nH (0603)</td>
</tr>
<tr>
<td>L3</td>
<td>1</td>
<td>16nH (0603)</td>
</tr>
<tr>
<td>R1</td>
<td>1</td>
<td>5kΩ potentiometer</td>
</tr>
<tr>
<td>U1</td>
<td>1</td>
<td>MAX7044 (8-pin SOT23)</td>
</tr>
<tr>
<td>Y1</td>
<td>1</td>
<td>Crystal, 13.56 MHz</td>
</tr>
</tbody>
</table>

|                      |     | Crystek 017001       |

Because the Peltier circuit has to be independent from the rest of the circuits, its ground plane is separated from the rest of the board. Rest of the signals (VCC, GND and Data) are taken from the system bus.

The PCB layout of the Peltier beacon is shown in Fig 3.7.

\(^3\)http://www.cadsoftusa.com/
3.4 Beacon

The beacon is a continuous wave transmitter sending the most critical data like the CubeSat identifier, and the status of the batteries to earth. With these data, any ground station capable of decoding the ASK signals can detect the presence of Cat-1.

The beacon used in the COMMS board is the WRL-10534 available through Sparkfun [27]. Even though the beacon is compact, it was deemed necessary to replicate the entire beacon circuitry to save space and improve flexibility. Thus, the task fell primarily to one of the students of the PAE group at UPC, Javier Jiménez Gil. It was later integrated in the COMMS board.

3.4.1 WRL-10534

The wireless transmitter, WRL-10534, is a COTS transmitter capable of transmitting at 433.92 MHz. Since the transmitter is compact, and is a simple layout to replicate, it was easier to integrate in the COMMS board.
The transmitter is not a space-qualified device. However, the tests performed in the NanoSat lab showed that it adheres to the space standards, and it surprisingly performed very well in such harsh conditions. The testing is elaborated in Chapter 4. The transmitter is shown in Figs 3.8 and 3.9.

Some of the specifications of the beacon are listed below:

- Frequency: 433.92 MHz
- Modulation: ASK
- Working temperature: -20°C to +85°C
- Output power: 14 dBm
- Supply voltage: 1.5 to 12 V

The beacon is capable of outputting 14 dBm (25.12 mW) output power. Normally, this transmit power is grossly insufficient to travel such large distance (~800 km for a LEO\textsuperscript{4}), and be detected at the ground station with acceptable error probability. But, with the ASK using Morse code, the signal bandwidth is also significantly reduced, and the signal is received as a mid-audio tone, which can be distinguished by the human ear. Because of these reasons, the beacon can actually transmit some data about CubeSat at relatively low power in a high noise environment.

\textsuperscript{4}Low Earth Orbit
However, it was soon discovered that for the beacon to transmit at its maximum power, it would need to be driven at its maximum voltage. The result was verified by Javier, and is given in Table 3.5 [28].

**Table 3.5: Power Consumption of the Beacon**

<table>
<thead>
<tr>
<th>Supply Voltage (V)</th>
<th>DC Current Consumption (mA)</th>
<th>DC Power Consumption (mW)</th>
<th>RF Power Output (mW)</th>
<th>Output Power (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>4.75</td>
<td>14.25</td>
<td>1.74</td>
<td>2.4</td>
</tr>
<tr>
<td>5</td>
<td>7.76</td>
<td>38.8</td>
<td>5.22</td>
<td>7.18</td>
</tr>
<tr>
<td>7</td>
<td>10.7</td>
<td>74.9</td>
<td>9.88</td>
<td>9.95</td>
</tr>
<tr>
<td>9</td>
<td>13.56</td>
<td>122.04</td>
<td>15.85</td>
<td>12</td>
</tr>
<tr>
<td>10</td>
<td>14.88</td>
<td>148.8</td>
<td>21.73</td>
<td>12.8</td>
</tr>
<tr>
<td>11</td>
<td>16.14</td>
<td>177.54</td>
<td>22.13</td>
<td>13.45</td>
</tr>
<tr>
<td>12</td>
<td>17.46</td>
<td>209.52</td>
<td>25.41</td>
<td>14.05</td>
</tr>
</tbody>
</table>

The above result shows that the RF power output is increased for an increase in supply voltage. The DC current and power consumption are also increased as the supply voltage is increased. The result is more intuitively presented with a graph in Fig 3.10.

![RF Power Output of the Beacon](image)

**Figura 3.10: RF Power Output of the Beacon**

The above results led us to consider the idea of having a separate power amplifier for the beacon. Originally, an RFIC amplifier, MGA-30889[^5], from Avago Technologies was selected as it had a 15 dB flat gain, high linearity, and 20 dBm output power at 1 dB gain.

[^5]: http://www.avagotech.com/docs/AV02-2250EN
compression. However, the typical current consumption for the amplifier was around 65 mA, much more than what the power budget of CubeCat could handle as the beacon would need to transmit continuously. Besides, the gain was not substantial once we had the beacon performing at full power as the amplifier showed high non-linearity once the output power exceeded 20 dBm beyond the 1 dB compression point. This reason, coupled with the fact that beacon data could be transmitted at as low the output power as 14 dBm, induced us to go with the stand-alone beacon.

However, it was still required to provide a constant maximum voltage to transmit at the maximum power. Therefore, a charge pump or a boost converter, which could supply a constant 11V to the beacon circuitry, was conceived, and designed with the help of Joan Muñoz working in the EPS (explained in 3.4.2). For safety reasons, the power was boosted to 11V and not to the absolute maximum of 12V.

The schematic of the beacon circuit is given in Fig 3.11. Note that the values of the components are unknown as they are directly taken out from WRL-10534 circuit.

The data input is provided through BUS-12, the voltage supply of 11 V through a boost converter (in 3.4.2), and the beacon output is fed to the power combiner (in 3.6). The 0 Ω resistor was simply added for layout considerations.
3.4.2 Boost Converter

The DC/DC boost converter regulates the output voltage above the input voltage. It is used in the beacon as the boost converter provides maximum voltage to the beacon, which is normally not available from the system bus in the CubeSat. The supply voltage from the EPS can vary from 5 to 10V depending on the battery conditions, the daylight period or the shadow period. Thus, it is important that the output power of the beacon doesn’t vary depending on these environmental effects. Instead, a boost converter is used to regulate the voltage to the beacon, which provides constant power output. Moreover, the converter used is a buck-boost DC/DC converter, LTC3129 from Linear Technology [29]. It has a wide input and output voltage range, which can regulate the output voltage above, below or equal to the input voltage.

The schematic of the boost converter is shown in Fig 3.12.

![Schematic of the Boost Converter: Beacon](image)

The input voltage and the enable are provided by the EPS through BUS-15 and BUS-11 respectively. The enable pin is required to duty-cycle the beacon so that the transmission is controlled by the EPS. The output voltage is then fed to the beacon at a constant 11 V.
The required components are listed in Table 3.6.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Qty</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1B, C2B, C6B, C7B, C8B</td>
<td>5</td>
<td>10(\mu)F, Ceramic (0603)</td>
</tr>
<tr>
<td>C3BT, C9B, C10B</td>
<td>3</td>
<td>10(\mu)F, Tantalum (0603)</td>
</tr>
<tr>
<td>C4B, C5B</td>
<td>2</td>
<td>22nF (0603)</td>
</tr>
<tr>
<td>L1B</td>
<td>1</td>
<td>7(\mu)H (1206)</td>
</tr>
<tr>
<td>R1B</td>
<td>1</td>
<td>8.36M(\Omega) (0805)</td>
</tr>
<tr>
<td>R1B1</td>
<td>1</td>
<td>0(\Omega) (0805)</td>
</tr>
<tr>
<td>R2B</td>
<td>1</td>
<td>1M(\Omega) (0805)</td>
</tr>
<tr>
<td>U3</td>
<td>1</td>
<td>LTC3129 (16-QFN)</td>
</tr>
</tbody>
</table>

A distinction has to be made regarding the 10 \(\mu\)F ceramic and tantalum capacitors. These capacitors are chosen in order to have a balanced frequency response. The ceramic capacitors have good low frequency characteristics, and tantalum ones have good higher frequency characteristics. Also, the capacitors were chosen in parallel instead of using a single capacitor of larger value. The implication of this is that less ripple is seen because the equivalent parasitic resistance of the capacitors in parallel is less than that of a single capacitor, and also these capacitors were the largest available in the market for that size.

### 3.4.3 Beacon PCB Layout

The beacon circuit, in its entirety, consists of both the boost converter as well as the beacon itself. After getting an enable signal from the EPS, the boost converter can supply the required voltage to the beacon. The data to be transmitted is then made available by the EPS through the system bus, and the beacon can modulate the signal, and transmit it through the antenna.

The layout is shown in Fig 3.13. Some modifications had to be done to accommodate the change of sides of the actual beacon.

### 3.5 Main Transceiver

The main transceiver is responsible for establishing the main communication link between the CubeSat and the ground station. The transceiver should be able to transmit at
sufficient power so that the data reaches the ground station with acceptable errors. Also, the transceiver should be efficient as energy is limited in a CubeSat. While it is very difficult to allocate power to other subsystems when the transceiver is transmitting at its full power, the transceiver should consume very less energy while in receive mode, so that it does not constrain the functionality of the other subsystems, and also because the transceiver is more in the receive mode than in the transmit mode. For these reasons, we have selected a transceiver unit, RFC1100H, consisting of a transceiver along with the other RF front end components.

### 3.5.1 RFC1100H

RFC1100H is a transceiver module, which contains a transceiver IC, CC1101 from Texas Instruments, and amplifiers and matching circuits with an RF output of 2 W [13]. The transceiver unit is shown in Fig 3.14.
RFC1100H can operate at 433 MHz at a data rate of 500 kbps. The transceiver CC1101 needs to have its FSM programmed so that it can transmit or receive. The OBC is responsible for controlling the state machine of CC1101, and, therefore, the program resides within the Portux in the OBC. Marc Mari and Joan Francesc Muñoz have successfully programmed the transceiver unit, and integrated and tested it with the OBC.

The pin assignment of RFC1100H is shown in Fig 3.15. This corresponds to the transceiver connector in the COMMS board (named COM) (see Fig 3.4). The transceiver is going to piggy-back into the COMMS board, and it is important that it is correctly connected to the COM connector, and eventually to the BUS connector as well.

The SPI\(^6\) interface is used for the communication between the OBC and the transceiver. For communication via the SPI interface, four pins are required - SI, SO, SCLK and CSn. Apart from these, the power and the ground pins are also required. The ground is connected to the common ground plane, but the power pins (VCC 5 and VCC 3.3) need to be regulated and duty-cycled. This is done in order to protect the transceiver, but

\[^6\text{Serial Peripheral Interface}\]
more importantly, it is done to activate the transceiver only when the communication with the ground station is required. Since, the transceiver requires tremendous amount of power during transmission, its duty-cycling clears up a large burden on the power budget of the whole CubeSat. For this purpose, two Points of Loads (POLs) for two voltage supplies (3.3V and 5V) are designed, and are controlled by the same enabling pin. The 3.3V is required by CC1101 while the 5V is required by the amplifiers and the other active RF components in RFC1100H.

### 3.5.2 Points of Loads (POLs)

The Points of Loads (POLs) supply regulated voltages of 3.3V and 5V to the main transceiver unit, RFC1100H. The POLs are designed around LTC3604 from Linear Technology \[30\]. The LTC3604 is a highly efficient synchronous buck regulator supplying a maximum output current of 2.5A.

The process of data transmission is a highly co-ordinated event among various subsystems like the OBC, the EPS, and the COMMS. They work, in conjunction, to find an optimal time in the orbit, when the ground station is in clear view (OBC), and when there is sufficient power to transmit (EPS). Afterwards, the EPS sends an enable pin to the POLs in the COMMS board while, in the meantime, the OBC starts sending packets of data from its buffer towards the transceiver through the system bus. Thus, the POLs are only activated when there is sufficient power to transmit, and when there is a need for communication.

The POLs have been designed by Joan Muñoz, but the layout has been modified for integration within the COMMS board. Even though both the POLs are similar except some of the resistors, which determine the output voltage, both are presented here for the convenience of the reader. The schematics are shown in the Figs 3.16 and 3.17.

The components lists for both the POLs are given in Table 3.7 and 3.8

The PCB layout with both the POLs can be seen in Fig 3.18. In the figure, both the POLs along with the COM connector and the BUS connector can be seen. The POL in the left is a POL for 5 V, and has its output connected to the port 1 and 3 of the transceiver while the POL in the right is that for 3.3 V. The POLs are made compact.
**Figura 3.16**: Transceiver Point of Load (POL): 3.3V

**Figura 3.17**: Transceiver Point of Load (POL): 5V

**Taula 3.7**: Component List for Point of Load: 3.3V

<table>
<thead>
<tr>
<th>Designation</th>
<th>Qty</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1P, C7P, C8P, C10P, C11P</td>
<td>5</td>
<td>10μF, Ceramic (0603)</td>
</tr>
<tr>
<td>C15P, C16P, C17P, C18P</td>
<td>4</td>
<td>10μF, Ceramic (0603)</td>
</tr>
<tr>
<td>C9P, C12P, C13P</td>
<td>3</td>
<td>10μF, Tantalum (0603)</td>
</tr>
<tr>
<td>C4P</td>
<td>1</td>
<td>10μF, Ceramic (0603)</td>
</tr>
<tr>
<td>C14P</td>
<td>1</td>
<td>22pF, Ceramic (0603)</td>
</tr>
<tr>
<td>L1P</td>
<td>1</td>
<td>4.7μH (1206)</td>
</tr>
<tr>
<td>R1P, R4P</td>
<td>2</td>
<td>100kΩ (0603)</td>
</tr>
<tr>
<td>R2P</td>
<td>1</td>
<td>21.5kΩ (0603)</td>
</tr>
<tr>
<td>R3P</td>
<td>1</td>
<td>160kΩ (0603)</td>
</tr>
<tr>
<td>U1</td>
<td>1</td>
<td>LTC3604 (16-QFN)</td>
</tr>
</tbody>
</table>
Chapter 3: Design of the Communications Subsystem

### Taula 3.8: Component List for Point of Load: 5V

<table>
<thead>
<tr>
<th>Designation</th>
<th>Qty</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1P1, C7P1, C8P1, C10P1, C11P1</td>
<td>5</td>
<td>10μF, Ceramic (0603)</td>
</tr>
<tr>
<td>C15P1, C16P1, C17P1, C18P1</td>
<td>4</td>
<td>10μF, Ceramic (0603)</td>
</tr>
<tr>
<td>C9P1, C12P1, C13P1</td>
<td>3</td>
<td>10μF, Tantalum (0603)</td>
</tr>
<tr>
<td>C4P1</td>
<td>1</td>
<td>10μF, Ceramic (0603)</td>
</tr>
<tr>
<td>C14P1</td>
<td>1</td>
<td>22pF, Ceramic (0603)</td>
</tr>
<tr>
<td>L1P1</td>
<td>1</td>
<td>4.7μH (1206)</td>
</tr>
<tr>
<td>R1P1, R4P1</td>
<td>2</td>
<td>100kΩ (0603)</td>
</tr>
<tr>
<td>R2P1</td>
<td>1</td>
<td>13.3kΩ (0603)</td>
</tr>
<tr>
<td>R3P1</td>
<td>1</td>
<td>160kΩ (0603)</td>
</tr>
<tr>
<td>U2</td>
<td>1</td>
<td>LTC3604 (16-QFN)</td>
</tr>
</tbody>
</table>

To save space, and placed as far away from the RF components as possible to avoid interference.

![PCB Layout of the POLs](image)

**Figura 3.18: PCB Layout of the POLs**

### 3.6 Signal Integration

The signal integration deals with integrating the three different RF signals coming from the beacon, the Peltier beacon and the main transceiver, and later splitting the signals with a 90° phase-shift to create a circular polarisation. At this point, all the trace lines
coming out of the beacons and the transceiver are 50 Ω transmission lines. The transmission lines must adhere to a certain width to maintain this impedance, as explained already in 3.2.1.

A power combiner with high isolation, low insertion loss, and good VSWR was chosen. The power combiner used is SCA-3-11 from Mini-Circuits [31]. The combined signal is then split into two in such a way that a phase-shift of 90° is introduced. The power splitter used, in this case, is QCN-5 from Mini-Circuits [32].

**SCA-3-11**

SCA-3-11 is a surface mount power splitter or combiner working in the wideband from 100 to 940 MHz, shown in Fig 3.19. Its electrical schematic is shown in Fig 3.20.

![SCA-3-11 Package](image1)

![SCA-3-11 Electrical Schematic](image2)

Some important specifications of the power combiner are given in Table 3.9. Table 3.10 shows the pin connections of SCA-3-11.

<table>
<thead>
<tr>
<th>Ratings</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Range</td>
<td>100 - 940 MHz</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-45°C to +85°C</td>
</tr>
<tr>
<td>Power Input (as a splitter)</td>
<td>0.5 W (max)</td>
</tr>
<tr>
<td>Insertion Loss</td>
<td>0.7 dB</td>
</tr>
<tr>
<td>Isolation</td>
<td>20 dB</td>
</tr>
</tbody>
</table>

The insertion loss given is the one above 4.8 dB, which is the ideal splitter loss of a 3-port splitter/combiner. When the SCA-5-11 is being used as a combiner (while transmitting), the combiner will introduce only the insertion loss of 0.7 dB in the transmit chain. For the receive chain, however, the total loss would include the insertion loss above 4.8 dB for a total of 5.24 dB at 446 MHz [31].

These combined signals are then sent to a power splitter, which also introduces a 90° phase-shift. QCN-5 is used as the power splitter.
Table 3.10: Pin Connections of SCA-3-11

<table>
<thead>
<tr>
<th>Designation</th>
<th>Port</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum Port</td>
<td>3</td>
</tr>
<tr>
<td>Port 1</td>
<td>6</td>
</tr>
<tr>
<td>Port 2</td>
<td>8</td>
</tr>
<tr>
<td>Port 3</td>
<td>10</td>
</tr>
<tr>
<td>Ground</td>
<td>1, 2, 4, 5, 7, 9</td>
</tr>
</tbody>
</table>

QCN-5

QCN-5 is a very small surface mount power splitter or combiner working in the frequency band from 330 to 580 MHz, shown in Fig 3.21. Its electrical schematic is shown in Fig 3.22.

![Figura 3.21: QCN-5 Package](image1)

![Figura 3.22: QCN-5 Electrical Schematic](image2)

Some important specifications of the power splitter are given in Table 3.11. Table 3.12 shows the pin connections of QCN-5.

Table 3.11: Specifications of QCN-5

<table>
<thead>
<tr>
<th>Ratings</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Range</td>
<td>330 - 580 MHz</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-55°C to +100°C</td>
</tr>
<tr>
<td>Power Input (as a splitter)</td>
<td>15 W (max)</td>
</tr>
<tr>
<td>Insertion Loss</td>
<td>0.4 dB</td>
</tr>
<tr>
<td>Isolation</td>
<td>22 dB</td>
</tr>
</tbody>
</table>

This power splitter/combiner has a splitter loss of about 3 dB, as is common with 2-port combiner/splitter. With the insertion loss of 0.4 dB, the total loss compounds to about 3.48 dB at 430 MHz [32]. However, while receiving, the splitter loss can be neglected, and the total loss includes only the insertion loss. But, there will be further losses in SCA-3-11.
**Taula 3.12: Pin Connections of QCN-5**

<table>
<thead>
<tr>
<th>Designation</th>
<th>Port</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum Port</td>
<td>1</td>
</tr>
<tr>
<td>Port 1 (0°)</td>
<td>4</td>
</tr>
<tr>
<td>Port 2 (+90°)</td>
<td>6</td>
</tr>
<tr>
<td>Ground</td>
<td>2,5</td>
</tr>
<tr>
<td>50 Ω Term External</td>
<td>3</td>
</tr>
</tbody>
</table>

The split signals can then be fed directly to the antennas.

The schematic of the power combiner and splitter is shown in Fig 3.23.

3.7 Antenna

The signals split from the 2-way-90° power splitter can be fed directly to the two antennas, each radiating at a phase difference of 90° with the other. However, the antenna being used is dipole, or rather a turnstile antenna, which requires a balanced line fed. The coaxial cable is an example of an unbalanced feeder. The conversion from an unbalanced line to a balanced line is required, which is done by baluns.
3.7.1 Balun

Dipoles are balanced antennas, which are best fed with balanced transmission lines. The balanced transmission line has the currents flowing in the conductors with equal amplitude, but 180° out-of-phase, so that the line transfers power without radiating it\textsuperscript{[33]}. If the coaxial cable is used to feed a dipole antenna, it is highly probable that the cable itself will radiate, thus, interfering with the antenna’s radiation pattern since the currents through the arms are not symmetric. To eliminate this problem, we can make use of a \textit{balun}, which in its long form is BALance UNbalance. Therefore, a balun is simply an electrical device that interfaces the unbalanced system with the balanced system, separating the antenna and the feed line, and keeping the feed line from being a part of the antenna.

A lattice-type LC Balun network has been used in the design\textsuperscript{[34]}. It consists of two inductors and two capacitors as shown in Fig 3.24. One branch produces a +90° shift while the other produces a -90° for a total phase difference of 180°.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig3_24.png}
\caption{Schematic of the Lattice-type LC Balun Network}
\end{figure}

The load impedance, $Z_L$, is usually balanced and the input impedance, $Z_1$, is unbalanced. The load impedance, in our case, is of the antenna while the input impedance is taken of the signal coming after being split with a 90° phase-shift.
At the frequency of operation,

$$\omega = 2\pi f$$

$$Z_c = \sqrt{Z_1 \cdot Z_L}$$

$$L = \frac{Z_c}{\omega}$$

$$C = \frac{1}{\omega \cdot Z_c} \quad (3.6)$$

The impedance looking into the balun with the split signal coming is a 50 Ω transmission line, $Z_1$. The load impedance, $Z_L$, depends on the impedance of the monopole. At a frequency of 433.92 MHz, if $Z_L$ is taken as 68.3 Ω, the values of the lumped components, using (3.6), can be computed:

$$\omega = 2\pi 433.92 \times 10^6 = 2.726 \times 10^9$$

$$Z_c = \sqrt{50 \cdot 68.3} = 58.43\Omega$$

$$L = \frac{58.43}{2.726 \times 10^9} = 21.43nH \simeq 22nH$$

$$C = \frac{1}{2.726 \times 10^9 \cdot 58.43} = 6.3pF \simeq 6.8pF$$

### 3.7.2 Design of the Turnstile Antenna

The turnstile antenna combines two orthogonal dipoles, which are fed 90° out-of-phase. This antenna was chosen for 3Cat-1 because of its ability to produce circular polarisation in the direction normal to the dipoles’ plane. Even though the turnstile antenna is made of two orthogonal dipoles, it can also be considered as a combination of four $\lambda/4$ monopole antennas, as shown in Fig 3.25.

**Deployment of the Antenna Arms**

For the design of the antenna, a measuring tape used to measure length is used. It is flexible around bends in a corner, which is useful in the deployment of the antenna. The antenna arms are closed during the CubeSat’s launch by a nylon wire going through the ends of all four antenna arms, and terminating into a low-value resistor. A low-power rating resistor is deliberately chosen, so that when a high current is passed through the resistor, the resistor burns. The nylon wire, attached to the resistor, also burns, and the
antenna arms can freely snap out, and take a proper shape. This flexibility has been made possible by the measuring tape.

The antenna deployment can only initiate after waiting a certain time of being ejected from the P-POD. The EPS is responsible for sending a high current signal to the COMMS to burn the resistor. The signal is sent at BUS-2 from the EPS.

During the design process, the tapes with different blade widths were considered. The wider blade provided a larger bandwidth (see 4.1) but was less flexible. So, a compromise had to be made between the flexibility of the tape and the bandwidth offered.

**Length of the $\lambda/4$ Monopole Antennas**

Having determined the width of the antenna, the length of each monopole arm can be deduced from $\lambda/4$, which for 433.92 MHz, is 17.28 cm. Various tests on the performance of the antenna like the radiation pattern will be discussed in 4.1.

The schematic of the baluns and the antennas is shown in Fig 3.26.
3.8 Final Layout

The final layout of the COMMS board consists of all the components mentioned in the chapter, except RFC1100H. The transceiver module, RFC1100H, is going to be attached to the COMMS board with the COM connector. The final layout is shown in Fig 3.27.
Chapter 3: Design of the Communications Subsystem

3.9 Summary

Chapter 3 has discussed the design of the entire communications subsystem, starting from the system bus connector, which acts as an interface with the rest of the subsystems, to the antenna, which is the very last stage of the whole CubeSat.

The three different signals coming from a data transceiver and two beacons are combined, and sent to earth using a turnstile antenna with circular polarisation. A turnstile antenna, a set of two orthogonal dipoles, is fed 90° out-of-phase to create circular polarisation. The data transceiver is capable of half-duplex communication, while the beacons provide simplex communication. The data transceiver transmits the payload data to the ground station, and is also capable of receiving tele-commands from earth. The beacons simply provide a means of tracking the CubeSat by continuously sending CubeSat identifier and critical satellite data like the status of the batteries.

The communications subsystem is one of the most important subsystems in a CubeSat, the design of which plays an important role in the success of a CubeSat mission. Strict adherence to the standards and the specifications are required in the design. Therefore, the communications subsystem design has been presented in a comprehensive manner to help the reader understand the sophistications and the nuances of the design.

The various tests performed on the communications subsystem will be presented next in Chapter 4.
Capítol 4

Test of the Communications Subsystem

Chapter 4 deals with the various tests performed on the communications subsystem. Every electronic component should undergo different tests before it can roll-out for use. However, with the components meant for space, the tests performed should include the environmental test to observe how they perform in space in addition to the functional test.

In this chapter, the first section deals with the electromagnetic functionality test of the COMMS board followed by an electrical functionality test of the whole system. Finally, the section also discusses about the deployment test of the antennas.

4.1 Electromagnetic Test

The electromagnetic test focusses on the electrical functionality test of the COMMS board. Since the COMMS board consists of RF components and the antenna, it is desirable to see the reflection coefficient at the design frequency. Also, this section includes the tests performed on the antenna, like the antenna pattern and the antenna efficiency.
4.1.1 Reflection Coefficient

When RF power is fed to the antenna, it can radiate the power, reflect it back to the input and/or dissipate it as losses. Reflection coefficient gives a measure of how much power is reflected back to the source, and it corresponds to the scattering parameters (S-parameters). In a two-port network, labelled port 1 and port 2, $S_{11}$ gives the reflection coefficient of the network at port 1, while $S_{22}$ gives the reflection coefficient of the network at port 2. Measurement of the S-parameters can be done with a Vector Network Analyser (VNA). If port 1 is connected to an antenna, and if $S_{11} = 0$, it implies that all the power from port 1 is reflected back from the antenna. If $S_{11} = -10$ dB, and if the input power is 3 dBm, the reflected power is -7 dBm. Normally, a reflection coefficient of -10 dB is specified as a sufficient measure for wireless applications [35].

The reflection coefficient measurement was deemed an important test for the RF circuitry in the COMMS board to see how the circuit behaved with the power combiners/splitters. First, the tests of the different-width monopole antennas were made to assess their viability, and later, the test was made of the whole COMMS board with a port connected to one of the inputs of the power combiner, SCA-3-11.

Reflection coefficient of the monopole antennas

The test of the monopole antennas was done to find out the optimal resonant length, and also to see the differences in the impedance and bandwidth of two monopole antennas with the widths of 6 mm and 12 mm. However, it must be noted that the impedance of the antenna mounted on the COMMS board (which is actually a turnstile antenna) can be drastically different than an ideal monopole antenna with an infinite ground plane. Thus, it is important to match the impedance to that seen in the whole COMMS board rather than to that of the monopole antennas.

The antenna comprises of a monopole and a groundplane. The monopole is mounted on an SMA connector, fed through a 100 mm square groundplane, as shown in Fig 4.1.

The reflection coefficient of both the monopole antennas is shown in Fig 4.2.

It can be seen that both the monopole antennas have reflection coefficient below -13 dB at the design frequency. The narrower monopole has a narrower bandwidth than the wider one.
Chapter 4: Test of the Communications Subsystem

**Figure 4.1:** Monopole Antennas Test

**Figure 4.2:** Reflection Coefficient of the Monopole Antennas
Also, the impedance of the monopole antennas can be computed from the measured reflection coefficient. The real and imaginary components of the impedances are shown in Figs 4.3 and 4.4.

The impedances of the monopole antennas match closely to the theoretical impedance of an ideal monopole antenna, $36.5 + j21.25 \, \Omega$. On close examination, however, the impedance increases slightly for the wider antenna. The resonant length of the monopole antenna is irrelevant in the final circuit as other circuit elements and the structure of the CubeSat also affect the resonance. A safe approach is to start from the theoretical
length of $\lambda/4$, and then increase or decrease the length of all arms of the antenna to properly tune at the design frequency. For the experiment, the length of the monopole was fixed at 16.55 mm.

Based on the above comparisons, both the monopole antennas have similar performance with regard to the impedance and bandwidth. Thus, it comes down to the radiation pattern, and the structural stability in the antenna deployment mechanism to decide which one is suitable for $3^\text{rd}$ Cat-1.

**Reflection coefficient of the COMMS board**

The initial untuned result was obtained for the given length of each monopole (17.32 cm), as shown in Fig 4.5.

![Reflection Coefficient](image)

**Figura 4.5:** Untuned Reflection Coefficient

Fig 4.5 shows that the antenna is not tuned exactly at the design frequency. With a proper tuning of the antenna (cutting the length of all the monopoles so the wavelength is shortened and the frequency is increased), a minimum value can be obtained at the design frequency, as shown in Fig 4.6.

The above result was obtained for a monopole length of 17 cm. If a reflection coefficient of -10 dB is considered acceptable, the antenna has a bandwidth of 70 MHz from 390 MHz to 460 MHz.
4.1.2 Antenna Radiation Pattern

The radiation pattern of an antenna is a graphical representation of the variation of the field radiated by the antenna as a function of spherical coordinates $\theta$ and $\phi$ [36]. The field patterns can be represented either in three-dimensional spherical coordinates or in plane cuts (as in $xz$ or $yz$ and $xy$ planes).

An antenna has two fields - a reactive field, characterised by the standing waves representing the stored energy, and a radiation field, characterised by the radiating waves representing transmitted energy. The reactive component of the antenna impedance creates the reactive field while the resistive component of the antenna impedance creates the radiation field. The field region of interest is the far-field (Fraunhofer) region, which is the region farthest away, where the field distribution is independent of the distance from the antenna.

The radiation pattern is useful in the determination of the circular polarisation inherent in the turnstile antenna.

Radiation patterns of the monopole antenna

The radiation patterns of the monopole and dipole antennas are interrelated. Physically, a monopole antenna is half the length of the dipole antenna, and, thus, has half the impedance. Also, the monopole antenna is twice as much directive [37].

A model of the monopole antenna was simulated in Ansoft HFSS. The elevation radiation pattern of the monopole antenna of widths 6 mm and 12 mm is constant for all $\phi =$
−180° to 180° and is shown, for \( \phi = 0° \), in Figs 4.7 and 4.8. The radiation patterns for both the monopoles are similar. However, the radiation pattern of the monopole antenna deviates from an ideal monopole antenna because of the effect of having a finite ground plane. A ground plane of 80 cm × 80 cm was considered in the model.

The azimuthal radiation pattern (\( \theta = 0° \)) is omnidirectional for both the monopoles.

Radiation pattern of the turnstile antenna

The radiation pattern of a turnstile antenna is different from that of the monopole antennas, as the turnstile antenna, being two orthogonal dipole antennas, introduces circular polarization. The antenna was mounted in the ISIS CubeSat structure as shown in Fig 4.9. The radiation pattern was measured in the anechoic chamber of the AntennaLab at UPC (Fig 4.10).

The radiation patterns of the turnstile antenna are shown in Figs 4.11 and 4.12.
Fig 4.11 shows the radiation pattern cut for $\phi = 0^\circ$. The blue and the red patterns are co-polar and the cross-polar cuts respectively. The co-polar and the cross-polar directions are orthogonal to each other. It can be noted from the pattern that, at any certain degree, the antenna is always radiating, even if it is only at co-polar or cross-polar direction.

Similarly, Fig 4.12 shows the radiation pattern cut for $\phi = 90^\circ$. The advantage of circular polarisation is that the ground station antenna is able to pick up the signal transmitted from the CubeSat, irrespective of the alignment of the antenna in space. If the CubeSat was transmitting with a linear polarisation, the ground station antenna or the CubeSat would need to be appropriately aligned for the communication to take place. If there is a polarisation mismatch in a linearly polarised antenna, the losses would amount to infinite. For a Right Hand Circular Polarisation (RHCP), there will always be a 3 dB loss if the receiving antenna has either horizontal or vertical polarisation. This is because the signals have to be split equally into two with a phase difference of $90^\circ$ to create circular polarisation.

### 4.2 Electrical Test

The electrical test focuses on the functionalities of several modules in the COMMS board like the Points of Loads, beacons etc. Some of these modules were fabricated separately to
measure the output signal, which would otherwise not be possible in the final integrated board.

**Points of Loads (POLs)**
The design of the Points of Loads (POLs) has already been discussed in Section 3.5.2. The POLs should provide an output close to 5V and 3.3V for the main transceiver unit, RFC1100H, to operate. The POLs are enabled by the EPS. The only parameters of interest are the voltage output of the POLs even when the supply voltage is oscillating. When the supply voltage was varied from 5V to 14V, the outputs of the two POLs were 5.1V and 3.39V. However, the second POL outputting 3.3V was not performing properly in the final integrated board because of the fabrication issues.

**Boost converter**
The boost converter is used to supply a constant voltage of 11V to the beacon. This voltage is necessary for the beacon to transmit at the highest power possible. The output of the boost converter is tested and found to be 10.86V, for $R_1 = 8.25 \, \text{M}\Omega$ and $R_2 = 1 \, \text{M}\Omega$.

**Peltier Beacon**
The Peltier beacon circuit was fabricated as an independent module, and the RF output was connected to a VNA to measure the reflection coefficient and the impedance.

The reflection coefficient is shown in Fig 4.13.

![Reflection Coefficient of the Peltier Beacon](image.png)

**Figura 4.13**: Reflection Coefficient of the Peltier Beacon
The Peltier beacon has a reflection of -16 dB at 432.5 MHz. The impedance is then computed from the reflection coefficient at the given frequency, and is shown in Fig 4.14.

At 432.5 MHz, the impedance is $67.73 + j1.846\Omega$. This value of impedance can be used to design an impedance matching network.

In order to reduce the loading effect on the rest of the circuits, it’s preferred to match the impedance to the $50\Omega$ line.

**Beacon**

The beacon circuit was also fabricated as an independent module. Its RF output was connected to a VNA to measure the reflection coefficient and the impedance.

The reflection coefficient is shown in Fig 4.15.

The beacon has a reflection of -10.5 dB at 433.2 MHz. The impedance is then computed from the reflection coefficient at the given frequency, and is shown in Fig 4.16.

The impedance at 433.2 MHz is $29.44 - j12.43\Omega$.

**Transceiver**

The transceiver module used is RFC1100H. It is an independent module developed by NewMsgTech\(^1\), consisting of CC1101 transceiver from Texas Instruments. The RF output of the module was connected to a VNA to measure its reflection coefficient and impedance.

\(^1\)http://www.rfinchina.com
The reflection coefficient is shown in Fig 4.17.

The beacon has a reflection of -23.7 dB at 434.6 MHz. The impedance is then computed from the reflection coefficient at the given frequency, and is shown in Fig 4.18.

The impedance at 434.6 MHz is $56.71 + j1.869\Omega$. An impedance matching network can be devised from this measurement to maximise power transfer. The SMA connectors can be appended in the COMMS board at three input feeds to measure how the structure is affecting the impedance in whole, and then design the impedance matching network based on that. This design has been discussed as future works in Section 5.2. The RFC1100H, however, was heating up when connected to the OBC. A better method to effectively sink the heat dissipating from the transceiver is required.
4.3 Antenna Deployment Test

The antenna needs to be deployed after being launched from the LV as the antenna protrudes outside the CubeSat structure. The CubeSat standard specifies that the antenna needs to be wrapped around the structure in whatever way possible in order for the structure to fit snugly in the P-POD. Therefore, the four ends of the antenna are tied by the nylon strings that pass through a resistor which burns once the current is passed through it.

The control circuit is designed in the EPS board. Once the CubeSat is launched from the LV, a timer activates the control circuit, and the resistor is burned, melting the nylon string, and springing the antenna arms free in space. A through-hole film resistor of
10 Ω and power rating 0.25 W was chosen. When a voltage of 6 V is passed across the terminals of the resistor, a current of 0.6 A is passed through it dissipating a power of 3.6 W. Since the resistor can only handle a power of 0.25 W, it gets burned, thus, melting the nylon wire, and freeing the antenna arms.

The antenna deployment before and after the resistor is burned is shown in Figs 4.19 and 4.20.

![Figure 4.19: Antenna Before Deployment](image1)

![Figure 4.20: Antenna After Deployment](image2)
Chapter 4: Test of the Communications Subsystem

4.4 Summary

Chapter 4 focused on the tests performed on the communications subsystem. The electromagnetic and the functional tests on different modules as well as the entire COMMS board were performed and discussed in the chapter. For space applications, it is also important to have the environmental tests to ascertain the device's functionality in the harsh space environment. Because the final integrated board didn't have all the modules working perfectly, the environmental tests had to be skipped.

The tests were performed on the two beacons as well as the transceiver. The beacons in the COMMS board were tested with the ground station, and the data, sent in the form of pulses, were successfully received. However, for the electromagnetic test, the beacons had to be tested with a model designed independently from the board. While the tests made on the board provide more accurate results, the tests performed on the individual modules also give sufficient performance characteristics. The results can then be utilised to improve the design of the impedance matching network.

The radiation pattern of the antenna showed that the antenna had a circular polarisation, ideal for the satellite applications. The beacons were successfully tested with the COMMS board, and the data were received in the ground station even with different orientation of the antenna.

This chapter concludes the work completed in the course of this master thesis. Chapter 5 provides the conclusions, and the future works to be done in the project.
Capítol 5

Conclusions and Future Work

The chapter concludes the thesis, and suggests some future works to improve the communications subsystem.

5.1 Conclusions

The purpose of this thesis was to design a communications subsystem of ³Cat-1, a CubeSat from UPC. The works undertaken in this thesis aim to establish a communication link between the CubeSat and the ground stations, using beacons to communicate the status of the nano-satellite, and a transceiver to transfer payloads data, and tele-commands. The subsystem was designed around UHF band (434 MHz) with a power combiner combining three different input signals, and then splitting the combined signal off with a 90° phase-shift before finally feeding them to a turnstile antenna to create circular polarisation.

The frequency band of choice was made taking into account the link budget and different regulations pertaining to this band. Sticking to a single frequency band simplified the design of antenna and the RF components. Also, the UHF band was found to be the choice of operation for most amateur satellite operators.

A CubeSat system interacts with several subsystems to operate effectively. The relation of these various subsystems with the COMMS has also been described in detail. The Peltier beacon, however, only needs to interact with the Peltier cells to operate, while
the other modules in the COMMS board are reliant on the EPS, the OBC and/or the payloads.

The design of the communications subsystem was based on the various specifications like power, and structural requirements of the CubeSat program. The mission requirements state that the COMMS should be as reliable as possible, and satisfy the low-cost and low-power constraints. With the use of the COTS components, the design was made feasible, achieving both the reliability and the flexibility offered by the COTS transceiver and the components.

The tests were also performed on the COMMS. The different modules of the COMMS board were working perfectly. The transmission test of the beacons with the ground station was also successful in the final integrated board even with different orientation of the antenna. However, the test was not successful with the transceiver in the final COMMS board mainly because of the overheating issues, even though it was possible to communicate with a different OBC. Because of the issues with some of the components, a full space environmental test was not possible.

The design had some issues with the fabrication, which can be solved by fabricating the board in a fabrication house. The design can still be improved with a better matching network to improve the power transfer among various modules. For a later design, the transceiver unit RFC1100H can also be integrated in the final design to save space and improve flexibility.

5.2 Future Works

While every attempt to make the design as final as possible was made during the project, there were still some things that needed improvement or the design had to be changed to accommodate the change in the specifications. Also, since the design is scalable in similar projects or even in other applications, a need to recommend some improvements or changes in the design was felt.

One of the improvements can be made in the design of the impedance matching network to improve the power transfer, and negate for the losses inherent in the RF front-end. Since the impedance offered by each of the three input feeds has been computed, the
matching network can be easily designed. For the next CubeSats, it seems logical to include the transceiver as well to the final board, which at the moment is piggybacking on the COMMS board as an independent module (RFC1100H from NewMsgTech).

### 5.2.1 Impedance Matching Network

The three RF inputs present different impedance to the COMMS board. If the input impedance is not matched to the impedance of the COMMS board, there will be reflections, and there will be more power loss. Therefore, it is important to design an impedance matching network.

Since there are three inputs, SMA connectors are placed next to the inputs in the test board. There are two test connectors in each of the two inputs of the beacon so as to measure the impedance looking towards the beacons and the impedance looking towards the COMMS board. It is shown in Fig 5.1. Note that the inputs are terminated with a 50 Ω resistor when they are not being used for measuring the impedance.

![COMMS Test Board](image)

**Figure 5.1:** COMMS Test Board

For the transceiver, the test can be done already, as the module is independent from the COMMS board. An impedance matching network was designed for the transceiver and
the COMMS board and simulated in ADS \(^1\). The schematic of the network is shown in Fig 5.2.

![Schematic of the Impedance Matching Network in ADS](image)

**Figura 5.2: Schematic of the Impedance Matching Network in ADS**

The output of the transceiver is connected to the impedance matching network. The impedance seen at the output of the impedance matching network should be the complex conjugate of the impedance seen at the input of the COMMS board. The impedances at these two ports are shown in Figs 5.3 and 5.4. The impedance at Port 1 is \(77.7 + j8.065\) \(\Omega\) while that at Port 2 is \(77.47 - j8.328\) \(\Omega\).

![Z-Parameter at Port 1 after matched impedance](image)

**Figura 5.3: Z-Parameter at Port 1 after matched impedance**

\(^1\)Agilent ADS
5.2.2 Integration of RFC1100H in the COMMS Board

The transceiver unit used in 3Cat-1 is a highly reliable, power-efficient transceiver unit, capable of transmitting up to +33 dBm of RF power. The unit consists of all the components of a RF front-end and is also complicated to design. However, Nil Vernis from PAE-CubeSat group was successful in reverse-engineering the transceiver.

The challenge is to integrate this board with the COMMS board. Since the COMMS board is only a 2-layer board with both the high speed digital circuitry as well as RF
circuitry, it is bound to create interference. Besides, there will be a lack of space to integrate the transceiver circuit in the COMMS board. Therefore, the COMMS board needs to be redesigned as a 4-layer board with power planes for both 5V and 3.3V, as well as the EPS supply voltage. This will create uniform power and ground planes. Also, the digital circuitry can be highly isolated from the RF circuitry, thus, minimising the interference. This work has been proposed for the future CubeSat project.
Apêndice A

COMMS Board

The top and bottom layers of the COMMS PCB are shown in Figs A.1 and A.2.

Figura A.1: Top Layer of the COMMS Board

Figura A.2: Bottom Layer of the COMMS Board

The schematic of the entire COMMS board is shown in Fig A.3.
Figura A.3: Schematic of the COMMS Board
Bibliografía


