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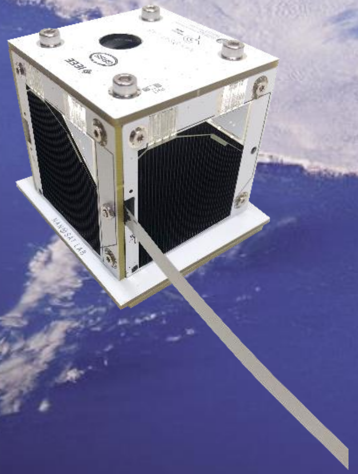


Design and Implementation of a Communications System for a PocketQube based on LoRa

DEGREE THESIS

Author: Daniel Herencia Ruiz

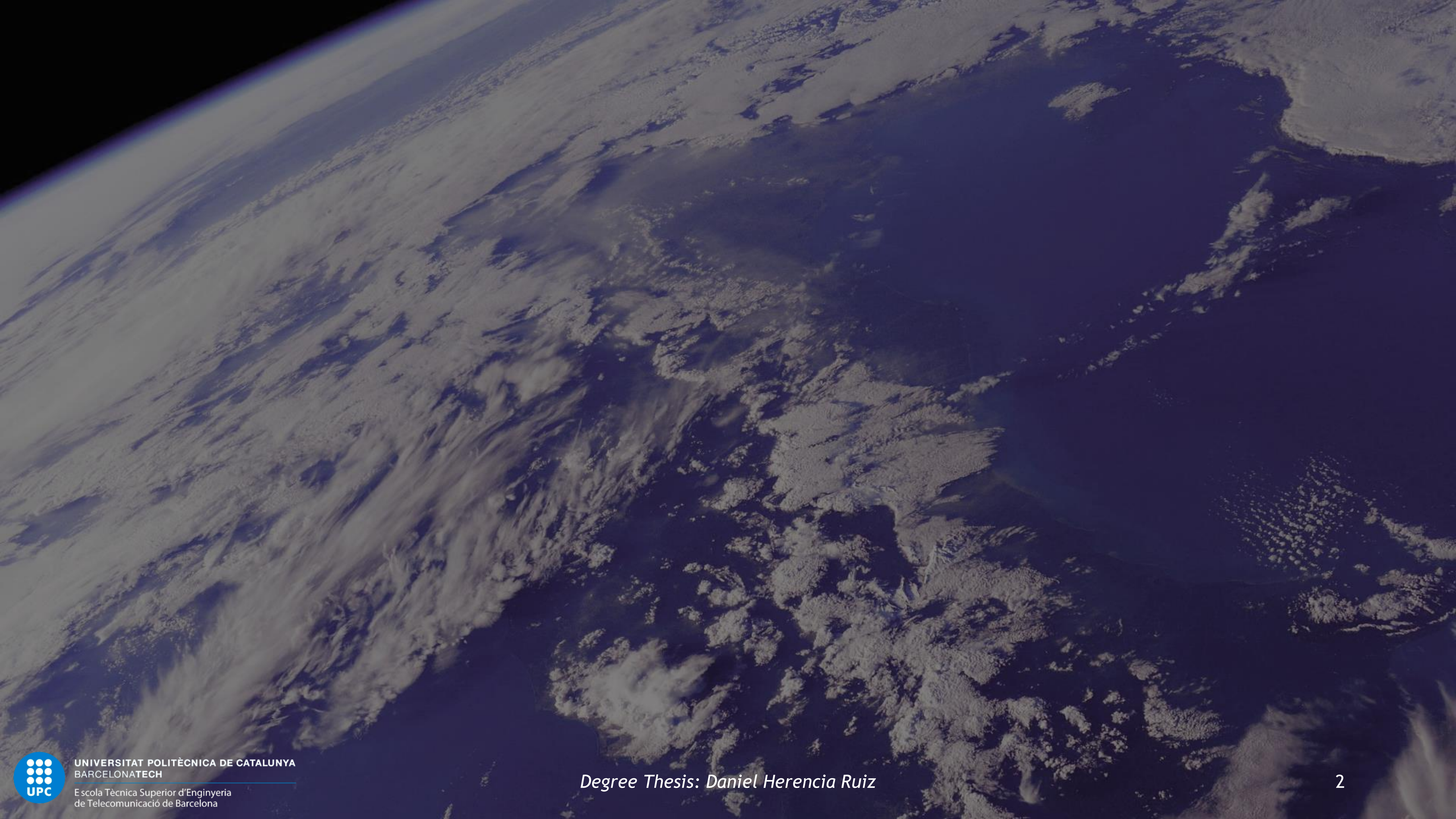
Advisor: Dr. Adriano Camps Carmona

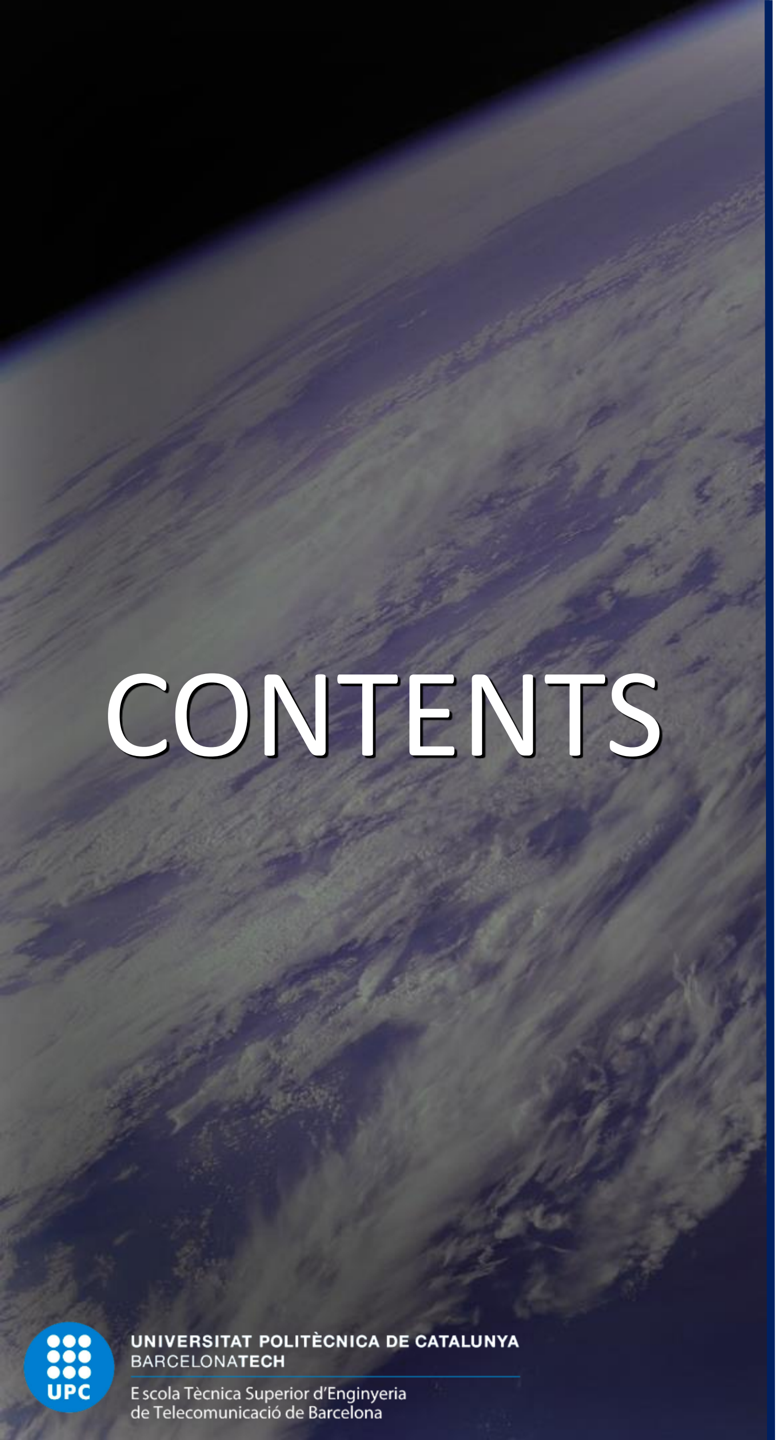
Degree: Telecommunications Technologies and Services Engineering

July 2022

telecos BCN

NANOSAT LAB





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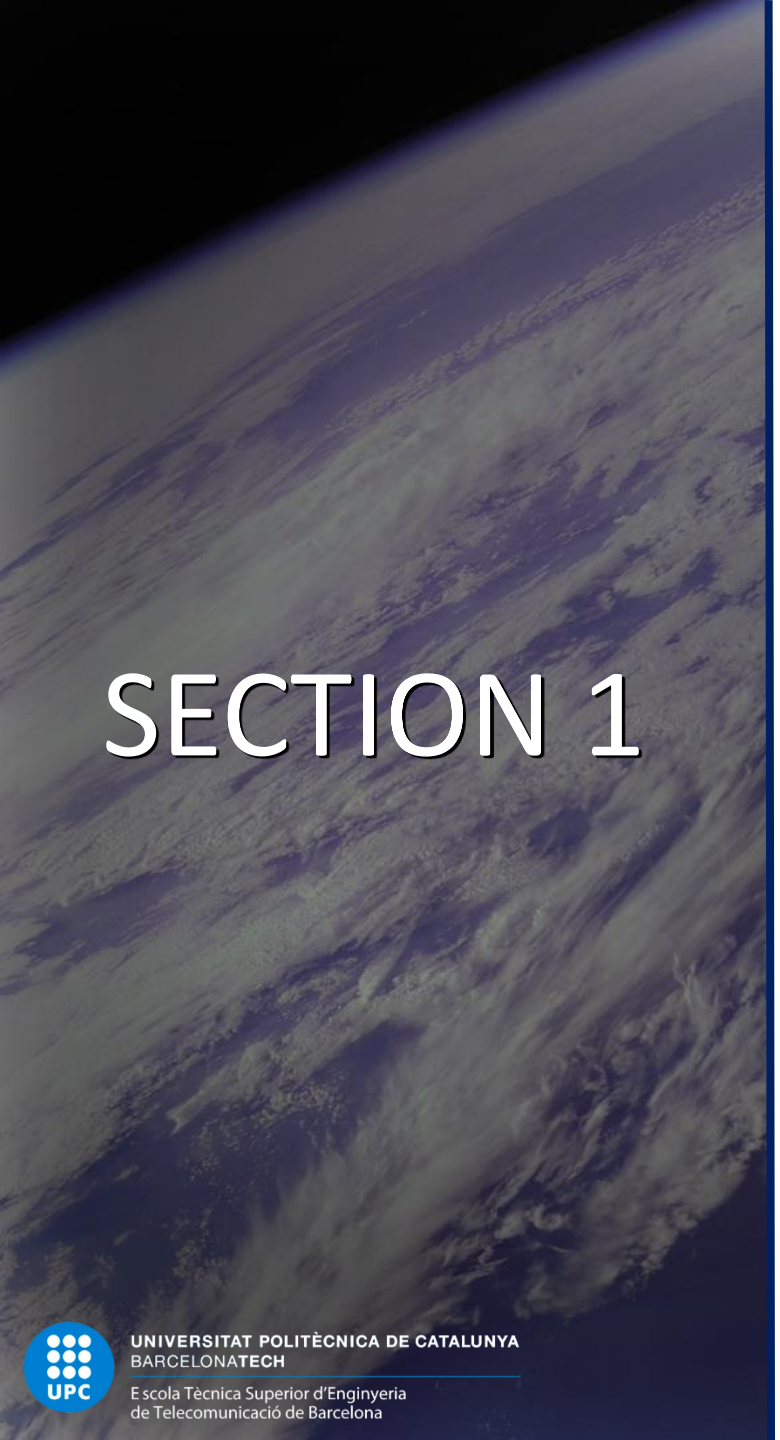
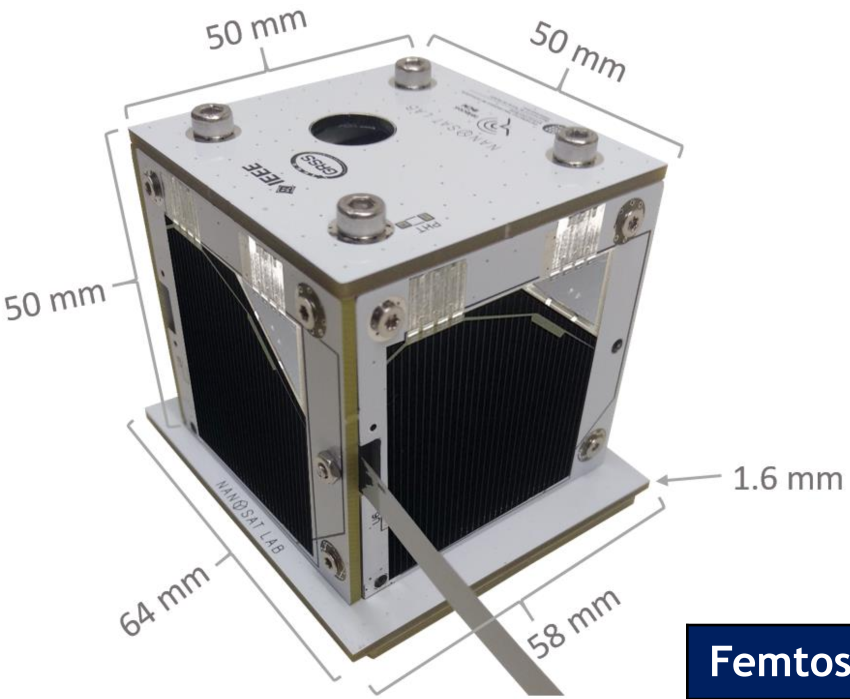
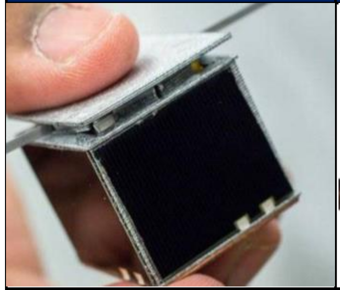
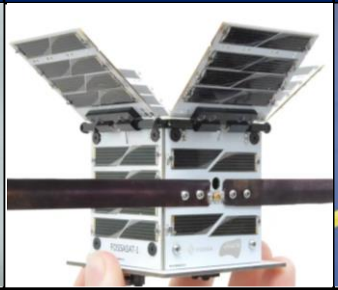
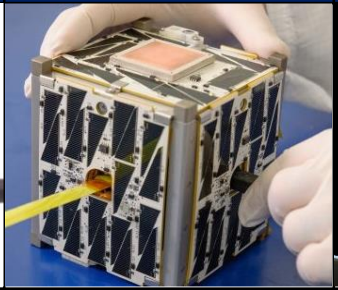
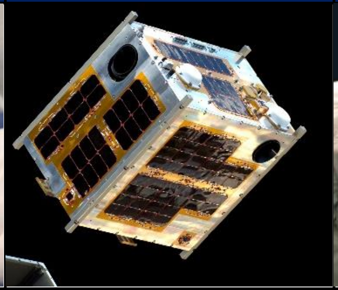


1. **Introduction**
   1.1. **PocketQube**
   1.2. **^{Po}CAT**
2. Objectives
3. System design and test
4. Protocol and Software
5. Link and data budget
6. Conclusions

1.1. PocketQube

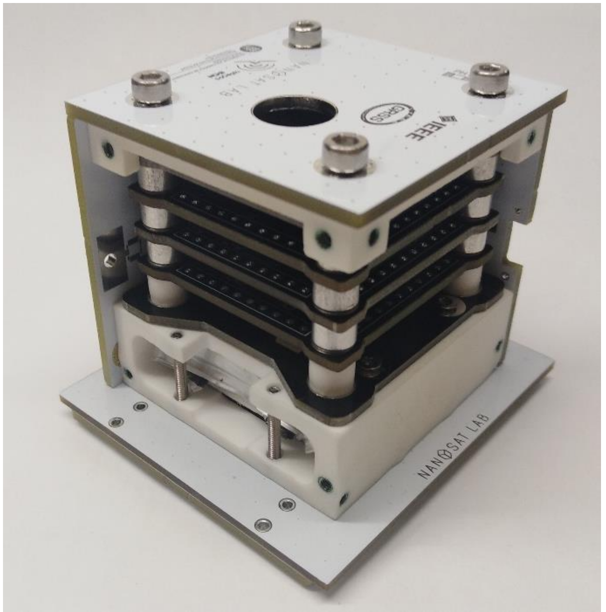


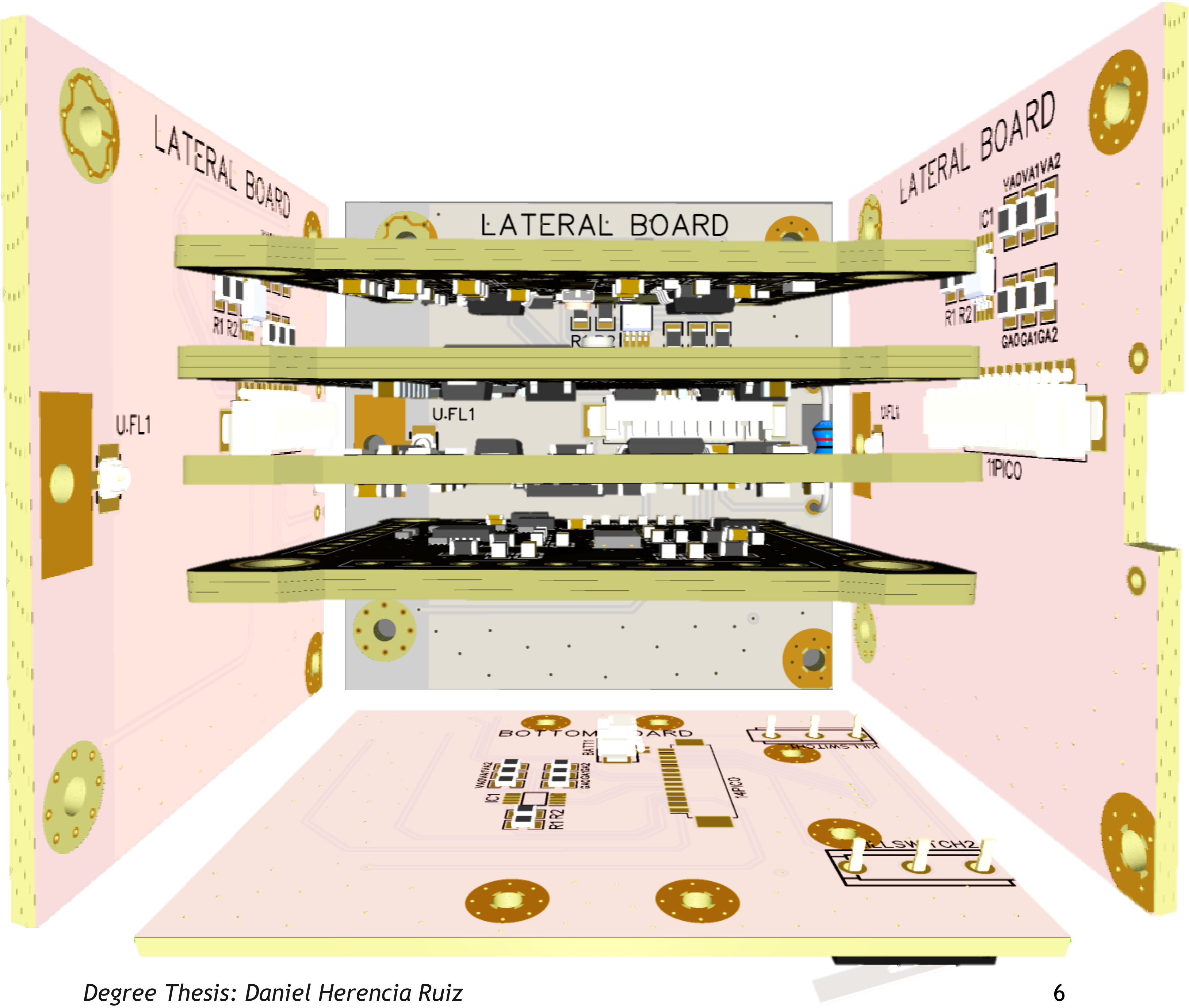
- **Picosatellites**
- **Proposed by:** Robert J. Twiggs in 2009
- **COTS components**
- **First launch:** November 2014
- **Standard 2018:**
  - 50x50x50 mm
  - Max. 10 mm envelope for deployables
  - Max. 250 g mass

Femtosatellite	Picosatellite	Nanosatellite	Microsatellite	Mini satellite
				
10 – 100 g	0.1 – 1 kg	1 – 10 kg	10 – 100 kg	100 – 1000 kg

1.2. PoCAT

- 3 PocketQubes
- Same design, different payload



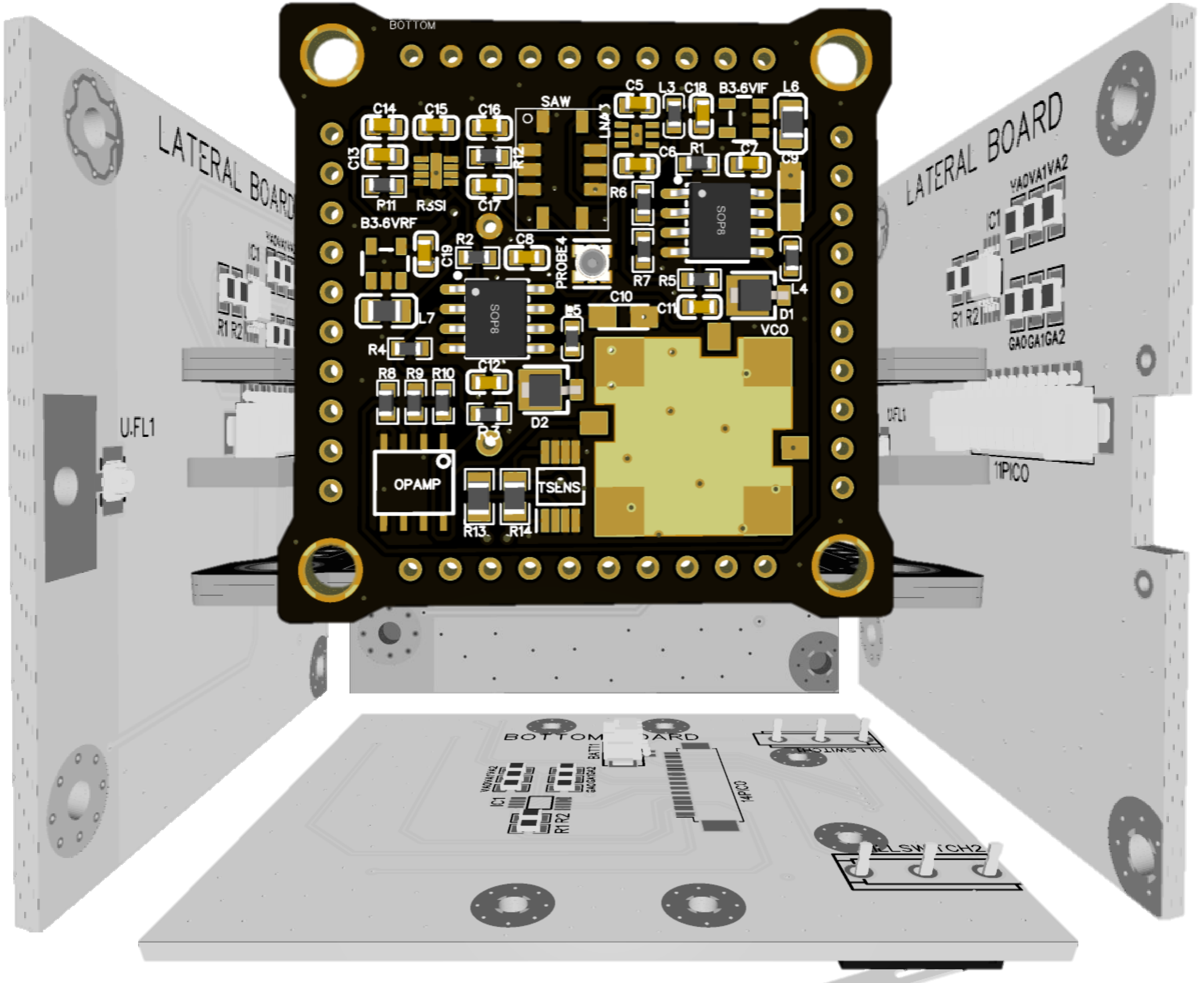


1.2. PoCAT

PAYLOAD:

- Defines the specific purpose of the satellite

- PoCAT-1: Camera
- PoCAT-2: RFI monitoring receiver [1,2] GHz
- PoCAT-3: RFI detector in 5G band ~24 GHz



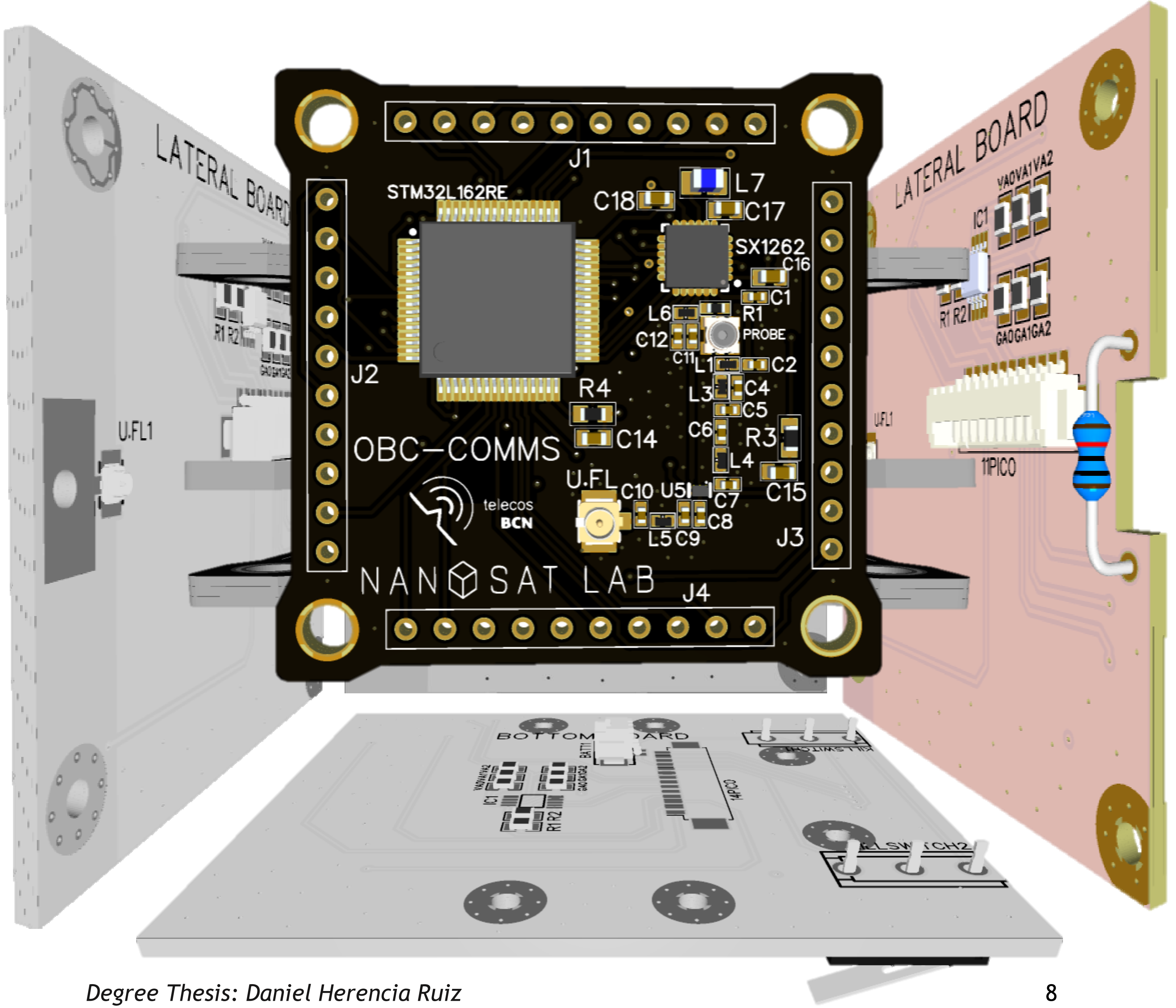
1.2. PoCAT

OBC:

- Controls and gives orders to the other subsystems

COMMS:

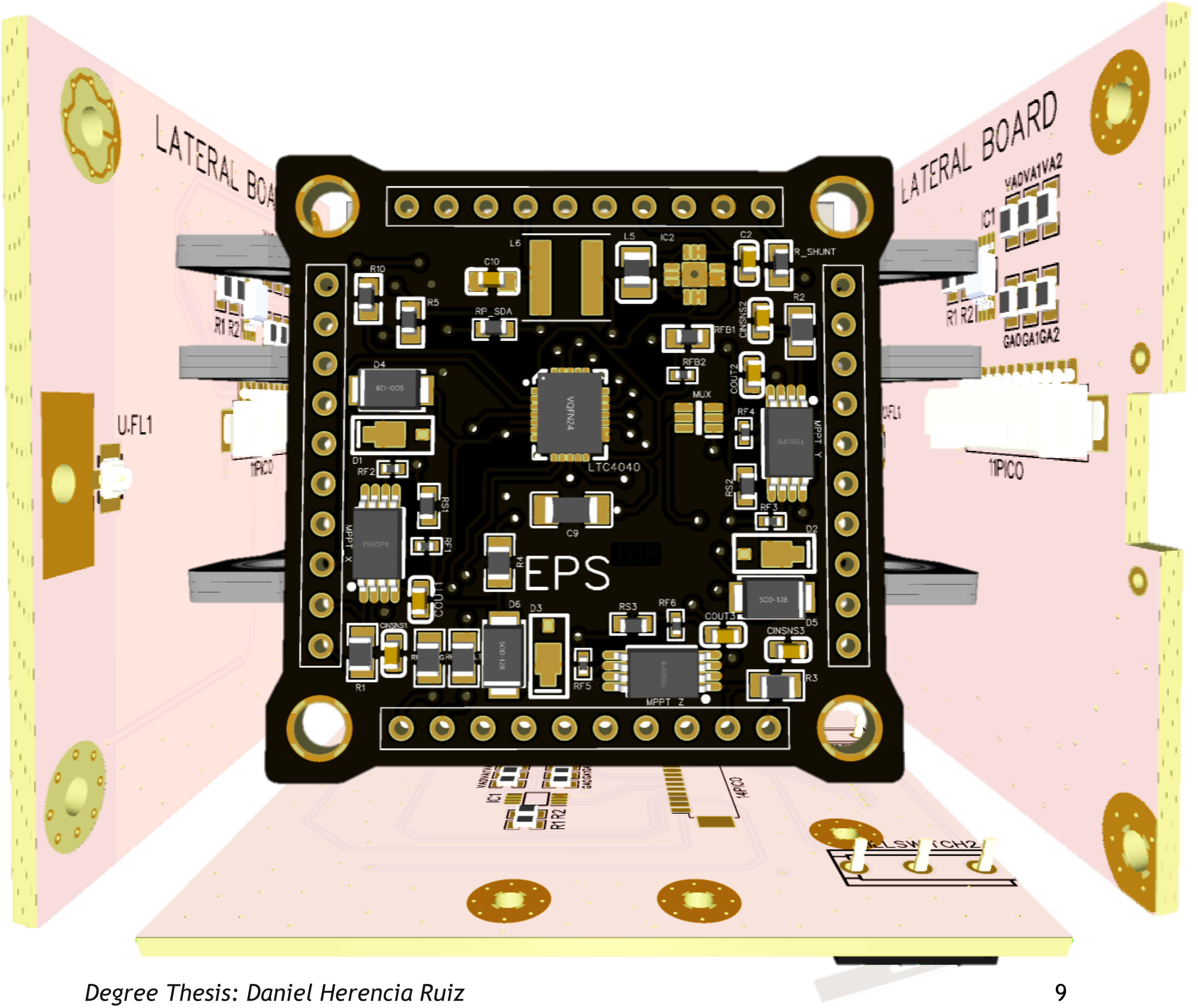
- Communicates the satellite with the Ground Station



1.2. PoCAT

EPS:

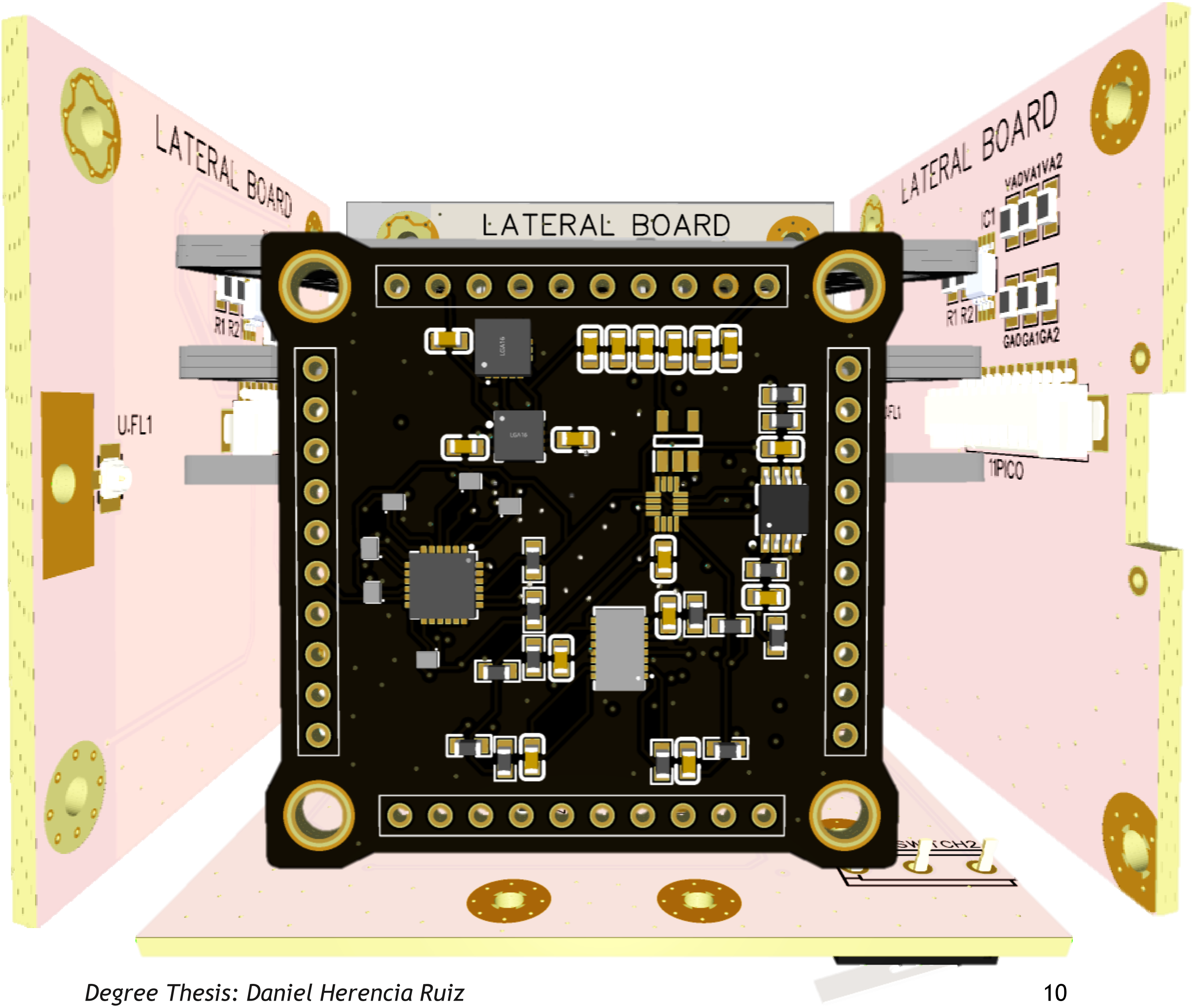
- Generates power with solar cells
- Stores it in the battery
- Distributes power to all subsystems

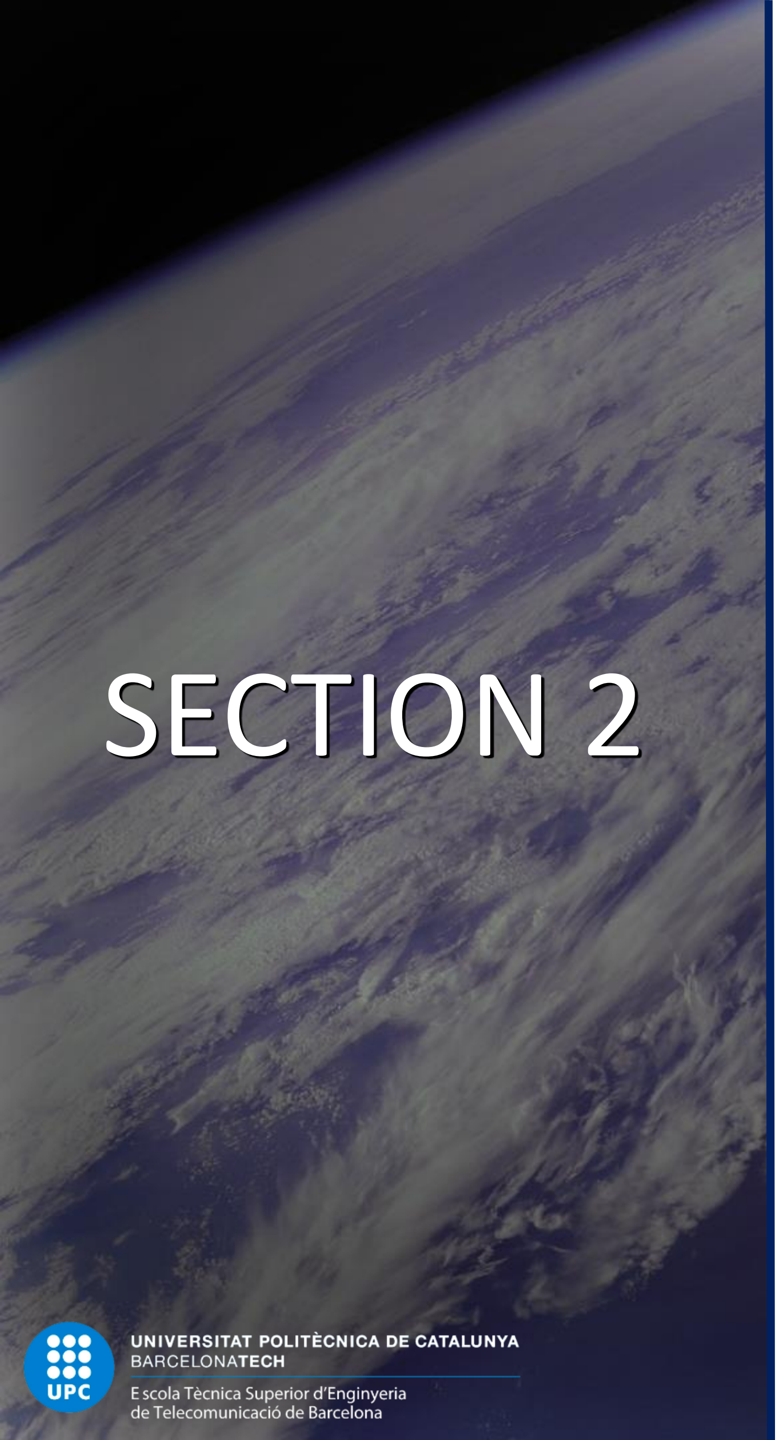


1.2. PocCAT

ADCS:

- Stabilizes rotation
- Determines attitude
- Points the satellite using coils printed in lateral PCBs





SECTION 2

1. Introduction
2. **Objectives**
3. System design and test
4. Protocol and Software
5. Link and data budget
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2. Objectives

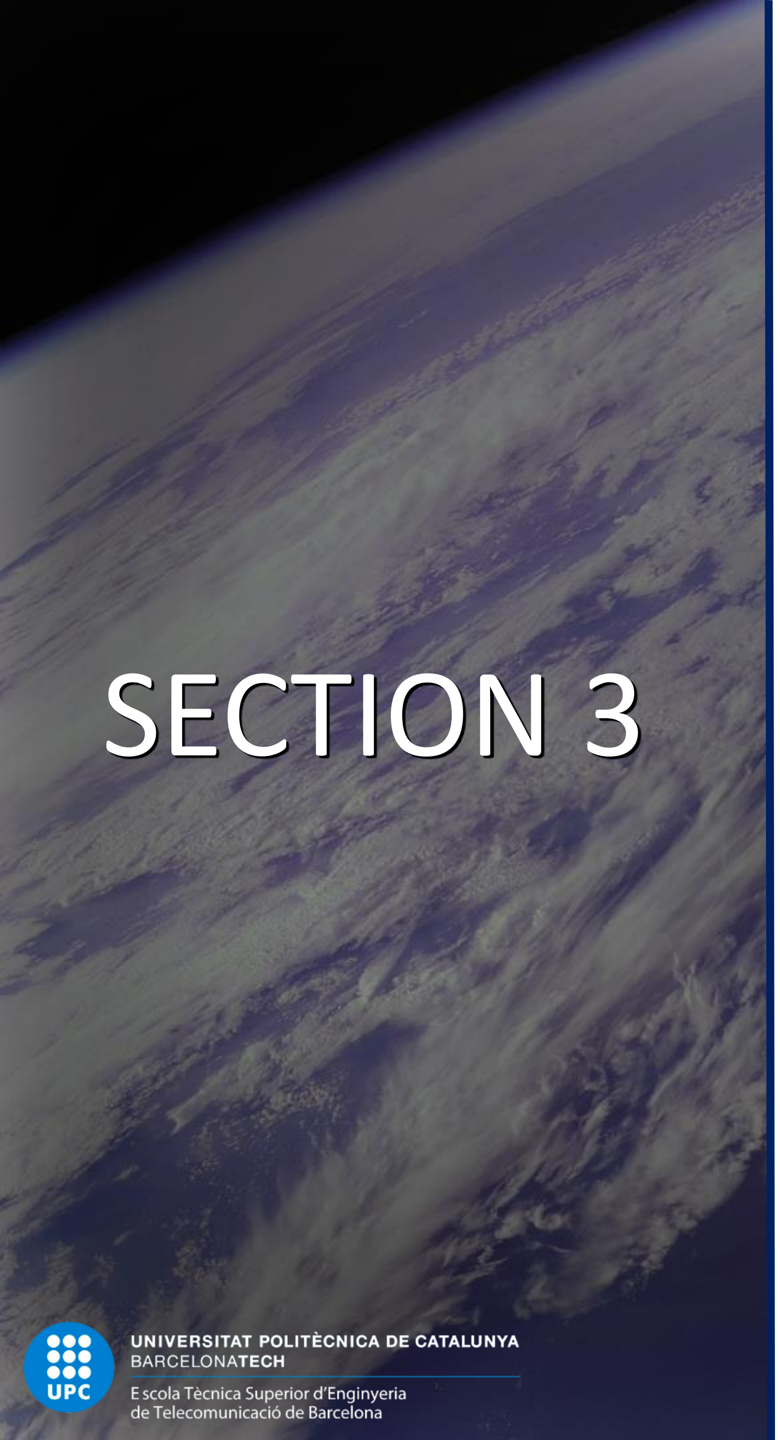
Main objective

Design, assembly and testing of a complete communications system for a PocketQube:

- Antenna, transceiver and circuit
- Protocol and software
- Link Budget

Requirements

- **M-COMMS-0010:** Send the satellite information to the GS
- **M-COMMS-0020:** Receive orders from the GS
- **S-COMMS-0030:** Low-power and long-range communications
- **S-COMMS-0040:** Antenna deployed once in orbit
- **S-COMMS-0050:** Link budget establishes when to exchange information
- **S-COMMS-0060:** Maximize the bit rate
- **S-COMMS-0070:** Minimize transmission errors


SECTION 3
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3.1. LoRa

	LoRa	NB-IoT	sigfox
Bandwidth (kHz)	10.4, 125, 250, 500	200	0.1
Modulation	CSS	QPSK	BPSK
Bit rate (kbps)	27	250	0.6
Delay tolerant	✓	✗	✓
Doppler compensation	✓	Complex	Complex
Frequency Band	ISM	LTE	ISM

3.2. Antenna Design: antenna selection

Specifications

- LoRa Europe ISM band: 868 MHz
- Antenna foldable that not exceeds the limits
- Wide beam width

Monopole

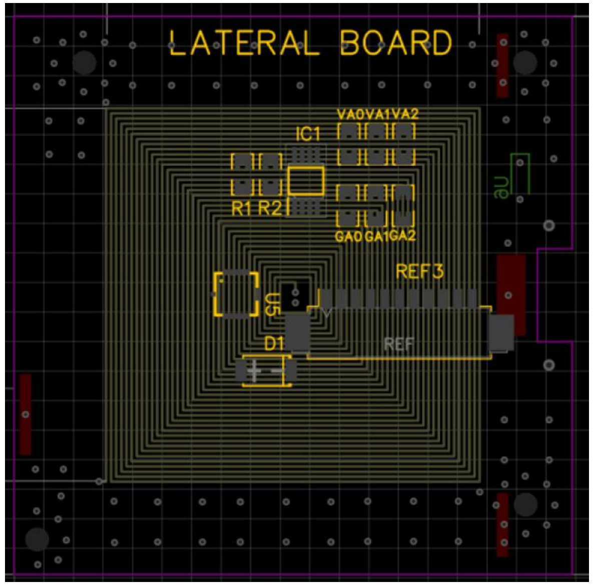
- **Unbalanced:** direct connection with coaxial
- One element (dipole has two)
- One hole to exit the lateral PCB

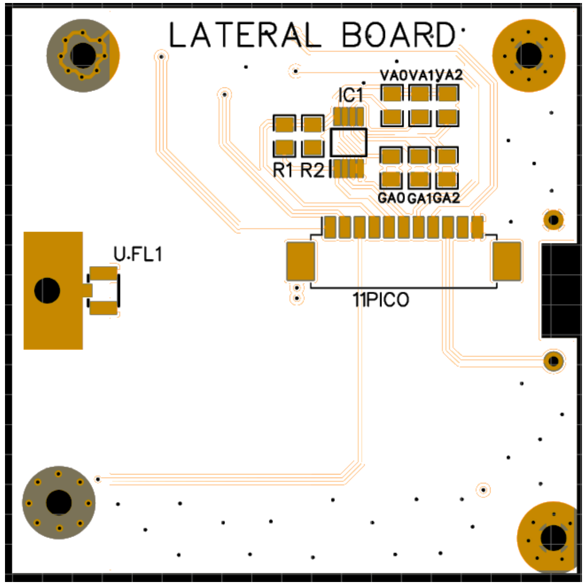
	Size	Foldable	Gain / Directivity	θ_{3dB}
Wire antenna	Medium	✔	Small	High
Aperture	Big	✘	Medium	Medium
Microstrip	Big	✘	Medium	High
Reflector	Big	Complex	High	Small
Array	Big	Complex	High	Small

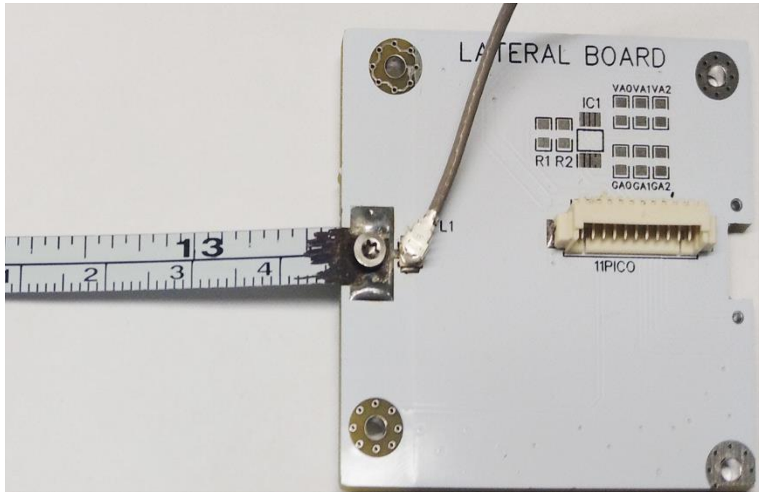
3.2. Antenna Design

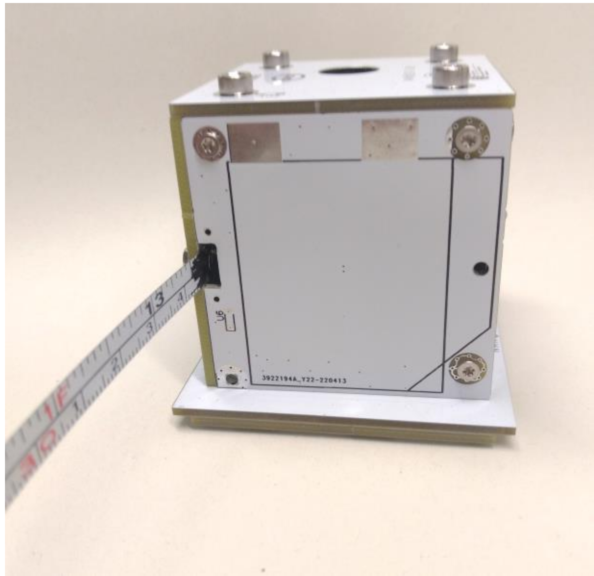
LATERAL PCB

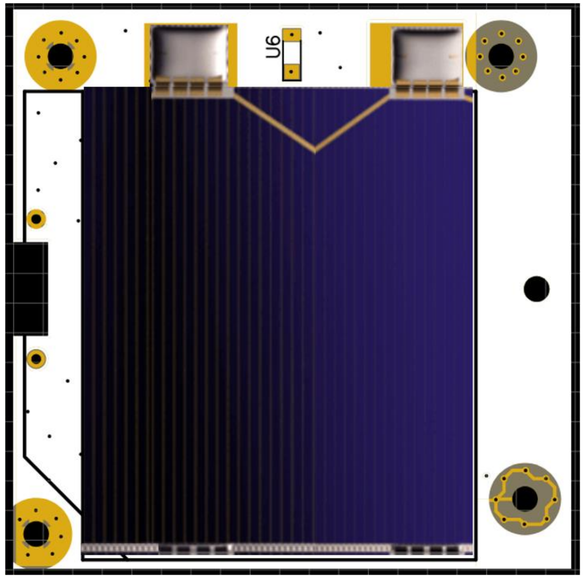
- Half ground plane of 5 cm
- Solar cells and ADCS coils act as GND
- Area to weld the antenna and hole to screw it
- Antenna made with tape measure







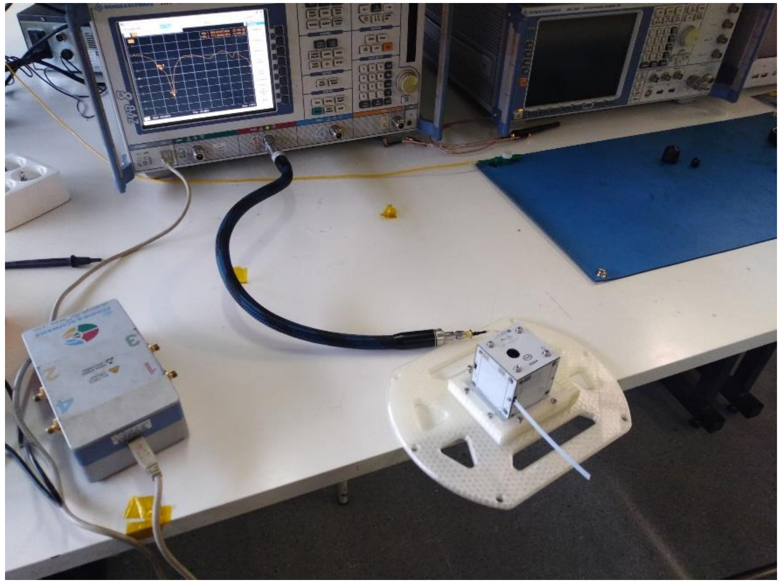


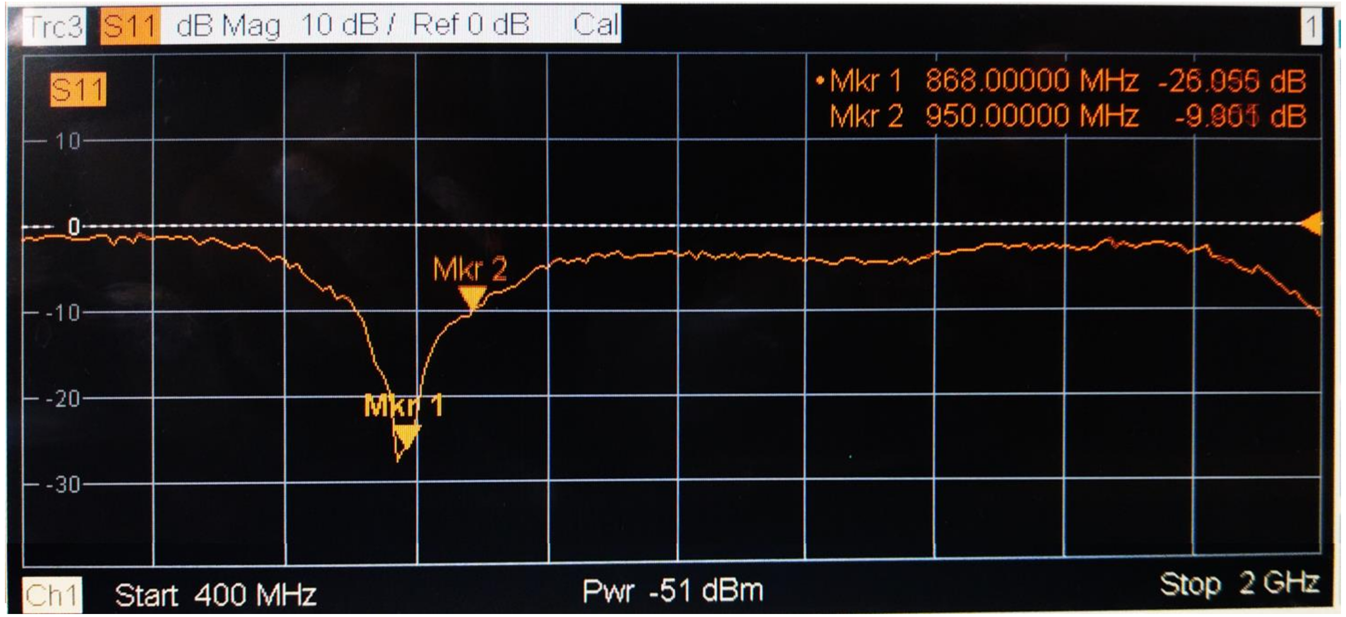


3.2. Antenna Design

MATCHING

- Return losses measured with the VNA (-26 dB)
- Place the peak at 868 MHz
- 8.6 cm above the ground plane

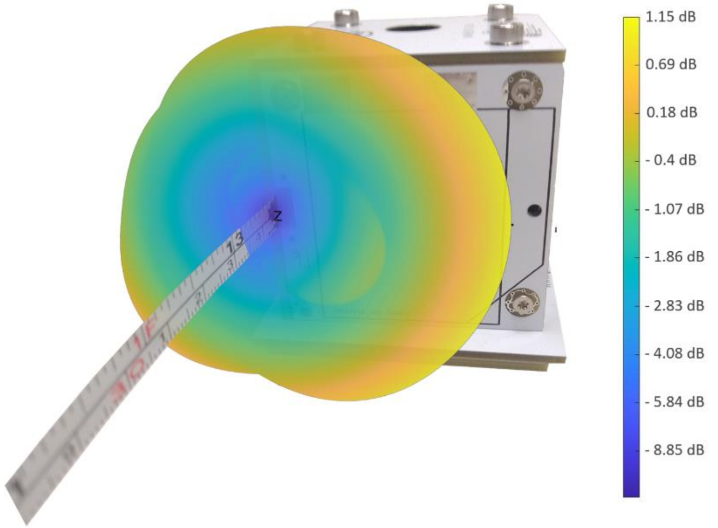


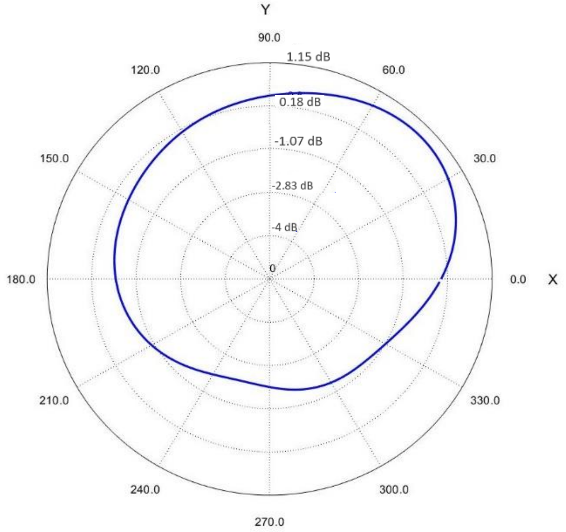


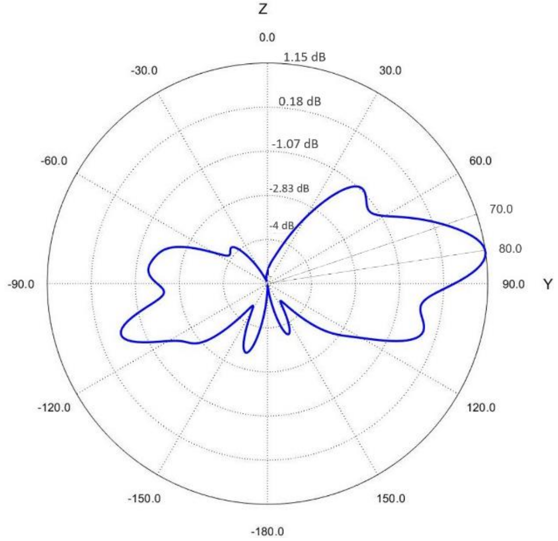
3.2. Antenna Design

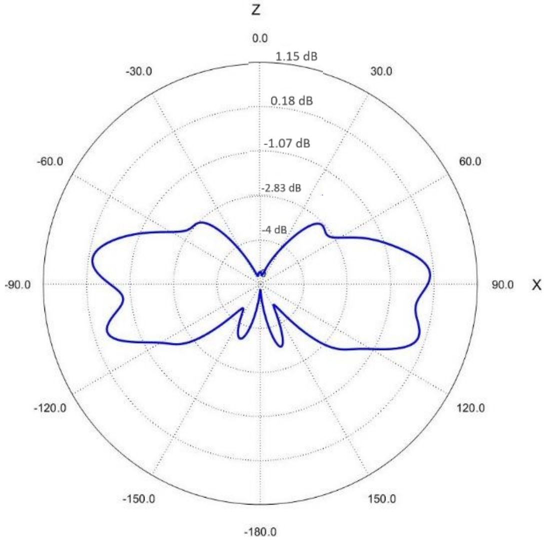
RADIATION PATTERN

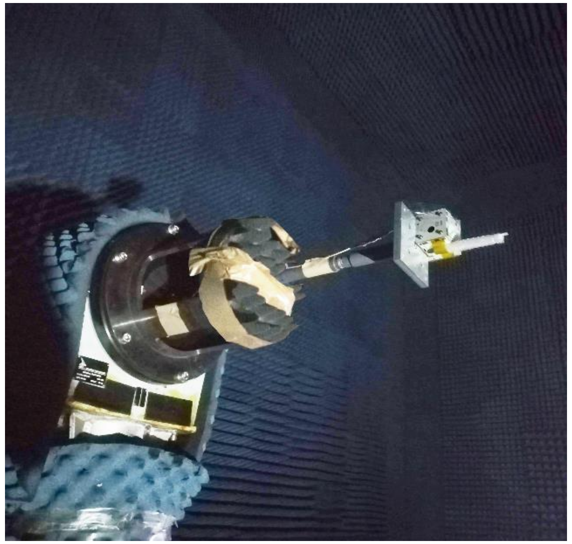
- **Maximum Gain:** 1.15 dB
- **Directivity:** 3.115 dB
- $\boldsymbol{\theta_{-3dB}}$: 60º











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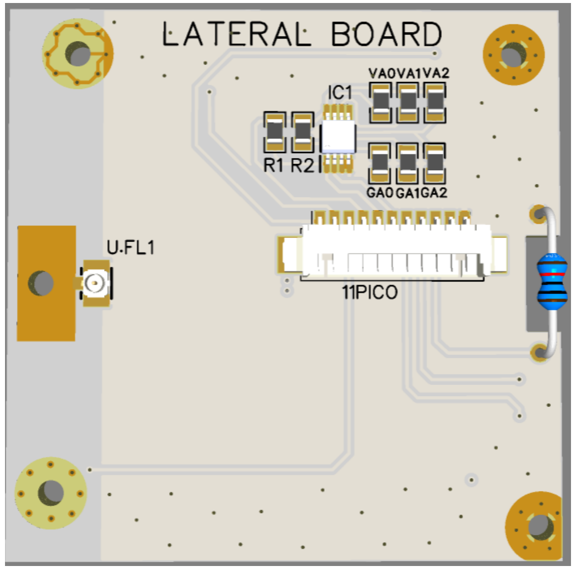
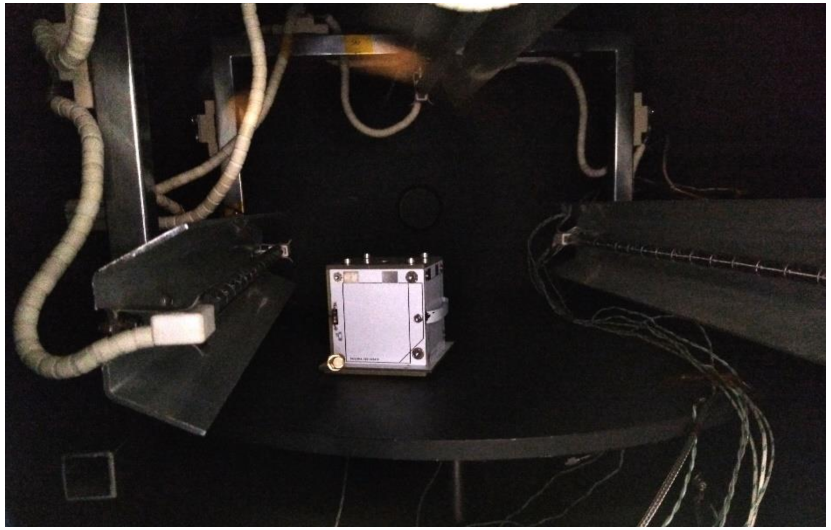


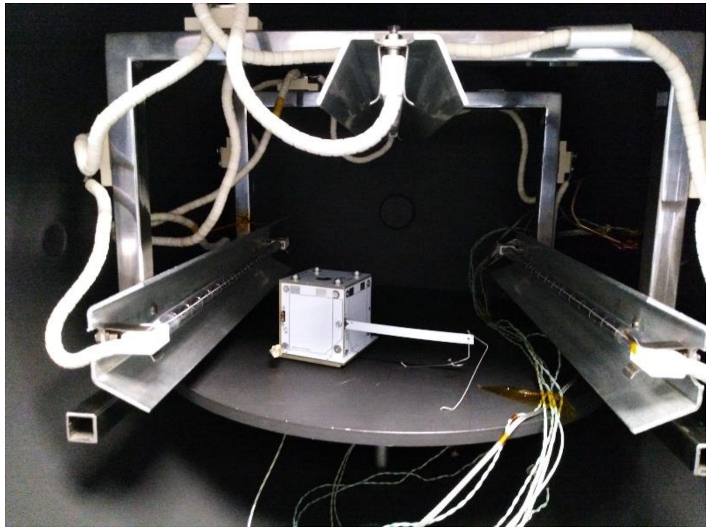
DEPLOYMENT MECHANISM

- Antenna tied with dyneema wire
- THT resistor burns the wire
- OBC controls the current with a switch

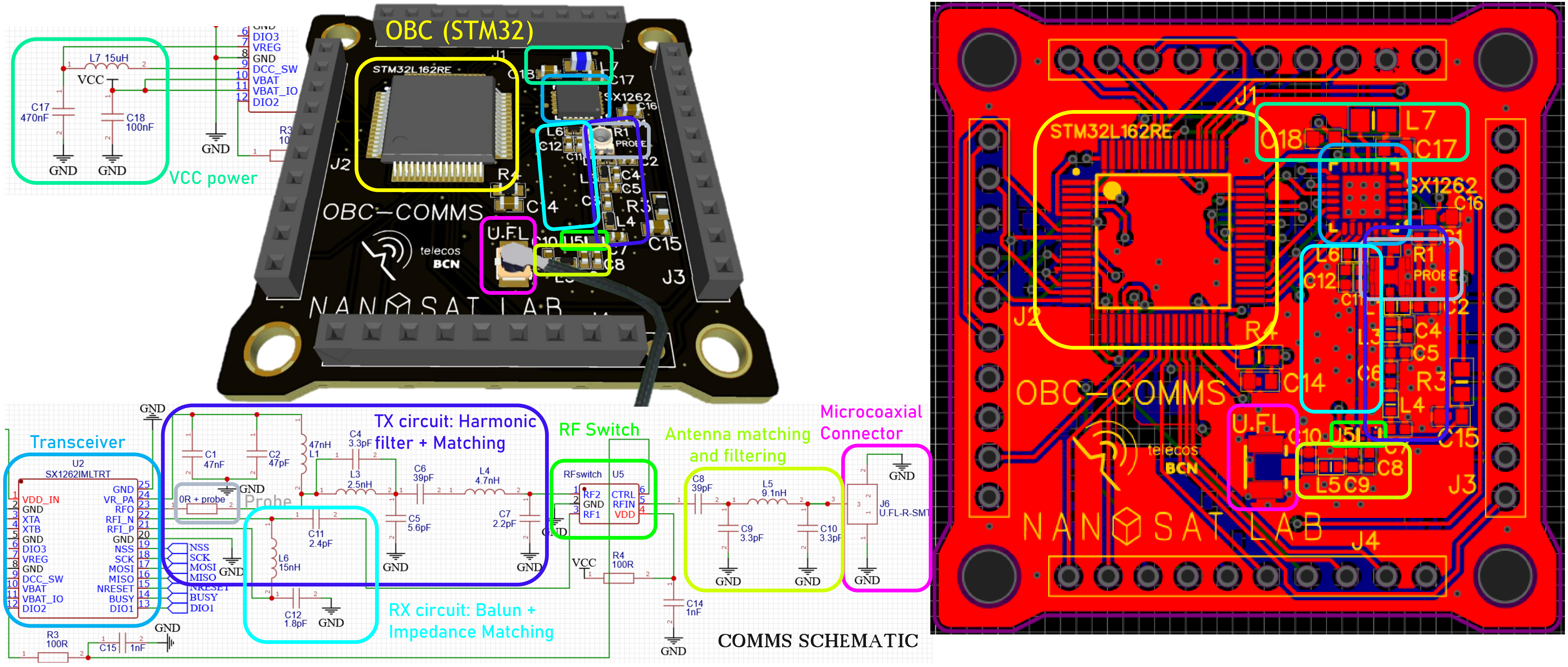
TVAC TEST

- $R = 7.5\ \Omega$
- $I_{max} = 0.57\ A \quad V = 3.3\ V$
- $t = 5\ s$

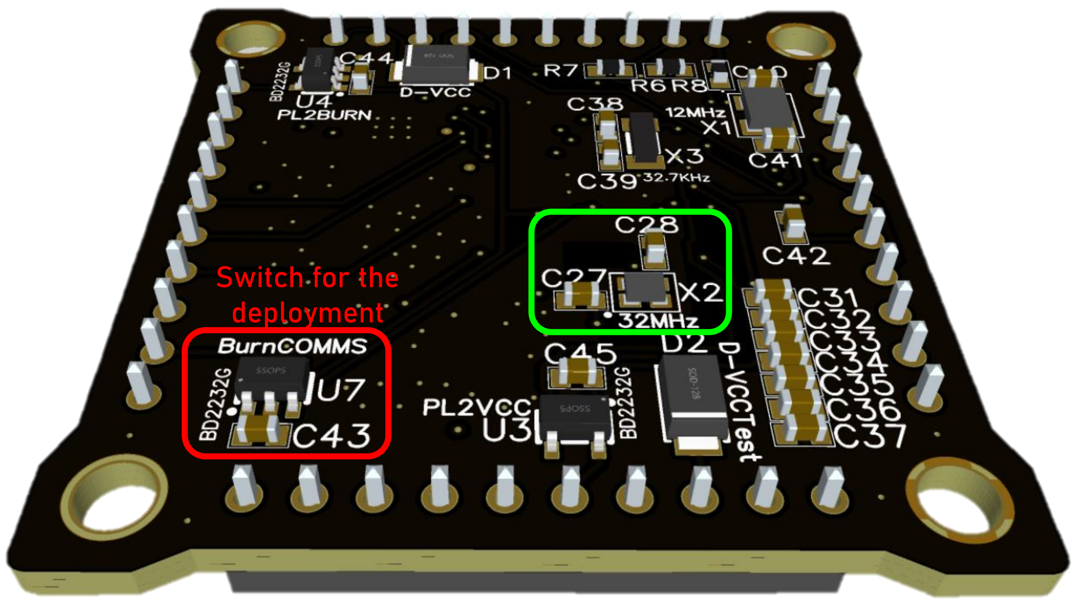


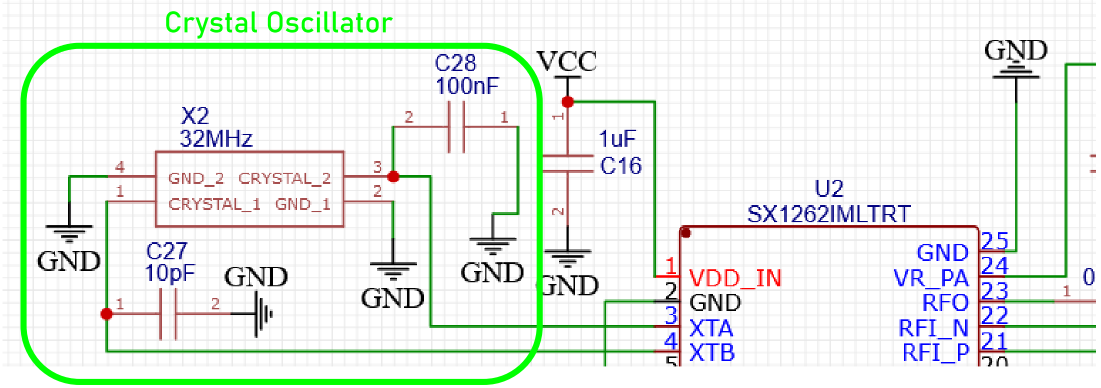


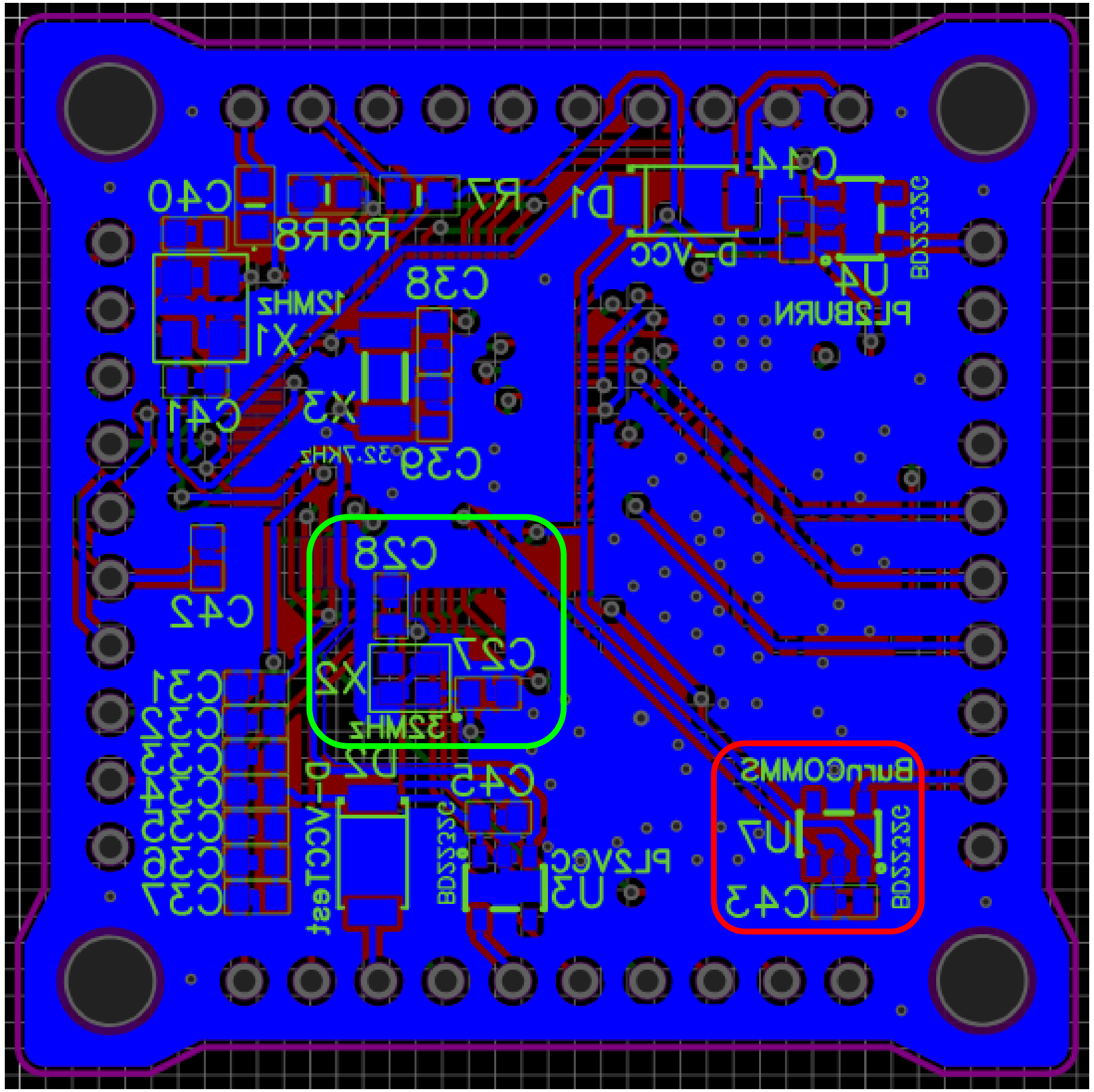
3.3. COMMS Circuit



3.3. COMMS Circuit







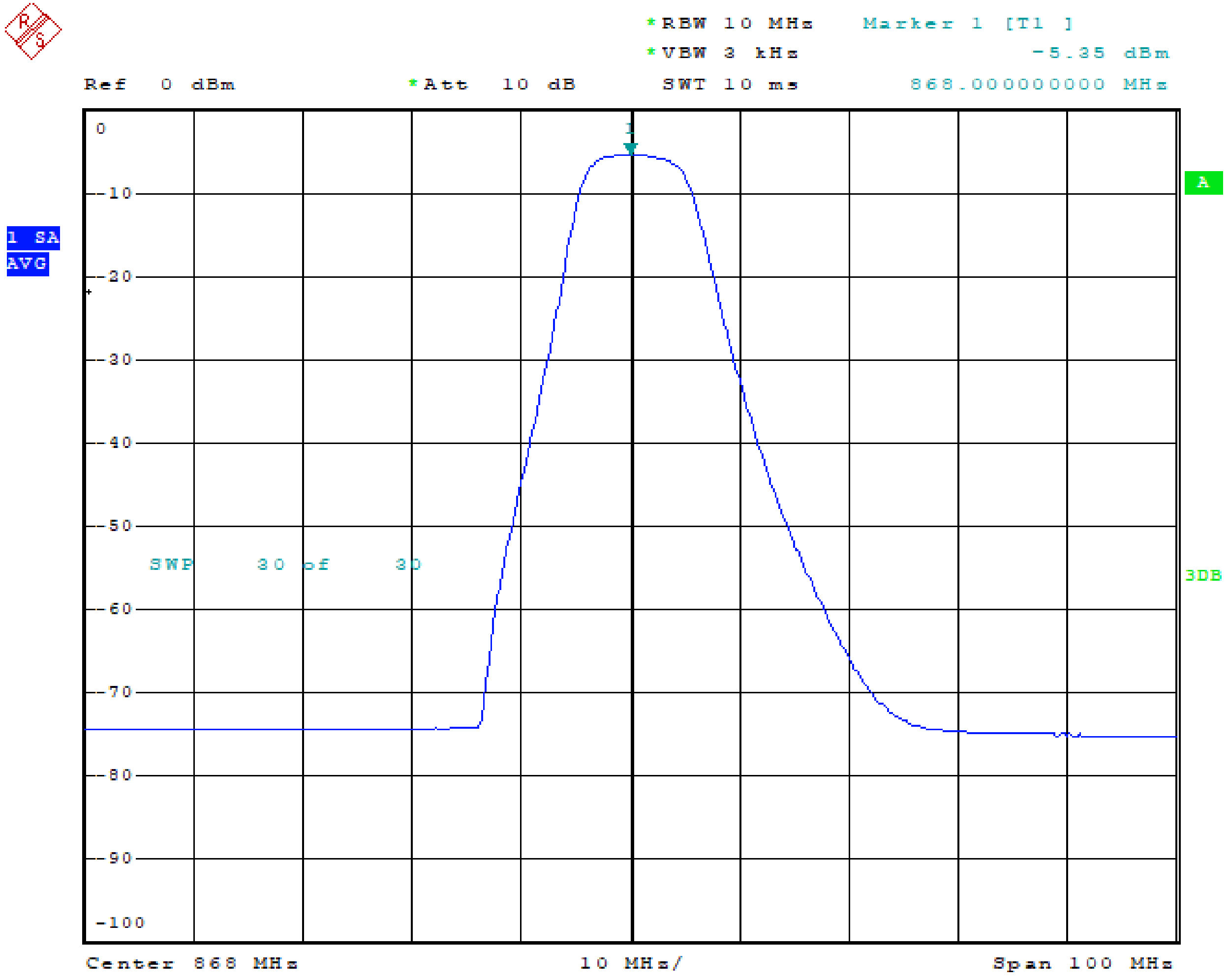
3.3. COMMS Circuit

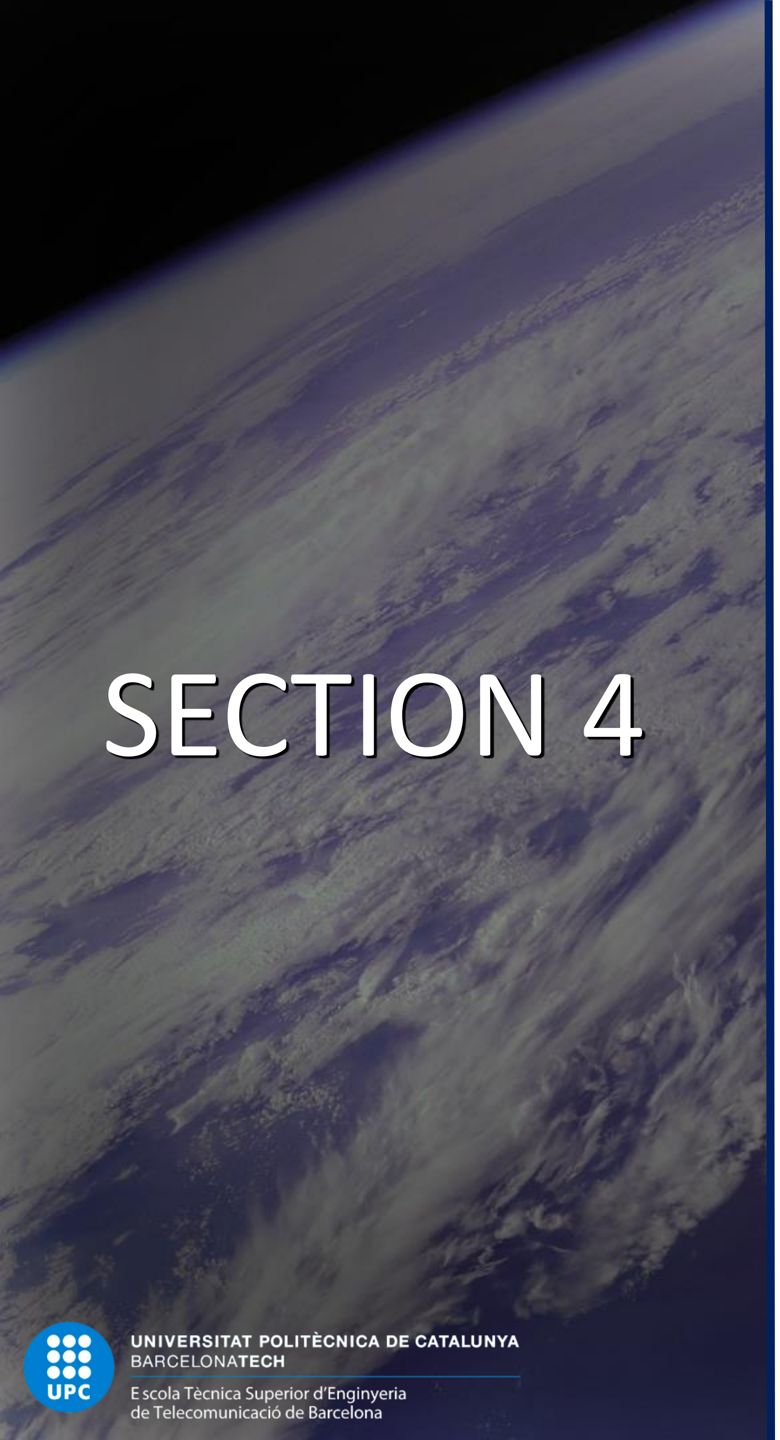
LOSSES WITH VNA

- S_{21} parameter
- First measurement: $-4.7\ dB$
- New pin-compatible switch
- Second measurement: $\boldsymbol{-3.07\ dB}$

LOSSES WITH SA

- Signal generator: pulse of $0\ dBm$
- Cable losses: $-2.65\ dBm$
- Spectrum Analyser: $-5.35\ dBm$
- Total COMMS circuit losses: $\boldsymbol{2.7\ dB}$ (with the old switch $5\ dB$)





1. Introduction
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4. **Protocol and Software**
    - **4.1 TT&C**
    - **4.2 State Machine**
5. Link and data budget
6. Conclusions

4.1. TT&C

PACKETS

- **BEACON:** Transmitted once every minute. Critical information. Makes it easier to track the satellite.
- **TELECOMMANDS (21):** Orders sent by the Ground Station. PIN as password.
- **REMOTE CALIBRATION:** Information sent by the Ground Station to calibrate the different sensors.
- **DATA PACKET:** When the telecommand *SEND_DATA* is received. Windows of 20 packets. (N)ACK to acknowledge them.
- **TELEMETRY:** Present status of the satellite and its sensors.
- **CONFIGURATION:** Current value of all the configurable parameters.

MISSION ID (1 byte)	SAT. ID (1 byte)	PACKAGE NUMBER (1 byte)	SATELLITE INFORMATION (not decided yet)	END FLAG (1 byte)

5 - 50 bytes

PIN (2 bytes)	ID (1 byte)	PAYLOAD (1-97 bytes)

4 - 100 bytes

MAGNETOMETER'S CALIBRATION MATRIX (36 bytes)	MAGNETOMETER OFFSET (12 byte)	GYROSCOPE CALIBRATION POLYNOMIALS (24 byte)	PHOTODIODES OFFSET (24 bytes)

96 bytes

MISSION ID (1 byte)	SAT. ID (1 byte)	PACKAGE NUMBER (1 byte)	PAYLOAD (1-96 bytes)	END FLAG (1 byte)

5 - 100 bytes

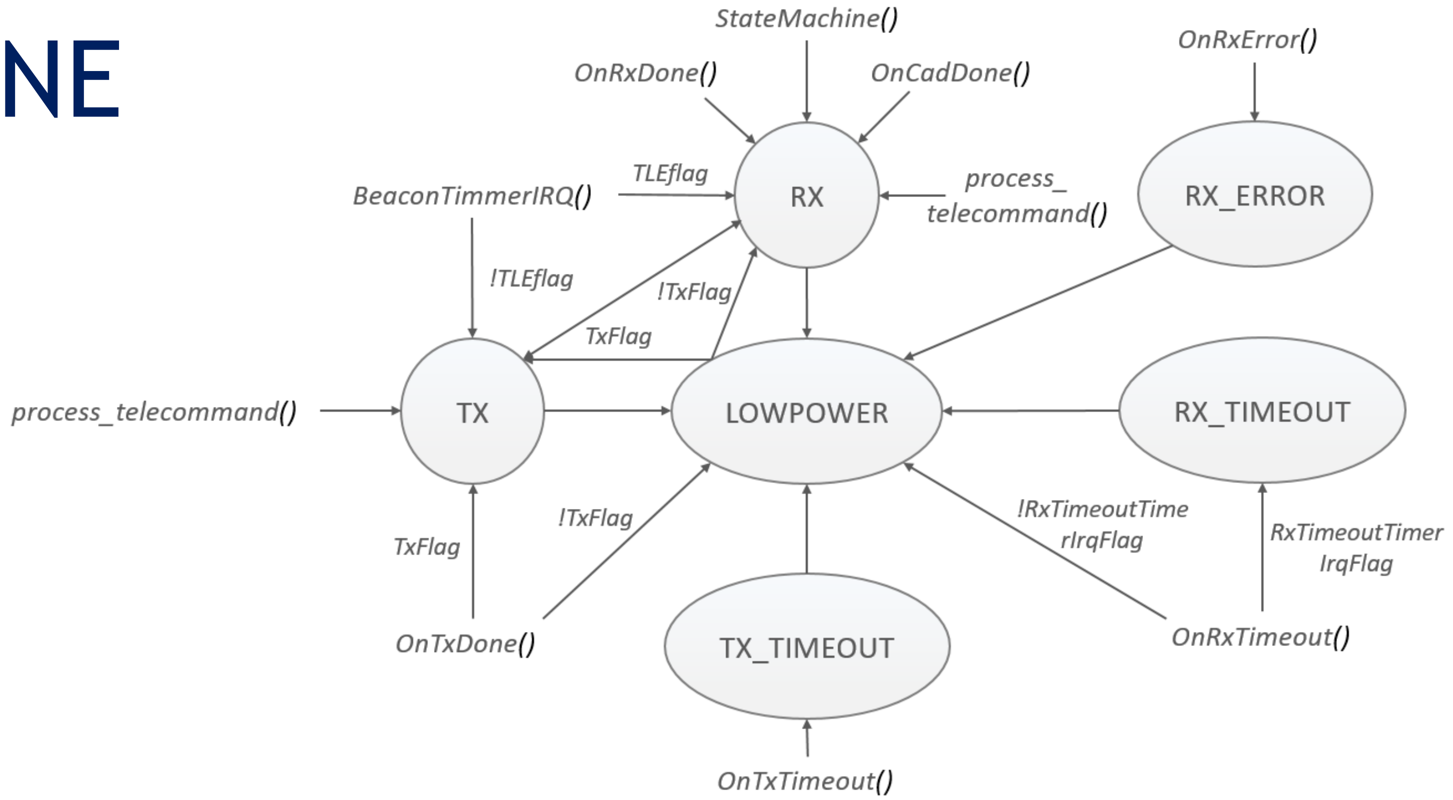
TEMPERATURE (8 bytes)	BATTERY (3 byte)	STATE (1 byte)	GYROSCOPE (6 byte)	MAGNETOMETER (8 bytes)	PHOTODIODES (8 bytes)

34 bytes

TIME (4 bytes)	COMMS PARAMS (4 byte)	PHODIODES CONFIG (5 byte)	PAYLOAD CONFIG (12 byte)	KP CONSTANT (1 bytes)	GYROSCOPE RESOLUTION (1 bytes)	BATTERY THRESHOLDS (3 bytes)

30 bytes

4.2. STATE MACHINE

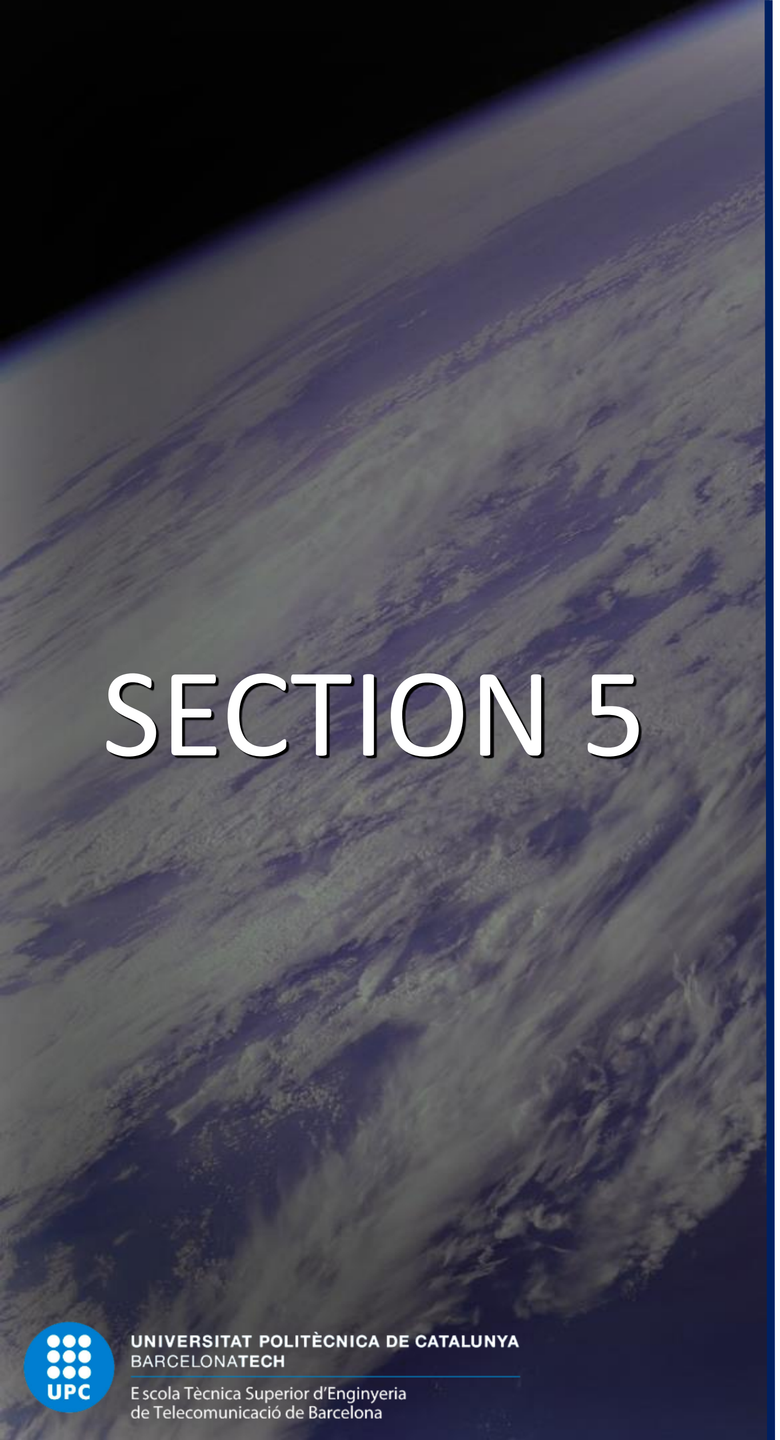


SOFTWARE

- Programmed in the STM32
- Multithread communicated with notifications
- C programming language
- SX1262 library

STATES

- TX: transmits the corresponding packet
- TX_TIMEOUT: aborts transmission in case of error
- RX: starts the reception process if channel activity is detected
- RX_ERROR: restarts the reception process
- RX_TIMEOUT: ends the reception process
- LOWPOWER: minimize the power consumption. Alternates between this state and RX



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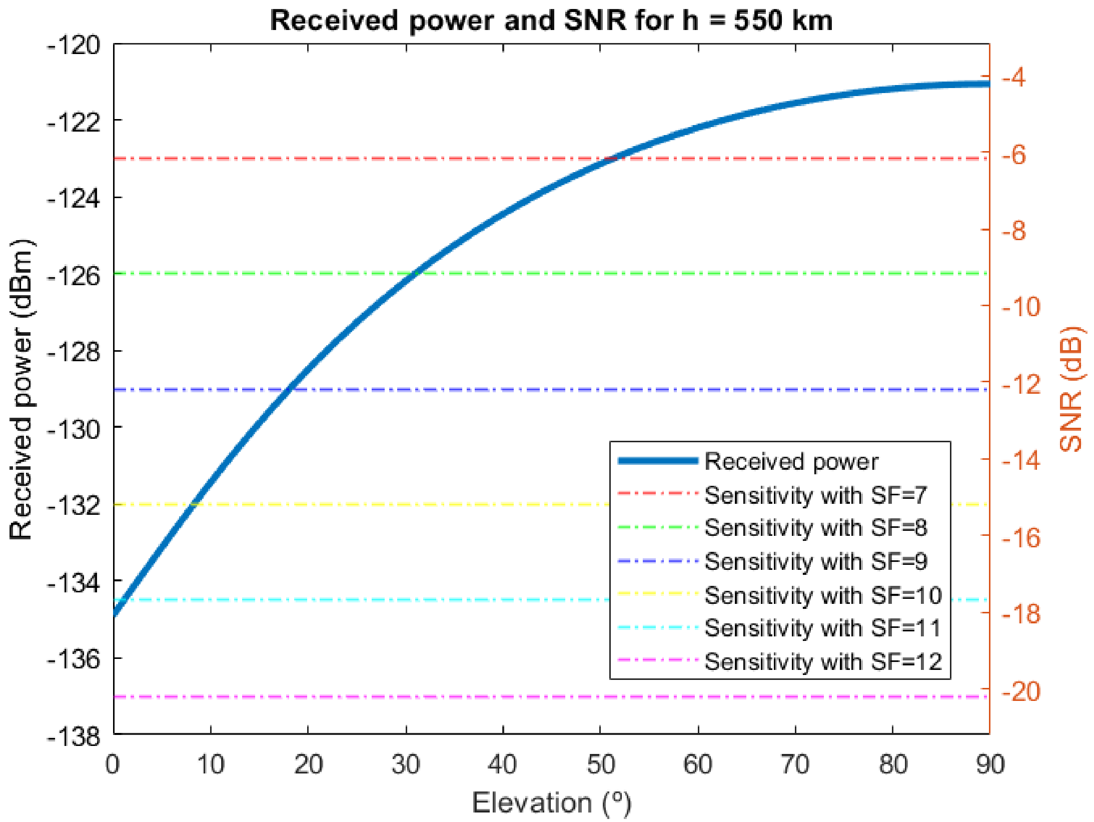
5.1. LINK AND DATA BUDGET

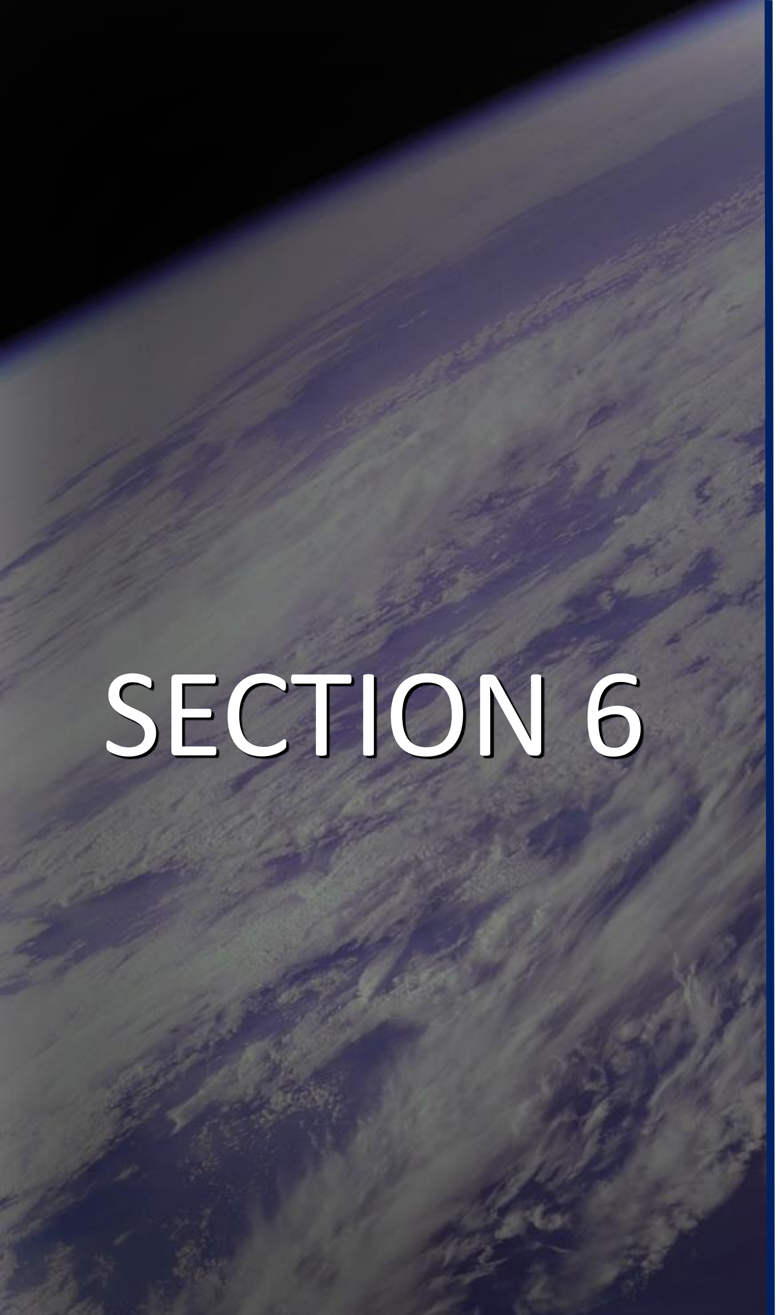
- **SF:** variable
- **BW:** 125 kHz
- **CR:** 4/5
- **h:** 550 km circular orbit



	SF 7	SF 8	SF 9	SF 10	SF 11	SF 12
El_{min}	51º	31º	18.5º	9º	1º	0º
Sensitivity (dBm)	-123	-126	-129	-132	-134.5	-137

	SF 7	SF 8	SF 9	SF 10	SF 11	SF 12
Max. Payload size (bytes)	222	222	115	51	51	51
Data packet size used (bytes)	100	100	100	50	50	50
Air time for data packet (ms)	189.7	338.4	615.4	698.4	1478.7	2793.5
Bit rate (bps)	4217	2364	1300	573	270	143

	SF 7	SF 8	SF 9	SF 10	SF 11	SF 12
Average contact time per day (s)	360	720	1200	1560	1560	1560
Data transmitted per day (kBytes)	189.77	212.76	195	111.74	52.65	27.89



SECTION 6

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6. CONCLUSIONS

Achievements

- **LoRa technology selected: low power and long range.**

Requirements

- **M-COMMS-0010:** Send the satellite information to the GS
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- **S-COMMS-0030:** Low-power and long-range communications
- **S-COMMS-0040:** Antenna deployed once in orbit
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- **The link budget establishes when the communication is possible and the optimum parameters to maximize the bit rate.**

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- Antenna designed and integrated in lateral PCB. Matched at 868 MHz, with 1.15 dB of gain and deployment in 5 s.
- Transceiver circuit designed and integrated in OBC-COMMS PCB.
- Protocol defined and programmed to rule the communications subsystem. Types of packet defined.
- The link budget establishes when the communication is possible and the optimum parameters to maximize the bit rate.
- **Redundancy added and a system of acknowledgment to retransmit the lost packets.**

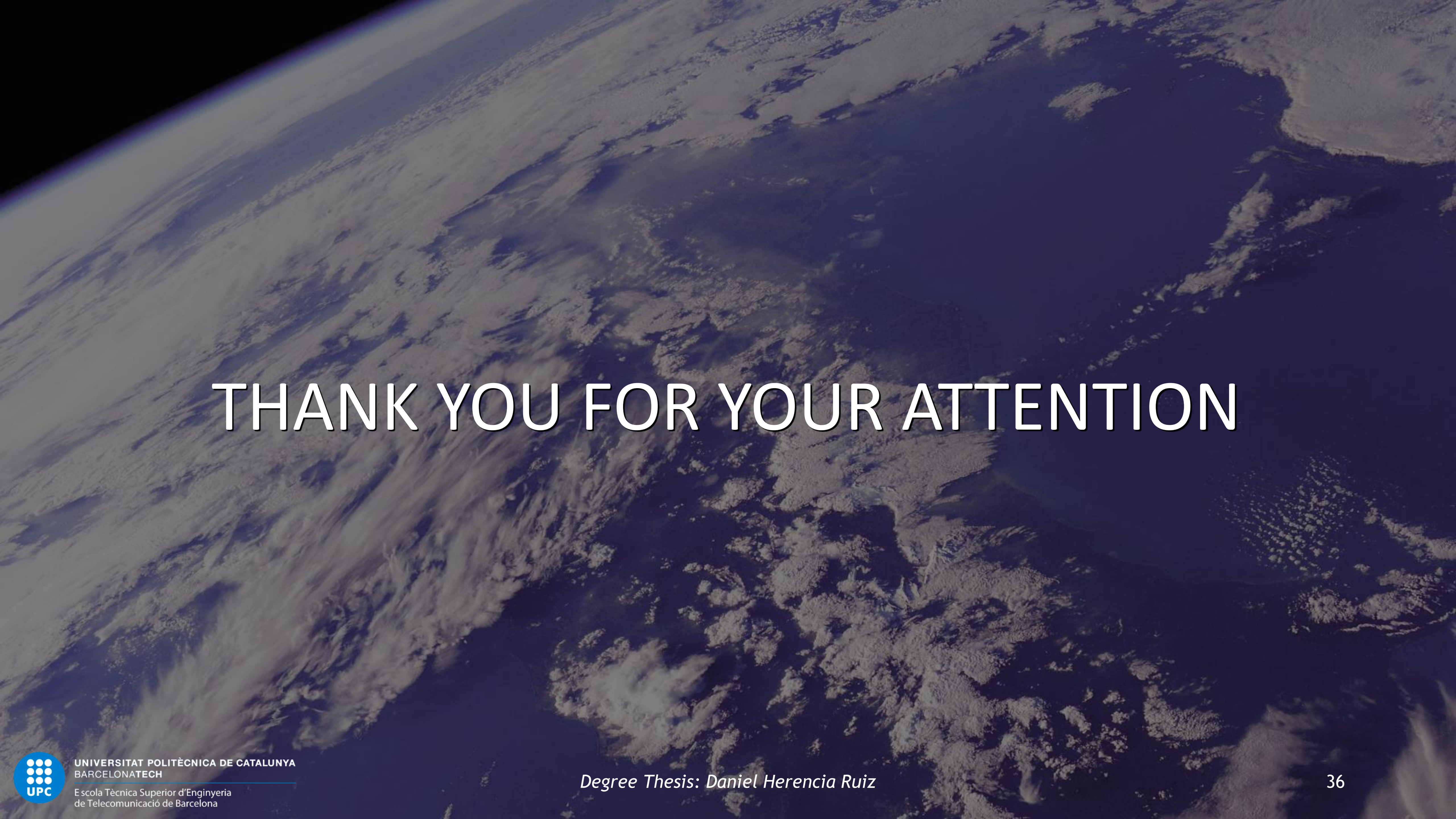
Requirements

- **M-COMMS-0010:** Send the satellite information to the GS
- **M-COMMS-0020:** Receive orders from the GS
- **S-COMMS-0030:** Low-power and long-range communications
- **S-COMMS-0040:** Antenna deployed once in orbit
- **S-COMMS-0050:** Link budget establishes when to exchange information
- **S-COMMS-0060:** Maximize the bit rate
- **S-COMMS-0070:** Minimize transmission errors

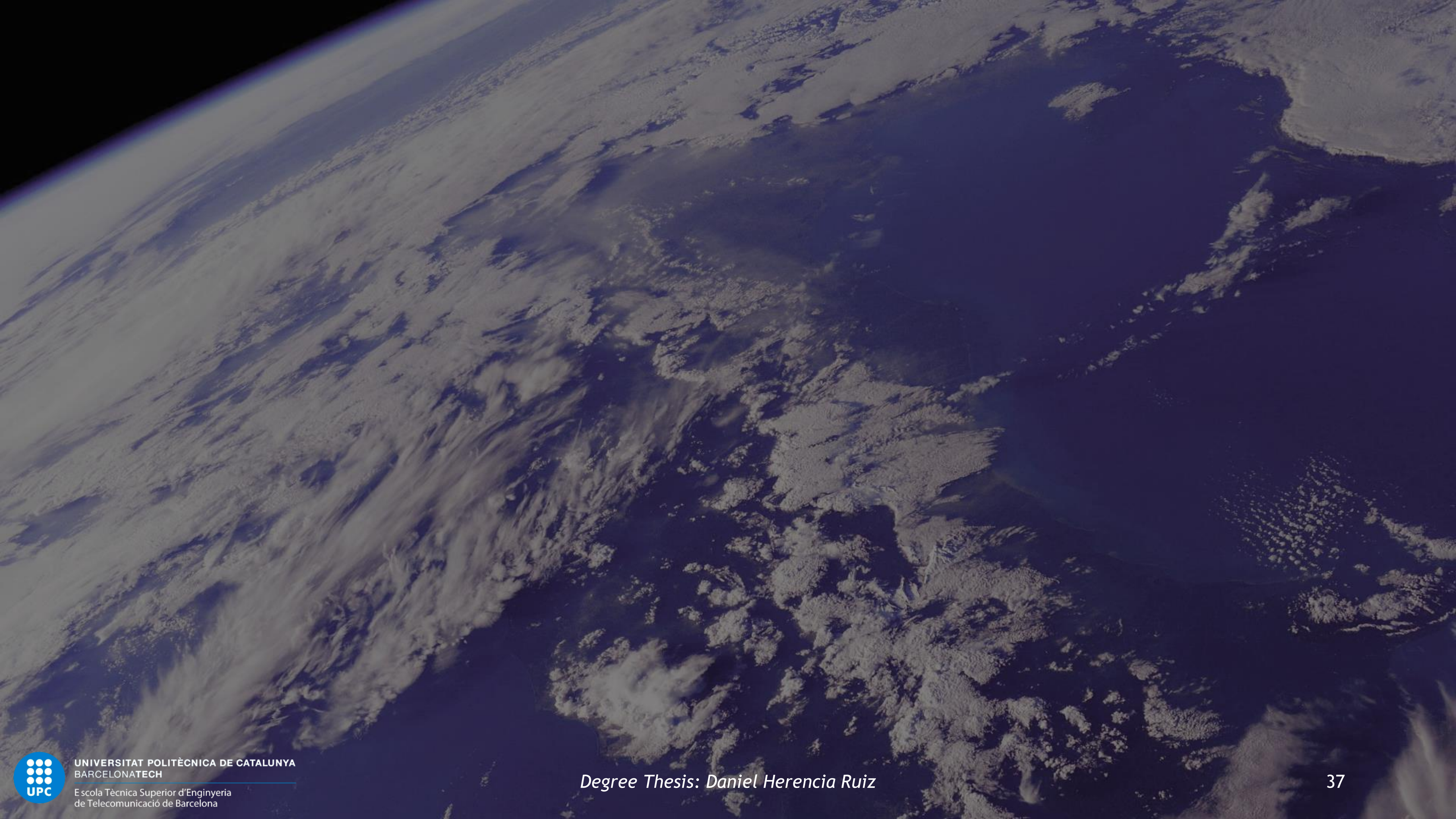
6. CONCLUSIONS

Future developments

- **Test the communication system together with the rest of the subsystems.**
- **Find the optimum RF switch to minimize the losses**
- **If there is enough memory in the OBC:**
    - More robust encoding: Reed-Solomon or convolutional codes
    - DES or AES encryption of the telecommands and packets



THANK YOU FOR YOUR ATTENTION

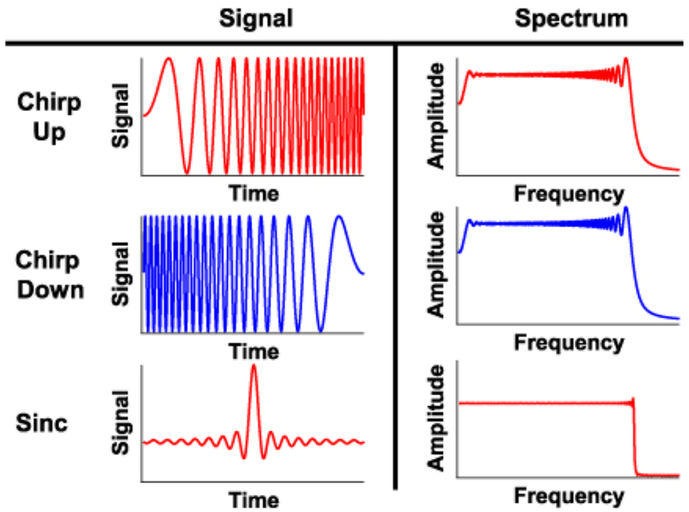


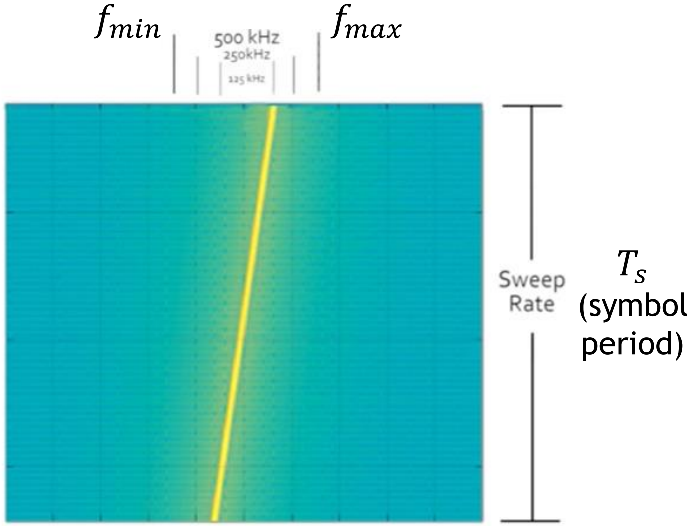
APPENDICES

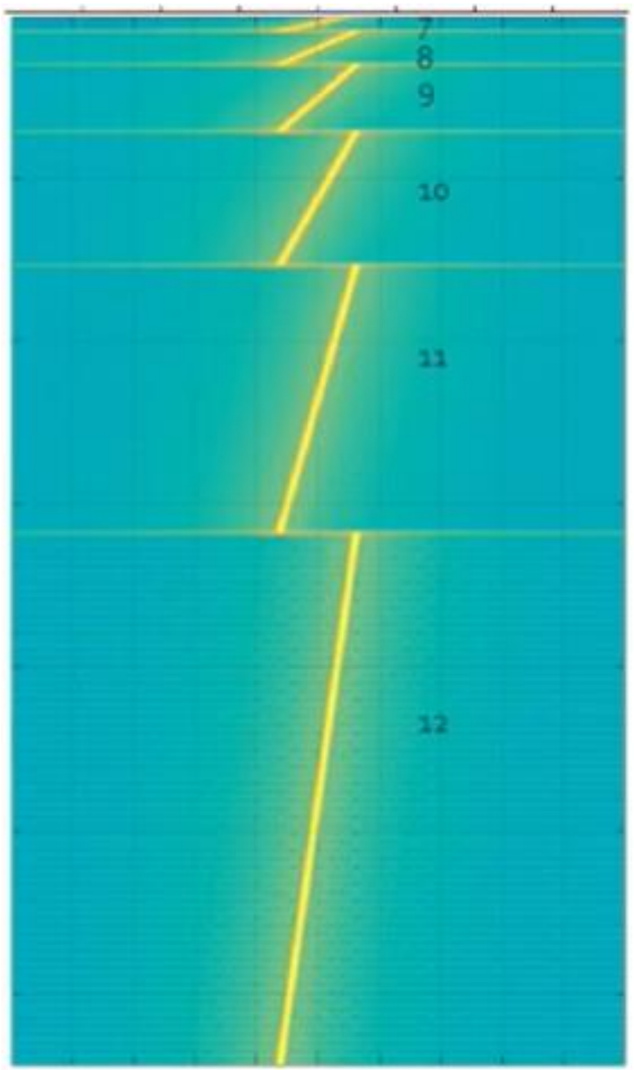
A. LoRa MODULATION

Chirp Spread Spectrum (CSS)

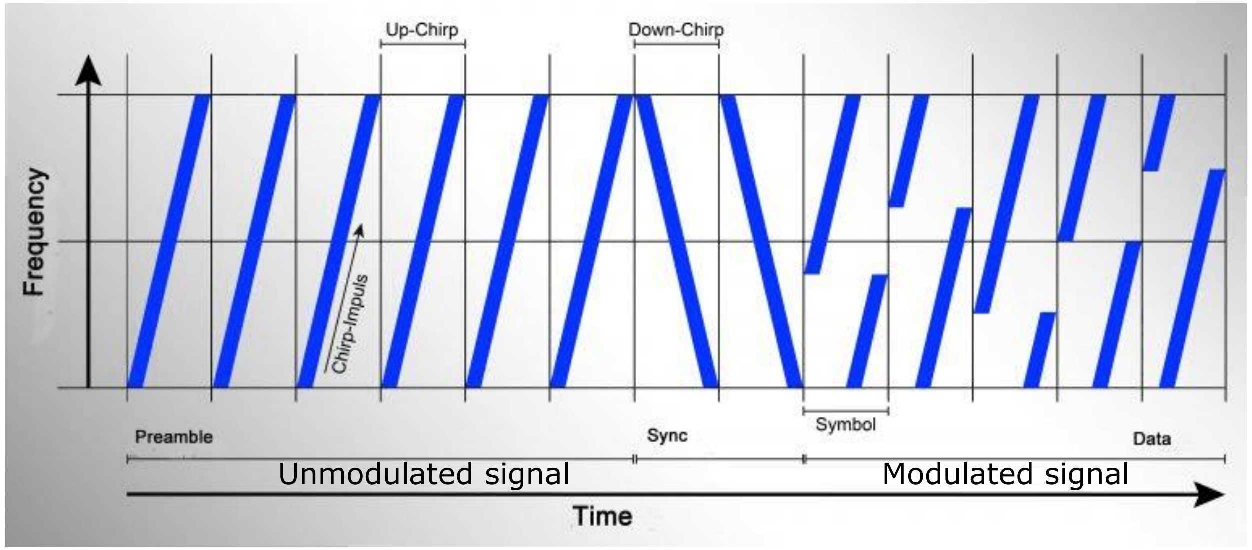
- Signal is spread in the frequency domain. Signal recovered with negative SNR.
- The spreading of the spectrum is achieved with chirp signals that continuously vary in frequency.
- A chirp, or sweep signal, is a tone in which the frequency increases (up-chirp) or decreases (down-chirp) with time.
- Uses wideband linear frequency modulated chirp pulses to encode information.





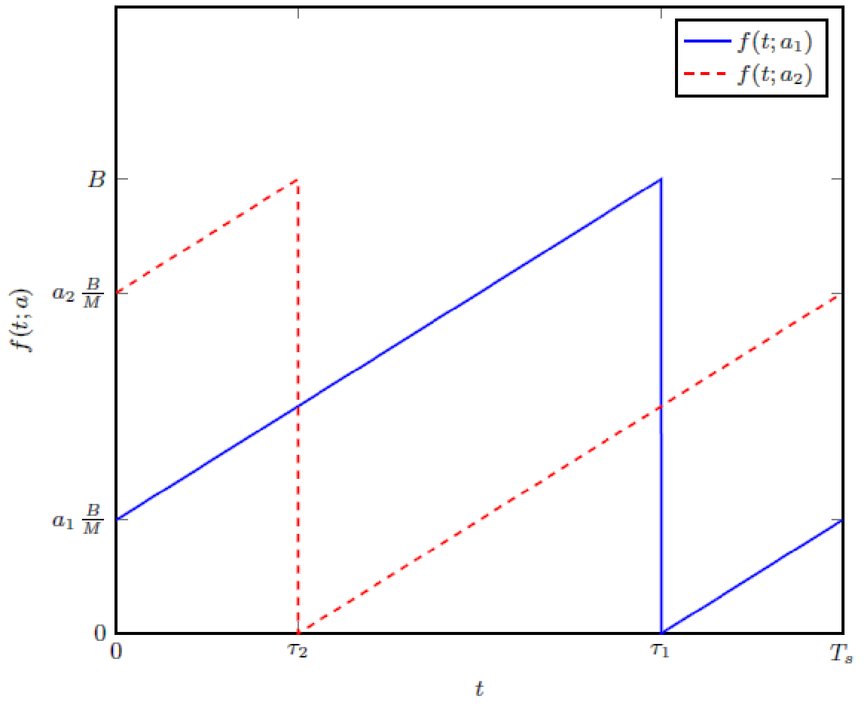


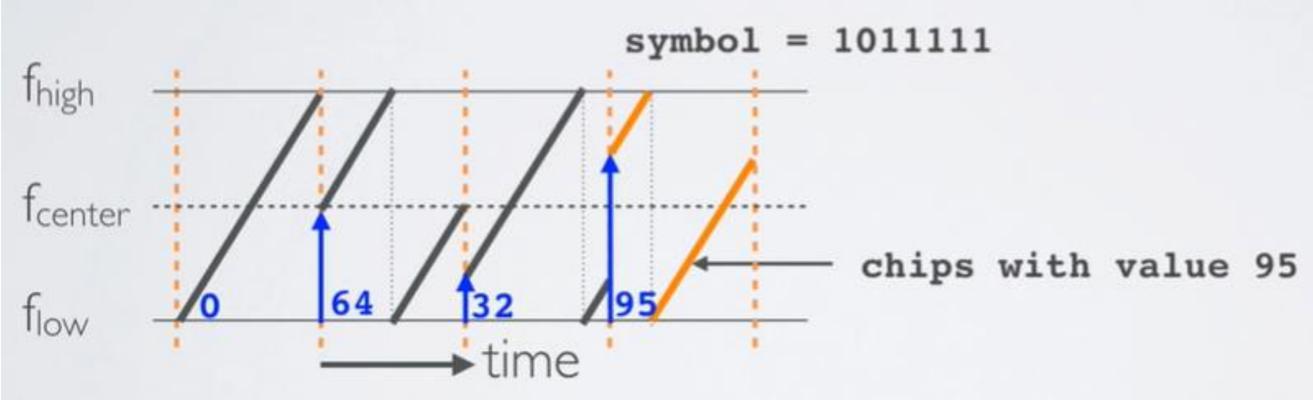
A. LoRa MODULATION



Chirp Spread Spectrum

- The number of raw bits that can be encoded in a chirp is the SF (SF = bits/symbol)
- M-ary digital modulation. $M = 2^{SF}$ different symbols (chips), a $\in [0\,, M-1]$
- Ex: symbol 1011111 (decimal 95) => 7 bits => can be encoded with SF = 7 => $a_1 = 95$

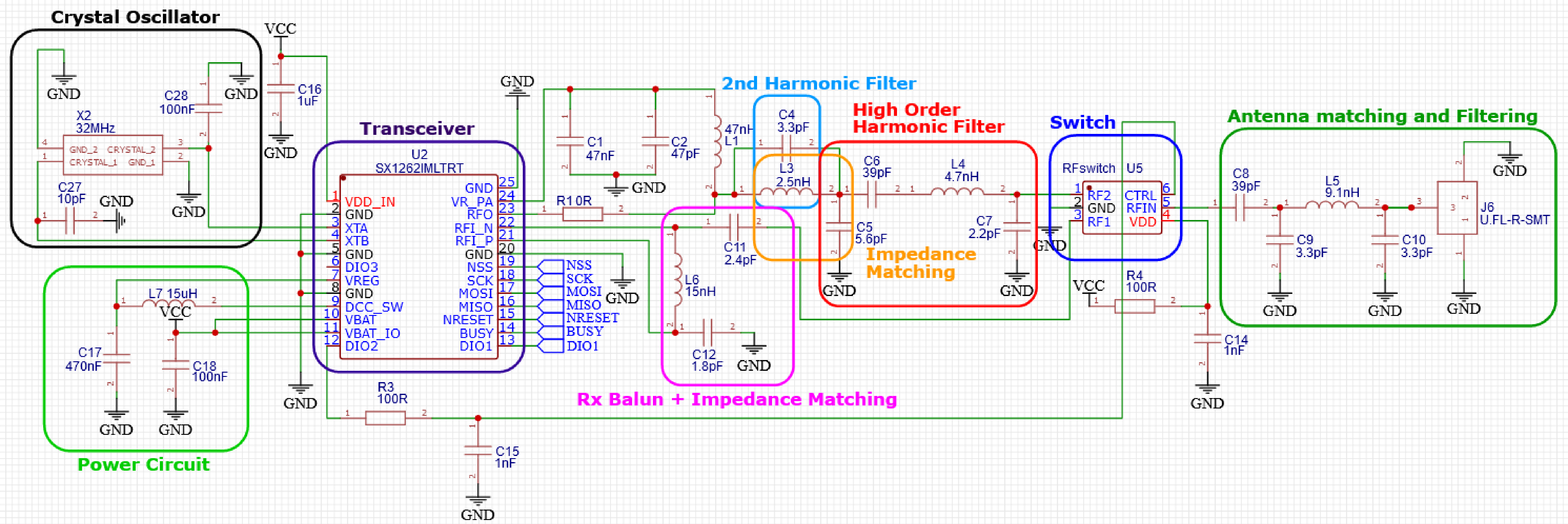




B. COMMS Circuit: Schematic

TRANSCEIVER

- Semtech SX1262 LoRa transceiver
- **Frequency:** 150-960 MHz
- **Output power:** $P_{max} = 22\ dBm$
- **Consumption:** $I_{max} = 108\ mA$



B. COMMS Circuit: PCB

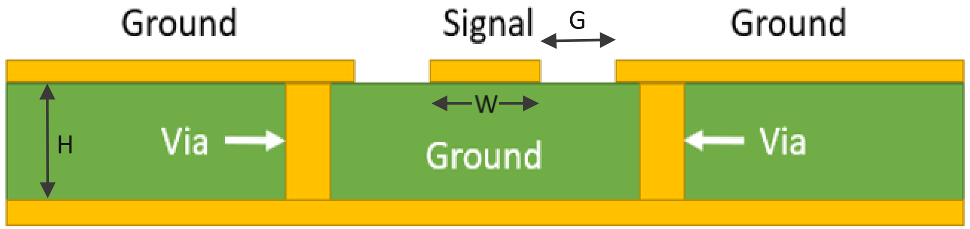
RF design

- 4 layers PCB
- Grounded coplanar waveguides
- Inspired in Semtech evaluation board
- Printed by JLCPCB

Magnitude	Value
Substrate ε_r	4.6 (FR4-STD)
Base Copper Weight	18 µm
Plating Thickness	35 µm
Conductor Width (W)	0.35 mm
Conductor Height (H)	0.2 mm
Conductor Gap (G)	0.2 mm
W/H	1.75
Z_o	49.84

Layer	Material Type	Thickness	
Top Layer1	Copper	0.035 mm	
Prepreg	7628*1	0.2 mm	
Inner Layer2	Copper	0.0175 mm	1.1mm (with copper core)
Core	Core	1.065 mm	
Inner Layer3	Copper	0.0175 mm	
Prepreg	7628*1	0.2 mm	
Bottom Layer4	Copper	0.035 mm	

Grounded coplanar waveguide

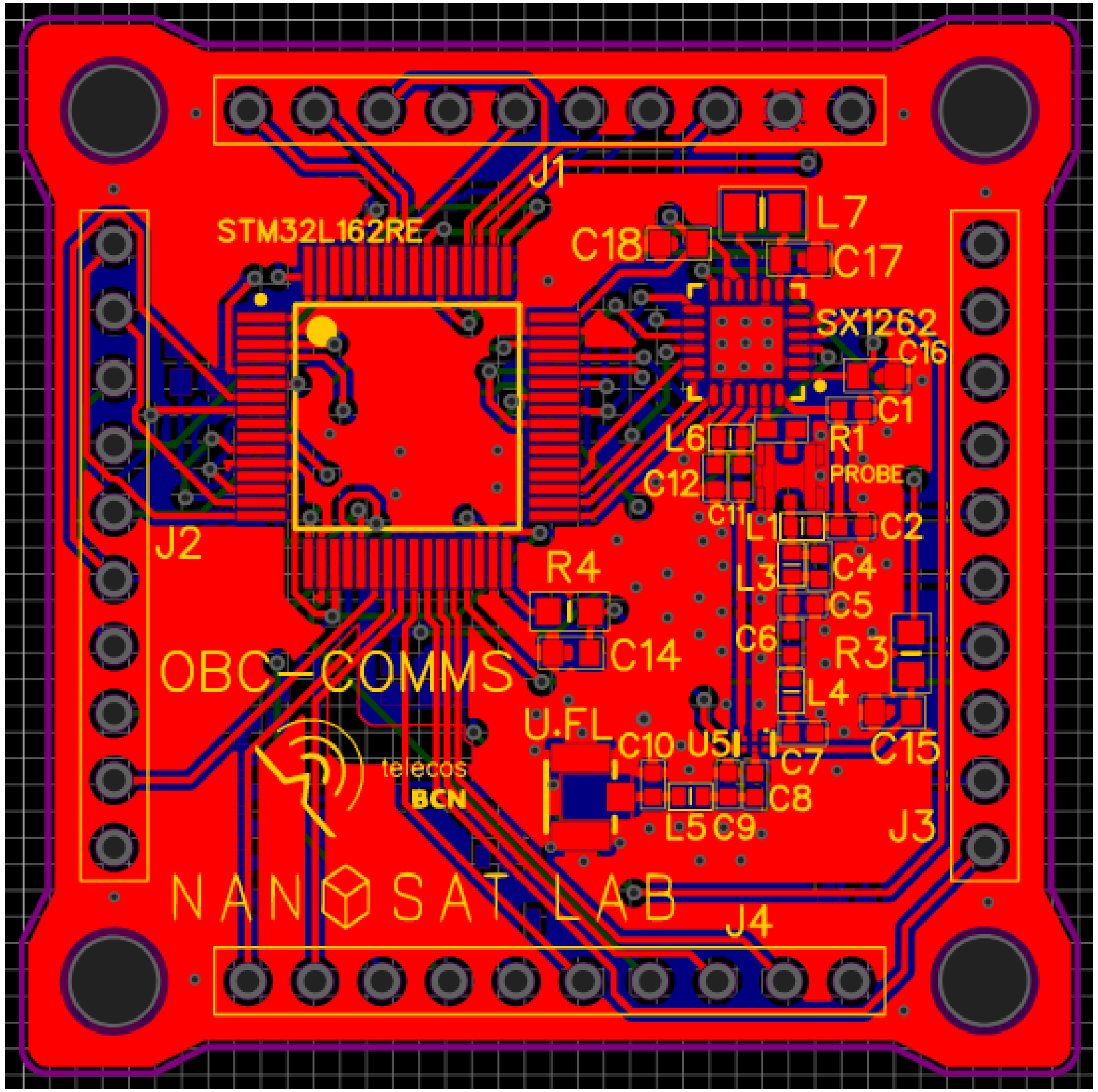


B. COMMS Circuit: PCB

TOP LAYER

- STM32 (OBC)
- COMMS RF circuit and components
- Routing lines to the lateral pins

Layer	Material Type	Thickness	
Top Layer1	Copper	0.035 mm	
Prepreg	7628*1	0.2 mm	
Inner Layer2	Copper	0.0175 mm	1.1mm (with copper core)
Core	Core	1.065 mm	
Inner Layer3	Copper	0.0175 mm	
Prepreg	7628*1	0.2 mm	
Bottom Layer4	Copper	0.035 mm	

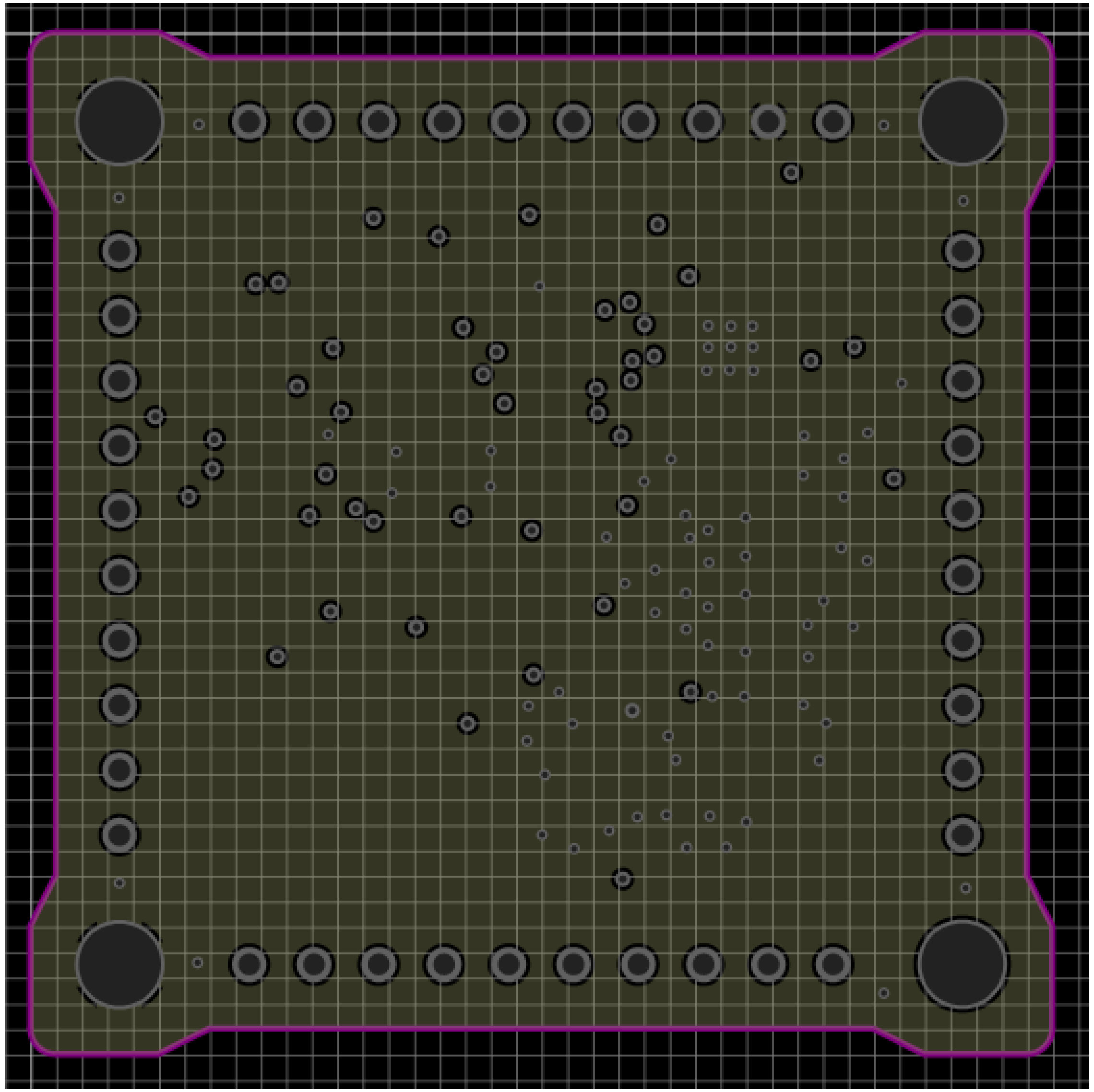


B. COMMS Circuit: PCB

INNER LAYER 1

- Reference ground for all the RF circuit

Layer	Material Type	Thickness	
Top Layer1	Copper	0.035 mm	
Prepreg	7628*1	0.2 mm	
Inner Layer2	Copper	0.0175 mm	
Core	Core	1.065 mm	1.1mm (with copper core)
Inner Layer3	Copper	0.0175 mm	
Prepreg	7628*1	0.2 mm	
Bottom Layer4	Copper	0.035 mm	

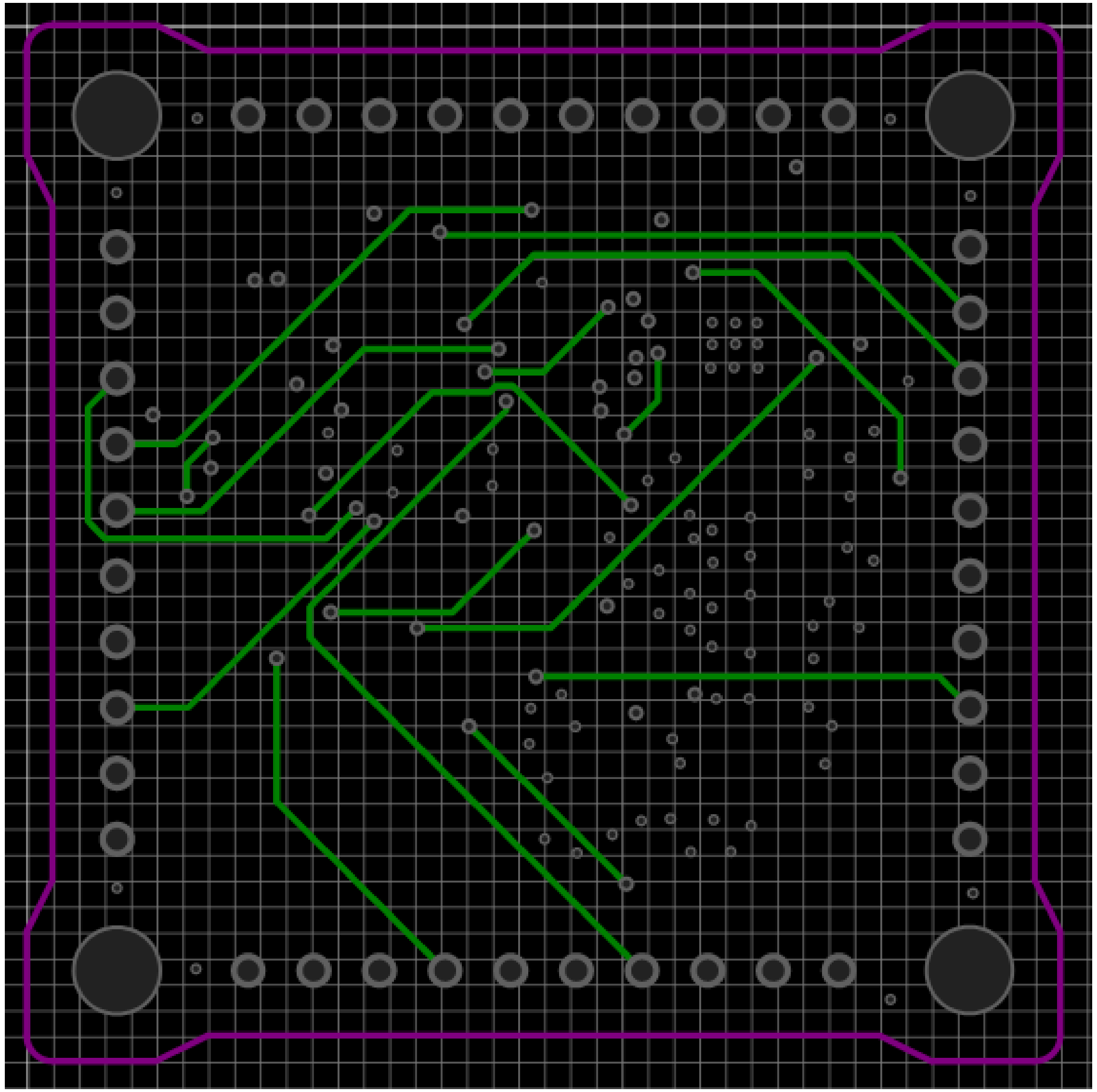


B. COMMS Circuit: PCB

INNER LAYER 2

- Routing lines for OBC connections and non-RF COMMS lines

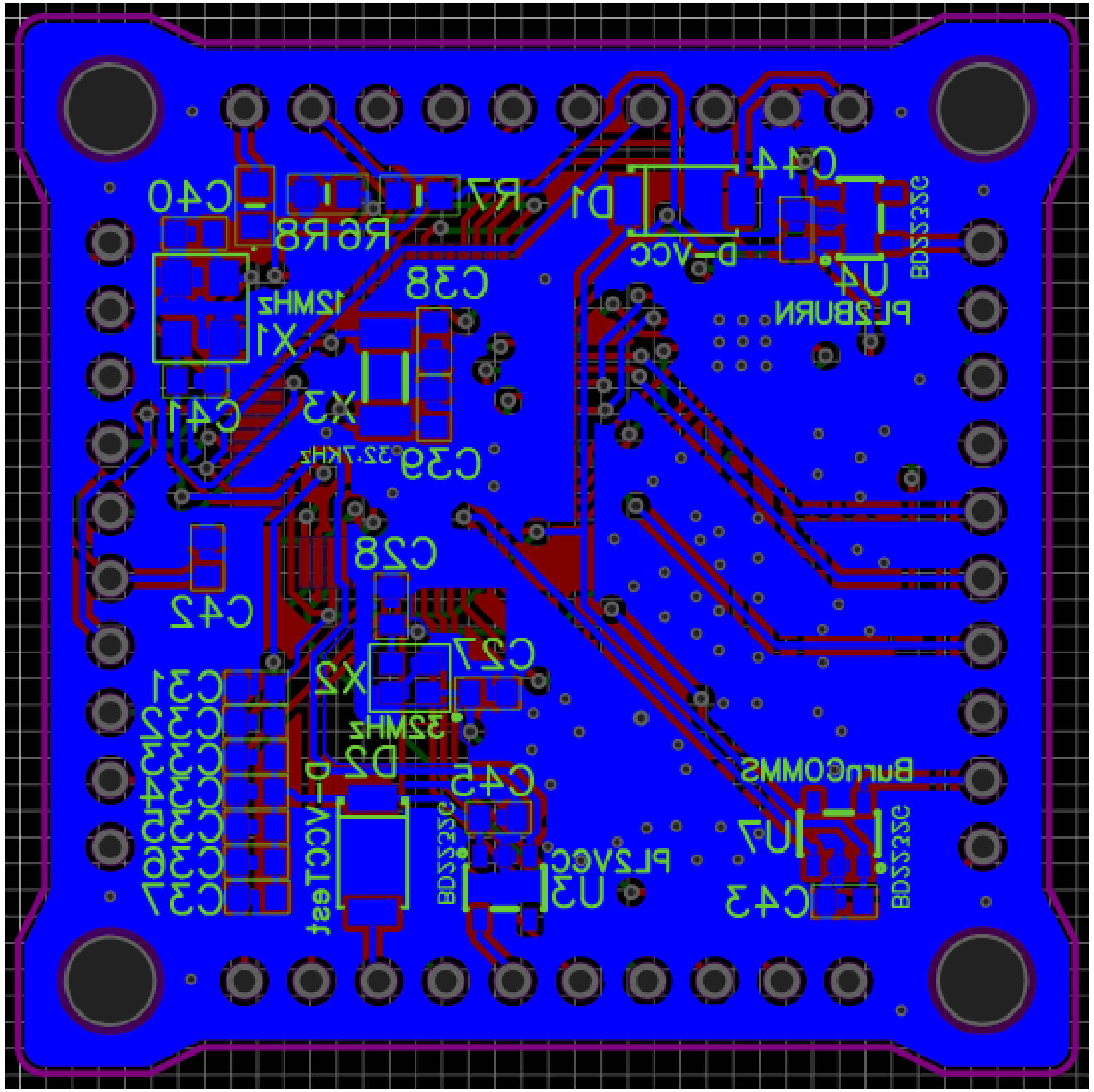
Layer	Material Type	Thickness	
Top Layer1	Copper	0.035 mm	
Prepreg	7628*1	0.2 mm	
Inner Layer2	Copper	0.0175 mm	
Core	Core	1.065 mm	1.1mm (with copper core)
Inner Layer3	Copper	0.0175 mm	
Prepreg	7628*1	0.2 mm	
Bottom Layer4	Copper	0.035 mm	



B. COMMS Circuit: PCB

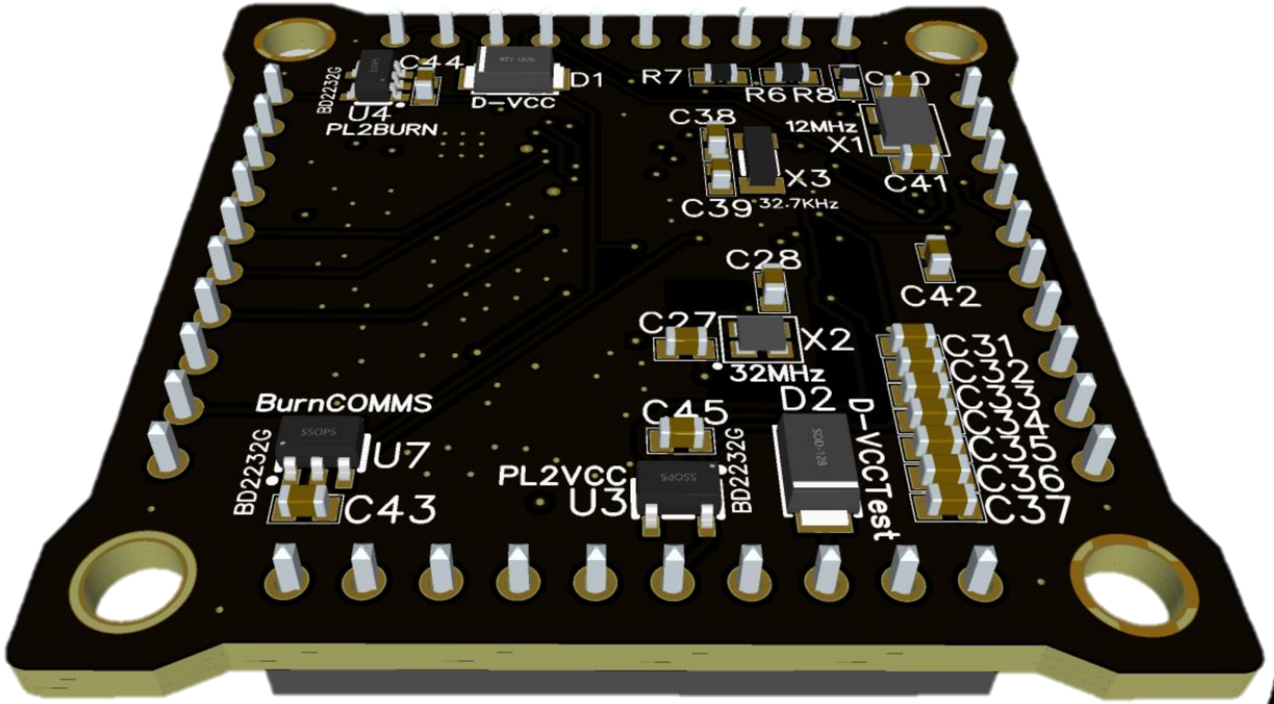
BOTTOM LAYER

- OBC components
- COMMS crystal oscillator
- Some routing lines

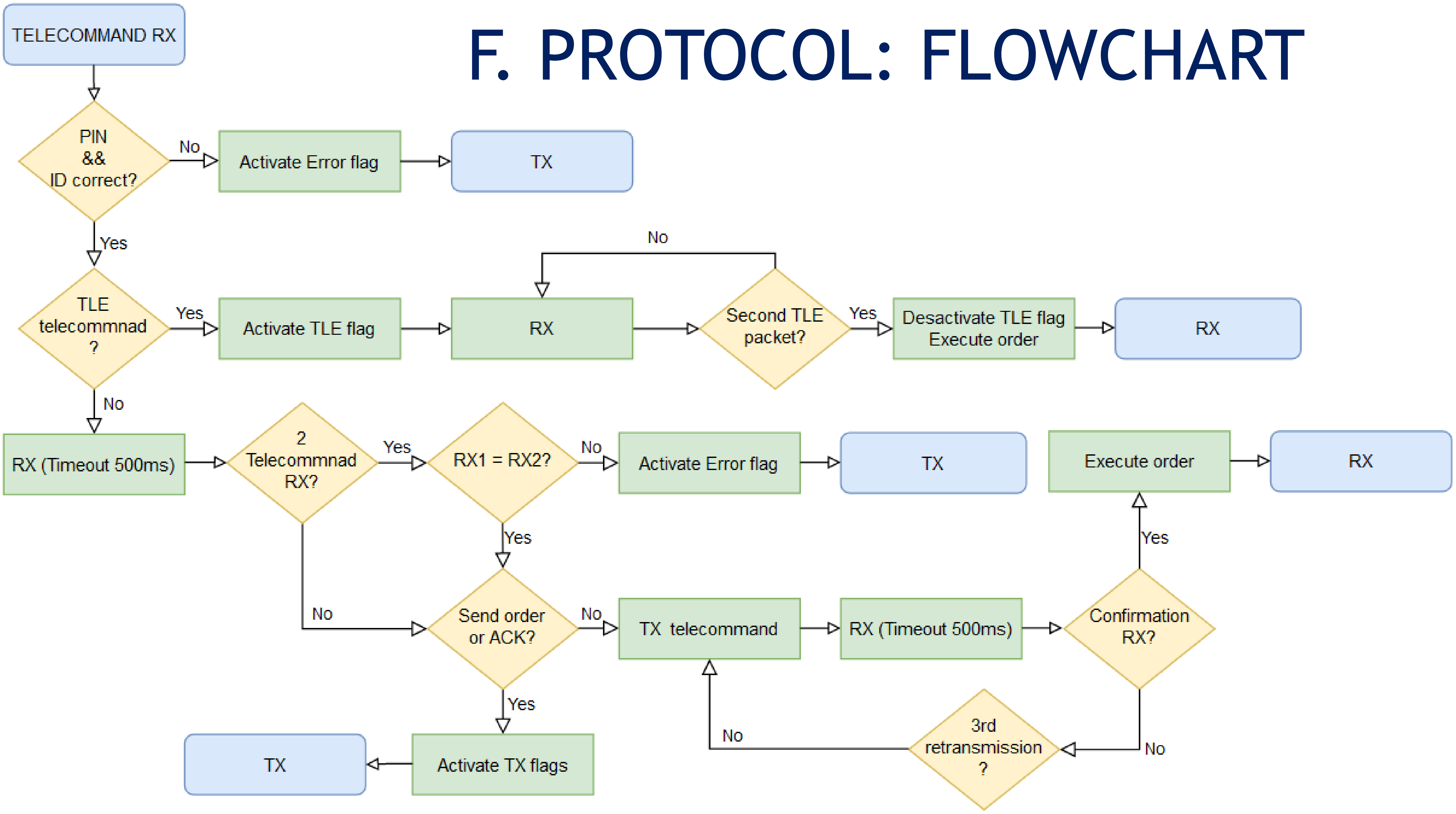


Layer	Material Type	Thickness	
Top Layer1	Copper	0.035 mm	
Prepreg	7628*1	0.2 mm	
Inner Layer2	Copper	0.0175 mm	1.1mm (with copper core)
Core	Core	1.065 mm	
Inner Layer3	Copper	0.0175 mm	
Prepreg	7628*1	0.2 mm	
Bottom Layer4	Copper	0.035 mm	

B. COMMS Circuit: PCB



F. PROTOCOL: FLOWCHART



F. PROTOCOL: TEST

```
Telecommand TX: C8 9D 14 0
Telecommand TX: C8 9D 14 0
```
Send data telecommand (PIN1, PIN2, telecommand ID, parameter)

```
Received paquet number 0
```
Number of the packet received by the GS

```
0x86, 0x64, 0x0,
```
Mission ID, satellite ID, packet number

Data received

```
0xFF, 0xD8, 0xFF, 0xE0, 0x0, 0x10, 0x4A, 0x46, 0x49, 0x46, 0x0, 0x1, 0x1, 0x0, 0x0, 0x1,
0x0, 0x1, 0x0, 0x0, 0xFF, 0xE2, 0x2, 0x28, 0x49, 0x43, 0x43, 0x5F, 0x50, 0x52, 0x4F, 0x46,
0x49, 0x4C, 0x45, 0x0, 0x1, 0x1, 0x0, 0x0, 0x2, 0x18, 0x0, 0x0, 0x0, 0x0, 0x4, 0x30,
0x0, 0x0, 0x6D, 0x6E, 0x74, 0x72, 0x52, 0x47, 0x42, 0x20, 0x58, 0x59, 0x5A, 0x20, 0x0, 0x0,
0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x61, 0x63, 0x73, 0x70, 0x0, 0x0,
0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0,
0xFF,
```
Final of the packet indicator

```
Received paquet number 1
```
2nd packet received

```
0x86, 0x64, 0x1,
0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x1, 0x0, 0x0, 0xF6, 0xD6, 0x0, 0x1,
0x0, 0x0, 0x0, 0x0, 0xD3, 0x2D, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0,
0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0,
0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0,
0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x9, 0x64, 0x65, 0x73, 0x63, 0x0, 0x0,
0x0, 0xF0, 0x0, 0x0, 0x0, 0x74, 0x72, 0x58, 0x59, 0x5A, 0x0, 0x0, 0x1, 0x64, 0x0, 0x0,
0xFF,
Received paquet number 2
```
3rd packet received

```
0x86, 0x64, 0x2,
0x0, 0x14, 0x67, 0x58, 0x59, 0x5A, 0x0, 0x0, 0x1, 0x78, 0x0, 0x0, 0x0, 0x14, 0x62, 0x58,
0x59, 0x5A, 0x0, 0x0, 0x1, 0x8C, 0x0, 0x0, 0x0, 0x14, 0x72, 0x54, 0x52, 0x43, 0x0, 0x0,
0x1, 0xA0, 0x0, 0x0, 0x0, 0x28, 0x67, 0x54, 0x52, 0x43, 0x0, 0x0, 0x1, 0xA0, 0x0, 0x0,
0x0, 0x28, 0x62, 0x54, 0x52, 0x43, 0x0, 0x0, 0x1, 0xA0, 0x0, 0x0, 0x0, 0x28, 0x77, 0x74,
0x70, 0x74, 0x0, 0x0, 0x1, 0xC8, 0x0, 0x0, 0x0, 0x14, 0x63, 0x70, 0x72, 0x74, 0x0, 0x0,
0x1, 0xDC, 0x0, 0x0, 0x0, 0x3C, 0x6D, 0x6C, 0x75, 0x63, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0,
0xFF,
```

Memory display

Address: 0x08010000 Size: 0x1000 Data Width: 32 bits

Device Memory @ 0x08010000 : Binary File

Target memory, Address range: [0x08010000 0x08011000]

Address	0	4	8	C	ASCII
0x08010000	E0FFD8FF	464A1000	01004649	01000001	ÿØÿà..JFIF......
0x08010010	00000100	2802E2FF	5F434349	464F5250	....ÿâ.(ICC_PROF
0x08010020	00454C49	00000101	00001802	30040000	ILE............0
0x08010030	6E6D0000	47527274	59582042	0000205A	..mntrRGB XYZ ..
0x08010040	00000000	00000000	63610000	00007073	..........acsp..
0x08010050	00000000	00000000	00000000	00000000	....
0x08010060	00000000	00000000	00000100	0100D6F6	...........öÖ..
0x08010070	00000000	00002DD3	00000000	00000000	....Ó-..........
0x08010080	00000000	00000000	00000000	00000000	....
0x08010090	00000000	00000000	00000000	00000000	....
0x080100A0	00000000	00000000	65640900	00006373	.........desc..
0x080100B0	0000F000	58727400	00005A59	00006401	.ð...trXYZ...d..
0x080100C0	58671400	00005A59	00007801	58621400	..gXYZ...x....bX
0x080100D0	00005A59	00008C01	54721400	00004352	YZ...Œ....rTRC..
0x080100E0	0000A001	54672800	00004352	0000A001	. ...(gTRC... ..
0x080100F0	54622800	00004352	0000A001	74772800	.(bTRC... ...(wt
0x08010100	00007470	0000C801	70631400	00007472	pt...È....cprt..
0x08010110	0000DC01	6C6D3C00	00006375	00000000	.Ü...<mluc......
0x08010120	00000100	6E650C00	00005355	00005800	......enUS...X..
0x08010130	73001C00	47005200	00004200	00000000	...s.R.G.B......

F. TT&C

BEACON

- Transmitted by the satellite once every minute
- Satellite ID and some critical information (battery state,…)
- Makes it easier to track the satellite

MISSION ID (1 byte)	SAT. ID (1 byte)	PACKAGE NUMBER (1 byte)	SATELLITE INFORMATION (not decided yet)	END FLAG (1 byte)

5 - 50 bytes

TELECOMMANDS

- Orders sent by the Ground Station
- 21 telecommands defined
- PIN as password

PIN (2 bytes)	ID (1 byte)	PAYLOAD (1-97 bytes)

4 - 100 bytes

F. TT&C

REMOTE CALIBRATION

- Information sent by the Ground Station to calibrate the different sensors

MAGNETOMETER'S CALIBRATION MATRIX (36 bytes)	MAGNETOMETER OFFSET (12 byte)	GYROSCOPE CALIBRATION POLYNOMIALS (24 byte)	PHOTODIODES OFFSET (24 bytes)

96 bytes

DATA PACKET

- When the telecommand *SEND_DATA* is received
- Windows of 20 packets
- (N)ACK to acknowledge 20 packets

MISSION ID (1 byte)	SAT. ID (1 byte)	PACKAGE NUMBER (1 byte)	PAYLOAD (1-96 bytes)	END FLAG (1 byte)

5 - 100 bytes

F. TT&C

TELEMETRY

- Present status of the satellite and its sensors

TEMPERATURE (8 bytes)	BATTERY (3 byte)	STATE (1 byte)	GYROSCOPE (6 byte)	MAGNETOMETER (8 bytes)	PHOTODIODES (8 bytes)

34 bytes

CONFIGURATION

- Current value of all the configurable parameters

TIME (4 bytes)	COMMS PARAMS (4 byte)	PHODIODES CONFIG (5 byte)	PAYLOAD CONFIG (12 byte)	KP CONSTANT (1 bytes)	GYROSCOPE RESOLUTION (1 bytes)	BATTERY THRESHOLDS (3 bytes)

30 bytes

Design and Implementation of a Communications System for a PocketQube based on LoRa