CUBESAT DEEP SPACE X-BAND TT&C TRANSPONDER (C-DST)

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1 INTRODUCTION

In recent years, there has been a clear trend of space mission projects to include planetary small spacecraft (e.g., CubeSats) that fly as secondary payloads, and are deployed at destinations to perform missions and communicate via the main spacecraft or direct to Earth. The added value for planetary science and exploration is twofold: (a) enhance primary science objectives; (b) enable new science and exploration in new, potentially dangerous environments. Furthermore, these small companion missions can be an excellent platform for testing novel technology demonstrators.
In addition, science investigators are usually more inclined to accept higher risk by exploring dangerous/unknown environments using relatively low-cost platforms. Recent examples of this paradigm are the Mars Cube One (MarCO, launched on May 5th, 2018 (with the Insight mission to Mars). This was the first ever interplanetary CubeSats flown in deep space, and these twin communications-relay CubeSats were built by NASA's Jet Propulsion Laboratory, Pasadena, California. Another example is ESA’s proposed Miniaturised – Asteroid Remote Geophysical Observer’, or M–ARGO, a nano-spacecraft based on the CubeSat design employing a 12-unit CubeSat, that would hitch a ride on the launch of a larger space mission, to study a little-known class of asteroid: small in size and rapidly spinning.
A key element of all these missions is the communication system, which needs to be DSN/ESTRACK compatible, small, light, and not power-hungry. Such a unit does not exist in Europe, at the moment. Bearing in mind JPL’s IRIS unit as a benchmark, we preliminarily proposed to ESA, in Feb 2019, our technical solution prepared by a consortium (**IMT srl**, **Thales Alenia Space Italy**, **Sitael** and **CIRI Aerospace of University of Bologna**) which brings together all necessary know-how and

expertise in the field of CubeSat and SmallSat technologies, digital and analog RF TT&C systems, power systems, radio science experiments.

Currently, the Project is in the MAIT phase.

This paper describes the results gained so far in the design and development of the Model to be validated/qualified in view of LUMIO and M-ARGO (ESA missions) and HENON (ASI/ESA mission).

2 THE PROJECT

The Project name, chosen by the consortium, is **C-DST**: "**CubeSAT Deep Space X-Band TT&C Transponder**".
The Contract with ESA was signed by IMT, as Prime Contractor, on sept. 2019.

The C-DST shall equip a CubeSat-based platform to be deployed beyond LEO orbits and able to sustain deep space condition.
The main challenge represented by this approach is represented by the lack of CubeSat standard equipments to be used for beyond-LEO orbit and for deep space application. Concerning the TT&C system perspective, this translates into the need to identify a specific architecture which allow to develop a TT&C system capable to:

- comply with the extreme miniaturization and low-power consumption requested by the CubeSat standard
- maintain the functionalities and performance usually requested to the TT&C for standard scientific mission
- provide the ground segment flexibility needed to reduce the launch and operation cost (i.e. allowing to catch piggybacking launch opportunities and optimizing the ground station use during the life).

The Nanosat TT&C system shall provide the following functionalities during all mission phases:

- Full-duplex operation in X-band for cat. A and B mission application
- Telecommand uplink
- Telemetry downlink
- Ranging and range rate operation including Delta-DOR

During the last years, the space market trends highlighted an increase in the CubeSAT and NanoSAT missions. These missions are characterized by low-cost subsystems based on COTS components. Besides, the key points for low-cost subsystem architecture are the low dimensions and low power consumption that, jointed to the adoption of COTS components, are the main topics for all state-of-art CubeSAT subsystems.
The C-DST activity regards the design and development of an X-Band transponder for NanoSAT / CubeSAT, with attention on the following aspects:

- **Modularity**: The transponder is designed for CubeSAT 12U (like as for M-ARGO/LUMIO/HENON platforms) as well as for CubeSAT 6U. This modularity gives high opportunities on the CubeSAT and NanoSAT market. Moreover, using the CubeSAT standard digital interfaces, such as CAN BUS (for the unit managing) and RS422 (for TLM/CMD and Payload data), as well as the possibility to accept a large range of power supply voltage (24V-33.6V as minimum), the transponder is suitable for also MicroSAT deep space missions.
- **Flexibility**: Thanks to the design flexibility (based on the Plug-and-Play philosophy), the transponder can cover several applications (in addition to the TT&C for Deep Space missions) maximizing the reuse of C-DST design. C-DST is compliant for CAT A (7190MHz-7235MHz / 8450MHz-8500MHz) and CAT B missions (7145MHz-7190MHz / 8400MHz-8450MHz). In

addition, the USO (Ultra Stable Oscillator) input option allows to perform radio occultation experiments for future deep space missions and different Signal Power Output values can be implemented with a re-design focused on the HPA Assembly, only. In addition, the LNA and HPA Assemblies can accommodate several configurations with the minimum re-design phase. The system can allow up to 3 antenna ports, depending on the satellite's architectural design.

3 C-DST ARCHITECTURE

In summary, the C-DST includes three assemblies:

- **Main Assembly**: it allocates the main functions of the unit, both DIGITAL and RF. It is composed of four modules, each one with a dedicated function (RX, TX, DIGITAL, POWER). The Main assembly is powered by the unregulated satellite bus (protected or unprotected lines), and it is connected to the OBC through the digital interfaces (discrete lines, CAN bus, and RS422 for TT&C/Payload data). In addition, internal interfaces ensure the power and data connections with the LNA assembly and HPA assembly.
- **LNA Assembly**: it provides the LNA chains. The assembly can accommodate up to 3 antenna input ports, and it can be located close to the antenna (to improve the RF performances) or in-stack with the Main Assembly. The LNA chains are selected by the CAN BUS command through the Main Assembly.
- **HPA Assembly**: it is composed of the power conditioning and the SSPA modules. The SSPA module could accommodate up to 3 SSPA chains with 3 different antenna ports (in the same way as LNA, the HPA chains are selectable by the CAN Bus through the Main Assembly)

The preliminary layout of the C-DST is reported Figure 1 and the additional characteristics in Table 1.

Table 1. C-DST Additional characteristics

Mass:	1.2Kg
Volume:	< 1.5U
Design Lifetime:	3 years
Power consumption:	STBY 8W RX mode 13W TX+RX mode 95W
Op Temp:	-20°c to +50°C
Carrier tracking signal range:	-60dBm to -150dBm
Output Power:	15W

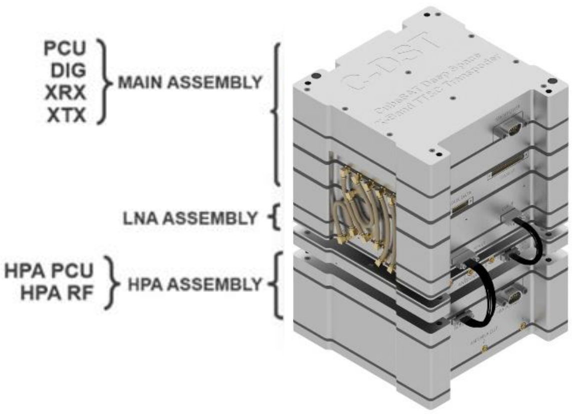

Figure 1. C-DST Preliminary Layout

The flexible layout allows changing on the front-end (LNA) and back-end (HPA) hardware (e.g. power transmission values) without the Main Assembly. This solution maximizes the re-utilizable design philosophy to increase the market competition (see Figure 2).

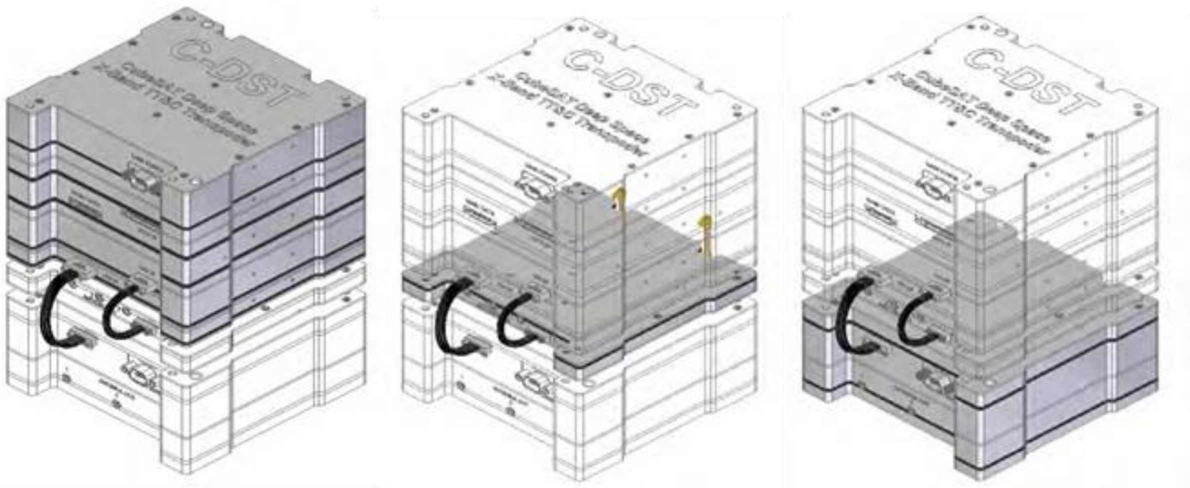

Figure 2. From left to right: Main Assembly, LNA Assembly and HPA Assembly

4 C-DST DESIGN

The assemblies can be mounted in-stack (see Figure 2 and Figure 3) or in separated configurations basing on the Spacecraft System Requirements. The LNA and HPA assemblies are connected to the Main Assembly through the Power/Data and RF connectors. The Figure 3 shows the stack-up configuration at the module levels. In particular:

- MAIN ASSEMBLY:
    - PCU
    - DIG
    - XRX
    - XTX
- LNA ASSEMBLY:
    - LNA PCU and RF
- HPA ASSEMBLY:
    - HPA PCU
    - HPA RF

Considering each assembly, the modules are connected thanks to the internal connectors (PCB to PCB connectors). The internal bus assures the digital, analog, and power interfaces for each module. RF connections are external and use cables and coaxial connectors.

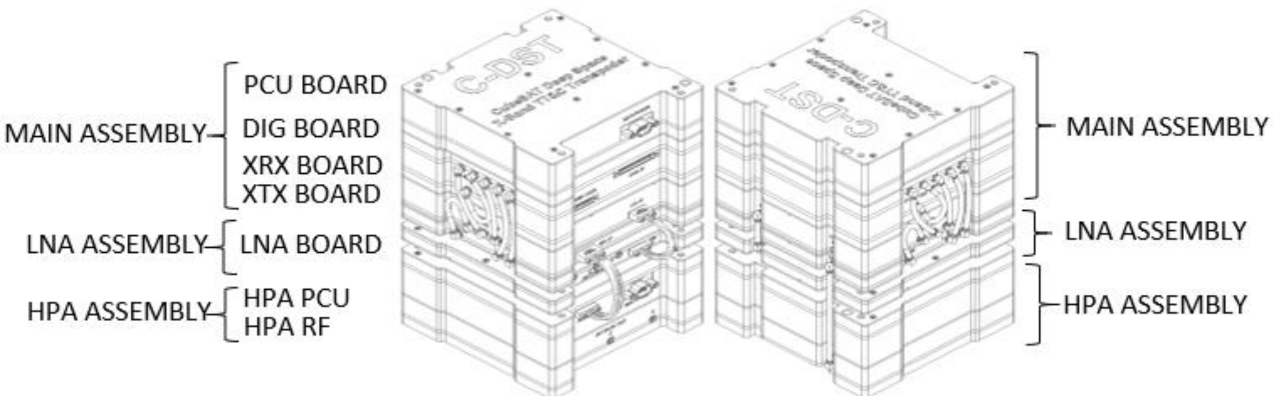

Figure 3. C-DST stack-up layout

The C-DST block diagram layout is shown in Figure 4. The dashed lines represent the optional I/Fs, like external USO or the supplementary LNA and HPA chains (N°2 and N°3 ports).
The LNA assembly is powered by the MAIN Assembly through the XRX module. It is switched on automatically whenever the XRX is powered-on.

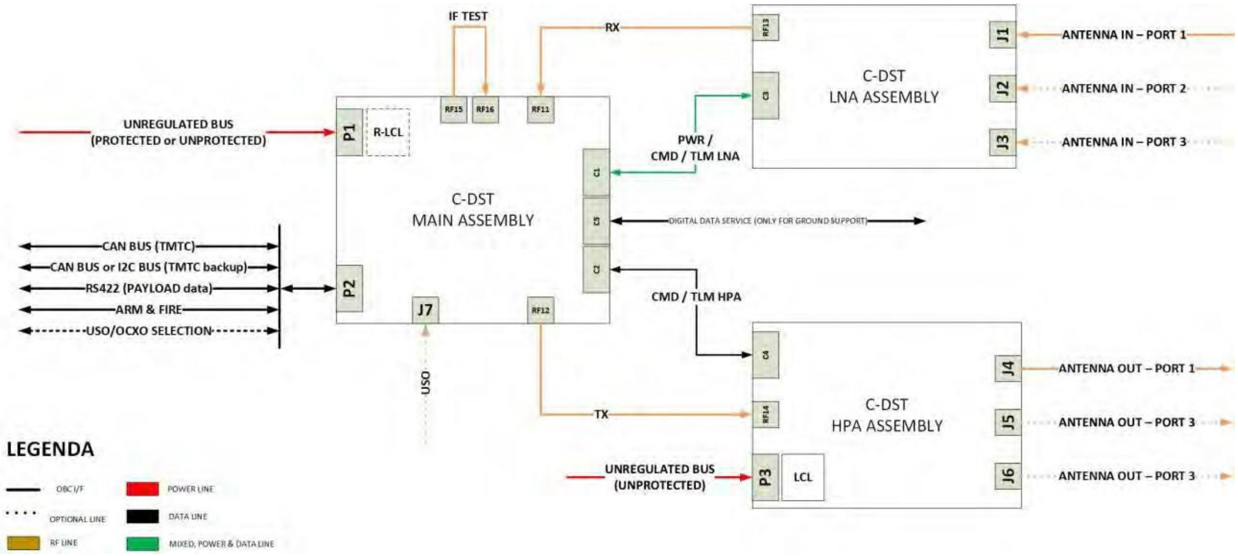

Figure 4. C-DST block diagram

The HPA Assembly is powered by the unregulated Satellite bus through a dedicated I/F and it is switched on by the MAIN Assembly (through the XTX module). LNA and HPA telemetries and commands are managed by the DIGITAL module (located in the MAIN Assembly). The RF connections with the Main Assembly modules are assured by coaxial cables.

C-DST provides to the spacecraft (through CAN Bus) the following TMs:
- Operating mode
- Selected Modulation scheme
- Selected coding scheme
- Selected modulation index
- Selected data rate
- Signal Eb/N0
- coherent/non coherent carrier AGC
- PN ranging AGC
- Internal temperatures
- Transponder voltage and current
- PA voltage and current
- Error status
- Carrier Lock Signal
- Data valid Signal
- Temperature (DIG, PCU, XRX, XTX, LNA 1-2-3, HPA 1-2-3)
- Current (DIG, PCU, XRX, XTX, OCXO, LNA 1-2-3, HPA 1-2-3)
- HPA Output Power (HPA 1-2-3)
- LNA ASSEMBLY and HPA Assembly Status (from the LCL circuits)

The unit is able to receive the following commands sent by the Satellite OBC, through CAN Bus or discrete commands:

- Set operative mode
- Set MODULATION scheme
- Set modulation index
- Set CODING scheme
- Turn transmitter ON
- Set RF input port
- Set RF output port
- Set data rate
- Get HK

In addition, the following discrete commands and telemetries are also implemented:

- Reset the C-DST (Arm/Fire HPC Commands)
- USO/OCXO Selections
- USO/OCXO Telemetries

4.1 XRX Module

The architecture of RX (Figure 5) is based on a single Down-Conversion heterodyne architecture. The board input is fed by the signal of the LNA assembly, mounted in a dedicated and separated Board (that can be placed close to the antenna) and connected to RX board by means of a coax cable. The Mixer, driven by a Local Oscillator, translates the received uplink signal at IF Intermediate Frequency. The local Oscillator is a fully integrated PLL, phase locked to an OCXO stable oscillator, physically placed on the RX Board. The OCXO can be substituted with an Ultra-Stable Oscillator (USO) for improved frequency stability, Allan deviation, and phase noise. The attenuators allow to control the gain for the overall chain and improve the return loss performance.

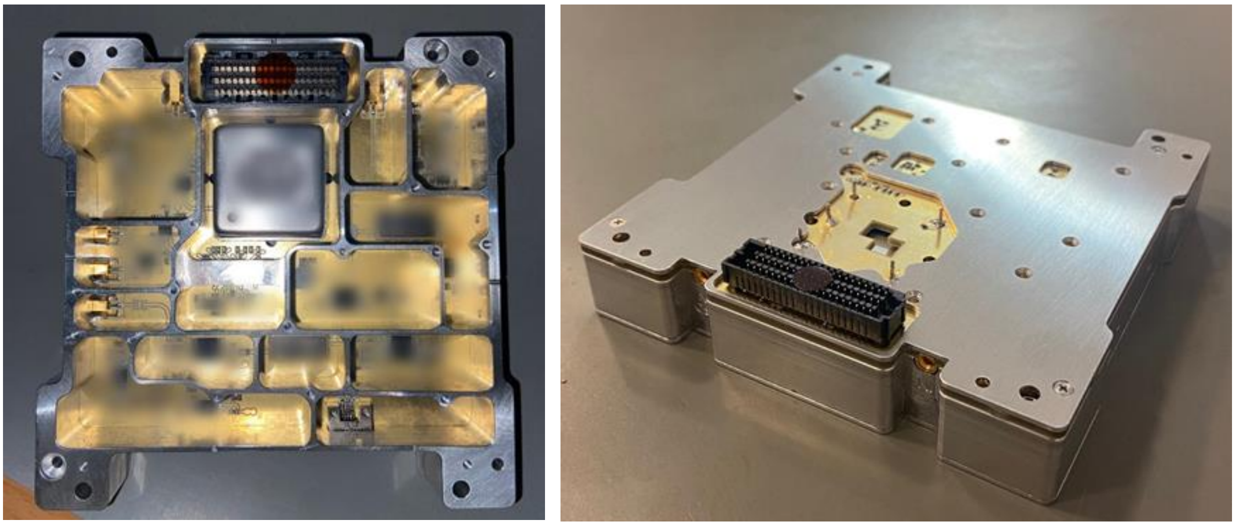

Figure 5. XRX board assembled in the module

4.2 XTX Module

The TX architecture (Figure 6) is essentially based on a X-band Vector modulator, driven by I/Q data signals provided by DACs in the Digital section. The output power of the digital section is very low and a first gain stage was inserted on the I and Q channels. The Output X-band modulated signal is filtered and provided to several amplifier stages that finally drive the HPA module with capability to provide up to 15 Watt of RF power. The attenuators allow to control the gain for the overall chain and improve the return loss performance.

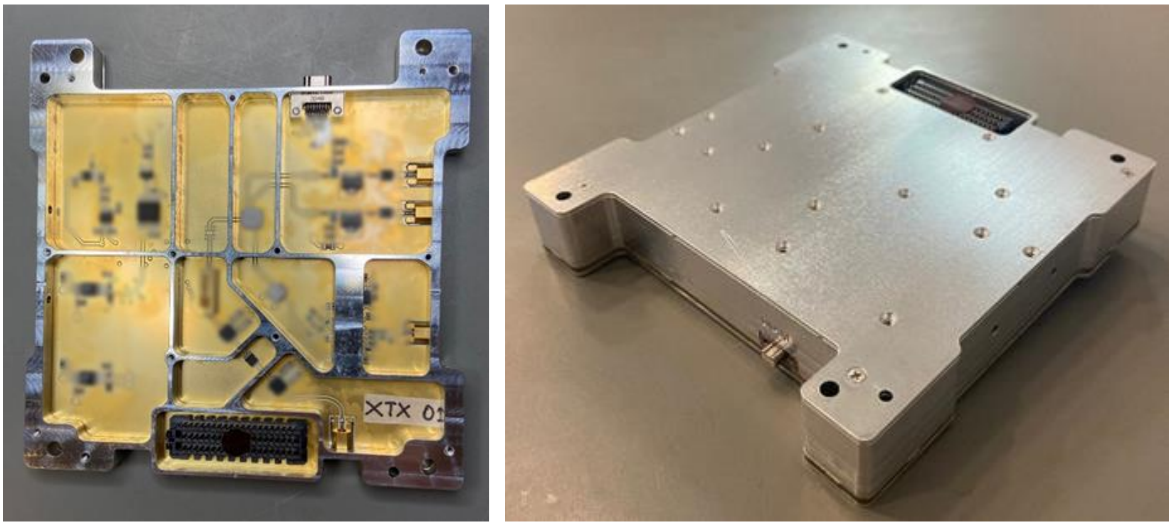

Figure 6. XTX board assembled in the module

4.3 Digital Module

The Digital board (Figure 7) represents the equipment core being devoted to the DSP (Digital Signal Processing) functions through the LEON2FT Microprocessor (µP) embedded in the FPGA. The TT&C DSP core is recurring from the DST/KaT ASIC which have been designed, developed and qualified in the frame of BepiColombo program and then used in several follow-on missions such as ExoMars, Solar Orbiter, Euclid, JUICE. The digital module is based on a PCB mounting the RT4G-150 FPGA from Microsemi (that embeds also the LEON2FT Microprocessor), the ADC, DACs, IF drivers and data memories.

The DSP FPGA implements the following main cores:

- LEON2FT Embedded Microprocessor
- TT&C DSP Core (based on KaT ASIC System-on-Chip (SoC) building blocks)
- CAN IP Core (main & redundant interface)
- I2C Core (as option)

The C-DST digital module consists of the following circuits:

- ADC for IF signal data conversion.
- ARM-&-FIRE interface to the FPGA
- Downlink Telemetry Interface
- Demodulated telecommand line drivers for data, clock, data valid and RF lock status
- Down-link Ranging/TM/Coh. DAC
- RF AGC Serial I/F to VCA
- PLL PISO Interface
- ADC for housekeeping telemetries
- General purpose PIO IF

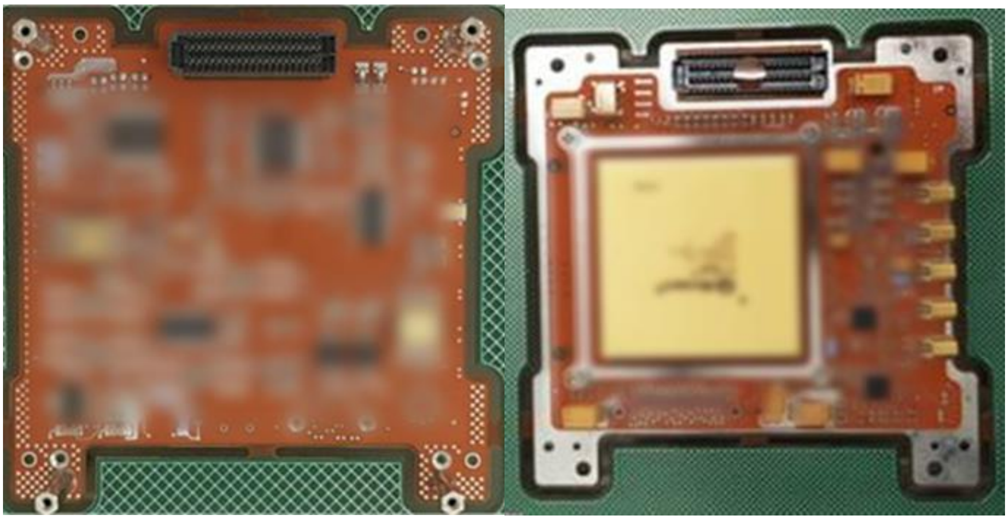

Figure 7. DIGITAL Boards

4.4 PCU Module

The PCU board (Figure 8) generates the power to the whole Transponder boards (Main Assembly) using the unregulated primary power bus provided by the S/C. The board can work correctly in the range 24 to 34 Volts. Total power capability of the board is about 15W The PCB is shown in Figure 8.

Main features of the PCU board are indicated below and detailed in the following paragraphs:

- R-LCL input protection;
- Input voltage monitor;
- Input EMI filter;
- Main Forward Switching Converter and linear regulators to provide external regulated voltages;
- Output current limiter and OVV Protection.

Figure 8. PCU Board

4.5 LNA Assembly

The Front-End Low Noise amplifier (Figure 9) is physically located in a dedicated board with scope to permit to install it close to Antenna port and with goal to minimize the input loss that provides a benefit for the RX Noise figure.

A non-reflective single-pole quad-throw switch is used to combine the three LNA section into the same Image Filter. A dedicated command, thru CAN BUS, drives both the active switch and the relevant LNA voltage regulators, in order to guarantee the minimum power consumption (only one active at a time).

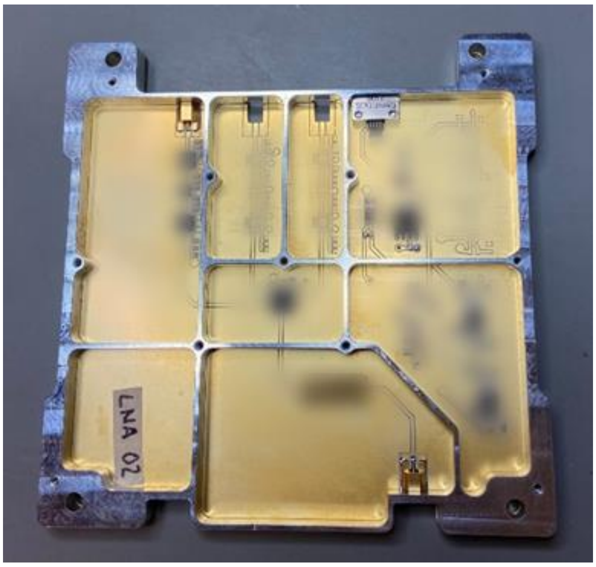

Figure 9. LNA board assembled in the module

4.6 HPA Assembly

The HPA Assembly covers the power amplifier aspects of the transponder. It could be located close to the antenna or in-stack mount with the main assembly. The RF module is placed on a thermal plate in order to reduce the temperature reached by the components during the operative mode. The HPA Assembly has two I/F connectors, the “Power I/F” for the power lines, connected to the unregulated satellite bus and the “HPA I/F”, connected to the XTX Module (Main Assembly) for TM and TC signals. In addition, one RF-IN connector (Main Assembly port) and three RF-OUT connectors (Antenna ports) are used for the RF purpose. The Assembly is composed by two modules:

- Power Conditioning Module (HPA_PCU): dedicated to all power needs (composed by DC/DC Converter, filters, LCL, etc..). This module is connected to the unregulated satellite power bus (24V-34V).
- High Power Amplifier Module (HPA_RF): dedicated to the SSPA amplifiers. Currently, one SSPA @ 15W is considered in the design but in the unit could mount up to three different chains (for three different antennas). The HPA channels are selectable by the Main Assembly through OBC CAN bus command.

The Front-End High-Power amplifiers is physically located in a dedicated board that allows the installation as close as possible to the Antenna port, aiming to minimize the output losses.
A non-reflective single-pole quad-throw switch is used to select the HPA chain. A dedicated command, thru CAN BUS, drives both the active switch and the relevant HPA voltage regulators, in order to guarantee the minimum power consumption (only one active at a time).

The HPA_PCU board generates the power to the HPA Assembly boards using the unregulated primary power bus provided by the S/C. The board can work correctly in the range 24 to 34Volts. Total power capability of the board is about 75W, the PCB is shown in Figure 10.

Figure 10. HPA_PCU Board

Thanks to the flexible architecture, the HPA ASSEMBLY can be provided by thermal straps to reduce the temperature gradient reached by the boards during the transmission phases. The thermal straps can be placed on the lateral side to improve the thermal conductance between HPA PCU and HPA RF, as shown in Figure 11.

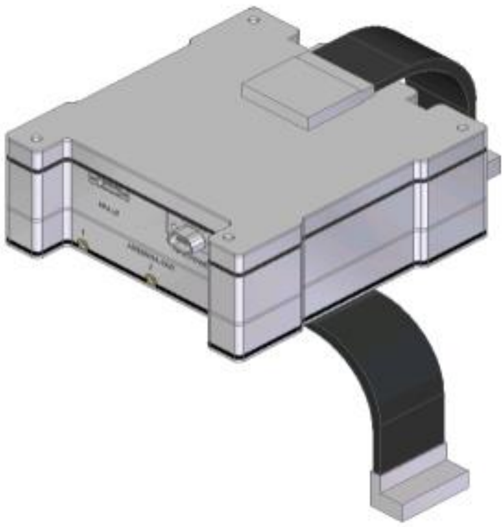

Figure 11. HPA Assembly with thermal strap. The figure is only representative purpose

5 GROUND SEGMENT

As far as the ground segment is concerned, the communication system shall rely on both 15m GS and 35m ESTRACK GS. In particular, the use of 15m GS shall be considered for LEOP in order to guarantee the flexibility required to be compatible with piggyback launch scenarios, where a large number of the ground stations are typically used for LEOP support to the primary mission, and in-time execution of the commissioning operation for proceeding as early as possible with the transfer correction manoeuvre to save the amount of required propellant.

On the other side, the limited performance of 15m GS would make them usable only up to a certain distance. From a preliminary evaluation, to maintain the TT&C sizing in line with the CubeSat size and power constraint, the 15m GS are expected to be usable up to the transfer and waiting phase. Beyond this limit, the 35m GS will become the main facility, leaving to 15m GS the role of backup station aimed to quick spacecraft status check and low-rate downlink-only operation.
For operations beyond 1AU, 35m G/S will be used up to maximum distance and main HGA antenna. TC operations shall be guaranteed also with LGAs regardless of S/C attitude.

6 C-DST PERFORMANCES

The Table 2 shows the C-DST main Perforformances.

Table 2. C-DST Main Performances

<table>
<tr><td>Network Compatibility</td><td colspan="2">ESTRACK</td></tr>
<tr><td>Design Lifetime</td><td colspan="2">3 years</td></tr>
<tr><td>Frequency Bands (Uplink)</td><td colspan="2">7145 MHz -7190 MHz (Cat. B missions)
7190 MHz - 7235 MHz (Cat. A missions)</td></tr>
<tr><td>Frequency Bands (Downlink)</td><td colspan="2">8400 MHz -8450 MHz (Cat. B missions)
8450 MHz -8500 MHz (Cat. A missions)</td></tr>
<tr><td>Coherency</td><td colspan="2">Coherent operations supported</td></tr>
<tr><td>Turn-around rations</td><td colspan="2">749 / 880</td></tr>
<tr><td>Ranging</td><td colspan="2">ESA STD ranging
PN regenerative ranging</td></tr>
<tr><td>Navigation Support</td><td colspan="2">2-way Doppler
PN regenerative Ranging (in accordance to CCSDS 414.1-B-2)
Delta-DOR (in accordance to CCSDS 401.0-B)</td></tr>
<tr><td>Volume</td><td colspan="2">< 1,5U (94 mm x 94 mm x 131,5 mm)</td></tr>
<tr><td>Oscillator</td><td colspan="2">Internal OCXO
External USO – Ultra Stable Oscillator (100 MHz) *</td></tr>
<tr><td>OCXO Allan Deviation</td><td colspan="2">< 1E^-10 at 1 sec</td></tr>
<tr><td>TM/TC Interface</td><td colspan="2">Redundant CAN bus
CAN Bus or I2C* as backup
HPC Command (ARM & Fire)</td></tr>
<tr><td>Payload Data Interface</td><td colspan="2">RS422</td></tr>
<tr><td>Operation Modes</td><td colspan="2">STBY
RX – Signal Detection, Carrier Acquisition, Carrier Tracking and TC Tracking
RX & TX</td></tr>
<tr><td rowspan="2">Power Consumption</td><td>Operative Mode</td><td>POWER</td></tr>
<tr><td>STBY
RX
RX & TX</td><td>7.7W
12.8W
94.4W @ 15W Output Power</td></tr>
<tr><td>Operative Temperature</td><td colspan="2">-20°C + 50°C</td></tr>
</table>

Non-Operative Temperature	-30°C + 60°C
Uplink symbol rate	Up to 4000 sps
Uplink modulation	PCM / PSK / PM (sine sub-carrier)
Uplink encoding	BCH LPDC (128, 64)
Carrier Tracking Signal Range	-60 dBm to -150 dBm
Carrier acquisition threshold	-145 dBm
Carrier tracking threshold	-150 dBm
Downlink symbol rate	Up to 60 ksps Up to 1 Msps * 8 Symbol rate selectable
Downlink modulation	PCM / PSK / PM (sine and square sub-carrier) SP-L *
Downlink encoding	Concatenated RS (255,223) and convolutional code rate ½ LDPC (2048,1024) Turbo rate ¼ *
Output power	15W @ antenna port

7 C-DST DIMENSIONS AND MASS

The C-DST unit is fully compliant with the CubeSAT mechanical interfaces and the overall dimensions are less than 1.5U. The three different sub-assemblies could be mounted in stack or localized separately inside the satellite, basing on the satellite system needs. The mass is about 1.4Kg

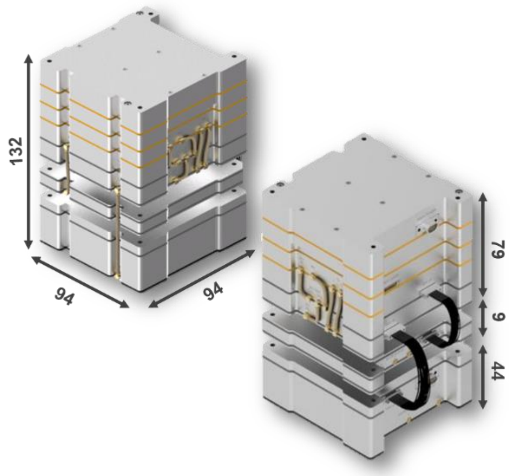

Figure 12: C-DST Dimensions

Table 3: C-DST Mass Budget

Assembly	Module	Mass (g)	Contin. (%)	Mass (g)
MAIN	*PCU*	191	5%	201
	DIG	182	5%	191
	XRX	149	5%	156
	XTX	89	5%	93
	Screws + Harness	15	5%	16
	TOT	626	5%	657
LNA	*Assembly*	100	5%	105
	Screws + Harness	10	5%	11
	TOT	110	5%	116
HPA	*HPA_PCU*	192	5%	202
	HPA_RF	373	5%	392
	Screws+Harness	5	5%	5
	TOT	570	5%	599
	Harness	10	5%	11
TOT		1316	5%	1382

8 CONCLUSION

The main objective to design and X-Band Transponder compatible with Cubesat 6U and 12U for Deep Space mission has been reached with the C-DST design and development that appear very promising for several low-cost space missions already established.
Currently, the C-DST has been selected for **LUMIO** (Lunar Meteoroid Impact Observer – ESA mission), it is candidate for **M-ARGO** (Miniaturised – Asteroid Remote Geophysical Observer – ESA mission) and for **HENON** (HEliospheric pioNeer for sOlar and interplanetary threats defeNce ASI/ESA mission)

The following roadmap is planned for the C-DST follow-on activities:

- Q3 2024 completion of ESA Validation
- Q4 2024/Q1 2025 CDR for HENON program