POLITECNICO DI TORINO

e-st@r-II program: *CubeSat description*	CubeSat polito team

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For detailed information and update on the e-st@r program and mission see the CubeSat Team website at http://www.polito.it/cubesat-team, or see the Twitter account (https://twitter.com/CubeSatTeam) and the Facebook page (https://www.facebook.com/CubeSatTeam).

1 Document control data

1.1 Document change log and record

Change Log			
Reason for change	Issue	Revision	Date
Draft version 1	0	1	13.07.2013
Issue version 1	1	0	31.07.2013
Issue version 2	2	0	13.09.2013
Issue version 2	2	1	08.10.2013
Issue version 2	2	2	16.12.2013
Issue version 2	2	3	10.01.2014
Issue version 2	2	4	03.02.2014
Issue version 2	2	5	14.02.2014

Change records Issue 1 Revision 0		
Reason for change	Page(s)	Paragraph(s)
Some minor changes	various pages	
Change records Issue 2 Revision 0		
Reason for change	Page(s)	Paragraph(s)
Added a legend for the requirements	9	8
Requirements are changed according to version 2.0 of SSD	9-10-11	8
Block diagram was not easily readable so it was divided into different parts	11	8
Added explanation of attitude control during detumbling phase	19	9.3.2
Added explanation of “burn” algorithm	23-24	9.6.1

Change records Issue 2 Revision 1		
Reason for change	Page(s)	Paragraph(s)
Removed heaters activation through command from GCS and before the launch	25	9.8
Power budget updated, Annex I added.	28-29	12.2
Change records Issue 2 Revision 2		
Reason for change	Page(s)	Paragraph(s)
Updated applicable documents	3	1.2
Added reference to FDS	9	8
Updated requirements name according to EST_SSD_131216_v2.2	9-10-11	8
Inserted explanation of CW stop command	23	9.6
Updated the description of GCS antenna	26	12
Added reference to Annex II	30	12.3
Updated Table 17 and Table 18 according to Annex II**Errore. L'origine riferimento non è stata trovata.**	31	12.3
Change records Issue 2 Revision 3		
Update paragraph 9	13	9
Update paragraph 9.8	26	9.8
Update S&M paragraph	26	9.7
Update GSE&AIV/AIT Software paragraph	28	11
Added Figure 19: CAD model of solar panels installed on the structure	23	9.4
Change records Issue 2 Revision 4		
Update paragraph 9.2	18-23	9.2
Change records Issue 2 Revision 5		
Update figure of battery charging during HIL test showing the reaching of EoC	35	12.2

1.2 Applicable and reference documents

Applicable documents:	[AD1] CubeSat Design Specification, revision 12, August 2009
	[AD2] EST_MDD_140110_v2.1 - e-st@r-II Mission Description Document
	[AD3] EST_SSD_140110_v2.2 - e-st@r-II System Specification Document
	[AD4] FYS_FDS_131025_draft3 - Fly Your Satellite! interface Design Specification
Reference documents:	[RD1] ECSS-E-ST-10C (6 March 2009) - System engineering general requirements

2 Table of Contents

3 Figures

4 Tables

5 Definitions and abbreviations

5.1 Definitions

N/A

5.2 Abbreviations

A-ADCS - Active Attitude Determination and Control Subsystem
AFSK – Audio Frequency Shift Keying
AMSAT - radio AMateur SATellite corporation
ARI - Associazione Radioamatori Italiani
ASSET - AeroSpace Systems Engineering Team
CDS - CubeSat Design Specification
CNC - Computed Numerically Controlled
CoM - Centre of Mass
COMSYS - COMmunication SubSYStem
COTS - Commercial Off-The-Shelf
CW - Continuous Wave
DIMEAS – Dipartimento di Ingegneria Meccanica e Aerospaziale
DoD - Depth of Discharge
DPCDU - Daughter Power Control and Distribution Unit
DS - Deployment Switch
E-ST@R - Educational SaTellite at politecnico di toRino
EEPROM - Electrically Erasable Programmable Read-Only Memory
EMF – Earth Magnetic Field
EoC – End of Charge
EOL - End Of Life
EPS - Electrical Power Subsystem
EQM - Engineering/Qualification Model
ESA - European Space Agency
FDS - Fly Your Satellite! interface Design Specification
FM - Flight Model
FMECA - Failure Mode, Effects and Criticality Analysis
FYS - Fly Your Satellite
GCS - Ground Control Station
GSE - Ground Support Equipment
HIL - Hardware In the Loop
I/O - Input/Output
I2C - Inter-Integrated Circuit
IARU - International Amateur Radio Union
IMU - Inertial Measurement Unit
LEO - Low Earth Orbit
MCX - Micro CoaXial
MDD – Mission Description Document
MGCS - Mobile Ground Control Station
MPPT - Maximum Power Point Tracker
MTs - Magnetic Torquers
OAP - Orbit Average Power
OBC - On-Board Computer
OS - Operating System
PCB - Printed Circuit Board

PCDU - Power Control and Distribution Unit
PCM - Power Control Module
PDM - Power Distribution Module
PIC - Peripheral Interface Controller
PICPoT - PIccolo Cubo del Politecnico di Torino
PoliTo - Politecnico di Torino
PWM - Pulse Width Modulation
RAAN - Right Ascension of the Ascending Node
RBF - Remove Before Flight
RF - Radio Frequency
RX - Receive
SD - Secure Digital
S&M – Structure&Mechanisms
SMD - Surface Mount Device
STAR - Systems and Technologies for Aerospace Research
SW – Software
TBC - To Be Confirmed
TBD - To Be Defined
TCS - Thermal Control Subsystem
TLE – Two-Line Element
TNC - Terminal Node Controller
TRR – Test Readiness Review
TX – Transmission

6 Introduction

The present document describes into the details the e-st@r-II (Educational SaTellite @ politecnico di toRino - II) mission carried out by the CubeSat Team of Politecnico di Torino (Turin, Italy).
The CubeSat Team is a student team born in 2009 for the development of the e-st@r program in the framework of the initiative “Educational Payload on the Vega Maiden Flight” proposed by ESA Education Office in 2008. The CubeSat Team is coordinated by ASSET (AeroSpace Systems Engineering Team) of the Mechanical and Aerospace Engineering Department of Politecnico di Torino, under the supervision of professor Sergio Chiesa (full professor of Aerospace Systems Design), and professor Sabrina Corpino (assistant professor of Space Systems and Mission Design).
In these years of activity, the CubeSat Team has achieved the great target of launching the e-st@r-I spacecraft, which is now one of the two first Italian CubeSats in orbit. Students got involved in the design, development, and verification effort and participated actively in the integration and launch campaign.
The hands-on practice approach has been recognised as an effective means for educating engineering students, and to emphasize the educational purpose of the activity, a students’ team (CubeSat Team @ PoliTo) has been set up to develop the program from the design phase to on-orbit operations, under the leadership of Sabrina Corpino (assistant professor of Space Systems and Mission Design at PoliTo). It consists permanently of PhD students, but undergraduate and graduate students are also involved in the project and join the team for short-term activities.
The CubeSat Team works at the System and Technologies for Aerospace Research Laboratory (STARLab) of the DIMEAS.

The e-st@r-II has been selected has been selected to participate in Phase 1 of the "Fly Your Satellite!" programme.
For detailed information and update on the e-st@r program and mission see the CubeSat Team website at http://www.polito.it/cubesat-team, or see the Twitter account (https://twitter.com/CubeSatTeam) and the Facebook page (https://www.facebook.com/CubeSatTeam).

7 Scope and content

7.1 Scope

This document is aimed at describing the e-st@r-II CubeSat. The purpose is to give a detailed description of the CubeSat and its subsystems and to explain how they work.

7.2 Content

The document structure goes through the description of the functions to be carried out by the CubeSat in order to accomplish the mission, the description of the payload and of the subsystems and main equipment of the bus.

8 CubeSat design requirements summary

E-st@r-II is a 1U CubeSat developed for demonstrating the autonomous active attitude control capabilities based on magnetic actuation: in fact, the payload is an Active Attitude Determination and Control System. The commissioning phase foresees that the payload is deactivated leaving the satellite in its free tumbling motion, without any attitude stabilization. The A-ADCS starts its work when commanded from GCS, controlling the angular velocities and the attitude of the satellite.

The stowed configuration of e-st@r-II is an aluminium-alloy cube-shaped box, 100 mm per side, with 5 out of the 6 faces occupied by solar panels. The sixth external surface (-X face, see Section 9.1) hosts the antenna system and the access ports for ground operations. After the satellite activation, the antenna system deploys two arms of the dipole that remain attached to the CubeSat structure.

E-st@r-II has been designed, developed and assembled taking into account all the applicable requirements and constraints given in the CubeSat Design Specification (CDS). Since e-st@r-II has been selected for FYS ESA initiative, it will be verified that all the requirements defined in the Fly Your Satellite! interface Design Specification (FDS) are satisfied, upon the release of that document.

A functional analysis was carried out to identify the functions that e-st@r-II has to perform in order to achieve mission objectives and to satisfy mission and program requirements (Figure 1).

In Table 2, a system requirements extract is shown. For the complete system requirements, see the System Specification Document [AD3].

Table 1: Requirement name structure

Requirement name typical structure is X-Y-Z.N_n							
X	MR	PR	OPS	ENV	EXT-INT	SSR	GSR
Y (if any)	na	na	na	S = Space Environment L = Launch Environment T = Transport Environment	M = Mechanical E = Electrical	ILS = Integrated Logistics Support PHY = Physical F = Functional TCS = Thermal Control OPS = Operational ENV = Environmental INT = Interface PHY = Physical D = Design EXT = Exterior Dimensions MAT = Materials STR = Structure COM = Communications OBC = On Board Computer EPS = Electrical Power ADCS = Payload (A-ADCS) HW = Hardware SW = Software CON = Configuration GUI = Graphical User Interface	
Z (if any)	na	na	na	na	na		
N	progressive number	progressive number	progressive number	progressive number	progressive number	progressive number	progressive number
n (if any)	progressive number	progressive number	progressive number	progressive number	progressive number	progressive number	progressive number

Table 2: System requirements extract

Id#	**Requirements**	**Derived from**
SSR.01	All parts shall remain attached to the CubeSat during launch, ejection, and operations. No additional space debris shall be created	PR.06
SSR.02	Pyrotechnics shall not be permitted	
SSR.03	No hazardous materials shall be used on the CubeSat	PR.06
SSR.04	Total stored chemical energy shall not exceed 100 Watt-hours	PR.06
SSR.05	The whole CubeSat shall be turned off by a deployment switch, including real time clocks	PR.06
SSR-F.01	The ADCS experiment shall be carried out	MR.14
SSR-F.02	Functions to support life and operations in orbit shall be implemented	MR.02
SSR-F.03	The CubeSat shall be able to determine its attitude	MR.04 MR.14
SSR-F.04	The CubeSat shall be able to control its attitude	MR.14 SSR-F.01
SSR-F.05	The satellite shall be able to receive and to transmit from/to ground. Downlink and uplink shall be established	MR.09 MR.10 MR.11
SSR-F.06	The space link shall be optimized for its specific use in the chosen orbit	

Id#	Requirements	Derived from
SSR-F.07	Downlink margin shall be higher than 6 dB	SSR-F.05
SSR-F.08	The downlink data rates shall be selected to be compatible with the data transmission requirements of all phases of the mission	SSR-F.07
SSR-F.09	Uplink budget calculations shall be based on a BER of 10^(-4) at the input to the telecommand decoder	SSR-F.05
SSR-F.10	EPS, ADCS, OBC, and COMSYS shall communicate via the e-st@r-II bus, using the communication protocol as defined in Estar2.11_(OBC) document	SSR-CON.04 SSR-OBC-F.01
SSR-F.10_01	The EPS shall provide the OBC with batteries and solar panels telemetry and housekeeping data, as defined in Estar2.11_(OBC) document	SSR-F.10 SSR-OBC-INT.02
SSR-F.10_02	The OBC shall provide the e-st@r-II telemetry and housekeeping data to the COMSYS, as defined in Estar2.11_(OBC) document	SSR-COM-INT.02 SSR-F.10
SSR-F.10_03	The OBC shall provide the EPS, ADCS, COMSYS, with data and commands, as defined in Estar2.11_(OBC) document	SSR-F.10
SSR-F.10_04	ADC microprocessor shall acquire the IMU/MAG data, using a serial port and a RS232 standard protocol	SSR-ADCS-F.08 SSR-ADCS-F.09
SSR-PHY.01	Equipment dimensions shall be compatible with the CubeSat external and internal dimensions	SSR-PHY-EXT.02 SSR-PHY-EXT.02_01 SSR-PHY-EXT.02_02 SSR-PHY-EXT.02_03 SSR-PHY-EXT.03
SSR-PHY.02	The CubeSat shall not have structural modes at frequencies lower than 120 Hz in hard-mounted configuration	MR.05 PR.06
SSR-PHY.03	Fracture control plan conforming to ECSS-E-32-01C Rev.1 shall be implemented by the CubeSat provider (TBC)	SSR.01
SSR-PHY-M.01	The CubeSat mass shall not exceed 1330g	PR.06
SSR-PHY-M.01_01	The EPS (including solar panels) mass shall not exceed 450 grams	SSR-PHY-M.01
SSR-PHY-M.01_02	The ADCS mass shall not exceed 120 grams. The mass includes the electronics, the sensors and the actuators	SSR-PHY-M.01
SSR-PHY-M.01_03	The COMSYS mass shall not exceed 150 grams. The mass includes the electronics, the transceiver, the antenna and its support and deployment mechanism	SSR-PHY-M.01
SSR-PHY-M.01_04	The OBC mass shall not exceed 100 grams	SSR-PHY-M.01
SSR-PHY-M.01_05	The structure mass shall not exceed 250 grams. The mass includes all main structural elements	SSR-PHY-M.01
SSR-PHY-M.01_06	The harness, fasteners and other minor components mass shall not exceed 100 grams. The mass includes all cables and connectors	SSR-PHY-M.01
SSR-PHY-M.03	The CubeSat Centre of Mass shall be located within a sphere of 2 cm radius from its geometric centre	PR.06
SSR-PHY-M.04	Moments of Inertia shall be calculated	SSR-PHY-M.03
SSR-PHY-MAT.01	Total Mass Loss (TML) shall be <= 1%	PR.06
SSR-PHY-MAT.02	Collected Volatile Condensable Material (CVCM) shall be <= 0.1%	PR.06
SSR-PHY-EXT.01	The CubeSat shall use the coordinate system as defined in Figure 3 of FDS	PR.06
SSR-PHY-EXT.02	The CubeSat configuration and physical dimension shall be per Figure 3 of FDS	PR.06
SSR-PHY-EXT.02_01	The CubeSat shall be 100.0±0.1 mm wide (X and Y dimensions per Figure 3 of FDS)	PR.06 SSR-PHY-EXT.02

Id#	Requirements	Derived from
SSR-PHY-EXT.02_02	A single CubeSat shall be 113.5±0.1 mm tall (Z dimension per Figure 3 of FDS)	PR.06 SSR-PHY-EXT.02
SSR-PHY-EXT.02_03	All components shall not exceed 6.5 mm normal to the surface of the 100.0 mm cube (the green and yellow shaded sides in Figure 3 of FDS)	PR.06 SSR-PHY-EXT.02
SSR-PHY-EXT.03	Exterior CubeSat components shall not contact the interior surface of the CubeSat Deployer, other than at the designated CubeSat rails	PR.06
SSR-PHY-EXT.04	Deployables shall be constrained by CubeSat. The CubeSat Deployer rails and walls shall not be used to constrain deployable	PR.06
SSR-CON.01	The CubeSat shall include at least one (1) deployment switch on the designated rail standoff (ref. Figure 3 of FDS)	PR.06
SSR-CON.02	All CubeSat umbilical connectors shall be within the designated Access Port locations, green shaded areas shown in Figure 3 of FDS	EXT-INT.01 PR.05 SSR-STR-F.06
SSR-CON.03	The CubeSat shall have all connectors (including RBF pin) on one single panel of the picosatellite	EXT-INT.01 PR.06 SSR-STR-F.06
SSR-CON.04	EPS, ADCS, and COMSYS shall be attached to the e-st@r-II bus, on the OBC board, as shown in Estar2.08	MR.03 MR.08
SSR-CON.05	The OBC, COMSYS, ADCS, and EPS shall be attached to the main structure as shown in Estar2.08	MR.03 MR.08 SSR-STR-F.05
SSR-D.01	The RBF pin shall not protrude more than 6.5 mm from the rails when it is fully inserted into the satellite	PR.06 SSR-PHY-EXT.02_03
SSR-D.02	No radio emission is allowed once the CubeSat has been integrated in the CubeSat Deployer to prevent any electrical or RF interference with the launch vehicle and primary payloads.	PR.06
SSR-D.02_01	The CubeSat shall include at least one (1) deployment switch to completely turn off satellite power once actuated	PR.06 SSR-D.02
SSR-D.03	The CubeSat shall include umbilical connectors to allow for its diagnostics and battery charging after the CubeSat has been integrated into the CubeSat Deployer	PR.06
SSR-D.04	The CubeSat shall include a RBF pin to cut all power to the satellite	PR.06

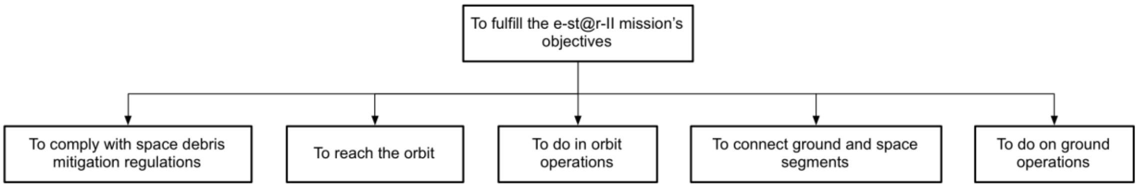

Figure 1: e-st@r-II functions

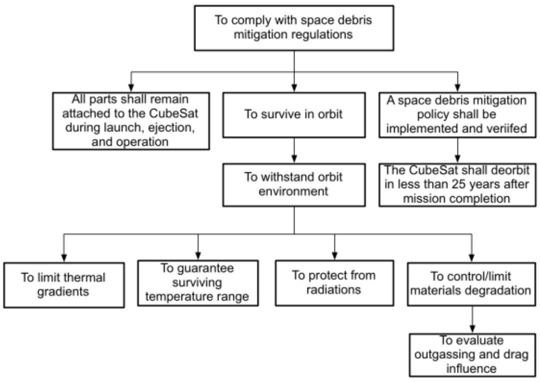

Figure 2: e-st@r-II functions – part 1

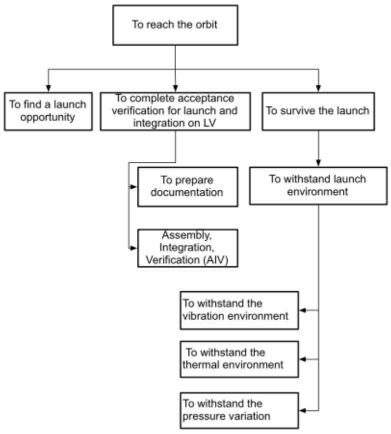

Figure 3: e-st@r-II functions – part 2

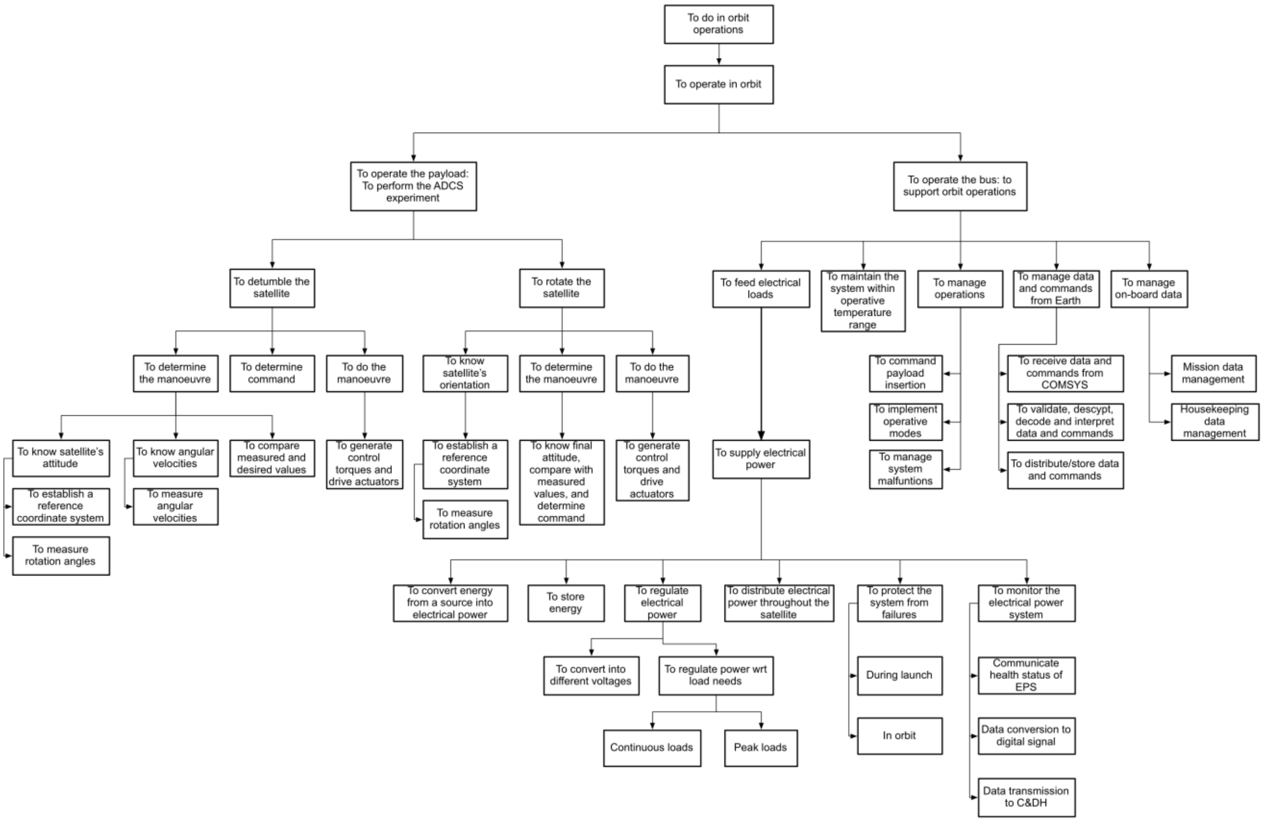

Figure 4: e-st@r-II functions – part 3

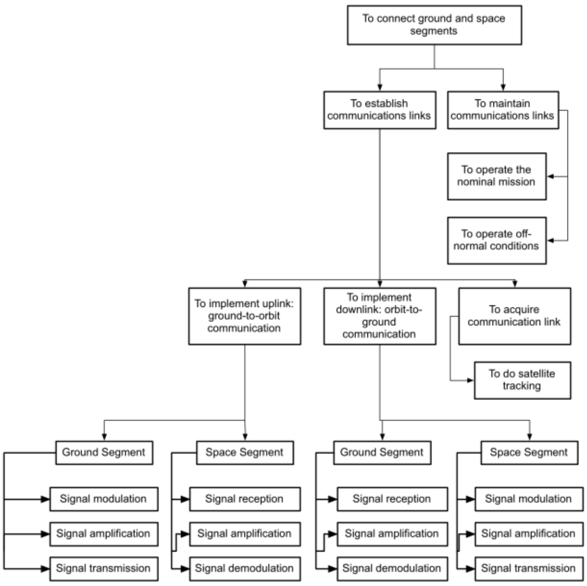

Figure 5: e-st@r-II functions – part 4

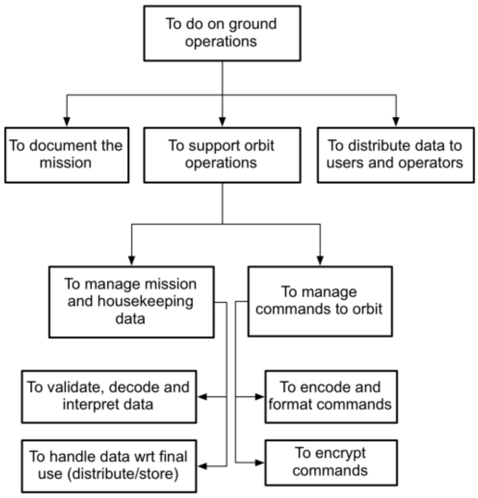

Figure 6: e-st@r-II functions – part 5

9 Spacecraft architecture

The platform in support of the payload (A-ADCS) was developed considering high level system requirements: it includes the Electrical Power Subsystem (EPS) devoted to provide, store, control and distribute the electrical power on-board, the Communication Subsystem (COMSYS) that provides the interface between the space and ground segments (no crosslink communications is envisaged), and the On-Board Computer (OBC) which handles and executes commands, manages and stores data and performs autonomous on-board operations. The Structure and Mechanisms subsystem (S&M) is devoted to carry the loads induced by the launch vehicle, to support and protect all other spacecraft subsystems, and to provide for spring plunger devices. Passive thermal control has been designed for the CubeSat. According to the requirements specified in [AD1] and [AD4], no pyrotechnics or other type of devices which allows to intentionally destroy the CubeSat are installed on e-st@r-II.

E-st@r-II is actually derived from the e-st@r-I design. E-st@r-I FM was built after the corresponding EQM was successfully verified. E-st@r-I was selected by ESA and was injected into orbit during the Vega Maiden Flight held on February 13th 2012.. We might say that e-st@r-II is a copy of e-st@r-I, but some considerations need to be specified.

We started from the operations and post-operations analyses of e-st@r-I mission, studying into the details any phase and all possible and actual failures that have occurred. Though new design has been avoided as much as possible and use of available hardware and tools preferred, the post-mission FMECA analysis suggested making some minor modifications both in the hardware and in the software of the system. In the following paragraphs, the subsystems of the new unit are described, and main differences between e-st@r-I and e-st@r-II are highlighted.

9.1 Coordinate Reference Frame and Spacecraft System Configuration

E-st@r-II main geometrical and mass characteristics are listed in Table 3. They refer to stowed and on-orbit configurations before deployment of the dipole antenna (for further details, see Section 9.5). No other deployable appendages are present in the design. Models in Figure 7, Figure 8 and Figure 9 show the satellite and its subsystems. In the diagram in Figure 10, all interfaces among subsystems are summarized. Figure 11 illustrates the CubeSat blocks scheme: each coloured-box represents a subsystem, while in grey the main satellite bus which connects all the subsystems is shown. Different colours have been used for types of connections: black links represent power connections, blue ones represent analogue signals and reds are digital data links.

Table 3: geometry and mass characteristics

Shape:	cube
Dimensions:	100 mm (side)
Mass:	975 g
CoM (with respect to the geometric centre and reference axes as per Figure 7):	
X:	1.426 mm
Y:	-3.725 mm
Z:	48.664 mm
Principal moments of inertia [kg*m^2]:	
I_{XX}:	< 0.002
I_{YY}:	< 0.002
I_{ZZ}:	< 0.002

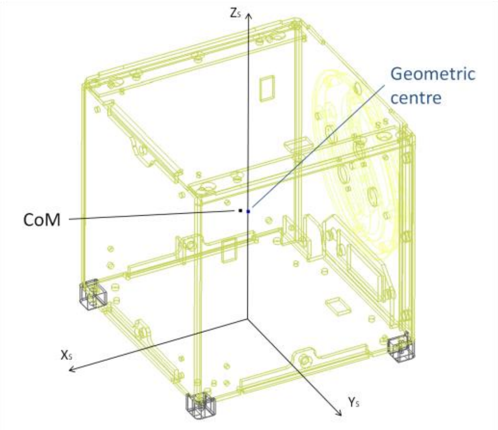

Figure 7: e-st@r-II wireframe model and coordinate reference system

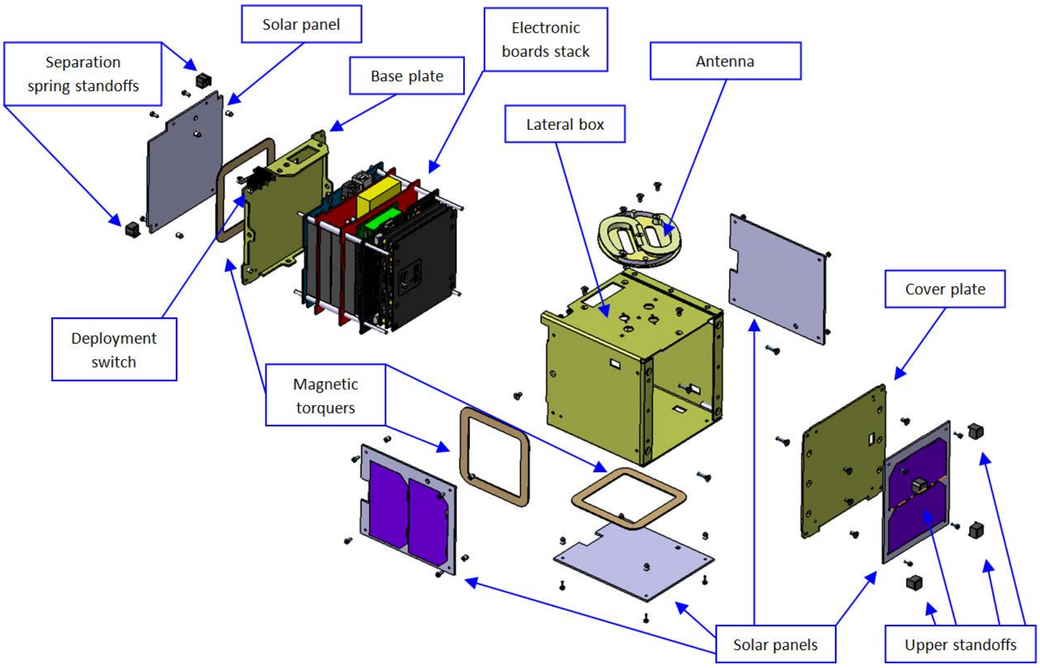

Figure 8: e-st@r-II exploded view

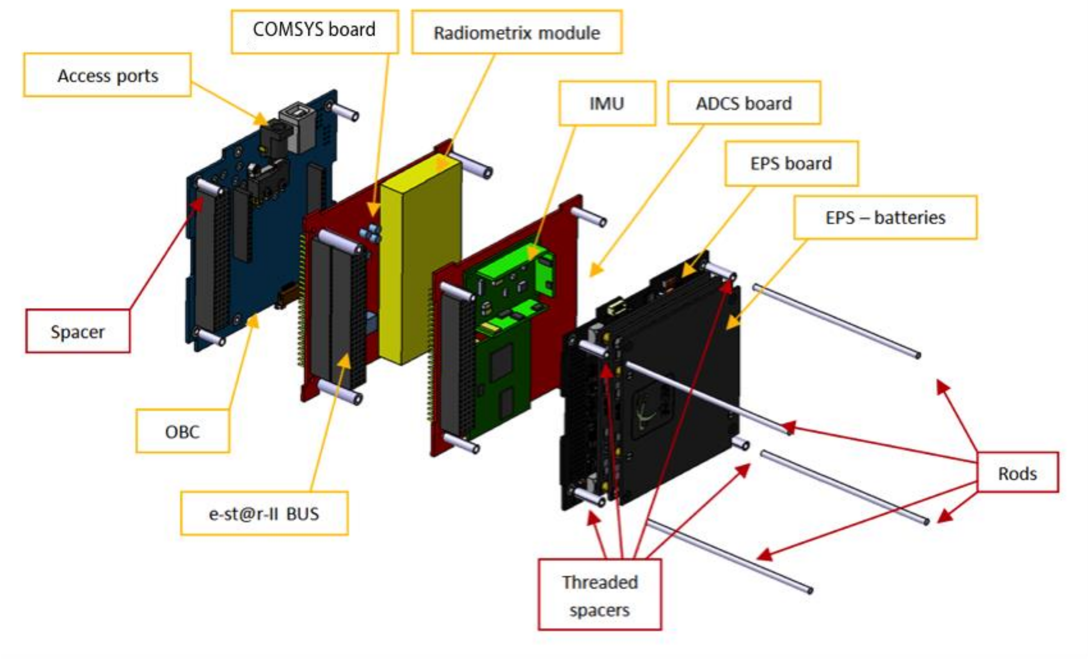

Figure 9: e-st@r-II exploded view with the electronic stack in evidence

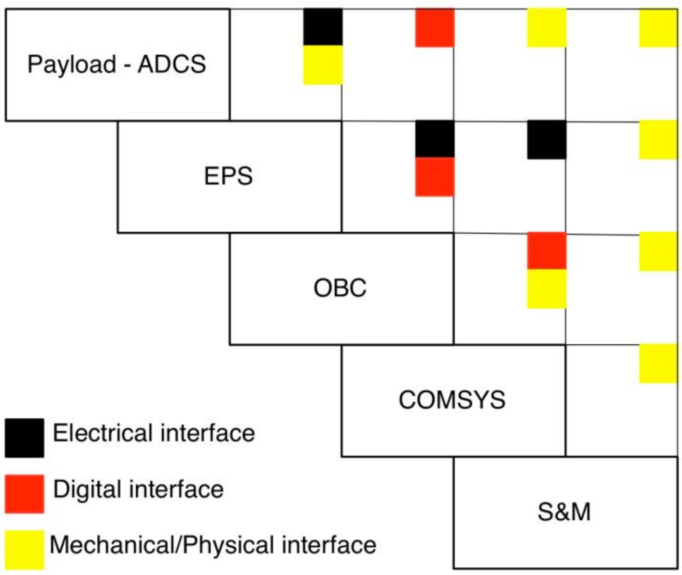

Figure 10: N2 diagram of subsystems interface

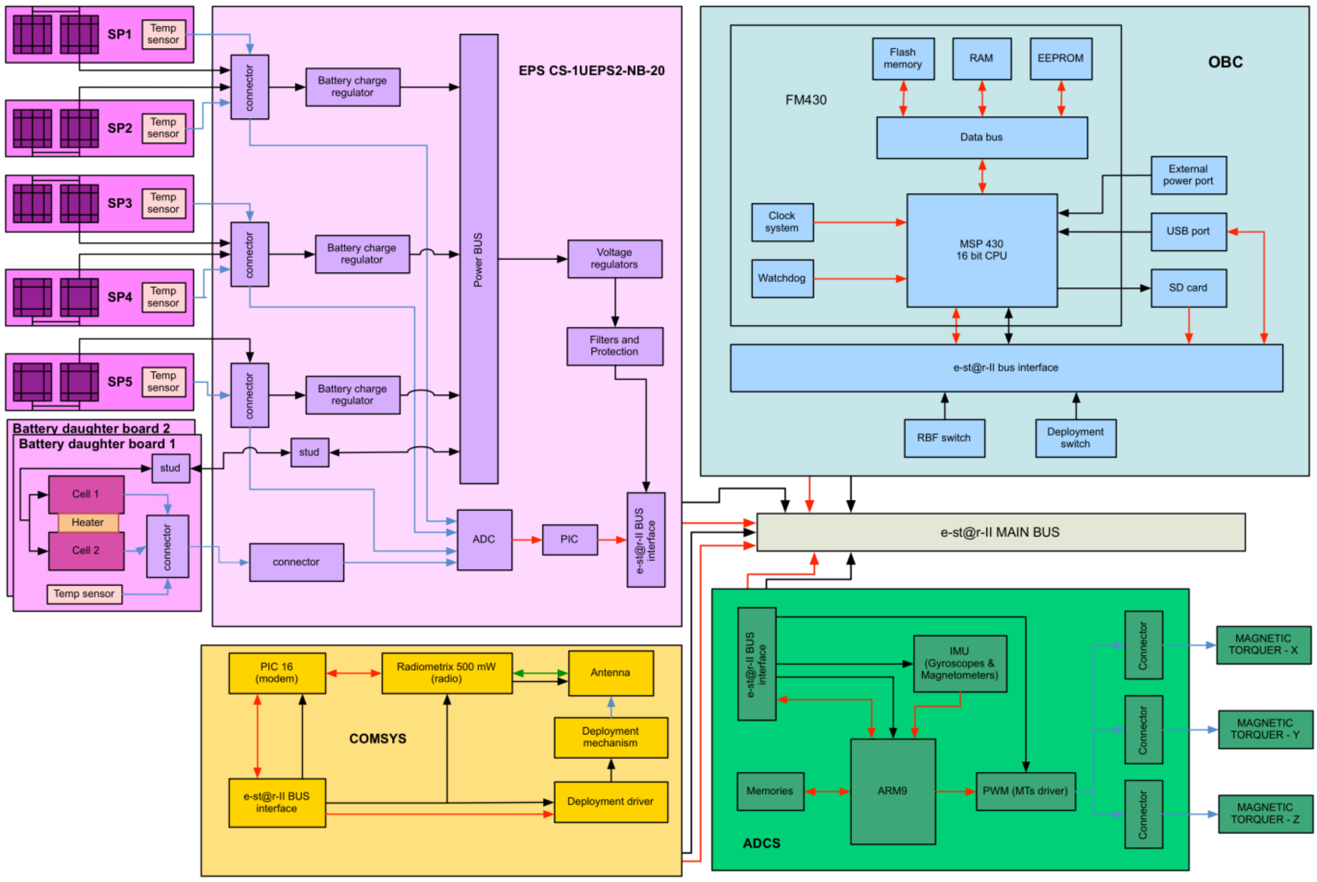

Figure 11: e-st@r-II system architecture blocks scheme

9.2 Payload: Active-Attitude Determination and Control System (A-ADCS)

The payload of e-st@r-II is an active attitude determination and control system based on inertial and magnetic measurements, with magnetic actuation.

The choice of this kind of payload derives straight from the definition of mission objectives (see [AD2]). Recently, CubeSats are gaining great success in scientific and industrial communities, because they represent a future alternative to traditional platforms. Before using them on a large scale for complex missions, it is necessary to investigate and solve challenging issues: among these, the attitude control is one of the most important. To date, only a small fraction of launched CubeSats has tested on-orbit an attitude control subsystem: 50 out of 110 launched CubeSats hosted A-ADCS, but excluding those that have never reached orbit due to launch failures and those that did not work, the number reduces to 19 out of 110 (11 are 1U CubeSat, 2 1.5U and 6 3U)[1]. This is one of the reasons for which testing an A-ADCS in orbit is a very fascinating challenge and crucial for the improvement of this small platform.

On e-st@r-II, the payload is activated only when the satellite reaches its final orbit. The system shall provide the desired (nadir) antenna pointing and/or proper reorientation manoeuvres when required upon commands from GCS.

The core of the system is an ARM9 microcontroller that manages the interfaces between sensors, actuators and OBC, performing the control tasks. Stabilization and slew manoeuvres are performed through the activation of three magnetic torquers (MTs) mounted on three perpendicular planes. The satellite attitude is determined processing the data provided by a COTS Inertial Measurement Unit (IMU), which integrates two bi-axial magnetometers.

Three operative modes have been defined for the payload:

- *mode 0 - standby*: this is the default mode, there is no active component

[1] Data based on public information available and updated to May 2013.

- *mode 1 - determination*: the microcontroller (ARM9) is active and performs its functions. IMU is active too, in order to measure the angular velocities and the EMF, and to estimate the attitude with proper algorithms executed by the ARM9
- *mode 2 - control*: this is the full mode, the microcontroller commands the MTs to detumble/stabilize (depending on the mission phase) the CubeSat.

Main changes w.r.t. e-st@r-I design are in the modes of operation of the payload rather than in the hardware configuration. In e-st@r-I the payload was activated autonomously on-board immediately after the CubeSat was released from the deployer. In the new design, the payload is activated upon command from the GCS. To permit this new functionality, a circuit has been added in the printed circuit board (PCB), w.r.t. e-st@r-I ADCS PCB.

Table 4: ADCS components

Type	Producer
Microcontroller ARM9	Elpa s.a.s.
Printed Circuit Board (PCB)	Millennium Dataware srl (on CubeSat Team design)
SMD components	RS Components S.p.A.
IMU	Xsens Technologies B.V.
Magnetic torquers	CubeSat Team
Assembly and integration	CubeSat Team
Software	CubeSat Team

Figure 12: ADCS electronics

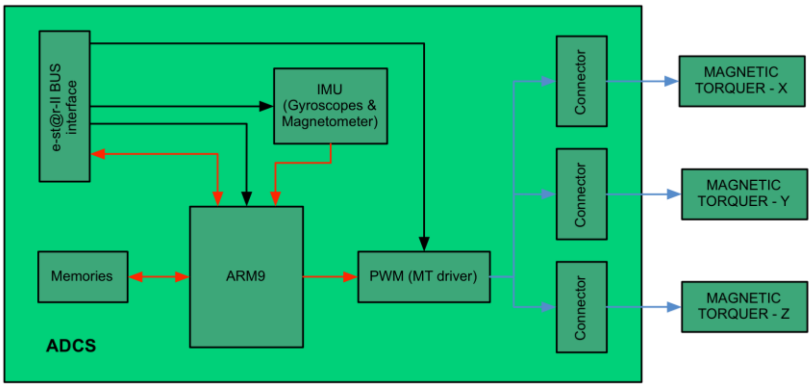

Figure 13: ADCS blocks scheme

9.2.1 Payload Hardware configuration

The electronic board has been designed and assembled in the STARLab of Politecnico di Torino. It hosts the electrical and logic circuits to meet the physical, mechanical, functional and interface requirements of the A-ADCS subsystem.

The core of the electronic board is the RD129 - ARM9 Embedded CPU produced by ELPA s.a.s. and its Operating System (OS) is Linux Embedded. Features of this CPU are listed in Table 5. ARM9 integrates various I/O logic circuits but only few are used: 3 serial ports, 3 internal clocks to handle PWM commands and some I/O generic pin used as analog-to-digital converters. The first serial port is used to communicate with IMU, that transfers data with a custom protocol. IMU is installed on the electrical board with four screws and any misalignment is corrected by software (the correct integration of the IMU on the ADCS board was verified by means of calliper and bubble level). The second serial port connects the microcontroller with the system bus and the last serial port is used during test as debug line.

The adopted IMU is the MT9 Inertial 3D Motion sensor produced by Xsens Technologies B.V. Its specifications are shown in Table 6 and in Figure 16 biases, gains and misalignments of gyroscopes, accelerometers and magnetometers are shown (this a screenshot of the Xsens software provided with the IMU). The company properly characterized the

IMU but in addition we tested it on a homemade rotation table to verify the correctness of its behaviour: it is quite similar to that expected, it does not deviate significantly, probably small variations could be related to the GSE (see TR_Estar2.012013_IMU characterization document for more details about the results of this test).
The actuators control circuit transforms the low voltage logic signal coming from the microcontroller and converts it into a square wave (0 - 5 V) with a duty cycle corresponding to the command for controlling the MTs. The circuit for the telemetry acquisition allows knowing the amount of current drawing through MTs, providing a voltage value (0 - 3.3 V) proportional to the current. The value is read by ARM9 from an I/O generic pin and then it is written on a virtual file.
In Figure 13 the ADCS block diagram is shown: black connections are power links (EPS supplies power through the interface bus), red and blue connections represent the data link respectively digital and analog.
As the MTs are concerned, they are properly sized to guarantee a dipole moment of 0.07 Am^2. The coils are positioned between the FR4 solar panels' supports and the satellite external surfaces (Figure 14). The coils have been designed and realized entirely by the CubeSat Team (Table 7 and Figure 15).

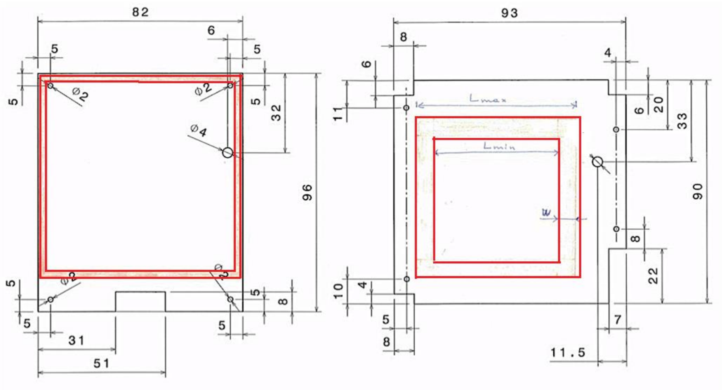

Figure 14: dimensional constraints on the +X/-Y faces (left) and -Z face (right)

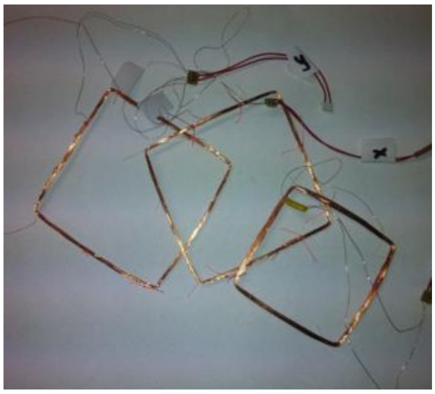

Figure 15: Magnetic torquers

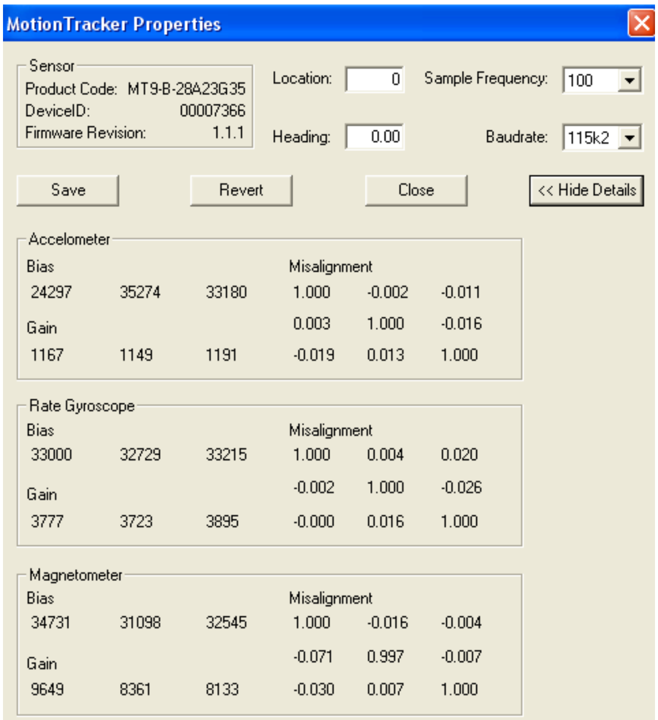

Figure 16: MT9 IMU properties

Table 5: ARM9 specifications

RD129 ARM9		
Technical features	**Physical specifications**	
32-bits ARM 9 CPU, clocked at 240MHz	Power	0.5W typical
32MB of SDRAM at 120MHz	Dimensions	45x40x8 mm
64MB of on board Flash memory	Temperature operating range	-25 / 85 °C
3 Serial interfaces		
2 USB host interfaces		
10-bits ADC converter		
I2C bus interface		
4 internal PWM timers		
Watchdog timer		

Table 6: IMU specifications

MT9 Xsens					
Sensor performance	**note**	**rate of turn [deg/s]**	**acceleration [m/s^2]**	**magnetic field [mGauss]**	**temperature [°C]**
Dimensions		3	3	3	-
Full scale	[units]	+/- 900	+/- 20	+/-750	-55 / +125
Linearity	[% of full scale]	0.1	0.2	1	<1
Bias stability	compensated [units 1σ]	5	0.02	0.5	-
	uncompensated [units per °C]	1	0.02	-	-
Scale factor stability	compensated [% 1σ]	-	0.05	0.5	-
	uncompensated [% per °C]	0.15	0.03	0.5	-
Noise	[units RMS]	0.7	0.01	4.5	0.0625
Alignment error	[deg]	0.1	0.1	0.1	-
Bandwidth	[Hz]	50	30	10	-
Physical specifications		**Maximum ratings**			
Interface	RS-232	Shock (any axis)	5000 m/s^2 powered		
Operating voltage	5.5 V		100000 m/s^2 unpowered		
Supply current	40 mA	Supply voltage	-0.3 / 12 V		
Temperature operating range	0 / 55 °C	Storage temperature	-5 / 60 °C		

Table 7: MTs specifications

		MT X		MT Y		MT Z	
number of turns	n	105		105		165	
wire reference resistance	R_w	1405	Ω/Km	1405	Ω/Km	1120	Ω/Km
wire diameter	d_w	0.125	mm	0.125	mm	0.14	mm
mean side length of MTs	L	78	mm	78	mm	62	mm
true resistance	R_true	50.6	Ω	50.8	Ω	48.4	Ω

9.2.2 Payload Software design

The software has been designed and implemented by students of the CubeSat Team on Linux Embedded OS. The software logic is depicted in Table 17. Blue blocks represent the setup and interface data management functions, yellow blocks represent attitude determination functions and green blocks denote the attitude control tasks.

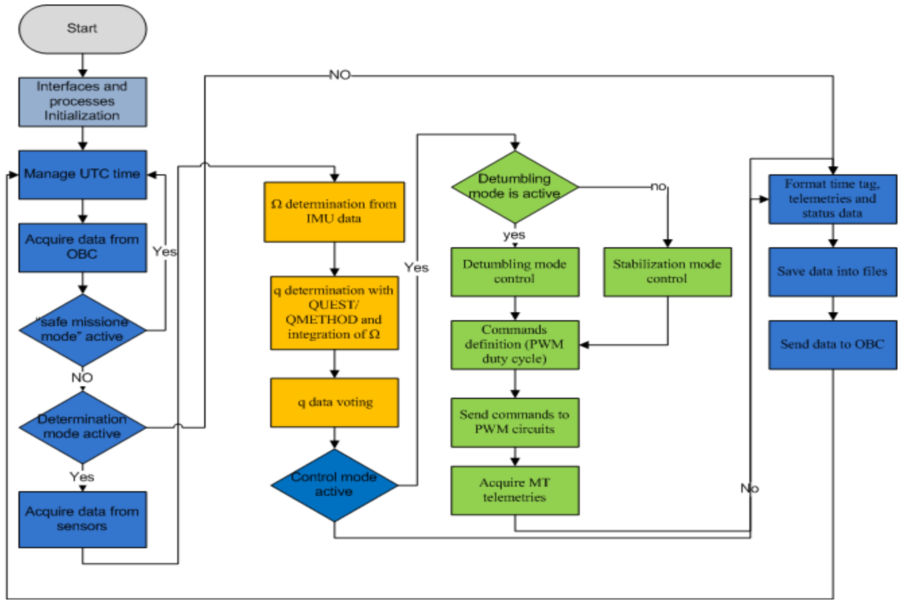

Figure 17: ADCS software flow chart

The ADCS software is structured in four parts:

- *"initialization":* where all the requested setups are made and the variables into the files are loaded;
- *"interface loop"*: it is an infinite loop in which the RD129 acquires sensors and status data and exchanges telemetries and commands with the OBC. Within the loop:
  - the time is managed, maintaining both the mission and the UTC time
  - the string with the OBC information is received, read and the data are extracted from the raw.
  - NORAD parameters and desired attitude are updated (if any) according to the received commands and the all the telemetry data from OBC are updated.
  - the operative mode is idetermined. If the *ADCS-MODE1* is active the execution flow passes to format and send the ADCS telemetry data to OBC and saves all the information into files (protection against the reboot). The determination loop is active too, while if *ADCS-MODE2* is active, also the control loop is active.
- "*determination loop*": it is a loop in which the angular velocities and the attitude of the satellite are determined using the chosen algorithms: QMethod and EKF.
- *"control loop"*: it is a loop in which the new commands are computed (according to the control laws) and the PWM values are set for the driving circuits.

All the implemented functions are developed and tested both step-by-step and integrated.

9.2.3 Determination algorithms

The chosen algorithm for the attitude determination is the QMETHOD: it belongs to the family of statistical determination methods, which use all the available measurements to estimate the rotation matrix (and so the quaternion) that describes the attitude of the satellite. It is based on the well-known Wahba's problem (minimization of a cost function J). This minimization problem is solved with QMETHOD, that is an exact method. The minimization of J is equal to maximization of its first derivative with the opposite sign (gain function, G):

It is possible to write rotation matrix in form of quaternion in order to obtain this gain function:

$$G(\bar{q}) = \bar{q}^T K \bar{q}$$

where K is:

$$K = \begin{bmatrix} S - \sigma I & Z \\ Z^T & \sigma \end{bmatrix}$$

with

$$B = \sum_{n=1}^{N} w_n \left(\bar{m}_{b-n} \bar{m}_{i-n}^{T} \right)$$
$$S = B + B^{T}$$
$$Z = \begin{bmatrix} B_{23} - B_{32} & B_{31} - B_{13} & B_{12} - B_{21} \end{bmatrix}$$
$$\sigma = trace(B)$$

QMETHOD is based on restating the problem of G maximization to obtain an eigenvalue (λ) problem, in this way the largest eigenvalue of K maximizes the gain function G and the corresponding eigenvector is the least-squares optimal estimate of the attitude.

$$G'(\bar{q}) = \bar{q}^{T} K \bar{q} - \lambda \bar{q}^{T} \bar{q}$$
$$stationary\ point\ when\ K\bar{q} = \lambda \bar{q}$$
$$\Downarrow$$
$$\begin{aligned} G(\bar{q}) &= \bar{q}^{T} K \bar{q} \\ &= \bar{q}^{T} \lambda \bar{q} \\ &= \lambda \bar{q}^{T} \bar{q} \\ &= \lambda \end{aligned}$$

QMETHOD is coupled with EKF (Extended Kalman Filter), which is applied on the satellite model: the first is used to determine the attitude after the end of the detumbling mode and fix it if needed.
The EKF estimated states are the angular velocities and the attitude. EKF is designed by using a Gaussian white noise (mean equal to 0 and correlation matrix equal or multiple of the identity matrix).

9.2.4 Control laws

To obtain the stabilization of the satellite, it was decided to divide the control in two different parts: the first is intended to reduce the angular velocity of the satellite after the release by the launcher, also called *detumbling*, while the second to bring the satellite in the correct attitude, that is the *stabilization*. The transition from first to second stage is managed by a suitable control logic based on the angular velocity of the satellite.
The detumbling phase is characterized by a low/high angular velocity (depending on the release conditions from CubeSat Deployer) with respect to the inertial frame so it is really difficult to evaluate the satellite attitude: the aim therefore is especially to reduce the angular velocity once the A-ADCS is activated by GCS. The applied controller is proportional (P) because of its high robustness and simplicity and it works until the estimated angular velocity of the body frames w.r.t. the inertial frame is at the same time less than 0.05 rad/s around each axis.
The commands are calculated considering the local magnetic field expressed in body coordinates, the angular velocity of the body frame w.r.t. the inertial frame and a positive constant matrix ($K_{detumbling}$):

$$\bar{m}_{detumbling} = K_{detumbling} (\bar{\omega}_{ib} \times \bar{B})$$

The stabilization control algorithm is based on PD (Proportional Derivative) and LQR (Linear-Quadratic Regulator) controllers. We have decided to divide the stabilization mode into two parts: PD control is applied for deviation from the nadir pointing over ±25 degrees while LQR works when deviation is below this value on each axis. In Table 8, the comparison between PID and LQR that led us to choose the controller for the second part of the stabilization mode is provided. In Figure 18 control loop architecture is depicted.

Table 8: PID and LQR comparison

	PD			LQR		
	x [deg]	**y [deg]**	**z [deg]**	**x [deg]**	**y [deg]**	**z [deg]**
Pointing accuracy	[5 : 7]	[-1 : 1]	[-6 : 0]	[+0.5 : 1]	[-0.5 : 0]	[-1 : 0]
Stability	0.5°/10000 s	1°/10000 s	1.5°/10000 s	0.05°/10000 s	0.1°/ 10000 s	0.5°/ 10000 s

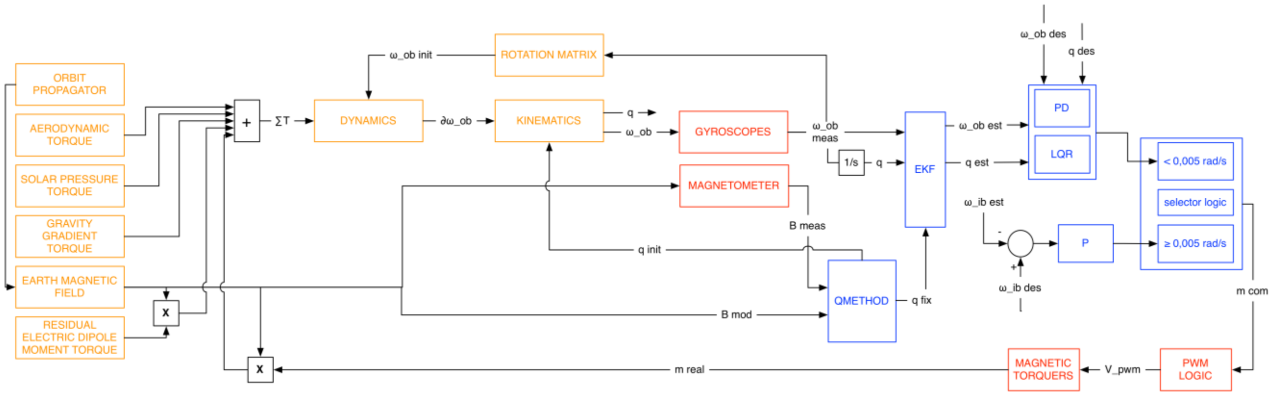

Figure 18: ADCS control loop architecture

9.3 Electrical Power Subsystem (EPS)

The EPS is the system devoted to provide, store, control and distribute the electrical power on-board the e-st@r-II CubeSat. The schematic of e-st@r-II EPS is depicted in the Figure 19: as before, red connections are digital data links, those blue are analog signals, and then blacks are power connections.

Taking into account the nature and envisaged duration of the e-st@r-II mission, Triple Junction GaAs solar arrays have been selected as primary energy source devices. The solar cells will be arranged in five solar panels mounted on the external faces of the CubeSat. One face (-X side) remains free to host the antenna, its deployment system, and the connectors' port. Each solar panel is constituted by two solar cells connected in series. The single solar cell dimensions are 4 cm x 7 cm, which is limited by the face dimensions. A temperature sensor is installed on each panel. CESI S.p.A. (Milan, Italy) is the supplier: the team started the collaboration with the company in 2005 with the realization of solar cells for PICPoT program and e-st@r-I in turn. The characteristics of the solar cells are listed in Table 9.

Table 9: solar cells characteristics

String type	Isc[A]	Voc[V]	Pmax[W]	Ipmax[A]	Vpmax[V]	PL[W]	IL[A]	F.F.	Eff.[%]
-Z1'	0.47837	2.609662	1.064561	0.45597	2.334717	1.039868	0.468409	0.852751	29.37597
-Z2'	0.46648	2.534995	1.012157	0.45063	2.246094	1.005567	0.452958	0.855929	27.92992
+Y1'	0.46793	2.541368	1.002265	0.44492	2.252686	0.997367	0.449264	0.842818	27.65695
+Y2'	0.47182	2.609056	1.051431	0.45762	2.297607	1.029528	0.463751	0.854124	29.01366
+Z1'	0.46799	2.547979	1.021276	0.45469	2.246094	1.015434	0.457403	0.856467	28.18156
+Z2'	0.46367	2.562065	1.02878	0.44338	2.320312	1.013912	0.456717	0.866011	28.38862
-Y1'	0.46597	2.54561	1.015433	0.45199	2.246582	1.009298	0.454639	0.856054	28.02031
-Y2'	0.48102	2.605362	1.00978	0.44426	2.272949	1.000465	0.45066	0.805741	27.86434
+X1'	0.46888	2.52856	0.983815	0.43887	2.241699	0.983059	0.442819	0.829809	27.14782
+X2'	0.46919	2.516329	0.983162	0.44715	2.19873	0.978445	0.440741	0.832739	27.12983

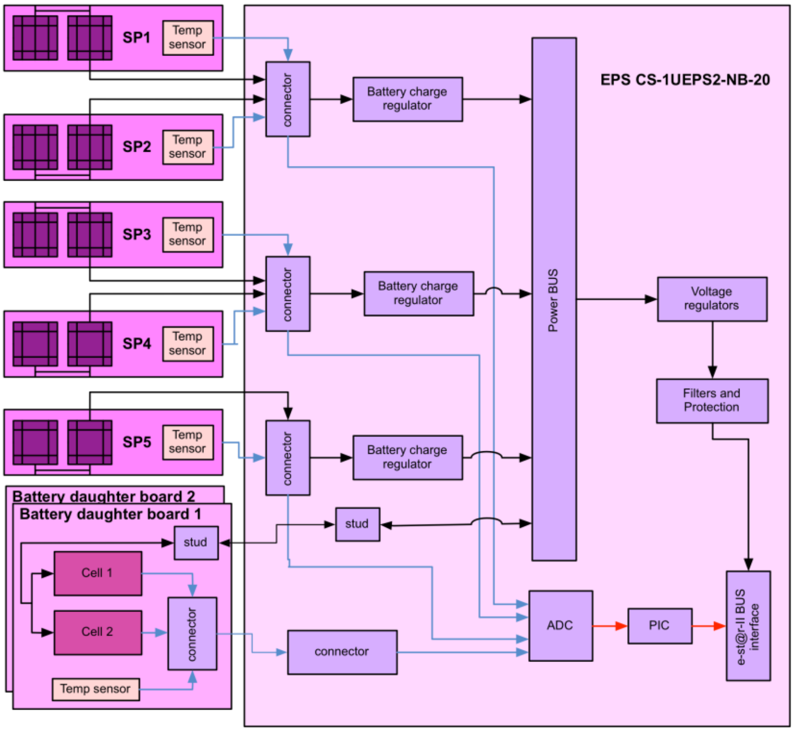

Figure 19: EPS blocks scheme

As far as the storage, regulation and distribution functions are concerned, we have identified a suitable COTS unit and decided to employ it in the satellite. The chosen unit is the 1U CubeSat Electronic Power System CS-1UEPS2-NB/-20 by Clyde Space Ltd.

The Clyde Space 1U EPS is compliant with the e-st@r-II requirements and needs. In particular, the board is optimised for LEO missions with a maximum altitude of 850 km. It is designed for integration with spacecraft that have six or less body mounted solar panels (i.e. one on each spacecraft face). The system integrates two daughter battery boards, which offer a total 20Wh capacity with low weight and volume. The battery systems host integrated heaters, which maintains the battery temperature above 0°C, enhancing operation at low temperatures. Over-current protection is provided to protect the cells in the event of a power line fault.

The power control and distribution (PCM/PDM) network provides an unregulated Battery Voltage Bus, a regulated 5 V supply and a regulated 3.3 V supply available on the satellite bus. The EPS integrates multiple inbuilt protection methods to ensure safe operation during the mission and full range of EPS telemetries.

Table 10: EPS components

Type	Producer
Electronic Board	Clyde Space Ltd.
Li-Po Batteries	Clyde Space Ltd.
Solar cells	Cesi S.p.A.
Solar panels assembly	CubeSat Team
Assembly and integration	CubeSat Team

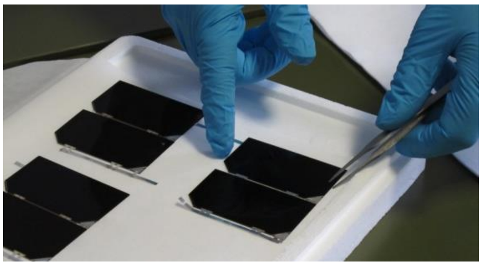

Figure 20: solar panels manufacturing

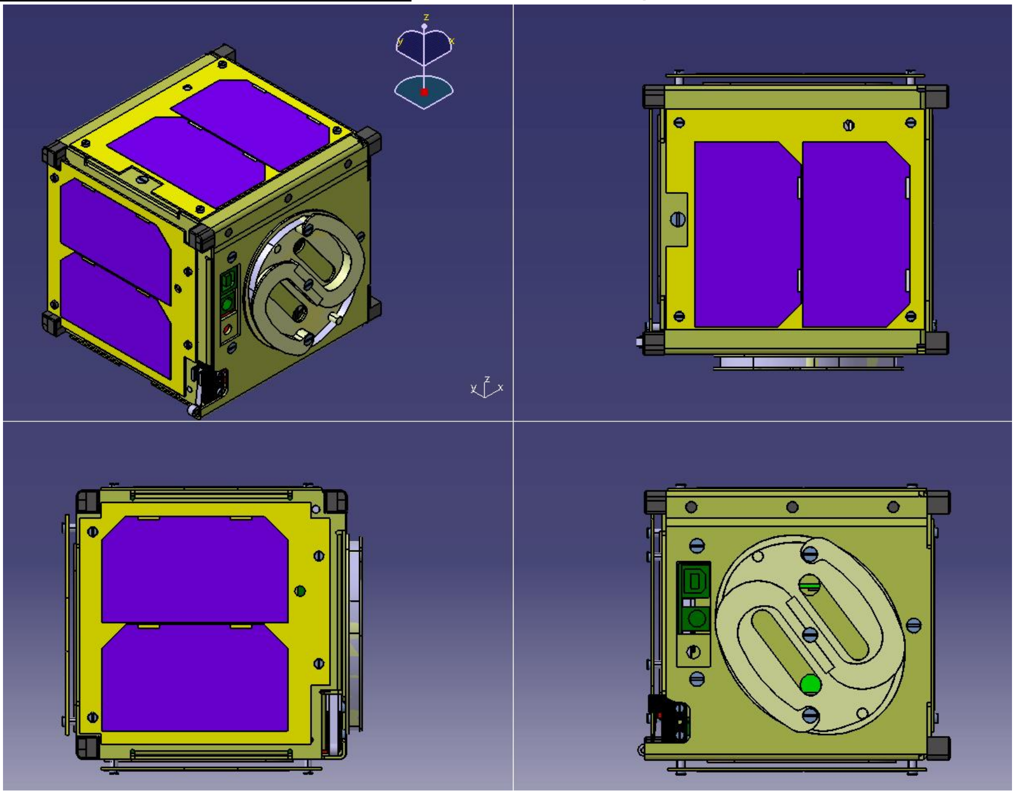

Figure 21: CAD model of solar panels installed on the structure

9.4 On-Board Computer (OBC) and Software

The On-Board Computer (OBC) is the *brain* of the whole space segment. The board is a COTS component, the FM430 provided by Pumpkin Inc. The system includes the motherboard, an extended operating temperature 2GB SD card memory, an electro-mechanical Deployment Switch (DS) and an electro-mechanical Remove Before Flight (RBF) switch.

Table 11: OBC specifications

Pumpkin FM430		
Technical features	**Physical specifications**	
16-bit MSP430 ultralow-power RISC microcontroller, at 7.4MHz	Operating voltage	5 V
2-10KB of RAM	Dimensions (PCB + components)	96x90x11.4 mm
50-60KB of on board Flash memory	Temperature operating range	-40 / 85 °C
48 I/O pins	Mass	81.3 g
2 USART, 2 SPI, 1 I2C		
12-bit ADC, 12-bit DAC		
multiple timers and clock sources		
on-board temperature sensor		
SD Card socket for mass storage (32MB / 2GB)		
Direct wiring for 10A Remove-Before-Flight and launch switches		
Independent latchup (device overcurrent) protection on critical subsystems		

The tasks accomplished by the On-Board Computer are:

- command handling and execution; OBC receives commands from GCS through the COMSYS, validates and processes them, and manages the operations required for their execution;
- data handling and storage; OBC gathers information from other subsystem, formats them according to AX.25 protocol, passes the obtained packet to the COMSYS for the sending to Earth. It also saves all the packets in a non-volatile memory, which are fully transmitted when a command from GCS is sent;
- management of the main on-board operations: OBC checks the health status, manages the operative modes, holds the mission time and the basic parameters and guarantees the time synchronization.

Table 12: OBC components

Type	***Producer***
Board	Pumpkin Inc.
Switches	RS components S.p.A.
SD memory	Delkin devices
Software	CubeSat Team

Figure 22: Pumpkin FM430

The blocks scheme in Figure 23 highlights the main components of the subsystem: in this case, there are only power (black) and digital data (red) connections. Communications with the other subsystems take place through the main e-st@r-II bus interface.

The telemetry packets and the entire mission data (i.e. time and health status) are saved in a SD card hosted on-board. The firmware and the software are loaded in an EEPROM. A watchdog circuit is present to avoid permanent failures on the OBC software execution flow.

Real Time Operating System is SALVO®, and the custom software is developed by the CubeSat Team in the C++ environment. Capabilities and robustness of the OBC software have been verified by means of several functional test, which demonstrated good synchronization and stable communication with the microcontroller of the payload (ADCS), successful data distribution to the COMSYS, and operative modes management in any phase of the mission simulation.

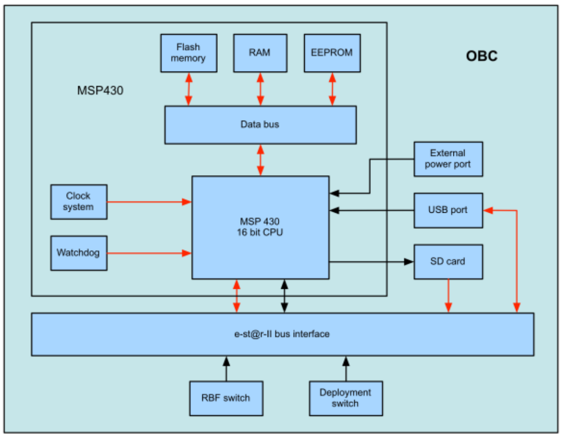

Figure 23: OBC blocks scheme

9.5 COMmunications subSYStem (COMSYS)

The communications subsystem is devoted to provide the interface between the satellite and ground segment. Payload mission data and satellite housekeeping telemetry pass from the spacecraft through this subsystem to operators and users. Commands from main GCS pass through the COMSYS in order to control the spacecraft and to operate the payload. The blocks scheme is illustrated in Figure 24: besides the usual connections (black is power, red is digital data and blue is analog signal), there is also a green connection that represents the RF signal.

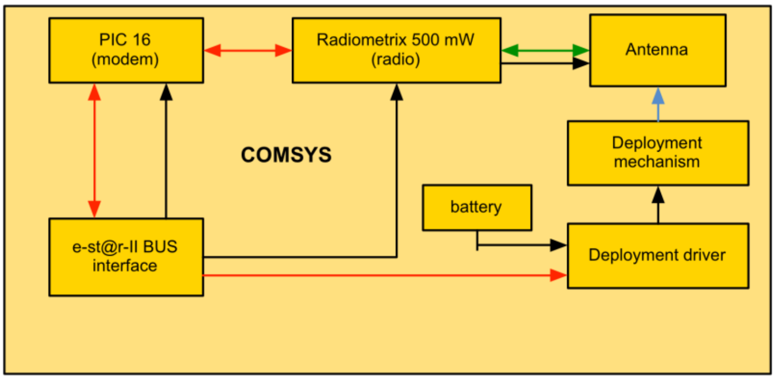

Figure 24: COMSYS blocks scheme

Functions of the on-board communications system are:

1. to receive and demodulate commands
2. to modulate and transmit telemetry
3. to provide its health and status telemetry
4. to detect autonomously faults and recover communications using stored software sequence and hardware reset. In particular, a beacon signal (self generated by the COM SYS and modulated in CW) has been implemented if no data are provided by the OBC for 5 minutes. In particular, the string “estar2” is transmitted in Morse code. In case of a request for RF cessation, CW transmission can be stopped using a specific command from GCS. This command also works in case of OBC failure because it is executed directly from the COMSYS.

The chosen communication protocol is the KISS AX.25 because is quite popular among the radio-amateurs, whose support to the mission is essential to collect large amounts of data.

Table 13: COMSYS components

Type	*Producer*
Tranceiver	Radiometrix Ltd.
Printed Circuit Board (PCB)	Millennium Dataware srl (on CubeSat Team design)
SMD components (resistances, capacitors, PIC, …)	RS Components S.p.A.
Antenna (design and production)	CubeSat Team
Assembly and integration	CubeSat Team

Figure 25: COMSYS board

COMSYS is designed, developed and built by students at the STARLab of Politecnico di Torino in cooperation with ARI-Bra radio-amateurs. It is constituted by an electronic board that hosts a COTS radio-transceiver, a microprocessor unit and electrical devices to amplify, filter the signal and support the microcontroller operations.

The antenna system is constituted by a RF part characterized by a dipole antenna, and a coaxial cable for the interfaces with the board, and by a mechanical device characterized by electro-mechanical components that deploy the antenna to its final articulation from the initial position in which is folded up. The antenna is closed using a Nylon cable with 0.29 mm diameter that has low elongation and total absence of mechanical memory characteristics. The idea is to use low ohm resistors (under-sizing wrt the absorbed power) in which the current flows from the regulated battery channel of the bus causing the increase of the resistor temperature, so that the wire leaned to resistances arrangement is cut. The support system is built by Computed Numerically Controlled (CNC) milling of a single block of PolyEther Ether Ketone (PEEK), that is a colourless organic polymer thermoplastic compatible with ultra-high vacuum applications. To perform the antenna deployment (which is the only activity which can produce debris) in such a way guarantees that no debris are created.

According to the selected frequency (437.485 MHz), the length of antenna is about 34 cm: it is composed by two arms with length of about 17 cm, connected to the COMSYS board by using a coaxial cable and a MCX connector. The antenna has been characterized using the MFJ-269 RF Analyser.

The main component for the modem function is the PIC16F88 that is the core of the system and performs the TNC/modem tasks. The data-rate is 1200 bit/s, which is sufficient for the telemetry packet (that is 110 bytes long) transmission. Buffering and flow control techniques are employed to ensure that data is not lost due to congestion.

The radio module is the BHX2 produced by Radiometrix ltd. The module offers a 500 mW RF power output, a current consumption of 350 mA (@7.6 V) in TX and 30 mA (@7.6 V)in RX, and it is powered with the regulated battery channel (@ 5.5 – 8.2 V).

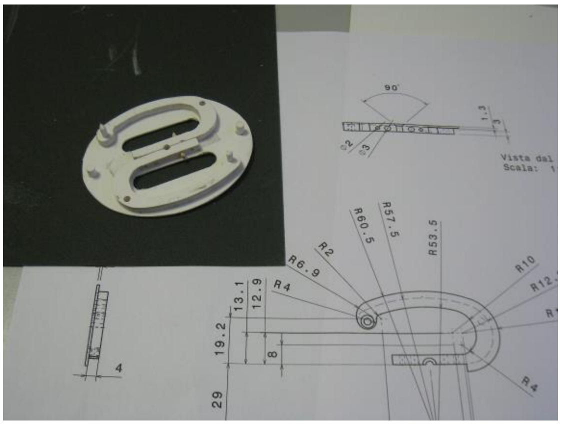

Figure 26: Antenna system design

Figure 27: Antenna system

9.5.1 "Burn" algorithm

A burn algorithm has been implemented to deploy the antenna: it consists of a series of burn commands that starts 30 minutes after the deployment of the CubeSat. Considering that the antenna deployment system includes two FR4 support with a SMD resistor each (here called resistor-A and resistor-B), the sequence is:

1. burn command on the resistor-A for 2.4 s
2. wait for 15 seconds
3. burn command on the resistor-B for 2.4 s
4. wait for 15 seconds
5. burn command on the resistor-A for 2.4 s
6. wait for 15 seconds
7. burn command on the resistor-B for 2.4 s
8. wait for 40 minutes
9. burn command on the resistor-A for 2.4 s
10. wait for 15 seconds
11. burn command on the resistor-B for 2.4 s

Steps from 8 to 11 are repeated until the command STOP BURN is sent from GCS and correctly received by COMSYS. The 40 minutes were chosen with a proper trade-off: it has been estimated that considering a generic LEO, this range of time is able to ensure that at least one of the burn is carried out not in eclipse avoiding that the environmental temperature is too low, although we didn't found during test problems with low temperatures. A timeout in the execution of this algorithm has not been implemented because we verified that the power consumption at each burn is acceptable w.r.t. the power budget. Introducing a timeout function was avoided because it would introduce the possibility not to deploy the antenna. Moreover, until the antenna is closed the RF signals do not reach the Earth and it compromises in any case the mission so it is important that the satellite tries to deploy the antenna.

9.6 Structure&Mechanisms subsystem (S&M)

The structure is the e-st@r-II subsystem devoted to withstand all the loads imposed by the launch vehicle and the environment, to support and protect the payload and other subsystems, and to provide for separation devices. The design has been driven by the guidelines of the project: simplicity (both of design and of technologies), reliability, volume maximization and mass minimization. The structure has been designed to meet mission requirements and in compliance with the CDS.

The designed structure consists of a lateral-box manufactured by a 100x410 mm sheet metal plate of 1.2 mm thickness, then appropriately folded and closed by means of rivets. The top and bottom panels are basically modified C-section plates, screwed to the lateral-box. One panel of the lateral-box is equipped to accommodate the antenna system and the ports to connect ground test equipment. These ports also allow to evacuate the air inside the CubeSat during the ascent avoiding air trapping. All other panels are covered by solar panels and related devices. The interface with the deployer and other CubeSats installed in the same deployer is guaranteed by means of two types of stand-offs and the deployment switch: two out of three supports in the bottom plate host the spring plunger devices, the third is a simple support (such as the four supports on the top plate) and the fourth is the DS.

Table 14: S&M components

Type	*Producer*
Main structure	ITD s.n.c (on design of CubeSat Team)
Fasteners	ITD s.n.c
Surface treatments	Lattes S.p.A.
Antenna support	ITD s.n.c (on design of CubeSat Team)
Assembly and integration	CubeSat Team

Figure 28: e-st@r-II structural elements

All the structure parts are made of metallic material, apart from the antenna support that is made of PEEK (see section 9.5). Lateral-box and plates are made of Aluminium alloy series 5005 H16 while stand-offs have been made of Aluminium alloy series 5083 H111. Both alloys guarantee mechanical and thermal characteristics similar to most aluminium alloys used in space field (7075 and 6061), but they are cheaper and easily available on the market. The surface of main structure has been alodined with a non-hexavalent chromium based process; the stand-offs and the box rails, which are in contact with the deployer and other CubeSats in the triplet, are hard-anodised Type III.

Figure 28 shows also other elements of the structure (all made to order products): fasteners (screws, rivets, nuts, etc.) for joining structural parts, rods and spacers for the assembly of the electronic stack.

9.7 Thermal Control Subsystem (TCS)

The basic principles in the selection of thermal control techniques have been simplicity and flexibility, since the thermal analysis of a satellite is a dynamic process constantly evolving, especially when the orbit is unknown for the mission. In the particular case of e-st@r-II, we have started by choosing a completely passive system without Multi-Layer Insulation and we have verified by thermal analysis (based on different orbit simulations) that it would be sufficient to satisfy the temperature requirements of all components, ensuring the survival and proper functioning of the satellite throughout his life in orbit. External and internal thermal stresses with both “hot” and “cold” thermal environment conditions have been defined, and temperature profiles estimated for the structure, on-board electronics, batteries, solar panels and surfaces.

Figure 29 shows an example of temperature profiles obtained with the analysis, for the central node of each external face, considering a circular orbit (height 600 km, i = 98 deg) with Earth at the aphelion and beta angle equal to zero. On the left the electronics is switched off (worst cold case), while on the right the electronics is considered active (practical cold case).

Since batteries represent critical device on-board, we decided to use the ClydeSpace EPS battery systems that integrate heaters for the active control of the local temperature. These are electrical resistors which serve to keep the temperature above 0 °C, therefore enhancing the EPS operations at low temperatures. The heater is part of a closed loop system that includes a sensor and a temperature controller and operates according to an on-off switch cycle.

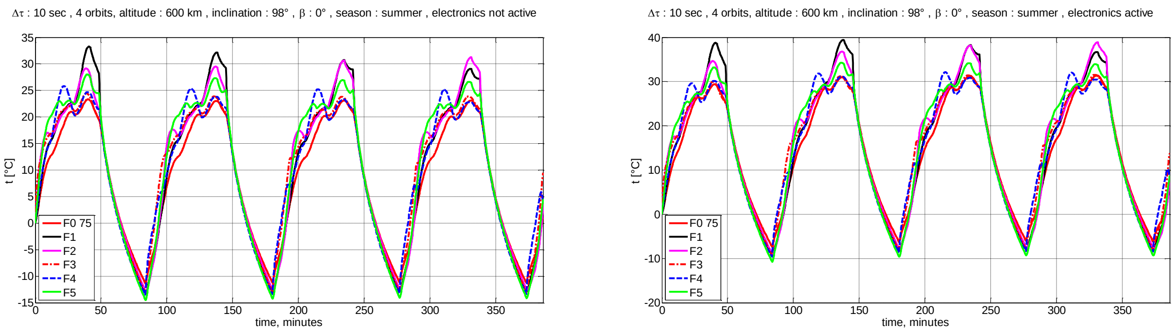

Figure 29: preliminary thermal analysis, external surfaces (cold case)

10 Ground Segment

The Ground Segment of the e-st@r-II project consists of two ground stations: the main Ground Control Station (GCS) is the ARI – section of Bra (Ham Radio Club – IQ1RY) and the second is the Mobile Ground Control Station (MGCS) located at Politecnico di Torino which is transportable and may be transferred everywhere.

ARI-Bra station (44.69942 N, 7.83686 E) is an existing radio amateur station that supplies all the elements needed to communicate with e-st@r-II satellite: it is able to send commands to the satellite and to receive the telemetry packets and the CW signal. The CubeSat Team tracked and communicated with e-st@r-I CubeSat from this station. The GCS is composed by 1) a Yagi antenna (in a near future, a parabolic antenna will be mounted), 2) a radio, 3) a TNC, 4) two PCs, 5) Antenna System Control Box, and 6) two rotors for antenna movement. The antenna is a UHF Tonna 2x19 elements Yagi (Figure 32), it has a 16.2dB gain and it is mounted on a vertical structure that hosts the two rotors. They are driven by the Antenna System Control Box, a Yaesu G-5400B AZ EL Controller, commanded by the outputs of a computer with Windows as OS. The commands are computed by the free software WXTRACK, able to compute orbit propagation of the satellite from TLE (Two Line Elements) and commands in order to steer the antenna to track and communicate with the satellite. The radio is an ICOM IC-910H Dual Band TRX with 100W on the frequencies range of 144MHz and 75W @ 430/440MHz, used to amplify the signals that are modulated/demodulated by a custom TNC. The other GCS’s PC with Linux OS manages the communication (handling data and commands) and provides the interface with the operators thanks to a C++ program with Graphical User Interface (GUI) developed by the CubeSat Team which clearly indicates the functions/commands of the GCS (which are activated through command buttons), displays data when requested by user, and saves the uplink and downlink history. The blocks diagram of the GCS is shown in Figure 30.

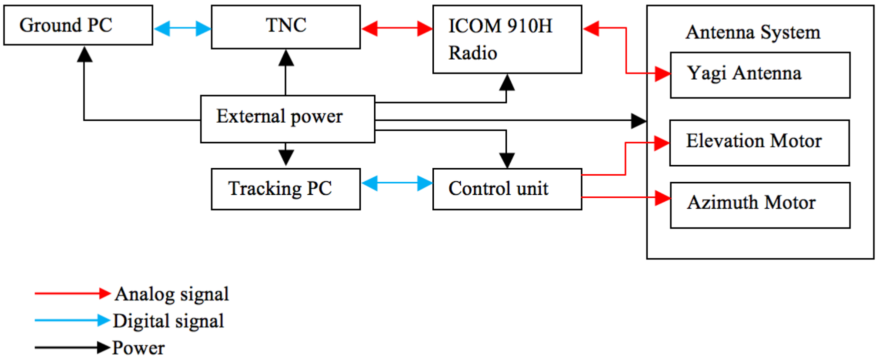

Figure 30: ARI-Bra GCS blocks scheme

The MGCS is mainly designed to receive the downlink data from the satellite, to be transportable and to help the ground tests and verifications. Indeed, all the MGCS items can be transported in a suitcase with a maximum dimension of 50x40x25 cm. The antenna is a stilo/omnidirectional SG7000 and it is not steerable (so there are not rotors, control box and PC for the management of the orientation). The radio is a portable Kenwood TH-F7E and the TNC is the 7-multi provided by NTG. The PC has the same features of the PC with Linux OS of the GCS.

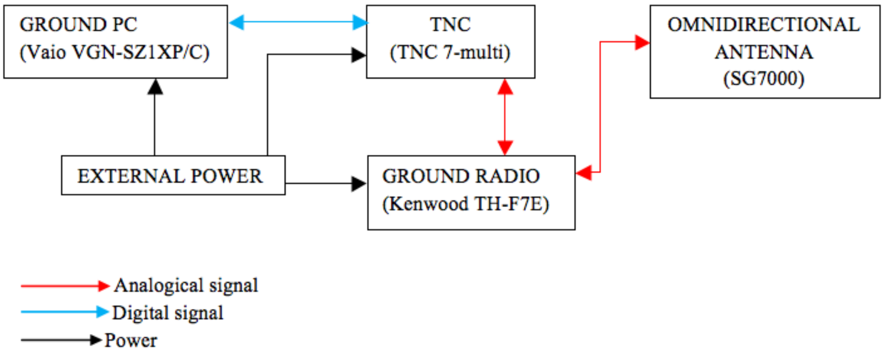

Figure 31: MGCS scheme

Figure 32: GCS antenna system

Figure 33: radio and control box in the GCS

11 Ground Support Equipment (GSE) and AIV/AIT software

The test facilities, tools and GSE used for the functional and mission tests are described in this section. The facilities involved in the e-st@r-II mission are the STARLab and the main GCS. The whole GSE required is constituted by:

- laboratory garments (gloves, headdress, etc.)
- the MGCS, mobile and transportable, which is used as ground station back-up and for testing
- PCs: two standard laptops. One of them (to be connected to OBC) with Windows OS and Hyperterminal SW. The second one (to be connected to the payload debug port) with Linux OS
- USB cable (standard-A/standard-B plug USB cable) that is used to connect the PC with the OBC

- ADCS debug cable (RS232 to USB) to connect PC with ADCS debug port
- two 3-channels power supplies, which are used to simulate the solar panels
- a standard multimeter to perform measurements of currents and voltages
- a digital oscilloscope (the STARLab is equipped with Tektronik TDS2004C, including four passive voltage probes)
- a lamp to perform flash test
- satellite's safe case

The GSE has been designed taking into account that the maximum distance between it and the CubeSat's access port is 5 meters.
A lot of functional tests were performed using a simulator (its software flow chart is shown in Figure 34) developed by the CubeSat Team and based on Hardware In the Loop (HIL) methodology, which was applied to investigate and evaluate the e-st@r-II performances by including the main hardware of the satellite in the loop. ADCS and OBC boards run their flight software, so HIL simulations carried out the verification of many functional and operational requirements, in particular, the following macro-verifications have been accomplished:

- transmission and receptions of telemetry and commands
- power consumption
- batteries charging and discharging
- attitude determination and control

Data acquired during the tests both by the simulator PC and by the GCS allow comparing the hardware behaviour and the simulated response obtained from the global simulation model.

Figure 34: simulator software flow chart

12 System Budgets and Relevant Margins

12.1 Mass Budget

The CubeSat has been digitally modelled using CATIA v5 and using this model the mass budget has been performed. The structure and fasteners masses have been evaluated by applying the material characteristics, while for the other components of the CubeSat, an estimation has been done based on similar or available components. This first estimation confirmed the preliminary mass budget with margin.

After that, the EQM and then the FM have been manufactured and all parts have been measured before integration. Once assembled, the models have finally weighted. The values for FM's parts masses are summarized in Table 15

Table 15: e-st@r-II mass budget

Component name	*Mass [g]*
Structure	224.8
EPS (PCDU + batteries)	235.0
Solar Panels (5x)	163.4
ADCS (electronics)	76.5
Magnetic Torquers (3x)	15.4

COMSYS (electronics)	100.1
OBC Board	81.3
Antenna & Mechanism	17.0
Miscellaneous (fasteners, rods, etc.)	61.1
Total Mass [g]	**974.6**
Maximum mass (from FDS 4.3.2.1) [g]	**1330**
Margin [g]	**355.4**

12.2 Power Budget

The power budget is prepared by estimating the power available and the power required by the payload and the spacecraft subsystems. The goal is to avoid a negative power budget, that is where the system requires more power than is available per orbit.

First, the orbit average power (OAP) is estimated. It defines how much power is available per orbit and determines how much power can be used. OAP is calculated as the value of maximum power for the worst solar cell (ca. 0,98 W), multiplied by the number of solar cells per panel, and increased by 40% (View Factor VF = 1,4 to take into account the average number of panels in-sun).

$$OAP = P_{max} * no_{cell} * VF$$

The preliminary budget does not take into account the contribution of the albedo, which would represent a positive contribution to the power input. The available power per orbit results 2,74 W.

For further information on solar cells' characteristics and a detailed description of the View Factor's calculation see Annex I.

The available power is basically OAP minus the power usage. We used a conservative 20% margin of uncertainty for the preliminary consumption assessment, and the resulting average power consumption per orbit is 1,4W. This value has been later confirmed by a detailed calculation made up testing the power consumption of the components in different modes of operations of the satellite (see Annex I). The power budget is reported in Table 16.

The following images show the capability to recharge the batteries, and therefore the good functionality of MPPT, also during that phase when the ADCS of the satellite is deactivated. The data were obtained by performing an HIL simulation: the telemetries of the batteries are real data, collected by the OBC every 2 minutes, which is the nominal interval of transmission of the satellite; instead, angular velocities and quaternion are obtained directly from the simulator.

In Figure 35, battery bus voltage trend is shown demonstrating that the batteries are fully recharged, despite the high tumbling rate (Figure 36) and the fast changes in the attitude (Figure 37) as well as the eclipse phases arose in the interval[3100 4160] seconds and [8920 10160] seconds.

Available Power						
			Pmax	no.cells	vf	**notes**
Orbit Average Power OAP	**2,74**	**W**	0,98	2	1,4	It defines how much power is available per orbit. It is calculated as the value of Pmax for the worst cell (ca. 0,98), multiplied by 2 (2cells = solar panel) and increased by 40% (View Factor = 1,4 to take into account the no. of panels in-sun)
Power Usage						
subsystem	equipment	power ConsumptionW	Avg.DutyCycle	Avg.PowerCons		
A-ADCS	IMU	0,23	1	0,23	W	
	ARM9	0,2	1	0,20	W	
	MTs	1,5	0,02	0,03	W	
EPS	Board	0,1	1	0,10	W	
TCS	Batt. Heaters	0,44	0,02	0,01	W	
OBC	Board	0,01	1	0,01	W	
COMSYS	TX	2,65	0,1	0,27	W	
	RX	0,35	0,9	0,32	W	
			subtotal	1,16	W	
			margin	1,2		20% margin due to uncertainty at the beginning of the project
			total	**1,4**	**W**	**Total Average Power Consumption per Orbit (W)**
Orbit Average Power	2,744					
Power reduction EOL and MPPT error	0,03					3% loss due to degradation with time and line losses
Adjusted EOL OAP	2,662					OAP*PowerReduction
Average eclipse power consumption	1,4	W				An Average Power Consumption value has been assumed for both in-sun and eclipse conditions
Max eclipse period	0,5	h				An eclipse period of 30 min is considered
Eclipse energy requirements	0,70	Wh				
Battery return factor (BRF)	1,1					The energy taken from the battery in eclipse needs to be replaced in sunlight + battery losses. The BRF measures the amount of energy applied to the battery versus the amount of energy extracted from that battery. (e.g. For 2 Ah delivered by the battery during discharge, 2*BRF Ah shall return to the battery during charge, due to losses during the charging operation).
Battery capacity required	0,76	Wh				This is the capacity required per orbit
Battery capacity available	20	Wh				Total battery capacity of e-st@r-II
Actual DoD per orbit	3,82%					This is the DoD per orbit: 0,77/20
Time in sunlight	1,1	h				66 min in sunlight have been assumed
Average charge power during sunlight	0,70	W				This is the power to battery in sunlight: 0,77 Wh / 1h
Path from solar arrays to power bus	0,9					suggested by ClydeSpace Ltd.
Path from power bus to battery	1					
Path from battery to power bus	1					
Summary						
Available solar array power at bus (EOL)	2,40	W				This is the Adjusted EOL OAP multiplied by path losses
Power to battery in sunlight	0,70	W				sunlight power required (consumption + battery charge)
Average Power Consumption per Orbit	1,4	W				
Margin	0,31	W				
Margin %	**12,93%**					

Table 16: e-st@r-II power budget

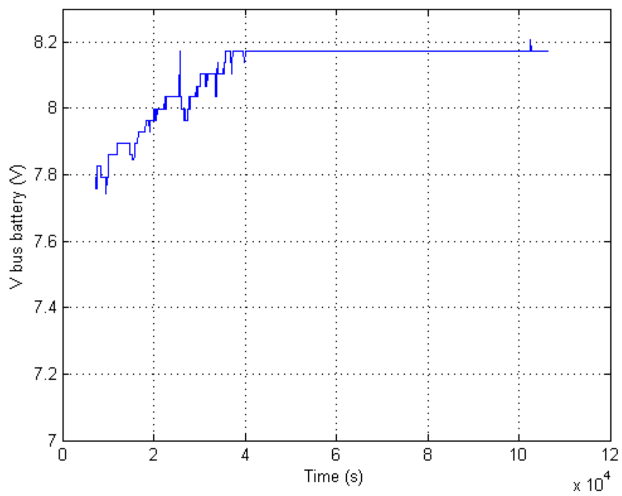

Figure 35: Battery bus voltage as a function of time

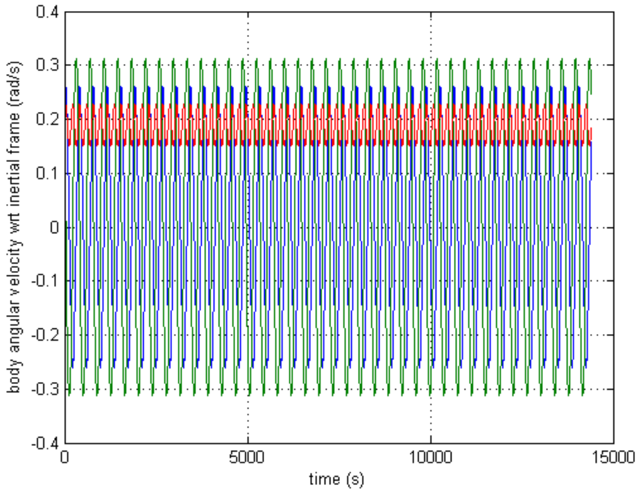

Figure 36: Angular velocities as a function of time (blue wrt X-axis, green wrt Y-axis and red wrt Z-axis)

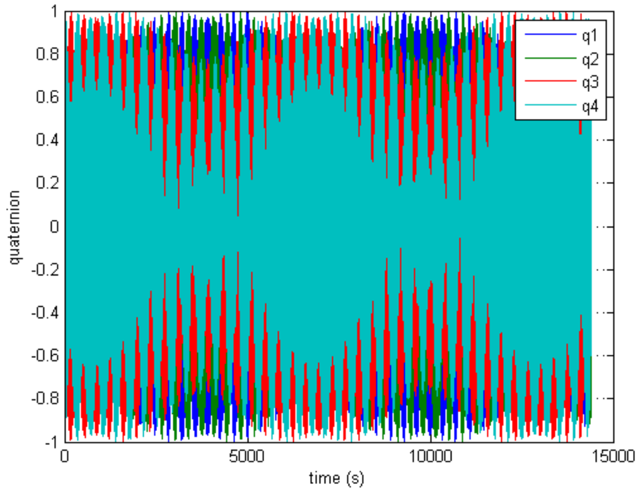

Figure 37: Quaternions as a function of time

12.3 Link Budget, data rate

For the downlink data rate the number and type of the telemetry data have been considered: on-board voltages, currents, temperatures, and actuators current consumptions are coded on one byte for each one; linear accelerations, angular velocities, and Earth Magnetic Field take up two bytes, while four bytes are devoted to quaternions. Moreover, eight status bytes and four bytes for the time-word have been defined. Hence, all these data are formatted according to KISS AX.25 protocol and they compose the downlink packet that is 110 bytes long. At the same way, the command string is designed: it is also formatted in KISS AX.25 and contains two byte for commands ID, followed (in some case) by 16 bytes of additional information. The total length of the command packet is 40 bytes. According to the low size of each packet an adequate data rate is 1200 bps, which has been chosen because it guarantees sufficient number of communications between the satellite and the GCS during the line-of-sight window.

Starting from the data rate definition, the link budget has been designed using the program “AMSAT/IARU Standard Budget System. Version 2.4.1”. The main inputs for the downlink and uplink budgets are summarized in Table 17.

The link margin results (in uplink and downlink) obtained from E_b/N_0 method and S/N method computation are summarized in Table 18.

We declare the link budget closed, as the value of 2.7dB is sufficiently close to the 3dB margin normally considered. Nevertheless, we will perform a characterization of the system in order to obtain an experimental BER curve, and to update the link budget removing the estimated data. In addition, it has to be noted that the estimation of the values

related to the GCS used in the link budget is very conservative, therefore the link budget can only benefit from the update of the estimated data.
For a detailed description of the link budget calculations see Annex II.

Table 17: main inputs for the downlink link design

Parameter	Value	Unit
Height of Apogee	600	Km
Height of Perigee	600	Km
Inclination	97.8	Degrees
RAAN	204	Degrees
Argument of Perigee	0	Degrees
Mean Anomaly	0	Degrees
Minimum elevation angle	5	Degrees
Frequency	437.485	MHz
Data rate	1200	bps
Satellite antenna (dipole) gain	2.15	dBiL
Satellite power transmission	0.5	W
Ground station antenna (Tonna 2x19 elements Yagi) gain	16.2	dBiC
Ground power transmission	50	W
Modulation type	AFSK	-
Coding	None	-
Bit Error Rate	1.00E-4	-

Table 18: link margin

	Uplink	Downlink
E_b/N_0 method	16.6 dB	2.7 dB
S/N method	3.4 dB	-9.0 dB