Master Project 2007

Phase B

System Engineering and development and test of the ADCS breadboard for SwissCube

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Space Center Abstract Master Project 23.02.2007

System Engineering and development and test of the ADCS breadboard for SwissCube

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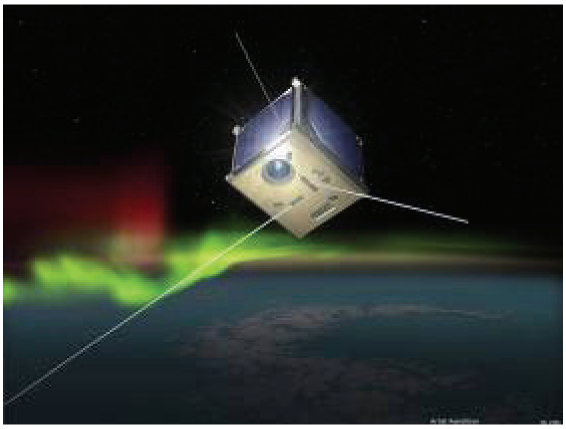
The EPFL Space Center is currently developing the first entirely Swiss satellite, called SwissCube. The satellite is designed following the CubeSat standards, cubic external shape, one kilogram maximal mass and one liter maximal volume. The SwissCube scientific task is to take pictures of the AirGlow, a light emitting phenomenon occurring in the low Earth atmosphere. The satellite will be launched in 2008 on a low Earth orbit between 400 and 1000 kilometers



SwissCube

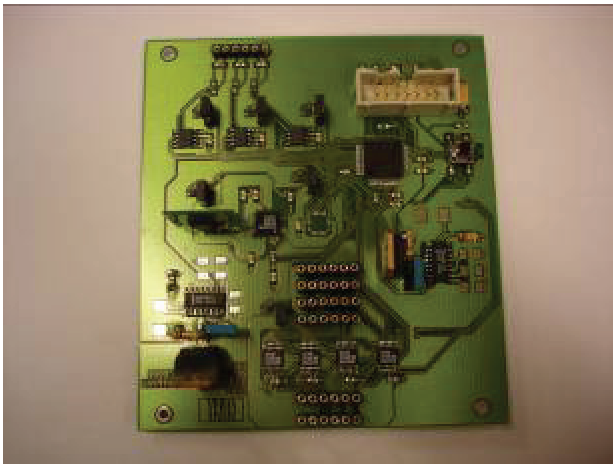
This master project focuses on two different subjects, system engineering tasks and the development of a breadboard for the Attitude Determination and Control Subsystem (ADCS) for the SwissCube.

System engineering

The satellite is composed of seven different subsystems, power, thermal, structure & configuration, command & data management, communication, attitude determination & control and a payload. The system engineering team makes sure that all the subsystems are compatible and come to a system.

ADCS

The main part of the master project concerns the development of a breadboard for the ADCS with the sensors and the actuators. The SwissCube shall be able to determine and control its attitude on the three axes to take the pictures. For the determination, three types of sensors are used, magnetometers, gyroscopes and sun sensors. The determination algorithm will use the sensor data to compute the state vector of the satellite. For the control of the satellite three perpendicular magnetic coils are used as the main actuators. They interact with the Earth magnetic field to generate torques. The control algorithm will generate the command values for the actuators.



ADCS development board

PROJECT: SwissCube Satellite **PHASE: B**	**WP REF: 1100**
Master Project Title: System Engineering and development and test of the ADCS breadboard for SwissCube **Responsible:** EPFL-Space Center, Muriel Noca **Student**: Bastien Despont **Start Date: 23-10-06** **End Date: 28-02-07**	**Sheet 1 of 2** **Issue Ref: 1** **Issue Date:** **05-10-06**

Introduction and schedule

This Work Package summarizes the work expected from the Space Center student during phase B (master's project) of the SwissCube Project. The expected duration of the work is 4½ months. The student shall:

- Prepare a schedule for the planning of his work with milestones. Any deviation from the plan shall be reported;
- Perform the technical work with supervision from Space Center, the HEVS Laboratory from Prof. Moerschell and the Project Engineering Team;
- Attend appropriate engineering meetings and prepare for major reviews;
- Deliver an end-of-project report and support additional documentation when and if necessary.

The project includes two main tasks. First the student shall continue partially his system engineering duties during no more than 20% of the time. These duties will ensure consistency of the satellite design at the system level. The second task consists of developing and testing the hardware breadboard for the Attitude Determination and Control of the satellite. This second task will be done under the supervision of Prof. Moerschell from the HEVS and is expected to be done at least 80% of the time.

The system engineering task and the definition phase of the hardware task will be done mainly at EPFL. Hardware implementation, integration and test will be done mainly at HEVS.

Technical Work Description

System Engineering Task (20%)

This task includes the following subtasks:

- Continue system design iterations;

- Continue book-keeping of the system budgets;
- Elaborate interface requirements (electrical, mechanical, data and thermal) in cooperation with the rest of the System Engineering team;
- Complete functional analysis in cooperation with the flight SW.

ADCS Hardware (HW) Task (80%)

This task can be divided in three phases for clarity:

First phase:

- Gather information about sensors & actuators performances and manufacturers;
- Write hardware functionalities (what does the subsystem need to do?);
- Define the ADCS HW design (how it is going to perform the functionalities?) taking into account electrical, mechanical, thermal and data interfaces, and environmental constraints;
- Define required performances (how well does the subsystem need to do it?), taking into account electrical, mechanical, thermal and data interfaces, and environmental constraints. Compare with available hardware performances. Select hardware components;
- Define operational requirements (how is the hardware going to be operated?).

Second phase:

- Purchase/procure HW;
- Model performances;
- Implement design on a breadboard respecting design rules used for the qualification and flight models.

Third phase:

- Write breadboard functional test objectives and test procedure;
- Test breadboard for functionalities and performance characterization under electrical and thermal environment.

Final phase

- Write test report and design report.

Deliverables:

- A report including all technical assessments;
- A breadboard for the ADCS HW subsystem;
- A presentation at the Preliminary Design Review that will conclude Phase B;
- A disk containing all analysis and documentation files for records.

FOREWORD

This Master project consists of a written thesis reporting the background, design processes and outcomes of a project conducted at the EPFL under the supervision of Mrs. Muriel Noca. It began October 23 2006 and will finish March 5 2007 with the Phase B Review (Preliminary Design Review).

The development of the ADCS hardware was divided in three different projects, the inertia wheel and motor, the command electronic for the motor and the main part of the ADCS hardware. This document summarizes the work done on the main part of the ADCS hardware during a Master thesis at EPFL. The duration of this project was four month. This task was done 80% of the time in parallel with other system engineering tasks (20%). This report summarizes mainly the work done on the ADCS.

This report presents first the ADCS hardware specifications, then all the assumptions that were made and the approach that was used to fulfill the objectives. The third part presents the actual design of the ADCS hardware. In the forth part the test procedures, the test plan and some results are presented. The last part summarizes recommendations for the future work. Some system information is presented just before the conclusion.

1 INTRODUCTION

The main purpose of this report is to present the development of the functional design for the Attitude determination and control subsystem (ADCS) of the picosatellite SwissCube. The SwissCube is the first entirely Swiss picosatellite program. The SwissCube project is based on the CubeSat program started by Stanford University and California Polytechnic State University (CalPoly).

1.1 CubeSat

The CubeSat project is a joint venture between California Polytechnic State University San Luis Obispo and Stanford University's Space Systems Development Laboratory. Started in 1999 the purpose of the CubeSat project is to provide a conventional standard for the design and development of picosatellites such that a common deployer can be used [R1]. The project attempts to reduce the cost and development time generally associated with satellite design, consequently increasing the accessibility to space for educational purposes. Currently there are more than 80 institutions around the world taking part or took part in the development of CubeSats.

The fundamental defining feature of the CubeSat standard is its dimensions. The standard specifies that the satellite must have the geometry of $10cm^3$ cube with a mass of no more than 1kg and that the center of gravity must be within 2cm of the geometrical center. The standard also specifies several other important guidelines that must be followed, which will be dealt with as the design progresses. The standards are outlined in the CubeSat Specification Document [R2]. It is the purpose of the specification document to ensure that each satellite developed will integrate properly with the deployer and will not interfere with other satellites, payloads or the launch vehicle. Figure 1 is an example of a CubeSat design. It has been included to give an understanding of the basic external geometry of a typical CubeSat.

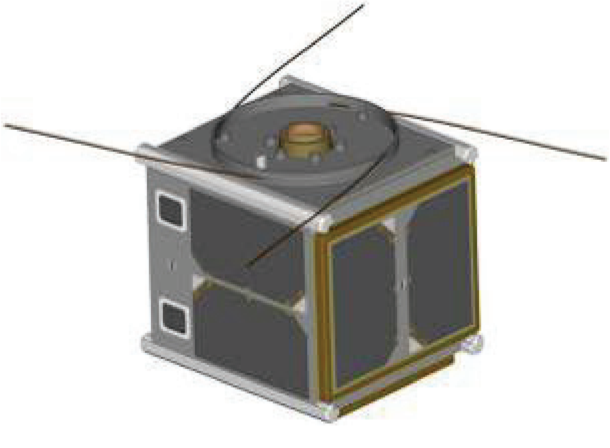


Figure 1: Example of a CubeSat (Aalborg University)

1.2 SwissCube

SwissCube is the picosatellite being designed by students and staff at the Swiss Federal Institute of Technology Lausanne (EPFL) to be developed and launched in line with the CubeSat specifications. The primary objective of developing this satellite is to provide a dynamic and realistic learning environment for undergraduates, graduates and staff in the development of small satellite technology [R3]. As a secondary objective it is hoped that the picosatellite will be able to house a science payload with the aim to take optical measurements and characterize the Nightglow phenomena (see Figure 2) over all latitudes and longitudes for at least a period of 3 months, with extended science mission duration up to 1 year [R4].

Figure 2: The Nightglow phenomena [R3].

In the design of the SwissCube, each of the subsystems like ADCS, EPS, etc., is being treated as an individual component and managed by a specific group of the SwissCube Team. Although each subsystem is being designed independently it is important to remember that each component is only one part of the complete satellite. Therefore to maintain a high level of integration between the various subsystems continuous communication and discussion is maintained between the designers of the individual subsystems. This report focuses on the ADCS hardware of the picosatellite.

Introduction: [R12]

1.3 ADCS

The ADCS hardware is the link between the physical state of the satellite and the algorithms that permit to determine and control the attitude. The current baseline design for the determination part of the ADCS subsystem includes magnetometers, gyroscopes and sun sensors. For the control the current baseline assumes 3 magnetic torquers for nominal operations and an inertial wheel for technology assessment.

The objectives of the ADCS Hardware project were divided into four phase. In the first phase the goal was to gather information about the various foreseen sensors and actuators in the phase A, to make a functional analysis and finally to write requirements and check the chosen hardware. The hardware was purchased and procured during the second phase, and the design of the bread board was implemented. In parallel, the ADCS functional analysis was refined and transformed in a flow diagram for the future work on the software. The third phase focused on the tests. The test plan and procedures were written and the tests were performed on the board.

Figure 3 shows the hardware block diagram of the ADCS board. The interfaces are thus data transfer (black line) with the ADCS microprocessor, power from the EPS, represented as the blue line on Figure 3 and connections with the actuators and the sun sensors that are placed behind the side panels.

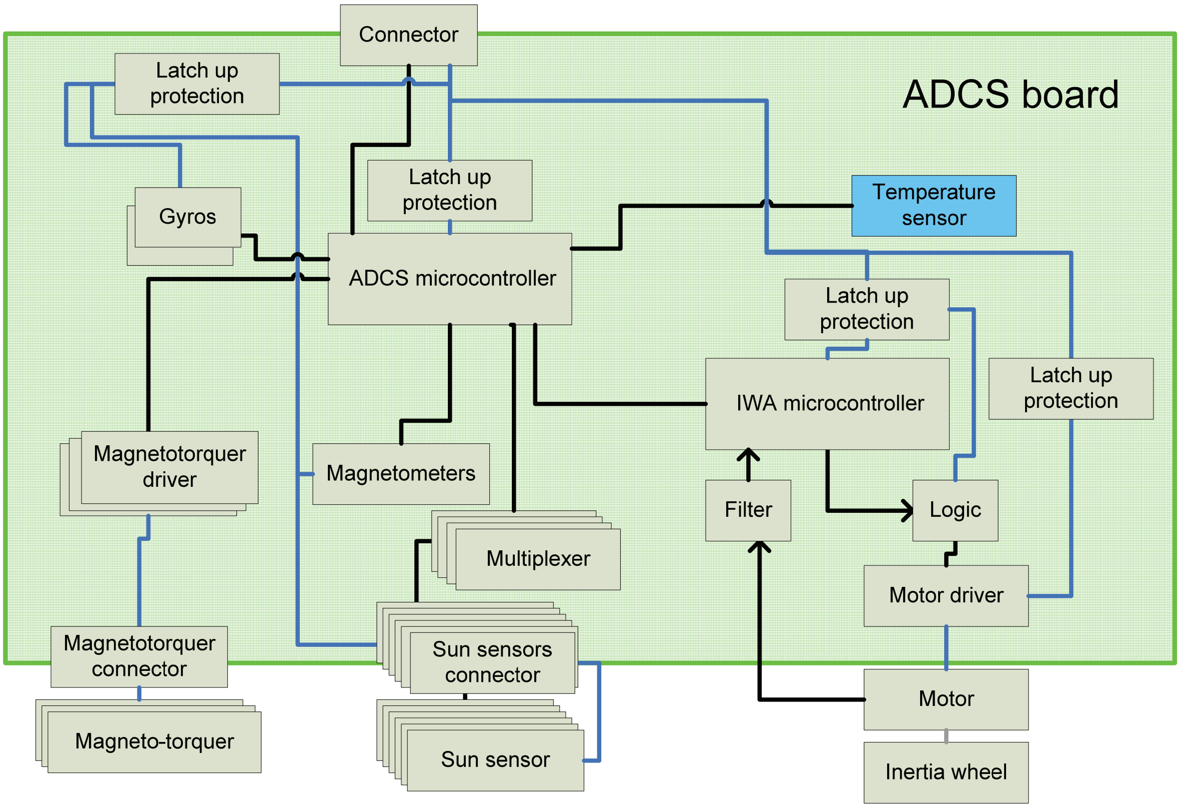


Figure 3: ADCS subsystem hardware block diagram.

2 DESIGN REQUIREMENTS AT LEVEL 4

The level 4 requirements are requirements that are related to the whole subsystem. The definitions and rules are defined in [R5].

2.1 Functional Requirements

4_ADCS_10_01: Interface

The ADCS shall provide an interface between sensors and CDMS as well as between CDMS and actuators. This includes the following functions:

Receive cmd from and send TM to CDMS

Power and command acutators

Power, command and receive TM, store and format data from sensors

To fulfill mission objective 3

3_SSR_10_02

4_ADCS_10_02: Determination

The ADCS subsystem shall provide determination of the attitude of the satellite.

To fulfill mission objective 3

3_SSR_24_02

4_ADCS_10_03: HK

The ADCS shall provide HK to determine its health.

To monitor health of the Space system

3_SSR_63_02

4_ADCS_10_04: Attitude control

The ADCS shall provide a control for the attitude of the satellite.

Pointing stability

3_SSR_24_04

2.2 Mission & Performance Requirements

2.2.1 Subsystem modes

4_ADCS_21_01: Subsystem modes

The ADCS system shall have the following modes: “WHEEL”, “NOMINAL”, “SENSOR”, “STAND-BY” and “OFF” modes.

To fulfill its function

4_ADCS_10_01

4_ADCS_21_02: “OFF” mode

In this mode the whole subsystem shall be turned off.

Off mode definition

4_ADCS_21_01

4_ADCS_21_03: “STAND-BY” mode

In this mode only the microcontroller shall be on and waiting for a command.

Stand-By mode definition

4_ADCS_21_01

4_ADCS_21_04: “SENSOR” mode

In this mode only the microcontroller and all the sensors shall be turned on. Actuators shall be switched off.

Attitude determination

4_ADCS_10_02

4_ADCS_21_05: “NOMINAL” mode

In this mode the microcontroller, the sensors and the actuators shall be on. The IWA shall be switched off.

Attitude determination and control

4_ADCS_10_04

4_ADCS_21_06: “WHEEL” mode

In this mode the microcontroller, the sensors and all the actuators shall be on.

Attitude determination and control

4_ADCS_10_04

2.2.2 Subsystem states

2.2.3 Subsystem H/W performances

4_ADCS_23_01: Consumption in “OFF” mode

The ADCS shall not consume any power in “OFF” mode.

SSR power budget

4_ADCS_23_02: Consumption in “STAND-BY” mode

The ADCS shall consume less than [30] mW in “STAND-BY” mode.

SSR power budget

4_ADCS_23_03: Consumption in “SENSOR” mode

The ADCS shall consume less than [90] mW in “SENSOR” mode.

SSR power budget

4_ADCS_23_04: Consumption in “NOMINAL” mode

The ADCS shall consume less than [250] mW in “NOMINAL” mode.

SSR power budget

4_ADCS_23_05: Consumption in “WHEEL” mode

The ADCS shall consume less than [300] mW in “WHEEL” mode.

SSR power budget

4_ADCS_23_06: Attitude determination

The ADCS subsystem shall provide determination data of the attitude of the satellite with an accuracy of [10] degrees on each axis.

MSR

3_SSR_24_02

4_ADCS_23_07: Attitude control

The ADCS subsystem shall provide a control for the attitude of the satellite with a stability [3] deg/s.

MSR

3_SSR_24_04

2.2.4 Subsystem S/W performances

4_ADCS_24_01: Command data

The ADCS shall accept the command signal for the actuators control electronics at least once every [10] seconds.

Control algorithm

4_ADCS_24_02: Data transmission

The ADCS shall be able to send attitude and HK sensors data at specific requests from the CDMS.

To fulfill its function

4_ADCS_10_01

2.2.5 Reliability and redundancy

4_ADCS_25_02: Latch up protection

The ADCS shall be designed with separate latch-up protection circuit.

To mitigate SEL

3_SSR_25_01

4_ADCS_25_03: SEU

ADCS H/W and S/W design for critical functions shall mitigated possible SEUs.

Protection

3_SSR_25_01

4_ADCS_25_04: Tests

Reliability of the electrical systems shall be demonstrated by tests.

Tests requirements

3_SSR_25_02

2.3 Design Requirements

2.3.1 Constraints

4_ADCS_31_01: Outgassing

The ADCS materials shall have a Total Mass Loss (TML) ≤ 1 % and a Collected Volatile Condensable Material (CVCM) ≤ 0.1 %.

Arianespace user's manual.

3_SSR_31_15

4_ADCS_31_02: Launch date

The ADCS shall be ready for integration in the Engineering Qualification Model by December 2007.

Launch date deadline.

3_SSR_31_09

4_ADCS_31_03: Contamination

NASA approved materials shall be used whenever possible to prevent contamination of other spacecraft during integration, testing and launch.

CalPoly spec.

3_SSR_31_13

2.3.2 Thermal

4_ADCS_32 _01: Temperature

The ADCS shall be capable of measuring its temperature.

Thermal analysis.

3_SSR_32_03

4_ADCS_32 _02: Temperature control

The ADCS shall have a passive temperature control.

Thermal analysis.

3_SSR_32_03

4_ADCS_32 _03: Thermal design

The thermal design of the board shall ensure that all components are maintained within their qualification temperature range throughout the lifetime of the subsystem.

Thermal analysis.

3_SSR_32_02

2.3.3 Maintainability

4_ADCS_33 _01: Electrostatic sensibility

The ADCS shall be handled with precaution against electrostatic discharges.

Manufacturer recommendation.

3_SSR_33_01

4_ADCS_33 _02: Maintenance during storage and ground operation

The ADCS shall be designed to require no maintenance during storage and ground life. If ground maintenance during storage or ground operation cannot be avoided, the maintenance requirements shall be documented.

To survive storage and ground life

3_SSR_33_01

2.4 Interface Requirements

2.4.1 Structural Interfaces

4_ADCS_41_01: Attachment

The ADCS shall be attached on the frame.

S&C

4_SC_10_02

2.4.2 Thermal Interfaces

4_ADCS_42_01: Subsystem

Thermal interfaces optimized considering the whole satellite thermal design.

TH

3_SSR_32_02

2.4.3 Electrical Interfaces

4_ADCS_43_01: Supply voltage

The ADCS shall use 3.3V or 5V. Any deviations shall be discussed with the EPS and System Engineering Team. (Requirement to be refined). 3.3 Volt shall be preferred.

EPS.

4_ADCS_43_02: Current

The ADCS shall use less than [150] mA.

EPS.

4_ADCS_43_03: Connectors

The ADCS shall use connectors compatible with the main data bus and the power bus.

SSR.

4_ADCS__10_01

2.4.4 Data Interfaces

4_ADCS_44_01: Data bus compatibility

The ADCS shall be capable of communicating with the main data bus.

Same data bus for the whole satellite.

4_ADCS_10_01

4_ADCS_44_02: TM

The ADCS generate TM with all the sensors and the IWA data.

SSR

4_ADCS_10_01

2.4.5 Physical Interfaces

4_ADCS_45_01: Size

The ADCS size shall be adapted to the structure.

S&C, detail shall be discussed with mechanical engineer

4_SC_10_01

4_ADCS_45_02: Mass

The ADCS mass shall weight less than [120] grams.

Mass budget.

3_SSR_45_01

2.5 Environmental Requirements

4_ADCS_50_01: Environment

The ADCS operates under the environment constraints described in the SwissCube Environment Requirements document [REF].

SSR.

3_SSR_50_01

2.5.1 Thermal

4_ADCS_51_01: Thermal

The ADCS subsystem shall operate at a temperature range between [-30 and +80 TBR] degrees Celsius.

Thermal analysis

4_ADCS_50_01

2.5.2 Static and dynamic loads

4_ADCS_52_01: Acceleration

The ADCS shall withstand a maximal acceleration of [10,4] g including margins.

Launch environment constraints

3_SSR_52_02

2.5.3 Vacuum

4_ADCS_53_01: Vacuum

The ADCS subsystem shall operate under vacuum conditions.

PR

3_SSR_53_01

2.5.4 Radiation

4_ADCS_54_01: Total dose

The ADCS shall support a TID of maximum [37.4]kRad.

Analysis using ESA Spenvis Tool, This is the value for 1 year in orbit

3_SSR_54_02

2.6 Operational Requirements

2.6.1 Autonomy

4_ADCS_61_01: Life time

The ADCS shall have a life time of [4] months after commissioning phase. The lifetime can be extended to [1] year.

SSR

3_SSR_61_01

2.6.2 Control

4_ADCS_62_01: Cmd reception

The ADCS shall be able to receive cmd from CDMS at all times when not in the “OFF” mode. [TBC]

SSR

2.6.3 Failure management

4_ADCS_63_01: Failure propagation

Failure of one part or element of the ADCS shall not result in consequential damage to the equipment or other satellite components.

To minimize failure propagation

3_SSR_63_01

3 DESIGN REQUIREMENTS AT LEVEL 5

3.1 Functional Requirements

5_ADCS/ACT_10_01: Actuators

The ADCS actuators shall provide torque to control the attitude of the satellite.

Actuators include: Magnetotorquers, IWA

4_ADCS_10_04

5_ADCS/ACT_10_02: Magnetotorquer axis control

The magnetotorquers shall provide controllability on all three axes.

To provide attitude control

4_ADCS_10_04

5_ADCS/DTS_10_01: Determination sensors

The ADCS determination sensors shall provide data for determination of the attitude of the satellite.

ADCS determination functions

Sensors include: magnetometers, gyroscopes, sun sensors

4_ADCS_10_02

5_ADCS/DTS_10_02: Sun sensors axis measurement

Sun sensors shall provide measurements on all 3 axis.

To determine the attitude

4_ADCS_10_02

5_ADCS/DTS_10_03: Gyroscopes axis measurement

Gyroscopes shall provide measurements on all3 axis.

To determine the attitude

4_ADCS_10_02

5_ADCS/DTS_10_04: Magnetometer axis measurement

The magnetic sensor shall measure the magnetic field strength along tree axis.

To determine the attitude

4_ADCS_10_02

5_ADCS/MCU_10_01: ADCS microcontroller function I

The ADCS MCU shall receive commands from CDMS.

Definition of ADCS function

4_ADCS_10_01

5_ADCS/MCU_10_02: ADCS microcontroller function II

The ADCS MCU shall turn on and off sensors.

ADCS determination function

4_ADCS_10_02

5_ADCS/MCU_10_03: ADCS microcontroller function III

The ADCS MCU shall collect sensor data.

Definition of ADCS function

4_ADCS_10_02

5_ADCS/MCU_10_04: ADCS microcontroller function IV

The ADCS MCU shall format the data from sensor.

ADCS function

4_ADCS_10_02

5_ADCS/MCU_10_05: ADCS microcontroller function V

The ADCS MCU shall send TM to CDMS.

ADCS function

4_ADCS_10_01

5_ADCS/MCU_10_06: ADCS microcontroller function VI

The ADCS MCU shall command the actuators.

ADCS attitude control function

4_ADCS_10_04

5_ADCS/PCB_10_01: PCB

The ADCS PCB shall provide a mechanical and electrical support for all the electronic.

To perform ADCS function

4_ADCS_10_01

5_ADCS/HKS_10_01: HK sensors

The ADCS HK sensors shall provide data to determine the health of the ADCS subsystem.

This includes: IWA state, Temperature sensors

4_ADCS_10_03

3.2 Mission & Performance Requirements

3.2.1 Subsystem modes

3.2.2 Subsystem states

3.2.3 Subsystem H/W performances

5_ADCS/ACT_23_01: Magnetotorquers power consumption in “WHEEL” mode

The mean magnetotorquer power consumption in “WHEEL” mode shall be less than [50] mW per magnetotorquer.

Power budget

4_ADCS_23_05

5_ADCS/ACT_23_02: Magnetotorquers power cons. in “NOMINAL” mode

The mean magnetotorquer power consumption in “NOMINAL” mode shall be less than [50] mW per magnetotorquer

Power budget

4_ADCS_23_04

5_ADCS/ACT_23_03: Magnetotorquers power cons. in “SENSOR” mode

The magnetotorquers shall not consume any power in "SENSOR" mode.

Power budget

4_ADCS_23_03

5_ADCS/ACT_23_04: Magnetotorquers power cons. in “STAND-BY” mode

The magnetotorquers shall not consume any power in "STAND-BY" mode.

Power budget

4_ADCS_23_02

5_ADCS/ACT_23_05: Magnetotorquers power cons. in “OFF” mode

The magnetotorquers shall not consume any power in "OFF" mode.

Power budget

4_ADCS_23_01

5_ADCS/ACT_23_06: Magnetotorquers magnetic moment

The magnetotorquers shall generate a magnetic moment of at least [0.0285] A^2m.

AHW report phase B

To control perturbations torques

4_ADCS_10_04

5_ADCS/DTS_23_01: Sensors power consumption in “WHEEL” mode

The mean sensors power consumption in “WHEEL” mode shall be less than [60] mW.

Power budget

4_ADCS_23_05

5_ADCS/DTS_23_02: Sensors power consumption in “NOMINAL” mode

The mean sensors power consumption in “NOMINAL” mode shall be less than [60] mW.

Power budget

4_ADCS_23_04

5_ADCS/DTS_23_03 Sensors power consumption in “SENSOR” mode

The mean sensors power consumption in “SENSOR” mode shall be less than [60] mW.

Power budget

4_ADCS_23_03

5_ADCS/DTS_23_04 Sensors power consumption in “STAND-BY” mode

The determination sensors shall not consume any power in “STAND-BY” mode.

Power budget

4_ADCS_23_02

5_ADCS/DTS_23_05 Sensors power consumption in “OFF” mode

The determination sensors shall not consume any power in “OFF” mode.

Power budget

4_ADCS_23_01

5_ADCS/DTS_23_06: Magnetometers measurement range

Magnetometers shall be capable of measuring magnetic fields in the range of [0.3 10^{-4}]T and [1.5 10^{-5}] T with an accuracy of +/- [1]%. (maximal magnetic field over the poles).

Sensor performances

4_ADCS_10_02

5_ADCS/DTS_23_07: Magnetometers measurement resolution

The magnetic sensor shall have a minimum resolution of [1.10-6]T.

Sensor performances.

4_ADCS_10_02

5_ADCS/DTS_23_08: Sun sensors measurement range

Sun sensors shall be capable of measuring the direction of the sun in the range of [0] deg and [60] deg with an accuracy of +/- [10]%.

Sensor performances.

4_ADCS_10_02

5_ADCS/DTS_23_09: Gyroscopes measurement range

Gyroscopes shall be capable of measuring angular rate in the range of [0.01] deg/s and [180] deg/s with an accuracy of +/- [1]%.

Sensor performances.

4_ADCS_10_02

5_ADCS/MCU_23_01 MCU power consumption in “OFF” mode

The microcontroller shall not consume any power in “OFF” mode.

Power budget

4_ADCS_23_01

5_ADCS/MCU_23_02 MCU power consumption in “STAND-BY” mode

The microcontroller power consumption shall be less than [30] mW in “STAND-BY” mode.

Power budget

4_ADCS_23_02

5_ADCS/MCU_23_03 Sensors power consumption in “SENSOR” mode

The microcontroller power consumption shall be less than [30] mW in “SENSOR” mode.

Power budget

4_ADCS_23_03

5_ADCS/MCU_23_04: Sensors power consumption in “NOMINAL” mode

The microcontroller power consumption shall be less than [30] mW in “NOMINAL” mode.

Power budget

4_ADCS_23_04

5_ADCS/MCU_23_05: Sensors power consumption in “WHEEL” mode

The microcontroller power consumption shall be less than [30] mW in “WHEEL” mode.

Power budget

4_ADCS_23_05

3.2.4 Subsystem S/W performances

5_ADCS/MCU_24_01: Command data

The microcontroller shall accept the command signal for the motor control electronics and the magnetic torquers control electronics at least once every [10] seconds.

4_ADCS_24_01.

5_ADCS/MCU_24_02: HK Data transmission

The microcontroller shall be able to send HK sensors data at specific requests from the CDMS.

4_ADCS_24_02

5_ADCS/MCU_24_03: Data transmission

The microcontroller shall be able to send attitude data at specific requests from the CDMS.

4_ADCS_24_02

5_ADCS/MCU_24_04: Determination sensors data storage

The microcontroller shall be able to store attitude sensor data for at least the last [10] readings.

AHW report phase B

Requirement to be refined

5_ADCS/MCU_24_05: HK sensors data storage

The microcontroller shall be able to store HK sensor data for at least the last [10] readings.

AHW report phase B

Requirement to be refined

3.2.5 Reliability and redundancy

5_ADCS/MCU_25_01: Actuators reliability and redundancy

The actuators shall comply to 4_ADCS_25_02, 03 and 04.

Level 4 ADCS requirements

4_ADCS_25_02

5_ADCS/MCU_25_02: Determination sensors reliability and redundancy

The determination sensors shall comply to 4_ADCS_25_02, 03 and 04.

Level 4 ADCS requirements

4_ADCS_25_02

5_ADCS/MCU_25_03: MCU reliability and redundancy

The MCU shall comply to 4_ADCS_25_02, 03 and 04.

Level 4 ADCS requirements

4_ADCS_25_02

5_ADCS/MCU_25_03: PCB reliability and redundancy

The PCB shall comply to 4_ADCS_25_02, 03 and 04.

Level 4 ADCS requirements

4_ADCS_25_02

3.3 Design Requirements

3.3.1 Constraints

5_ADCS/ACT_31_01: Magnetotorquers design constraints

The actuators shall comply with 4_ADCS_31_01, 4_ADCS_31_02 and 4_ADCS_31_03.

Level 4 ADCS requirements

4_ADCS_31_01

5_ADCS/DTS _31_01: Determination sensors design constraints

The actuators shall comply with 4_ADCS_31_01, 4_ADCS_31_02 and 4_ADCS_31_03.

Level 4 ADCS requirements

4_ADCS_31_01

5_ADCS/DTS_31_02: Magnetometer

Magnetometer bias may be lessened by winding small coils near the magnetometer in series with the larger control coils.

In order to avoid as well as it is possible disturbances.

5_ADCS/MCU_31_01: MCU design constraints

The actuators shall comply with 4_ADCS_31_01, 4_ADCS_31_02 and 4_ADCS_31_03.

Level 4 ADCS requirements

4_ADCS_31_01

5_ADCS/PCB_31_01: PCB design constraints

The actuators shall comply with 4_ADCS_31_01, 4_ADCS_31_02 and 4_ADCS_31_03.

Level 4 ADCS requirements

4_ADCS_31_01

3.3.2 Thermal

5_ADCS/ACT_32_01: Actuators thermal design

The actuators shall comply with 4_ADCS_32_01, 4_ADCS_32_02 and 4_ADCS_32_03.

Level 4 ADCS requirements

4_ADCS_32_01

5_ADCS/DTS_32_01: Determination sensors thermal design

The determination sensors shall comply with 4_ADCS_32_01, 4_ADCS_32_02 and 4_ADCS_32_03.

Level 4 ADCS requirements

4_ADCS_32_01

5_ADCS/MCU_32_01: MCU thermal design

The microcontroller shall comply with 4_ADCS_32_01, 4_ADCS_32_02 and 4_ADCS_32_03.

Level 4 ADCS requirements

4_ADCS_32_01

5_ADCS/PCB_32_01: PCB thermal design

The PCB shall comply with 4_ADCS_32_01, 4_ADCS_32_02 and 4_ADCS_32_03.

Level 4 ADCS requirements

4_ADCS_32_01

3.3.3 Maintainability

5_ADCS/ACT_33_01: Actuators maintainability

The actuators shall comply with 4_ADCS_33_01 and 4_ADCS_33_02.

Level 4 ADCS requirements

4_ADCS_33_01

5_ADCS/DTS_33_01: Determination sensors maintainability

The determination sensors shall comply with 4_ADCS_33_01 and 4_ADCS_33_02.

Level 4 ADCS requirements

4_ADCS_33_01

5_ADCS/MCU_33_01: MCU thermal maintainability

The microcontroller shall comply with 4_ADCS_33_01 and 4_ADCS_33_02.

Level 4 ADCS requirements

4_ADCS_33_01

5_ADCS/PCB_33_01: PCB maintainability

The PCB shall comply with 4_ADCS_33_01 and 4_ADCS_33_02.

Level 4 ADCS requirements

4_ADCS_33_01

3.4 Interface Requirements

3.4.1 Structural Interfaces

5_ADCS/ACT_41_01: Magnetotorquers

Magnetotorquers shall be located in perpendicular planes.

Control on three axes.

5_ADCS/ACT_10_02

5_ADCS/DTS_41_01: Sun sensor location

Sun sensors shall be mounted on the 6 faces, 1 sensor per face.

Need 3 sensors to determine direction of the Sun at all times, need 6 sensor heads to cover all possible directions.

5_ADCS/DTS_10_06

5_ADCS/DTS_41_02: Magnetometer location

The magnetometers shall be placed at a distance at least greater than [xx]mm from the magnetotorquers plane.

In order to avoid as well as it is possible disturbances.

5_ADCS/PCB_41_01: PCB placement

The placement of the PCB shall be optimized to be as distant as possible from the magnetotorquers and the IWA.

Magnetic perturbations on magnetometer.

3.4.2 Thermal Interfaces

5_ADCS/ACT_42_01: Magnetotorquers

Magnetotorquers shall be thermally connected to the frame.

TH

4_ADCS_32_02

5_ADCS/PCB_42_01: PCB

The PCB shall be thermally connected to the frame.

TH

4_ADCS_32_02

3.4.3 Electrical Interfaces

5_ADCS/ACT_43_01: Magnetotorquers supply voltage

The magnetotorquers and their electronic shall use 3.3V.

ADCS supply

4_ADCS_43_01

5_ADCS/ACT_43_02: Magnetotorquers connection

The magnetotorquers shall be connected to ADCS board.

Decrease number of interfaces.

4_SC _10_01

5_ADCS/DTS_43_01: gyroscopes supply voltage

The gyroscopes and their electronic shall use 3.3V.

ADCS supply

4_ADCS_43_01

5_ADCS/DTS_43_02: magnetometers supply voltage

The magnetometers and their electronic shall use 3.3V.

ADCS supply

4_ADCS_43_01

5_ADCS/DTS_43_03: sun sensors supply voltage

The sun sensors and their electronic shall use 3.3V.

ADCS supply

4_ADCS_43_01

5_ADCS/DTS_43_07: sun sensors connection

The sun sensors shall be connected to ADCS board.

Decrease number of interfaces.

4_SC _10_01

5_ADCS/MCU_44_01: Microcontroller supply voltage

The microcontroller and its electronic shall use 3.3V.

ADCS supply

4_ADCS_43_01

5_ADCS/PCB_44_01: Board supply

The main board shall be connected to the power bus and use use 3.3V.

ADCS supply

4_ADCS_43_01

3.4.4 Data Interfaces

5_ADCS/DTS_44_01: Magnetometer master clock frequency

The magnetometer shall use a master clock frequency of [8] or [10] MHz.

Magnetometer's report.

5_ADCS/MCU_44_01: Microcontroller main bus interface

The microcontroller shall be capable of communicating with the main data bus.

Same data bus for the whole satellite.

5_ADCS/MCU_44_02: Microcontroller sensor interface

The microcontroller shall be capable of communicating with each sensor.

Anolog signal reading, and serial data interface reading capability.

5_ADCS/MCU_10_02

5_ADCS/MCU_44_03: TM

The microcontroller shall generate TM with all the sensors and the IWA data.

[TBD]

4_ADCS_44_02

3.4.5 Physical Interfaces

5_ADCS/ACT_45_01: Magnetotorquer mass

Each coil shall weight less than [16] grams.

Mass budget.

4_ADCS_45_02

5_ADCS/ACT_45_02: Magnetotorquer size

Magnetotorquers external dimensions shall not exceed [82x90x4]mm on X and Z axis, and [82x86.5x4]mm on Y axis in SRF

S&C.

4_ADCS_45_01

5_ADCS/DTS_45_01: Sun sensors dimensions

The external sun sensors PCB dimensions shall not exceed [20x16x3.5] mm.

S&C.

4_ADCS_45_01

5_ADCS/PCB_45_01: Card dimensions

The external ADCS card dimensions shall not exceed [80x85x10] mm, and the value of [10] shall not be reached on the entire surface.

S&C.

4_ADCS_45_01

5_ADCS/PCB_45_02: Card mass

The ADCS card (PCB and components) shall weight less than [34] grams.

Mass budget.

4_ADCS_45_02

3.5 Environmental Requirements

3.5.1 Thermal

5_ADCS/ACT_51_01: Thermal environment

The actuators shall comply with 4_ADCS_51_01 and 4_ADCS_51_02.

Level 4 ADCS requirements

4_ADCS_51_01

5_ADCS/DTS_51_01: Thermal environment

The determination sensors shall comply with 4_ADCS_51_01 and 4_ADCS_51_02.

Level 4 ADCS requirements

4_ADCS_51_01

5_ADCS/MCU_51_01: Thermal environment

The microcontroller shall comply with 4_ADCS_51_01 and 4_ADCS_51_02.

Level 4 ADCS requirements

4_ADCS_51_01

5_ADCS/PCB_51_01: Thermal environment

The PCB shall comply with 4_ADCS_51_01 and 4_ADCS_51_02.

Level 4 ADCS requirements

4_ADCS_51_01

3.5.2 Static and dynamic loads

5_ADCS/ACT_52_01: Acceleration

The actuators shall comply with 4_ADCS_52_01.

Level 4 ADCS requirements

4_ADCS_52_01

5_ADCS/DTS_52_01: Acceleration

The determination sensors shall comply with 4_ADCS_52_01.

Level 4 ADCS requirements

4_ADCS_52_01

5_ADCS/MCU_52_01: Acceleration

The microcontroller shall comply with 4_ADCS_52_01.

Level 4 ADCS requirements

4_ADCS_52_01

5_ADCS/PCB_52_01: Acceleration

The PCB shall comply with 4_ADCS_52_01.

Level 4 ADCS requirements

4_ADCS_52_01

3.5.3 Vacuum

5_ADCS/ACT_53_01: Vacuum

The actuators shall be able to operate under vacuum conditions.

Space environment

4_ADCS_53_01

5_ADCS/DTS_53_01: Vacuum

The determination sensors shall be able to operate under vacuum conditions.

Space environment

4_ADCS_53_01

5_ADCS/MCU_53_01: Vacuum

The microcontroller shall be able to operate under vacuum conditions.

Space environment

4_ADCS_53_01

5_ADCS/PCB_53_01: Vacuum

The PCB shall be able to operate under vacuum conditions.

Space environment

4_ADCS_53_01

3.5.4 Radiation

5_ADCS/ACT_54_01: Total dose

The actuators shall support a TID of maximum [37.4]kRad.

Analysis using ESA Spenvis Tool. This is the value for 1 year in orbit

4_ADCS_54_01

5_ADCS/DTS_54_01: Total dose

The determination sensors shall support a TID of maximum [37.4]kRad.

Analysis using ESA Spenvis Tool. This is the value for 1 year in orbit

4_ADCS_54_01

5_ADCS/MCU_54_01: Total dose

The microcontroller shall support a TID of maximum [37.4]kRad.

Analysis using ESA Spenvis Tool. This is the value for 1 year in orbit

4_ADCS_54_01

5_ADCS/PCB_54_01: Total dose

The PCB shall support a TID of maximum [37.4]kRad.

Analysis using ESA Spenvis Tool. This is the value for 1 year in orbit

4_ADCS_54_01

3.6 Operational Requirements

3.6.1 Autonomy

5_ADCS/ACT_61_01: Life time

The actuators shall be designed to operate during [4] months including commissioning and nominal activities. The lifetime can be extended to [1] year.

SSR

4_ADCS_61_01

5_ADCS/DTS_61_01: Life time

The determination sensors shall be designed to operate during [4] months including commissioning and nominal activities. The lifetime can be extended to [1] year.

SSR

4_ADCS_61_01

5_ADCS/MCU_61_01: Life time

The microcontroller shall be designed to operate during [4] months including commissioning and nominal activities. The lifetime can be extended to [1] year.

SSR

4_ADCS_61_01

5_ADCS/PCB_61_01: Life time

The PCB shall be designed to operate during [4] months including commissioning and nominal activities. The lifetime can be extended to [1] year.

SSR

4_ADCS_61_01

3.6.2 Control

5_ADCS/ACT_62_01: Magnetic incompatibility

The magnetotorquers shall be turned off during measurements with magnetometers. [TBR]

5_ADCS/MCU_62_01: Microcontroller

The microcontroller must be able to receive a data request from CDMS at all times when not in the “OFF” mode. [TBC]

[TBD]

4_ADCS_62_01

3.6.3 Failure management

5_ADCS/ACT_63_01: Failure propagation

Actuators failure shall not result in consequential damage to the equipment or other satellite components.

To minimize failure propagation

3_SSR_63_01

5_ADCS/DTS_63_01: Failure propagation

The determination sensors shall not result in consequential damage to the equipment or other satellite components.

To minimize failure propagation

3_SSR_63_01

5_ADCS/MCU_63_01: Failure propagation

Microcontroller failure shall not result in consequential damage to the equipment or other satellite components.

To minimize failure propagation

3_SSR_63_01

5_ADCS/PCB_63_01: Failure propagation

PCB failure shall not result in consequential damage to the equipment or other satellite components.

To minimize failure propagation

3_SSR_63_01

4 DESIGN ASSUMPTIONS AND APPROACH

In this section the various assumptions that were made are discussed. It summarizes the approach for doing the work and some analysis. The assumptions are the points not described in the requirements part of the report.

4.1 Approach

The first part of the project was to recalculate the disturbances in order to have reliable values for the dimensioning of the actuators, wheel and magnetotorquers, and for the development of the attitude controller. The second step was to do a functional analysis to know in detail which functions the ADCS PCB shall fulfill. In parallel searches were made to find the different components. They were compared, and one per category was chosen. Once the components were chosen, the electronic circuit and the PCB layout were designed. During the PCB production time, the magnetotorquers were redimensioned. A preliminary study was made during phase A, but it was necessary to refine the design in accordance to the development done after the phase A review.

Once the hardware was ordered and produced, the next step was to define the software that will be needed to test and run the system. The list of TC/TM was also defined.

It is important to mention that the hardware was not selected only on the performances, but on availability, compatibility with the system and physical characteristics such as size and mass criterion.

4.2 Disturbances

In order to have precise dimensioning requirements, a disturbances analysis was made. The analysis completes and refines the one done during Phase A.

The disturbances the satellite has to go through are mainly due to four sources of torques on low-altitude Earth orbits. They are gravity-gradient effects, magnetic fields, disturbance by solar radiation and aerodynamic torques. The torques are categorized as secular and cyclic. Cyclic torques vary in a sinusoidal manner during an orbit and secular accumulate with time and don't average out over an orbit. For an Earth-oriented spacecraft, gravity-gradient and aerodynamic torques are secular and solar radiation and magnetic field cyclic.

The disturbances torques were separately calculated in the very worst case for every altitude between 400 kilometers and 1000 kilometers with a step of 100 kilometers. Very worst case means that each parameter was taken at its maximal value. For this reason no margin was added at this point. The major disturbance factor is aerodynamic up to 600km. The summarized results can be seen in Figure 4 and Table 1.

For the dimensioning of the actuators, twice the worst case was taken. The worst case happens at the altitude of 400 km. The torque that the actuators shall produce is 2x3.6e-7=**7.2e-7 Nm.** [R6]. For example, the torque used for the actuators dimensioning is twelve times greater than the disturbance torque at the altitude of 700 km.

The detailed calculation and explanation are presented in Appendix A.

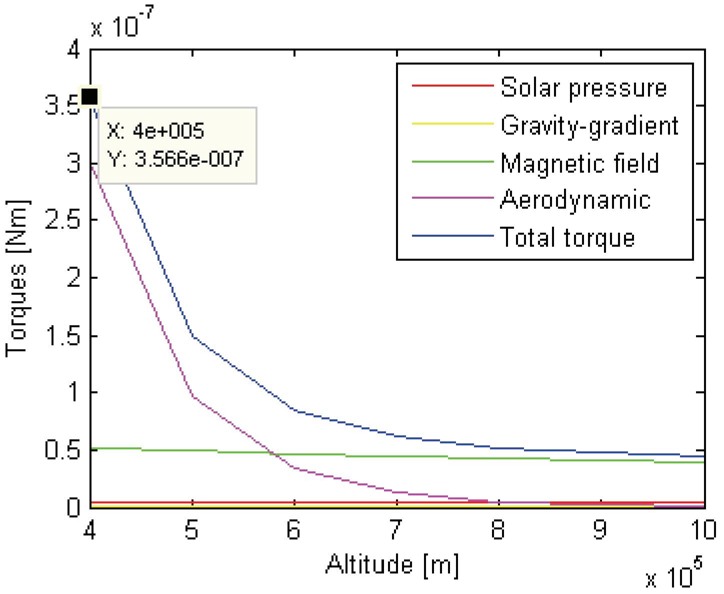


Figure 4: Disturbances in function of altitude.

Altitude [km]	Solar pressure [Nm]	Gravity-gradient [Nm]	Magnetic field [Nm]	Aerodynamic [Nm]	Total torque [Nm]
400	3.6e-9	3.6e-10	5.1e-8	3.0e-7	**3.6e-7**
500	3.6e-9	3.4e-10	4.9e-8	9.7e-8	**1.5e-7**
600	3.6e-9	3.3e-10	4.7e-8	3.5e-8	**8.6e-8**
700	3.6e-9	3.2e-10	4.5e-8	1.3e-8	**6.2e-8**
800	3.6e-9	3.0e-10	4.3e-8	5.2e-9	**5.2e-8**
900	3.6e-9	2.9e-10	4.1e-8	2.2e-9	**4.7e-8**
1000	3.6e-9	2.8e-10	3.9e-8	8.9e-10	**4.4e-8**

Table 1: Analysis results for disturbances.

4.3 Electrical and data assumptions

According to the last developments before starting working on this subsystem in phase B, there is only one data bus with all subsystems connected on it. The data bus is an I2C bus. The used microcontroller shall be compatible with it.

The ADCS microcontroller will not support determination and control algorithm. It will be used to collect the sensors values and to store them until the main controller on board (CDMS) will use them. It will also be used control the actuators once the main computer has calculated the command values.

In order to minimize power losses and simplify the design of the EPS, the choice of components using a supply voltage of 3.3V was preferred.

4.4 Hardware

At the end of phase A several assumptions were made on the hardware. The hardware elements chosen for the development of the ADCS were kept for phase B. The sensors and actuators that will be used are outlined in gray in Figure 5. The white boxes represent other possibilities for sensing and actuating.

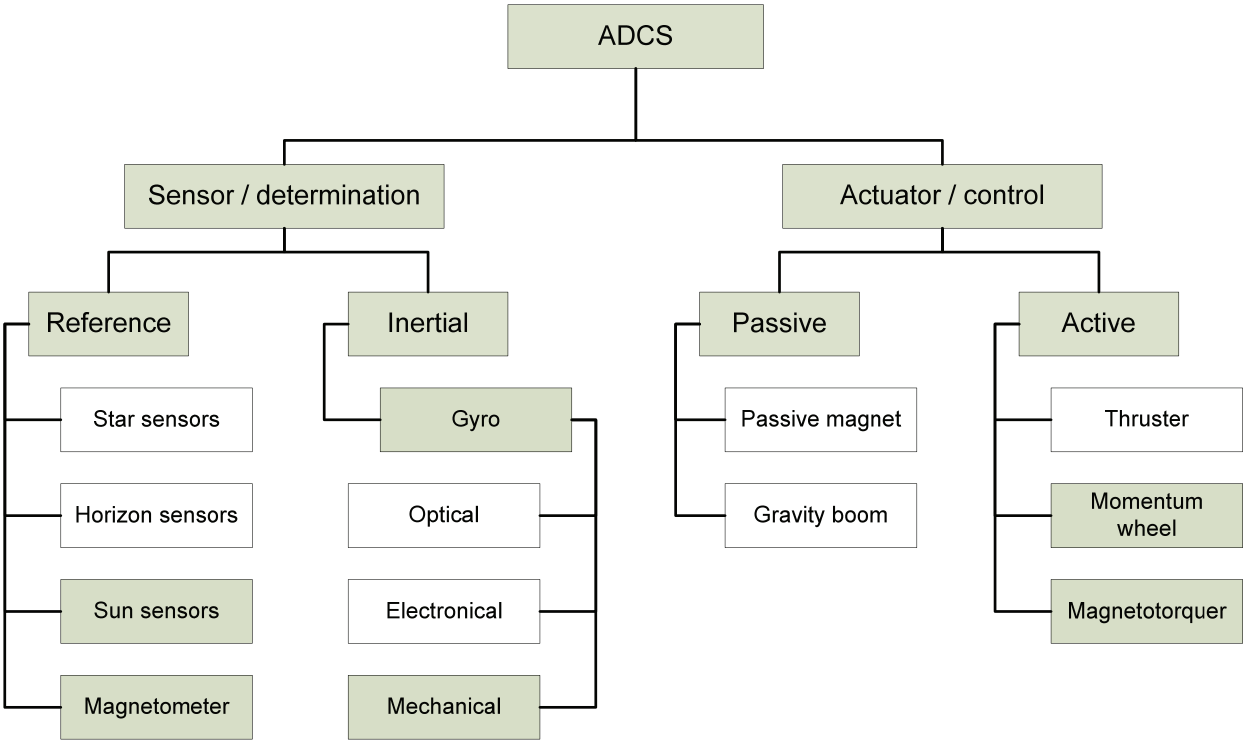


Figure 5 ADCS hardware trade-off.

5 TECHNICAL DESCRIPTION

This section describes the chosen hardware, its implementation, the electronic layout and some of the software aspects needed to fulfill the different functions of the ADCS board.

5.1 Sensors

The kind of sensors was made according to phase A specifications. For each category of sensor several criteria were taken in account such as the weight, the size, the supply voltage, the power consumption, the accuracy, the market availability, the price. The selection process for each sensor is described below.

During daylight, the three kinds of sensors are used, gyroscopes, sun sensors and magnetometers. According to preliminary calculations, the solar panels don't offer enough accuracy to be used as sensors. It was decide to check for more precise sun sensors. For the magnetometers a separate semester project was done to choose the appropriate sensor.

During the eclipse, the sun sensors will become useless. The magnetometers and the gyroscopes will still be used. Due to drift, the gyroscopes will probably need to be recalibrated. It will be done by using the sun sensors during daylight.

The gyroscopes and magnetometers shall be able to measure on three axes. The sun sensors shall be placed on the six faces even if one will never face the sun.

The planned sensor power consumption during phase A (30mW) was misestimated. The precise consumption will be calculated during the test phase.

5.1.1 Sun sensors

This section describes the choice of the sun sensor, the chosen sensor and its implementation on a PCB.

5.1.1.1 Choice of the sensor

In Table 2, all the sun sensors that were found during the search phase are listed. All criteria are important for the final choice. One that is not represented is availability of the sensor. Due to structural interfaces requirements, the size was critical. On this point the TNO and DTU sensors are better choices. The necessary electronic is included in the size of the DTU sensor but not in the TNO one. On the weight criteria, again the TNO and DTU are the lightest. In terms of power consumption and power supply very few data were available, so could not be a selection criterion. The highest accuracy and the biggest field of view are given by the TNO sensors.

According to all these criteria, the two best-fitting sensors are the one from DTU and TNO. The final choice is the sensor of DTU, because of the unavailability of the TNO sensor.

Model		Weight [g]	Size [mm]	Power supply	Power cons. [mW]	Accuracy [deg]	FoV [deg]	prize
Optical Energy Technologies	1	40	40x10	+/-5 to +/-15	50	+/- 0.5	100	16'000
Aero astro coarse sun sensor	2	20	23 x 9	NA	NA	+/- 5	120	NA
Aero astro medium sun sensor	3	36	35 x 10.5	NA	NA	+/- 1	134	NA
TNO without packaging	4	NA	10x10x2	NA	NA	0.2	128	NA
TNO with packaging	5	50	30x30x14	NA	NA	0.2	128	NA
DTU with PCB	6	1	20x16x1.5	3.3 V	NA	1	120	Free

Model		Weight [g]	Size [mm]	Power supply	Power cons. [mW]	Accuracy [deg]	FoV [deg]	prize
Optical Energy Technologies	1	--	--	-	NA	+	-	--
Aero astro coarse sun sensor	2	-	-	NA	NA	--	+	NA
Aero astro medium sun sensor	3	--	--	NA	NA	-	++	NA
TNO without packaging	4	+	++	NA	NA	+	++	NA
TNO with packaging	5	--	--	NA	NA	+	++	NA
DTU with PCB	6	++	+	++	NA	-	+	++

Table 2: List of possible sun sensors.

Since the DTU sun sensors have not been commercialized yet, no proper calibration was made. This will be done during next semester. According to information by the supplier, the sensors should have an accuracy of 1 degree within +-30 degrees FOV and 5 degrees within +-60 degrees FOV.

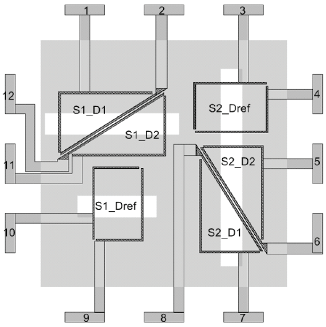


Figure 6: DTU Sun sensor chip.

The design of the sun sensors PCB was implemented according to [R7] for the amplification of the signals. Each sun sensors has four outputs, one for each direction in the horizontal plane of the chip and one reference for each direction. In Figure 7 the electronic for one direction of one sensor is shown. The second direction needs exactly the same circuit. The sensing parts are represented with diodes. Each direction has two sensing parts. The exact connexion and the list of the used components are detailed in the appendix B.1.

The sensors will give out analogic signals. The signals are amplified and redirected to the main board. The conversion to a digital signal will be made by the microcontroller. The description of the connexion between the sun sensor PCB and the microcontroller is documented in 5.3.

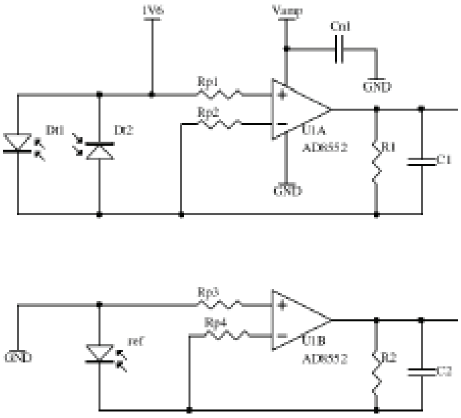


Figure 7: Electronic for one direction.

In order to minimize the size of the PCB and to make it possible to glue it on the side panels of the satellite, the sun sensor itself is glued on the face of the PCB facing the outside of the satellite and the electronic components on the other face. The electrical connection between the sensitive chip and the PCB will be made by wire bonding. The values of the resistor and capacitors will be the same as for DTU test in a first time. They will be changed if needed during the characterization phase.

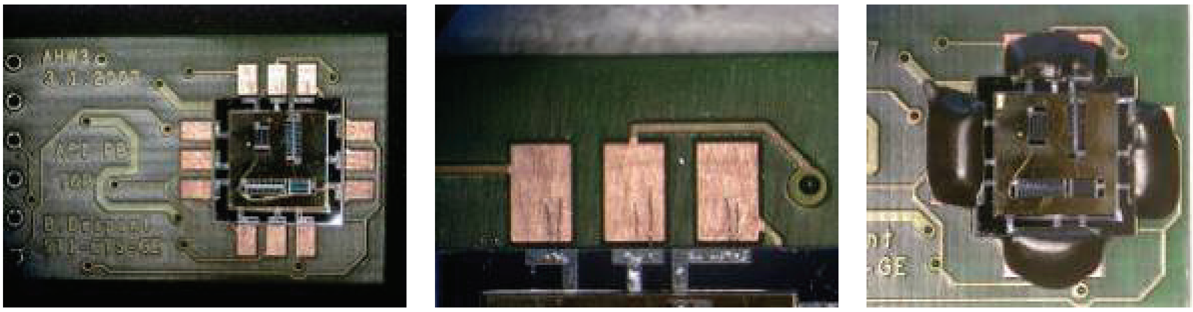


Figure 8: Left, sun sensor with PCB. Center, wire bond. Right with coating (courtesy of A. Baderstcher).

5.1.2 Magnetometers

The choice of the magnetometers was made in a separate project taking into account the constraints of the ADCS board about the supply voltage, the power consumption, the number of axis measured, the range and accuracy of measurement. The detailed analysis can be seen in [R8][R8][R8].

The AKN sensors were chosen and integrated in the design of the ADCS Board. The electronic implementation is documented in 5.3.

5.1.3 Gyroscopes

The goal of the selection process was to find gyroscopes that minimize the complexity of the design such as different supply voltage or the implementation of a dedicated small structure to ensure the perpendicularity of the three axis. Ideally the final component should be able to measure all three-axis with a single chip and with the same power supply as the other components on the board. The three different gyroscopes that were selected can be seen in Table 3.

Model		Mass [g]	Size [mm]	Power supply [V]	Power cons. [mW]	Sensitivity [mV/°/s]	Rate [deg/s]	prize
ADXRS150 1-Axis	1	< 0.5	7x7x4	4.75 to 5.25	30 (90)	12.5	+-150	30
TR0150S050 3-axial	2	< 5	18x18x10	4.75 to 5.25	90	12.5	+-150	1300
Dual Axis Gyro - IDG300	3	< 0.5	6x6x1.5	3 to 3.3	30	2	+-500	50

Model		Mass [g]	Size [mm]	Power supply [V]	Power cons. [mW]	Sensitivity [mV/°/s]	Rate [deg/s]	prize
ADXRS150 1-Axis	1	++	+	--	--	-	-	+
TR0150S050 3-axial	2	-	-	--	--	-	-	--
Dual Axis Gyro - IDG300	3	++	++	++	+	++	++	+

Table 3: List of possible gyroscopes.

Compared to the others, the IDG300 sensor has advantages in terms of mass, size, compatibility of power supply, power consumption, sensitivity and rate. The only disadvantage is that it measures only two axes, so it will need an additional PCB for the third axis and its peripheral electronic. A small structure shall be designed to guarantee the perpendicularity with the other axes. In this functional version of the board, the size of the third axis PCB has not been optimized yet. For the choice of the different peripheral components (resistors and capacities), the manufacturer recommendations were respected. According to the same recommendations a low-pass filter with a cut-off frequency of 2 kHz was designed. The list of components for the third axis can be found in B.2.2.

It is foreseen to convert the analog values with a 12-bits converter. It means that it is possible to obtain a resolution of 1 mV and so an angular resolution of 0.5 degree per second.

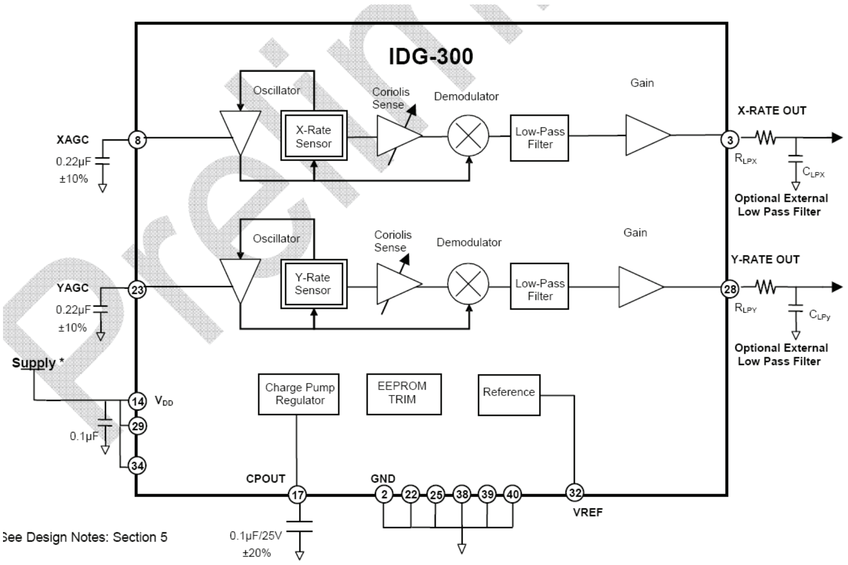


Figure 9: IDG300 gyroscope schematic.

5.1.4 The All-in-one sensor

During the selection process a sensor including a three-axes magnetometer, a three-axes gyroscope and a three-axes accelerometer was found. It was not chosen because of its size, mass, supply voltage and power consumption that were to important. The procurement of this component is also not in the philosophy of a student project because of its very high prize (CHF 2000.-). The sensor reference will be kept for future satellite.

Model	Weight [g]	Size [mm]	Power supply	Power cons.	Performances	prize
MAG02-0150S050	< 5	18x18x10	4.75 to 5.25	250 mW	+-150 ± 1.9 Gauss ± 2 g	2000

Table 4: All in one sensor characteristics.

5.1.5 Sensor summary

The three tables below summarize the sensors characteristics and announced performances.

DTU sun sensor	Mass (with PCB and amplification) [g]	1
	Size (with PCB) [mm]	20x16x1.5
	Supply voltage [V]	3.3
	Power [mW]	NA
	Accuracy [deg]	1
	Field of view	1200
	Prize [$]	Free

Gyroscope IDG300	Mass (with PCB and amplification) [g]	0.5
	Size [mm]	6x6x1.5
	Supply voltage [V]	3.3
	Power [mW]	30
	Sensitivity [mV/deg/s]	2
	Rate [deg/s]	+/- 500
	Prize [$]	50

Magnetometer AK8970N	Mass [g]	0.4
	Size [mm]	5x5x1
	Supply voltage [V]	3.3
	Power [mW]	24
	Sensitivity [mV/mT]	8.33
	Resolution [uV]	100
	Prize [$]	free

Table 5: Sensors summary.

5.2 Actuators

Two different sorts of actuators are planned to be used. An inertial/momentum wheel has been developed to be tested on the SwissCube. It was developed separately to the main board and shall be integrated to it during next phase. The description of the IWA will be made in [R9].

The main actuators are three perpendicular coils, called magnetotorquers. Their size is maximized according to the available space given by structural constraints.

All actuators were sized based on twice the maximum disturbance torque.

5.2.1 Magnetotorquers

The value that characterizes the magnetotorquers is their magnetic moment whose units is Am^2 and is defined as:

$$M = NIA\vec{n}$$ **Equation 1**

I is the current in the coil, N the number of turns and A the area of the coil plane.

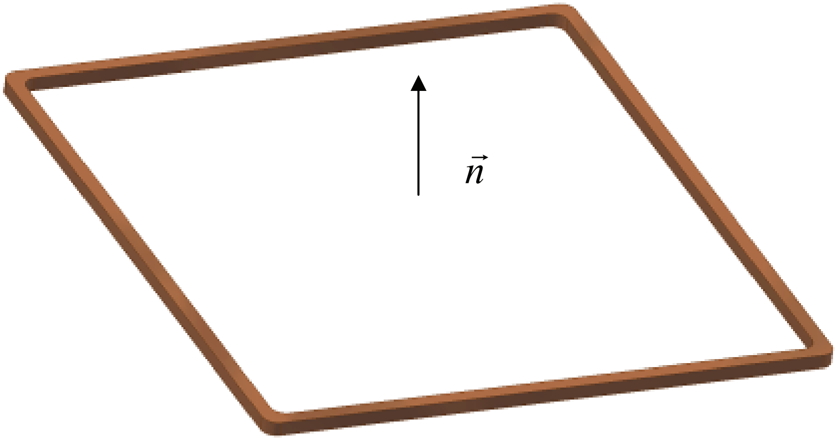


Figure 10: The magnetic torquer coil schematic.

The torque produced by the magnetic torquer is the cross product of the magnetic field strength in Teslas, with the magnetic moment of the magnetic torquers.

$$T_{Mag} = \mathrm{M} \times \mathrm{B}$$ **Equation 2**

The minimal needed magnetic moment M_N to counteract perturbations and to change the satellite attitude is:

$$M_N = \frac{T_{\max} R^3}{B_o}$$ **Equation 3**

Where Tmax is the maximum perturbation torque for each altitude multiplied by 2, R is defined as $R = \frac{R_E + h}{R_E}$ with R_E the radius of the earth and h the altitude taken from the ground. B_0 is the magnetic field at the Equator at the surface, which is the weakest. Indeed, the weakest the field is, the strongest the magnetic moment must be. In this case the magnetotorquers have to provide the maximum magnetic moment. The development to obtain equation 3 starting from equation 2 is presented in [R11].

Combining equation 1and equation 3 it is possible to calculate the needed number of turns N_N, where I = P/V with P the available power and V the bus voltage.

$$N_N = \frac{M_N}{I \cdot A} = \frac{M_N \cdot V}{P \cdot A}$$

Equation 4

According that the resistance of copper wire is $R = \frac{\sigma l_w}{A_w}$, where A_w, l_w and σ are the cross-sectional area, the length and σ is the resistivity of the wire material and also $R = \frac{V^2}{P}$ we can rewrite the resistance equation as:

$$A_w = \frac{P\sigma D N_N}{V^2}$$

Equation 5

Where D is the length of one turn. The total mass of one torquer is:

$$m_{cu} = \rho \cdot .N_N \cdot D \cdot A_w$$

Equation 6

Combining the above equations, defining ρ as the density of the wire material and substituting the term for resistivity with its expression with respect to temperature $\sigma = \sigma_o (1 + \alpha T)$ σ_0 is the resistivity of the material, α is the temperature change coefficient, $\alpha = \frac{d\sigma}{dT}$ and T is the temperature in Kelvin, the mass can be calculated with the following equation:

$$m_{Cu} = \frac{P\sigma_0 (1 + \alpha T) \rho D^2}{V^2} \left(\left\lceil \frac{M_N V}{P \ A} \right\rceil \right)^2$$

Equation 7

In order to have the maximum magnetic moment created with a minimum mass and predefined power and voltage, the enclosed area A shall be maximized and the number of turns minimized. Due to geometrical constraints there is a maximal space where the magnetotorquers can be placed. For two magnetotorquers the maximal available space is 82 mm by 90 mm and for the third one 82 mm by 86.5 mm. [R12]. The thickness of the coil is limited for the same reasons. It is limited to 4 mm.

Since the satellite total mass is very limited (1 kg) a short analysis was made to determine if it could be advantageous to chosen an aluminum wire instead of a standard copper wire (appendix B.3.3). The result is that the copper wire will be better and also easier to procure. Once the material of the wire was chosen, the minimum required diameter needs to be calculated in function of the maximum current density and the maximum current. The maximum current is determined with the available power and the supply voltage. The maximum current density was set to 2 Ampères/mm2, even if it is possible to go up to 8. This is a security factor to avoid a wire burning due to the absence of convection. The chosen wire is a CAB-200 and has diameter of 150 microns.

With outer dimension and the wire diameter it is possible to dimension the coils. Because the inner surface is used to determine the magnetic moment and the fact that only the outer dimensions of the coils are given, it is necessary to calculate iteratively the real number of turns. The process starts by choosing approximately the inner surface so that the number of turns can be calculated. With the number of turns and the external dimensions it is possible to determine completely the dimensions of the coil and so the inner dimensions. These new values are needed to refine the calculation of the number of turns. And so on. The MatLab code that was used is to be seen in B.3.1. Table 6 shows the parameters and the results that used for the dimensioning of the three coils. Parameters that depend on the altitude were taken at the worst case (400 km).

Maximal disturbance torque (design margin of 2)	7.2e-7 Nm
Magnetic field at surface level at equator (B0)	0.3e-4 T
Voltage	3.3 V
Power	50 mW
Maximum current density	2e6 A/m^2
Copper resistivity	1.72e-8 Ohm m
Temperature change coefficient	3.9e-3 K^{-1}
Current	15 mA
Magnetic moment	2.85e-2 Am^2
Wire	CAB-200
Wire diameter	150e-6 m

Table 6: Magnetotorquers parameter and general performance requirements.

Due to geometrical constraints and in order to maximize the coil surface, two different magnetotorquer sizes were implemented. The two next tables summarize the dimensions of the coils.

Outer dimensions	82x90 mm
Inner dimensions	77.8x85.8 mm
Cross-section dimensions	2.1x4 mm
Number of turns	283
Coil resistance	45 Ohm
Coil inductance	168 mH
Time constant	3.7 ms

Table 7: Dimensions for the coils in X and Z (SRF).

Outer dimensions	82x86.5 mm
Inner dimensions	76.7x82.1 mm
Cross-section dimensions	2.2x4 mm
Number of turns	297
Coil resistance	45 Ohm
Coil inductance	176 mH
Time constant	3.8 ms

Table 8 Dimensions for the coil in Y (SRF).

To guarantee the dissipation of the power given to the torquers a resistor of $R= U^2/ P = 220$ Ohm is required. Since the coil has resistance of 45 Ohm an additional resistor if 180 Ohm is placed in series.

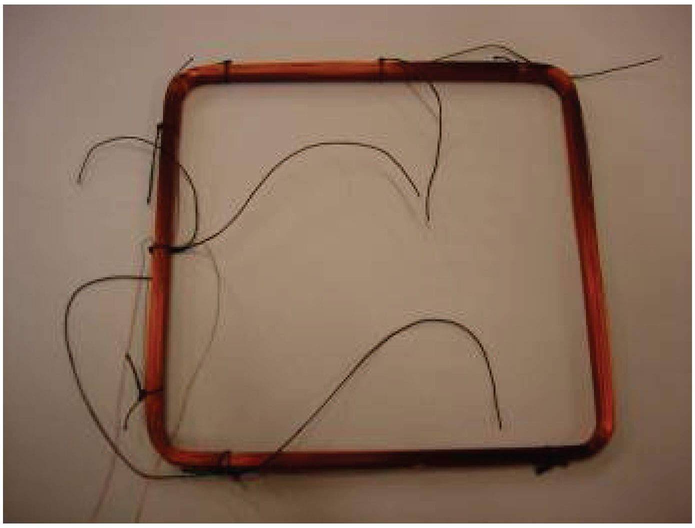


Figure 11: Magnetotorquer

5.2.2 IWA

The IWA was developed separately from the other ADCS components. The conclusions are to be seen in [R9]. The control electronic will be integrated to the ADCS main board during the next project phase.

5.3 Main printed circuit board

The PCB is the heart of ADCS in terms of hardware. The board includes a microcontroller, the non-photosensitive sensors, the driver stage for the main actuators and all the electronics such as latch-up protection, switches and filters.

The external dimensions of the PCB are limited by the available space in the structure. The PCB will be directly attached to the frame. The outer dimensions are described in Figure 12.

In this section, each functional part of the card is presented separately. The whole board schematic is shown in appendix B.4.1.

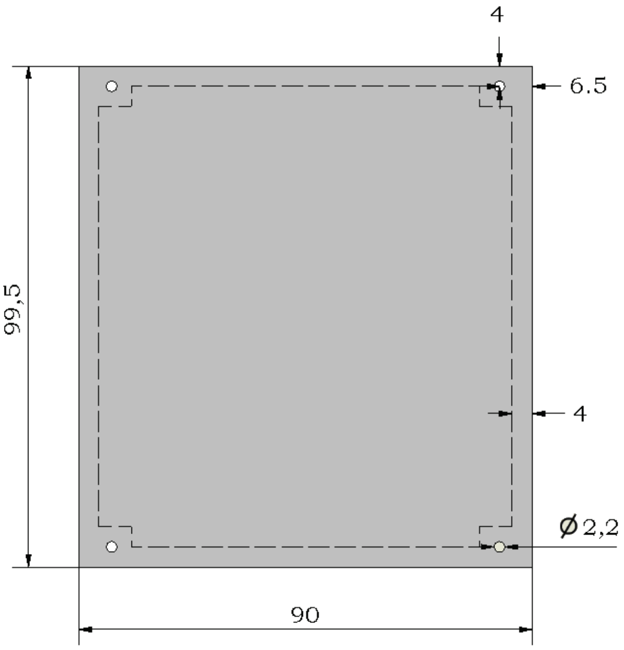


Figure 12: PCB dimensions.

The material used for this test board is FR-4 with a thickness of 0.8 mm and two layers. The bottom plane is used as ground and the top plane contains the supply and the routing to connect the components. A four layers PCB would be advantageous for thermal reasons. The PCB would have one plane only for the supply voltage and one ground plane. These planes will make possible to lessen thermal hot points. A four layers PCB offers also more available surface for the routing.

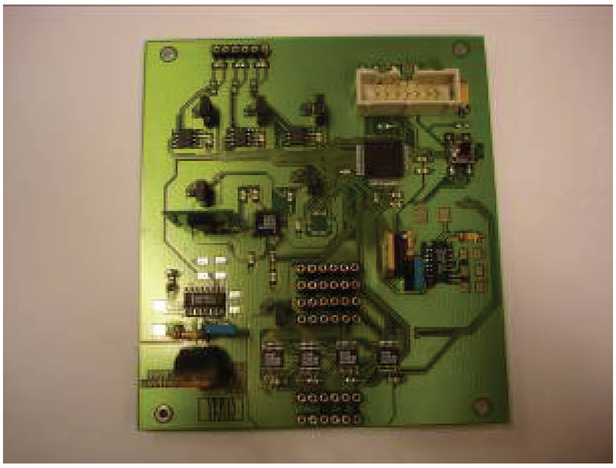


Figure 13: Main Board.

5.3.1 Magnetometer

Due to magnetic perturbations induced either bay the magnetotorquers or the IWA, the measurements with the magnetometer will be perturbed. In order to reduce the importance of those, the sensor shall be placed in the middle of the ADCS PCB. For the same reasons, the PCB shall be placed as far as possible from the actuators (magnetotorquers and IWA).

Figure 14 shows the electrical schematic of the magnetometer. The component on the right of the figure is the sensor itself. It uses a serial data interface to communicate with the microcontroller. The chip needs a clock signal to make possible the internal analog to digital conversion. The two capacitors, C1 and Cmm in the figure, are decoupling capacitors used as a filter to lower the noise coming from the power supply and the clock signal. The component welding was made carefully in order to respect the chip alignment with the PCB axes. Both referential (sensor and satellite) will be aligned, just the axis are not the same.

A switch was added to make possible the complete shut down of the sensor. It is commanded by the microcontroller by a change of the logic level. Additionally, a jumper, Jmm, was implemented to disconnect physically the sensor during the tests.

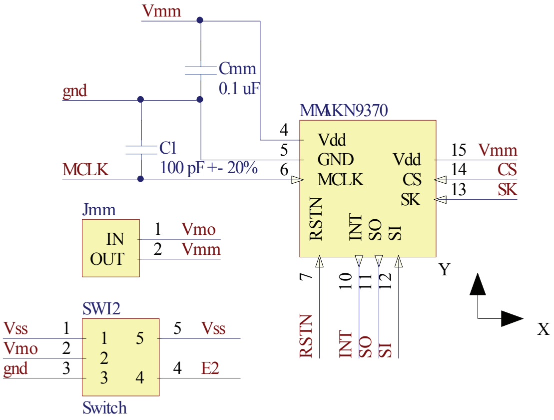


Figure 14: Implemented circuitry for magnetometer.

5.3.2 Gyroscopes

The problem with the chosen gyroscope chip is that it measures only on two axes. The chip for axis X and Y, in the plane of the PCB, was aligned with its axes. For the third axis, the same chip is used. A small PCB was developed. Once the component will be welded, it will be analyzed if an additional small structure will be needed to guarantee the perpendicularity and if the connector is sufficient to resist to the vibration test.

The implementation was made on the manufacturer recommendations. On the second chip (Z-axis) one of the outputs was left unconnected. A low-pass filter is designed at every output to attenuate the high frequency noise generated by the proof-masses of the sensors. The filter is dimensioned with a cut-off frequency of 2 kHz (R= 750 Ohm, C=0.1 uF). A decoupling capacitor of 100 nF is placed between the power supply and the ground of both chips. In Figure 15, the XAGC and YAGC are compensation capacitors for the amplitude control loop. In the control loop, an oscillation circuit controls the amplitude to maintain constant sensitivity over the temperature range. The two output signals, ADCX and ADCY, are analogical signals. The conversion to digital will be made by the ADCS microcontroller.

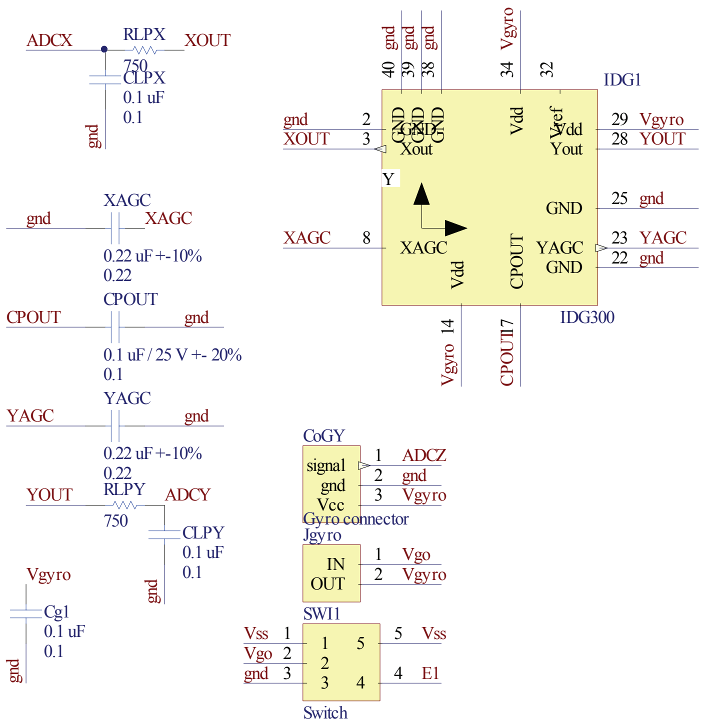


Figure 15: Electrical schematic for gyroscope.

At the bottom of Figure 15, three components can be seen. CoGY is the connector for the gyroscope's third axis, Jgyro is a jumper to disconnected totally the gyroscopes manually during certain test phases and SWI1 is a switch that is commended by the microcontroller.

5.3.3 Sun sensors electronic

Only a part of the sun sensors electronic is placed on the main board. The sensor output signal is amplified as close as possible from the sensor. The amplification is placed on the back plane of the small PCB. The amplified signal is transported to main board by electrical cables. Each sun sensors generates 4 signals. Each signal is redirected to a multiplexer. This means that multiplexer 1 collects the output 1 signal from each sensor. The second multiplexer collects all the reference 1 signals, multiplexer 3 the second output and finally the fourth multiplexer the second reference signal. Four control bits generated by the microcontroller allows to choose one of the six sun sensors on each multiplexer. The four values are directed toward the analog to digital converter of the microcontroller. The digital signal can be processed either on the ADCS microcontroller to give an angle or on the CDMS. This choice remains to be made.

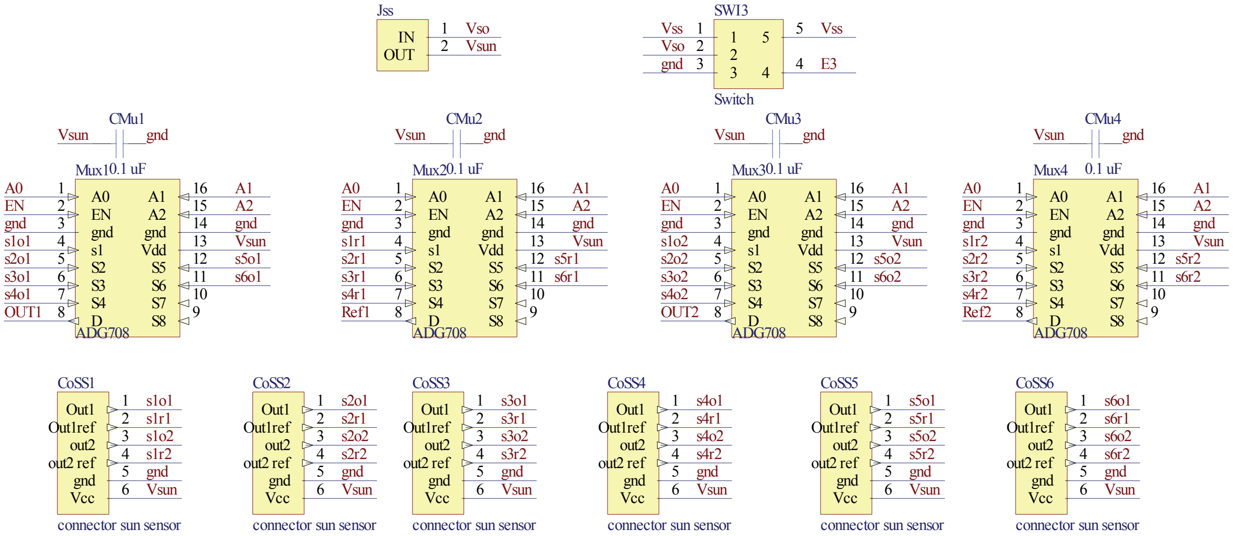


Figure 16 Sun sensors connection and electronic.

To avoid noise problems, each multiplexer and each sun sensors have decoupling capacitors. Again for this part of the electronic circuit, a jumper and a switch were implemented.

5.3.4 Latch-up protection

The latch-up protection was implemented as recommended in [R13]. Two protections were placed in the circuit. The first one is used to protect the microcontroller and the second one to protect the sensor part. The microcontroller protection was designed for a normal current of 10 mA. At this stage, it is not possible to dimension it precisely for the sensors because the overall current is not known yet. The protection was dimensioned fro an estimated current of 80 mA. This value will be measured during the test phases. Table 9 summarizes the Latch-up peripheral components that were implemented on the functional card.

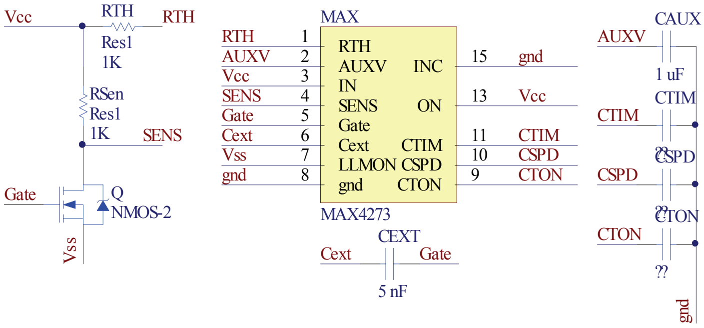


Figure 17: Latch-up protection electrical schematic.

Components Parameters	Microcontroller	Sensors
I_{slow}	10 mA	80 mA
R_{sense}	4.7 Ω	1 Ω
R_{th}	None. R_{th} pin on chip connected to gnd	None. R_{th} pin on chip connected to gnd
C_{auxvc}	1 µF	1 µF
C_{TIM}	None, pin on chip left floating	None, pin on chip left floating
C_{TON}	None, pin on chip left floating	None, pin on chip left floating
C_{SPD}	None, pin on chip left floating	None, pin on chip left floating
C_{ext}	5 nF	5 nF

Table 9: Latch-up protection peripheral components.

5.3.5 Magnetotorquer driver stage

The magnetotorquers are commanded with a PWM signal generated by the microcontroller on a command of CDMS. By changing the duty cycle of the signal, the voltage level can vary between 0 and 3.3 V. A duty cycle of 100 % means that the output voltage of the driver stage is 3.3 V. Varying this voltage, the current will also change proportionally. With the different current values it is possible to vary the strength of the magnetotorquers effects. The dimension that varies is the magnetic moment. The driver stage is composed of an H-bridge and a low pass filter. The H-bridge is a four transistors bridge and allows changing the direction of the created magnetic moment.

In Figure 18, if T1 and T4 are switched on, the output A will be at a potential of Vdd and output B will be at the potential of S_B, in this case 0V. T2 and T4 are "open". To have the other direction, T1 and T3 will be switched of and T2 and T4 switched on. The S_A and S_B pins were both connected to the ground.

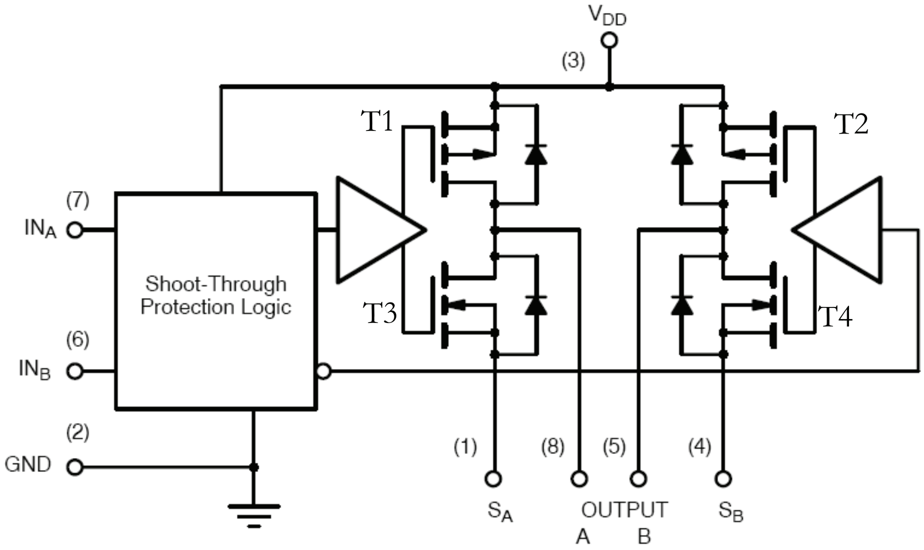
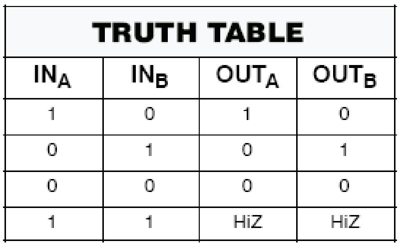


Figure 18: H-bridge schematic.

There are a couple of different integrated circuits that permit to do an H-bridge. For the SwissCube, the component Si9987 form Vishay has been chosen. It offers the advantage that protection logic is already integrated and that the user does not need to control the four transistors separately. Only an input signal on the right pin is required to give out a signal in the chosen direction. The integrated logic commutes the right transistors pair automatically. The IC follows the truth table presented in Table 10. Since there are 3 coils and that they need to function in two directions, six signals are necessary.



TRUTH TABLE

IN_A	IN_B	OUT_A	OUT_B
1	0	1	0
0	1	0	1
0	0	0	0
1	1	HiZ	HiZ

Table 10: H-bridge truth table.

The electrical schematic is represented in Figure 19. The same design was implemented for the three magnetotorquers. The circuit offers the possibility the switch on or off each coil. The command signal on the three switches is generated by the microcontroller. Additionally, the power supply of each coil can be manually cut. The jumpers will be removed once the design will be validated. At the input of the H-bridge, decoupling capacitors were placed. A low-pass filter was added at their output to obtain a constant voltage level.

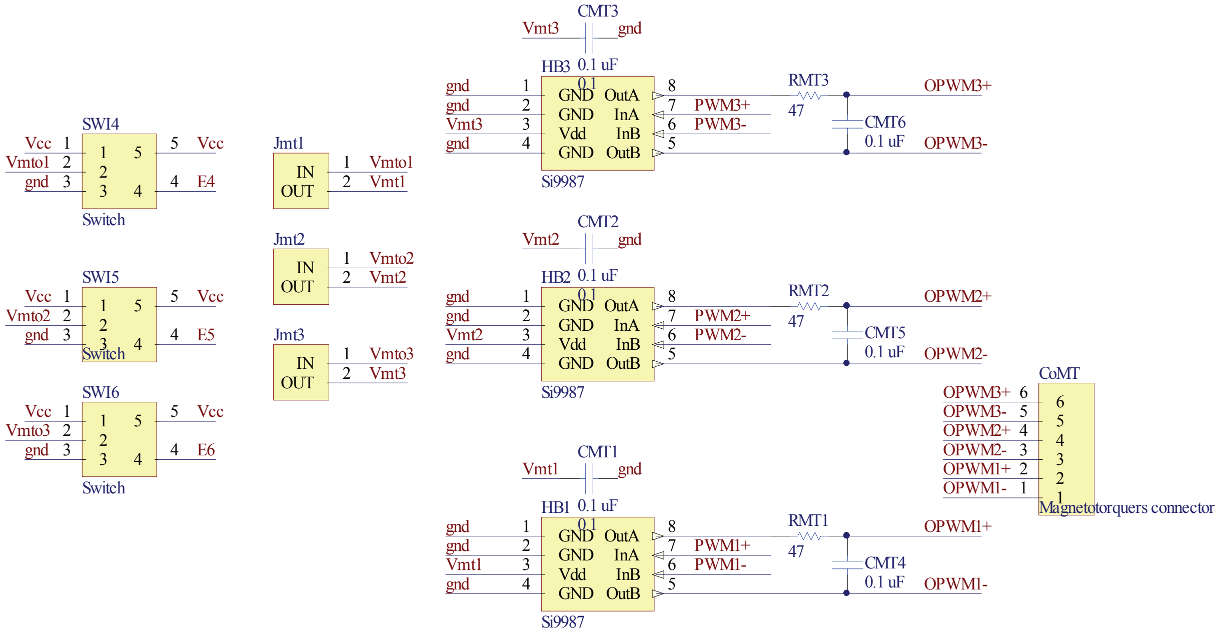


Figure 19: Magnetotorquer electronic schematic.

5.3.6 Microcontroller

The microcontroller chosen just after phase A is a MSP430F169 from Texas Instrument. The peripheral required electronic was implemented under the recommendations of the manufacturer (for example decoupling capacitors). Seven of the ADC inputs are used, four for the sun sensors and three for the gyroscopes. The serial data interface is used to read the magnetometer. This microcontroller has also a I2C interface that can be connected to the main data bus. Several digital ports are used as outputs to switch on or off the different sensors and actuators and to serve as command signals for the multiplexers. Six outputs are used for PWM signal that commands the magnetotorquers.

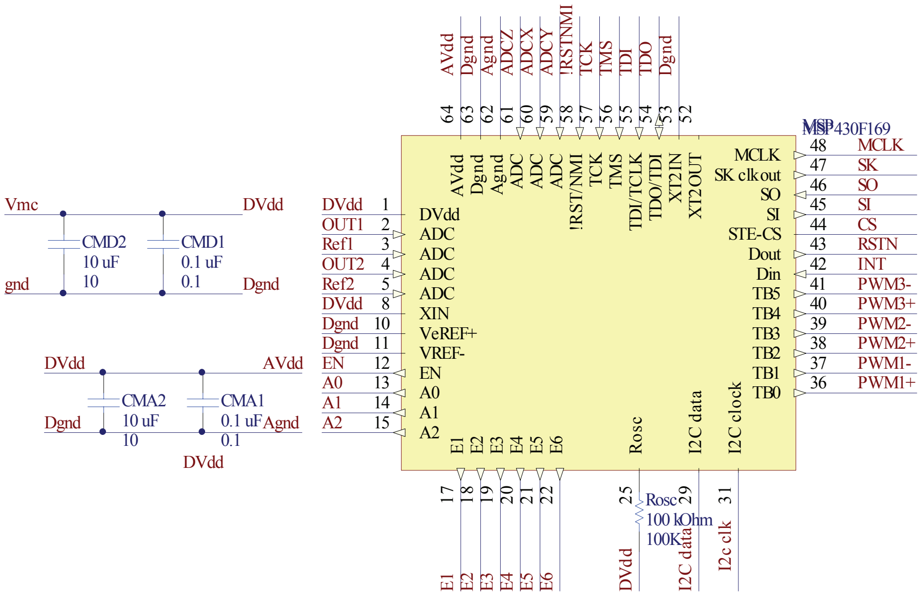


Figure 20: Microcontroller schematic.

An external resistor was added and connected to the pin 25 of the microcontroller. With this resistor it is possible to push the frequency of the microcontroller up to 10 MHz instead of 8 MHz. Another advantage of this design is that the frequency will be less temperature dependant.

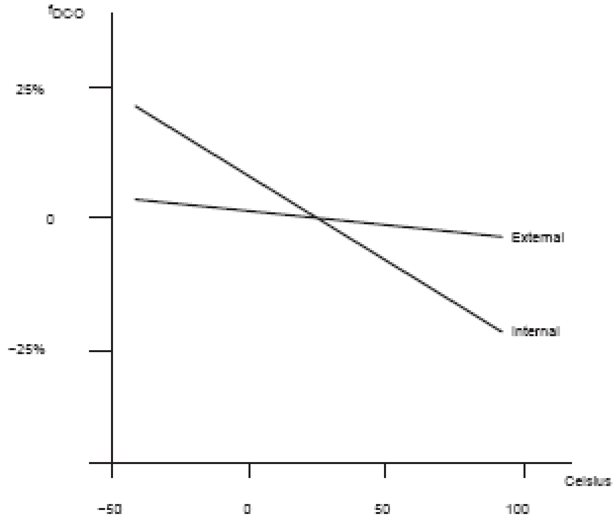


Figure 21: Microcontroller internal clock frequency vs. temperature.

5.3.7 Connector and reset button

In order to load the software on the microcontroller and to debug it, a programming interface is required. The MSP430 microcontroller offers the possibility to do it through a standard interface called JTAG. A programmer is required to link the developed card to the computer. A 3 Volts power supply is available directly from the computer. Since the card uses a 3.3V power supply, it is necessary to provide an external supply. The JTAG has 5 digital data lines:

TDI, Test Data In

TDO, Test Data Out

TCK, Test Clock

TMS, Test Mode Select

!RST/NMI, Reset

These lines do not need additional pull-up resistor, apart from the reset, and are directly connected to microcontroller (JTAG port). A pull-up resistor limits the current that flows to microcontroller and guarantee the logic level. The resistors are already implemented in the microcontroller. They are required on the lines for the main data bus. A reset push button was implemented for the test phase. It will be removed on the final version. Reset of the microcontroller can also be made externally from the debug interface through a dedicated line.

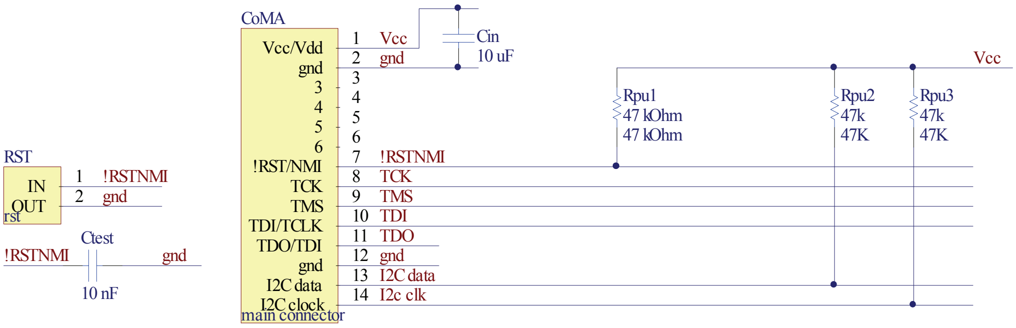


Figure 22: Card main connector and reset button schematic.

An adapter was developed to interface the computer JTAG programmer and the card JTAG because the pin layout was not implemented with the same configuration. This will be corrected for the next version of the card. Figure 23: JTAG adapter. Figure 23 shows the electrical routing between the board and computer connectors.

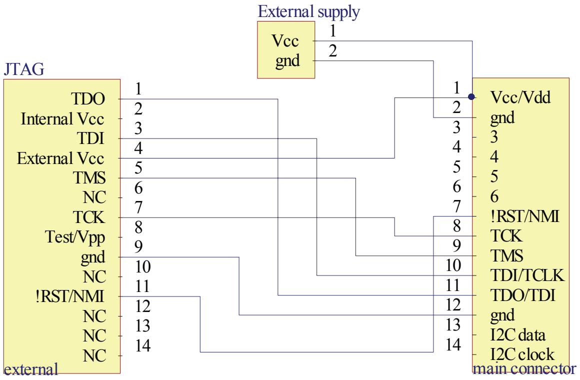


Figure 23: JTAG adapter.

5.3.8 Electrical and data Interfaces

The ADCS card has not only interfaces with other subsystem for the power or data transfer but also with its own components that are not placed on the PCB. The power interface requires two lines, positive power supply (Vcc) and ground , the data interface also two connection, one for the clock signal and the other for the data. Each magnetotorquer requires two electrical connections, six in all. The sun sensors need 6 connections. Two are for the power supply and four for the analog signals. Without the IWA, the ADCS has 46 electrical interfaces. The complete list with the name of the connectors and pins is presented in the appendix B.4.4.

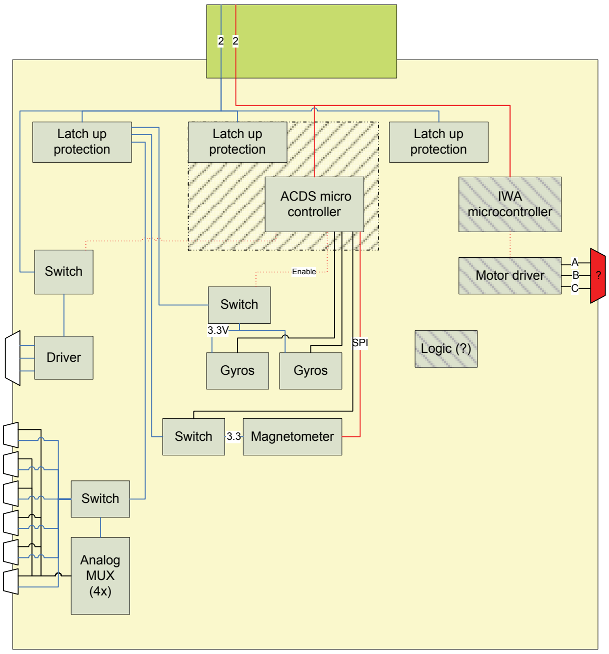


Figure 24: ADCS main board schematic with interfaces (R. Krpoun).

5.4 Functional/flow diagrams and software considerations

5.4.1 Preliminary functional analysis

The functional analysis presented in Figure 25 is a high level analysis. It lists the main functions that the ADCS shall fulfill apart from the algorithms for the determination and control. The list is non-exhaustive.

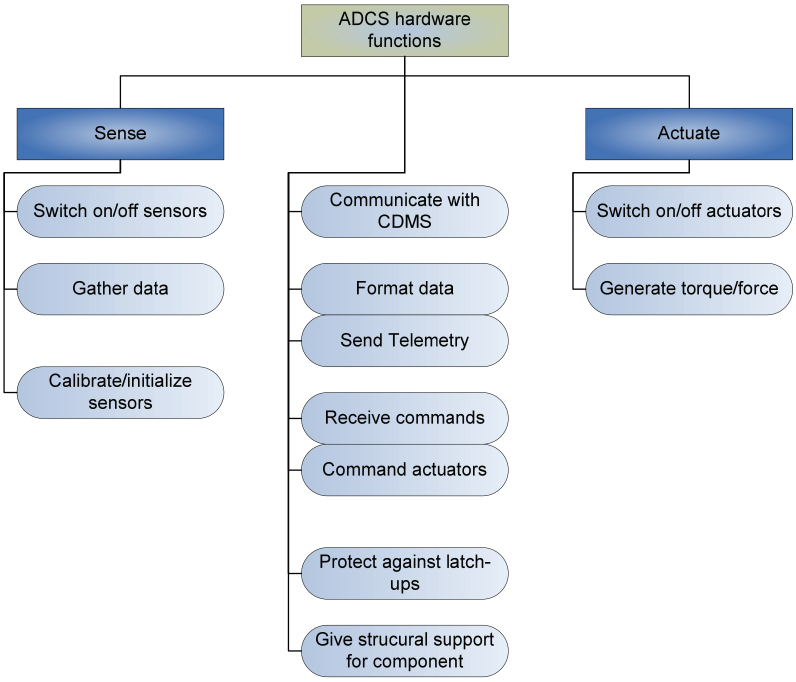


Figure 25 ADCS H/W functions

5.4.2 Flow analysis

This section describes the preliminary analysis that was made for the operations of the ADCS. It does not include the determination and control calculation. The objective is to present the possible operation modes and a possible way to organize the ADCS software. The booting sequence is shown in Figure 26. Each rectangle box represents a process. The orange boxes are for CDMS actions, the greens are for EPS actions and the grays for the ADCS's. The ADCS will only starts when the CDMS will give a command to the EPS to switch on the subsystem. The EPS will just supply the whole card. If there is not enough available energy to start the board, the EPS will send back an acknowledgement that it was not able to switch the subsystem on. Once the ADCS will be supplied, only the microcontroller should start. It will go through its own boot sequence, initialize the sensors with pre-stored values and perform some functional test on them. It should send an acknowledgement or test report to the CDMS and enter in a STAND-BY mode. The STAND-BY mode will be a waiting mode in which only the microcontroller will be in function. The microcontroller will be ready to receive TC's from the CDMS and change the operational mode.

A possible mode is the OFF mode. It is planned that in this mode the microcontroller will deactivated sensors and actuators and save some critical values before sending a reply to CDMS, so that the CDMS can give a command to the EPS to switch off the subsystem.

The third foreseen mode, the SENSOR mode, only the sensors and the microcontroller will be in functions.

The NOMINAL mode is almost the same as the SENSOR mode, the difference is just that the magnetotorquers will be in action.

And finally the WHEEL mode is the NOMINAL mode plus the fact that IWA will be in action.

The change from one mode to another shall only be commanded by the CDMS.

The implementation of these modes can be made in, at least, two different ways. The first possibility is to stay in infinite loop for each mode until an interruption is generated by the CDMS and the mode change. It may need a lot of resources and increase the complexity of the code. A more elegant solution will be to use the microcontroller timer to generate interruption automatically at certain time to launch small functions, such as sensors reading, magnetotorquers switch. Between the interruptions the program will stay in a main loop ready for the next interruption or TC from the CDMS.

The detail of each phase can be found in Appendix C.

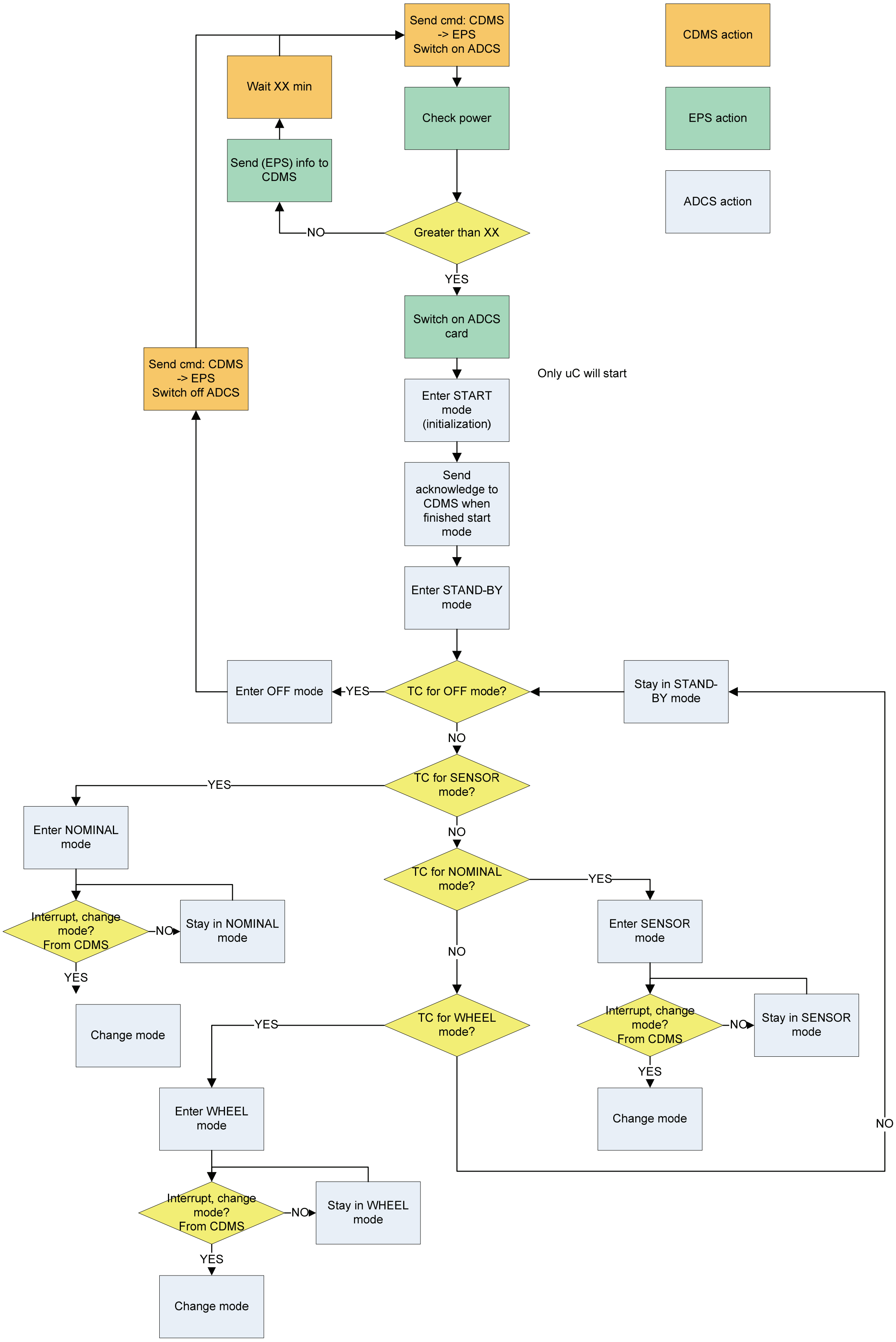


Figure 26: Flow diagram.

5.4.3 Software functions

In order to test the different functional part of the development board, software codes need to be implemented on the microcontroller. The software will be developed under the code composer v2.0 emulator. Following functions are required:

First of all the program shall initialize the clock system. The internal digital clock system is the bas signal that will be used for the other clock signals and all the time dependant operations.

Apart form the special pins of the microcontroller like power supply or ground, the other pins can be configured in at least two states, the general purpose input/output (GPIO) or specific functions. Specific functions can be ADC inputs, PWM outputs, clock signal output, SPI, I2C, etc. For more details refer to [R14].

The microcontroller shall communicate with the CDMS through the main bus, actually an I2C bus. The configuration to communicate with the appropriate pins of the microcontroller shall be implemented. Each command received from the CDMS should generate a interruption, resulting in action such as sending TM/HK, changing parameters.

To collect the sensor data two kinds of function are required. For the magnetometer a SPI interface is required. The microcontroller will be the master. The gyroscopes and the sun sensors generate analog signals. These signals will be converted to digital signal by the microcontroller. A timer allows to set the sampling time of the conversions. An interrupt is set every second for example. The conversion starts at the interruption. No CPU operation are needed except for the transfer of the data from the buffer in storing registers.

The command signals for the driver stage of the actuators are PWM. They will be generated by the timer B of the MSP430. Six outputs are necessary with the actual setup. The timer control registers can be configured with a lot of option. The programming of the microcontroller was started at the end of the project for this part.

6 TESTS

The test procedures presented in this section describe the functional testing. Before making thermal, vacuum, vibration, supply voltage variation tests, the design shall be validate in laboratory conditions. Some of the components can be tested separately from the main board with independent set-ups. It is foreseen to test first the actual version of the card in parallel to the sensors to prove the functionality of each functional part separately. Once it is done, a card close to the flight model shall be developed and test in mission like conditions.

This section presents a preliminary view of the tests that shall be made. Unfortunately the actual results are very limited.

6.1 Main board

The main board is the heart of the ADCS hardware. All functionalities except the sun sensors, their amplification electronic and the coils can be tested on it.

6.1.1 Test objectives

The objective is to prove that the design fulfill the functional analysis and the requirements. It means that the programmability of the microcontroller, the generation of the actuation signals, the reading of sensors and the communication capability with the main bus will be proven. These points include the functional test of all the components necessary to achieve the functionalities. In a second phase the board shall be tested in mission like conditions and the frequency dependency to supply voltage variations shall be characterized.

6.1.2 Identification and configuration of the test article

A full mounted version of the development board is required to test all the capabilities. It is possible to start the test with a minimal configuration of the board. The minimal configuration is the PCB with the microcontroller and its peripheral components such as the main connector, resistors and capacitors. For more detail, refer to the electrical schematic. The other components can be added during the test process. If the board is entirely mounted, the jumpers that were included in the design allow disconnecting completely each part of the system that is not necessary for the tests.

The documentation required for the test is the datasheets for the corresponding components.

Reference based sensors and actuators will be tested on separate test benches. A particular reference frame is not required at this stage.

6.1.3 Test set-up identification

For testing the functionality and electrical parameters, a programming and debugging interface, a multi channel oscilloscope, a voltage stabilized source are required. The interface between the card and the main board shall be ensured with the available development tools, parallel to JTAG interface or USB to JTAG interface.

6.1.4 Test conditions

Functional test can be made in laboratory conditions at beginning. The card will be tested in mission conditions after the functionality of all parts is proven.

6.1.5 Step by step instruction for operation

Start emulator

Connect devices

Program functions

Measure parameters (clock, current, voltage, temperature)

Document

The exact procedure will be defined during the next semester.

6.1.6 Safety and security instructions

6.1.7 Personal required and responsibility

1 person is required at least. Since several cards were developed, it is possible to test in parallel.

The ADCS system engineer will be responsible.

6.2 Sun sensors

The sun sensors will be tested separately from the main board in a first phase. Once they will be properly characterized, the sensors will be added to the ADCS and the reading will be tested.

The solar cells require similar test. They were tested in the industry. The tester shall ask the person responsible for the solar cells to see if it is possible to use the existing set-up.

6.2.1 Test objectives

The main objective is to test the accuracy that can be measured in function of the angle of incidence of sun rays and temperature. Another objective is to measure the power consumption refine the power budget. The sensor should also be tested under vibration conditions to test the wire bonding and the gluing.

6.2.2 Identification and configuration of sun sensor

The PCB developed during phase B will be used. The sensor shall be placed on a horizontal plane looking upward. The planarity shall be verified between the sensitive head and the table. The sensitive head is the reference for the angular dependency.

6.2.3 Test set-up identification

The test set-up shall capable to rotate the sensor along two directions, pitch and roll, for the incidence angle characterization. The set-up shall be able to convert the sensor signals from analog to digital signals. A special light shall offer the same spectral range as the sun and parallel rays for valuable data. The set-up shall measure electrical characteristics.

6.2.4 Test conditions

Several tests in the same conditions should be performed to check the repeatability of the angle dependency.

6.2.5 Step by step instruction for operation

Fix sun sensor on table.

Start measurement set-up.

Ensure electrical connections.

Start illumination.

Vary incidence angle.

Measure signals and currents.

Store data.

Model performances.

Document

6.2.6 Safety and security instructions

6.2.7 Personal required and responsibility

1 person is required

The ADCS system engineer will be responsible.

6.3 Gyroscopes

For the gyroscopes, small test PCB was developed so that the first test can be conducted only on it. In a second phase, the development board shall be used to test the three axes performances

6.3.1 Test objectives

The objectives are verify the performances given by the data sheet and characterize the drift during eclipse and accuracy. The linearity of measurement shall be characterized in function of the temperature.

6.3.2 Identification and configuration of the gyroscope

The PCB developed for the third axis should be used for the first tests. Then the gyroscopes of the main board should be tested

6.3.3 Test set-up identification

The sensor shall be placed on a rotary table. The angular speed shall be adjustable -1 rad/sec and 1 rad/sec. The set-up shall be able to convert the sensor signals from analog to digital signals. Or the ADCS main board shall be used for the conversion. The set-up shall measure electrical characteristics.

6.3.4 Test conditions

Tests should be longer as eclipse duration, since the gyroscopes can only be recalibrated during daylight.

6.3.5 Step by step instruction for operation

Fix gyroscope on table.

Start measurement set-up.

Ensure electrical connections.

Start rotation.

Vary rotation.

Measure signals and currents.

Store data.

Model performances

6.3.6 Safety and security instructions

6.3.7 Personal required and responsibility

1 person is required

The ADCS system engineer will be responsible.

6.4 Magnetotorquers

For the magnetotorquers testing it is necessary to test the main board before. Once the PWM generation with the microcontroller is validated, they can be tested.

6.4.1 Test objectives

The objectives of the test are to characterize the electrical parameters of each coil and the magnetic field generated. In second phase it is to characterize the interaction of the three coils. Another objective is to check to disturbances induces in the other signal lines on the PCB, in order to refine the design to avoid those. The magnetotorquers shall be tested with different PWM rates. The change of electrical parameters of the coils shall be characterized under vacuum conditions when there is no convection. Supply voltage variation shall also be tested.

6.4.2 Identification and configuration of the magnetotorquers

For the testing of the electrical characteristics, the test can be made on only one coil. No specific configuration is required. For the test with the three coils, they shall be attached on a test frame in a way that the perpendicularity is guaranteed.

6.4.3 Test set-up identification

The test set-up will be composed of the main board with its programming interface, a multi channel oscilloscope a stabilized voltage source. The three coil test requires the same set-up plus a structure to maintain the three magnetotorquers perpendicular to each other.

6.4.4 Test conditions

In a first phase the coils shall be tested in laboratory conditions. Test s in a vacuum chamber are necessary in second phase.

6.4.5 Step by step instruction for operation

Connect elements

Start software, PWM sequence with different rates

Measure current, voltage, temperature

Document

6.4.6 Safety and security instructions

6.4.7 Personal required and responsibility

1 person is required.

The ADCS system engineer will be responsible.

6.5 Tests after integration

As said before, once the component will all be tested separately, the ADCS shall be put together and test under mission-like conditions (temperature, vacuum, voltage variation, main bus data interface).

A magnetometer measurement test shall be done, once the system is integrated. The aim is to characterize the measurement with the magnetotorquers and the wheel functioning in a Helmholz coil to determine the disturbances induce by the actuators.

6.6 Results

The program is under development. The first result is that the main card is programmable, that the master clock works, the magnetotorquers switch can be configured. PWM can be generated.

7 RECOMMENDATIONS

The actual board is a functional card. The placement of the components was not optimized. The power supply and main data bus connectors shall be placed to be compatible with the mother board. The sun sensors and magnetotorquers connectors shall be placed on the side of the card in order to simplify and shorten the cabling. The size of PCB for the gyroscope third axis shall be first reduced to the minimum. A mechanical structure shall be designed to fix the PCB mechanically and to guarantee the perpendicularity of the sensor. The placement of the gyroscope module shall be checked to make sure that the card can be inserted in the structure. The card shall placed as close as possible to middle of the satellite and the components facing the center, where is space available.

The sun sensors shall be cabled before gluing on the carbon panels, if not, the glue goes in the connection holes. According to last minute information of the structure and configuration subsystem, their size can be increased of 3 mm in the length. The surface available for the gluing will be larger. This will improve the quality of the mechanical interface.

The sun sensors give out two pairs of signals. An angle is calculated with each. pair. When possible the angle should be calculated directly in the ADCS microcontroller, so the CDMS do not need to allow calculating power to this task. This will be evaluated during the next semester.

The magnetometer requires a clock signal for its internal ADC. Actually the magnetometer uses the master clock signal MCLK of the microcontroller. MCLK is also the CPU clock signal. It is advantageous to use sub main clock signal if the clock frequency of the magnetometer should be adjusted without changing the CPU clock

The connection of the PWM outputs contains a mistake. The first output was used as standard PWM output, but its compare threshold is used on the six other PWM to determine the upper limit of the counter. The six other compare threshold can be set independently to fix the duty cycle. For the detailed information about the microcontroller timer and PWM outputs, refer to [R14].

Magnetotorquers were built during the project for the test phase. Due to structural interface modifications they are not at the right size anymore. They shall be resized in accordance to the structural constraints. After the first tries to make magnetometers, it was observed that it will not be possible to obtain precise outer dimension. In order to solve this problem, it is recommended to undersize the coil of a tenth of millimeters, to put the coil in a mould and to cast epoxy over it.

Once the design is validated the design of the IWA shall be integrated to the rest of the ADCS board. When possible both should use the same microcontroller.

8 SYSTEM ENGINEERING

This section summarizes the mass and power budgets at system level. The other system engineering tasks described in the work package were overtaken by other students at the end of the semester and presented in the other System engineering reports.

For information about the subsystems, refer to the specific report or to [R17].

8.1 Mass budget

The mass budget is based on the work done during Phase A. It was updated during the whole Phase B. Just as a reminder a CubeSat shall weight less than 1 kilogram. After Phase A, the overall mass of the SwissCube was 913 grams. It means a margin of about 10%. During Phase B it was possible to refine the estimation made before, because most of the hardware was available. Table 11 presents the mass allocation of each subsystem. Actually the satellite weights 709 grams, so a margin of about 30%.

Subsystem	Mass [g]
Structure & Configuration	273
EPS	188
ADCS	114
CDMS	33
Payload	47
COM	30
Mechanism & antenna	20
Thermal	4
Total	709

Table 11: Subsystems mass budget.

Table 12 gives another representation of the mass allocation. The mass is distributed over the different boards and faces. By face it is meant the sun sensor, the magnetotorquer if placed behind it the composite panel and in one case the antennas.

Boards / Faces	Mass [g]
EPS board	162
ADCS board	28
CDMS board	33
Payload module	48
COM board	30
General structure	214
face +x	20
face -x	36
face +y	49
face -y	35
face +z	36
face -z	20
Total	709

Table 12: Board and faces mass budget.

8.2 Power budget

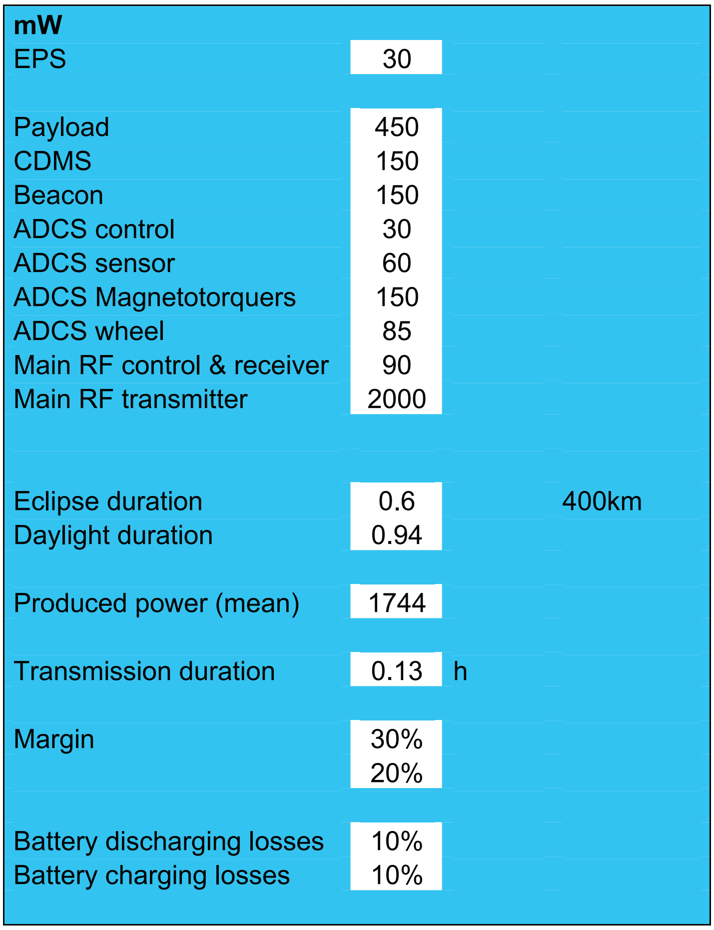
The actual power budget is based on the work done during phase A and B. The establishment of the power budget is done with many assumptions. The worst case in term of orbit duration is considered and an 30 % margin is book kept.

8.2.1 Assumptions

To calculate the total amount of energy (mWh) needed for one orbit around the Earth, assumptions were made. Some of them come from the projects requirements and others will define new system requirements. These assumptions are listed below.

- One orbit is 92.6 minutes long, 36 minutes in eclipse and 56.6 minutes in daylight. This is the worst case because this is the longest eclipse duration and it corresponds to an altitude of 400 km.
- Science takes pictures during the eclipse and when possible also during day time
- RF reception is always on
- The beacon sends a 15 seconds long message every 30 seconds
- ADCS Magnetotorquers are always in use and need 50 mW each on average
- ADCS controller and sensors are always on
- EPS is on all the time (eclipse and daylight)
- RF Data transmission sends 7.5 minutes long data message
- Payload picture capture is 10 seconds long
- The energy taken from the battery generate 10% losses

The power, in watts, needed by each subsystem is presented in Table 13.



mW			
EPS	30		
Payload	450		
CDMS	150		
Beacon	150		
ADCS control	30		
ADCS sensor	60		
ADCS Magnetotorquers	150		
ADCS wheel	85		
Main RF control & receiver	90		
Main RF transmitter	2000		
Eclipse duration	0.6		400km
Daylight duration	0.94		
Produced power (mean)	1744		
Transmission duration	0.13	h	
Margin	30%		
	20%		
Battery discharging losses	10%		
Battery charging losses	10%		

Table 13: Power required per subsystem.

8.2.2 Power production profile

The mean power production over the worst case orbit (400 km) was calculated using the STK simulator and Simulink. The incidence angle on each face is calculated with Simulink/MatLab taking different vector from STK. With a basic model of the SwissCube, the incidence angle of the solar rays on each satellite face can be computed. The results of each face are summed the power production profile over the orbit can be determined. The average over the orbit is taken and so the power production. Figure 27 shows the power production in function of time.

The solar cells of the model have a limit angle of 20 degrees. It means that if the solar ray it the side panel with an angle below 20 degrees, no power will be produced.

The produced power is constant on one face, +y or –y depending of the kind of orbit. The peaks correspond to the illumination of the four other faces.

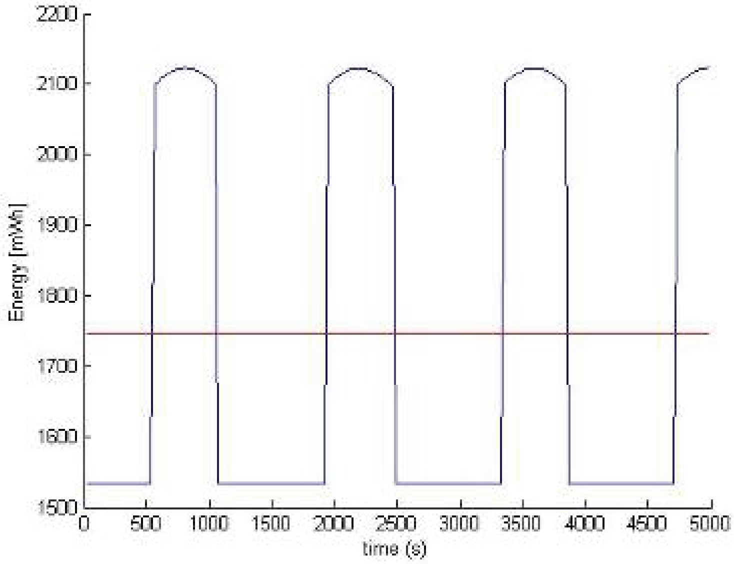


Figure 27: Power production in function of time with mean value.

8.2.3 Power modes

Once the satellite is in function which is corresponding to the nominal mode of the operational modes, there are 8 different possible power consumption states, 4 during daylight and 4 during the eclipse. In each part of the orbit the satellite can be transmitting or not and taking pictures or not. The different states are listed in Table 14, with their corresponding energy consumption.

DTS	Daylight WITH transmission and WITH science	1090 mWh
DTnS	Daylight WITH transmission but WITHOUT science	1088 mWh
DnTS	Daylight WITHOUT transmission but WITH science	789 mWh
DnTnS	Daylight WITHOUT transmission and WITHOUT science	787 mWh
ETS	Eclipse WITH transmission and WITH science	1021 mWh
ETnS	Eclipse WITH transmission but WITHOUT science	1020 mWh
EnTS	Eclipse WITHOUT transmission but WITH science	559 mWh
EnTnS	Eclipse WITHOUT transmission and WITHOUT science	558 mWh

Table 14: Power modes.

In order to have to have power modes for complete orbits, the different cases above have to be combined. The combination gives 16 (4x4) different power states. Table 15 shows the sum of the divers states (unit mWh).

	ETS	ETnS	EnTS	EnTnS
DTS	2'266	2'265	1'884	1'883
DTnS	2'265	2'264	1'883	1'882
DnTS	1'923	1'921	1'541	1'539
DnTnS	1'921	1'920	1'539	1'538

Table 15: Power consumption combinations.

8.2.4 Consumption scenario

The 16 different combinations are list in Table 16. Once the satellite is in nominal mode of operation, it will be in one of these power consumption combinations. At an altitude of 400 kilometers, the satellite will orbit about 15 times around the Earth. It will have three opportunities to communicate with the ground segment (assumption that only one ground station is used for communication). The imagined scenario is that the satellite will take pictures once a day, that the communication will be established three times a day and that during the remaining eleven orbits, no science and no transmission will occur. The energy consumed for each orbit is summed, so the total consumption per day is known. As it is to be seen in Table 16 the total power consumed power in one day is less than the total amount of produced energy during the fifteen orbits.

Phase	Number of orbits	Energy/phase	Energy
DTS ETS		2'266	0
DTS ETnS		2'265	0
DTS EnTS		1'923	0
DTS EnTnS		1'921	0
DTnS ETS		2'265	0
DTnS ETnS		2'264	0
DTnS EnTS		1'921	0
DTnS EnTnS	3	1'920	5'759
DnTS ETS		1'884	0
DnTS ETnS		1'883	0
DnTS EnTS		1'541	0
DnTS EnTnS		1'539	0
DnTnS ETS		1'883	0
DnTnS ETnS		1'882	0
DnTnS EnTS	1	1'539	1'539
DnTnS EnTnS	11	1'538	16'916
Total			24'215
Power production	15	1'639	24'590

Table 16: Scenario.

9 CONCLUSION

Most of the objectives of the ADCS part of the project were fulfilled. The ADCS breadboard was developed and 3 boards are now available for the software programming and the tests. Unfortunately it was not possible to finish the test and to make the characterization of the gyroscopes, sun sensors and magnetotorquers. The choice of the components and the development took more time than expected. The tests on the main board have been started. Its programmability was tested proven. At this stage it was noticed that certain point of the actual design shall be improved in the next version of the card. They are listed in the recommendation chapter, 7.

At system level, the design iterations were continued and the different budgets book kept. Despite the fact that a lot of hardware has been developed, it remains some points that are not totally defined and so the budgets and diagrams need to be refined. For example a detailed mission planning will be necessary to make a precise power budget. Actually only the mean consumption was taken in account and not the peaks. The system functional analysis was continued and is now refined functional within the frame work of another master thesis. The reflections about the interfaces definition were taken into account for the block diagrams updates, but they need to be refined.

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11 ABBREVIATED TERMS

ADCS	Attitude Determination and Control System
ADC	Analog to digital converter
DTU	Dansk Technical University
EPS	Electrical Power System
JTAG	Joint Test Action Group
NA	Not available
PWM	Pulse Width Modulation
SRF	Satellite Reference Frame
TNO	Name of Dutch technology research institute
USB	Universal Serial Bus

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