System Specifications

for

Attitude Determination and Control System

Version	Date	Paged Modified	Observations
0.1	05/10/2016	All	Creation of the document. Global part, ADCS System
0.2	21/02/2017	Algorithm	One page algorithm

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I. Terminology

ADCS:	Attitude Determination and Control System
CTRL:	ADCS Controller
ECE:	Ecole Centrale d'Electronique
EDT:	Electrodynamic Tether
EPS:	Electrical Power System
ESA:	European Space Agency
ISS:	International Space Station
LEO:	Low Earth Orbit
OBC:	On-Board Computer
PV:	Photovoltaïc
PSS:	Photosensors Set
SENS:	ADCS Sensors System
TBD:	To Be Determined
TCS:	Telecommunication System

II. Global project

1. Space debris

Since the beginning of the space race in 1957, the number of objects sent into orbit is continuously growing, as does the amount of space debris orbiting the Earth. This is becoming a real threat for operational space missions around the Earth. Space debris can be the result of:

- A collision between 2 satellites, 2 debris or a satellite and a debris/meteoroid
- A battery which became unstable and exploded
- Fuel leftovers in a satellite or a launcher stage which became unstable and exploded
- A planned destruction
- An out of control satellite or a launcher stage

Today, the population of space debris is estimated to be more than 500 000 trackable objects where 20 000 of them are bigger than a tennis ball. In addition, there are millions of pieces too small to be detected.

The vast majority of space debris is located in Low Earth Orbit (LEO) where most space missions are located or planned. Figure 1 illustrates the distribution of debris around the Earth in 2013.

Figure 1 : Representation of the distribution of the space debris in LEO in 2013. Source: ESA

Even with the direct threat to space missions that space debris represents, the real threat comes in the long-term management of the Earth orbit. Indeed, the Clean Space department of ESA calculated that the population of debris would keep on growing in an exponential way if the space industry does not change or if every space activity stops (Figure 2); thus preventing any orbital activity. The same forecast considered the limitation of debris creation, End of Life (EOL) management, debris removal (Figure 3) and the limitation of orbital objects.

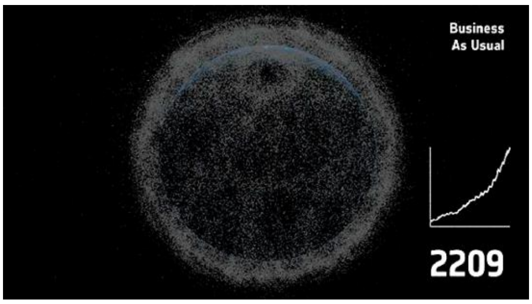


Figure 2 : Space debris population forecast in 2209 if nothing is done to mitigate them.

Figure 3 : Space debris population forecast in 2209 if space debris mitigation is implemented.

One part of the implementation of the space debris mitigation is made through the development of solutions to give the tools to the new satellites to perform deorbiting maneuvers to either cemetery orbits where the satellite is passivated (batteries and tanks emptied) or toward Earth to disintegrate upon re-entry into the atmosphere. Several types of deorbiting systems are currently being developed such as the aerodynamic sail, chemical engine, and electric/ionic engine.

2. CubeSat

A CubeSat is a nanosatellite respecting a standard set by California Polytechnic State University stating that a one unit (1U) CubeSat has a strict volume of 1L within a cube of 10 cm and a mass equal or lesser than 1.33 kg. It is possible to increase the size of a CubeSat by adding units. For example, CubeSat composed two units (2U) and 3U CubeSat and more are obtained this way.

CubeSats are very attractive due to their development speed and their low costs but it is often done with little regard to quality and a lot of them fail in their missions, thus becoming space debris. A CubeSat in lower earth orbit around 400 km will naturally deorbit within a few months but when the altitude rises, around 600 km, natural deorbiting takes more time and does not respect the 25 years' rule (Figure 4).

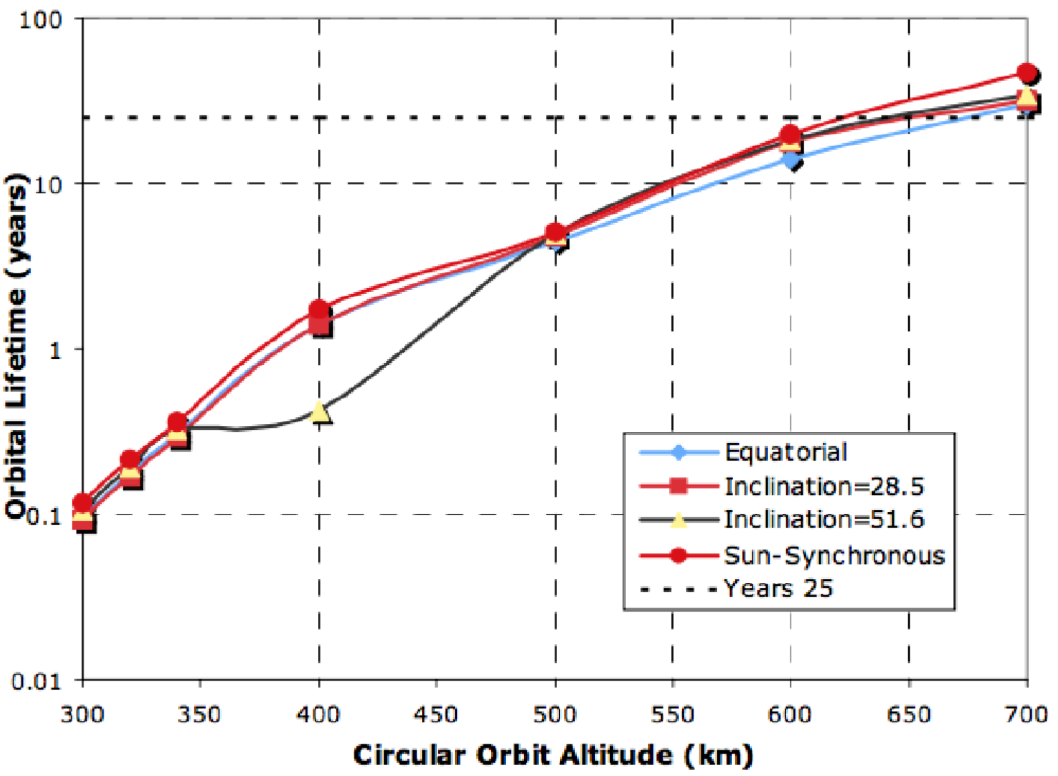


Figure 4 : Lifetime of CubeSat in orbit regarding its altitude.

3. Subsystems from CubeSat

The ECE³SAT system is divided in subsystems to facilitate the work. So in each subsystem there are specific objectives. And each subsystem remains linked to the other subsystems.

All subsystems:

- EPS
- ADCS
- OBC
- TCS
- EDT

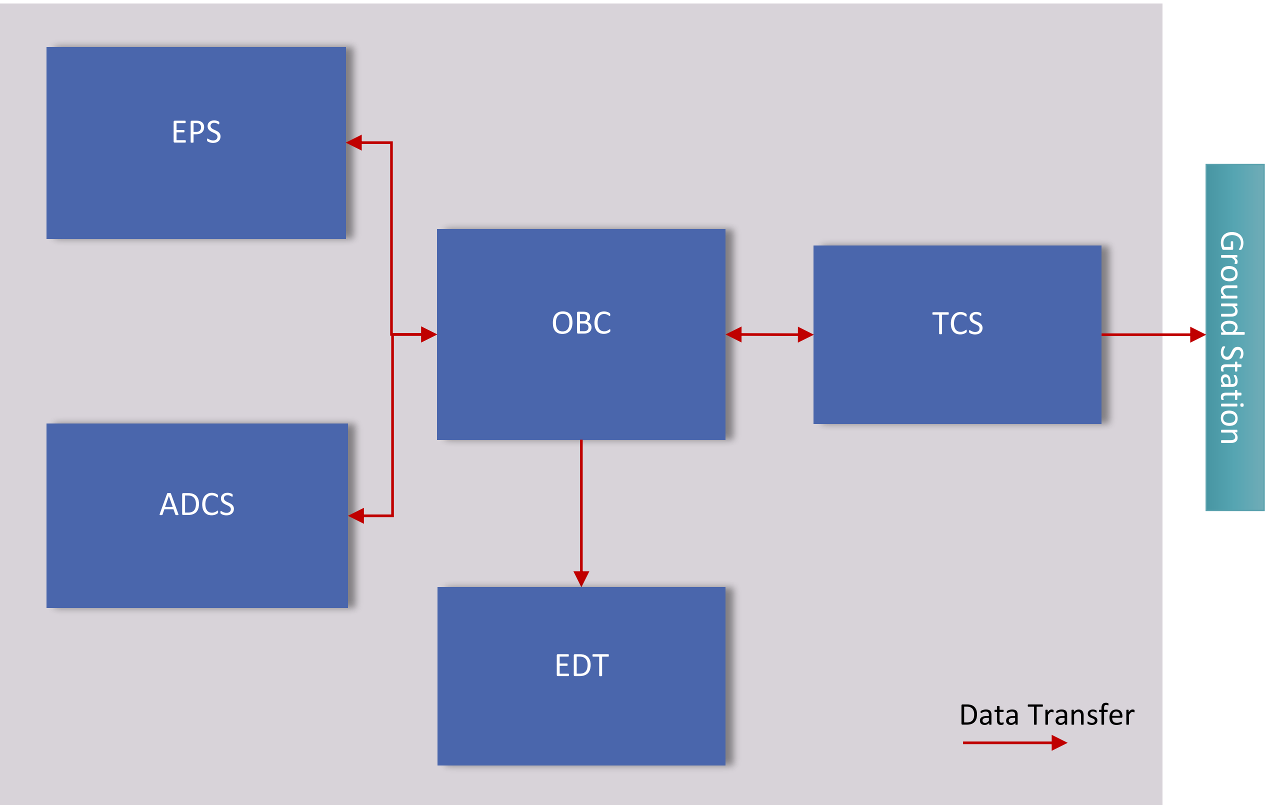


Figure 5 : Links between subsystems

III. ADCS

1. ADCS functionality

The ADCS has a support role through the CubeSat mission. He has to maintain all other modules in an operational situation. So as an entry it takes the sensors and as an output it uses actuators.

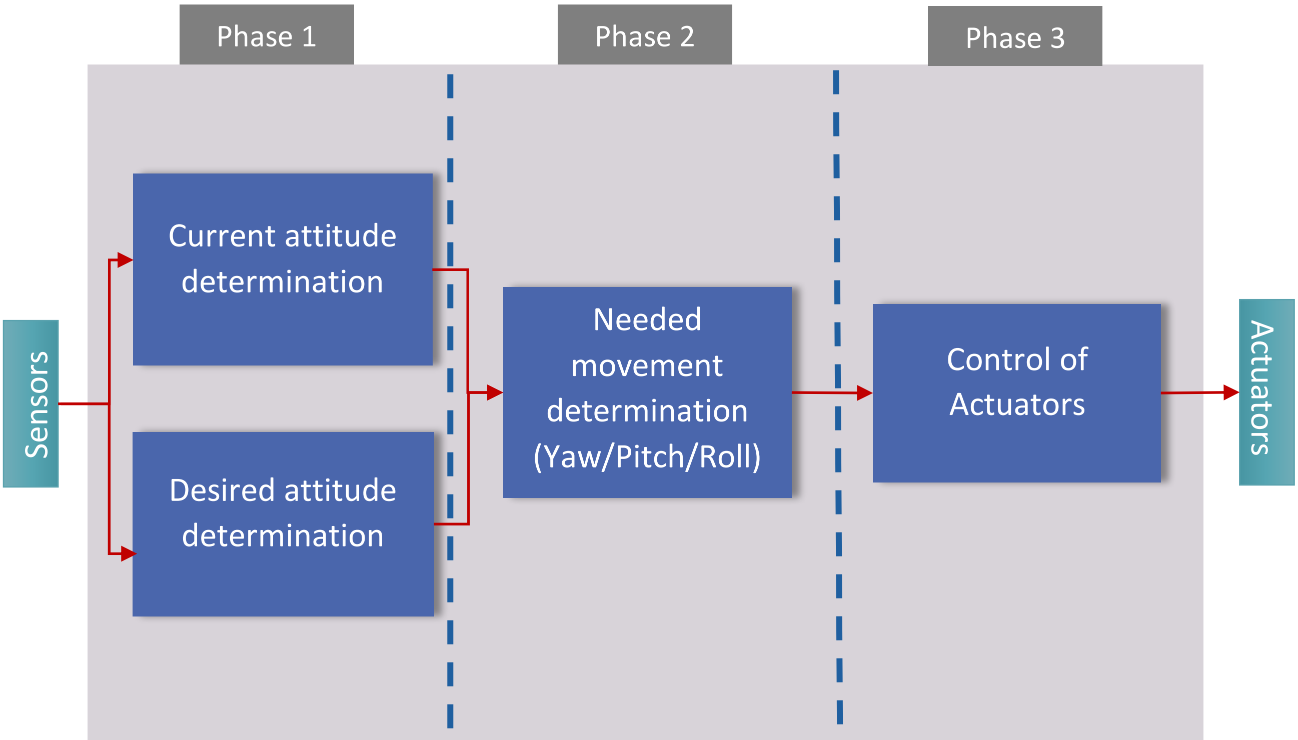


Figure 6 : ADCS Functioning

2. ADCS Modules

The ADCS is divided into 4 modules. It is important to note that the ADCS system is currently based on a preliminary design and is subject to changes. The objectives of each module are depicted in the following list:

- The SENS is composed of a set of sensors. This set will have to harvest data in order to get information about the CubeSat position.
- The ACT are the CubeSat attitude actuators. ACT will have to adapt the CubeSat's attitude according to the mission needs.
- The ADCS controller objectives are to collect data from sensors and to process it to get reliable positioning information. Then the ADCS will send orders to ACT in order to correct/modify the CubeSat's attitude if OBC and EPS subsystems allow it.
- The Interface module has for objective to ensure good connection with other systems of the satellite and to send data to the other systems.

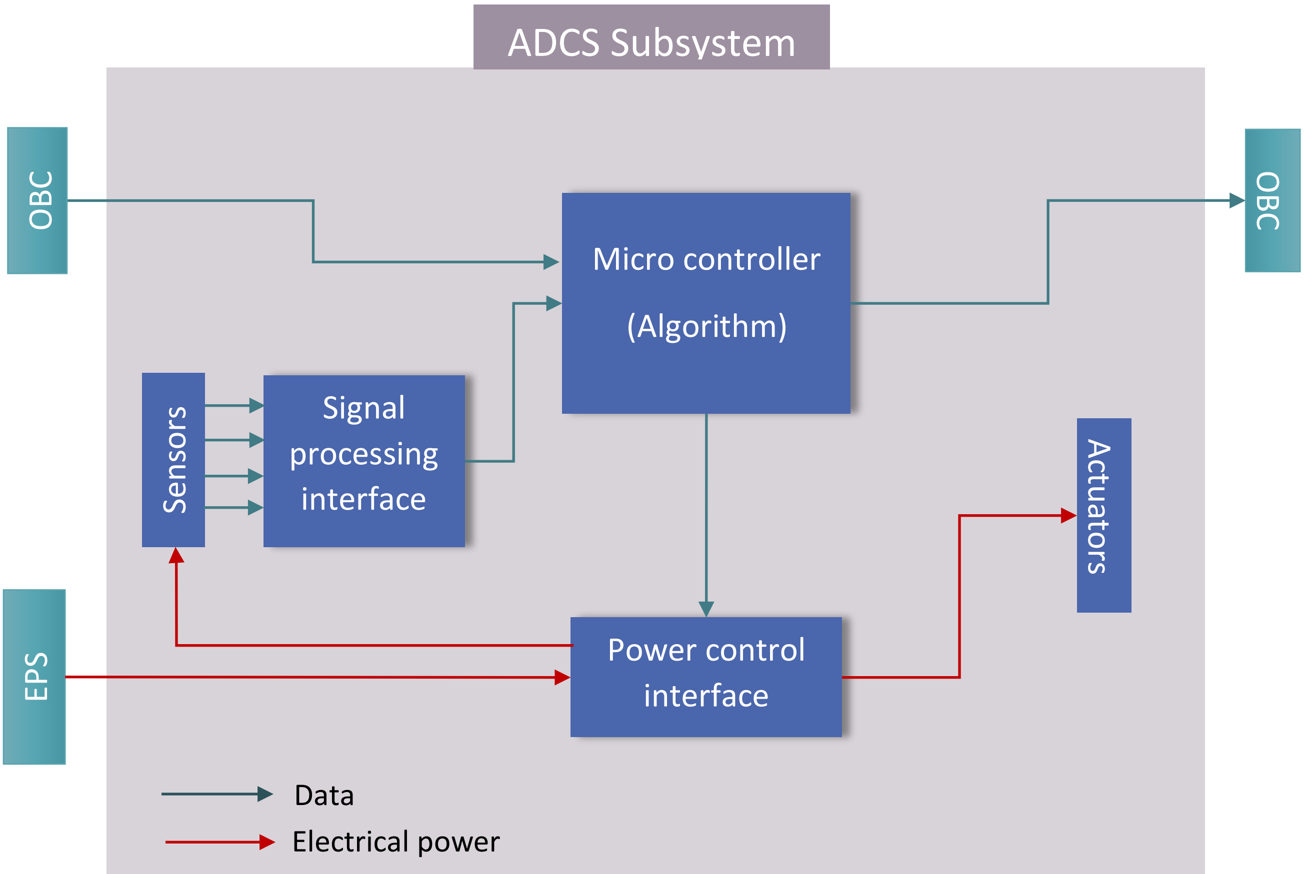


Figure 7 : ADCS module dependence

a) Sensors System (SENS)

ADCS Sensors system will be composed of absolute sensors to get constant access to the attitude relative to an external frame. And relative sensors to get access to the current attitude relative to the previous one.

b) Actuators System (ACT)

The actuators goal is to position the CubeSat in the target attitude by rotation it around 3 axes.

- Yaw / Pitch / Roll

So the Actuators System will be placed to have control over the 3 axes (X, Y, Z).

c) Controller (CTRL)

The ADCS Controller will calculate the attitude in which the CubeSat is thanks to the data coming from Sensors. Also the Algorithm inside the controller will calculate the targeted attitude. And then will determine the rotations to accomplish for each axis.

d) Interface (INT)

The ADCS Interface is the hardware part of ADCS which transmit the signal received from Sensors to the micro-controller and it also distributes power supply coming from the EPS subsystem to the Actuators.

3. Recap on ADCS

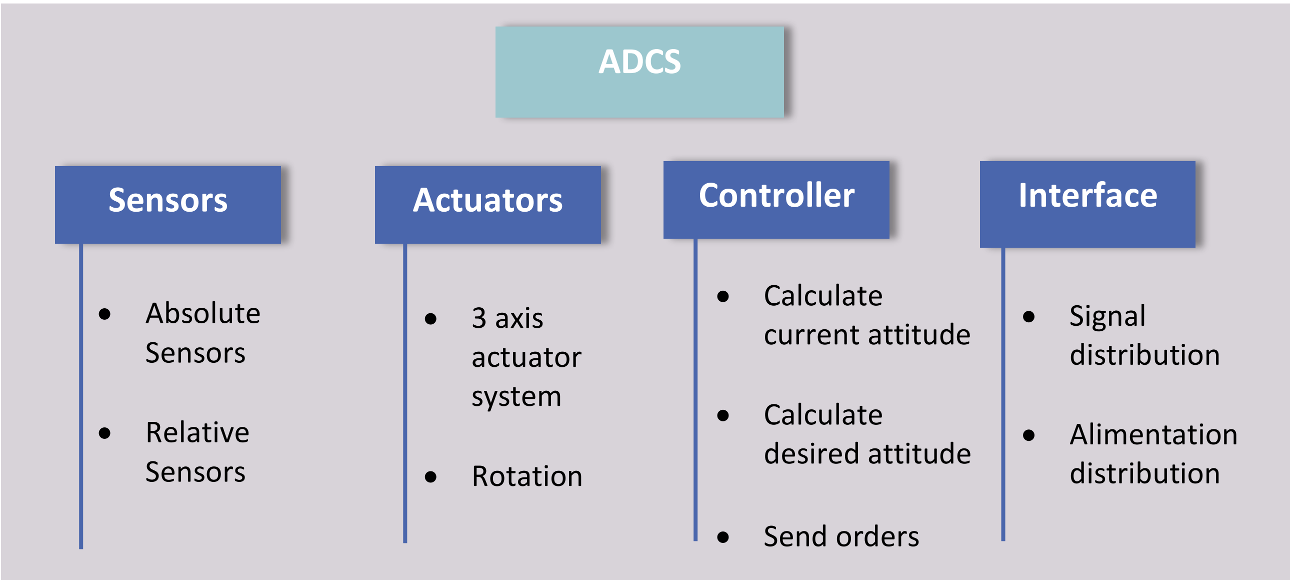
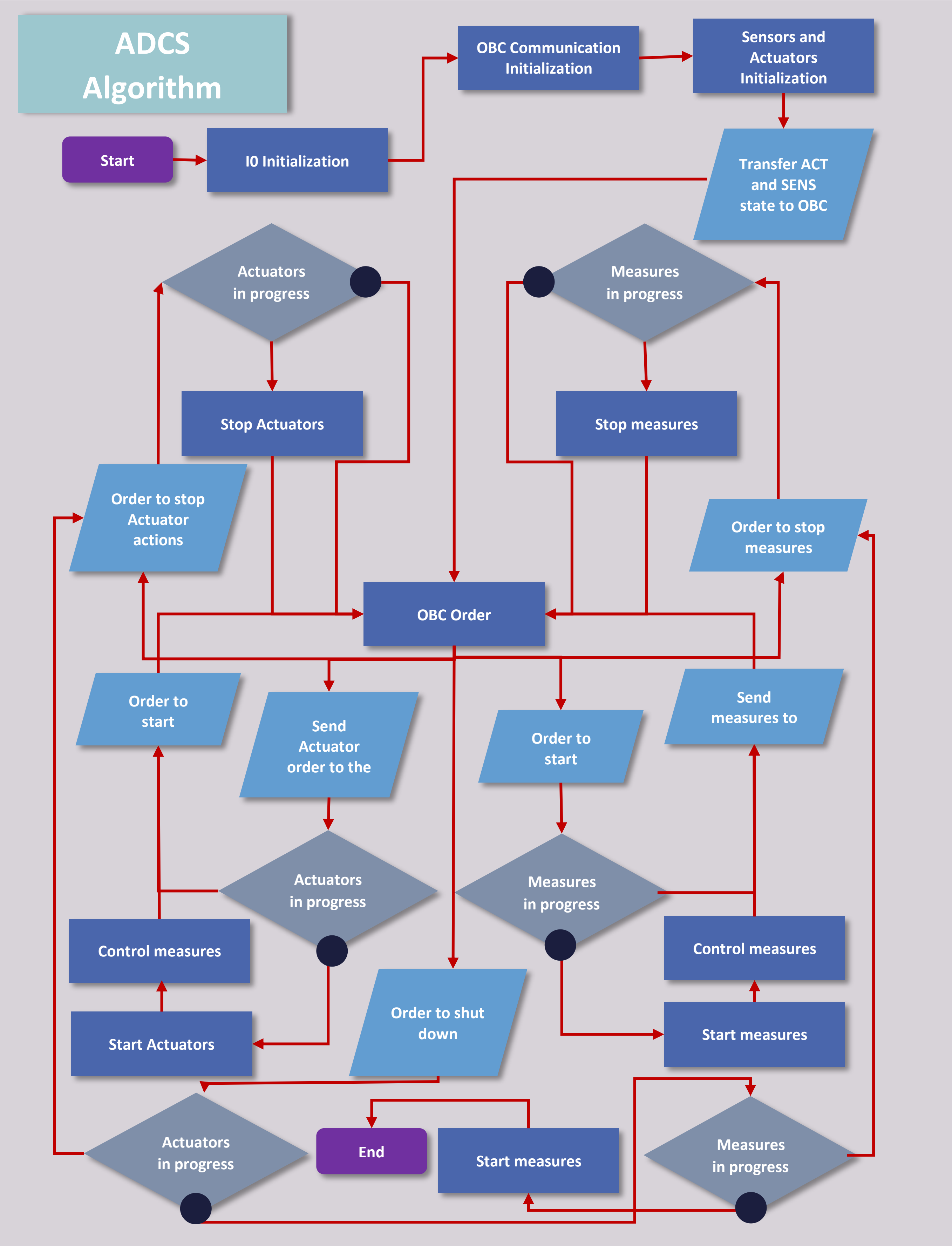


Figure 8 : ADCS module division


ADCS Algorithm
Start
I0 Initialization
OBC Communication Initialization
Sensors and Actuators Initialization
Transfer ACT and SENS state to OBC
Actuators in progress
Measures in progress
Stop Actuators
Stop measures
Order to stop Actuator actions
Order to stop measures
OBC Order
Order to start
Send Actuator order to the
Order to start
Send measures to
Actuators in progress
Measures in progress
Control measures
Control measures
Start Actuators
Order to shut down
Start measures
Actuators in progress
End
Start measures
Measures in progress

IV. Requirements

1. Applicable standards

- ECSS-Q-ST-40C
    - Safety/Launch authority safety requirements

- ECSS-Q-70-71A
    - Data for selection of space materials and processes

- ESA-ADMIN-IPOL (2014)2
    - Space Debris Mitigation for Agency Projects

2. Requirement level

Requirement level	Definition
Shall	The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*). First order of importance. The requirement is vital. It must be validated in priority.
Should	The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*). It is a second level of importance. It means that a *Should* requirement must be validated after a *Shall* requirement.
May	The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*). It is a third order of importance. The requirement is a plus to the system. A *may* requirement must be validated after a *Should* requirement.

3. ADCS Requirements

a) Global ADCS Requirements

RQ CODE	Requirement name	Details	Level
RQ01-ADCS	Each ADCS system has to switch ON on OBC orders.	The OBC activates the CTRL to control ADCS system	**Shall**
RQ02-ADCS	Each ADCS system has to switch OFF on OBC orders.	This is to prevent any issues from compromising the mission.	**Shall**
RQ03-ADCS	Each ADCS system has to be shielded against environmental disturbance.	Resistance against high and low temperatures, radiations and magnetic fields.	**Shall**
RQ04-ADCS	Each part of ADCS system has to not interfere with other modules from CubeSat.	Do not disturb other modules in an unintended way.	**Shall**
RQ05-ADCS	The ADCS module shall fit inside of the CubeSat		**Shall**
RQ06-ADCS	The ADCS module shall have a limited mass		**Shall**
RQ07-ADCS	The ADCS module shall have a limited power consumption		**Shall**

b) Actuators System Requirements

RQ CODE	Requirement name	Details	Level
RQ01-ACT	ACT has to be turned ON and OFF on CTRL order.	The OBC activates the CTRL which activates the ACT.	**Shall**
RQ02- ACT	ACT has an independent action on each axis.	Means the 3 axis are independently controller.	**Shall**
RQ03- ACT	ACT must orientate CubeSat to have EDT module facing the Earth.		**Shall**
RQ04- ACT	ACT should position with precision.	Need to have a good orientation.	**Should**

c) Sensors System Requirements

RQ CODE	Requirement name	Details	Level
RQ01-SENS	SENS has to be turned ON and OFF on CTRL orders.	The OBC activates the CTRL which activates the SENS.	**Shall**
RQ02-SENS	SENS has to send data to the CTRL.	The data collected will be sent to CTRL.	**Shall**
RQ03-SENS	SENS has to be able to realize a measurement session with only one type of sensor (GSCS, PSS, MMS).	The measurement session will be able to ask data from only one sensor	**Shall**
RQ04-SENS	SENS has to realize a complete measurement session on CTRL order.	A measurement session means that SENS will be activated to collect data.	**Shall**
RQ05-SENS	A specific warning is sent to CTRL for each sensor if it gives inaccurate measure.	Depends on the kind of sensor, some do analyze their values.	**Shall**
RQ06-SENS	A specific warning is sent to CTRL for each sensor if it fails.	Different warnings to turn OFF the right sensor.	**Shall**
RQ07-SENS	SENS should be redundant.		**Should**
RQ08-SENS	SENS has a fast answer time.		**Should**
RQ09-SENS	SENS hardware is low power consumption and lightweight.	Also, means the less possible pins.	**Should**

d) Controller Requirements

RQ CODE	Requirement name	Details	Level
RQ01-CTRL	CTRL has to react accordingly to the process order sent by OBC.	The OBC is the headmaster.	**Shall**
RQ02-CTRL	CTRL has to send SENS's processed data to the OBC.	Data from sensors can be used by all modules.	**Shall**
RQ03-CTRL	CTRL has to manage each ADCS system independently.	The ADCS system will be made of functions inside the CTRL allowing all parts to be independent.	**Shall**
RQ04-CTRL	CTRL has to process the SENS's data.	Data coming from the SENS's.	**Shall**
RQ05-CTRL	CTRL has to give orders to ACT.	Orders like ON/ OFF and also for positioning each axis	**Shall**
RQ06-CTRL	CTRL has to send periodically an activity report to the OBC.	OBC needs to know if there are issues in ADCS.	**Shall**
RQ07-CTRL	CTRL has to be able to determine the actual attitude.	Algorithm to get the current attitude.	**Shall**
RQ08-CTRL	CTRL has to be able to determine the wanted attitude.	Algorithm giving the wanted attitude.	**Shall**
RQ09-CTRL	CTRL has to be able to determine the correction necessary on the attitude.	Algorithm giving the correction to apply on ACT's.	**Shall**

V. ADCS Scenarios description

1. SENS scenarios

SC01_SENS

Requirements:	RQ03-SENS, RQ05-SENS, RQ07-SENS, RQ06-SENS
Initial conditions:	SENS is responding to orders from CTRL.
Scenario:	**SC01-SENS**: SENS has to send data to the CTRL.
External interface used:	Order from the CTRL, Energy from the CTRL
Exit conditions:	CTRL sends inactive order
Test cases	**TC01-SENS**: Test if SENS activates on CTRL orders. **TC02-SENS**: Test if SENS reacts accordingly to CTRL orders. **TC03-SENS**: Test if SENS inactivates on CTRL orders

SC02-SENS

Requirements:	RQ05-SENS, RQ06-SENS, RQ07-SENS
Initial conditions:	One sensor measurement does not match the expected range of the measured phenomenon.
Scenario:	**SC02-SENS**: Determination of the questioned sensor and warning raising to the CTRL.
External interface used:	Order from the CTRL, Energy from the CTRL
Exit conditions:	CTRL adds this sensor to the black list.
Test cases	**TC04-SENS**: Test if sensors sends warning to the CTRL if out range measurements.

SC03-SENS

Requirement:	RQ03-SENS, RQ04-SENS, RQ05-SENS, RQ06-SENS, RQ07-SENS
Initial conditions:	One sensor measurement does not respond to CTRL order.
Scenario:	**SC03-SENS**: Determination of the questioned sensor and alert raising to the CTRL.
External interface used:	Order from the CTRL, Energy from the CTRL
Exit conditions:	CTRL adds this sensor to the black list.
Test cases	**TC05-SENS**: Test if SENS sends alerts or respond to CTRL.

SC04-SENS

Requirements:	**RQ03-SENS, RQ04-SENS, RQ05-SENS**
Initial conditions:	SENS gets orders from CTRL.
Scenario:	**SC04-SENS**: SENS measures the light intensity. Values transmitted are almost null.
External interface used:	Order from CTRL, Power from the CTRL.
Exit conditions:	SENS don't detect sun light, CS hiding from sunlight.
Test cases	**TC06-SENS**: Test if SENS goes to sunlight mode.

SC05-SENS

Requirements:	**TBD**
Initial conditions:	After measurement, solar and magnetic vectors are collinear and ADCS can't describe CS position.
Scenario:	**SC05-SENS**: The determinist algorithm is offline and CS use only Kalman Extended Filter and GSCS are used to estimate attitude.
External interface used:	Order from CTRL, Power from the CTRL.
Exit conditions:	Both vectors are non-collinear. Determinist algorithm is back online.
Test cases	**TC08-SENS**: Test if collinear vectors are detected.

SC06-SENS

Requirement:	**TBD**
Initial conditions:	One actuator is not responding to the CTRL.
Scenario:	**SC06-SENS**: All ACTs are switched off, Kalman Extended Filter and GSCS are used instead as attitude estimation. TLE data should be sent in accelerated rate to avoid too much error in estimation.
External interface used:	Power from the CTRL
Exit conditions:	The ACT is responding to the CTRL or specific new order from the CTRL.
Test cases	**TC09-SENS**: Test if the ACTs goes offline as requested by CTRL

SC07-SENS

Requirements:	**TBD**
Initial conditions:	CS is launched, one PSS is not responding to the CTRL.
Scenario:	**SC07-SENS**: The corresponding PV panel is used instead of the PS for calculation
External interface used:	Power from the CTRL
Exit conditions:	The PSS is responding to the CTRL or specific new order from the CTRL.
Test cases	**TC10-SENS**: Test if ADCS gets measure of PV panels.

SC08-SENS

Requirements:	**TBD**
Initial conditions:	One PSS is not responding to the CTRL.
Scenario:	**SC08-SENS**: The CTRL put the PSS offline, Kalman extended filters and GSCS are used instead for attitude estimation.
External interface used:	Power from the CTRL
Exit conditions:	The PSS is responding to the CTRL or specific new order from the CTRL.
Test cases	**TC11-SENS**: Test if ADCS gets measure of PV panels.

SC09-SENS

Requirements:	**TBD**
Initial conditions:	One GSCS is not responding to the CTRL in detumbling mode.
Scenario:	**SC09-SENS**: The detumbling is done with the axis remaining. Then MMS and PSS are used to detumble the last axis.
External interface used:	Power from the CTRL
Exit conditions:	The GSCS is responding to the CTRL or specific new order from the CTRL.
Test cases	**TC11-SENS**: Test if MMS and PSS can calculate angular rates.

SC10-SENS

Requirements:	**TBD**
Initial conditions:	CS is launched, one GSCS is not responding to the CTRL in non detumbling mode.
Scenario:	**SC10-SENS**: CTRL send the GSCS offline
External interface used:	Power from the CTRL
Exit conditions:	The GSCS is responding to the CTRL or specific new order from the CTRL.
Test cases	**TC11-SENS**: Test if MMS and PSS can calculate angular rates.

SC11-SENS

Requirements:	**TBD**
Initial conditions:	CS is launched, no initial parameters are given to CS and attitude estimation can't be done
Scenario:	**SC11-SENS**: SENS measurement rate is slowing down and are stocked in CTRL and not treated
External interface used:	Power from the CTRL
Exit conditions:	Initial parameters are sent
Test cases	**TC11-SENS**: Test if SENS is changing rate with no initial parameters

2. ACT scenarios

SC01-ACT

Requirements:	**TBD**
Initial conditions:	CS is launched but the attitude does not match with the expectation.
Scenario:	**SC01-ACT**: Determination of the failure
External interface used:	Order (energy) from the CTRL
Exit conditions:	CTRL sends inactive order; the failure is founded
Test cases	**TCO1- ACT**: Test if MTS activates on CTRL orders **TC02- ACT**: Test if MTS reacts accordingly to CTRL orders **TC03- ACT**: Test if MTS inactivates on CTRL orders **TC04- ACT**: Test the reaction of each MT

3. CTRL scenarios

SC01-CTRL

Requirements:	**TBD**
Initial conditions:	CTRL has received and processed data from SENS and they are inaccurate
Scenario:	**SC01-CTRL**: CTRL raises a warning to the OBC
External interface used:	CTRL/OBC/ SENS
Exit conditions:	CTRL sent the warning to the OBC
Test cases	**TCO1-CTRL**: Test if CTRL figures out inaccurate data SENS **TC02-CTRL**: Test if CTRL can send a proper warning to the OBC

SC02-CTRL

Requirement:	**TBD**
Initial conditions:	CTRL did not receive an expected answer from the SENS
Scenario:	**SC02-CTRL**: CTRL raises a specific alert to the OBC
External interface used:	CTRL/OBC/ SENS
Exit conditions:	CTRL sent the alert to the OBC
Test cases	**TCO3-CTRL**: test if CTRL figures out if an SENS failed **TC02-CTRL**: Test if CTRL can send a proper alert to the OBC

SC03-CTRL

Requirements:	**TBD**
Initial conditions:	CTRL has figured out that the current attitude isn't matching expectation.
Scenario:	**SC03-CTRL**: CTRL raises a specific alert to the OBC
External interface used:	CTRL/OBC/ SENS
Exit conditions:	CTRL sent the alert to the OBC
Test cases	**TCO5-CTRL**: test if CTRL figures out an attitude which doesn't match with expectation. **TC02-CTRL**: Test if CTRL can send a proper alert to the OBC.

SC04-CTRL

Requirement:	**TBD**
Initial conditions:	CTRL did not receive any answer from the OBC
Scenario:	**SC04-CTRL**: CTRL is switching to Stand-by mode and ping the OBC periodically
External interface used:	CTRL/OBC
Exit conditions:	CTRL receives an order from the OBC
Test cases	**TCO6-CTRL**: turn on the ADCS whereas the OBC is shut down and then switch the OBC on.

VI. State of the Art

The state of the art is included in the specifications and describe the functionalities described in part ADCS.

1. Positioning method and algorithm:

Needs:

- Calculate CubeSat orientation:
  - Estimate an angular rotation
- Determine the trajectory to have, to reach the desired orientation.
- Calculate the orientation:
  - Chose the priority (solar productivity / Tether orientation)
  - Determine the most interesting position
- Traduce it in physical input for actuators

Representation of attitude for a system:

To fix the attitude of any object we first need reference frame called (X, Y, Z) and then a frame for our mobile system (X', Y', Z').

a) Euler angles:

OXYZ basis is related to solid OX'Y'Z 'by three successive rotations:

-The Precession around Oz (going from OXYZ to OUVZ)

-The Wobble around OR (going from OUVZ to OUWZ ')

-The Own rotation around OZ '(going from OUWZ' to OX'Y'Z ')

$$\vec{\Omega} = \dot{\psi}\,\vec{z} + \dot{\theta}\,\vec{u} + \dot{\varphi}\,\vec{z}\,'$$

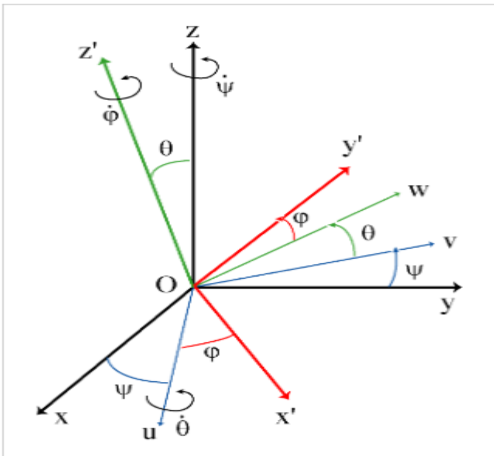


Figure 9 : Euler Angles representation

Then the instantaneous rotation vector is:

Thus, any vector x in a given base can be expressed in another frame as a composition of rotations:

$$\vec{t} = \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}_M = Rz'.Ru.\,Rz.\begin{bmatrix} x \\ y \\ z \end{bmatrix}_R$$

With vectors of rotation:

$$Rz' = \begin{bmatrix} \cos(\psi) & \sin(\psi) & 0 \\ -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad Ru = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & \sin(\theta) \\ 0 & -\sin(\theta) & \cos(\theta) \end{bmatrix}$$

$$Rz = \begin{bmatrix} \cos(\varphi) & \sin(\varphi) & 0 \\ -\sin(\varphi) & \cos(\varphi) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

However, there are singular points that prevent the orientation calculation in certain positions. Indeed, when the second rotation around the axis u is zero or multiple of π, it is impossible to differentiate the two other rotations because in this case the Z and Z ' axes are confused (related to cosine / sine)

And with the composition of rotations it is possible to set up symmetrical rotations {R121, R131, R212, R232, R313, R323} and antisymmetric rotations or gimbal angles {R123, R132, R213, R231, R312, R321}

b) Gimbal angles:

- roll angle (around X) defined in [-π, π]
- pitch angle (around Y) defined in [-π / 2, π / 2]
- yaw angle (around Z) defined in [-π, π]

As the Euler angles, the gimbal angles contain points called "Gimbal lock" (when the second angle theta is equal to +/- π / 2)

There are other representations which have no singular points (such as the representation of quaternions).

c) Quaternions:

This representation, unlike the Euler Angles, is not intuitive at all but the associated calculations are less complex. Thus it requires less computation power, time and less energy.

The quaternions respect the following properties:

$$i^2 = j^2 = k^2 = ijk = -1$$

The rotation quaternion is represented as such:

$$q = w + x\mathbf{i} + y\mathbf{j} + z\mathbf{k} = w + \vec{v}\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \cos(\alpha/2) + \vec{u}\sin(\alpha/2)$$

Where $\vec{u}$ is a normalized vector that gives the direction of the rotation axis and α is the rotation angle in rad.

To rotate any vector $\vec{v}$ around the $\vec{u}$ axis by the α angle, we can apply the following equation:

$$\vec{v'} = q\vec{v}q^{-1} = \left(\cos\frac{\alpha}{2} + \vec{u}\sin\frac{\alpha}{2}\right)\vec{v}\left(\cos\frac{\alpha}{2} - \vec{u}\sin\frac{\alpha}{2}\right)$$

Where $\vec{v'}$ is the rotated vector.

In our case, we have the initial and the final attitude ($\vec{v}$ and $\vec{v'}$). We can use the quaternion representation to get the rotation quaternion (q) with relatively simple operations from a computational point of view. We can then deduce the rotation axis and angle and convert them to the Euler angle format, that we can use to calculate the output to the actuators.

d) Measuring the attitude:

Two non-collinear and non-zero vectors within two frames are sufficient to determine the attitude of a solid. In many systems they point on far fixed stars from the system (using Star Tracker), the Sun (using Sun sensors), or the Earth (using magnetometer and Earth sensors).

In the terrestrial reference frame, the magnetic fields and the gravitational acceleration are known

eg Paris g = 9.81 m/s and Bh = 20.6µT and Bv = 42.24µT with: $\vec{g} = \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} et\ \vec{B} = \begin{bmatrix} Bh \\ 0 \\ Bv \end{bmatrix}$

We must then measure the vectors of two fields in the mobile frame. Let's call A the accelerations on each axis and M the magnetometers measurements on the axis:

$$\begin{bmatrix} Ax \\ Ay \\ Az \end{bmatrix} = R.\vec{g} = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix}$$

$$\begin{bmatrix} Mx \\ My \\ Mz \end{bmatrix} = R.\vec{B} = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \cdot \begin{bmatrix} Bh \\ 0 \\ Bv \end{bmatrix}$$

By developing:

$$Ax = R_{13}.g \qquad Mx = R_{11}.Bh + R_{13}.Bv$$

$$Ay = R_{23}.g \qquad My = R_{21}.Bh + R_{23}.Bv$$

$$Az = R_{33}.g \qquad Mz = R_{31}.Bh + R_{33}.Bv$$

Then, using the Gimbal angles (R 321) the equations are obtained:

$$Ax = -\sin(\theta)$$
$$Ay = \sin(\psi).\cos(\theta)$$
$$Az = \cos(\psi).\cos(\theta)$$
$$Mx = \cos(\theta).\cos(\varphi).Bh - \sin(\theta).Bv$$
$$My = (\sin(\psi).\sin(\theta).\cos(\varphi) - \cos(\psi).\sin(\varphi)).Bh + \sin(\psi).\cos(\theta).Bv$$
$$Mz = (\cos(\psi).\sin(\theta).\cos(\varphi) + \sin(\psi).\sin(\varphi)).Bh + \cos(\psi).Bv$$

Solving the system:

$$\theta = -\arcsin(Ax)$$
$$\psi = arctg2\left(\frac{Ay}{Az}\right)$$
$$\cos(\varphi) = \cos(\varphi)(Mx, Bh, Bv, \theta)$$
$$\sin(\varphi) = \sin(\varphi)(My, Bh, Bv, \theta, \psi, \cos(\varphi))$$
$$\varphi = arctg2\left(\frac{\sin(\varphi)}{\cos(\varphi)}\right)$$

Arctg 2 is equivalent to Arctg on - π / π

This method is rarely used because it requires a large number of trigonometric calculations.

e) TRIAD Algorithm:

Triad algorithm is one of the earliest and simplest solutions to the spacecraft attitude determination problem. It consists in constructing two orthonormal bases using two pairs of vector measurements.

Two in the orbital reference frame, noted $r_1$and r_2 and two in the body reference frame, noted b_1 and b_2, representing the same magnitude expressed in a different referential.

The following equations are used to build $R_b = \begin{bmatrix} t_{1b} & t_{2b} & t_{3b} \end{bmatrix}$, the basis attached to the body referential and $R_r = \begin{bmatrix} t_{1r} & t_{2r} & t_{3r} \end{bmatrix}$ the basis attached to the orbital referential.

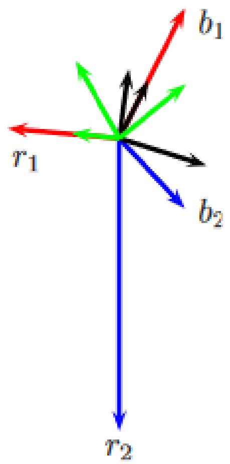


Figure 10 : [t1b t2b t3b] are represented in black and [t1r t2r t3r] in green

Given the knowledge of two vectors in the reference and body coordinates of a satellite, the TRIAD (TRIaxis Attitude Determination) algorithm obtains the direction cosine matrix relating both frames. The two vectors are typically the unit vector to the sun and the Earth's magnetic field vector (it can also be unit vector to two star using star tracker for example).

This algorithm is not an optimal solution, but it provides a reliable estimation of the satellite's attitude while being quite cheap regarding computation needs.

f) Kalman Filter:

The Kalman filter uses mathematical method to **filter signal from noise or inaccurate measure**. It is useful to determine position or orientation even with potential measurement errors. This filter can be used to filter, smooth or predict data (past/present/future). One of its advantage is that it **provides an estimation of the error**.

In a discrete context, the Kalman filter is a recursive estimator: to estimate the current state it only needs the previous state and the current measures.

To use Kalman filter, the system **needs** to be **linearly modeled**. But if the modeling is too approximate, the filter will not be efficient enough and the estimation error will not converge fast enough.

The Kalman filter has 2 distinct states:

- Prediction (using the previous state it estimates the actual state)
- Correct (uses measurement to correct the predicted state)

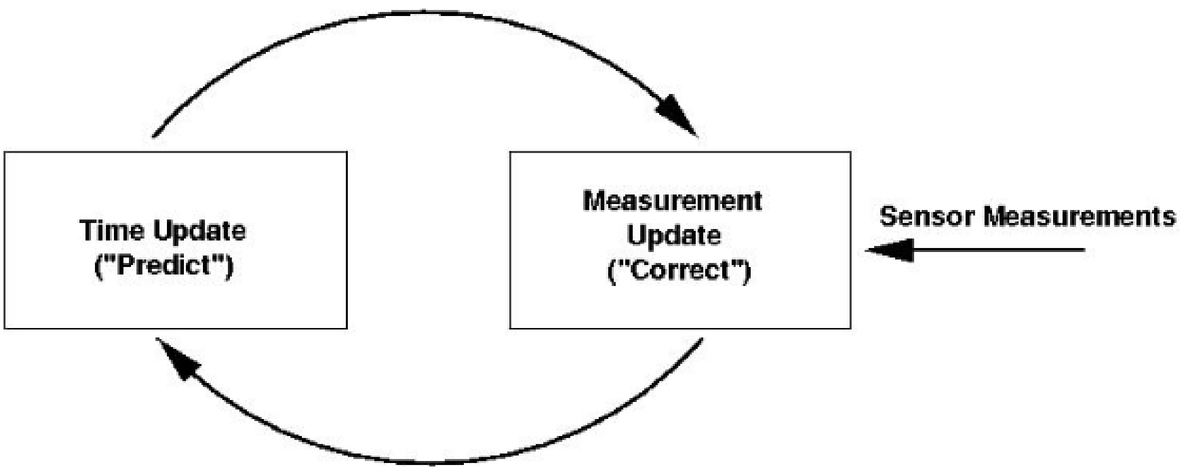


Figure 11 : The 2 states from the Kalman Filter

An extended version of the Kalman filter exist, the principal difference being the possibility to use differentiable function instead of linear (for observation and prediction).

2. Sensors:

Needs:

- Data redundancy
- Data for both situations: eclipse and sun
- Question of sampling frequency
- Location and size/weight
- Ability to resist to environment
- Low consumption
- Low price

a) Gyroscope

Micro Electro-Mechanical (MEM) Gyroscopes:

MEMs gyroscopes have some form of oscillating component from where the acceleration and hence direction change, can be detected. This is because the conservation of motion law says that a vibrating object continues vibrating in the same plane, and any vibrational deviation can be used to derive a change in direction.

Advantage:

- Compact
- Affordable

Disadvantage:

- Noisy: drift ~0.5° per minute

Figure 12 : Micro Electro-Mechanical (MEM) Gyroscopes

Stellar:

This device tracks the motion of stars in the field of view. Stars are detected using the difference of color between pixels. Attitude propagation is based on successfully performing correspondence of these stars between camera frames.

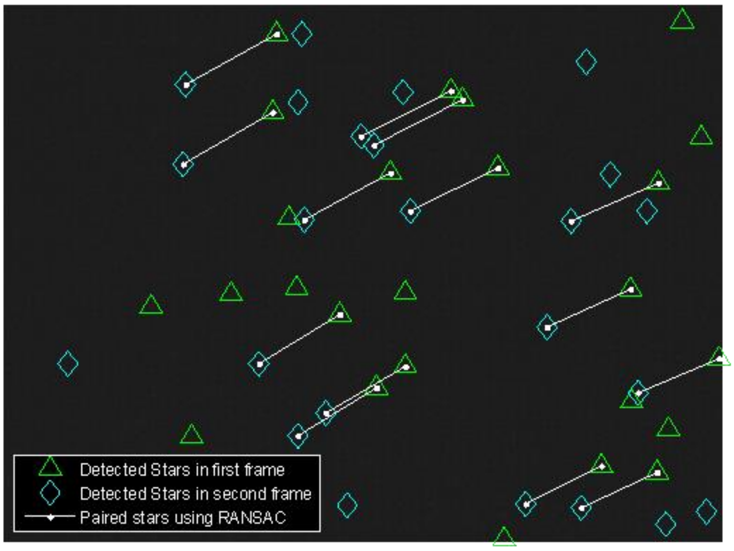


Figure 13 : Stellar

Advantage:

- Tolerates large amount of noise
- Can assist MEMS gyros by limiting drift

Disadvantage:

- Requires a digital signal processor on board the spacecraft
- Add computational requirement
- Too large for a CubeSat

Ring Laser gyroscope (RLG):

A **ring laser gyroscope** consists of a ring laser having two independent counter-propagating resonant modes over the same path; the difference in the frequencies is used to detect rotation.

Advantage:

- High accuracy

Disadvantage:

- Large
- Expensive

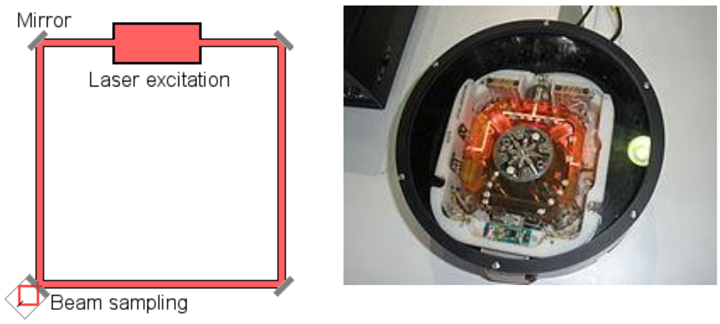


Figure 14 : Ring Laser gyroscope (RLG)

Piezo Gyroscope:

Use the deformation of a piezo electric bar to calculate the angle.

Advantage:

- High accuracy
- Quick
- Lightweight

Disadvantage:

- Vibration
- Need high speed processor

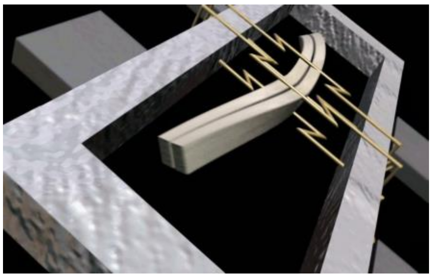


Figure 15 : Piezo Gyroscope

b) Gyrometer

Gyrometer is an instrument which measures an angular acceleration. Two types exist:

Optic

A fiber optic gyroscope (FOG) senses changes in orientation using the Sagnac effect, thus performing the function of a mechanical gyroscope. However, its principle of operation is instead based on the interference of light which has passed through a coil of optical fiber which can be as long as 5 km.

Figure 16 : Optic Gyrometer

Advantages:

- extremely precise
- No moving parts => most reliable to the mechanical gyroscope

Disadvantages:

- Requires calibration
- Too big for a CubeSat

Mechanic

Thanks to rotation parts, it can use the inertial moment not to move the central access and calculate its inclination to the support.

Advantage:

- No calibration needed

Disadvantages:

- Doesn't work in space
- too big for a CubeSat (takes a lot of space)

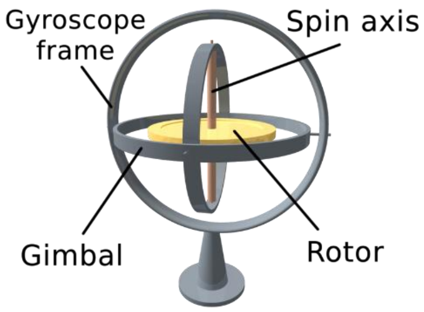


Figure 17 : Mechanic Gyrometer

c) Sun sensor

It is an optical device that detect the position of the sun. The photons coming from the sun enter in a photosensitive chamber. Using two sensors perpendicular to each other, the direction of the sun can then be determined.

The output can be either discrete or analog.

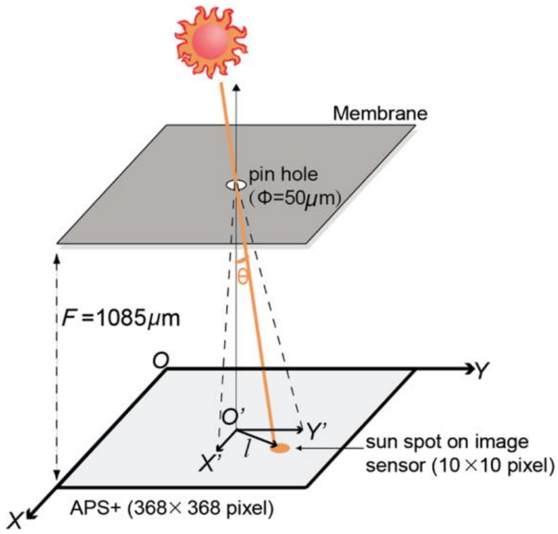


Figure 18 : Sun Sensor operation

Sun Sensor IDD-Ax (analog)

Advantages:

- High reliability
- Low power consumption

Disadvantages:

- Accuracy (1° in Field of View of 30°)

Coarse Bi-axis sun sensors

Advantages:

- Low cost
- High strength
- High temperature range
- Standard FOV

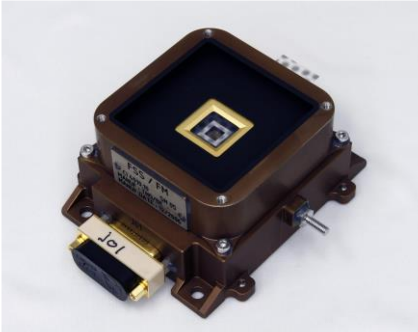


Figure 19 : Bi-axis sun sensors

Disadvantages:

- They need direct sunlight (so they need to be on the sides of the CubeSat)

d) Star tracker

This optical device images a part of the sky and compares it to a map from the memory. This helps it to determine its orientation relatively to the stars

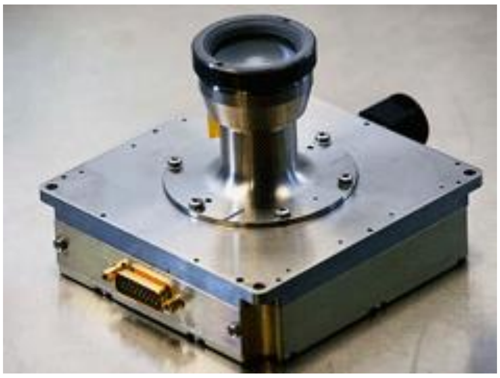


Figure 20 : Star Tracker

Advantages:

- High accuracy

Disadvantages:

- Need a reference map
- Need heavy data processing
- Size and weight (too much for a CubeSat)

e) Horizon sensors

Uses the relative difference between the dark of space and the light of earth to find earth's horizon.

Advantages:

- Low cost
- Fast response time

Disadvantages:

- Low accuracy (about 1°)

Figure 21 : Horizon sensors

f) Magnetometer

A Magnetometer is a device that measures a magnetic field. There is a lot of different methods to do so but some are better for CubeSat.

Laboratory magnetometers

- Superconducting quantum interference device:
  - Extremely sensitive but noise sensitive
- Inductive pickup coils:
  - Detects the current induced in a coil
- Vibrating sample magnetometer (VSM):
  - Uses vibration of sample inside a coil in order to detect induced current
  - Heat due to vibration can be a constraint
  - Fragile sample can be impractical
- Pulsed Field extraction magnetometer:
  - Similar to VSM but this time it is the magnetic field that changes instead of the sample's vibration.
- Torque magnetometer:
  - Indirect measure of magnetism: measures the torque resulting from a uniform magnetic field

- Faraday force magnetometer:
    - Uses gradient coils
- Optical magnetometer:
    - Uses light on a sample which leads to an elliptical measurable trajectory

Disadvantages:

-Needs samples

Survey magnetometers

- *Scalar magnetometers* (measures the strength of the magnetic field but not the direction:
    - Proton precession magnetometer (uses nuclear magnetic resonance to measure the resonance frequency of protons)
    - Overhauser effect magnetometer
    - Caesium vapour magnetometer
    - Potassium vapour magnetometer

- *Vector magnetometers* (measures the component of the magnetic field in a particular direction):
    - Rotting coil magnetometer:
        - Uses a rotating coil to induce a sin wave
        - Old technology
    - Hall effect magnetometer:
        - Produces a voltage proportional to the applied magnetic field
        - Used where the magnetic field strength is relatively large
    - Magneto resistive devices
    - Squid magnetometer
    - Spin exchange relaxation free atomic
    - magnetometers
    - Fluxgate magnetometer

Fluxgate magnetometer

The principle of this magnetometer is to use 2 coils: one is alimented with an alternative current, in the other coil the induced AC is measured (intensity and phase). When a change occurs in the external magnetic field, the output of the secondary coil is changed. This change can then be analyzed to determine the intensity and orientation of the flux lines.

Advantages:

- Electronic simplicity
- Low weight

Disadvantage:

- Can be sensitive to magnetic perturbations coming from inside the spacecraft

<u>RECAP magnetometers:</u>

Spacecraft magnetometers basically fall into three categories: **fluxgate, search-coil and ionized gas magnetometers**

With the data collected from the magnetometer, we can with the **B-Dot** controller (or also the B bang bang) in link with the International Geomagnetic Reference Field (**IGRF**) determine the **magnetic field vector**.

g) Temperature sensors

A lot of measuring technologies exists:

- Thermometer:
  It is a device that measures temperature or a temperature gradient

- Bimetal:
  A Bimetal is an object that is composed of two parts of metal, joined together. When the temperature changes one of those two parts changes size which results in a deformation. The device measures this deformation.

- Thermocouple:

  A thermocouple is an electrical device consisting of two different conductors forming electrical junctions at different temperatures. It produces a temperature dependent voltage as a result of the thermoelectric effect, and this voltage can be interpreted to measure the temperature.

- Resistance thermometers:

  Same as thermocouple, but the resistance changes value when the temperature evolves (it replaces thermocouples in industrial applications below 600°C)

- Silicon bandgap temperature sensor

  This extremely common sensor is used in electronic equipment. The main advantage is that it can be included in a silicon integrated circuit at very low cost. Here is the output voltage from the sensor:

$$V_{BE} = V_{G0}(1 - \frac{T}{T_0}) + V_{BE0}(\frac{T}{T_0}) + (\frac{nKT}{q})ln(\frac{T_0}{T}) + (\frac{KT}{q})ln(\frac{I_C}{I_{C0}})$$

Where:

T = temperature in Kelvin
T_0 = *reference temperature*
V_{G0} = bandgap voltage at absolute zero
V_{BE0} = junction voltage at temperature T_0 and current I_{C0}
K = Boltzmann's constant
q = charge on an electron
n = a device-dependent constant

h) Summary

There is a lot of sensors, some of them need the sunlight, but as we will rotate around the Earth, we will also have to manage the CubeSat's attitude during the eclipse phase. Moreover, redundancy is a necessity for sensors.

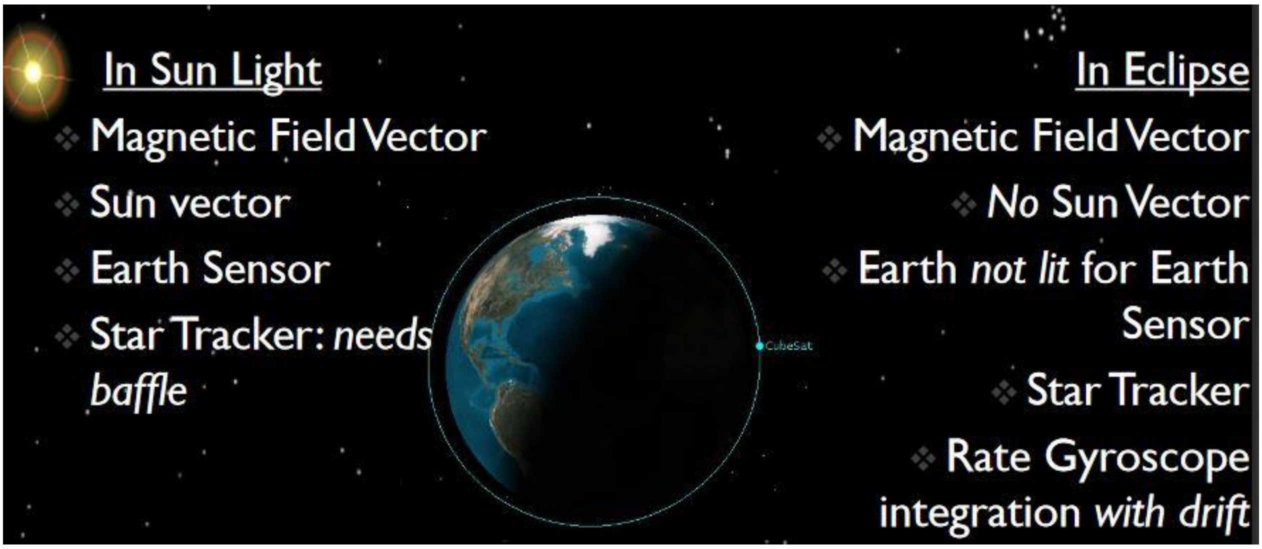


Figure 22 : Activity sensors in sun light and in eclipse

The following figure presents the sensors which can be used in each case:

Looking at this data some tendency can identified:

- We need two vectors during both the eclipse and sun lit phase. that is why the sensors we think to use would be:
    - Sun sensor (to get sun vector but does not work while in eclipse)
    - Magnetometer to get the magnetic field vector (also works while in eclipse)
    - Another sensor for the eclipse phase (probably MEMS gyroscope)

3. Actuators:

Needs:

- Physically act to modify attitude
- Compact design

a) Reaction wheel

Reaction wheels (RW) are primarily used by spacecraft for attitude control. The flywheel is attached to an electric motor, which makes it rotate when it moves. Due to the third law of newton the CubeSat will then start to counter-rotate.

Because a reaction wheel can only make the CubeSat rotate around one axis, we would need 3 of them.

Advantages:

- They are very efficient

Disadvantages:

- It has to be close to the center of mass
- Needs too much energy and space to be accurate in a CubeSat.

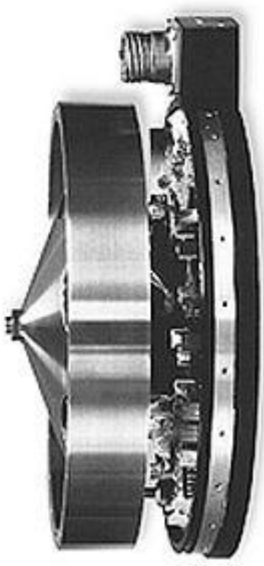


Figure 23 : reaction wheel

b) Momentum wheel

This device always spins at high speed to stabilize the spacecraft (gyroscopic effect). It makes the spacecraft resistant to changes relative to its attitude.

c) Control momentum gyroscope

Figure 24 : Gyroscope

Works on the same principle as the reaction wheels do, but it can also change the spin axis (it's a sort of combination of reaction and momentum wheel).

Advantages:

- Slightly more efficient than Reaction wheel (power consumption and torque)
- They are very efficient
- Useful for frequent and fast change of attitude

Disadvantages:

- Weight and size

d) Magnetorquer

Earth' Magnetic Field

The Earth's magnetic field is believed to be generated by electric currents in the conductive material of its core.

It can be considered as a magnetic dipole as if there were a giant bar magnet placed at the center of the Earth.

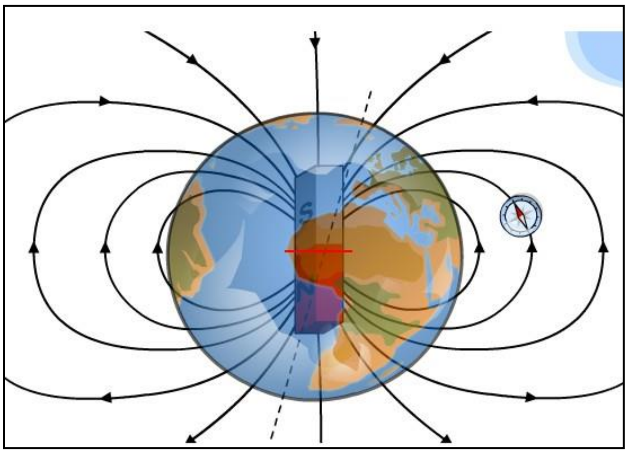


Figure 26 : Giant dipole

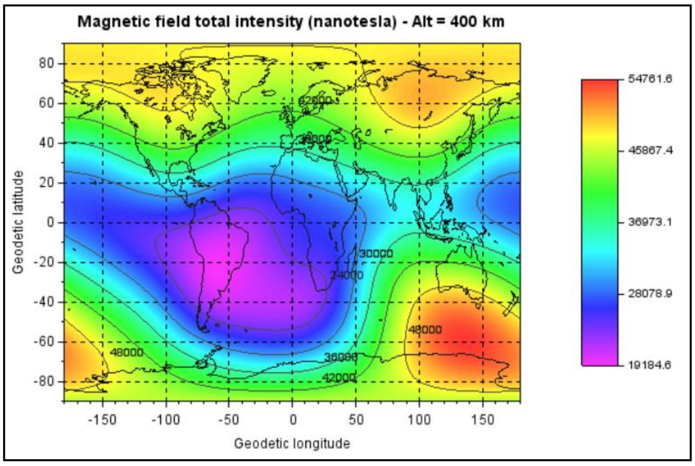


Figure 25 : IGRF with SciLab

The International Geomagnetic Reference Field called IGRF is a standard mathematical which describes this field with this series development:

Where R is the Earth radius, r is radius vector, ϕ is satellite longitude, θ is latitude, P_n^m is Schmidt polynome.

$$V(r,\Phi,\theta)=R\sum_{n=1}^{L}\left(\frac{R}{r}\right)^{n+1}\sum_{m=0}^{n}\left[g_n^m \cos(m\Phi)+h_n^m \sin(m\Phi)\right]P_n^m(\cos\theta)$$

$$B_Z=B_r=-\frac{\partial V}{\partial r}\quad B_X=B_{nord}=\frac{1}{r}\frac{\partial V}{\partial\theta}$$

$$B_{Est}=-\frac{1}{r\cos\theta}\frac{\partial V}{\partial\Phi}=-B_Y$$

There are several types of magnetorquers but only two designed for CubeSat: Linear magnetorquer (coil with an iron or nickel heart) and Integrated magnetorquers (inside of the solar panel).

They create a magnetic field which interacts with the Earth's creating a torque. Indeed, magnetorquers are electrically supplied solenoids so the Ampere's theorem gives us a B field vector of the form:

- For a solenoid:

$$\vec{B_{int}}\,(M,t)=\mu_0 n i(t)\,\vec{U_z}$$

$$\vec{B_{ext}}\,(M,t)=0$$

- For a torus:

$$\vec{B_{int}}\,(M,t)=\frac{\mu_0 n i(t)}{2r\pi}\,\vec{U_o}$$

$$\vec{B_{ext}}\,(M,t)=0$$

Typical values for a CubeSat:

At 400 km, the magnetic field is approximately 25 µT (and 23 at 600 km).

As our solenoids are in space, they interact with the Earth's magnetic field:

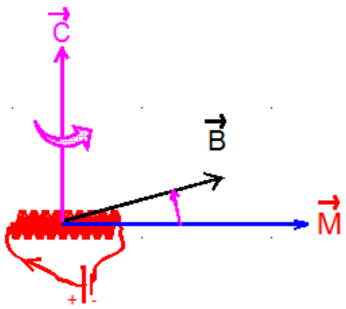
A magnetic device is subject to a force:

$$\vec{R}=\vec{grad}\,(m.B)$$

And a torque

$$\vec{T}=\vec{m}\wedge\vec{b}=NIS\,\vec{n}\wedge\vec{B}$$

With I the intensity in the solenoid, S its surface, N the number of coils and B the Earth's magnetic field.



$$\vec{C}=\vec{M}\wedge\vec{B}$$

Figure 27 : Magnetorquer operation

Advantages:

- Does not need electric current to work
- Light and efficient

Disadvantages:

- The magnetic field generated can lead to false inputs and interpretations
- The attitude control on the 3 axes can be complicated because the torque will only be orthogonal to the Earth's magnetic field.

e) Permanent magnet

It is also possible to use passive actuators. One quarter of all CubeSat do use permanent magnet instead of magnetorquers. Permanent magnet is not precis with the angle to Nadir but are good enough to align on the magnetic field.

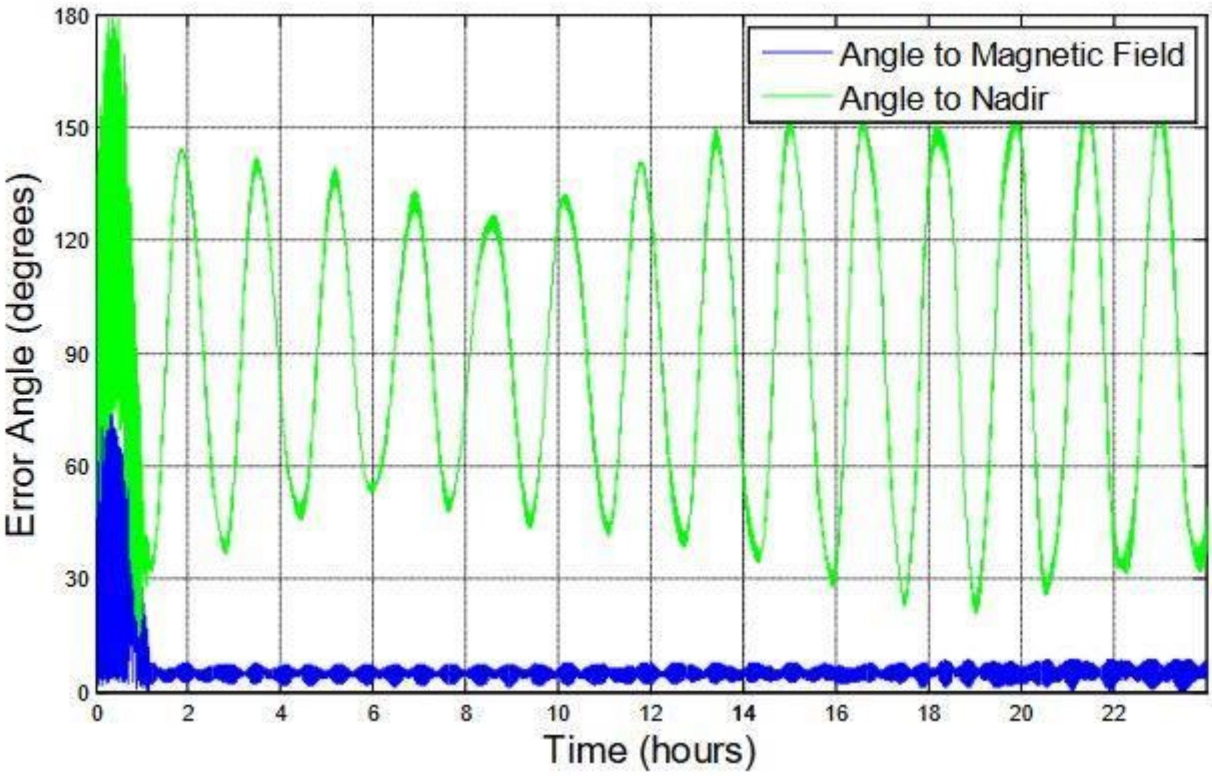


Figure 28 : Evolution of the Nadir and Magnetic field angle from the CubeSat

This graph shows that the angle to Magnetic Field is quickly stabilize but that the angle to Nadir is not at 90 degrees. It varies from 30 to 120 degrees.

4. Electronic board: State of the art

The ADCS electronic board is composed of two parts: the hardware and the software. The hardware of the ADCS is a critical subsystem of the CubeSat. It has to combine the entire sensor system that the CubeSat needs in order to determine the satellite's attitude. It will run attitude determination and control algorithms.

a) Hardware

ADCS hardware has to:

- Get the sensor data.
- Process the data.
- Sample/correct them (for example Kalman filter).
- Determine the current attitude
- Determine the target attitude
- Control the magnetorquers to reach the target attitude.
- Handle the tether

There are different hardware method to achieve the ADCS CTRL function.

- By using a FPGA card
- By using a PIC-Controller

The FPGA card is more developed because it can calculate faster than a PIC and also it can handle a multiple signal treating. In a small satellite, as a CubeSat, the ADCS hardware can also be combined with the OBC. Usually even if the ADCS is on the OBC there is an actuator board to make the link between the ADCS and the OBC. One card is shown on the next figure.

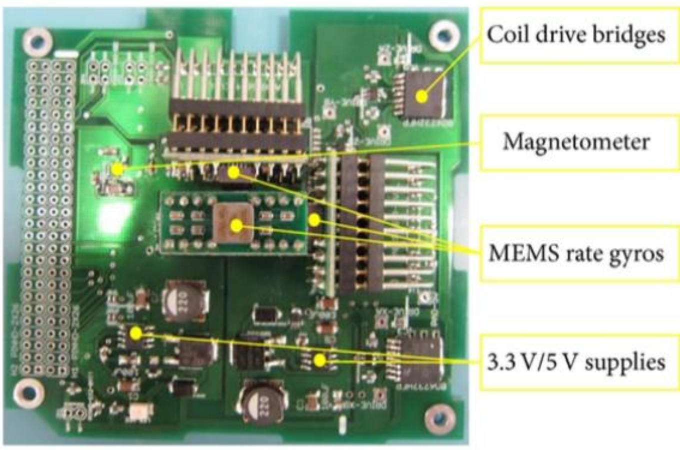


Figure 29 : example of ADCS board

b) Hardware constraint

Space is a harsh environment, that is why the hardware has to be designed to withstand many constraints:

- It has to resist the temperature differences. In space, the temperature can fluctuate between -40 and 60 degree on the side panels and the temperature is around 10 to 40 degree inside of the satellite[1].
- The vacuum in space causes some materials destruction (especially plastic). If air bubbles are trapped in a component, it can create some cracks and in the worst case explode or damage components.
- The components are also exposed to radiations which can decrease the performance. And they are also exposed to ultraviolet radiations which can create some hardware failures.
- The hardware has to withstand high accelerations.
- Stay well oriented in order to let the tether deorbit our CubeSat.
- It also has to stay well oriented for the solar panels.

[1] Data recorded in January 9th 2010 on the Ørsted satellite. Source: ADCS for AAUSAT3.

c) Software approach

The software will handle the same functions that we enumerated for the hardware because both are very close. So obviously, the software will be designed to realize the same functions:

- Get the sensors' data
- Process, sample and correct the data (Kalman Filter)
- Determine the target attitude with ADCS CTRL Algorithm
- Calculate the rotations to reach the target attitude
- Control the actuators to modify the attitude accordingly

The CubeSat will be able to adapt in each situation thanks to an algorithm processing different states.

State	Sensor sampling	Attitude estimation	Control
OFF	NO	NO	NO
SLEEP	NO	NO	NO
STANBY	YES	YES	NO
Tether ON	YES	YES	ADVANCED
DETUMBLE	YES	NO	ADVANCED
Pointing	YES	YES	YES

5. Simulations

We need to run simulations to validate our choice of components. In order to do this the software will have some constraints:

- Simulate the concerned part in the space environment (force models, vacuum, radiation, temperature…).
- Model parts of our system in blocks.
- Parameters (such as elevation, weight …) need to be modifiable.

This is what we think could be useful for our project:

Actuators sizing:

The goal for the simulation software will be to validate actuator's specificity and reaction time. The aim is to choose the best actuator for CubeSat.

This software needs some characteristics, at least:

- A HCI (Human Control Interface)
- A database to save tests.

On the HCI we will be able to choose some variables:

- CubeSat's information (elevation, mass, center of mass)
- Coil's information (number of coils, number of layers, maximum electrical Power, coil's area)

The software needs to run tests in different conditions:

- Earth's magnetic field
- CubeSat's rotation
- CubeSat's orientation
- Coil's alimentation time

To simulate our moving body in space condition, we consider using STK (Systems Tool Kit), which provides in the free version those features:

Accurate Earth representation	WGS84, MSL and Earth motion (pole wander, nutation, sidereal time)
Dynamic vehicle position	Great arc, ballistic, two-body, J2, J4 SGP4, SPICE and STKExternal (data file)
Dynamic vehicle orientation	Coordinated turn, nadir and velocity oriented, pre-computed (data file)
Sensor field of view (FOV) and pointing	Simple conic and rectangular FOV, fixed and external pointing (data file)
Pre-defined vector geometry	Points, vectors, angles, axes and coordinate systems
Standard object database	Thousands of satellites, facilities, aircraft and sensors
Import, analyze and export GIS data	Import and export KML and shapefiles

As we can see this software is pretty complete and allows to run tests such as defining the trajectory of the satellite projected on earth, see the evolution of our satellite in space and mode sensors.

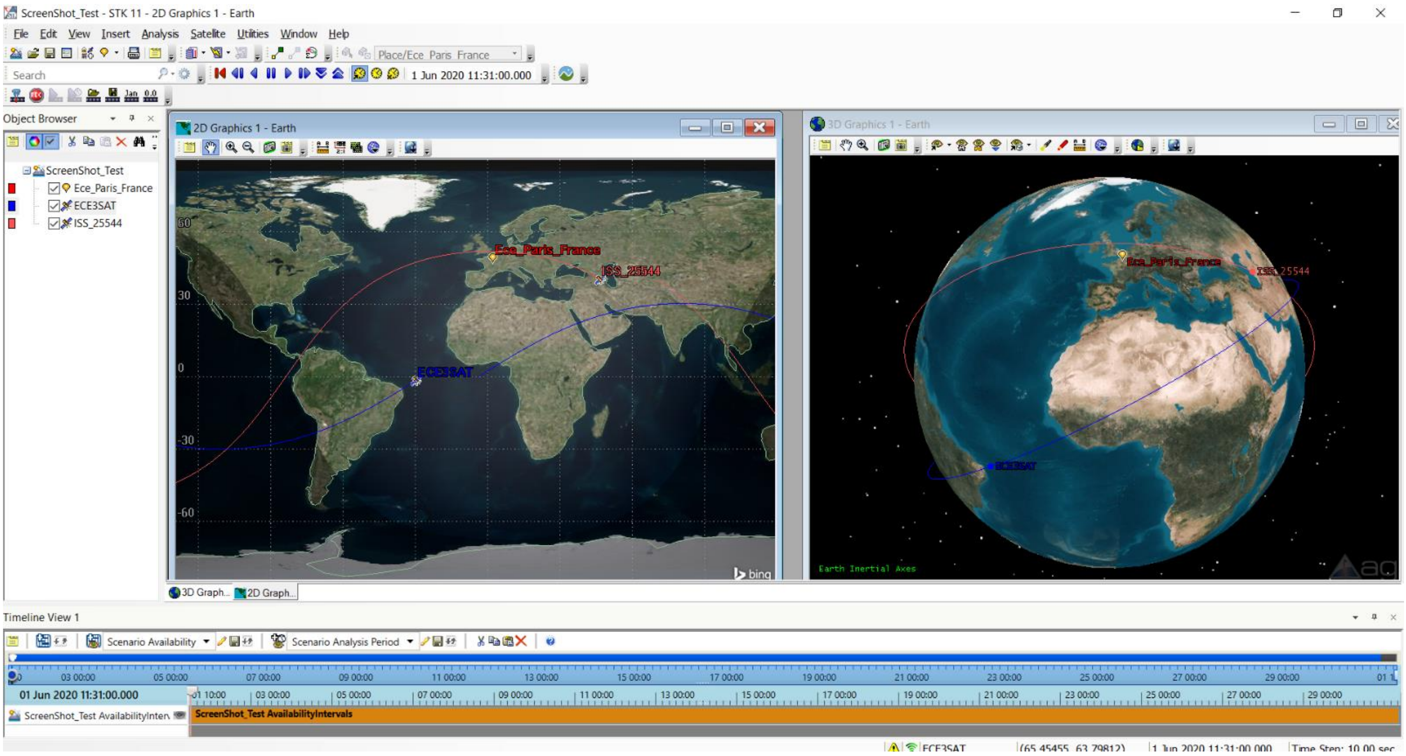


Figure 30 : view in STK software

To fulfil the simulation's needs, we will also use other software such as Matlab/Scilab.

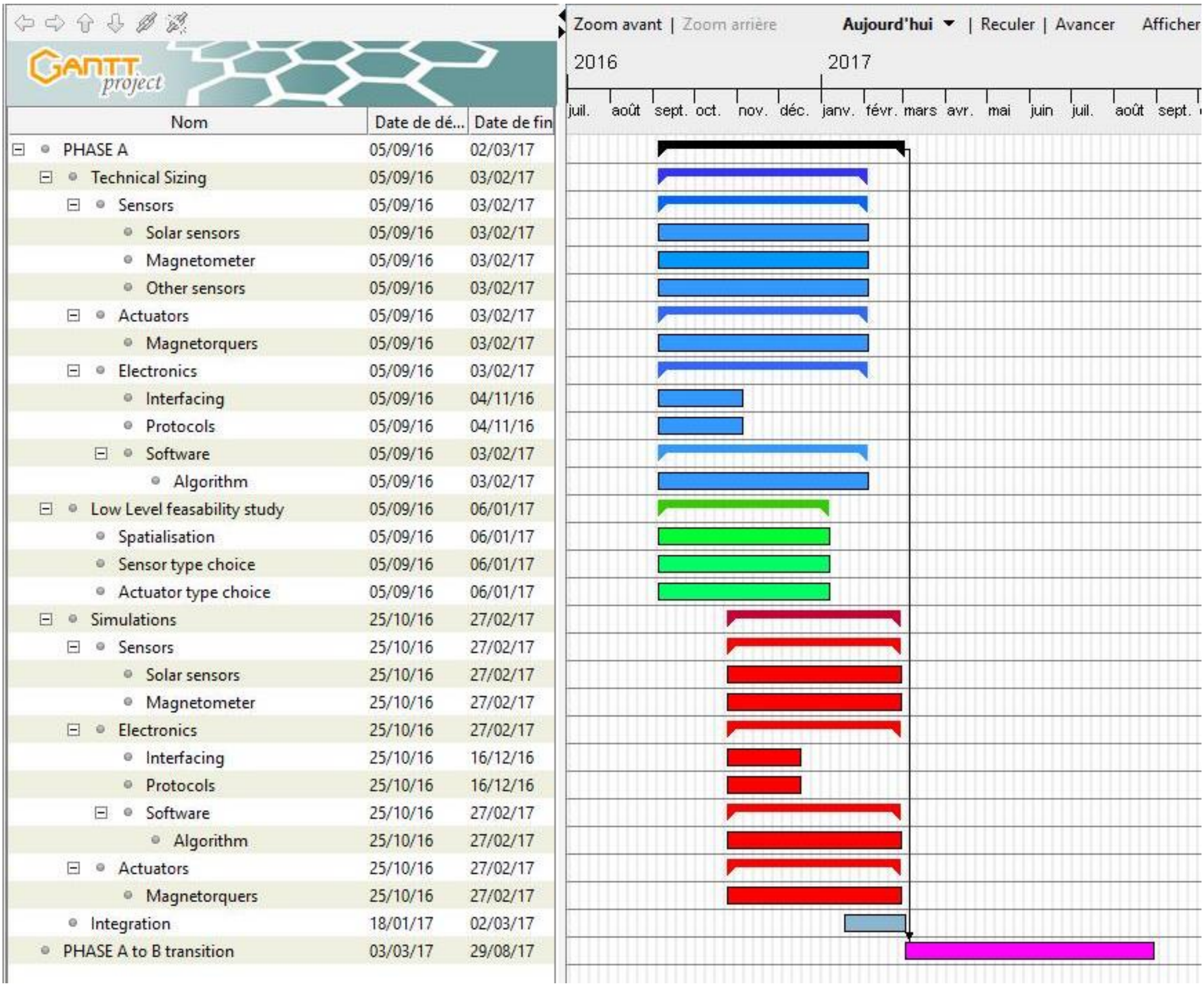
Those software will be useful to draw block diagrams, leading to exploitable data. Moreover, some code or complementary modules can be implemented for precise simulations.

For example, the Control Toolbox module provides interesting tools for CubeSat missions such as:

Spacecraft Control Toolbox Product Comparison

Topic	Feature	CubeSat	SCT Academic	SCTPro
License		**University team**	**Students, Classroom**	**Single User or Site License**
Attitude Dynamics and Control	*Rigid body, gyrostat*	✔	✔	✔
	Multibody, flex, wire		✔	✔
	Control	PID 3 axis	+ loop shaping, discrete time, state space, LQ, eigenstructure assignment	
	Pointing budgets		✔	✔
	Sun nadir, bias momentum, spinner with wheels			✔
	Landing and ascent GN&C			✔
Actuator/Sensor Models	*Reaction wheel, blowdown propulsion*		✔	✔
	Gyros, sun sensor, horizon sensor, magnetometer		✔	✔
	Star camera model, high fidelity RWA, GPS models			✔

VII. Planning



Nom	Date de dé...	Date de fin
PHASE A	05/09/16	02/03/17
Technical Sizing	05/09/16	03/02/17
Sensors	05/09/16	03/02/17
Solar sensors	05/09/16	03/02/17
Magnetometer	05/09/16	03/02/17
Other sensors	05/09/16	03/02/17
Actuators	05/09/16	03/02/17
Magnetorquers	05/09/16	03/02/17
Electronics	05/09/16	03/02/17
Interfacing	05/09/16	04/11/16
Protocols	05/09/16	04/11/16
Software	05/09/16	03/02/17
Algorithm	05/09/16	03/02/17
Low Level feasability study	05/09/16	06/01/17
Spatialisation	05/09/16	06/01/17
Sensor type choice	05/09/16	06/01/17
Actuator type choice	05/09/16	06/01/17
Simulations	25/10/16	27/02/17
Sensors	25/10/16	27/02/17
Solar sensors	25/10/16	27/02/17
Magnetometer	25/10/16	27/02/17
Electronics	25/10/16	27/02/17
Interfacing	25/10/16	16/12/16
Protocols	25/10/16	16/12/16
Software	25/10/16	27/02/17
Algorithm	25/10/16	27/02/17
Actuators	25/10/16	27/02/17
Magnetorquers	25/10/16	27/02/17
Integration	18/01/17	02/03/17
PHASE A to B transition	03/03/17	29/08/17

Figure 31 : Gantt planning

VIII. Technical sizing

BOARDS all integrated

Seller	Name	Price	Features	Interface	Properties				Performance		
					Mass (grams)	Temperature range (°C)	Dimensions (mm)	Supply Voltage (V)	Actuation (Am²)	Power Consumption (W)	Slew Rate
ISIS	ISIS Magnetorquer Board	8 000 €	- 3 axis magnetometer - 3 actuators - 1 gyroscope	I2C	~196	-40 to +70	95.9 x 90.1 x 17	5	0.2	- No actuation : 0.175 - Full actuation : < 1.2	
NewSpace Systems	NSS CubeSat ACS board	16 000 $	- 1 magnetometer 3-axis - MEMS gyros - 2 magnetorquers	I2C UART	<200	-25 to +50	96 x 96 x 15	3.3 / 5	0.2	2	
NewSpace Systems	NSS CubeSat ACS board	25 000 $	- 1 magnetometer 3-axis - MEMS gyros - 1 stellar gyro - 2 magnetorquers	I2C UART	<200	-25 to +50	96 x 96 x 15	3.3 / 5	0.2	2	
NewSpace Systems	NSS CubeSat ACS board	35 000 $	- 1 magnetometer 3-axis - MEMS gyros - 1 stellar gyro - 2 magnetorquers - GPS	I2C UART	<200	-25 to +50	96 x 96 x 15	3.3 / 5	0.2	2	
Maryland Aerospace	MAI-200 ADACS	?	- 3 mini reaction wheels - 3 torque coils - ADACS Computer -optionnal sun sensor			-40 to +80	100 x 100 x 79	12			
Blue Canyon Tech	XACT Lite	?	- sun sensors - magnetometers - IMU instead of star system	RS422	700		10 x 10 x 5	12			>10°/s for 3U, 8kg
Berlin Space Technologies (BST)	IADCS	?	-3 reaction wheels -3 magnetorquer -Star Tracker -MEMS gyro 3-axis -magnetometer -accelerometer	I2C RS485	250	-20 to +40	95 x 90 x 32			-0.5 (nom) -1.8 (peak)	30 arcsec 200 arsec

SENSORS

				Properties							Performance					
Seller	**Name**	**Price**	**Interface**	**Mass (grams)**	**Temperature range (°C)**	**Dimensions (mm)**	**Supply Voltage (V)**	**Radiation (krad)**	**Vibration (g or g rms)**	**Shock (g)**	**Power Consumption (mA)**	**Accuracy (°)**	**Precision (°)**	**Field of View (°)**	**Update Rate (Hz)**	**Output Voltage (mV)**
Sun sensor																
SolarMEMS	nanoSSOC-A60	2 200 €	Analog	4	-30 to +85	27.4 x 14 x 5.9	3.3 / 5	30	14.1	3 000	< 2	< 0.5	< 0.1	60		
SolarMEMS	nanoSSOC-D60	3 600 €	Digital	6.5	-30 to +85	43 x 14 x 5.9	3.3 / 5	30	14.1	3 000	< 23	< 0.5	< 0.1	60		
NewSpace Systems	Fine Sun Sensor	12 000 $	Digital	35	-25 to +75	34 x 32 x 20	28	14	14	1 000	7.5 average / 26 peak	< 0.1		140	5	
NewSpace Systems	CubeSat Sun Sensor	3 300 $	Analog	<5	-25 to +50	33 x 11 x 6	5		20		< 10	< 0.5		114	> 10	
Maryland Aerospace	MAI Sun Sensor	5 940 $ (for 6 sensors)	Analog			2 x 0.75 x 0.08										0 to 250
Crystal Space	Crystalspace S1U Sun sensor			<5	-25 to +85	26 x 26 x 6		hardened by design	tested	tested	< 20mW active mode < 9mW sleep mode		0.5	45		
Nano Avionics	Digital Sun Sensor		SPI / UART	15	-20 to +60	60 x 27 x 12	5				10	0.5		30		
				Properties							Performance					
Seller	**Name**	**Price**	**Interface**	**Mass (grams)**	**Temperature range (°C)**	**Dimensions (mm)**	**Supply Voltage (V)**	**Radiation (krad)**	**Vibration (g or g rms)**	**Shock (g)**	**Power Consumption (mA)**	**Accuracy**	**Sun Keep Out (°)**	**Field of View**	**Update Rate (Hz)**	**Max track rate (°/sec)**
Star Tracker																
TY-Space	Nano Star Tracker NST-1	80 000 €	RS422	245	-30 to +60	50 x 50 x 113	5	30	13		< 1 W	<7"		15° x 12°	10	>2
Blue Canyon Tech	Thin Slice NST			200		100 x 100 x 30					< 1.5 W peak		90	10° x 12°		
Blue Canyon Tech	Standard NST			350		100 x 55 x 50					< 1.5 W peak		45	10° x 12°		
Blue Canyon Tech	Extended NST			1 300		250 x 100 x 100					< 1.5 W peak		17,5	10° x 12°		
Blue Canyon Tech	RH NST			2 000		300 x 100 x 100					2.5 W peak		10	10° x 12°		
MaryLand Aerospace	MAI-SS Space Sextant		UART TTL / I2C	193.4	-40 to 85	42.3 x 47.1 x 49.5	3.3				1.5W (average) 0.7A (peak)	0.013°			4	>1
NewSpace System	Star mapper		CAN / RS422	<800	-20 to +55	136 x 136 x 280	28		15		<2W				>1	0.5

SENSORS

Seller	Name	Price	Interface	Properties							Performance						
				Mass (grams)	Temperature range (°C)	Dimensions (mm)	Supply Voltage (V)	Radiation (krad)	Vibration (g or g rms)	Shock (g)	Power Consumption (mA)	Measurement Range	Resolution	Update Rate (Hz)	Sensivity (V/gauss)	Band Width (kHz)	Output Voltage
Magnetometer																	
NewSpace Systems	Magnetometer		RS485	85	-25 to +70	96 x 43 x 17	5	10	14		725mW	-60 000 nT to +60 000 nT	7.324 nT	10			
HoneyWell	HMC2003_3-axis magnetic sensor hybrid		RS 232		-40 to +85	20 x 12 x 27	6 to 15		2.2	100	20	-2 to +2 gauss	40 µgauss		1	1	0.5 to 4.5
HoneyWell	HMR2300R_3-axis strapdown magnetometer		RS 422 / RS 485	40 (board only)	-40 to +85		6.5 to 15				45-55	-2 to +2 gauss	67 µgauss				
HoneyWell	HMR2300_smart digital magnetometer		RS-232 / RS-485	98	-40 to +85		6.5 to 15				27-35	-2 to +2 gauss	67 µgauss				
Surrey (SSTL)	Magnetometer		D-type DC	190	-20 to +50	36 x 90 x 130	12	5	15		300mW	-60 to +60 µT			10nT	10 Hz	
MEDA, Inc	TAM-2 Series			500	-39 to 76	44.5 x 143 x 76.2	21 to 38.6	>100			20-25	-1000 to +1000 mgauss			10 mV/mgauss (unbiased) 2.5 mV/mgauss (biased)		
SpaceQuest, Ltd	MAG-3 Satellite Magnetometer		9 Pin Male "D" Type	100	-55 to +85	35.1 x 32.3 x 82.6	15 to 34 VDC or 5V regulated	>10			30				100 µV/nT		

Seller	Name	Price	Interface	Properties							Performance		
				Mass (grams)	Temperature range (°C)	Dimensions (mm)	Supply Voltage (V)	Radiation (krad)	Vibration (g or g rms)	Shock (g)	Power Consumption (mA)	Rotation (dps)	Accuracy
Gyroscope													
HoneyWell	GG1320AN Digital Laser Gyro		RS-422	454	-54 to 85	45 x 88	5 15			100	1.6W 0.375		
ST	MEMS motion sensor A3G4250D		I2C / SPI		-40 to +85	4 x 4 1.1	2.4 to 3.6					245	

Seller	Name	Price	Interface	Properties							Performance		
Earth sensor													
Maryland Aerospace	MAI-SES		I2C / SCI	33		4.33 x 3.2 x 3.2	3.3		>12		40	>7°	>1°

IX. Existing CubeSat

Name	COSPAR ID SATCAT N°	Type	Organisation	Mission	Mission status	Launch Date (UTC)	Launch Vehicle	Remarks	Actuators	Sensors	REF	OBC microcontroller
AAU CubeSat	2003-031G 27846	1U	Aalborg University	Imaging	Failed	30 Jun 2003	Rokot/Briz-KM	Battery problems, deactivated on 2003 Sep 22	-magnetorquers	-Sun sensors -magnetometer		C161 (Siemens) 4MB RAM 512KB PROM 256 KB Flash ROM Operating at 10MHz
AAUSAT-II	2008-021F 32788	1U	University of Aalborg, Denmark	ADCS system and a gamma ray detector	Active	28 Apr 2008	PSLV-CA		-3x coils (magnetorquers) -3x Reaction weel	-1x 3 axis magnetometer -Photodiodes -6x 1-axis gyroscope		AT91SAM7A1 (Atmel) 32-bit microcontroller 4KB of RAM External Bus Interface Operates up to 40MHz
AAUSAT3	2013-009B 39087	1U	University of Aalborg, Denmark	Double AIS system for tracking ships in Arctic regions.	Active	25 Feb 2013	PSLV-CA C20	Denmark's CubeSat number 4	-3x coils (magnetorquers) -1 magnet	-1x 3 axis magnetometer -24x SunSensor(photodiodes) -1x 2axis gyroscope 1x 1axis gyroscope		
AeroCube 1		1U	Aerospace Corporation		Destroyed	26 Jul 2006	Dnepr	Launch failure	-6x whiout iron core magnetorques -3 whit iron core magnetorques	-1x sun sensor -1x temp sensor -1x gyroscope -1x magnetometer		-ADF 7021-N -AT90CAN128
AeroCube 3	2009-028E 35005	1U	Aerospace Corporation			19 May 2009	Minotaur I		-permanent magnets -hysteresis rods	-Two axis sun sensor -2 axis Earth sensor		
Antelsat	2014-033AA 40034	2U	FING-IIE (Facultad de Ingeniería de la Universidad de la República, Instituto de Ingeniería Eléctrica), Antel (Administración Nacional de Telecomunicaciones)	Open source satellite to encourage students, engineers and technicians, to learn and develop space technology. UHF telemetry, VHF telecommand, S-Band download data from color & infrared cameras	Active	19 Jun 2014	Dnepr	First entirely Uruguaian artificial satellite.	-3 axis magnetorquers	-3 axis magnetometer		
ArduSat1	1998-067DA 39412	1U	Nanosatisfi LLC	Allow general public to use the satellite sensors for their own creative purposes.		3 Aug 2013	H-IIB 304 to ISS	Deployed from ISS 2013 Nov 19.		-3 axis magnetometer -3 axis gyroscope -3 axis accelerometer		

Name	COSPAR ID SATCAT N°	Type	Organisation	Mission	Mission status	Launch Date (UTC)	Launch Vehicle	Remarks	Actuators	Sensors	REF	OBC microcontroller
BeeSat-1	2009-051C 35933	1U	Berlin Institute of Technology	Reaction wheel technology qualification	Active	23 Sep 2009	PSLV-CA		-3 microwheels -6 coils	-6x photocells -2x 3 axis magnetometers -3x gyroscopes	HMC1053	
BeeSat-2	2013-015G 39136	1U	Berlin Institute of Technology	Reaction wheel technology qualification	Active	19 Apr 2013	Soyuz		-reaction wheels -magnetic coils	-Sun sensors -Earth magnetic field sensors -gyros	HMC1023 SLCD-61N8 ADXRS401	
BeeSat-3	2013-015E 39134	1U	Berlin Institute of Technology	Reaction wheel technology qualification	Active	19 Apr 2013	Soyuz		-permanent magnet	-6x sun sensors -3x MEMS gyros	HMC6343 SLCD-61N8 IDG1215 ISZ1215	
BRICSat-P		1.5U	U.S. Naval Academy	Transponder experiment, electric propulsion technology	Active	20 May 2015	Atlas V		-4 thrusters (electric propulsion) -permanent magnet	-gyroscope -magnetometer		
CanX-1	2003-031H 27847	1U	UTIAS	Technology demonstration	Failed	30 Jun 2003	Rokot/Briz-KM	No signal from spacecraft	-3x Magnetorqueurs	-Sun sensor -1x Magnetometer		AT91SAM (ARM7 fromATmel) 32bit microcontroller 512kB SRAM 32MB flash-RAM Operating at 40MHz
CanX-2	2008-021H 32790	3U	University of Toronto, Canada	Technology demonstrator for formation flying	Active	28 Apr 2008	PSLV-CA		-3 magnetorquer coils -1 reaction wheel	-sun sensors -3 axis magnetometer -Horizon tracker Star Tracker		2 x ARM7 (Atmel) 32-bit microcontrollers 2MB of SRAM 16MB of Flash Operates up to 15MHz
CHASQUI - I		1U	UNI	Technology demonstration	Unknown	9 Jan 2014	Cygnus CRS Orb-1 to ISS	Peruvian. Deployed from ISS 17 Aug 2014	-6 electromagnetic coils -1 permanent magnet	-1 GPS -12 sun sensor -3 gyroscopes -3-axis magnetometer		

Name	COSPAR ID SATCAT N°	Type	Organisation	Mission	Mission status	Launch Date (UTC)	Launch Vehicle	Remarks	Actuators	Sensors	REF	OBC microcontroller
COMPASS-1	2008-021E 32787	1U	FH Aachen	Demonstration of commercial off-the-shelf components and taking photos	Active	28 Apr 2008	PSLV-CA		-magnetorqer	-magnetometers -sun sensors -gps	HMC6352 digital compass by Honeywell	C8051F123 (Silicon Laboratory) 8448 Bytes of RAM 128KB of Flash Operates up to 100MHz
CP-1		1U	California Polytechnic University		Destroyed	26 Jul 2006	Dnepr	Launch failure	-1x Magnetorquer	-Sun Sensor		PIC18LF6720(Microchip) 8-bit microcontroller 128KB Flash (1kB boot ROM) 4KB RAM Operates at 4MHz
CP-2		1U	California Polytechnic University		Destroyed	26 Jul 2006	Dnepr	Launch failure				PIC18LF6720 (Microchip) 16-bit microcontroller 1kB ROM 4kB RAM 128kB Flash Operating at 4MHz
CP-3	2007-012N 31129	1U	California Polytechnic University		Active	17 Apr 2007	Dnepr		-Magnetorquers	-3x 2axis magnetometer		
CP-4	2007-012Q 31132	1U	California Polytechnic University		Active	17 Apr 2007	Dnepr		-Magnetorquers	-Sun sensor -Magnetometer		PIC18LF6720 (Microchip) 16-bit microcontroller 1kB ROM 4kB RAM 128kB Flash Operating at 4MHz
CSTB1	2007-012F 31122	1U	Boeing		Active	17 Apr 2007	Dnepr		-Magnetorquers	-4x sun sensor -5x 2axis magnetometer		
CUTE-I (Oscar 55)	2003-031E 27844	1U	Tokyo Institute of Technology	Amateur radio	Active	30 Jun 2003	Rokot/Briz-KM		-Piezoelectric vibrating gyroscope (4pcs) -magnetorqer	-CMOS horizon sensor and star-tracker -GPS receiver -magnetometer		
Delfi-C3	2008-021G 32789	3U	Delft University of Technology, The Netherlands	On-orbit testing of thin film solar cells (TFSC) and autonomous wireless sun sensor (AWSS), Demonstrating the world's first linear amateur radio transponder on a CubeSat	Active	28 Apr 2008	PSLV-CA		-2 magnetorquer coils -3 reaction wheels	-6 sun sensors -3-axis magnetometers		

Name	COSPAR ID SATCAT N°	Type	Organisation	Mission	Mission status	Launch Date (UTC)	Launch Vehicle	Remarks	Actuators	Sensors	REF	OBC microcontroller
Delfi-n3Xt	2013-066N 39428	3U	Delft University of Technology, The Netherlands	Technology demonstrations of a micro-propulsion system developed by TNO in cooperation with TU Delft and University of Twente called T3μPS and an in-orbit configurable, high-efficient transceiver platform developed by ISIS BV, in cooperation with TU Delft and SystematIC BV called ITRX.	Active	21 nov. 2013	Dnepr	http://www.delfispace.nl	-Reaction weel -Magnetorquers	-Sun sensors -Magnetometer -Gyroscope		
DICE-1	2011-061B 37851	1.5U	Space Dynamics Laboratory	Ionospheric research	Active	28 oct. 2011	Delta II via ELaNa-3		-3X magnetorquer	-1x 3axis magnetometer -gps -sun sensor -horizon sensor	-HMC1043	
DTUsat	2003-031C 27842	1U	DTU	Tether research	Failed	30 Jun 2003	Rokot/Briz-KM	No signal from spacecraft	-magnetorquers	-1x 3-axis magnetometer -5x dual-axis sun angle sensors		AT91M40800 (ARM7 from Atmel) 32 bit microcontroller 1MB RAM 16 KB ROM 2MB flash RAM Operating at 16MHz
e-st@r	2012-006C 38079	1U	Politecnico di Torino	Development and test of an active ADCS Test of COTS	Tumbling	13 Feb 2012	Vega		-magnetorquers	-Magnetometer -NEMS Sun sensors -IMU (Inertial Measurement Unit)		Pumpkin Kit based on MSP430F149 (T. I) 16-bit microcontroller 60KB+256B of Flash 2KB of RAM Operates up to 10MHz
ESTCube-1	2013-021C 39161	1U	University of Tartu	Space test of the electric solar wind sail	Active	7 May 2013	Vega	First Estonian satellite	-3x coils (magnetorquers)	-6x 2axis SunSensor -magnetometer -gyroscope		
ExoCube		3U	Cal Poly PolySat	Space weather		31 Jan 2015	Delta II via ELaNa-X		-magnetorquers	-magnetometers -solar array sensors -gyroscope		
FITSAT-1 (NIWAKA)	2012-038C 38853	1U	Fukuoka Institute of Technology	The main mission objective is to demonstrate the developed high-speed transmitter.	Active	4 oct. 2012	H-IIB to ISS	Deployed from ISS 2012 Oct 4.	-permanent neodymium magnet (axe Z)			