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Phase B/C

ADCS System Engineering

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1 INTRODUCTION

The main purpose of this report is to present the development of the Attitude Control and Determination System (ADCS) of the SwissCube satellite after the Delta-Preliminary Design Review (Δ-PDR), which took place on 3 September 2007.

The whole ADCS system had to be completely revisited after this review, because it did not satisfy the requirements and because there were too many uncertainties on this system.

Therefore, a big workforce has been attributed to the ADCS this semester in order to try to catch up with the delay: Patrick Thevoz worked on the Sun sensors [R4], Laurent Hauser on the Magnetotorquers [R7], Rakesh Prajapati on the Gyroscopes [R3], Jean-Pierre Perin on the Magnetometers [R6], Martin Ehrensperger on the control and determination algorithms [R9], Jonathan Lugon on the perturbation models and STK interface and Ahmed Slama on the need for gyroscopes and computations methods simplification.

As ADCS System Engineer, I coordinated the work of these different students. This was really my major task during this semester and it is important to note that it will not be detailed in this report.

Based on the CubeSat program started by the Stanford University and the California Polytechnic State University (CalPoly) the SwissCube is the first entirely Swiss picosatellite program. The primary objective of developing this satellite is to provide a dynamic and realistic learning environment for undergraduates, graduates and to improve the development of small satellite technologies. The secondary objective is to house a science payload in order to take optical measurements and characterize the Nightglow phenomenon (see Figure 1-1) over all latitudes and longitudes for at least a period of 3 months, with extended science mission duration up to 1 year.

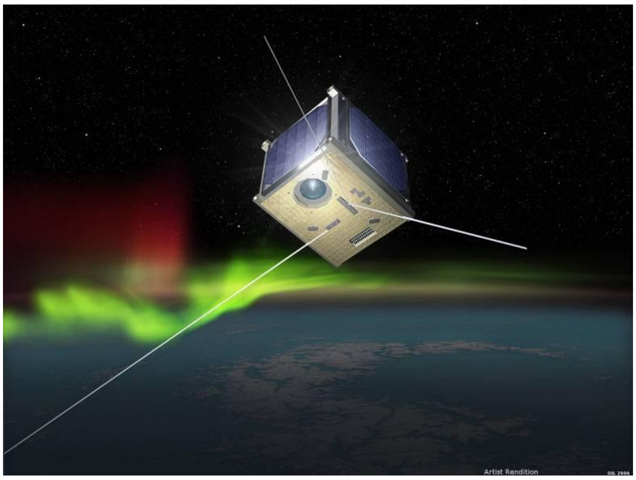

Figure 1-1 : Artist View of the SwissCube

The ADCS must determine the position, velocity and orientation and also control the satellite. The determination is the most important point, because we must know where the payload is pointing to characterise the nightglow phenomenon. The major concern of the control is to reduce the spinning rate of the satellite after the launch and, if it is technically possible, to orient the payload in a precise direction in order to take photographs. As explained later, this last point has been deleted.

The ADCS algorithms run on the CDMS microcontroller (which is the main computer of the SwissCube). The ADCS board itself is in charge of the sensors readings and actuators control.

2 DESIGN ASSUMPTIONS AND APPROACH

2.1 Delta-Preliminary Design Review conclusions

The following issues appear during the review:

- The SwissCube ADCS is too complex and it is why we were not able to control the satellite at this moment; simpler control algorithms such as "B-dot" could be used. They are also more robust. The computation requirements are also a limitation to the use of complex algorithms.
- The control goals are too ambitious; we do not necessary need a 3-axis control at all time.
- The magnetometer (AK8970N) seems to have a too poor accuracy and resolution. Moreover it has never flown in space (it is the main sensor for a B-dot controller).
- Are gyroscopes really needed? The current gyroscopes (IDG-300) are useless because of their resolution.
- Are the sun sensors really needed? If the sun sensors (DTU Sun Sensors) are too complex to use, simple photodiodes could be used.

It is important to mention here that the hardware was not selected (in phase B) only on the performances, but on availability, compatibility with the system (voltage) and physical characteristics such as size and mass criteria.

2.2 Approach

To begin the review of the ADCS, some other CubeSat team working on ADCS have been contacted; especially the AAUSAT-II team has been contacted (it is their 2nd satellite and it is ready to launch) in order to be sure that our ADCS was coherent and that our requirements were more or less correct.

Then a research of new sensors (MM, Gyro, SS) was started. The ADCS requirements were also checked and refined.

In order to be able to test all new sensors easily, it has been decided to build one test board for each ADCS part (MM, Gyro, SS, MT). The complete new ADCS board would be built only at the end of the semester when all these parts should be tested and qualified.

2.3 Hardware assumptions

- The ADCS microcontroller will not support determination and control algorithms. It will be used to collect, format and store the sensors values onboard until the main controller (CDMS) will use them. It will also be used to control the actuators once the main computer has calculated the command values (current).
- All data are sent to the ADCS using the main I^2C bus. These data mainly come from the CDMS and the EPS.
- The ADCS board has only one supply voltage of 3.3V thanks to the EPS design. Thus its components must comply with that.

- The ADCS is not a critical system, therefore no redundancy is needed. But to ensure reliable operation, current limitations must be implemented for each electrical wire going to a sensor or an actuator. This prevents the shutdown of the whole ADCS board if short circuits occur (thanks to EPS overload protection).
- The MT will be glued inside the faces of the satellite. They will be then subject to high temperature variation. According to values calculated in [R11] plus a margin of 10°C, the MT should sustain a temperature between -45°C and +70°C.
- With a margin of 20°C, the temperature range for the ADCS board will be -30°C to +60°C (it is inside the satellite).

3 COMPARISON BETWEEN AAUSAT-II AND SWISSCUBE

	SwissCube				AAUSAT-II				comments
Requirements	Orbit altitude	400 to 1000km			Orbit altitude	500 to 700km			Our requirements seems to be correct
	Max angular vel. after launch	1-10°/s			Max angular vel. after launch	5.7°/s			
	Max angular vel. (payload)	1.25°/s			Detumbling time	3 orbits			
	Determination precision (3 axis)	<12°			Detumbling used up to	1°/s			
					Attitude precision (maintain)	5°			
					Min rotation speed to go in position (control)	2.6°/s			
CPU	AT91M55800A	@ 4 to 33MHz (adjustable)			AT91SAM7A1	@ 8 to 40MHz (adjustable)			AAUSAT: complete ADC algo. can't run onboard, but on the ground! We have a very similar CPU
Actuators	3x Magnetotorquer	Dipolar moment = 28.5 mAm2			3x Magnetotorquer	Dip. moment = 17.2 to 20.5 mAm2			Our MT provide a higher torque, but we have no Inertial wheel
					3x Inertial Wheel				
		Resolution	Sensitivity	Full Range		Resolution	Sensitivity	Full Range	
Sensors	3-axis Magnetometer AK8970N	0.6uT	0.6uT/bit, 8.3uV/uT	+-70uT	3-axis Magnetometer HMC1053	>= 12nT	10uV/V/uT --> 30uV/uT with 3V	+-600uT (no OA)	need a high amplification ~500
	2x 2-axis gyro IDG-300	0.305 °/s	2mV/°/s	+-500 °/s	6x 1-axis gyro ADXRS401 (5V)	0.068°/s (12-bit ADC without OA, but 5V)	15mV/°/s	+-75 °/s	They tried to amplify the output --> Advice: use a 16-24bit ADC instead
	IDG-1000	0.018°/s	33.3mV/°/s	+-30°/s					
	6x 2-axis DTU sun sensors	?	?	+-70°	6x Photodiod SLCD-61N1	?	Isc~=0.5mA	0.5*Imax@ 60°	DTU SS is the best solution, but have to obtain them
					They can update the ADC algorithms, so it seem they are not finished ; they will test different solutions				

According to that comparison, our requirements seem to be quite correct. But our sensors have clearly lower precision. So it also indicates that we might change them.

4 ADCS ARCHITECTURE

4.1 Architecture evolution and changes

The ADCS was too complex, so it has been decided to change the overall architecture.

Since the beginning of the SwissCube project, the ADCS system architecture has always been a major issue. In phase A, there was one inertial wheel aboard the SwissCube, but it has been suppressed in phase B because only one wheel did not seem to help to control the satellite (but in the contrary did increase the complexity of the algorithms). The satellite should have had 3 inertial wheels in order to have 3-axis controllability at any times, which were the control requirements at this design phase. The main problem here is that it is very hard to put 3 inertial wheels in a CubeSat due to size and mass constraints.

Some solutions were studied in phase B, such as the use of permanent magnets, but without success (see [R1]). Then it has been decided to reduce the constraints on the ADCS requirements: indeed it is not necessary to have a full control of the satellite in order to be able to take pictures with the payload if the determination is correct. In other words, **it is sufficient to determine the satellite in order to know when to take pictures and where points the payload**. **The control part of the ADCS will then only detumble the satellite after launch (reduce the overall rotation speed) and keep the rotation speed in a given range without real control** in order to avoid blurring effect on the pictures and to keep a minimum rotation speed to be able to point in a lot of different directions in a global time scale.

As a consequence of these new requirements, the ADCS is now separated in 2 parts which are no more really linked: the Determination and the Control parts. Figure 4-1 shows the new architecture of the ADCS. The only link between determination and control is the eventual supervision of the rotations speed in order to change the B-dot gain to keep the rotation speed in a given range. Basically, the B-dot controller can increase or decrease the satellite kinetic energy depending on the B-dot gain sign.

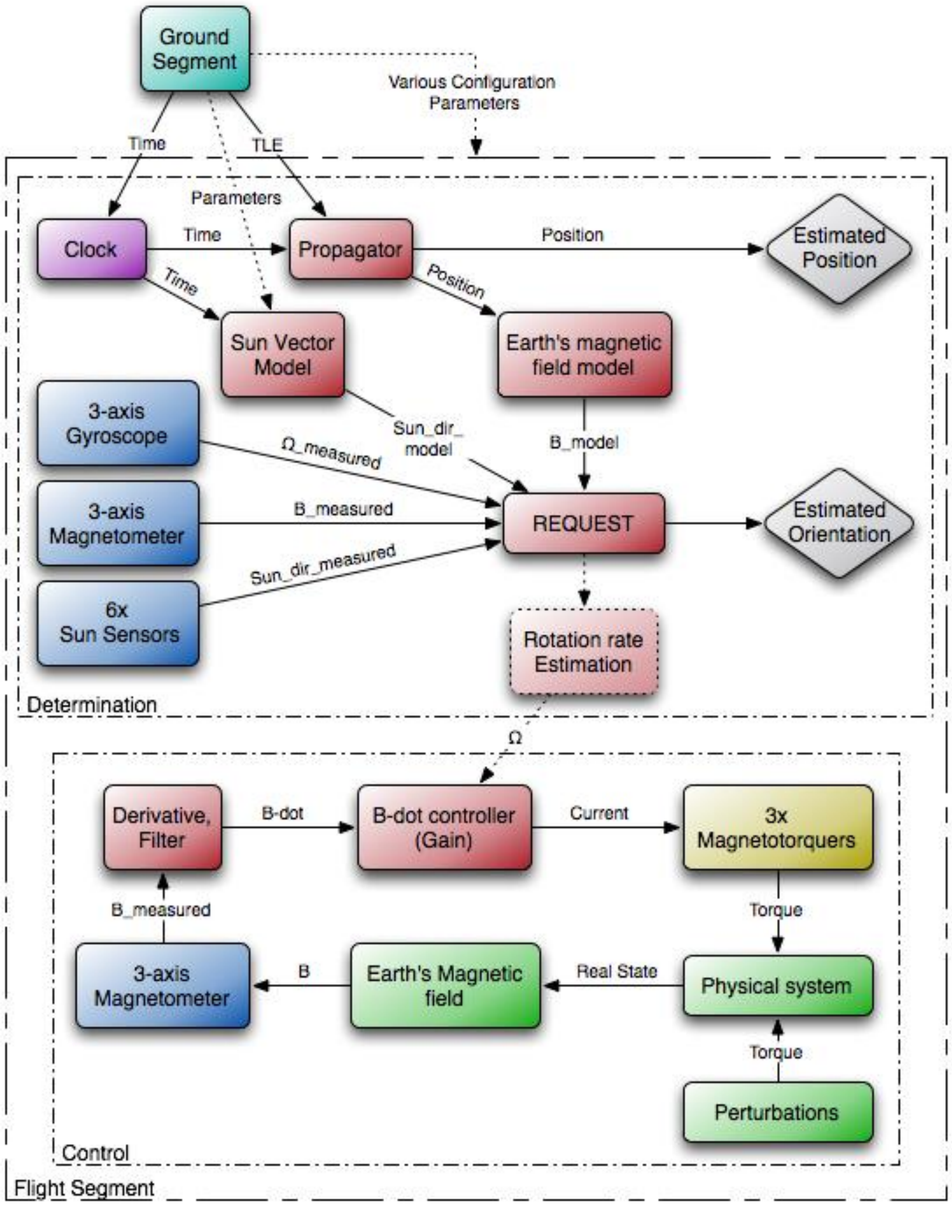

Figure 4-1 : ADCS Architecture diagram

4.2 Determination

The determination is the most complex part of the ADCS. It needs the following algorithms and models (software):

- **Propagator:** It computes the position of the satellite along the orbit with the TLEs send by the ground station.
- **Earth's Magnetic field Model:** It computes the magnetic field intensity and direction at a given point around the Earth (see [R2]) with look-up tables stored onboard.
- **Sun Vector Model:** It computes the direction of the sun according to the position along the orbit.

- **REQUEST:** It is the main algorithm. It is a recursive filter (see [R8] and [R9]). It takes all the measurements from sensors and all values from models to propagate them according to the satellite dynamic and estimates the orientation with a *high* precision.

The sensors needed for the determination are:

- A **3-axis magnetometer** (MM) to measure the Earth's magnetic field (EMF) intensity and direction and then compare it with the model. This model can locally have important errors due to special temporarily conditions (Ex: Sun storm).
- **6 Sun sensors** (SS) to find the direction of the Sun; they provide a 2nd set of measurements which increase the final determination accuracy and robustness. It could also help suppressing some initialization problems of the recursive filter. It is important to note that **these sensors are not available during the eclipse period** (about half of the orbit).
- A **3-axis gyroscope** (GYR) to measure the spinning rate for each axis; A precise knowledge of the rotation rate is very important for the REQUEST algorithms in order to propagate correctly the data (this algorithm does not integrate the speed to compute the position, so there is no "drift" over time). This rotation speed could be estimated with the SS and MM, but it should be more precise to also have gyroscopes.
- *Temperature sensors to compensate the temperature drift of the other sensors.*

4.3 Control

The control part is based on a **B-dot controller**. This kind of controller is very simple; basically it is a proportional controller which takes the derivative of the ambient magnetic field in input and the give commands to the magnetotorquers as outputs.

An important issue here is to compute the derivative of the measured magnetic field (derivation amplifies noises). Therefore is it imperative to have a very precise **3-axis magnetometer**. The only actuators the SwissCube has are **3 magnetotorquers** (MT) or coils; they produce a torque proportional to the electrical current thanks to their interaction with the Earth's magnetic field.

As explained previously, the gain of the B-dot controller could be adapted dynamically (controller with hysteresis).

5 REQUIREMENTS

The requirements according to the new objectives have been refined. Regarding the sensors, it is very hard to know precisely what accuracy is needed in order to achieve the determination requirements (payload) because all measurements from all sensors are “mixed” in the recursive filter (REQUEST), so there is not direct relationship.

According to Lars Alminde, **a good rule of thumb is that a sensor should have ideally accuracy 10 times to 30 times greater than the final accuracy we want to obtain** (in order to give useful data to the recursive filter).

As we will see later, unfortunately it is very hard to find sensors which satisfy these requirements and the power consumption and size requirements. So these values can be considered to be “ideal”; in practice it would be hard to obtain them, especially when taking into account the temperature drift of the sensors (unfortunately the SwissCube is “hardware-driven”).

The tables below show a summary for all ADCS parts. The detailed requirements of level 3 to 5 are currently not up-to-date for the ADCS. Some calculations of different values are shown in Appendix F.

ADCS Requirements Summary		
General	Value (Indicative, subject to change)	Units
Orbit and launcher		
Polar orbit, almost circular orbit		
Orbit altitude	400 to 1000	km
Difference between semi-major and semi-minor axis	??	km
Max angular velocity after launch	10	°/s
Payload		
Max angular vel. (payload) (overall norm for the 3 axis)	1.25	°/s
Determination precision (3 axis) (or pointing knowledge)	<12	°
Software and Algorithms		
Control		
Must detumble the satelitte, no 3-axis control needed		
Detumbling time to go from launch velocity to operational angular velocity	<10	orbits
Must maintain angular velocity (nominal) between	0.6 and 1.1	°/s
Must be able to run on the 32-bit CDMS microntroller (ARM7 AT91M55800A@33MHz, no FPU)		
Determination		
Must be able to run on the 32-bit CDMS microntroller (ARM7 AT91M55800A@33MHz, no FPU) --> must preferably use 32bit integers for all computations		
Determination precision (3 axis)	<12	°
Determination Rate (output)	≤2 (2 nominal)	Hz

Harware -ADCS board and Sensors	
ADCS board	
Main power supply	3.3±0.23 V
Power consumption (standby mode)	<30 mW
Power consumption (sensor mode)	<90 mW
Power consumption (nominal mode)	<250 mW
Peak current	<150 mA
Mass (whole ADCS)	<120 g
Mass (ADCS board)	<34 g
Magnetometer	
Main power supply	3.3±0.23 V
Power consumption (mean)	<10 mW
Temperature range	-30 to +60 °C
Measurement range	±65 µT
Resolution	<100 nT
Accuracy	<500 nT
Measurement Rate	≤2 (2 nominal) Hz
Magnetotorquer	
Main power supply	3.3±0.23 V
Power consumption (total)	<150 mW
Temperature range (Coil)	-45 to +70 °C
Temperature range (electronic)	-30 to +60 °C
Must be switched off when magnetometer is taking measurements	
Dipole magnetic moment	≥28.5 mAm^2
Current regulation accuracy	<10 %
Current regulation resolution	<0.4 mA
Current regulation command rate	≤2 Hz
Outgassing TML	<1 %
CVCM	<0.1 %
External dimensions	70x80x5 mm
Gyroscopes	
Main power supply	3.3±0.23 V
Power consumption (mean)	<90 mW
Temperature range	-30 to +60 °C
Measurement range	±15 °/s
Resolution	<0.01 °/s
Accuracy	<0.04 °/s
Measurement Rate	≤2 (2 nominal) Hz
Sun Sensors	
Main power supply	3.3±0.23 V
Temperature range	-45 to +70 °C
Field of View	>90 °
Resolution	<0.1 °
Accuracy	<1.2 °
Measurement Rate	≤2 (2 nominal) Hz

6 TECHNICAL DESCRIPTION

6.1 Magnetometer

For more details about the MM, see [R6]. See [R1] and [R5] for the test procedures.

6.1.1 Sensor Description and choice

The former MM was a 8-bit digital sensor (AK8970N). This lead to a quite bad resolution but the sensor was easy to integrate on the ADCS board. The thermal drift was also a major problem.

The **HMC1043** from Honeywell has been chosen for the new magnetometer for the following reasons:

- It is a 3-axis high sensitivity magnetoresistors (AMR) sensor (analog) with a very low intrinsic noise.
- The sensor offset and offset temperature dependence can be cancelled using special device feature (Set/Reset). Then the only important parameter is the sensor sensitivity (temperature dependent).
- It has the same characteristics as the HMC1053, but it is a new version designed for high sales volumes and thus it is cheaper.

The cons are that this sensor needs a quite complex additional hardware to work (see [R6] and Appendix A.1.3).

Because of the bridge offset voltage, a **16-bit ADC** (AD7798) must be used in order to obtain a sufficient resolution; with an amplifier gain of 200, we obtain a minimum (worst case, according to datasheet) **resolution of 27nT/LSB** with a 16-bit ADC (430nT with 12s-bit ADC which is clearly not enough). With a 100Hz bandwidth, the intrinsic noise of the sensor should be around 70nT (see Appendix F). Measurement must be done in order to find the maximum resolution of the sensor (limited by noise and linked to bandwidth).

Ymatron AG provided us 8 HMC1043, but it is possible to obtain more if needed without any problems (see Chapter 10).

6.1.2 Testing

Each chip has different characteristics because of the manufacturing processes. Therefore each sensor chip that will flight in the final satellite must be fully characterized (mainly sensitivity and temperature dependence). Because it is quite difficult to characterize the sensors using the final ADCS board, a test setup must be build (of course some simple tests must have to be done on the final satellite in order to check some eventual errors).

In order to be able to test many sensors without soldering them definitely, the first idea was to use a socket to connect electrically the sensor to a test PCB containing the electronics. Indeed the unsoldering process is quite bad for a chip (if it survives, we can suppose it could lead to a shift of some parameters values). Unfortunately, it has been difficult to find sockets for the HMC1043 (16-pin 3x3 LPCC). Moreover, the socket should not have magnetic or iron parts, because this would disturb the magnetic field around the sensor and then add errors in the measurements.

Then another solution was found. It is largely inspired from the one that has been used for the Sun Sensors; the HMC1043 are glued backward (temporarily) on an intermediate PCB with some connectors. Each sensor pad is then connected with small wires soldered by hand (similar to wire bonding, see Figure 6-1). Therefore the unsoldering process is quite easy and will not destroy the sensor. It is important to mention that this process is only valid because we have to test only a few sensors (<8).

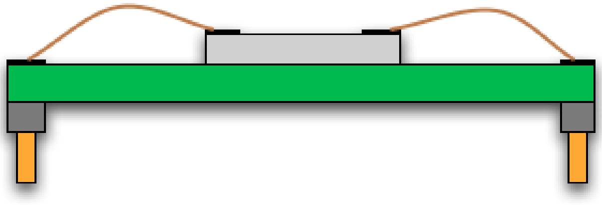

Figure 6-1 : Magnetometer test mounting schematic

The test PCB can have a microcontroller to communicate with the ADC using the SPI interface, or another way would be to use a **direct LabView SPI interface** (as used in [R5]). This could simplify the characterization because a lot of measures have to be taken.

6.2 Gyroscopes

For more details about the Gyro, see [R3].

6.2.1 Sensor Description and choice

The previous gyroscope (IDG-300) clearly did not satisfy the requirements and unfortunately we were unable to obtain the IDG-1000 from Invensense. Then another solution had to be found.

Most of the MEMS gyroscopes works with a 5V supply, therefore we chose to mount a **step-up converter** on the ADCS board in order to be able to use 5V gyroscopes (3.3V→5.4V; LTC3459). An LDO voltage regulator is also mounted in order to reduce the power supply noise and undulation due to the converter (5.4V→5.0V; LTC1761).

We chose to use a new sensor from Analog Device: the **ADXRS614**. This sensor not yet in full production, so **it has also be quite difficult to obtain some samples**. ARROW CE provided us 4 ADXRS614 (they had only 10 parts in stock at this moment)(see Chapter 10). About 8 parts remains to be bought, **so be sure it is possible to obtain them; call ARROW CE!**

It has a low power consumption and satisfies the sensitivity requirements; the main problem was to find a gyroscope capable of measuring very low rotation rate (0-10°/s). It has two analog outputs: one proportional to the temperature and the other to the rotation rate. Unfortunately it is a 1-axis sensor only, thus 3 sensors must be mounted perpendicularly.

An **external 16-bit ADC** (AD7795) is used in order to comply with the different voltages (3.3V for the microcontroller and 5.0V for the gyroscopes) and to obtain a very high resolution (0.0015°/s/LSB, see Appendix F) with a high sensitivity (the AAUSAT-II team also advised us to do that because of their own experience).

For information, 2 other gyroscopes from different manufacturer with almost the same characteristics were found: the MLX90609-N2 from Melexis and the XV-8000CB from Epson Toyocom.

6.2.2 Mounting

Two gyroscopes are mounted on two *small PCB* which will be fixed perpendicularly to the ADCS board using an aluminium angle; all these parts are screwed (see Figure 6-2). The way to connect the small PCB to the ADCS board has not been clearly defined for the moment: it is really a critical point and it can be subject to fatigue if it is too rigid (direct soldering). The actual solution is to use small wire soldered in a hole on the small PCB and soldered on the surface of the ADCS board. The small PCB is put through a slit in the ADCS board. The main drawback of the whole system is that it takes a lot of space.

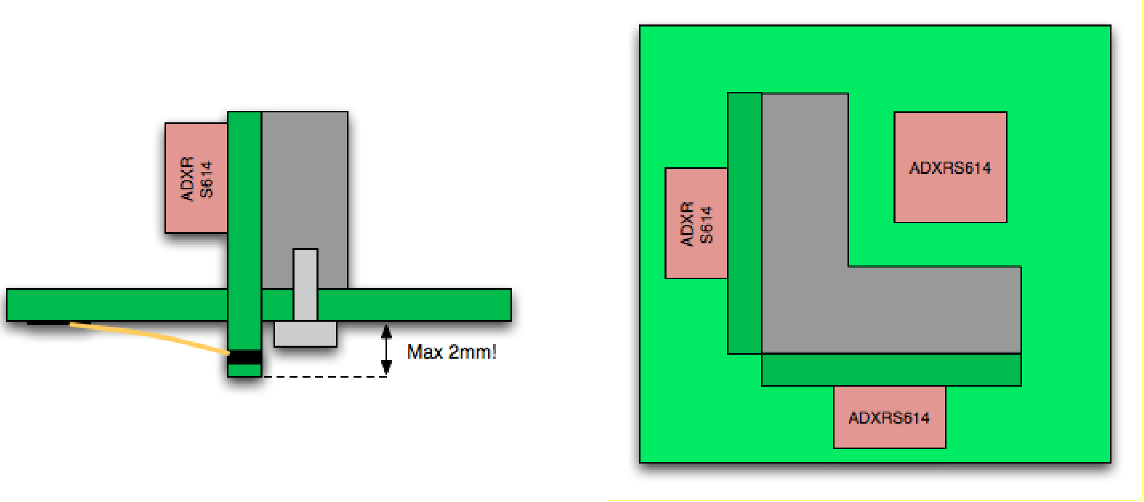

Figure 6-2 : Gyroscope mounting schematic

A first version of the small PCB has been designed. The following point must be corrected (see Appendix A.1.5):

- R1 and W1 can be suppressed.
- The Screws must not be connected to the ground plane (they are connected to the aluminium square which is connected to GND_MECA).
- A 5th pin must be added to the connector: DVcc_G.
- The connector footprint must be adapted to the final solution retained for the connection between the boards.

6.2.3 Testing

All gyroscopes chip should also be fully characterized for the same reasons than for the MM. The ADXRS614 has a 32-BGA package which can be soldered only once. Therefore, a test PCB with a socket and the whole gyroscopes electronics (step-up, ADC,…) should be built.

The test PCB can have a microcontroller to communicate with the ADC using the SPI interface, or another way would be to use a **direct LabView SPI interface** (as used in [R5]). This could simplify the characterization because a lot of measures have to be taken.

6.3 Sun Sensors

The sun sensors (SS) have not changed. They are provided by DTU (see Chapter 10); it has been quite difficult to obtain them in sufficient number because they are still under development. They can measure the sun direction on 2 axis (2 angles). One sun sensor stands on each face of the satellite (6 at all). Their output is a current which is converted into an analog voltage with an operational amplifier (AD8552). Each sun sensor has 4 outputs: 2 references related to the ambient luminosity and other conditions and 2 signals related to the sun direction.

The 2 references are in fact simple photodiodes, so if it is too complex to use the angles, these photodiodes could be used (as proposed during the Delta-PDR).

The 24 signals are read trough 4 analog multiplexers AD708 with the 12-bit ADC of the ADCS microcontroller. Because all these signals transit for a quite long distance near noisy digital signals, **low pass analog filters have been added** on the ADCS board in order to reduce the final noise (see Appendix A.1.2). The cut-off frequency is chose to be around **10kHz.** Therefore be cautions with the switching time of the multiplexers and the slew-rate of the amplifiers (OPA334).

Regarding reliability, the failure of 1 multiplexer will causes the failure of all sun sensors. Unfortunately it is not possible to have 6 multiplexers because the microcontroller does not have 6 analog inputs. To increase reliability, it would be possible to connect the signals differently on the multiplexers, but it also increase the risk of making a software error.

Because the SS are passives sensors, only the operational amplifiers need power; it represents a peak current about 26mA for the 24 amplifiers. This is supplied through a 3V low-noise LDO regulator TPS79330 which stabilize the voltage and limits the short-circuit current for the power wires ($I_{sc} \leq 600mA$). The current limit for the signal wires is smaller due to the AD8552 short-circuit current ($I_{sc} \leq 30mA@3V$).

For more details about the SS, see [R4].

6.4 Magnetotorquers

The magnetotorquers design has had few changes, then it will not be detailed in this report (see [R1] and [R7] for more information). Regarding the hardware side, a current probe has been added and regarding the software a **current regulator** has been implemented in order to control precisely the currents in the magnetotorquers, and therefore the torque.

6.5 ADCS main board

The overall electrical schematic for the next ADCS board has been almost completed (see Appendix A.1). Some remaining points are:

- Some inductances values (component choice) and some footprints.
- Choice of the H-Bridges.
- Checking of the MM circuit.

The main difficulties with this board are that a lot of very sensitive analog signals are present near digital signals or devices. Therefore electromagnetic compatibility (EMC) is really a major problem (especially with 16-bit ADC). It is important to mention here that **increasing the values of the capacitor is not good solution regarding the filtering of high frequencies signals or noises** (the real capacitors are not perfect and have maximum operational frequency). It is why a small capacitor is often put in parallel to a big capacitor for the decoupling applications.

The PCB layout will have to be completely redesigned for a **6-layers** IS-420 substrate. The components and connexions must be placed according to the new available space on the board (see Appendix A.2). A lot of components have been added since last version of the board and the available space has been largely reduced; therefore the routing and component placement will be very tricky.

Regarding EMC, **different ground planes and power planes must be designed on different layers** which will lead to a very complex board (notation refers to Appendix A.1):

- 1 Digital power layer with 2 planes:
    - DVcc33 for general purpose (3.3V EPS)
    - VCC_MT for the magnetotorquers (3.0V LDO)
- 1 Digital ground plane/layer : DGND33
- 1 Analog power layer with 3 different power planes:
    - AVcc33 for the microcontroller (3.3V EPS)
    - AVcc_MM for the magnetometers (3.0V LDO)
    - AVcc_G for the gyroscopes (5.0V LDO)
- 1 Analog ground layer with 3 different ground planes:
    - AGND33 for the microcontroller and sun sensors (separation at the microcontroller power supply)
    - AGND_MM for the magnetometer (separation at the MM ADC)
    - GND_G for the gyroscopes (separation at the gyro ADC)
- 1 Mechanical ground and power dissipation layer: GND_MECA

DVcc_G and AVcc_SS are not planes but simple power lines.

Power dissipation will also be a problem for some components (gyroscopes, LDOs, step-up,…) and some **via and multiple thermal planes** must be placed to increase the thermal conductivity to the dissipation layer; it is important to note that **GND_MECA must not be electrically connected to the others ground planes**.

All unused pins or any metallic parts should be electrically connected to one ground in order to avoid charge trapping (and then electrostatic discharges or voltage shift).

Regarding the component placement, **gyroscope step-up and inductances must be placed as far as possible to the MM. This one must also not be placed beside the payload, because it contains some iron parts**.

Analog lines and devices should be placed as far as possible to the digital parts and signals such as magnetotorquers power supply.

6.6 Power budget

The ADCS power budget has been corrected and completed according to the new electrical schematic and components.

The ADCS microcontroller is assumed to be in sleep mode (LPM0) when it is not used. The measurement rate is set to 2Hz.

All sensors are assumed to be switched off when no measure is needed. The LDO regulators are not directly taken into account because they simply dissipate overpower. So the power supply can be considered to be 3.3V (or 5.4V) for all components.

The MT are assumed to be always switched on with their maximum power consumption. This is not realistic and the final power consumption should be lower. See [R9] for more details on the MT power consumption during the different control phases.

The gyroscopes are assumed to be always on, because it might introduce some errors if they are switched on and off. This has not been demonstrated for the moment; therefore their power consumption could be reduced if it is not the case.

This budget shows the maximum peak currents in order to choose the wires and LDO, and check if the EPS can supply this current. The datasheet typical and maximal values are used for each component in order to have more details.

Part/function	Number	Voltage [V]	Typ Current [µA]		Max Current [µA]		ON Time [ms]	ON frequency [Hz]	Duty cycle	Max Peak Current [mA]	Mean Max Current [mA]	Max Peak Power [mW]	Mean Typ Power [mW]	Mean Max Power [mW]
			ON	OFF	ON	OFF								
Microcontroller :														
MSP430F1611 @7MHz and LPM0	1	3.3	3563	588	4263	693	4	200	0.8	4.26	3.55	14.07	9.79	11.71
REF3225	1	3.3	115	1	135	1	1000	1	1	0.14	0.14	0.45	0.38	0.45
MC-146	1	3.3	0.15	0	0.30	0	1000	1	1	0.00	0.00	0.001	0.0005	0.001
								Total uC :		**4.4**	**3.7**	**14.5**	**10.2**	**12.2**
Sensors :														
- Magnetometer														
HMC1043 Bridge	1	3.3	9009.01	0	13274.3	0	20	2	0.04	13.2743	0.53097	43.8053	1.18919	1.75221
HMC1043 Set/Reset	1	3.3	1320000	0	2200000	0	0.02	4	8E-05	1	0.176	3.3	0.34848	0.5808
AD8552	2	3.3	1900	0	2150	0	20	4	0.08	4.3	0.344	14.19	1.0032	1.1352
AD7798	1	3.3	180	1	300	1	20	4	0.08	0.3	0.02492	0.99	0.05056	0.08224
resistor divider	1	3.3	80	0	80	0	20	4	0.08	0.08	0.0064	0.264	0.02112	0.02112
- Sun Sensors														
DTU Sun Sensor	6	0	0	0	0	0	20	2	0.04	0	0	0	0	0
AD8552	12	3.3	1900	0	2150	0	20	2	0.04	25.8	1.032	85.14	3.0096	3.4056
ADG708	4	3.3	0.0001	0	1	0	1000	1	1	0.004	0.004	0.0132	1.3E-06	0.0132
OPA334	4	3.3	350	2	450	2	20	2	0.04	1.8	0.07968	5.94	0.21014	0.26294
REF3212	6	3.3	115	0	135	0	20	1	0.02	0.81	0.02	2.67	0.05	0.05
- Gyroscopes														
ADXRS614	3	5.4	3500	0	5000	0	1000	1	1	24.5455	24.5455	81	56.7	81
AD7795	1	5.4	165	1	185	1	1000	1	1	0.30273	0.30273	0.999	0.891	0.999
LTC3459	1	3.3	2269	0.13	3230	0.13	1000	1	1	3.23026	3.23026	10.6599	7.48683	10.6599
- Temperature														
LM94022	2	3.3	5.4	0	9	0	20	2	0.04	0.018	0.00072	0.0594	0.00143	0.00238
								Total sensors :		**75.5**	**30.3**	**249.0**	**71.0**	**100.0**
Actuators :														
- Magnetotorquers														
Coil	3	3.3	15000	0	15000	0	1000	1	1	45	45	148.5	148.5	148.5
H-Bridge A3901	2	3.3	600	0.1	600	0.1	1000	1	1	1.2	1.2	3.96	3.96	3.96
MAX4072	3	3.3	100	10	250	10	1000	1	1	0.75	0.75	2.475	0.99	2.475
REF3212	1	3.3	115	0	135	0	1000	1	1	0.14	0.14	0.45	0.38	0.45
								Total actuators :		**47.1**	**47.1**	**155.4**	**153.8**	**155.4**
								Total :		**127**	**81**	**419**	**235**	**268**

The LDOs are not taken into account because they simply dissipate the power between 3.3V and 3.0V or 5.4V and 5.0V

Current limited with hardware protection on ADCS board

According to current simulations, this value should be lower when the satellite is detumbled : less than 100mW

Table 6-1 : ADCS power budget

We can observe the power budget is now at the limits of the requirements. But this should not be a problem because the satellite has now enough power thanks to the solar cells on the 6th side.

7 RECOMMENDATIONS AND FUTURE WORK

First I would like to advise the reader to take a look at my previous report ([R1]), because it contains a lot of information that have not been reminded in this report (but keep in mind it is not up-to-date).

7.1 Hardware

A lot of tests remain to be done with all sensors. The different temperature compensations should be implemented in the software and validated. One very big problem is that almost each sensor has different characteristics, **so all sensors of the final satellite must be fully characterized in offset and sensitivity.** The DCO frequency of each MSP should also be measured if it is necessary.

Regarding the ADCS board, the component placement and routing must be done very carefully (be careful with magnetometers, inductances, step-up and iron parts of the payload). I strongly recommend sending me the files containing the placement and routing in order to check them before building the 6 layer PCB.

It is also very important that **all ceramic capacitors should have a X7R dielectric material**. Cheaper dielectrics can have a very high shift in temperature (>50%!).

7.2 Software and algorithms

The ADCS microcontroller software must be completed; be careful with the starting times and low-pass filters cut-off frequencies in order to reduce power consumption (although it seems not to be a major concern at the moment); here there is a **tradeoff between power consumption and filtering** of the different measures. **Do not forget the MT should not be on when MM is measuring: the most secure way would be to attribute a time slot for measurement (all sensors!), a 2nd time slot for actuation** (magnetotorquers) **and a 3rd time slot corresponding to a dead time** (because of magnetic and electrical time constants). With this solution it is certain the magnetotorquers will not disturb the different measurements.

The **influence of radio communication** on the different sensors should also be investigated.

Regarding the sun sensors, the sun vector model remains to be perfected. The eclipse detection should also be implemented on the ADCS microcontroller (by watching the reference sun sensors voltages).

For the **perturbations** which act on the satellite, a precise estimation or measure of the **residual dipole** remains to be performed. Also the impact of the **antenna deployment** has not been fully modeled for the moment.

A second iteration must be performed to the **Earth's magnetic Field model** (see [R2]). Because there is sufficient available memory on the CDMS, it is currently possible to **store more look-up tables** to be able to compute the magnetic field for a **broader range of altitude** (Ex: 400km to 1000km in a single model). This modification is quite simple. Another modification would be to change the coordinate system used in the look-up tables. It is indeed necessary to use a different coordinate system for the determination; the onboard computation could be then reduced by using an appropriate coordinate system to compute the look-up tables. This modification is a little bit more difficult. It is important to check the results to be sure the model is correct.

Then the overall ADCS algorithms should be implemented on the CDMS microcontroller.

The ADCS should not count the time in the same manner than the others subsystems, because this clock (at least TimerA0) is also used for a precise sensor synchronization and waiting routines; a minimum increment of 62.5ms is largely too long. Each increment (of TimerA0) should be around **3.906ms** which represents 1/256th of second and 128 pulses of the 32'768Hz external clock oscillator. A 2nd Uint32 global variable can be implemented to count the time normally with an increment each 62.5ms.

8 CONCLUSION

The ADCS is a very complex system and a lot of work, tests and simulations remain to be performed to qualify it for flight. Unfortunately we were unable to catch up with all the delay during this semester, but the analysis performed and results we have had allow saying that the ADCS is currently in the right way.

The requirements are currently realistic and the architecture developed should be able to fulfil them. But there are still some important issues, especially regarding the final accuracy of the sensors (gyroscopes, magnetometers and sun sensors).

Another important point is the orbit of the satellite. The last orbit proposed with the Vega launcher is an elliptical orbit with a maximum altitude of 1200km and a minimum altitude of 300km. This could be a problem for the ADCS, especially regarding the magnitude of the perturbations. Further analysis remains to be done at this level.

Lausanne, 10/01/2008

Hervé Péter-Contesse

9 ACKNOWLEDGMENTS

I would like to thank Peter Bruelmeier and André Badertscher for their great help about the PCB layout and components soldering.

I give thanks to Roland Dupuis for having winded and molded the magnetotorquers.

Many thanks to Werner Hirschi from Montena emc SA for his great help and expertise regarding the design of the new ADCS board (grounding and electromagnetic compatibility).

Thanks to the SwissCube team for the nice working atmosphere and their help.

10 CONTACTS

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Werner Hirschi	werner.hirschi@montena.com	Montena emc SA CEO – EMC analysis

11 REFERENCES

[R1] Hervé Péter-Contesse, *S3_Phase_B-C-ADCS-1-3-ADCS_HW_and_System*, EPFL, June 2007

[R2] Hervé Péter-Contesse, *S3-C-ADCS-1-2-Earth's Magnetic Field Model*, EPFL, June 2007

[R3] Rakesh Prajapati, *S3_Phase_B-C-ADCS-2-1-Gyroscopes*, EPFL, January 2008

[R4] Patrick Thevoz, *S3_Phase_B-C-ADCS-2-1-Sun_sensors*, EPFL, January 2008

[R5] Vasko Vitanov, *S3-B-ADCS-1-3-Magnetic_sensor,* EPFL, February 2007

[R6] Jean-Pierre Perin, *S3_Phase_B-C-ADCS-1-1-Magnetometer*, EPFL, January 2008

[R7] Laurent Hauser, *S3_Phase_B-C-ADCS-1-1-Magnetotorquers*, EPFL, January 2008

[R8] Jordi Martin-Benet, *S3-B-C-ADCS-1-1-Determ Alg (SwissCube Attitude Determination Algorithm Design and Validation)*, EPFL, July 2007

[R9] Martin Ehrensperger, S3-C-ADCS-1-0-ADCS Algorithms, EPFL, 2008

[R10] Daniel Hakansson, *S3_Phase_B-C_Mission_design*, EPFL, June 2007

[R11] Oscar de la Torre, *S3-B-TCS-1-1-Thermal_Management*, EPFL, February 2007

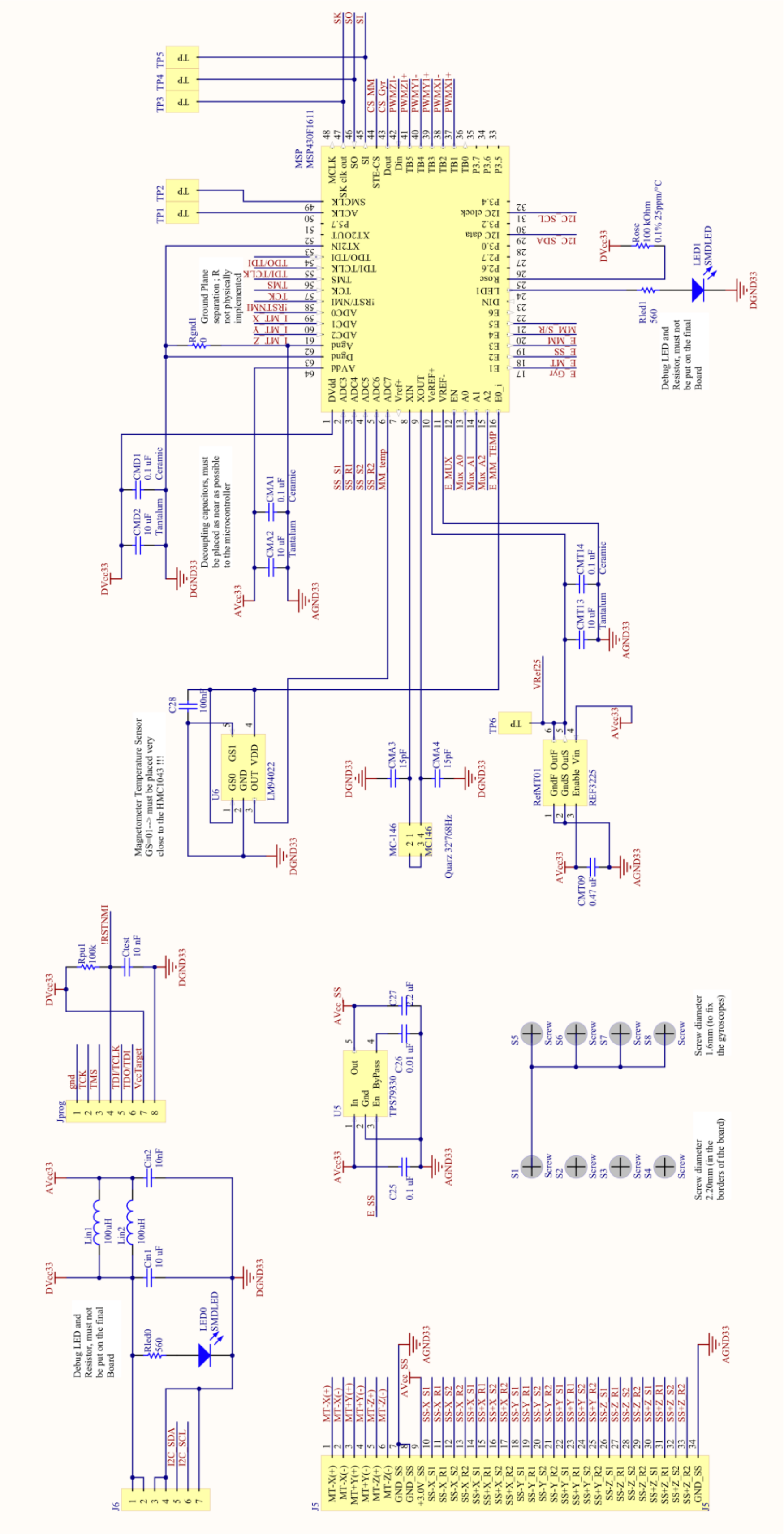
12 ABBREVIATED TERMS

ADC	Analog to Digital Converter
ADCS	Attitude Determination and Control System
CB	Connection Board
CDMS	Command Data Management System
DCO	Digitally Controlled Oscillator
EMC	ElectroMagnetic Compatibility
EMF	Earth's Magnetic Field
EPS	Electrical Power System
GYR	Gyroscope
ICD	Interface Control Document
LDO	Low Dropout linear voltage regulator
LUT	Look-up Table
MM	Magnetometer
MSP	Mixed Signal Processor
MT	Magnetotorquer
PWM	Pulse Width Modulation
RMS	Root Mean Square
SS	Sun Sensors
STK	Satellite Tool Kit
SV	Secular Variation of the Earth's magnetic field
TC	Telecommand
TL	Telemetry
TLE	Two Line Element from NORAD

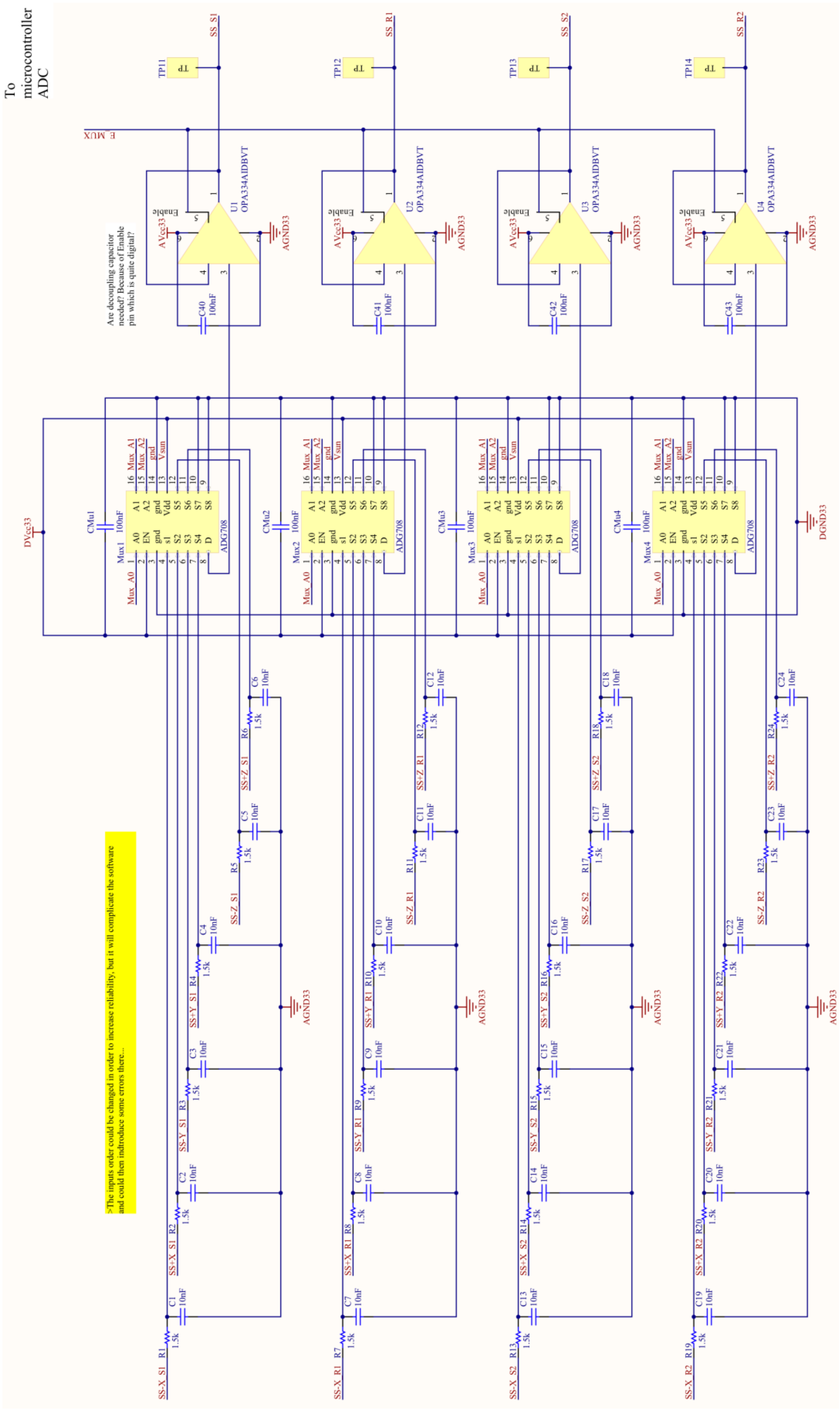
Appendix A ADCS board electrical schematic and PCB

A.1 AHW3.0 Electrical Schematic

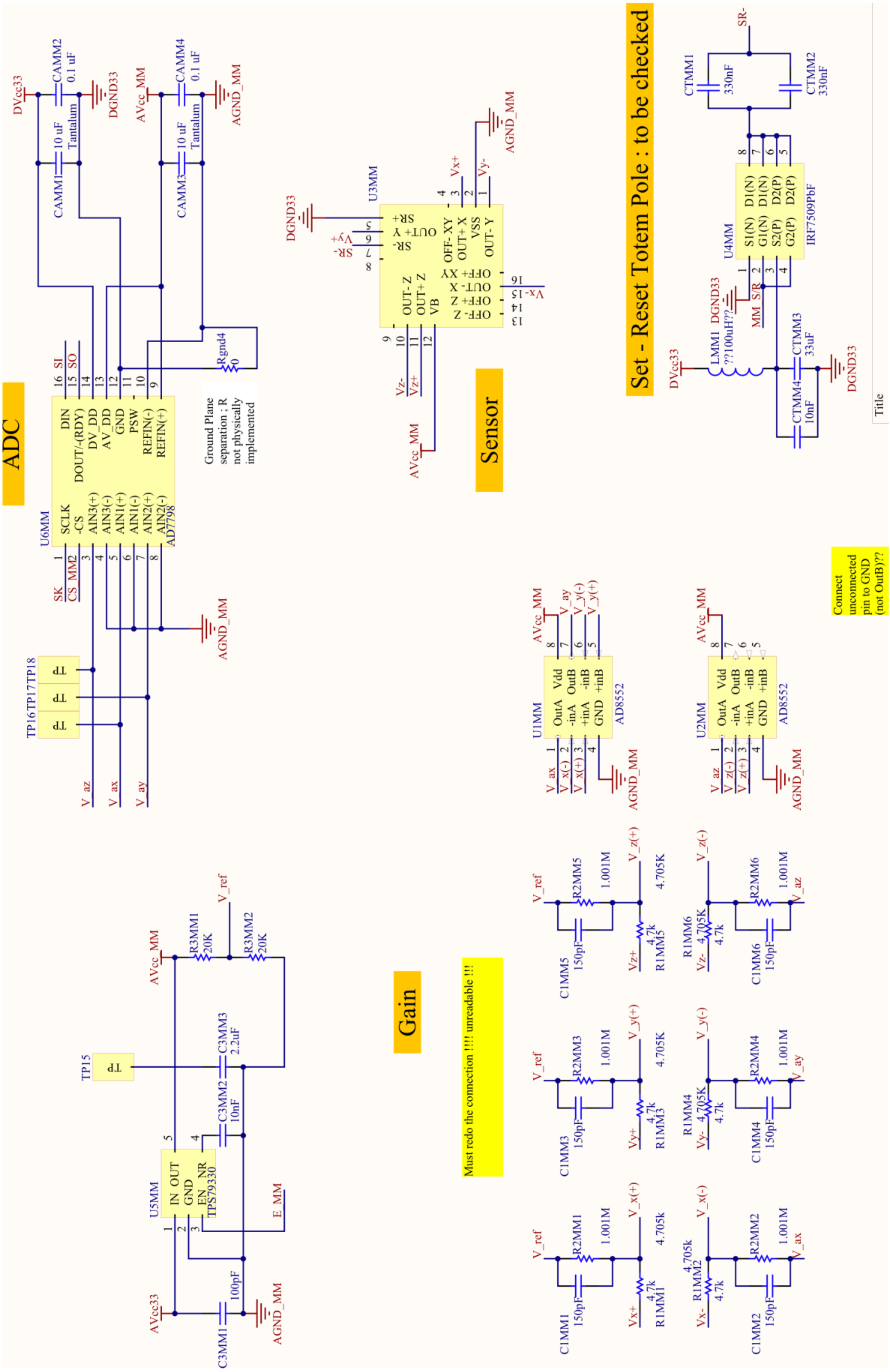
A.1.1 Microcontroller



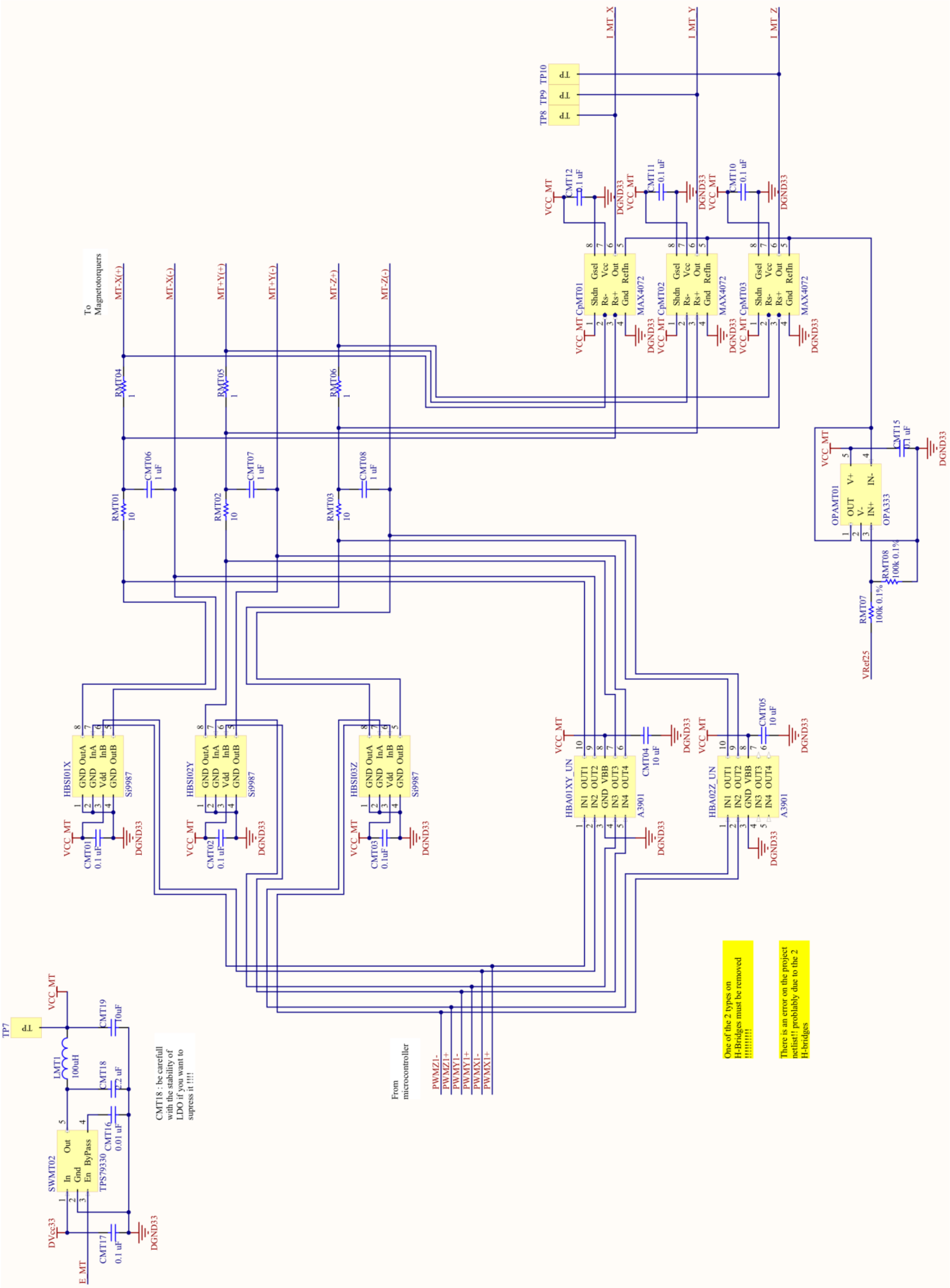
A.1.2 Sun Sensors inputs



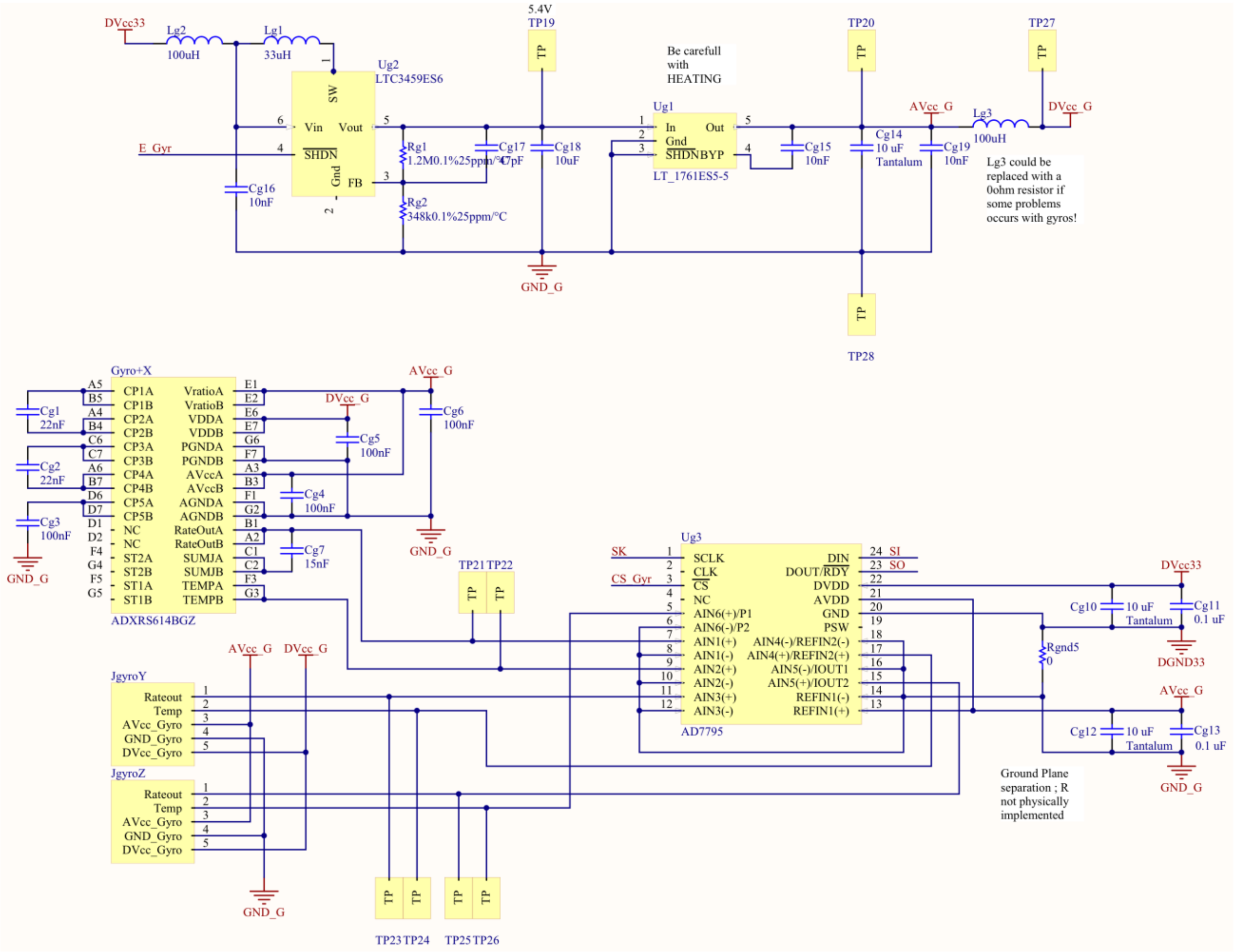
A.1.3 Magnetometer



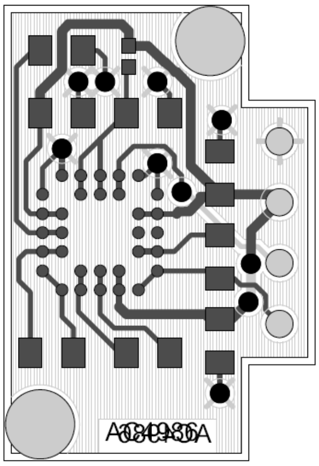
A.1.4 Magnetotorquers

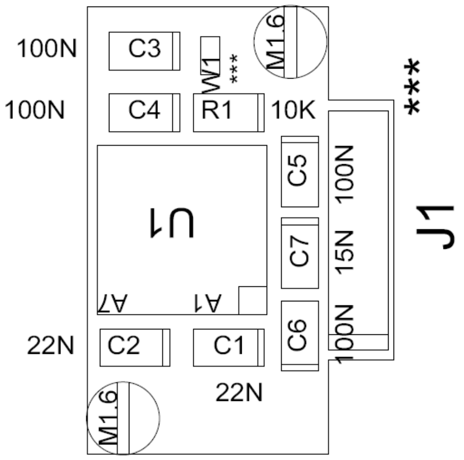


A.1.5 **Gyroscopes**

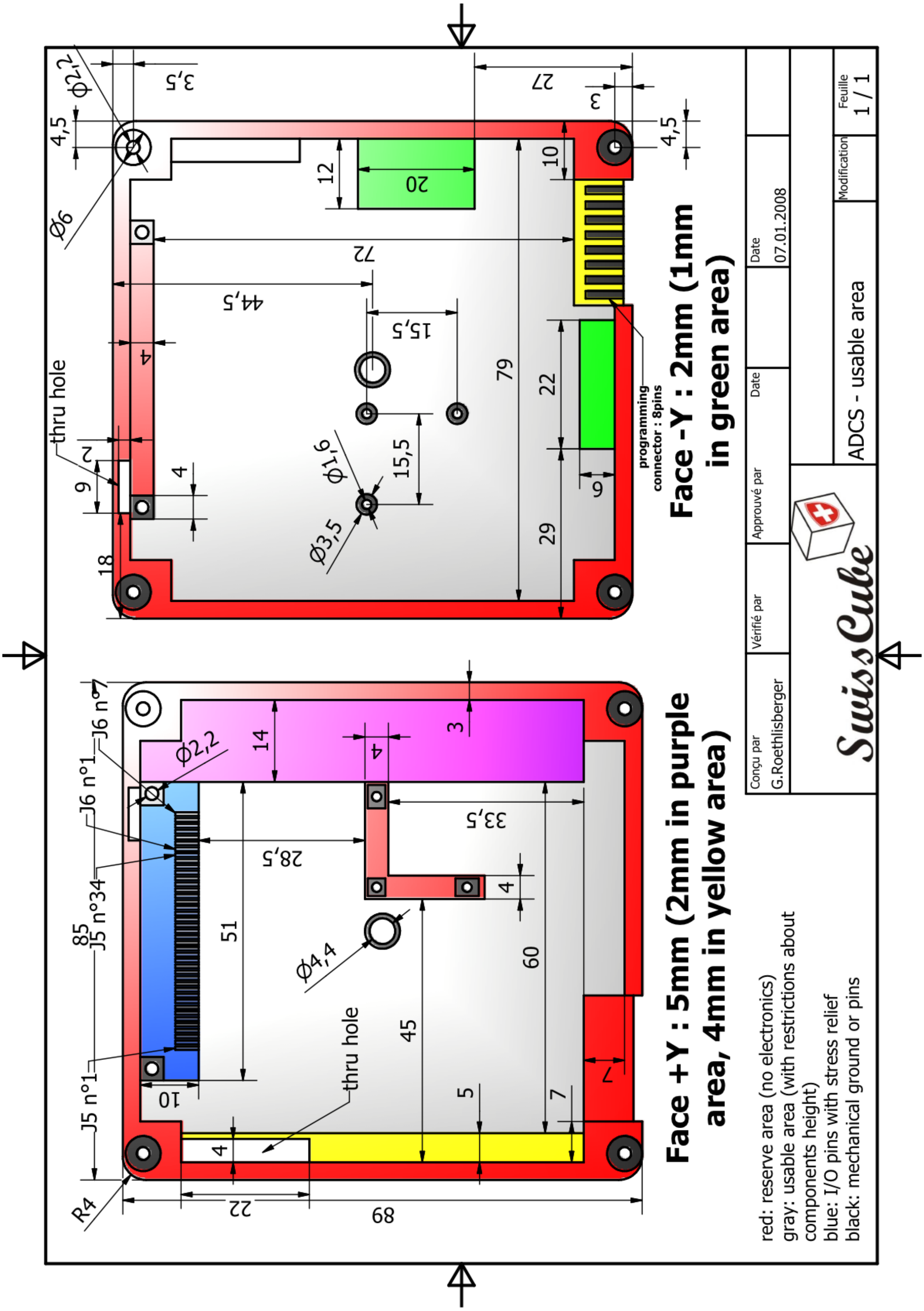


Current small/perpendicular PCB layout:



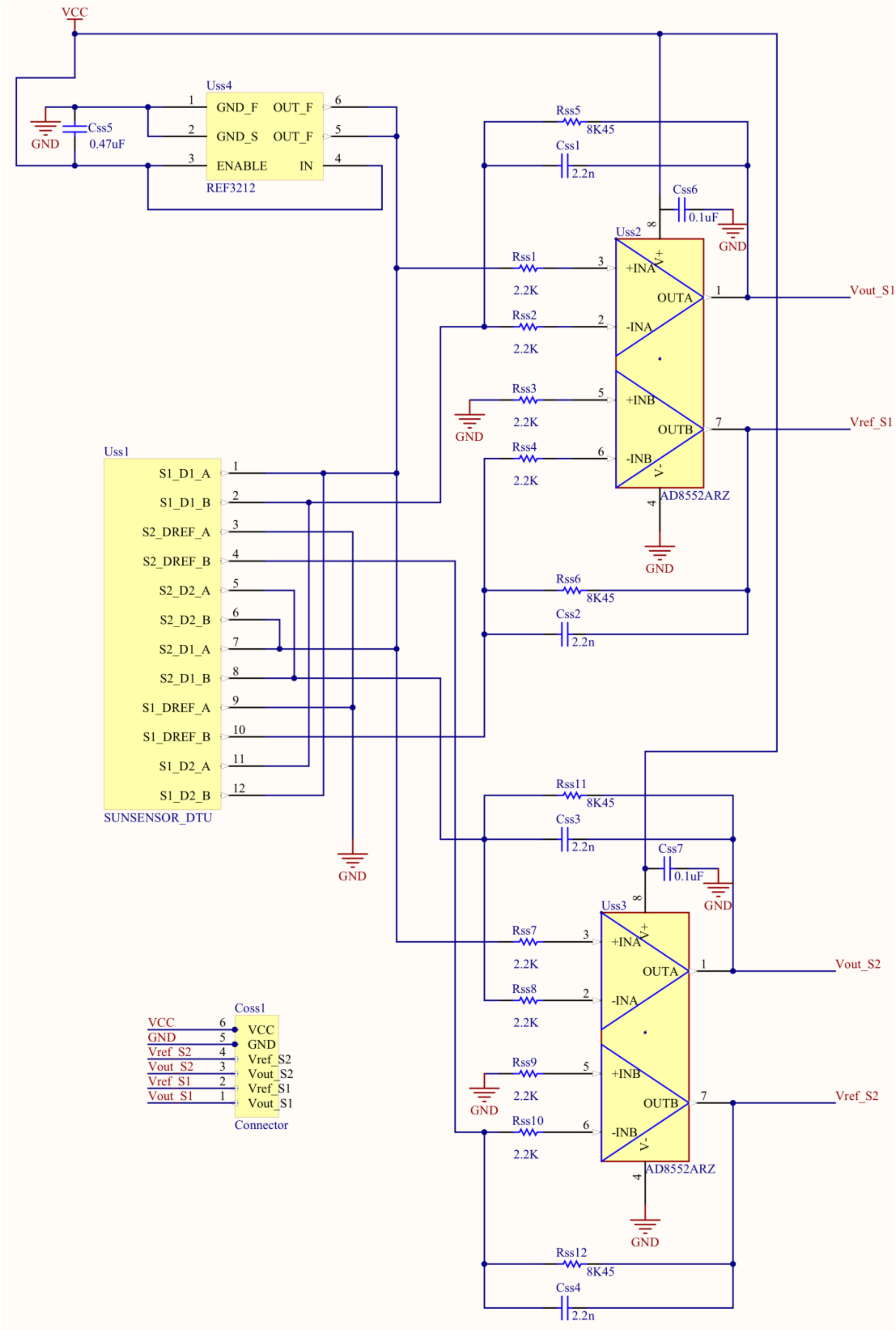


A.2 ADCS PCB usable area



Appendix B Sun Sensors Electrical schematic

Here is the electrical circuit which is needed for each sun sensor (6x) (extracted from [R4]). It must be placed below/near the sun sensor on each satellite sides PCB.



Appendix C Interface Control Documents

C.1 Electrical

PIN #		PIN NAME	TYPE	I/O	Voltage [V]	Mean max Current [mA]	Peak max current [mA]	To (in case of output)	From (in case of input)	Purpose / Description
J5	1	MT-X(+)	Power	O	0 - 3		25	MT -X		Magnetotorquers PWM signals and power
	2	MT-X(-)	Power	O	0 - 3		25	MT -X		
	3	MT+Y(+)	Power	O	0 - 3		25	MT +Y		
	4	MT+Y(-)	Power	O	0 - 3		25	MT +Y		
	5	MT-Z(+)	Power	O	0 - 3		25	MT -Z		
	6	MT-Z(-)	Power	O	0 - 3		25	MT -Z		
	7	GND_SS	Power	O	0	0.015	13	SS		
	8	GND_SS	Power	O	0	0.015	13	SS		
	9	+3.0V_SS	Power	O	3	0.03	26	SS		
	10	SS-X_s1	Analog	I	0-2.5				SS -X	Sun sensors analog outputs: 2 signals and 2 references per sun sensor
	11	SS-X_r1	Analog	I	0-2.5				SS -X	
	12	SS-X_s2	Analog	I	0-2.5				SS -X	
	13	SS-X_r2	Analog	I	0-2.5				SS -X	
	14	SS+X_s1	Analog	I	0-2.5				SS +X	
	15	SS+X_r1	Analog	I	0-2.5				SS +X	
	16	SS+X_s2	Analog	I	0-2.5				SS +X	
	17	SS+X_r2	Analog	I	0-2.5				SS +X	
	18	SS-Y_s1	Analog	I	0-2.5				SS -Y	
	19	SS-Y_r1	Analog	I	0-2.5				SS -Y	
	20	SS-Y_s2	Analog	I	0-2.5				SS -Y	
	21	SS-Y_r2	Analog	I	0-2.5				SS -Y	
	22	SS+Y_s1	Analog	I	0-2.5				SS +Y	
	23	SS+Y_r1	Analog	I	0-2.5				SS +Y	
	24	SS+Y_s2	Analog	I	0-2.5				SS +Y	
	25	SS+Y_r2	Analog	I	0-2.5				SS +Y	
	26	SS-Z_s1	Analog	I	0-2.5				SS -Z	
	27	SS-Z_r1	Analog	I	0-2.5				SS -Z	
	28	SS-Z_s2	Analog	I	0-2.5				SS -Z	
	29	SS-Z_r2	Analog	I	0-2.5				SS -Z	
	30	SS+Z_s1	Analog	I	0-2.5				SS +Z	
	31	SS+Z_r1	Analog	I	0-2.5				SS +Z	
	32	SS+Z_s2	Analog	I	0-2.5				SS +Z	
	33	SS+Z_r2	Analog	I	0-2.5				SS +Z	
	34	NC	Unused							Reserve
J6	1	Vcc	Power	I	3.3	32	60		EPS	ADCS Board power supply
	2	Vcc	Power	I	3.3	32	60		EPS	
	3	GND	Power	I	0	32	60		EPS	
	4	GND	Power	I	0	32	60		EPS	
	5	I2C_data	Digital	IO	0 - 3.3				Main bus	Main communication Bus
	6	I2C_clock	Digital	IO	0 - 3.3				Main bus	
Jmec	1	GND_FRA	Thermal	I					Mec	Frame ground for thermal dissipation

C.2 Data

Data direction	Description	Data type	Data length [bits]	Units	Nominal range	Max values (due to data type)
ADCS --> CDMS	Magnetometer X,Y and Z	3x int16 + 1x Uint32 (TS)	80	1e-8 T	± 60.00mT	± 327.67mT
	Sun Sensors -X,+X,-Y,+Y,-Z and +Z	12x int16 + 1x Uint32 (TS)	224	0.1°	± 70.0°	± 3276.7°
	Gyroscopes X,Y and Z	3x int16 + 1x Uint32 (TS)	80	1e-2°/s	± 10.00°/s	± 327.67°/s
	Gyroscopes temperatures	3x int8	24	°C	-30 to + 60°C	± 127°C
	ADCS Board and Magnetometer Temperature	1x int8	8	°C	-30 to + 60°C	± 127°C
CDMS --> ADCS	Magnetotorquers Current X,Y and Z	3x int8	24	% from max value	± 100%	± 127%

TS = Time Stamp, Uint32 = 32bit unsigned interger

Appendix D ADCS Budget and costs

ADCS budget after 30 oct 07

Part name/Component	Number of part needed	Part bought before 30 oct 07	Part bought between 30 oct 07 and 1 dec 07	Remaining to buy	Free Samples obtained	Price/ part CHF	Total cost CHF	Remaining cost after 30 oct 07 CHF	Distributor	Reference number or contact info
Sensors:										
Honeywell HMC 1043	8	0	8	0	0	22.9	183.2	0	www.ymatron.ch	mailto:msterf@ymatron.ch
ADXRS614BBGZ	12	0	4	8	0	56.2	674.4	449.6	AD Yverdon	thierry Jaton : TJATON@arrowce.com
DTU Sun sensors "rectangular"	15	0	0	0	15	0	0	0	DTU (Technical University of	Jan Hales : jhh@mic.dtu.dk
DTU Sun sensors "finger"	12	0	0	0	12	0	0	0	DTU (Technical University of	Jan Hales : jhh@mic.dtu.dk
SLCD-61N1	0	0	20	0	0	3.88	77.6	0	www.farnell.ch	1218986
Operational Amplifiers and analog:										
opa333AIDCKTG4	10	0	20	0	5	5.55	111	0	www.farnell.ch	1230457
OPA334AIDBVTG4	20	0	0	15	5	3.4	51	51	www.farnell.ch	1207113
AD8552ARZ	42	24	0	18	0	18.95	795.9	341.1	www.farnell.ch	9425845
AD8851ARZ	5							0		
ADG708BRUZ	24	20	0	4	0	8.25	198	33	www.farnell.ch	9604340
REF3225AIDBVTG4	10	0	10	0	5	4.7	47	0	www.farnell.ch	1180177
REF3112AIDBVTG4	26	0	6	20	0	8.45	219.7	169	www.farnell.ch	1180175
AD7798BRUZ	5	0	0	3	2	14.05	42.15	42.15	www.farnell.ch	1078328
AD7795BRUZ	5	0	0	3	2	18.15	54.45	54.45	www.farnell.ch	1274227
TPS79330DBVRG4	30	0	30	0	6	1	30	0	www.farnell.ch	1287688
MAX4072		0	0					0		
								0		
LT1761ES5-5		0	0	0				0		
LTC3459ES6#TRMPBF		0	0	0	4			0		
Resistors, capa. and elec. others:										
R 0805 8K45 0.1%	90	0	24	66	0	1.15	103.5	75.9	www.farnell.ch	1353315
R PCF0805R 20KBI.T1 0.1%	10	0	0	10	0	1.45	14.5	14.5	www.farnell.ch	1160218
R PCF0805R 1M0BI.T1 0.1%	30	0	0	30	0	1.45	43.5	43.5	www.farnell.ch	1160303
R PCF0805-13-4K7-B-T1 0.1%	30	0	0	30	0	2.75	82.5	82.5	www.farnell.ch	1108882
R PCF0805R 100KBI.T1 0.1%	20	15	0	5	0	1.45	29	7.25	www.farnell.ch	1160261
R SR732ATTD1R00F 1ohm 1%	15	0	0	15	0	0.16	2.4	2.4	www.farnell.ch	1399710
C 10uF tantalum TAJB106K010R	20	0	0	20	0	0.99	19.8	19.8	www.farnell.ch	498660
IRF7509PBF	6	0	0	6	0	3.55	21.3	21.3	www.farnell.ch	9102108
A3901		0	0		6		0	0	allegro microsystems	
Si9987		0	0		10		0	0	Vishay	
Others:										
EPO-TEK 920	2	1	0	1	0	114	228	114	Polyscience AG (CH)	Beatrice Iten ; EP92045
PCB 6 layers	1	0	0	1	0	600	600	600		
BGA socket for gyroscope	1	0	0	1	0	400	400	400		
						estimation				
							4028.9	2521.45		
					Margin	0.3	5237.57	**3277.885**		

Appendix E Software

E.1 Microcontroller programming in C recommendations

This appendix explains the basics for programming microcontrollers in C code (for use on the 16bit-MSP430 and 32bit-ARM7 microcontrollers).

- Microcontrollers have a small computation capability: divisions and multiplications takes many CPU cycles, so their number should be minimized. Additions, subtractions, shift,… takes few CPU cycles (1 or 2).
- To do a multiplication by 2^x , type : $a = b<<x$
- To do a division by 2^x , type : $a = b>>x$
- **Never use floating point numbers (*double* or *float*)!** The microcontrollers have no FPU (floating point unit) and all floating point operations are emulated in software with the C compiler. For example, a simple addition with 2 floats will take about 250 CPU cycle and only 1 or 2 cycles with integer.
- **Integers should be used!** For the MSP430: if the number can be stored in a 16bit integer (*int* or *short int*), don't use a 32bit integer (*long int*)! For the ARM7, all computations can be done with 32bit integer, except for tables, where you should minimize the memory size using 8bit (*char*) or 16bit integer if it's possible.
- **Always use look-up tables** to compute a sinus, cosines or other complex functions!

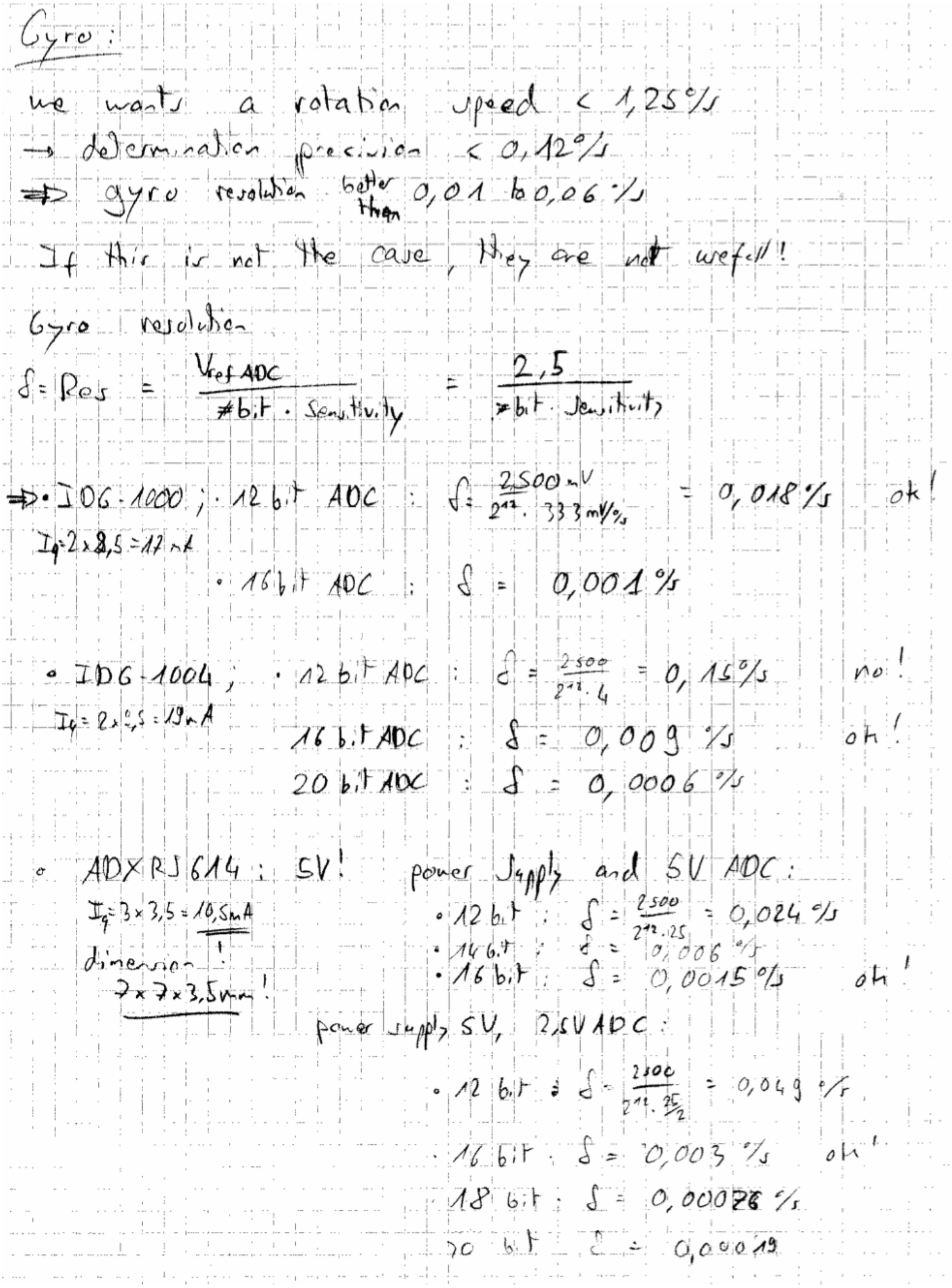
E.2 MSP430 CPU Cycles for common mathematical instructions

The microcontroller is programmed in C code with Composer Essentials 2.0. The building optimisations are not used. The operations are done and stored using same types of numbers. If over types are used, we can suppose there is an automatic cast to the type of higher rank. The measurements have been done 2 times with different values (the numbers below are not min/max values).

	Number of CPU cycles (MSP430F169)						
	Assignement	Addition/Substraction		Multiplication		Division	
int8	5	10		38		181	
int16	5	10		36		179	
int32	9	19		69		450	
float	9	155	157	177	332	430	397
double	9	165	193	179	316	397	403

The number of CPU cycles can vary; particularly regarding operations with *float* or *double,* especially for the multiplications and divisions.

Appendix F Various Calculations



Gyro:

we wants a rotation speed < 1,25°/s
→ determination precision < 0,12°/s
⇒ gyro resolution $\overset{\text{better}}{\underset{\text{than}}{}}$ 0,01 to 0,06 °/s

If this is not the case, they are not usefull!

Gyro resolution

$\delta = Res = \dfrac{V_{ref\,ADC}}{\#bit \cdot Sensitivity} = \dfrac{2,5}{\#bit \cdot Sensitivity}$

⇒ • IDG-1000 ; • 12 bit ADC : $\delta = \dfrac{2500\,mV}{2^{12} \cdot 3{,}33\,mV/°/s} = 0{,}018\,°/s$ ok!
$I_q = 2 \times 8{,}5 = 17\,mA$
• 16 bit ADC : $\delta = 0{,}001\,°/s$

• IDG-1004 ; • 12 bit ADC : $\delta = \dfrac{2500}{2^{12} \cdot 4} = 0{,}15\,°/s$ no!
$I_q = 2 \times 9{,}5 = 19\,mA$
16 bit ADC : $\delta = 0{,}009\,°/s$ ok!
20 bit ADC : $\delta = 0{,}0006\,°/s$

• ADXRS614 : 5V! power supply and 5V ADC :
$I_q = 3 \times 3{,}5 = \underline{\underline{10{,}5\,mA}}$!
dimension !
$\underline{7 \times 7 \times 3{,}5\,mm}$!
• 12 bit : $\delta = \dfrac{2500}{2^{12} \cdot 25} = 0{,}024\,°/s$
• 14 bit : $\delta = 0{,}006\,°/s$
• 16 bit : $\delta = 0{,}0015\,°/s$ ok!

power supply 5V, 2,5V ADC :
• 12 bit : $\delta = \dfrac{2500}{2^{12} \cdot \frac{25}{2}} = 0{,}049\,°/s$
• 16 bit : $\delta = 0{,}003\,°/s$ ok!
18 bit : $\delta = 0{,}00076\,°/s$
20 bit $\delta = 0{,}00019$

Magnetomètre HMC 1043, compensation offset AN212

full range : ± 70 µT = ±700 m Gauss   température: $-30 \leftrightarrow 60°C$
Bridge Voltage : 2,5V $T_0 = 20°C$

HMC 1043 :
- Offset : ∓1,25 mV/V
- offset tempco : 10 ppm/°C
- sensitivity : 0,8 - 1,2 mV/V/gauss.
- sensitivity tempco : < -3000 ppm/°C (voltage)
  (+600 ppm/°C (current))

$\rightarrow$ max sensitivity : $1{,}2 \cdot (1 + -3000 \cdot 10^{-6} \cdot (-50°C)) = \underline{1{,}38}$ mV/V/Gauss
Offset max : ∓1,25 mV/V (température dépendance negligible)

$\rightarrow V_{off} = \pm 1{,}25 \cdot 2{,}5 = \pm 3{,}125$ mV

$V_{field} = 1{,}38 \cdot 10^{-3} \cdot 2{,}5 \cdot 700 \cdot 10^{-3} = \pm 2{,}415$ mV

$\rightarrow V_o = \pm 5{,}54$ mV

Ampli op rail : ±100mV → ADC can be used to measure between +0,1V and + 2,4V → 1,25 ± 1,15 V

$\Rightarrow$ gain $= 1{,}15 / 5{,}54 \cdot 10^{-3} = 207{,}6 \Rightarrow \underline{\underline{200}}$

$\Rightarrow$ final sensitivity :

min : $0{,}8 \cdot 10^{-3} (1 + (-3000 \cdot 10^{-6}) \cdot 40) \cdot 200 = 140{,}8$ mV/Gauss
max : $= 276$ mV/Gauss

12 bit ADC : $\frac{2{,}5}{2^{12}} = 0{,}61$ mV/LSB

ADC 16-bit : 27 nT/LSB

$\rightarrow$ résolution : min : $\frac{0{,}61}{140{,}8} = 4{,}33 \cdot 10^{-3} \frac{Gauss}{LSB} = \underline{0{,}433}\ \mu T/LSB$
max : $= 0{,}22\ \mu T/LSB$

(si on prend full range ± 60 µT : $V_o = 5{,}195$ mV → gain 221 → 220
$S_{final} = 154{,}8$ → res min = 0,39 µT/LSB)

bruit : Noise Density $50 \frac{nV}{\sqrt{Hz}}$ → bande passante 100Hz : 500nV

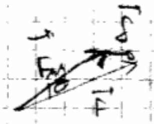
→ 71 nT au max

requirement :

positionnement < 12° → détermination 1,2° $\xrightarrow{\text{capteur}}$ 0,12°

à 400km : EMF, F = [~~19,5~~ 15,5 , 55] µT

modèle de champ, $\Delta_{RMS} \sim 100nT \overset{\text{WMM2005 error}}{\Rightarrow} \Delta_{RMS} \sim 300nT$



$$|\vec{\delta}| \leq \sqrt{\underset{\uparrow\ \text{erreur MM}}{\delta_x^2} + \delta_y^2 + \delta_z^2} = \delta\sqrt{3}$$

$$\rightarrow \tan\theta = \frac{|\vec{\delta}|}{|\vec{F}|} = \frac{\sqrt{3}\delta}{F} \qquad \theta = \arctan\frac{\delta\sqrt{3}}{F}$$

$$\rightarrow \delta = \frac{F\tan\theta}{\sqrt{3}} = \frac{15{,}5\ 10^{-6}\tan 0{,}12°}{\sqrt{3}} \cong 20\ nT$$ bruit du capteur !

→ avec δ = 100nT → θ = 0,64° (F = 15,5µT)   0,18° (F = 55µT)

δ = 400nT → θ = 2°

Appendix G Other

All other information, components datasheets, source codes… can be found in the project CD-ROM.