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ELECTRONICS DESIGN AND TESTING FOR ESTCUBE-2 ON-BOARD COMPUTER SYSTEM WITH SENSORS FOR ATTITUDE DETERMINATION

Master's thesis (30 EAP)

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Abstract

Electronics design and testing for ESTCube-2 on-board computer system with sensors for attitude determination

ESTCube-2 will be a 3U picosatellite planned to launch in 2019 to perform experiments in low Earth orbit. On-board computer system is required to control the satellite while powered up and has to provide computational power and reliable storage for other subsystems. Attitude and orbit control system is responsible for satellite's detumbling, pointing, spin-up and for controlling thrusters. This thesis presents a prototype electronics board developed for both systems. On-board computer system features STMicroelectronics Cortex-M7 microcontroller with common bus interfaces and point-to-point signaling lines for all other systems planned for ESTCube-2. Data and programs are stored in three types of external non-volatile memories - QSPI NOR flash, FRAM and MRAM. For attitude determination sensors a dedicated connector and a demonstration prototype expansion board were developed featuring magnetometer, accelerometer and two gyroscopes. To test the developed boards simple firmware was written using manufacturer's provided hardware abstraction layer and an initialization source code generator.

CERCS: T170 Electronics, T320 Space technology

Keywords: miniaturized satellite, on-board computer system, attitude and orbit control system, electronics, ESTCube-2, Cortex-M7, MRAM, FRAM, QSPI flash

Resümee

Elektroonika projekteerimine ja testimine ESTCube-2 pardaarvutile koos asendi määramise sensoritega

ESTCube-2 saab olema 3U suurune kuupsatelliit, mis saadetakse Maa orbiidile 2019. aastal. Pardaarvuti on vajalik, et juhtida satelliidi tööd ja pakkuda arvutusjõudlust ja usaldusväärset andmete säilitamist teistele alamsüsteemidele ja eksperimendimoodulitele. Asendi ja orbiidi juhtimise süsteem peab suutma stabiliseerida ja suunata satelliiti ettenähtud suunas ning samuti panna satelliit pöörlema ning orbiiti muutma täiturite abil. Selle töö eesmärk oli välja töötada pardaarvuti prototüübi elektroonika koos asendi määramise sensoritega. Pardaarvuti jaoks kasutati STMicroelectronics Cortex-M7 mikrokontrollerit ja seda kasutades loodi andmesideühendused teiste satelliidi alamsüsteemidega. Andmete talletamiseks kasutati kolme välist säilmälu - QSPI NOR välkmälu, FRAM ja MRAM. Asendi määramise sensorite jaoks arendati eraldi elektroonika laiendusplaat, mille peal on magnetomeeter, kiirendusandur ja kaks güroskoopi. Elektroonika testimiseks kirjutati püsivara, milleks kasutati mikrokontrolleri tootja poolt pakutavat riistvara abstraktsioonikihti ja lähtekoodi generaatorit.

CERCS: T170 Elektroonika, T320 Kosmosetehnoloogia

Keywords: kuupsatelliit, pardaarvuti, asendi ja orbiidi juhtimise süsteem, elektroonika, ESTCube-2, Cortex-M7, MRAM, FRAM, QSPI välkmälu

Contents

List of Figures

List of Tables

List of Listing

Abbreviations

OBCS - On-board computer system
AOCS - Attitude and orbit control system
CHDS - Command and data handling system
EPS - Electrical power system
COM - Communications system
TID - Total ionizing doze
SEU - Single event upset
SEL - Single event latch-up
COTS - Commercial off-the-shelf
MRAM - Magnetoresistive random-access memory
FRAM - Ferroelectric random-access memory
SPI - Serial peripheral interface
QSPI - Quad serial peripheral interface
I^2C - Inter-integrated circuit
UART - Universal asynchronous receiver/transmitter
USART - Universal synchronous/asynchronous receiver/transmitter
CAN - Controller area network
USB - Universal serial bus
I/O - Input/output
GPIO - General purpose input output
EXTI - External interrupt/event controller
FPU - floating point unit
ADC - Analog to digital converter
PCB - Printed circuit board
RTC - Real time clock
LED - Light emitting diode
SWD - Serial wire debug
SWO - Serial wire output

1 Introduction

Space technology is a fast growing industry with advancements going on in areas like space mining and solar system exploration. Since distances in space are vast and traveling from one place to another takes a lot of time and fuel for conventional propulsion engines, a better way is needed. The electric solar wind sail offers a possible solution [1]. It uses solar wind ions and long, thin electrically charged wires to generate thrust. To test the technical solution ESTCube-1 mission was launched, but since it was not able to conduct the experiment [2], a new one is planned. ESTCube-2 will be a one part of the next two missions to test Coulomb drag propulsion and plasma brake [3]. In the case of ESTCube-2 the experiment will be conducted in low Earth orbit while ESTCube-3 is planned to perform the experiment in solar wind intersecting orbit. ESTCube-2 will be a miniaturized satellite of 3U defined in ”CubeSat Design Specification” [4]. Its dimensions will be around 10 x 10 x 30 cm and it will weigh less than 4 kg. This confined space will host the following systems: electrical power system (EPS), communications system (COM), scientific payloads, on-board control system (OBCS) and attitude and orbit control system (AOCS) [5]. All of them have a specific purpose and must communicate with each other for a successful mission. The goal of this thesis is to develop prototype electronics board for OBCS and AOCS. The main focus will be on on-board computer system which is used scheduling, distribution and handling of telecommands, satellite health monitoring, hosting algorithms for attitude determination and control, providing compression and storage of mission data for most of the payloads. Since the selection of the attitude determination sensors is not final, the sensors would be implemented on expansion boards to aid in the characterization of new sensors. Finally hardware functionality testing must be performed.

1.1 Thesis goals

1. Develop schematics for on-board computer system.
2. Develop schematics for attitude determination sensors.
3. Create PCB design for on-board computer system.
4. Create PCB design featuring attitude determination sensors for attitude and orbit control system.
5. Assemble first prototype boards.
6. Write firmware for hardware functionality testing.

1.2 Space environment

Satellites in low Earth orbit and in outer space are not protected from radiation - without the atmosphere they are affected by trapped particles in Earth's magnetic field, particles from solar events and cosmic rays [6]. With the ESTCube-2 mission taking place in low Earth orbit, it will be mainly susceptible to trapped protons and electrons, galactic cosmic ray ions, interplanetary solar flare protons and alpha particles, heavy ions [7]. In circuits three different kinds of damages can be caused by these particles.

- Total ionizing doze (TID) damage
- Single event upset (SEU)
- Single event latch-up (SEL)

Accumulating TID causes rapid aging of electronic components. In low Earth orbit, a few years may be enough to cause commercial off-the-shelf (COTS) components to fail completely. For example, the effects may be permanently increased leakage currents, drifts in voltage levels and clock frequencies. If special radiation hardened components are used, mean time to failure will typically be well over 10 years. [8] For a short mission taking place only for two years, COTS components can successfully be used. Compared to the space grade components, they have a lot lower price, weigh less and are smaller. COTS components are widely available and have good documentation and good support for software development.

Single event upsets and single event latch-ups can be caused by particles with high kinetic energy. Single event upsets are non-destructive and create soft errors including volatile bit flips in memory and registers. These sorts of errors can be detected and corrected by software using error correction algorithms. More concerning from electronics point of view are single event latch-up events, where charged particles create high current paths in CMOS substrate that can permanently damage components. Latch-up protection should be implemented in the electronics design to power off the component with internal short circuit and allow for the charges to dissipate before switching it back on. [8]

1.3 Other on-board computer systems

During normal operations ESTCube-1 was controlled by the command and data handling system (CDHS). It stored mission and housekeeping data from all subsystems. CDHS also ran all the processes for the attitude determination and control system. It featured two STM32F103 microcontrollers in cold redundancy. This means that the electrical power system powered up only one of the microcontrollers at a time and if one failed the other could still be used. Bus switches were used to disconnect unused microcontroller from all the lines to make sure it would not interfere with the other one. For redundancy all the connections between subsystems were point-to-point with forwarding. CDHS stored data in three SPI flash memories, total of 48 MB, five FRAM memories, total of 1280 KB, and in microcontroller's internal memory, 768 KB of flash and 96 KB of SRAM. [9] During ESTCube-1 mission command and data handling system was improved with additional functionality enabled by in-orbit firmware updates [2].

The AAU-Cubesat was launched into space in 2003 and its on-board computer system used Siemens C161 16-bit 16 MHz microcontroller. It only featured one camera payload and all the communication was done over I^2C bus. It featured PROM for original software and flash memory for updated software. [10] Today there are already commercially available on-board computer systems. One of those is Innovative Solutions In Space on-board computer (iOBC). It is flight qualified and uses ARM9 processor, 64 MB of SDRAM, 1 MB NOR flash for code storage and 256 kB FRAM for critical data. For mass storage it has two 2 GB SD cards with fail safe file system. They also optionally offer software for faster development. [11] A lot of research has been done on fault tolerant on-board computer systems. STSAT-3 was designed using FPGA with a triple modular redundancy scheme which was immune to proton energies up to 20.3 MeV during testing. Two flash memories were used to hold the original and updated version of the FPGA configuration. [12]

2 Hardware

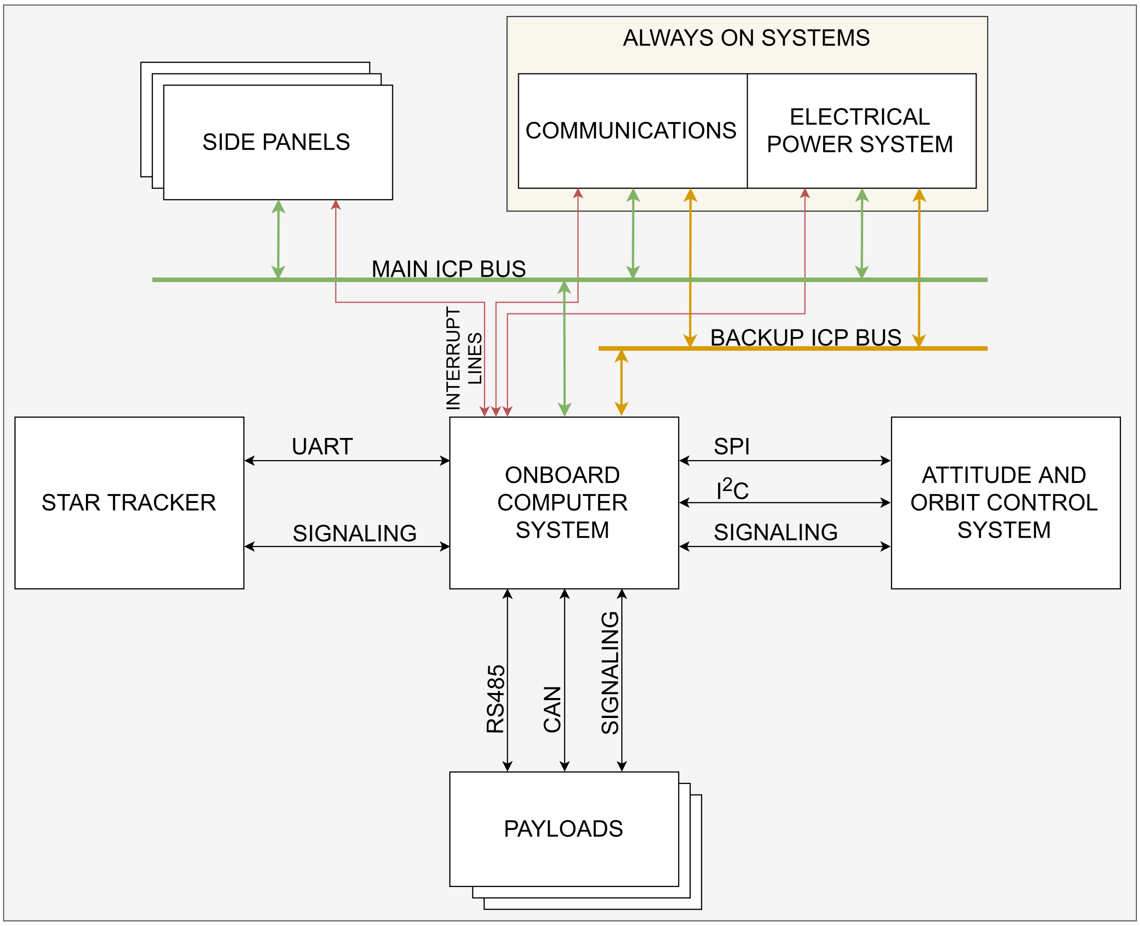


Figure 2.1: Block diagram of ESTCube-2 with communication buses from on-board computer system's view.

ESTCube-2 is divided into multiple subsystems, each with a specific purpose. The subsystems are listed on figure 2.1. Electrical power system is responsible for energy storage, power distribution and monitoring, as well as performing high-level current limiting. EPS also acts as the central timekeeper since it is always powered. Another subsystem, that is always powered, is the communications system, which is responsible for receiving and transmitting data between satellite and ground stations. Side panels are responsible for tracking Sun's position and collecting energy with maximum power point tracking (MPPT). ESTCube-2 will also feature a star tracker that allows increased accuracy in measuring satellite's orientation. ESTCube-2 will have at least three payloads - optical payload, E-sail payload and high-speed communications payload. On-board computer system controls satellite during nominal operations by receiving commands from the ground station through COM to schedule and handle them, possibly when the satellite is out of range from the ground stations. It keeps log of the satellite's operations, compresses and stores recorded data and programs in memory while supporting other systems where needed. ICP, RS485, RS232, USB, CAN, SPI and I^2C communication buses are used to achieve maximum performance and to accommodate different development teams (Figure 2.1). [5] This sets a list of requirements that the on-board computer system and attitude determination sensors must comply to, described in section 2.1.

2.1 Requirements

1. First prototype must include at least the following interfaces for testing and debugging purposes: JTAG or SWD and UART with USB serial adapter.
2. Electronics board must support at least two power sources - USB and EPS.
3. On-board computer system and attitude determination sensors must work from 3.3 V supply.
4. All the components must have industrial temperature range of at least -40 to 85 °C.
5. Commercially off-the-self components must be used that are widely available for lower cost.
6. Printed circuit board design must not use blind or buried vias, traces thinner than 0.2 mm nor vias smaller than 0.2 mm.

On-board computer system specific requirements

1. Microcontroller must be able to control the power of the on-board computer system's subcomponents such as memories, communication drivers and sensors.
2. On-board computer system must not source current from other systems other then electrical power system.
3. On-board computer system must feature current consumption measurement capability for on-board memories, communication drivers and attitude determination sensors.
4. Temperature measurement must be available near memories and communication interfaces.
5. On-board computer system must include on-board mass storage for data logging, firmware images and custom functions.
6. On-board computer system must include dedicated low-power memory for storing mission critical data such as bootloader command list, configuration tables, error logs.
7. On-board computer system must include additional non-volatile high speed random-access memory for attitude and orbit control system algorithms and data compression.
8. Radiation tolerant memory should be used where possible.

AOCS sensor board specific requirements

1. Attitude and orbit control system sensors must be on an expansion board since final sensor selection is not available.

2. On-board computer system must be able to power cycle attitude determination sensors.

3. I^2C should be avoided if possible. [5]

4. Sensors must be redundant, in order to enable averaging between measurements or to have a backup in the case that a sensor fails permanently.

5. Same type of sensors must be on different buses to mitigate the failure of a communication bus.

6. Temperature sensors are required as close as possible to all the sensors for calibration purposes.

	STM32F767II [13]	ATSAME70Q21 [14]	STM32F401VE [15]
Clock	216 MHz	300 MHz	84 MHz
Core	Cortex-M7	Cortex-M7	Cortex-M4
FPU	Double precision	Double precision	Single precision
Flash	2 MB	2 MB	512 KB
SRAM	512 KB	384 KB	96 KB
GPIO	132	114	81
UART/USART	4/4	5/3	0/3
SPI	6	2	4
QSPI	2	1	0
I^2C	4	3	3
Other	L1-cache 2x16 KB JPEG codec	L1-cache 2x16 KB	
Package	LQFP-176	LQFP-144	LQFP-100
Current consumption	440 μA/MHz	300 μA/MHz	146 μA/MHz
Performance	1082 CoreMark 462 DMIPS at 216 MHz	1512 CoreMark 645 DMIPS at 300 MHz	285 CoreMark 105 DMIPS at 84 MHz

Table 2.1: Comparison between different microcontrollers considered for the on-board computer system.

2.2 On-board computer system

Microcontroller

At the center of the on-board computer system (Figure 4.46), there is a microcontroller to communicate with and to perform computation intensive tasks for other systems on the satellite. Compression of mission logs and experiment data will use an FFT based algorithm. For this, Cortex-M7 has digital signal processing (DSP) instructions that would speed up calculations. AOCS will be implementing Kalman and Particle filters that would greatly benefit from double precision floating point unit and tightly coupled memory. Different microcontrollers were considered (Table 2.1), but in the end STM32F767IIT6 was chosen. There were mainly three reasons:

1. ESTCube's team familiarity with the STMicroelectronics microcontrollers and the standardization that sees only two microcontroller types being used - one for computation intensive systems and the other for always on subsystems that must have low power consumption [2].

2. The second reason was that this particular microcontroller had one of the best CoreMark scores, standardized benchmark indicating execution of simple code [17], and had just become available.

3. The third reason was the number of pins and peripherals required to implement all the required communication, memory and AOCS sensor interfaces. STM32F7 family also supports bigger packages (Table 2.1) with more pins to extend the on-board computer system capabilities for the next design iterations if needed.

With previous electronics designs done with STM32F4 series and its pin-to-pin compatibility with STM32F7 family - the transition to the new and better microcontroller was easy. Although 400 MHz STM32H7 family with 2020 CoreMark has been announced, it is not yet available and has smaller transistors (40 nm technology) which might make it more susceptible to single event effects [16].

One of the biggest shortcomings that the STM32F7 microcontroller family has for the on-board computer system is its external interrupt/event controller (EXTI) that support only 16 external interrupt lines at any single given time [13]. With the current design the total number of available interrupt lines is more than 32 as demonstrated in table 2.3. Although many of the AOCS interrupts may never be used, they still are needed while software is being developed in case they become relevant in later phases of the project. To handle less frequent interrupts, an external input/output extender MCP23S17 was used as a workaround. It has two 8-bit ports that can be configured as external interrupt input lines. On a single port all the interrupts can be OR'ed or AND'ed together and a single line can be used to signal microcontrollers EXTI so that the software can read through SPI on which line the interrupt occurred. In the current prototype the I/O expander added support for 14 additional interrupts. [18] Some of the possible interrupt lines were left out because of the design constraints and low importance. If those interrupts become necessary, test points can be used to connect them to pin headers for software development purposes on the first prototype board.

Memories

On-board computer system in ESTCube-2 has to keep logs of the satellite operations, hold configuration data for sensors and algorithms, store several firmware images, custom functions and their metadata, as well as offer storage for other systems. All of these tasks require different types of memory which is additionally made even more challenging by the space environment. Bit flips are quite serious in registers when entering or returning from an interrupt, function call or when looping. They can also cause serious issues in attitude or orbit control system algorithms. For example, a single bit flip might cause thrusters to go off with maximum thrust. Thus, it would make sense to have these algorithms keep their variables in radiation tolerant memory. Another layer of security will be provided by implementing error correction and data scrubbing.

High speed parallel magneto-resistive random-access memory (MRAM) was selected because it is non-volatile and radiation tolerant by design which makes it less susceptible to single event effects. It can still be affected during read and write operations due to being based on CMOS technology. [19] Everspin Technologies 16 Mb parallel MRAM MR4A16B was used in 54-TSOP2 package for its availability and user-friendly package. It uses 20-bit address bus and 16-bit data bus with dedicated access to the upper and lower byte through signaling pins (Figure 4.13). The parallel communication bus is compatible with the bus used in most parallel static random-access memories. [20] This made it possible to connect MR4A16B to the STM32F767 using flexible memory controller and SRAM controller to hide the actual signaling from the programmer. MRAM is used to keep the data of running programs which can be recovered if power is lost abruptly thanks to its non-volatile nature. MRAM will be used to run AOCS algorithms and data compression.

Since ferroelectric random-access memory (FRAM) is low density and uses serial interface, it's best to use it for configuration tables, error logs, on-board statistics, for data that don't need to

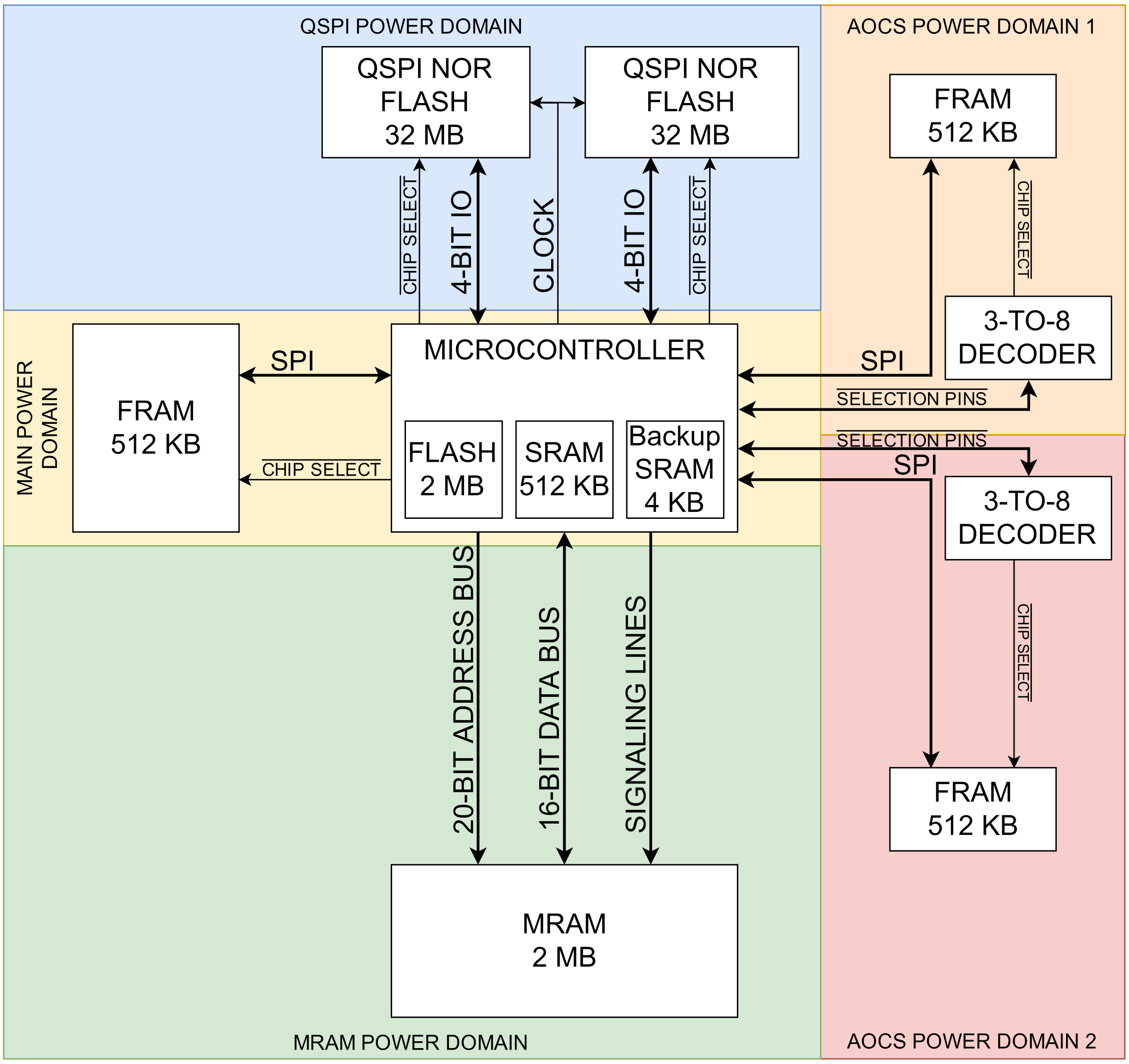


Figure 2.2: Block diagram of the memories used in the on-board computer system and their communication buses.

be accessed very often and data without strict latency restrictions. It has been tested in laboratory environment to have radiation tolerance against single event upsets [21] but its interfacing electronics uses CMOS technology which is still susceptible to all the radiation effects [22]. [24] On-board computer system uses FRAM for its low power consumption - 300 μA active current at 1 MHz. Cypress CY15B104Q was chosen since it offers the highest capacity currently available - 4 Mb. For communication, it uses SPI - this allowed to put this memory on different buses used for other purposes for redundancy. [23] Three memory modules are distributed around on-board computer system. The first FRAM module is on the same bus with the I/O expander and real time clock (Figures 4.3, 4.11, 4.15 and 4.16). Two other memory modules are on the same bus with the two attitude and orbit control system's sensor groups as demonstrated on figure 2.2. Maximum communication speed is limited by the CY15B104Q which support SPI clock up to 40 MHz [23].

Availability of COTS radiation tolerant memories is limited and their capacity is not very big. For mass storage NOR flash memory was used to keep data and segments of firmware. One of the communication protocols used to transfer data between memories is quad serial peripheral interface (QSPI). It can either be used as a single SPI bus or as four bidirectional lines for im-

	MRAM (MR4A16B)	FRAM (CY15B104Q)	Flash (MT25QL256)
Capacity	16 Mb	4 Mb	256 Mb
Interface	Parallel	SPI	Quad SPI
Data bus width	16	1	4(8[1])
Clock	28 MHz	40 MHz	108(90[2]) MHz
Standby current	5 mA	100 μA	30 μA
Read current	60 mA	300 μA/MHz (12 mA)	28 mA
Write current	152 mA	300 μA/MHz (12 mA)	35 mA
Volatility	Non-volatile	Non-volatile	Non-volatile
Radiation tolerance	Yes[3]	Yes[3]	No
Package used	54-TSOP2	TDFN	W-PDFN-8

1. Dual bank mode.
2. Double transfer rate mode.
3. Read/write electronics not radiation tolerant.

Table 2.2: On-board computer system's external memory comparison (ordered by clock rate).

proved throughput. Two MT25QL256ABA1EW9 [25] are used, resulting in 64 MB for mass storage (Figures 4.7 and 4.14). Both STM32F767 and the flash memory support execute-in-place (XIP) which makes it easier to load program instructions directly from memory without writing additional signaling software. In dual bank mode, both flash memories are accessed simultaneously. With double transfer rate mode and dual bank mode throughput up to 180 MB/s can be reached [13,25]. Flash memory is used to keep different versions of firmware, as well as to store on-board measurements and payload data except for camera images that are stored by the payload.

Other memories available in on-board computer system are flash and SRAM inside the microcontroller. STM32F767II has 2 MB of flash memory organized in two banks allowing read-while-write, 512 KB of SRAM and 4 KB SRAM for backup to use in low-power modes. It also supports tightly coupled memory interface which allows the CPU to access parts of the SRAM at clock speed. [13]

All the external memories used have standard package and communication protocol, which makes it easy to replace them if the need arises or higher memory capacity versions become available. QSPI flash has multiple alternatives available. Up to 1 Gb memory module is available - it was not used because it stacks memory layers on top of each other and possibly makes it more susceptible to single event effects [26].

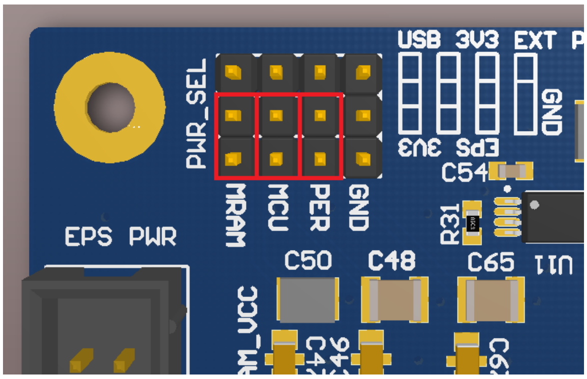
Communication interfaces

Different systems in the ESTCube-2 will have to communicate with each other. The control systems will use the internal communication protocol (ICP) to interact with each other. This bus will be implemented using half duplex RS485 and two signaling lines (Figures 4.4, 4.10, 4.22 and 4.26). STM32F767's UART/USART modules support RS485 by implementing driver enable signal in hardware. To drive the RS485 lines using UART/USART, LTC2850 by Linear Technology was used. It supports maximum of 20 Mbps data rate with a low operating current [27]. These data rates are probably never reached since other microcontrollers on the line are low power MSP430FR's running at 16 MHz. To conserve the pins needed from the on-board computer's microcontroller, the driver enable (DE) and receiver enable (RE) pins were connected together so that only read or write operation can be done at a time (Figure 4.22). RS485 differential lines also require terminating resistors at both ends of the bus which were added and will be soldered based on the location the on-board computer system ends up at the time of testing. Two signaling lines that ICP supports are SHUTUP and ACCESS (Figure 4.3) [28]. SHUTUP is used for stopping the communication on the bus in case there is a rogue subsystem keeping the bus busy by repetitively transmitting packets. It is a bidirectional open-drain line with interrupt capability. For both the main and backup ICP bus an EXTI pin was used. ACCESS line is a means to minimize the probability of packet collisions, as well as to wake systems on packet reception. Wakeup capable pins were used to bring microcontroller out of sleep modes. On the main ICP bus there will be on-board computer system, electrical power system, communications system and side panels. On the backup ICP bus there will be OBCS, EPS and COM but no side panels, as these would need too many interconnections and are not mission critical (Figure 2.1). Additionally there is one open-drain bidirectional interrupt line reserved for low latency signaling and synchronization between each system - OBCS and EPS, OBCS and COM, OBCS and side panels. There are also additional interrupt lines between other systems that are not shown in the figure 2.1. All the communication lines make sure that if one of those fails there is a backup. All the connections are brought out on the prototype board by the IDC pin header named "SYSTEM BUS" (Figure 4.2).

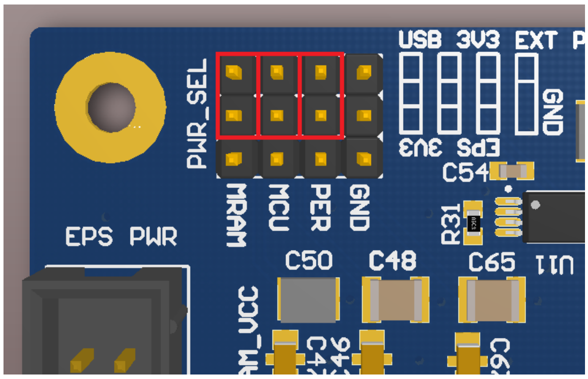
For star tracker there is a dedicated point-to-point RS232 communication bus and one bidirectional interrupt line (Figure 2.1). RS232 bus is driven by the STM32F767's internal UART and interrupt line is connected directly to EXTI. Star tracker can interface with on-board computer system using IDC pin header named "STAR TRACKER BUS" on the prototype board (Figure 4.2).

ESTCube-2 will have multiple payloads by different suppliers with different control interfaces. For this reason RS485 and CAN (Figures 4.21 and 4.22) were implemented on the prototype board. RS485 driver is controlled by the microcontroller's UART and can support data rates up to 27 Mb/s with a compatible RS485 driver for increased data rates and throughput. For CAN there is a dedicated peripheral in the STM32F767 named basic extended controller area network (bxCAN). Bit rates go up to 1 Mb/s and support both 2.0A and 2.0B Active standards. CAN is used for high reliability messaging. The current prototype board also supports three unidirectional interrupt lines connected directly to microcontrollers EXTI and three output signaling lines for the payloads.

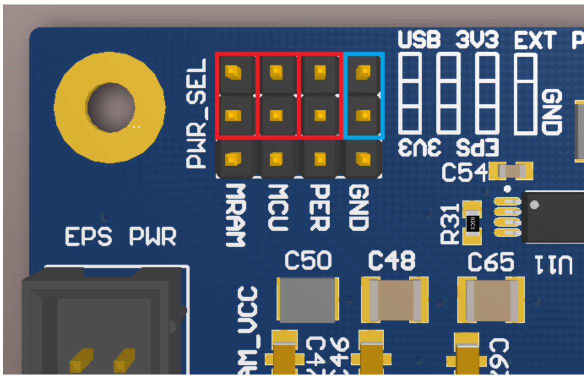
All the signaling and interrupt lines are disconnected from the microcontroller using bus switches whenever the entire system or a part of it is powered down. This guarantees that other systems can't drain power from on-board computer system nor can they supply current while it might be powered down. If bus switches are not used, then injected current might damage the microcontroller or cause undefined behavior. Also, any system connected but powered off might enter an undefined state due to draining power from the OBCS via ESD protection diodes. 2-bit SN74CB3Q3306A and 8-bit SN74CB3Q3245 FET bus switches were used for this purpose. Both of them have an I_{off} circuitry that prevents current backflow while they are powered down [29, 30].



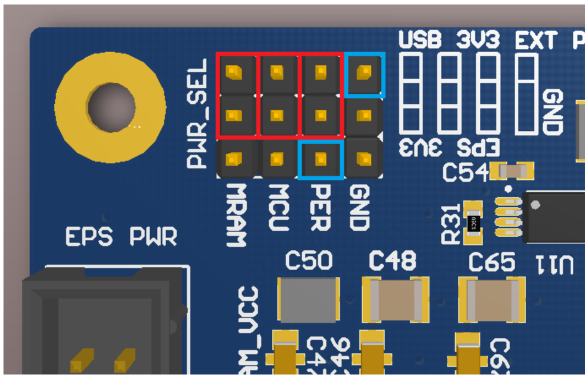
(a) Powered by EPS.



(b) Powered by USB.



(c) Powered by external power supply or USB.



(d) Powered by EPS or USB. Blue pins connected together with a jumper wire.

Figure 2.3: Onboard computer system's power configuration options.

Power distribution

The current on-board computer system design assumes that the electrical power system delivering three 3.3 V power rails each capable of supplying up to 300 mA. This is necessary so that overcurrent events can be averted with a minimal amount of component overhead. Biggest power consumers on the on-board computer system are microcontroller and magnetoresistive random-access memory. STM32F767IIT6 has a maximum current consumption rated at 293 mA [13] and MRAM has a maximum current consumption rated at 180 mA [20]. Third power rail is dedicated for external peripherals that have their own power switches. These are in the design so that on-board computer system can power down parts of the system to consume less power and to reset them if needed. These power switches also provide additional overcurrent protection for parts of the OBCS which can happen in various circumstances. One of those possible events is caused by the radiation's single event latch-up. In this case, when the transistor is hit by a particle, its state may change and create a high current path which can only be removed by powering down. In on-board computer system latch-off power switches are used that cut the power if an overcurrent event is detected. After this, they signal microcontroller through fault line which is connected to the EXTI through I/O expander.

Two different power switches were used for the prototype design. One for power domains that require less than 40 mA and one for those requiring more. TPS22943 (Figure 4.18) was used to supply power to attitude and orbit control system sensors and to temperature sensors. It can supply up to 40 mA and has a low resistance of 0.5 Ω at 3.3 V. If the current limit is exceeded

Component	Number of interrupts	Assignment
Attitude and orbit control system sensors	10	4 EXTI + 4 I/O expander
Real time clock	2	1 I/O expander
Power switch faults	6	6 I/O Expander
ICP interrupts	4	2 EXTI + 2 Wakeup
Electic and power system	1	MCU EXTI
Communications system	1	EXTI
Star tracker	1	1 EXTI
Side panels	1	1 EXTI
Payloads	3+	3 EXTI
Temperature alert	3	

Table 2.3: On-board computer system interrupt lines and their assignment with the current design.

the power switch will cut the power and raise a fault signaling line after which the application can decide what to do next. [31] The other power switch was TPS2553-1 (Figure 4.19) that works similarly to the previously described power switch except its current latch-off level can be set by an external resistor. [32] This was used for ICP bus, payload interfaces and QSPI memories. The current latch-off threshold I_{OSnom} can be found by the equation 2.1 where R_{ILIM} is the external resistor connected between the ILIM pin on the power switch and ground (Figure 4.19). [32]

$$I_{OSnom} = \frac{23950\ V}{R_{ILIM}^{0.977}\ \text{k}\Omega} \tag{2.1}$$

The current prototype board has three connectors for power supply where one is configurable header to select the actual power source. Since USB gives out a 5 V power rail, then it's necessary to convert it to 3.3 V. For this purpose a step-down DC/DC switching regulator was used. For the situations where power supplying USB host doesn't have a current limiting or other protection capability, a resettable 0.75 A fuse is used between the power regulator and the USB connector. To allow supplying power from multiple sources a power source multiplexer was used. It is set up so that USB power is secondary and used only in cases when no other power supply is present (Figure 4.9). For the first prototype there is an EPS power header that supplies power to the entire OBCS from a single rail and also power rail for reaction wheels used by the AOCS. To select the power source, there is a header which allows selecting different power configurations. Figure 2.3 shows some possible combinations to supply power to the on-board computer system where the red and blue rectangle represents jumpers.

Sensors

Over the spacecraft's lifetime, both radiation as well as temperature can affect current consumption, voltage level and clock rate. Radiation dose is measured externally by dosimeters connected to the side panels. Both current consumption and temperature are measured by OBCS components. Current sense amplifiers were put after each power switch which measures voltage drop on a shunt resistor (Figure 4.20). Linear Technology LT6105 was used for this purpose. It has a 1 % gain accuracy and low operating current at 150 µA. The output voltage which is measured by the microcontroller's analog to digital converter follows equation 2.2 where R_{OUT} is 10 kΩ and R_{IN} is 100 Ω (Figure 4.20). [33] This gives a 100 time amplification to the output voltage compared to the voltage drop on the shunt. The actual current that goes through the shunt is then calculated using Ohm's law and taking into account ADC reference voltage and temperature variations.

$$V_{OUT} = V_{SENSE} * \frac{R_{OUT}}{R_{IN}} \tag{2.2}$$

For temperature measurements near flash memories, MRAM and CAN driver, MCP9808 (Figure 4.17) was used which has a typical accuracy of 0.25 °C over the whole operating temperature. It is available in a small 2 x 3 mm package and consumes only 200 µA while operating. Communication with the microcontroller is over I^2C bus. To support multiple temperature sensors on the same bus MCP9808 has three address configuration pins supporting up to eight or sixteen sensors at the time. Temperature sensor address configurations are shown in the figure 4.8. Current prototype features power switch and a resistor to bypass it. This is for initial testing to see if the temperature sensors could be powered through current limiting resistor to lower the component count and pins required from the microcontroller. The disadvantage of using resistors is that if a short circuit event happens then it can only be mitigated by powering down the entire on-board computer system. Power consumption of the temperature sensors is very low and for that reason its current consumption is not measured separately.

Debugging and programming

Software development often runs into issues which require dedicated tools to debug. To program and debug the microcontroller a 2x10 IDC header is available that works with tools like J-Link and ST-LINK/V2 [36]. It supports SWD that is used to program Cortex-M microcontrollers and SWO that can be used to send trace data to the development environment. SWD uses four lines - SWDIO for data transfer and SWDIO for clock, nRST to reset the microcontroller and a power pin to detect if the microcontroller is powered up. SWO uses single asynchronous line to send trace data (Figure 4.10). [37] USB to UART interface was implemented on the prototype board through which software developers could send and receive data. FTDI FT230XS was used which supports transfer rates from 300 bps to 3 Mbps [34]. It is only turned on when the microcontroller has been powered up and USB cable is connected. Since this was not the default configuration for the chip, it had to be reprogrammed using FTDI's FT_Prog software. Figure 4.9 shows that CBUS0 is used as a voltage sense pin which had to be set as a VBUS_Sense in the FT_Prog [35].

For visual feedback there are nine LEDs - two LEDs for USB and microcontroller power indication, two LEDs for indicating USB receiving and transmitting data, one LED to indicate boot pin status, two LEDs that are directly connected to the microcontrollers GPIO and two LEDs that programmers can manipulate but share a pin on microcontroller with push button and I/O expander's port B interrupt (Figure 4.10). There are two pushbuttons: one for resetting the microcontroller, the other for triggering user events. In order to select whether the microcontroller boots its internal bootloader or firmware in Flash, a boot pin is used. The state of the boot pin can be changed with a slide switch (Figure 4.10). Testing pin header can be used to measure current sense amplifier outputs (Figure 4.2). Test points were added for OBCS board to measure voltage levels in different power domains and capture signals on QSPI, CAN and UART buses. The actual number of debugging and testing interfaces were limited by the number of pins on the microcontroller and available space on the prototype board. For this reason only the most important debugging and programming interfaces were implemented.

2.3 Attitude determination sensors

Attitude and orbit control system is responsible for moving the satellite into the correct orientation and spinning the satellite to perform the E-Sail experiment. For this, AOCS requires sensors to measure the satellite's movement. These sensors will be placed on the same PCB with on-board computer system. This is done to save space for other systems in ESTCube-2. Because final sensor selection is not yet finished and algorithm development requires unrestricted movement of sensors, the expansion board was developed. Component free areas on the OBCS PCB makes it possible to easily integrate the content of the expansion boards into the main PCB later. The sensor selection was based on Georgi Olentšenko's thesis "Prototype design of ESTCube-2 attitude and orbit control system" [38].

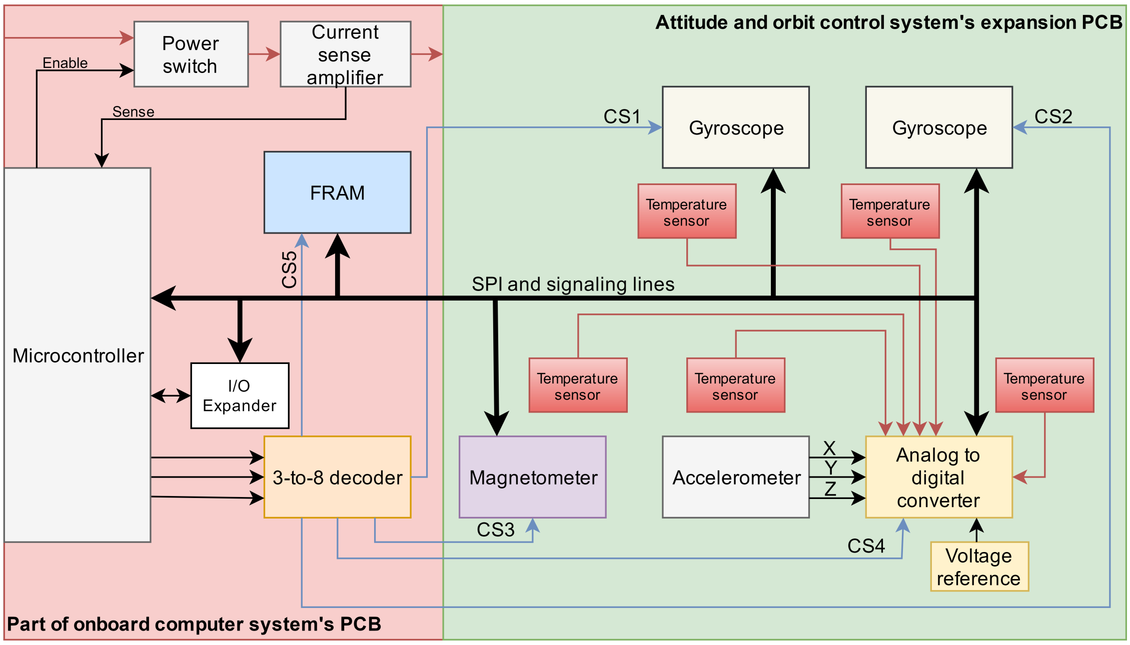


Figure 2.4: Block diagram with one of two attitude determination sensor groups and its connections to the on-board computer system.

Two identical sensor groups are used for attitude and orbit control system to provide redundancy in case of failure. A single sensor group has two digital gyroscopes, one analog accelerometer with analog to digital converter, one digital magnetometer and an FRAM. Each sensor and analog to digital converter has its own analog temperature sensor to allow for temperature compensation. Each AOCS sensor group (Figures 4.3 and 4.5) has its own power switch and current sense amplifier. If a particular sensor group is not used, then it can be powered off. Also, if some error has been detected, then power switch can reset all the sensors. Current sense amplifier is used to measure current consumption for diagnostic and testing purposes. To keep calibration data, each AOCS sensor group has its own memory module. FRAM was used to keep power consumption low, to have better protection against radiation effects and to make accessing the memory similar to sensor communication. All the devices communicate through SPI (Figure 4.34) and the device used can be selected through a 3-to-8 decoder (Figure 4.24). This only requires three pins from the microcontroller and supports up to seven SPI devices on a single bus.

Analog to digital converter used for attitude determination sensor board is Texas Instruments ADS8332 (Figure 4.35). It has 8-channels and uses 16-bit successive approximation ADC with sampling rate up to 500 ksps. Power consumption at maximum sample rate is typically 5.2 mA. [39] Voltage supplied by the electrical power system will most likely be too unstable for accurate ADC measurement. For this reason a 3 V high accuracy voltage reference ADR3430 (Figure 4.35) by Analog Devices was used [40]. ADC measures accelerometer's all three axes outputs and temperature sensors (Figure 2.4). The ADS8332 has pins MUXOUT and ADCIN which can be used to implement a single low pass filter for all the input channels. To support this feature a pin header was added to expansion board. If no filter circuitry is connected to these pins a jumper must be connected so that the ADC can function properly (Figure 4.35).

Attitude determination sensors selected for the expansion board were based on their performance and communication interface. Since there were problems with I^2C interface in the ESTCube-1 [2], decision was made to only use SPI for ESTCube-2. Analog accelerometer KXRB5-2050 (Figure 4.36) [41] was chosen for the prototype board for its low noise density [38]. It has three analog outputs that indicate acceleration and all of them are connected to the analog to digital converter (Figure 4.34). All the digital magnetometers tested for AOCS satisfied the requirements [38], LIS3MDL (Figure 4.37) [42] was chosen for its availability at the time as was MPU-6000 (Figure 4.38) [43] that was used for gyroscope.

On-board computer system's electronics board features a pin header (Figure 4.23) that is used to connect with attitude and orbit control system's sensor board (Figure 4.33). The connector was designed to allow different boards to be connected. This enables quick replacement of AOCS sensors without redesigning the OBCS board. The connector features two communication interfaces: an SPI and an I^2C bus. To lower pin count on the microcontroller 3-to-8 decoder was used to select between SPI devices. Four select lines are connected to the connector while one select line is connected to the FRAM. The connector has three general input/output pins directly connected to the microcontroller out of which two can be used with EXTI. Four other pins are routed through I/O expander which can be configured to generate interrupt for the microcontroller. If SPI or I^2C is not used, then three or two pins respectively are available for signaling. Connector is designed so that connecting it in the wrong way would not power up the sensor board. Each attitude sensor board features a single LED to indicate that the board is powered up by the on-board computer system.

On the on-board computer system prototype board there are three connectors dedicated for reaction wheels which are used to rotate the satellite in space by attitude and orbit control system. The connectors provide an I^2C bus and are powered up from the electrical power system's connector. Current prototype design shares I^2C bus with temperature sensors. This is not ideal, but there is one available I^2C interface on the microcontroller currently used for debugging purposes. In the next design reaction wheels will get a dedicated bus for communication.

3 Software

3.1 Development tools

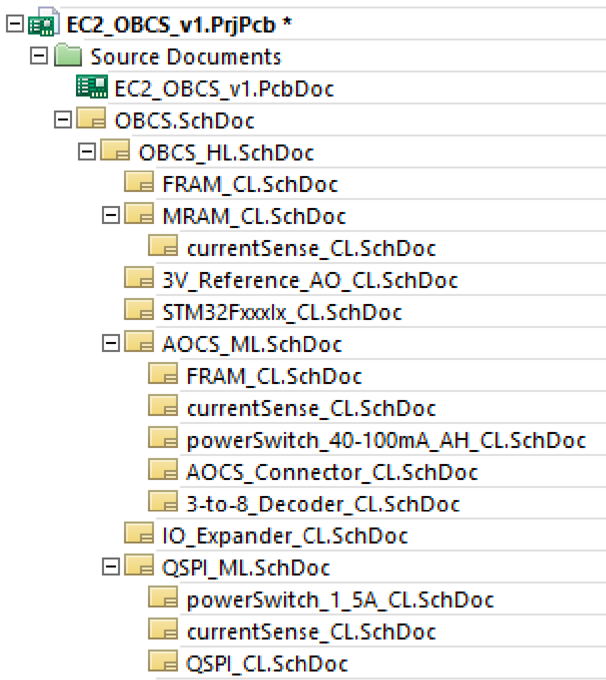


Figure 3.1: Part of the Altium Designer project tree with hierarchical structure.

For on-board computer system's hardware development three software tools were used. PCB design was performed using Altium Designer 16, which offered feature rich schematic and layout tools that sped up the development. For schematics design, hierarchical structure was used, meaning that schematics could add other schematics as components (Figure 3.1). This allowed designing complex electrical circuits while keeping actual details about specifics in separate sheets and making designs more readable. Schematic design was supported by the STM32CubeMX software developed by STMicroelectronics. It allowed to set up microcontroller pins, peripherals, clocks which provided additional confidence that all the connections were made correctly and no hidden features were overlooked. To make sure that all the hardware functions correctly, software had to be written. Since ESTCube-2 OBCS team develops its own hardware abstraction layer which was not ready for hardware testing, STM32F7 HAL was used. It hid most of the hardware registers and supplied high level functions that were easy to use for validating the hardware design. For software development Atollic TrueStudio was used. It is an integrated development environment built on eclipse to develop software specifically for ARM microcontrollers. STM32CubeMX directly supports TrueStudio, making it possible to generate project files without the need for any additional configuration.

3.2 Hardware validation and testing firmware

Software generated initialization code was used for hardware testing. All the possible initial configurations could be set from the STM32CubeMX software. For debugging, USART6, connected to UART to USB converter, was configured with a baud rate of 115200 bps, word length 8-bits, no parity and one stop bit. After the code was generated only two functions and one structure were needed to make a simple command and response interface that made the software easy to extend while maintaining repeatability. Listing 3.1 shows a simple command parser used for testing the hardware. It allowed sending commands that were separated by newline characters. To regenerate new source code and to keep user code, all the source code had to be written between comments "/* USER CODE BEGIN x */" and "/* USER CODE END x */". This made possible validating hardware functionality at low communication bit rates and test the hardware later using maximum possible configurations supported by the hardware. Most of the testing performed was sending bytes between communication interfaces and reading out device identification strings.

While developing firmware for the electronics, care must be taken that microcontroller does not source current to devices that are powered down. This may create undefined states on different lines that can affect other systems. All the pins that are connected to the external devices with dedicated power switch must be configured as inputs on two conditions, either the power switch is about to be turned off or a fault is detected on the power switch fault signaling line.

```
/* Infinite loop */
/* USER CODE BEGIN WHILE */
while (1)
{
        uint8_t data;
        if (HAL_UART_Receive(&huart6, &data, 1, 0) == HAL_OK)
        {
                if (data == '\n' && counter > 0)
                {
                        command[counter++] = '\0';
                        run_command();
                        counter = 0;
                }
                else if (data == '\n')
                {
                        counter = 0;
                }
                else
                {
                        command[counter++] = data;
                }
        }
/* USER CODE END WHILE */

/* USER CODE BEGIN 3 */
}
/* USER CODE END 3 */
```

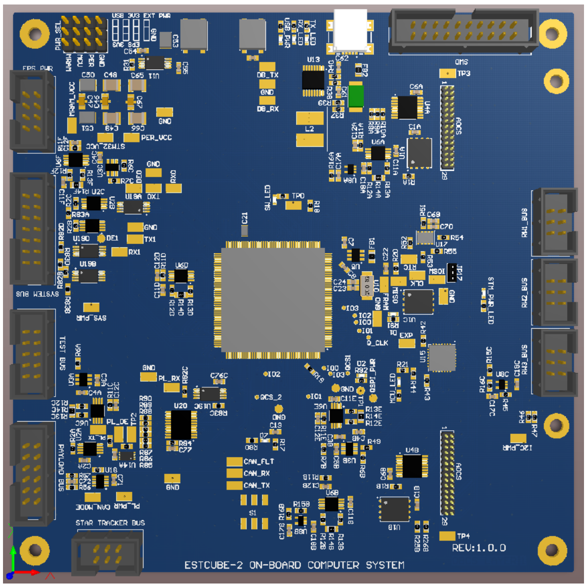
Listing 3.1: Simple USB debugging interface that supports commands separated by the newline character in main function.

4 Results

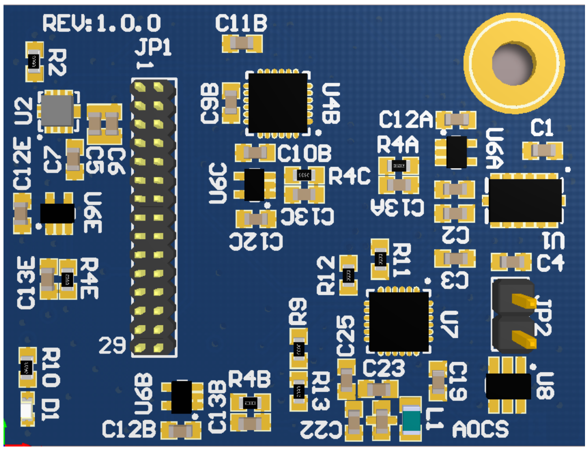
Two prototype PCBs were developed (Figure 4.1) - one for on-board computer system (a, c) and one for attitude determination sensors (b, c) used by the attitude and orbit control system. Prototype board dimensions for OBCS were 130 x 130 mm which exceeds the dimensions of the final engineering model that would not have that many debugging, programming interfaces and test pads. IDC connectors were used which take more space on the PCB, but they make it easier to connect cables between different systems. Both electronics boards use six layer PCB's. One layer is used only for ground plane (Figures 4.28 and 4.41) and one layer is dedicated for power distribution (Figures 4.31 and 4.44). All other layers were used for component placement and for traces (Figures 4.27, 4.29, 4.30, 4.32, 4.40, 4.42, 4.43 and 4.45). For development only COTS components (Tables 4.1 and 4.3) were used that met the required industrial temperature range of at least -40 to 85 °C. Developed boards works from 3.3 V power source and it can be supplied through USB or from external source. Microcontroller can power down parts of the on-board computer system and bus switches are used to make sure that no current is injected into the system while powered down. Three different memory types were used - low power FRAM, high speed parallel MRAM and QSPI flash for mass storage. Both the FRAM and MRAM are radiation tolerant by design. For attitude determination only SPI devices were used but also I^2C was added to the connector if needed for future design. For redundancy two sensor groups were implemented, each featuring a magnetometer, an accelerometer, two gyroscopes and an FRAM.

The only shortcoming for the selected microcontroller was its limited support for external interrupts. As a workaround I/O expander was used to extend the support for up to 30 interrupt lines. During initial testing a couple of problems with the first prototype came out. There are missing pull-up resistors on the MRAM schematic on figure 4.13. All the signaling lines require them. If the microcontroller is in the reset state it has all the pins configured as inputs. This causes an undefined state on the signaling lines used to control the MRAM. During testing, memory corruption was encountered. The other problem occurred with I^2C. Also, considerable crosstalk was witnessed between the I2C SCL and SDA lines at 400 kHz clock. It did not have any effect on the communication but it could damage components that can't handle negative spikes of around 0.9 V.

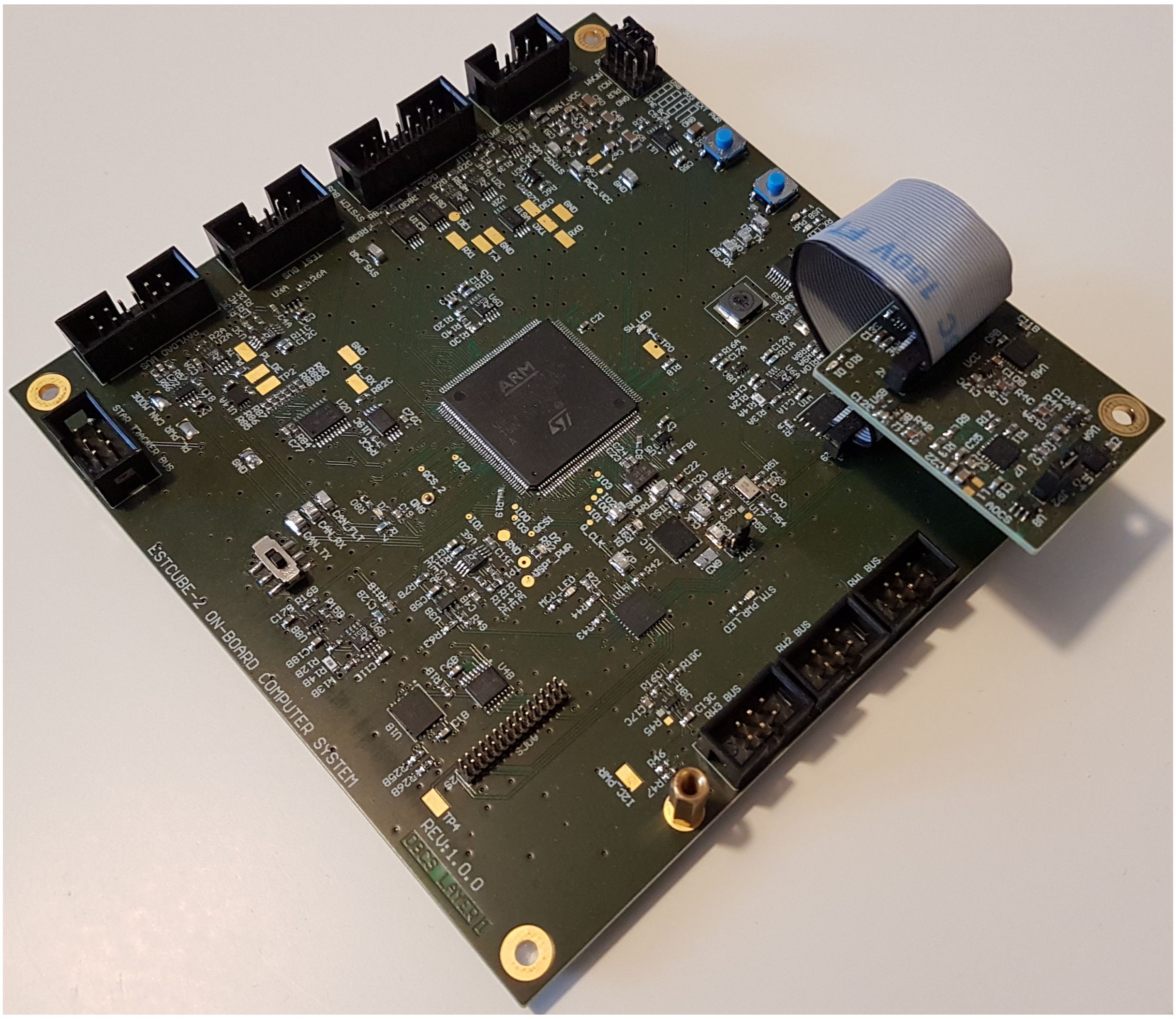
A potential improvement for the current prototype boards is to add LEDs and improve PCB silk screen. On-board computer system can power up different parts of the system and LEDs should have been used to indicate their statuses. LEDs on interrupt line would also make firmware debugging easier. With multiple schematic design iterations, some of the names given for the components do not describe their actual function. Also, there are missing silk screen labels for buttons and connector pins. Currently their names have to be checked from the documentation every time an external connection needs to be made.



(a) PCB editor 3D top view of on-board computer system.



(b) PCB editor 3D top view of attitude determination sensor board.



(c) Assembled prototype board for on-board computer system with attitude determination sensors.

Figure 4.1: 3D PCB models and assembled PCB image of on-board computer system prototype board and attitude determination sensor expansion board.

Conclusion

The purpose of this thesis was to develop an electronics prototype board for ESTCube-2 on-board computer system with attitude determination sensors. STM32F767 was chosen to be the microcontroller that runs the system. Different communication interfaces were implemented to communicate with other systems in the satellite. ICP bus is used to communicate with EPS, COM and side panels. RS232 is used for star tracker and for payloads RS485 and CAN were implemented. For data storage three different types of memory were used out of which FRAM and MRAM have increased radiation tolerance against SEU. FRAM can be accessed over SPI supporting low power consumption while MRAM uses parallel interface and offers high speed random-access memory to the microcontroller. For mass storage two QSPI NOR flash memories were used that feature dual bank and double transfer rate modes to achieve high throughput and execute programs directly from it. Latch-off power switches were used for three reasons - to mitigate possible damage caused by a single event latch-up, to reset and to power down for low power consumption. Current sense amplifiers and temperature sensors are used to monitor and diagnose the on-board computer system. SWD bus with asynchronous SWO was implemented to program and debug the microcontroller. Additionally, UART to USB converter was added to easily exchange data between development PC and microcontroller. The PCB features test points for probing the traces of on-board communication buses, if needed. Attitude determination sensor board was developed for initial software and algorithm testing. The sensor board connector provides SPI, I^2C and multiple interrupt and signaling lines which would allow for the testing of different sensors without requiring a redesign of the OBCS board. The attitude determination board features an analog accelerometer, analog temperature sensors, an analog to digital converter, a digital magnetometer and two gyroscope. Simple firmware was developed for functionality testing of the hardware. For this, STM32CubeMX initialization source code generator was used for. All the requirements set at the beginning of the thesis were fulfilled. At the time of writing most of the hardware has been successfully tested. Communication interfaces like RS485, RS232, SPI, I^2C and USB can send and receive data. Interrupts are triggered in the EXTI and signaling pins can be manipulated. Current consumption can be measured using testing bus and microcontroller's ADC. Communication with FRAM and MRAM has been established and sensor registers have been accessed.

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PDF: https://store.invensense.com/datasheets/invensense/MPU-6050_DataSheet_V3%204.pdf, 16.05.2017, 16:00 (UTC).

Annexes

Value/Name	Description	Designator	Quantity
100nF	Ceramic capacitor	C1A, C1B, C1C, C2A, C2B, C2C, C3A, C3B, C3C, C4A, C4B, C4C, C5A, C5B, C5C, C6A, C6B, C8, C11A, C11B, C11C, C11D, C11E, C11F, C12A, C12B, C12C, C12D, C12E, C12F, C14, C15, C18A, C18B, C18C, C19, C26, C29, C30, C31, C32, C33, C34, C35, C36, C37, C38, C39, C40, C41, C42, C43, C44, C45, C54, C55, C59, C63A, C63B, C63C, C64, C64_2, C69	63
1uF	Ceramic capacitor	C7, C17A, C17B, C17C, C27	5
10uF	Ceramic capacitor	C9A, C9B, C10A, C10B, C13, C16, C53	7
2.2uF	Ceramic capacitor	C20, C21	2
1nF	Ceramic capacitor	C22	1
2.2pF	Ceramic capacitor	C23, C24	2
100 nF	Feed-Through Capacitor	C25, C46, C47, C67	4
4.7uF	Ceramic capacitor	C28	1
10uF	Ceramic capacitor	C48, C49, C50, C51, C65, C66	6
22uF	Ceramic capacitor	C56, C57	2
200nF	Ceramic capacitor	C60	1
47pF	Ceramic capacitor	C61, C62	2
100nF	Ceramic capacitor	C68A, C68B, C71, C72, C76A, C76B, C76C, C76D, C77	9
10nF	Ceramic capacitor	C70	1
10uF	Ceramic capacitor	C73, C74, C75	3
LED	Light Emitting Diode	D1, D2, D7, MCU_LED, RX_LED, STM_PWR_LED, SW_LED, TX_LED, USB_PWR	9

MINISMDC075F	Resettable fuse	F1	1
2508056017Y2	Ferrite bead	FB1, FB2	2
* nH	Inductor	L1	1
6.2 uH	Inductor	L2	1
100k	Resistor	R1A, R1B, R1C, R3A, R3B, R3C, R6A, R6B, R6C, R7A, R7B, R7C, R8A, R8B, R9A, R9B, R10A, R10B, R15A, R15B, R15C, R16A, R16B, R16C, R41A, R41B, R41C, R42, R43, R44, R50A, R50B, R51, R52, R53, R54, R58, R81A, R81B, R81C, R81D, R82A, R82B, R82C, R82D, R83A, R83B, R83C, R83D, R84, R85, R86, R87, R88, R89, R90	56
120R	Resistor	R2A, R2B, R2C	3
10k 0.1%	Resistor	R11A, R11B, R11C, R11D, R11E, R11F	6
100R 0.1%	Resistor	R12A, R12B, R12C, R12D, R12E, R12F, R13A, R13B, R13C, R13D, R13E, R13F	12
0Rxx	Shunt	R14A, R14B, R14C, R14D, R14E, R14F	6
10k	Resistor	R17, R20, R30, R33, R34, R39	6
0R	Resistor	R18, R19, R21, R55	4
270R	Resistor	R22, R23, R24, R35, R36, R80, R91, R92	8
3.9k	Resistor	R25A, R25B, R26A, R26B	4
1k	Resistor	R29	1
500R	Resistor	R31	1
560R	Resistor	R32	1
4.7k	Resistor	R37, R46, R47	3
27R	Resistor	R38, R40	2
100R	Resistor	R45	1
109k	Resistor	R48	1
75k	Resistor	R49	1
60R	Resistor	R56, R57	2
*R	Resistor	R59	1
JS202011SCQN	2-position slide switch	S1	1
EVQQ	Push buttob	S2, S3	2
CY15B104Q-LHXI	FRAM 4Mb	U1A, U1B, U1C	3
LTC2850IMS8	RS485 driver	U2A, U2B, U2C	3
TPS2553DBVR-1	Power switch	U3A, U3B, U3C	3
SN74HC138PW	3-8 line decoder	U4A, U4B	2

ADR3430ARJZ-R7	Voltage reference	U5	1
LT6105	Current sense amplifier	U6A, U6B, U6C, U6D, U6E, U6F	6
MR4A16BCYS35	MRAM 16Mb	U7	1
TPS22943DCKR	Power switch	U8A, U8B, U8C	3
STM32F767IIT6	Microcontroller	U9	1
7A-24.000MAAJ-T	Crystal	U10	1
TPS2111PW	Power distribution switch	U11	1
TPS62046DGQ	Step-down converter	U12	1
FT230XS-R	USB to UART IC	U13	1
MCP9808T-E/MC	Temperature sensor	U14A, U14B, U14C	3
MCP23S17T-E/ML	16-bit I/O Expander	U15	1
MT25QL512ABB	QSPI flash memory	U16A, U16B	2
RV-3049-C3	RTC	U17	1
TCAN337GDCNT	CAN bus transeiver	U18	1
SN74CB3Q3306A	2-bit bus switch	U19A, U19B, U19C, U19D	4
SN74CB3Q3245	8-bit bus switch	U20	1

Table 4.1: Onboard computer system's bill of materials.

Value/Name	Description	Designator	Quantity
100nF	Ceramic capacitor	C1, C5, C7, C9A, C9B, C11A, C11B, C12A, C12B, C12C, C12D, C12E, C18, C19, C23, C25, C31, C32	18
3.9nF	Ceramic capacitor	C2, C3, C4	3
1uF	Ceramic capacitor	C6, C17	2
2.2nF	Ceramic capacitor	C10A, C10B	2
1nF	Ceramic capacitor	C13A, C13B, C13C, C13D, C13E	5
100uF	Ceramic capacitor	C22	1
10uF	Ceramic capacitor	C30, C37	2
100 nF	Feed-Through Capacitor	C38	1
LED	Light Emitting Diode	D1	1
* nH	Inductor	L1	1
100k	Resistor	R1, R2, R3A, R3B, R4A, R4B, R4C, R4D, R4E, R9, R11, R12, R13	13
270R	Resistor	R10	1
KXRB5-2050	Accelerometer	U1	1
LIS3MDL	Magnetometer	U2	1
MPU-6000	Gyroscope	U4A, U4B	2
LMT86DCK	Analog Temperature Sensor	U6A, U6B, U6C, U6D, U6E	5
ADS8332IRGET	16-Bit, 500-kSPS, 8-Channel ADC	U7	1
ADR3430ARJZ-R7	Voltage reference	U8	1

Table 4.3: Attitude and orbit control system’s expansion board bill of materials.

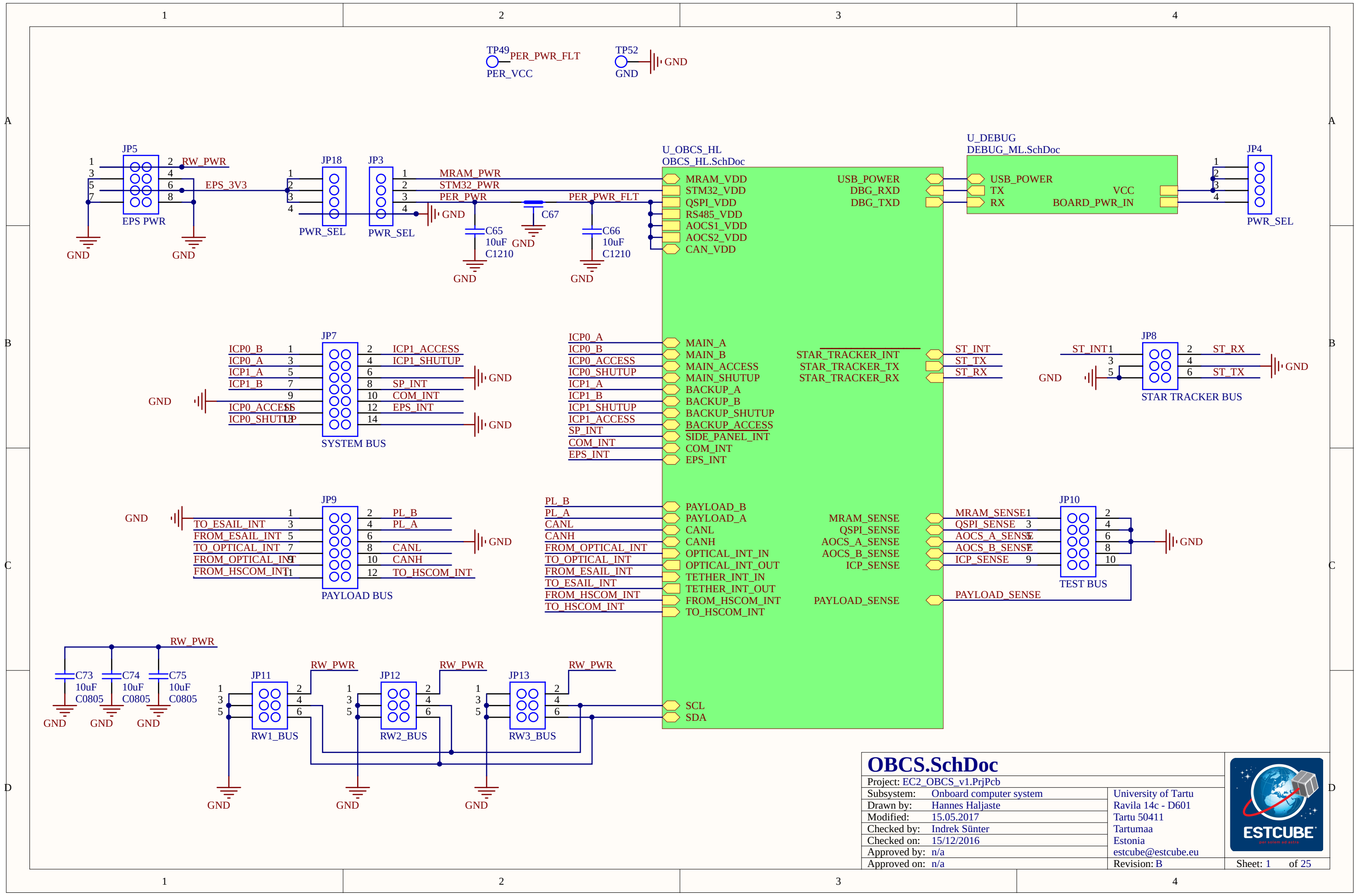

Figure 4.2: On-board computer system connectors with system's high level overview.

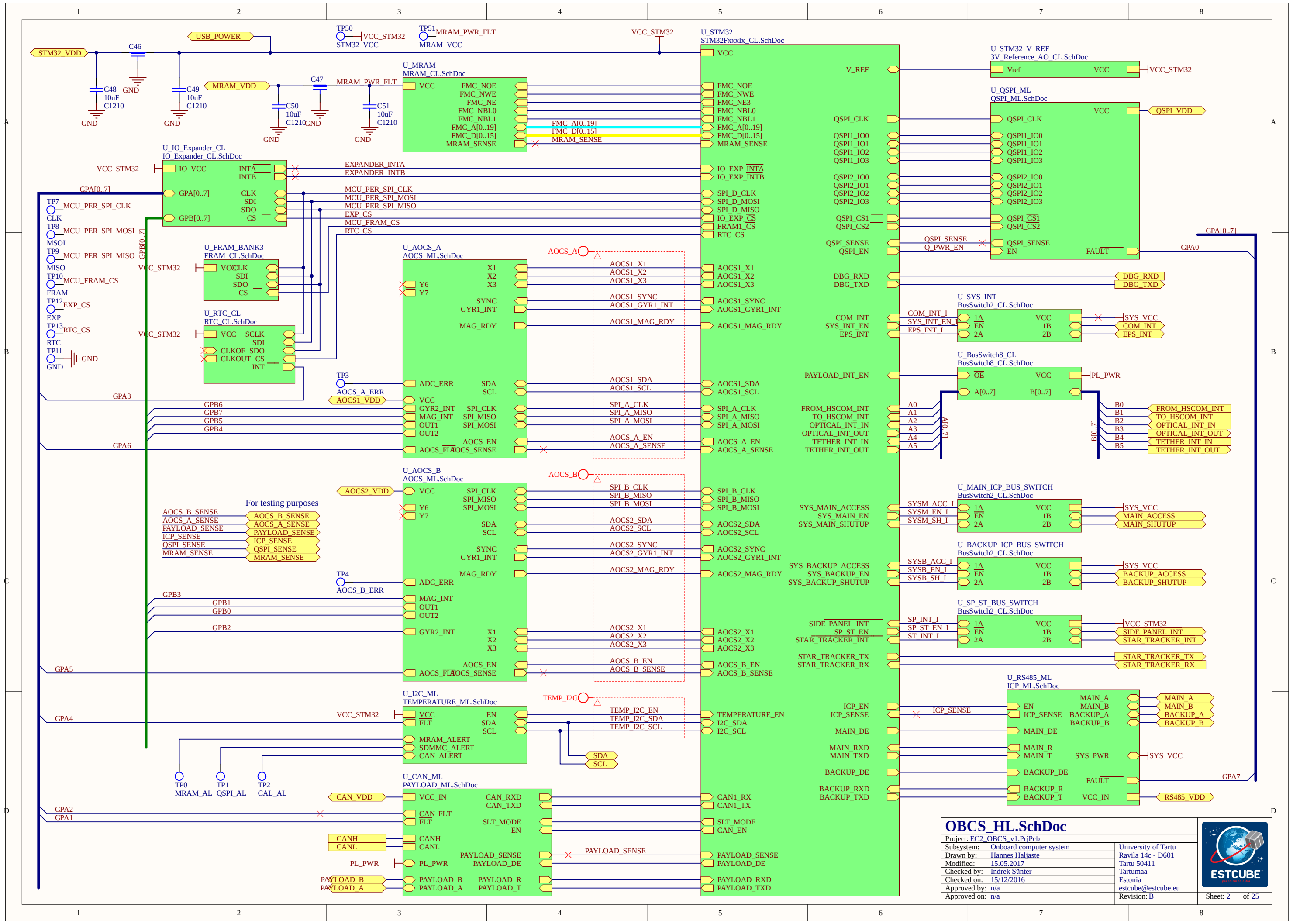

Figure 4.3: On-board computer system's bus schematic between different parts.

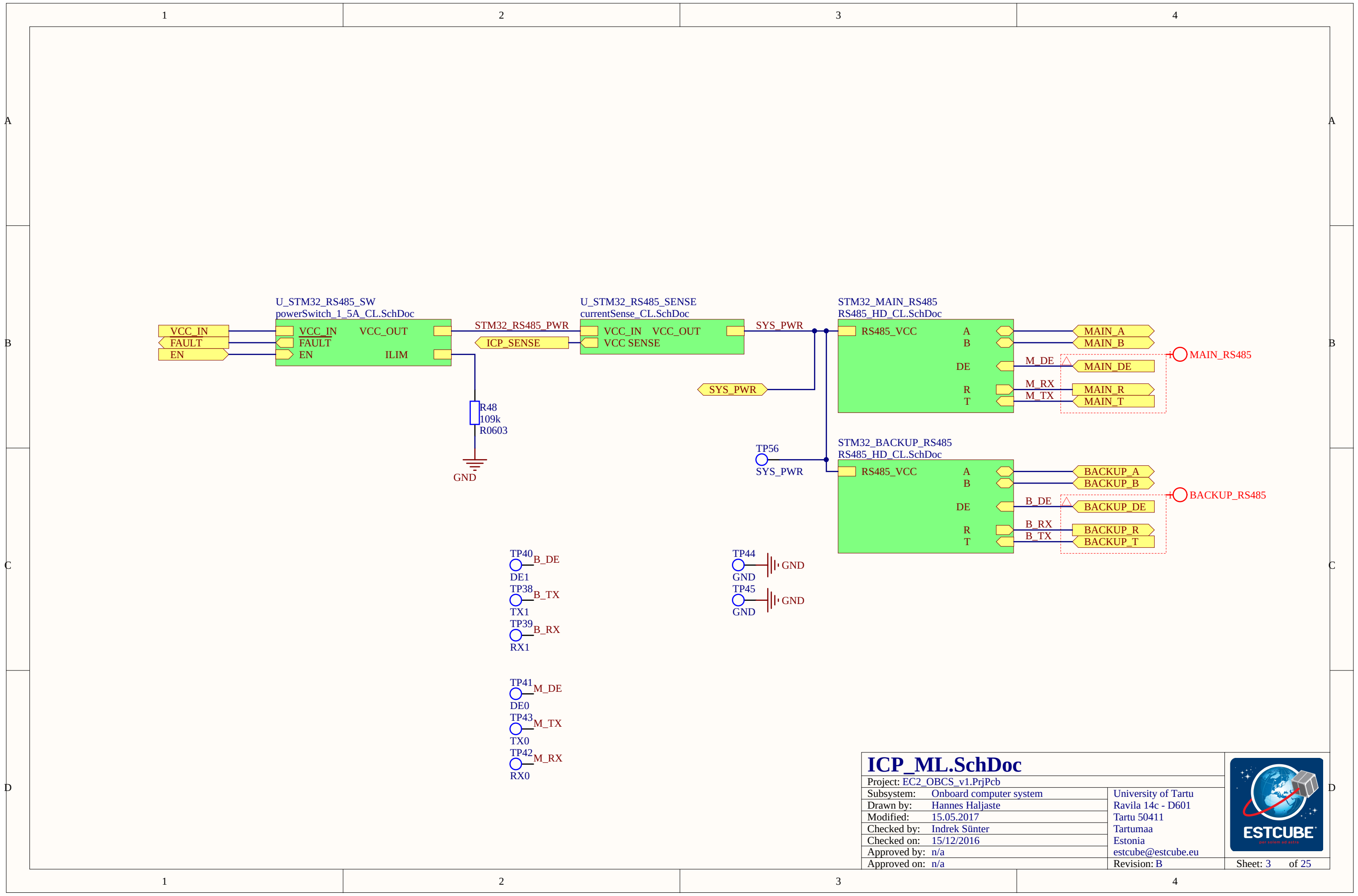

Figure 4.4: On-board computer system's ICP schematic.

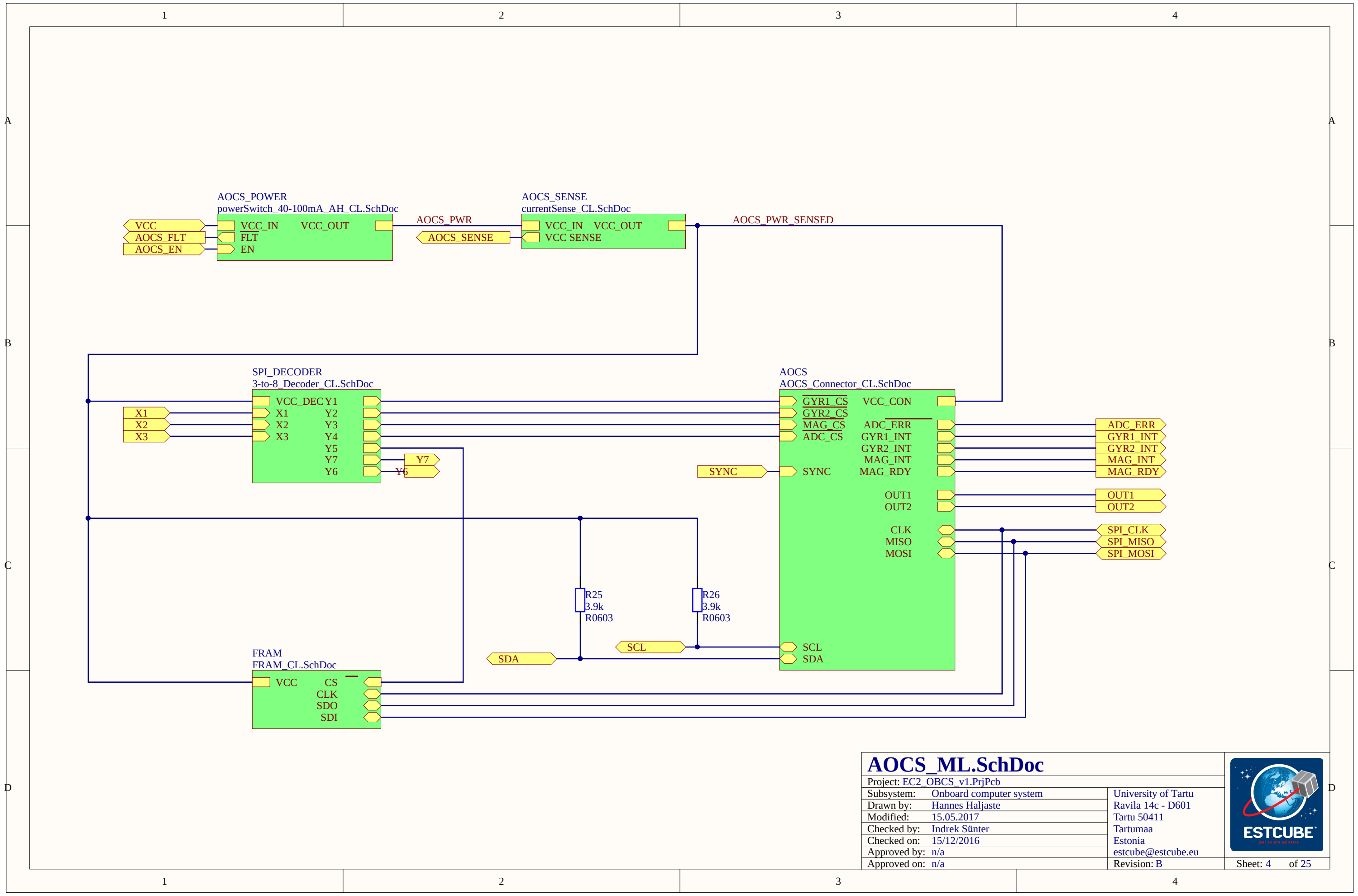

Figure 4.5: Attitude and orbit control system's component connection schematic on on-board computer system.

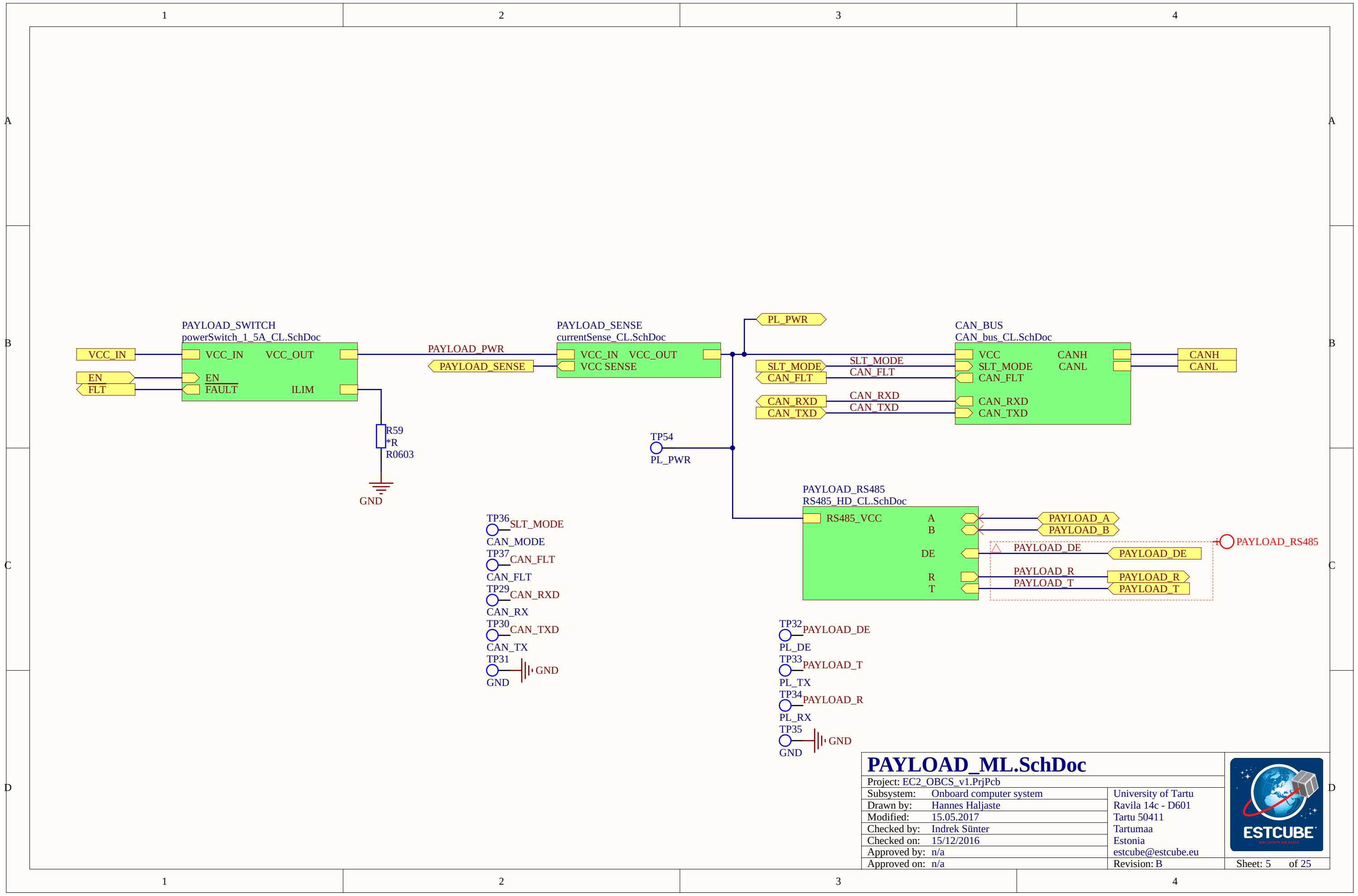

Figure 4.6: On-board computer systems payload interfaces schematic.

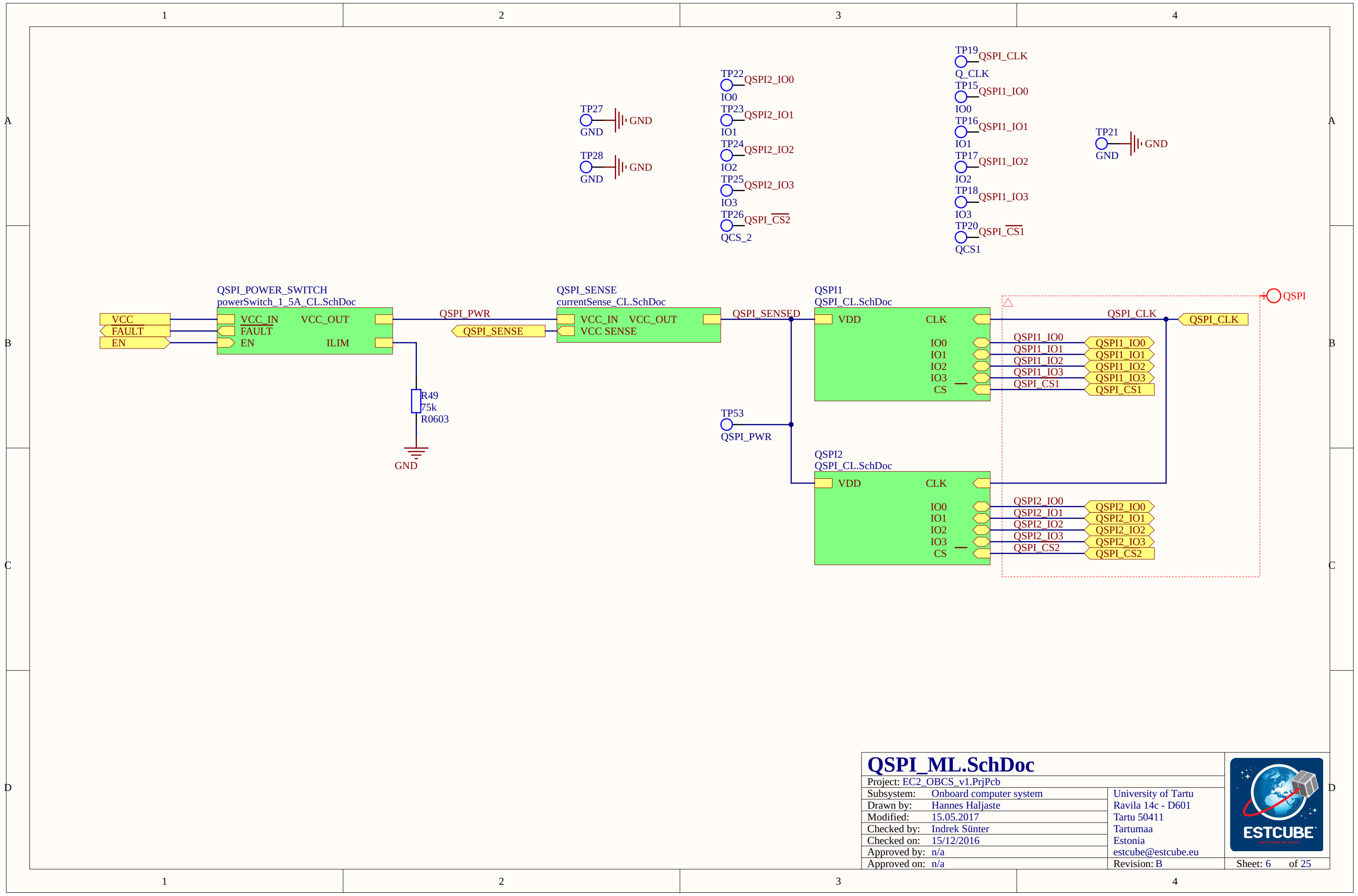

Figure 4.7: QSPI flash memory components schematic.

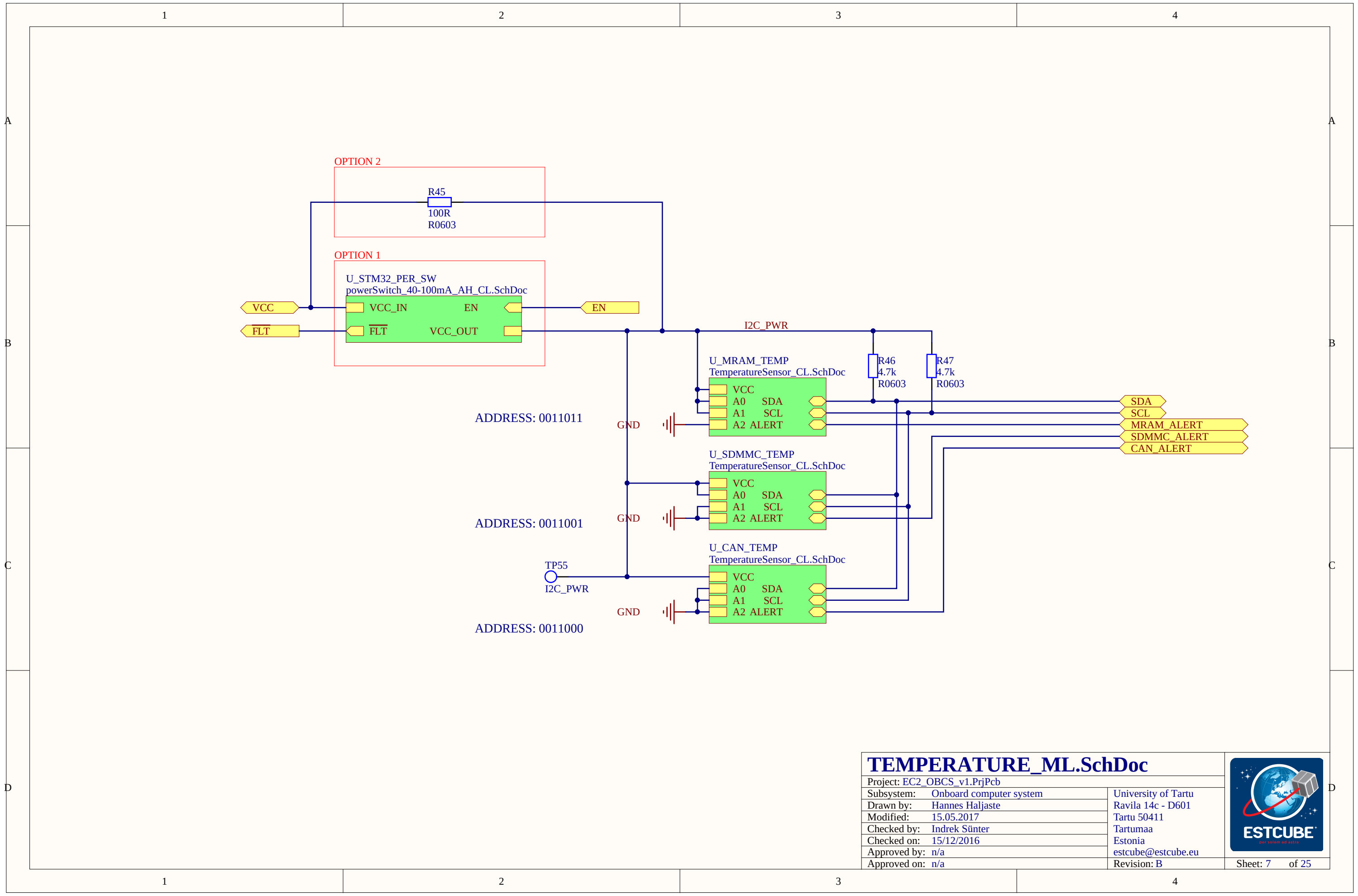

Figure 4.8: Temperature sensor components schematic.

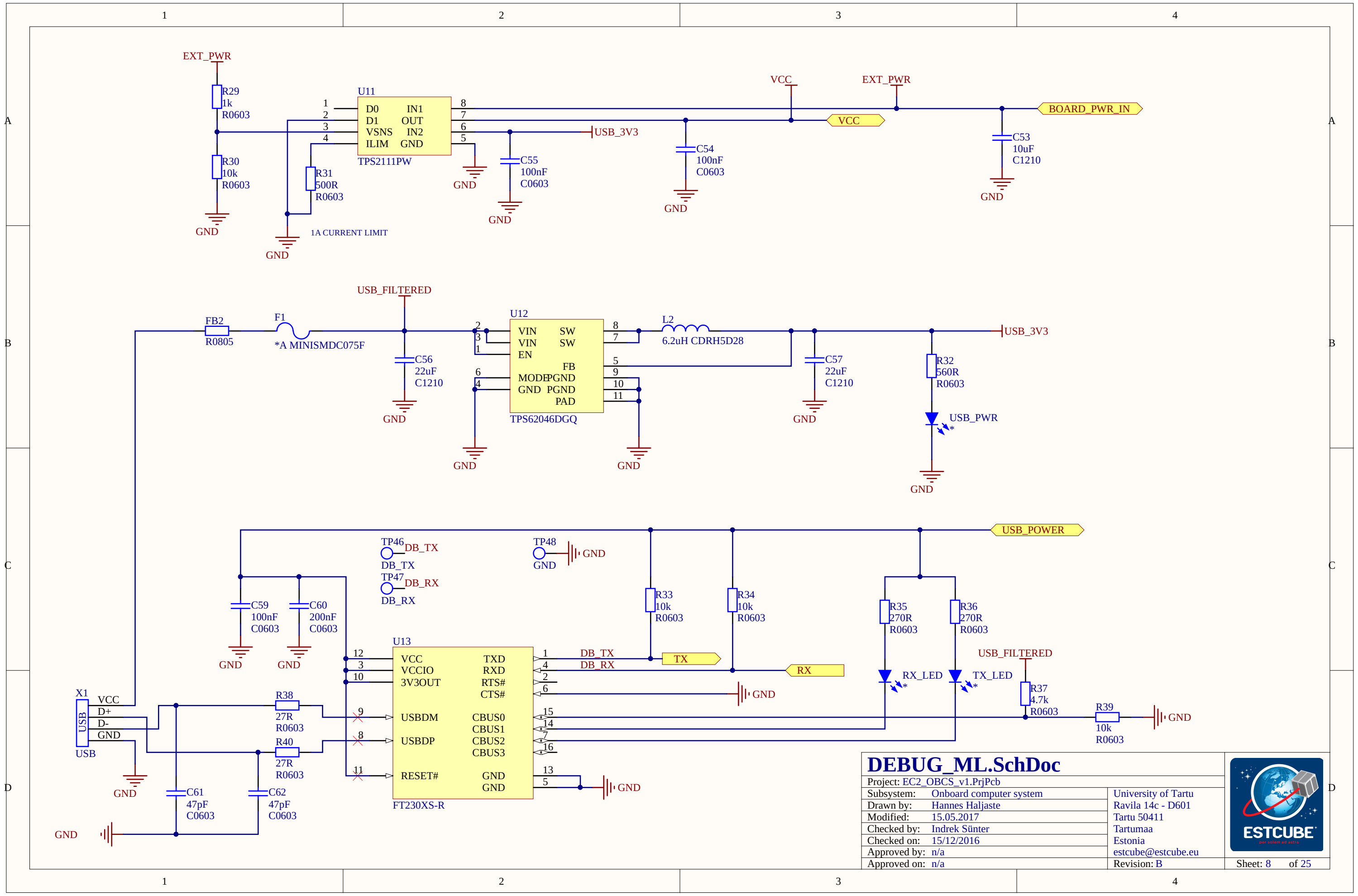

Figure 4.9: USB debug interface and power source selection schematic.

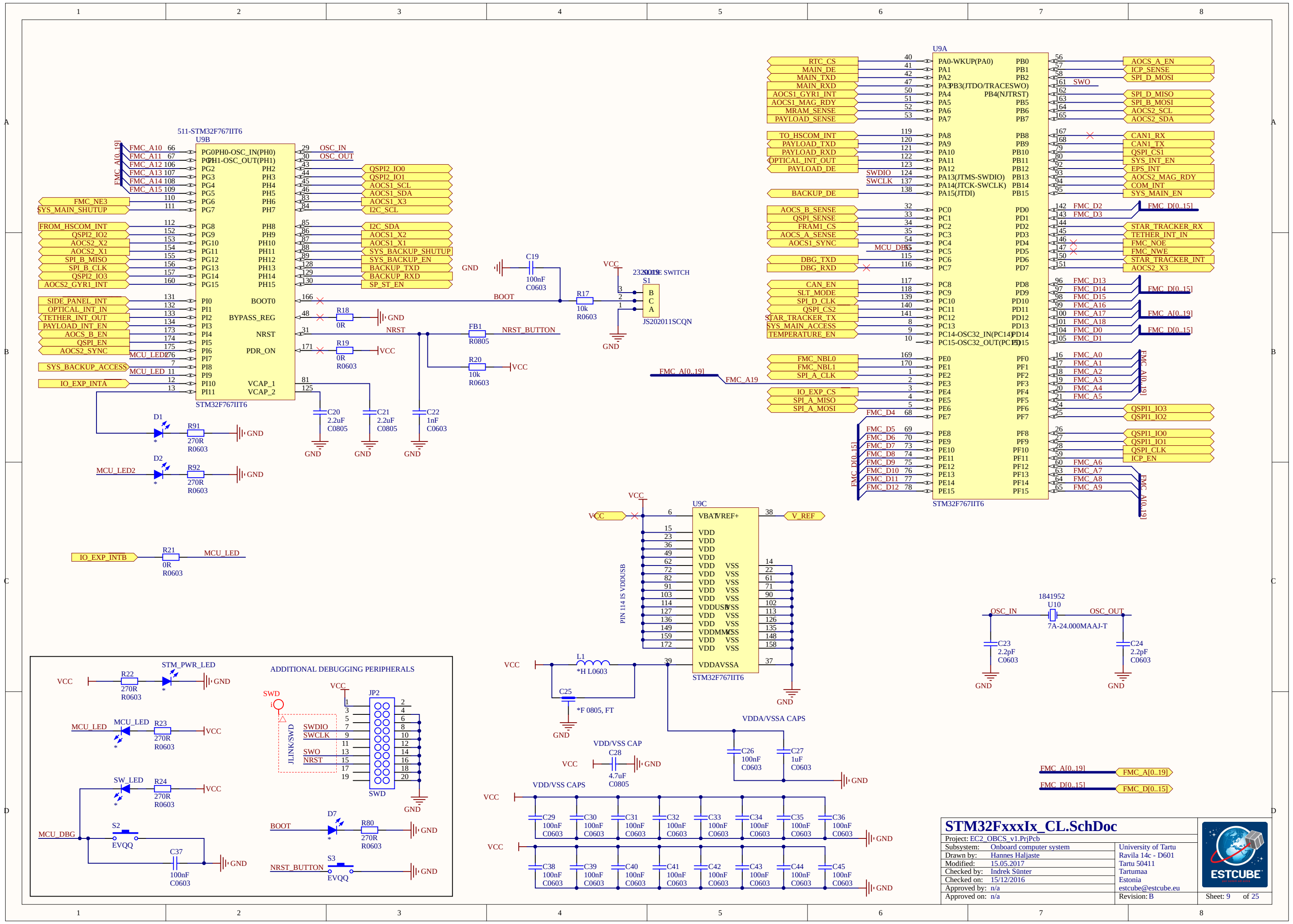

Figure 4.10: Microcontroller's connections and support peripherals schematic.

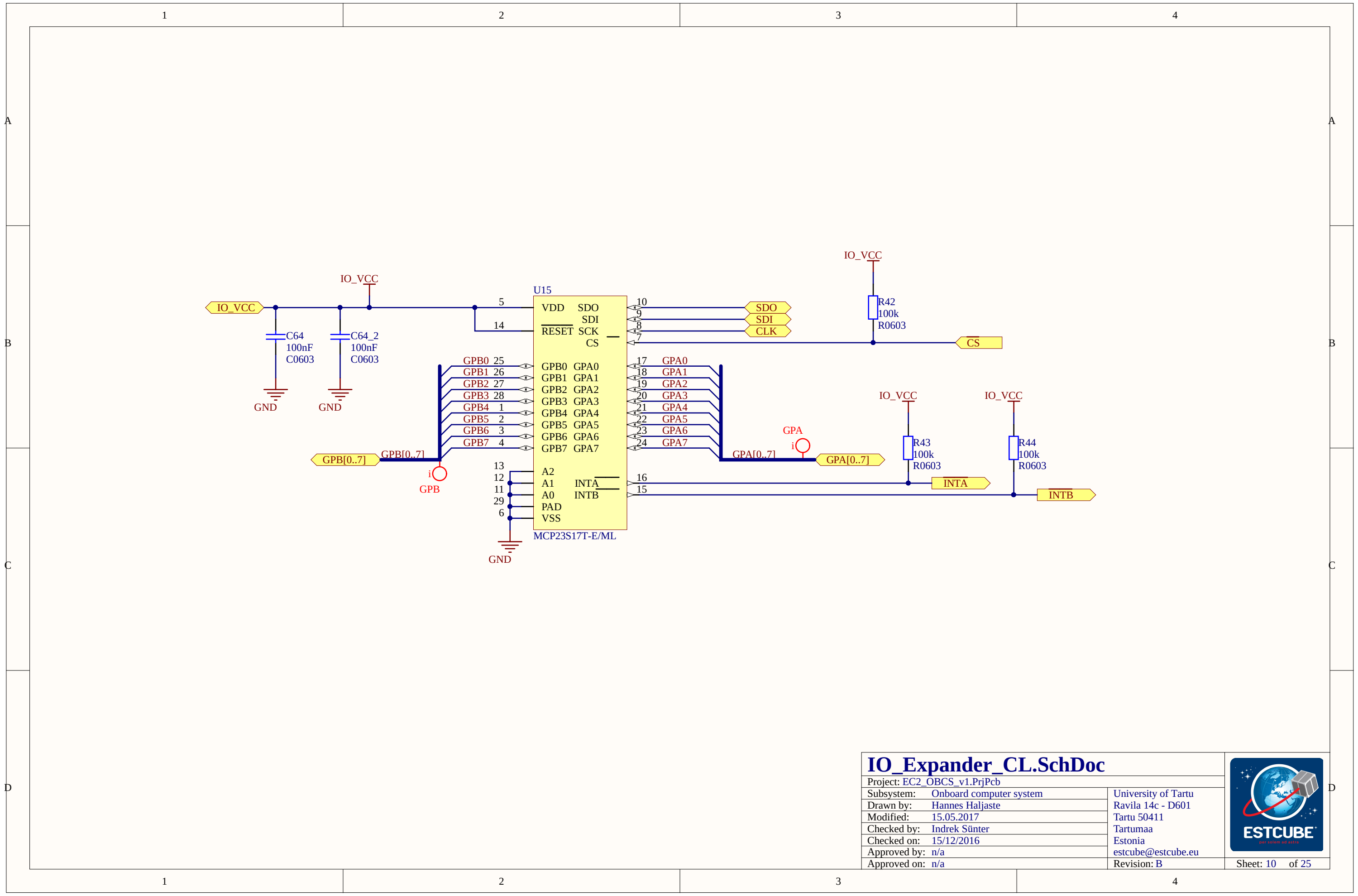

Figure 4.11: I/O expander schematic.

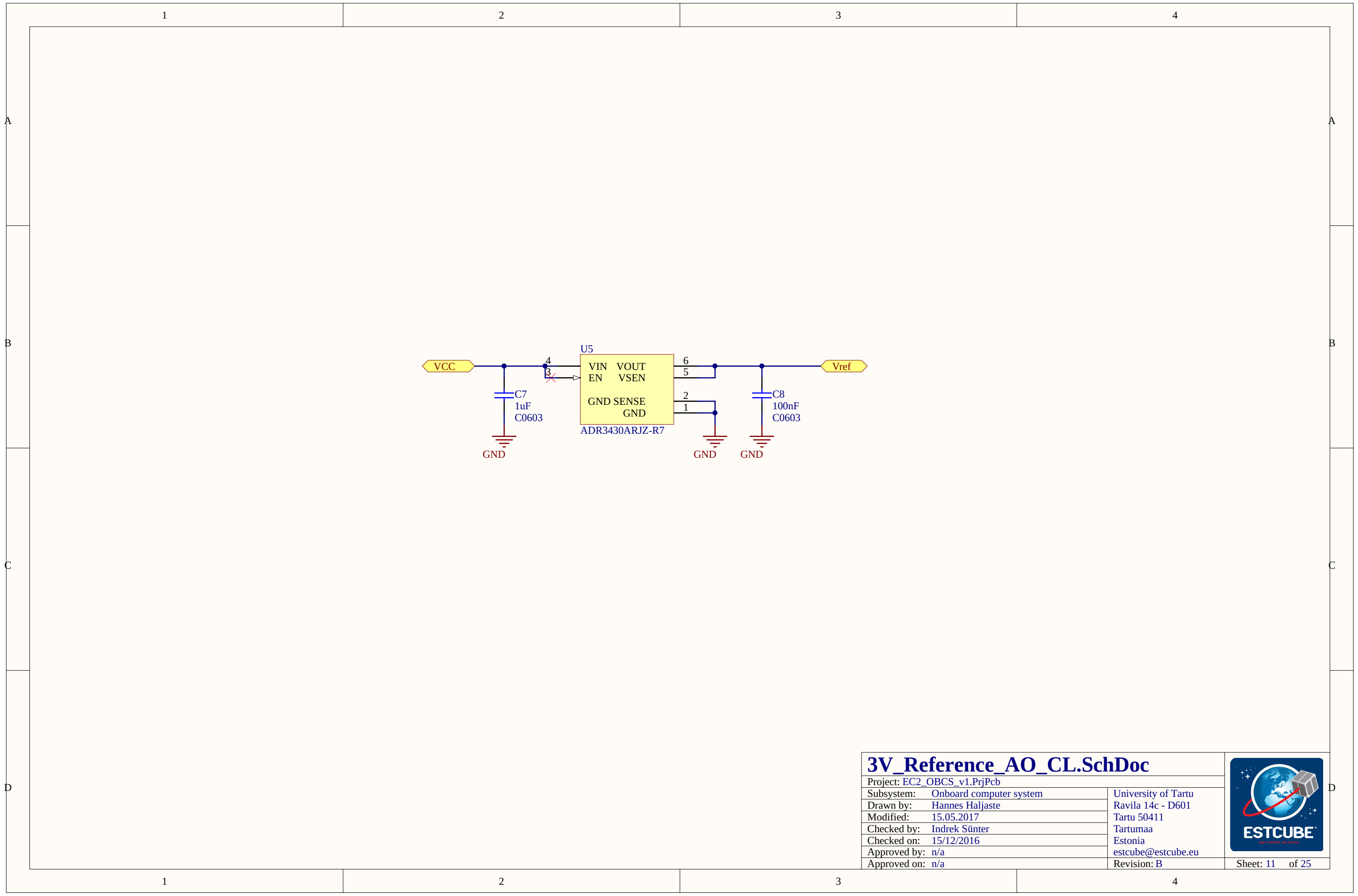

Figure 4.12: 3 V reference schematic.

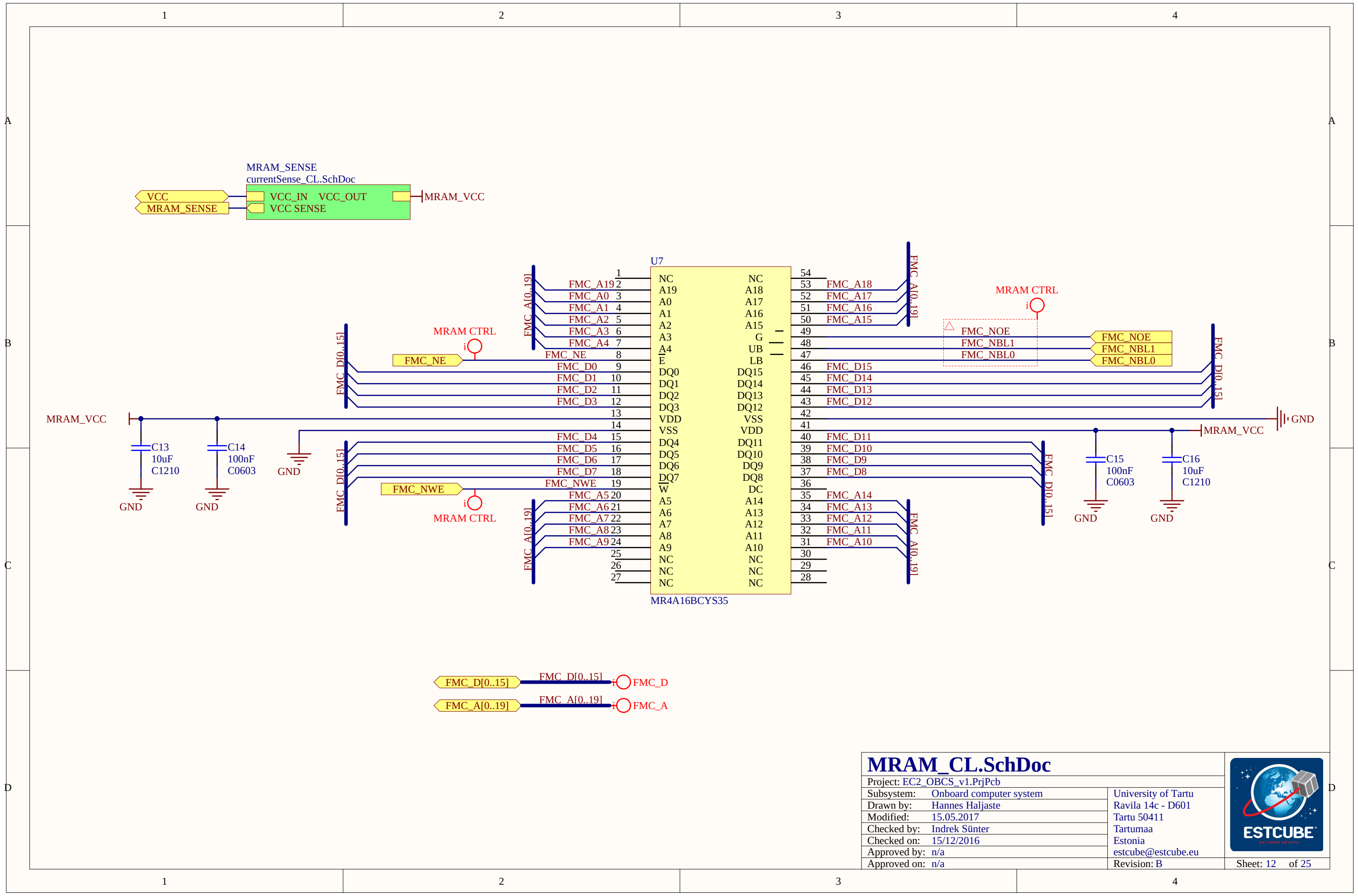

Figure 4.13: Magnetoresistive random-access memory schematic.

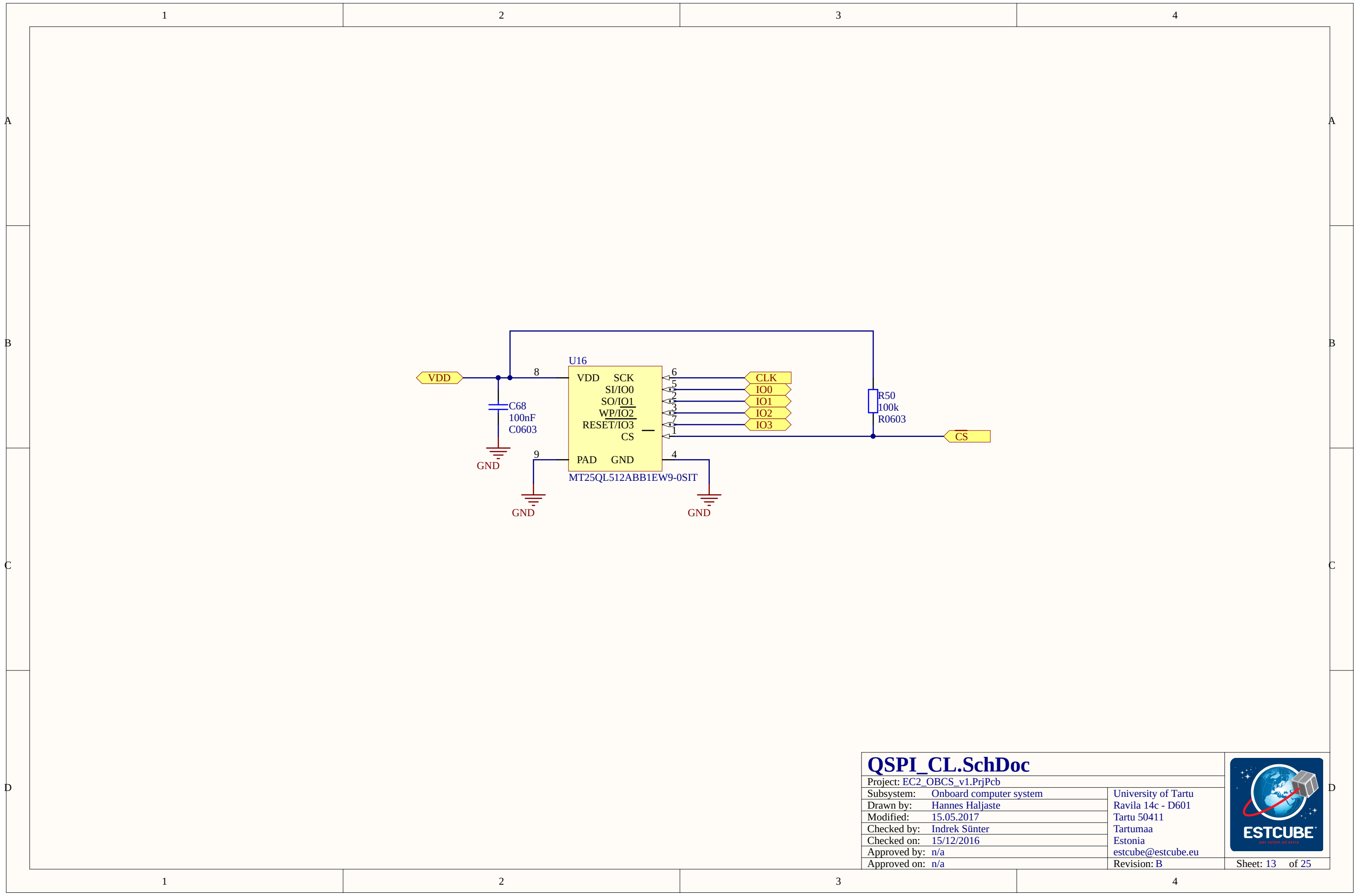

Figure 4.14: QSPI NOR flash schematic.

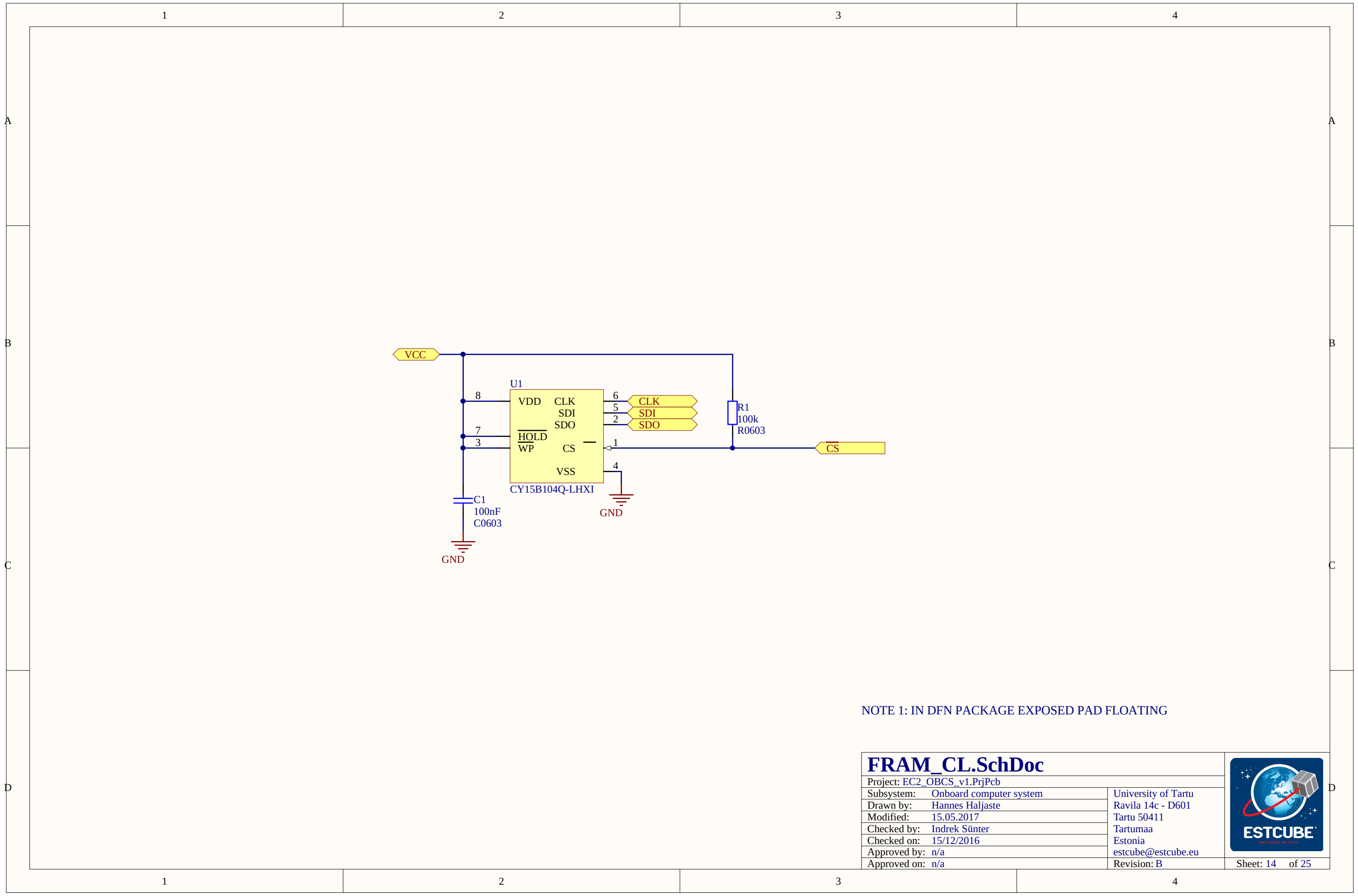

Figure 4.15: FRAM schematic.

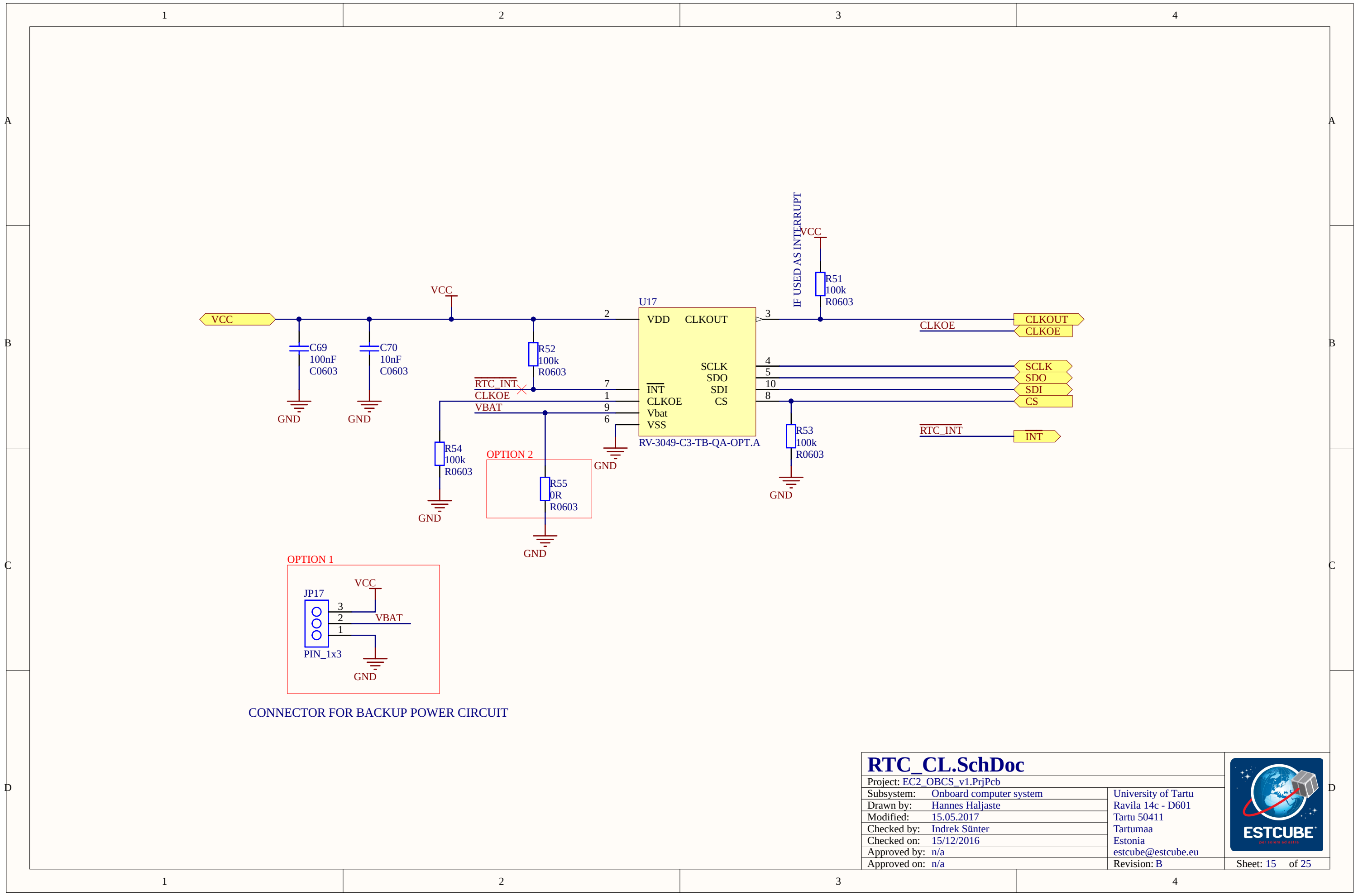

Figure 4.16: Real time clock schematic.

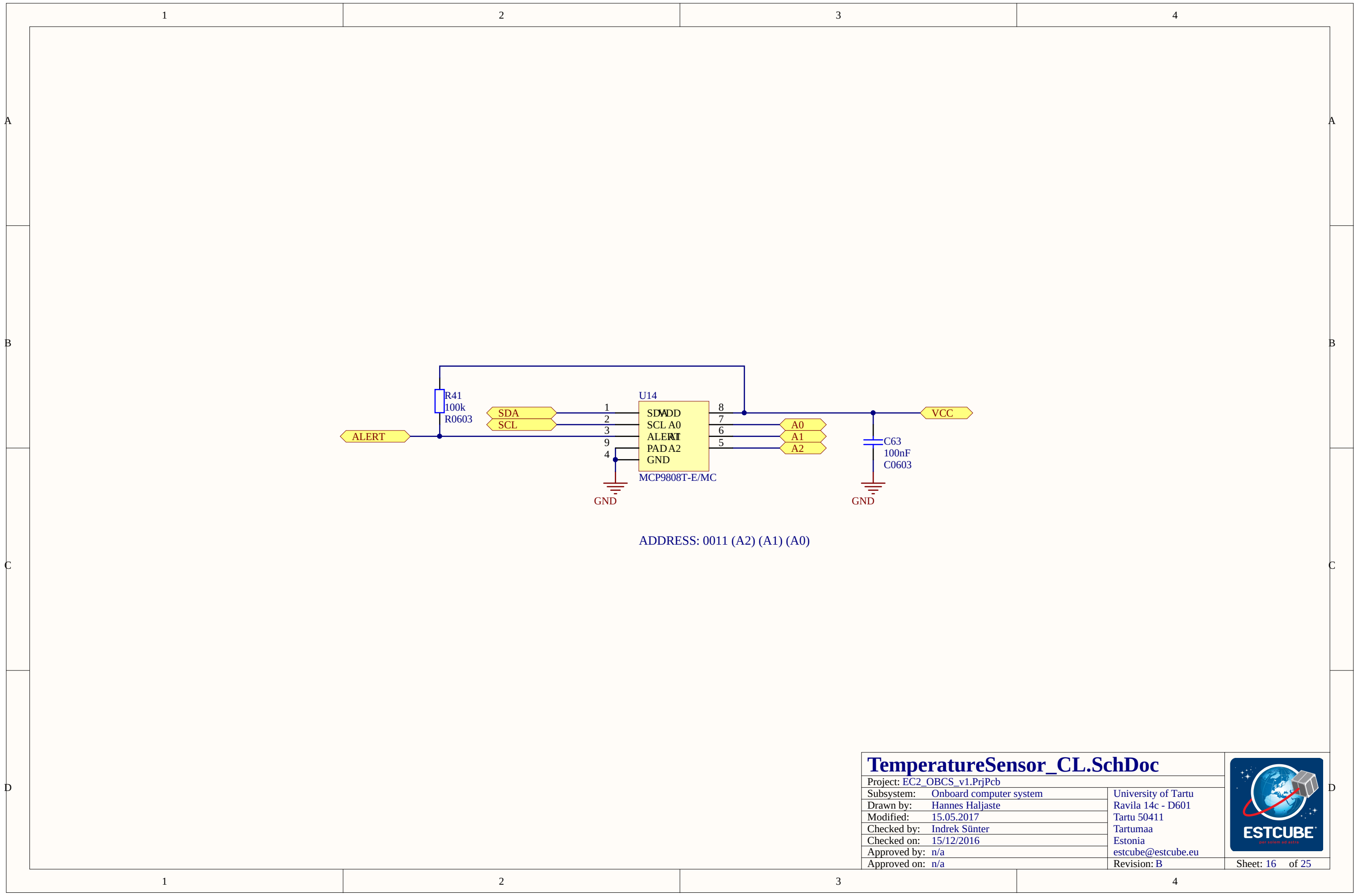

Figure 4.17: Temperature sensor schematic.

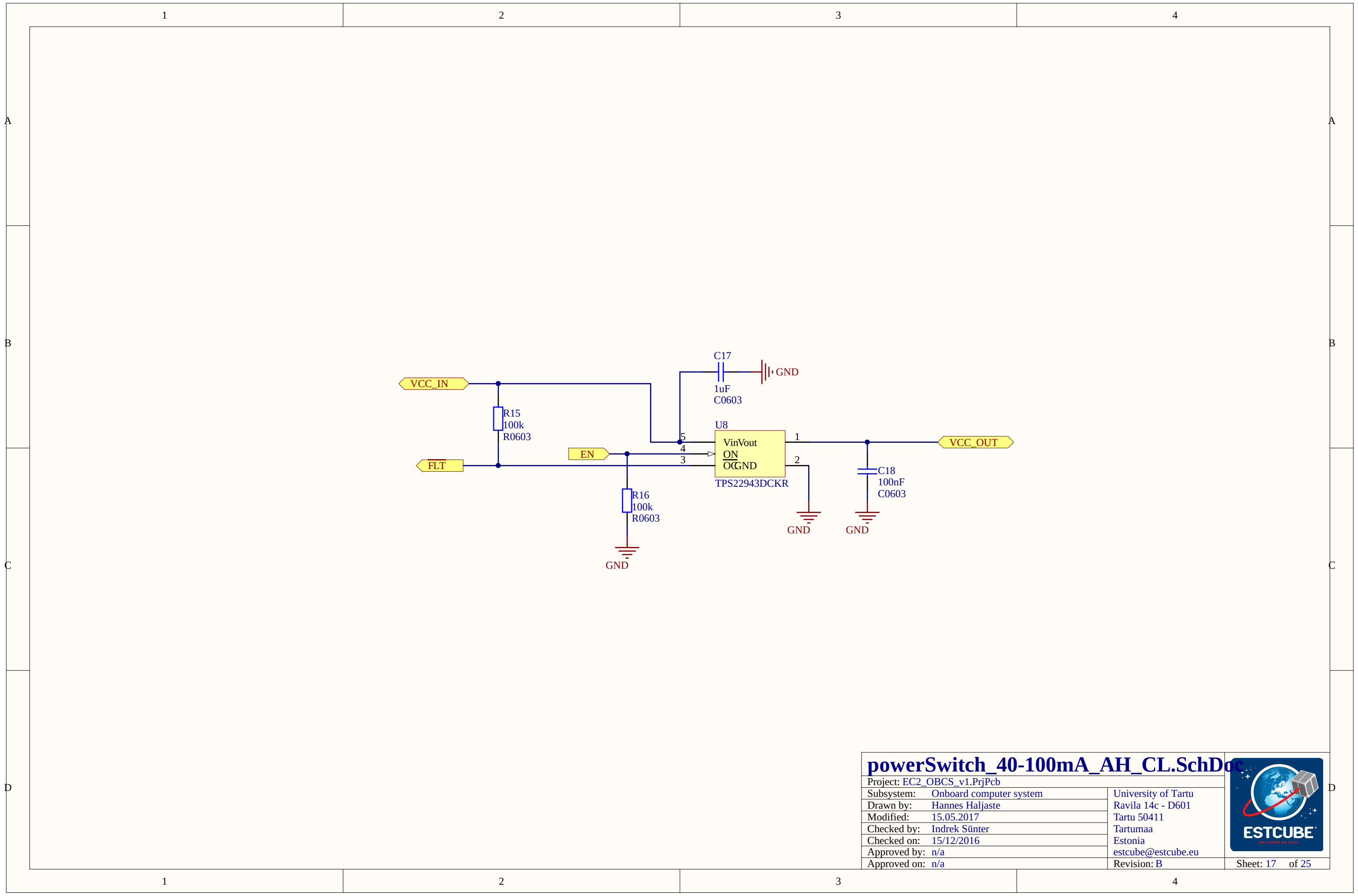

Figure 4.18: 40 mA current limit power switch schematic.

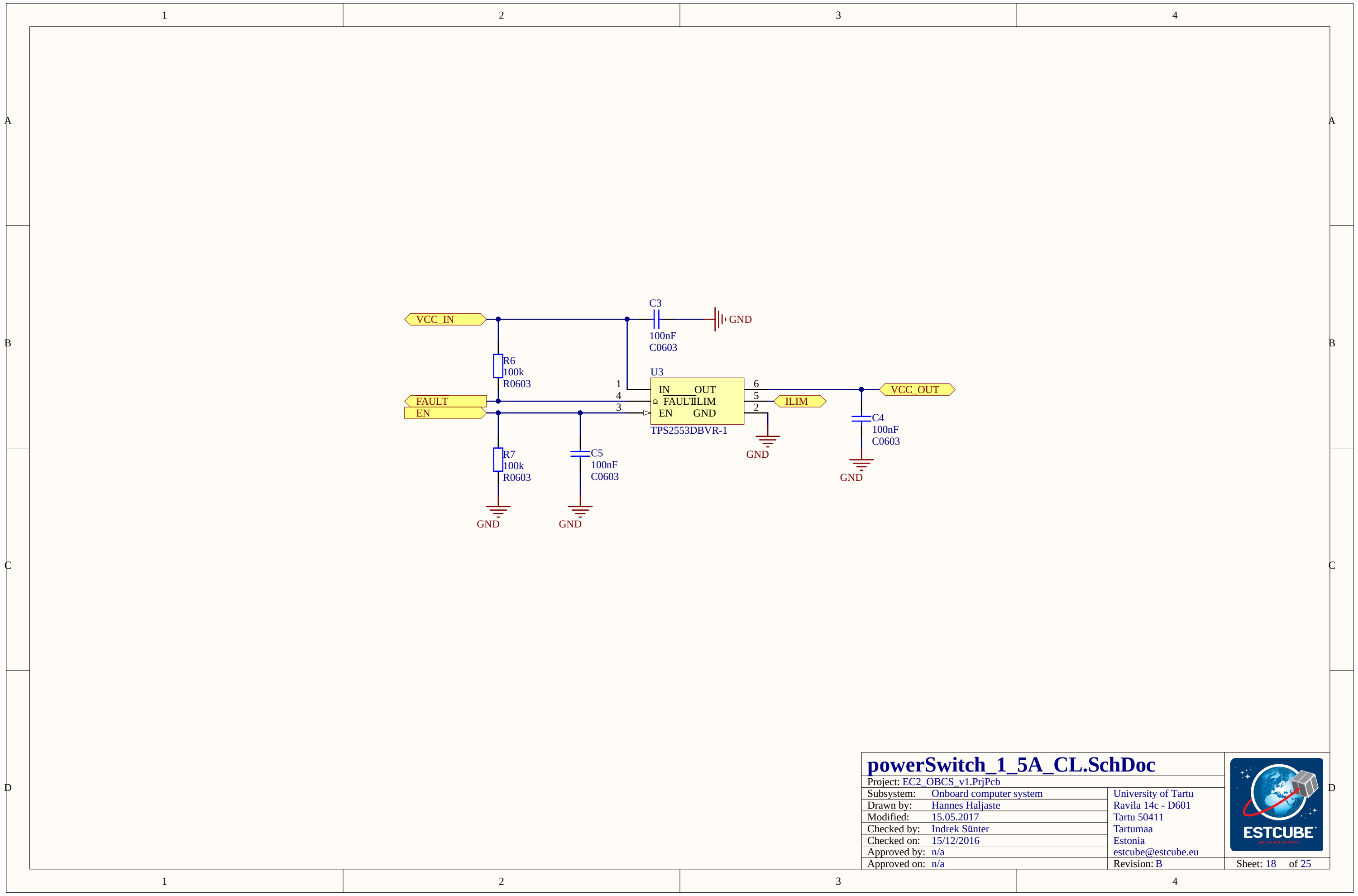

Figure 4.19: Adjustable current limit power switch schematic.

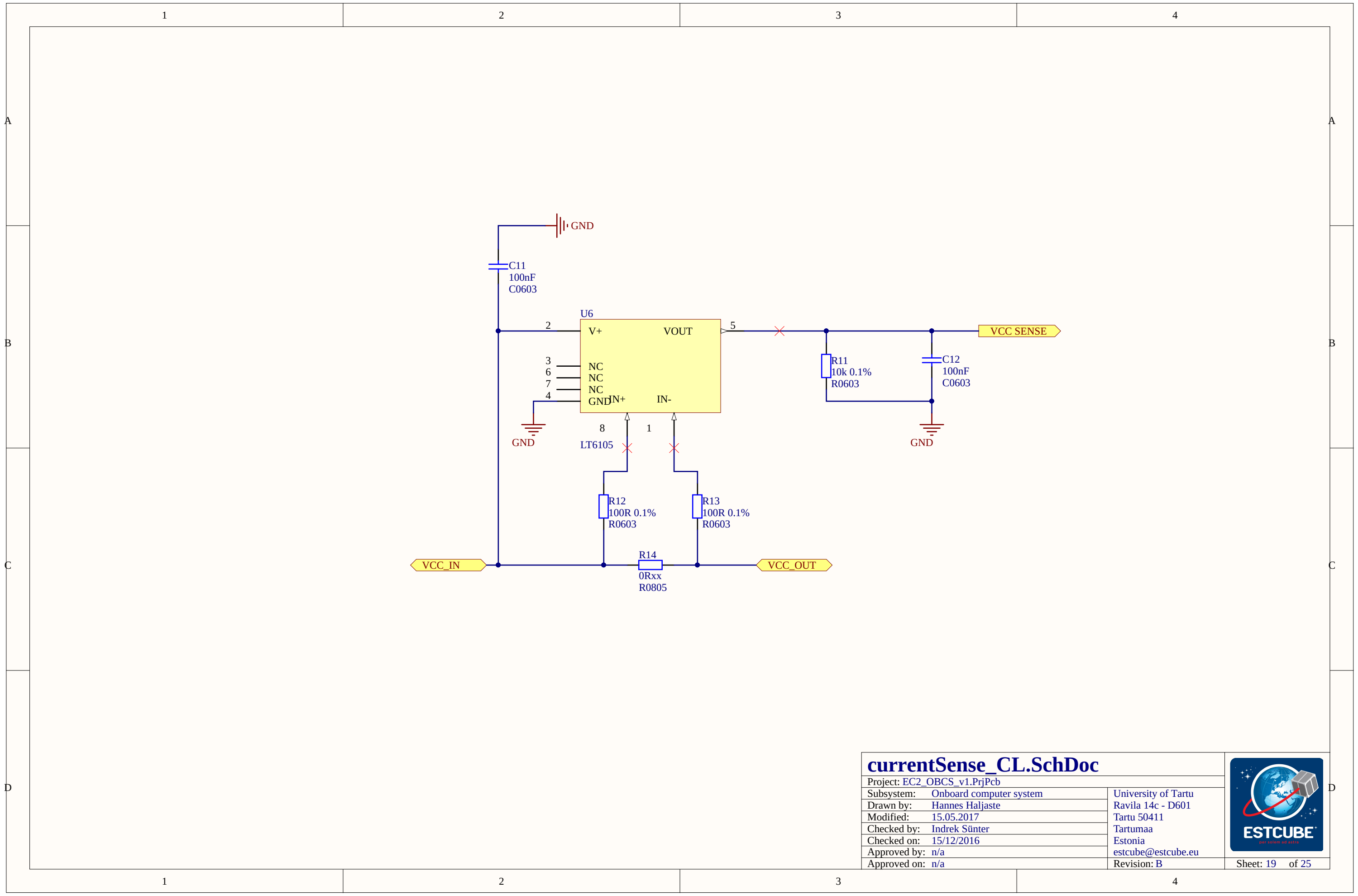

Figure 4.20: Current sense amplifier schematic.

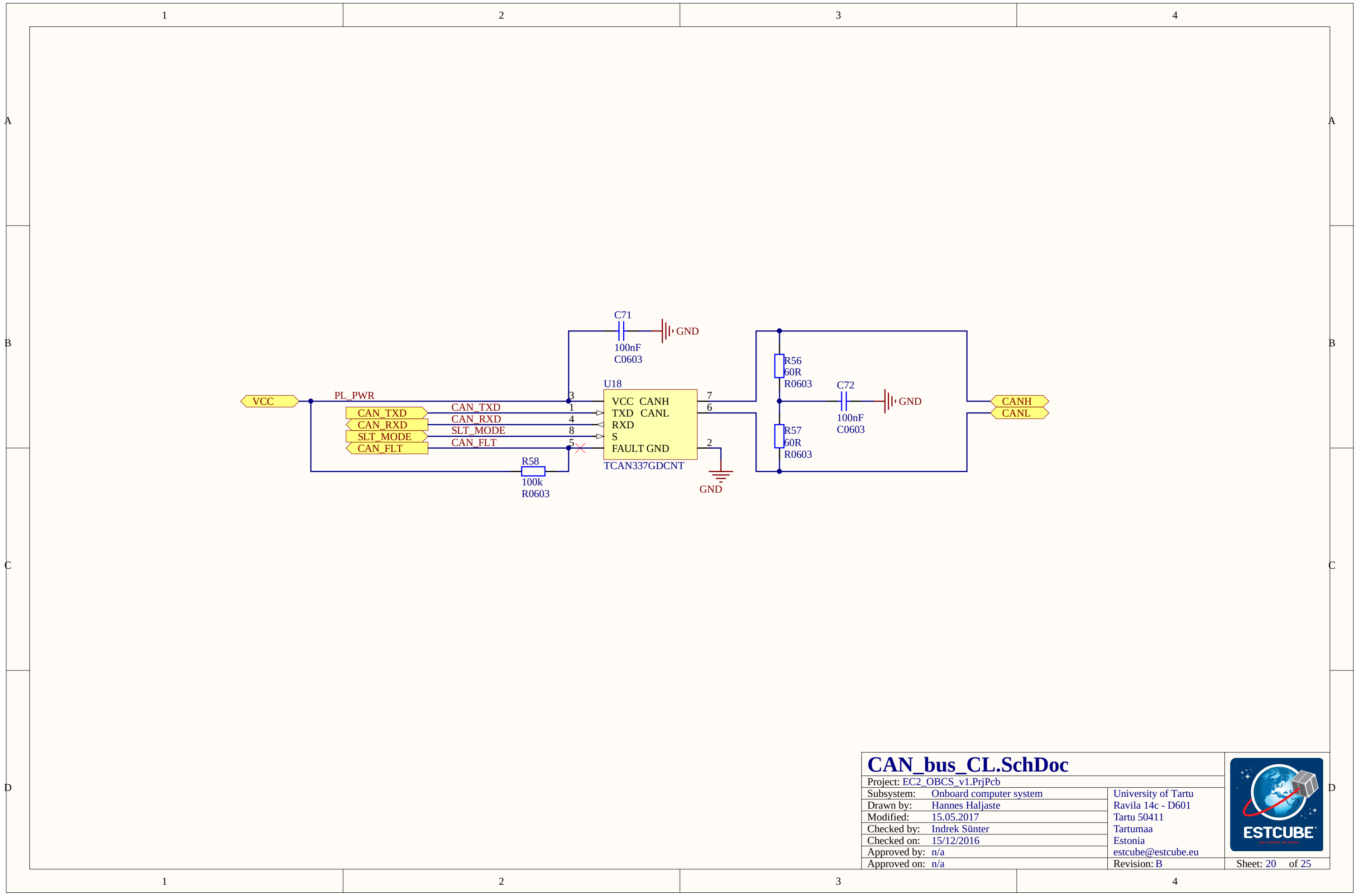

Figure 4.21: CAN bus driver schematic.

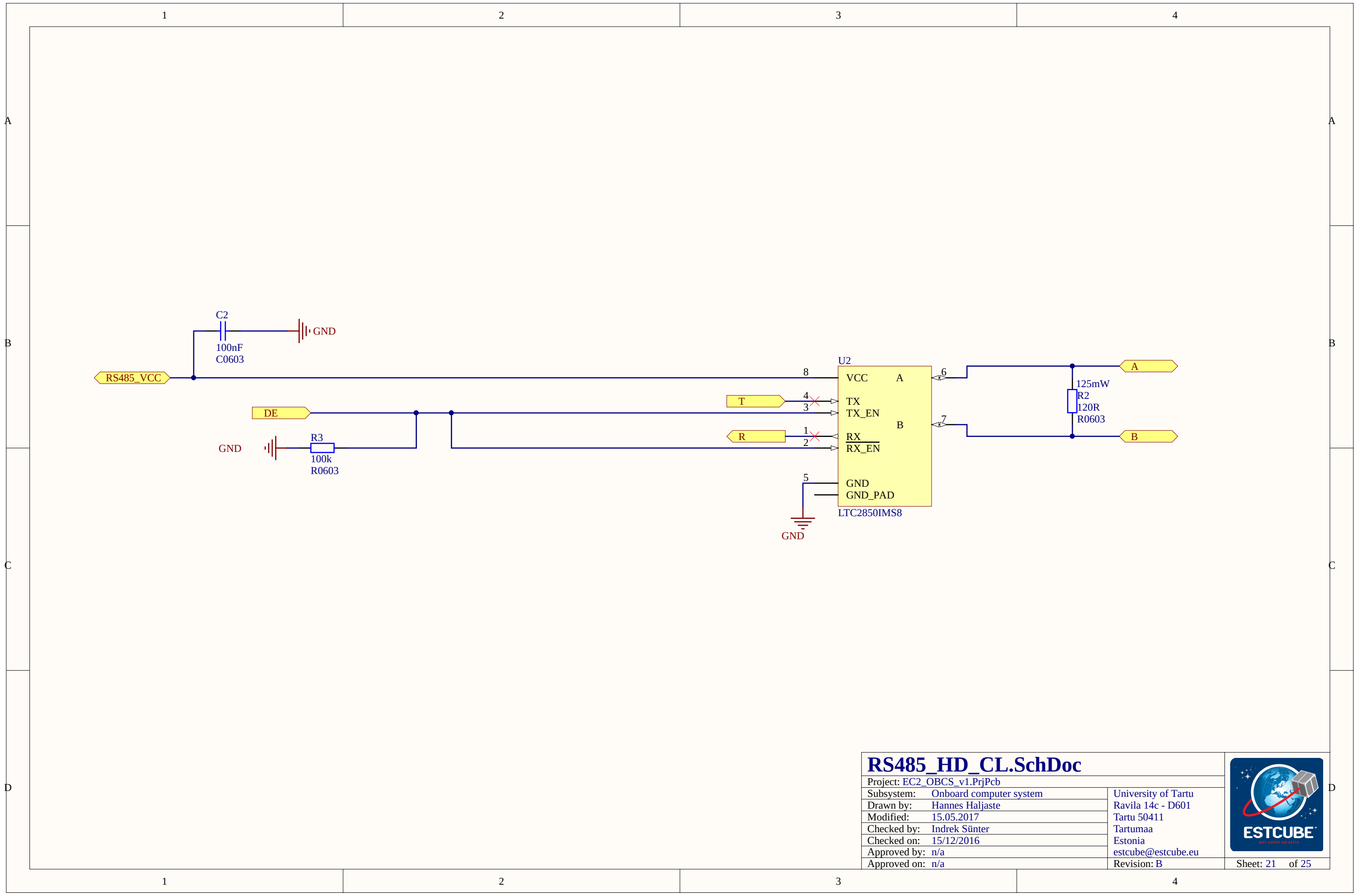

Figure 4.22: Half duplex RS485 driver schematic.

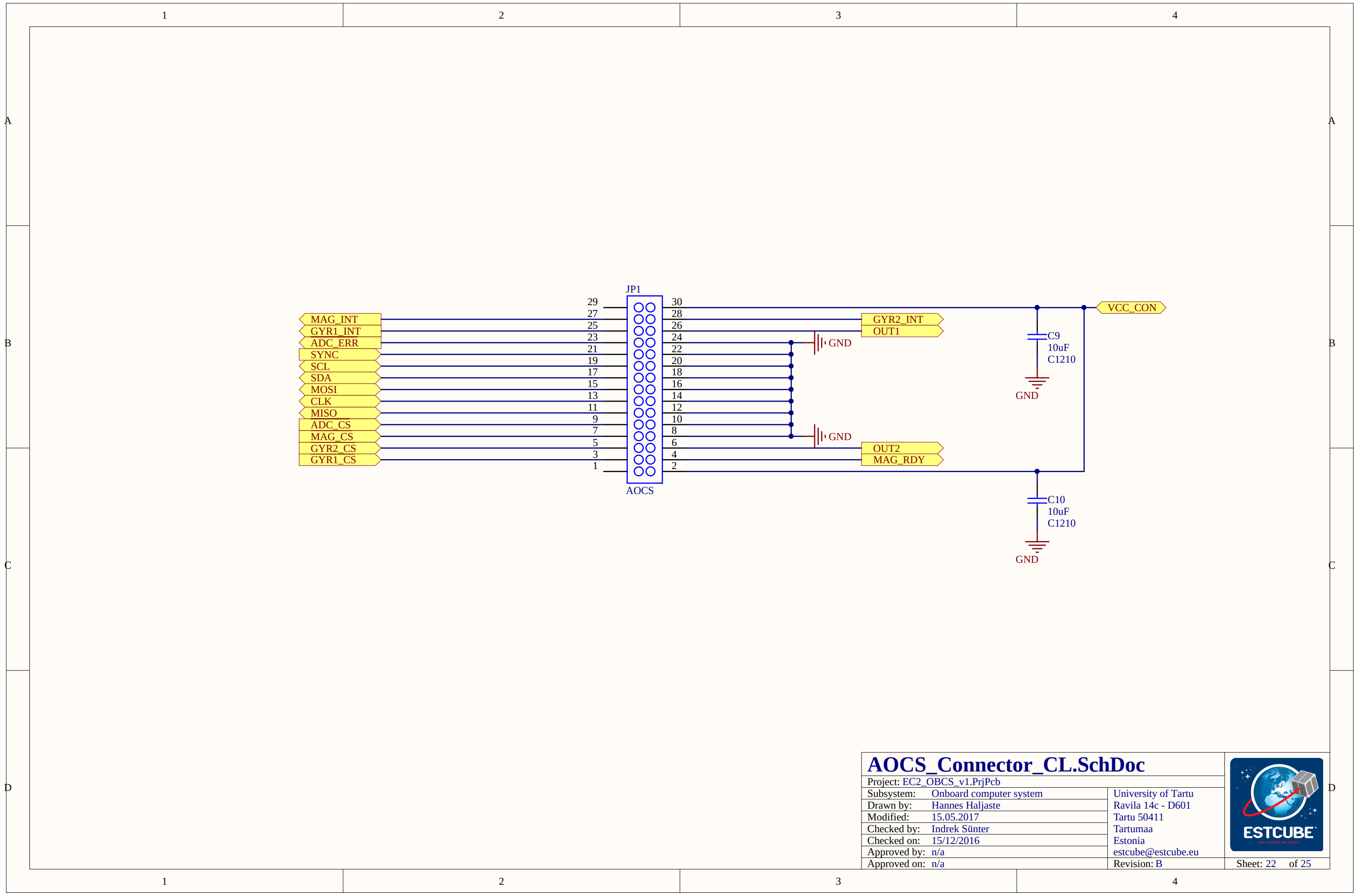

Figure 4.23: On-board computer system's AOCS connector schematic.

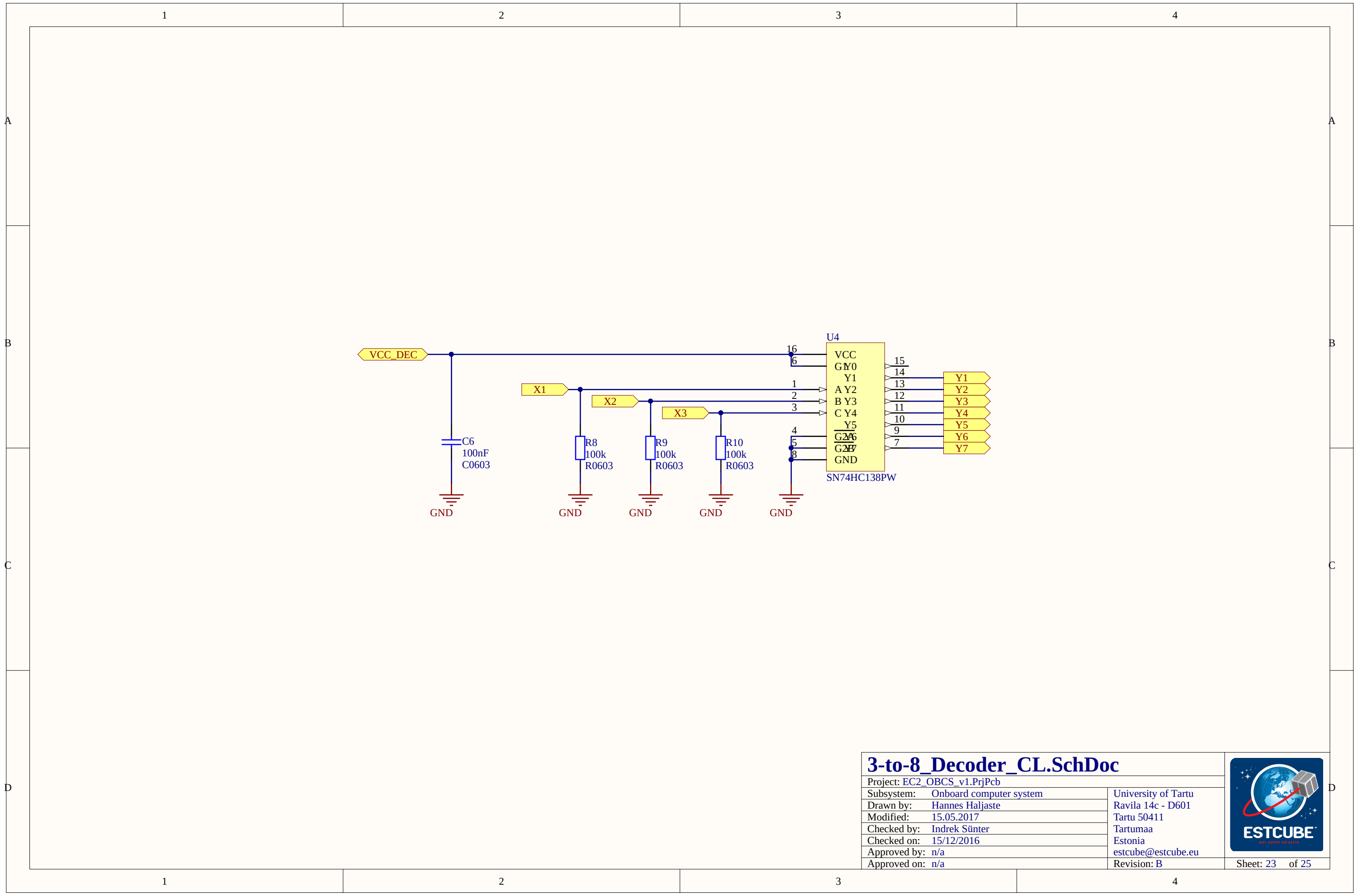

Figure 4.24: 3-to-8 decoder schematic.

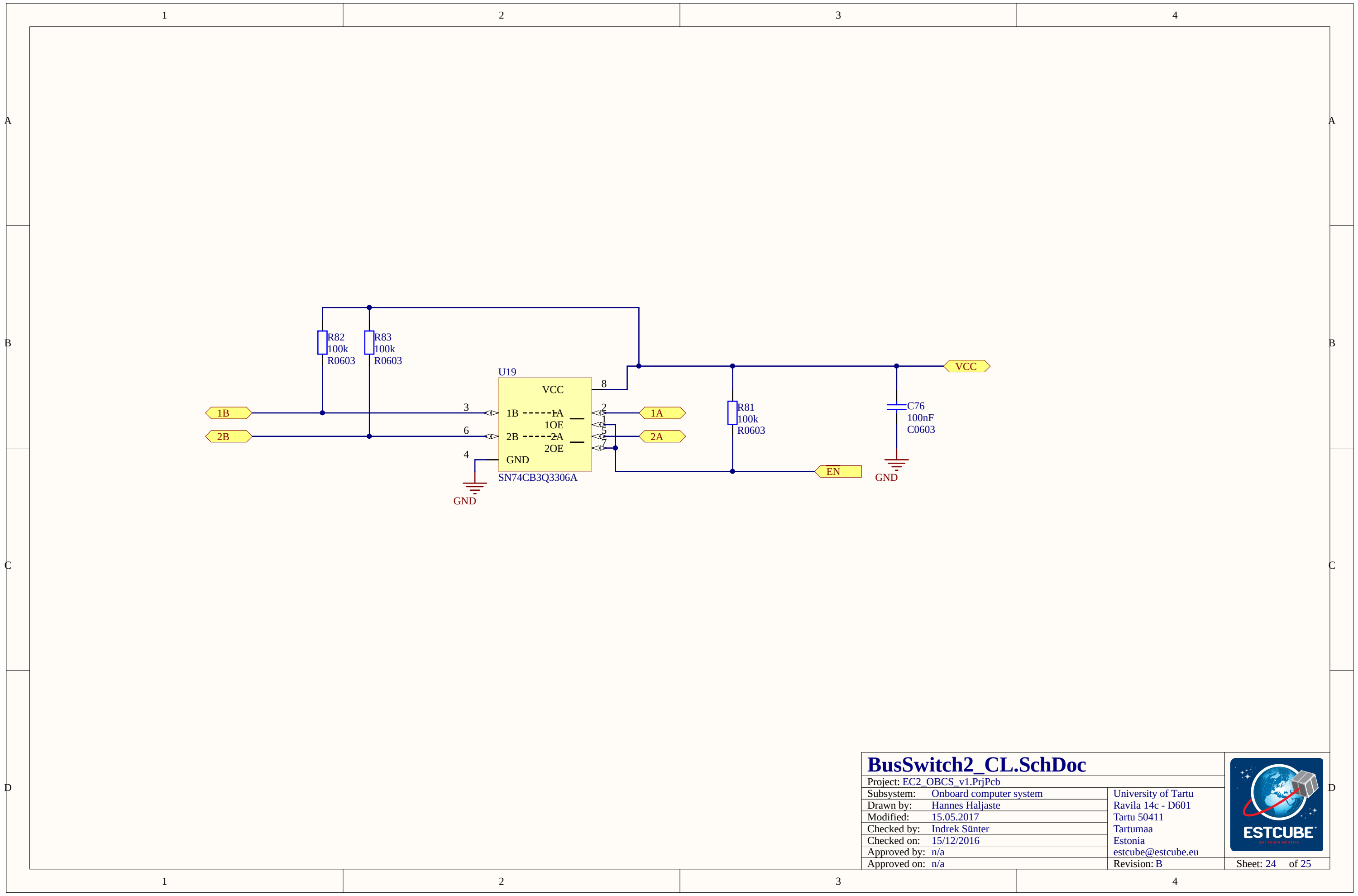

Figure 4.25: 2-channel bus switch schematic.

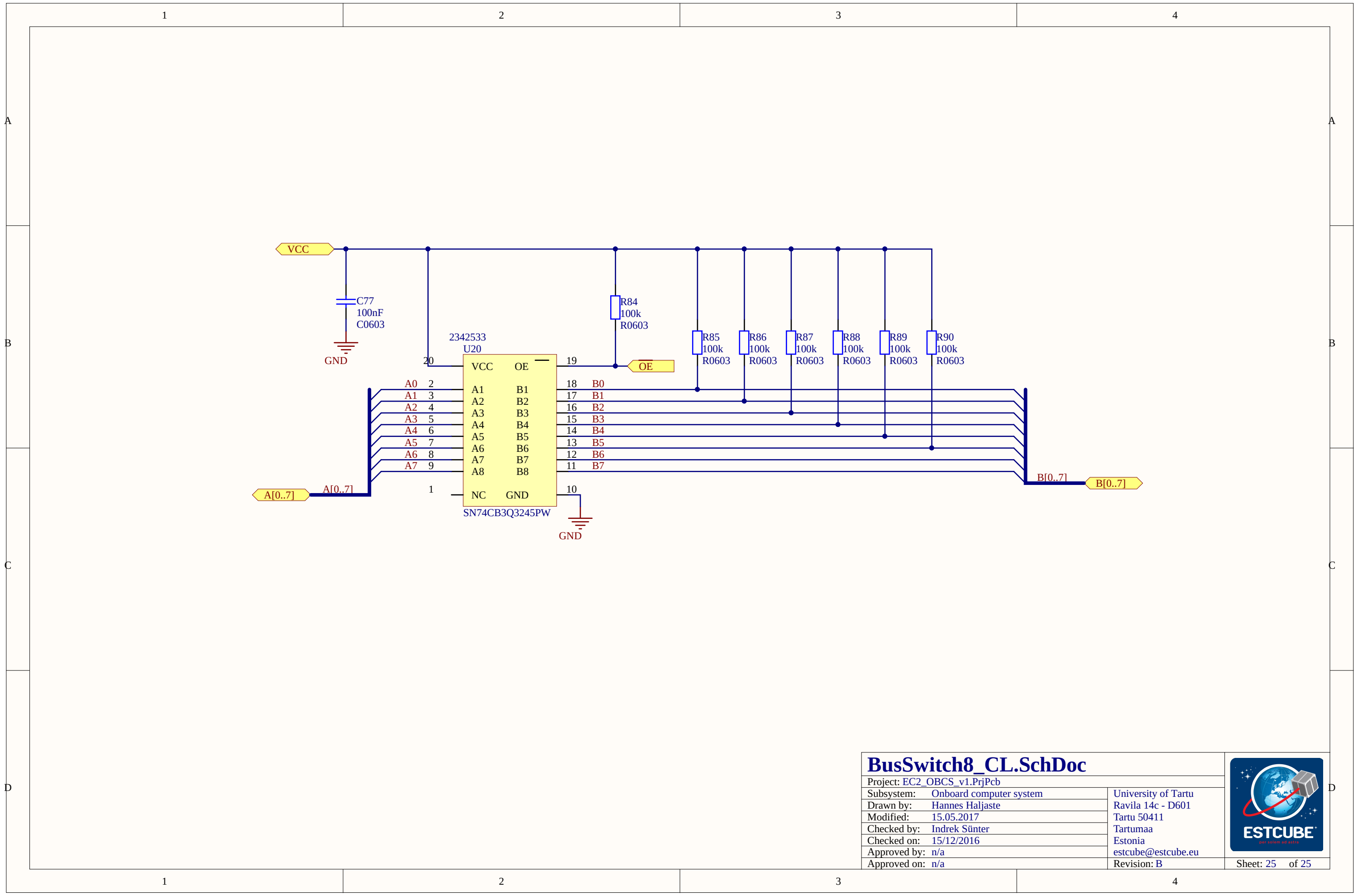

Figure 4.26: 8-channel bus switch schematic.

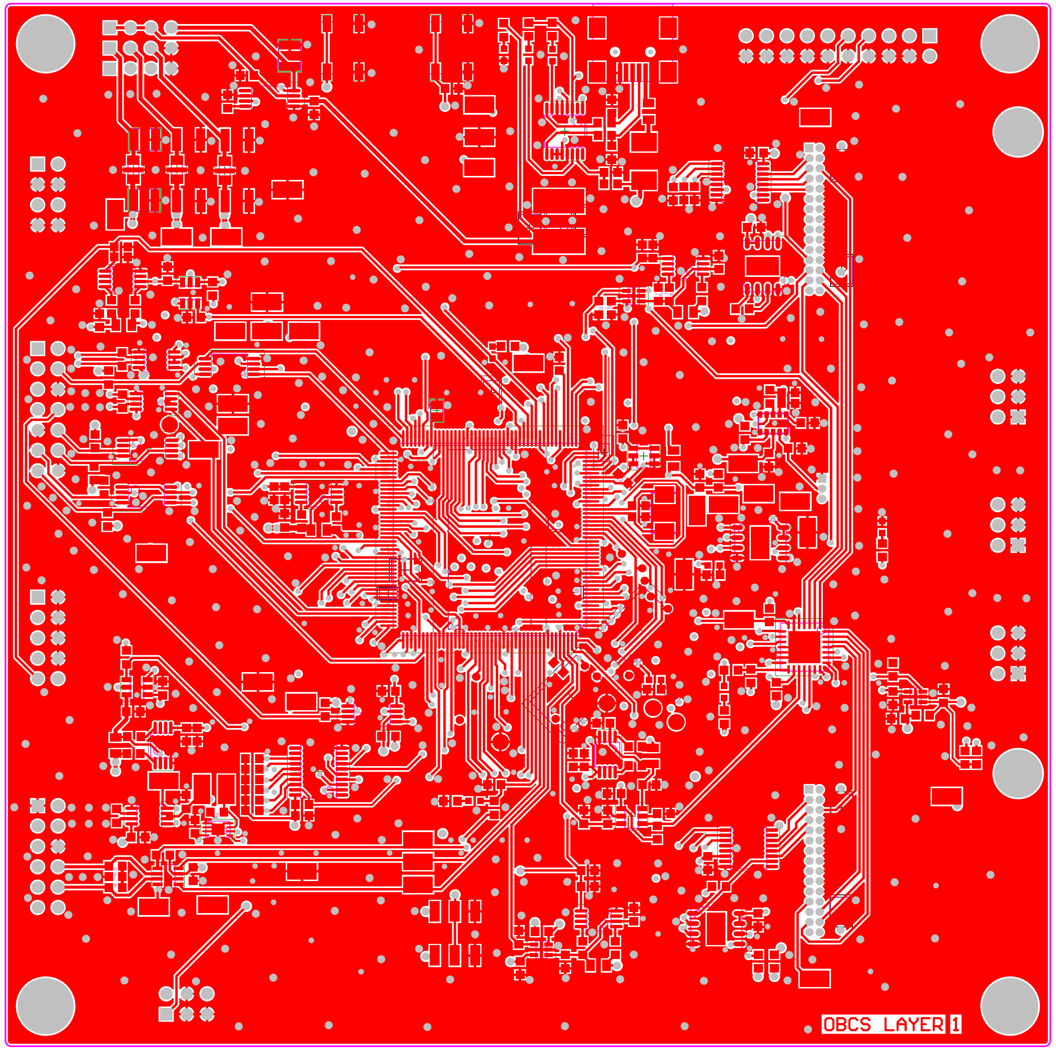

Figure 4.27: On-board computer system's printed circuit board layer 1 - component and signal plane.

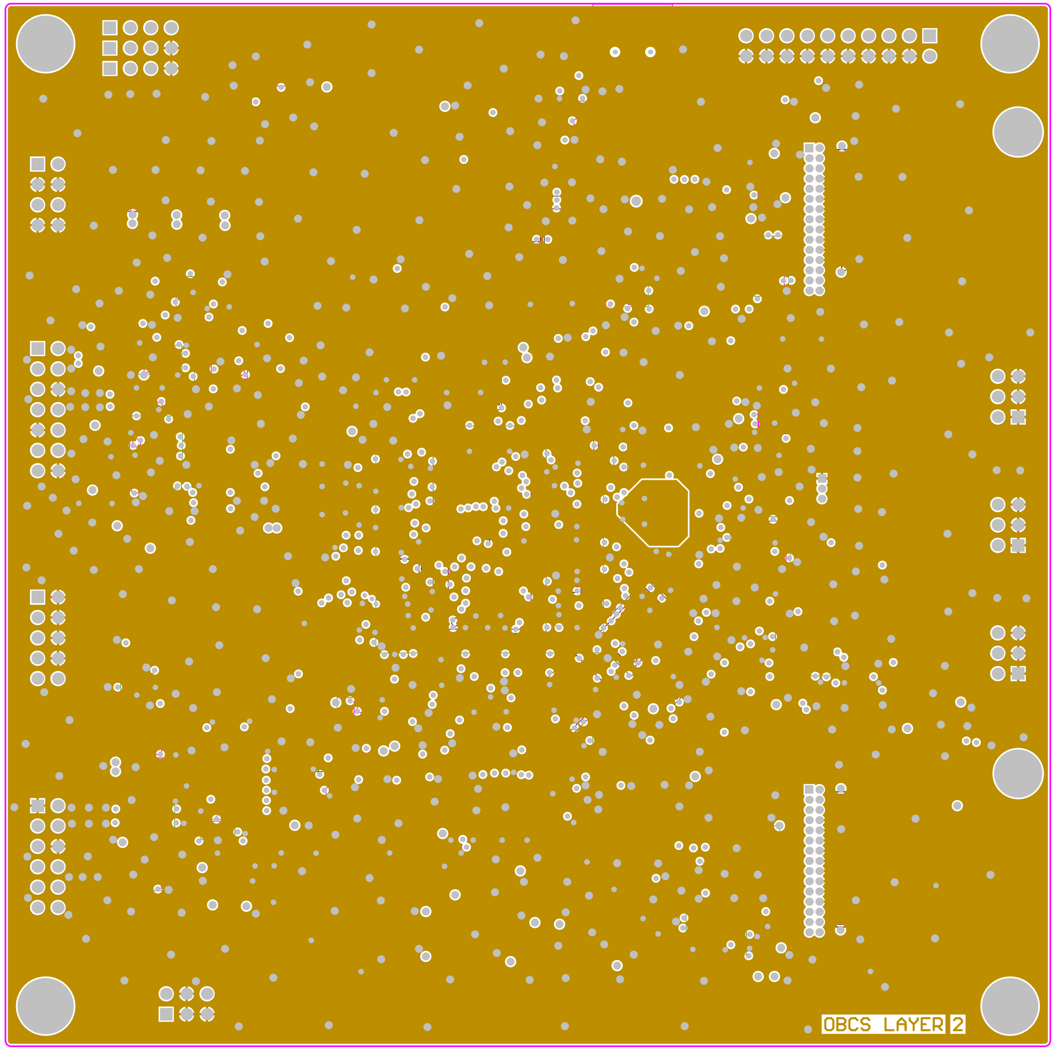

Figure 4.28: On-board computer system's printed circuit board layer 2 - ground plane.

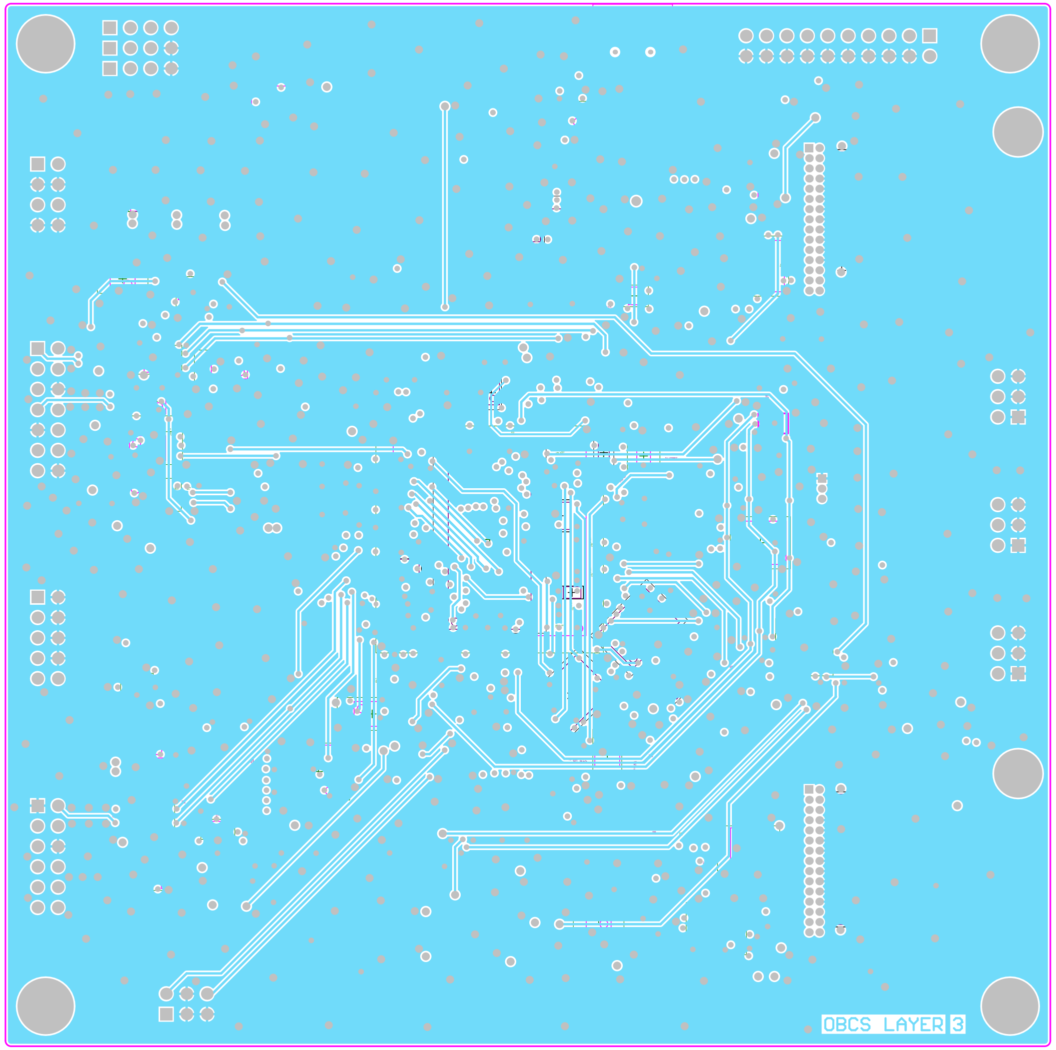

Figure 4.29: Onboard computer system's printed circuit board layer 3 - signal plane.

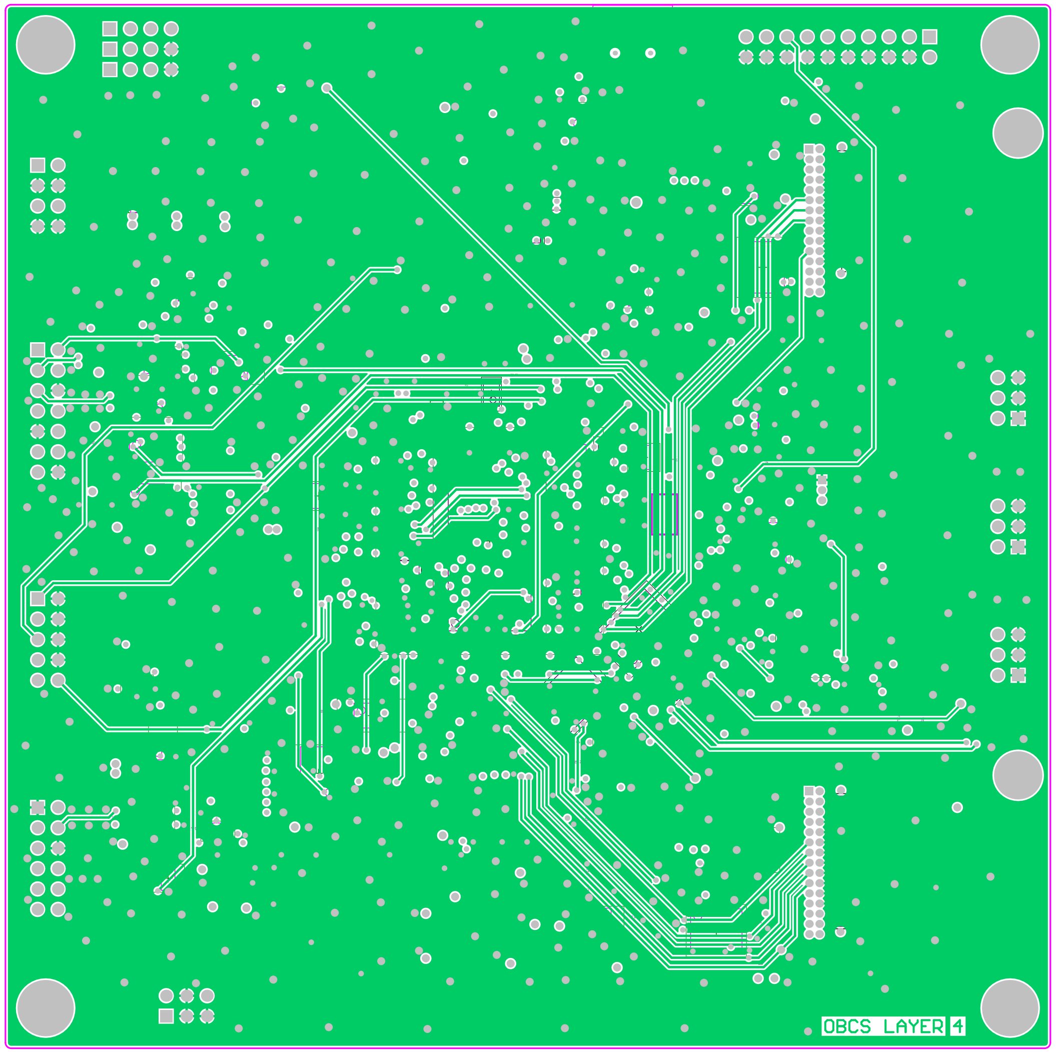

Figure 4.30: On-board computer system's printed circuit board layer 4 - signal plane.

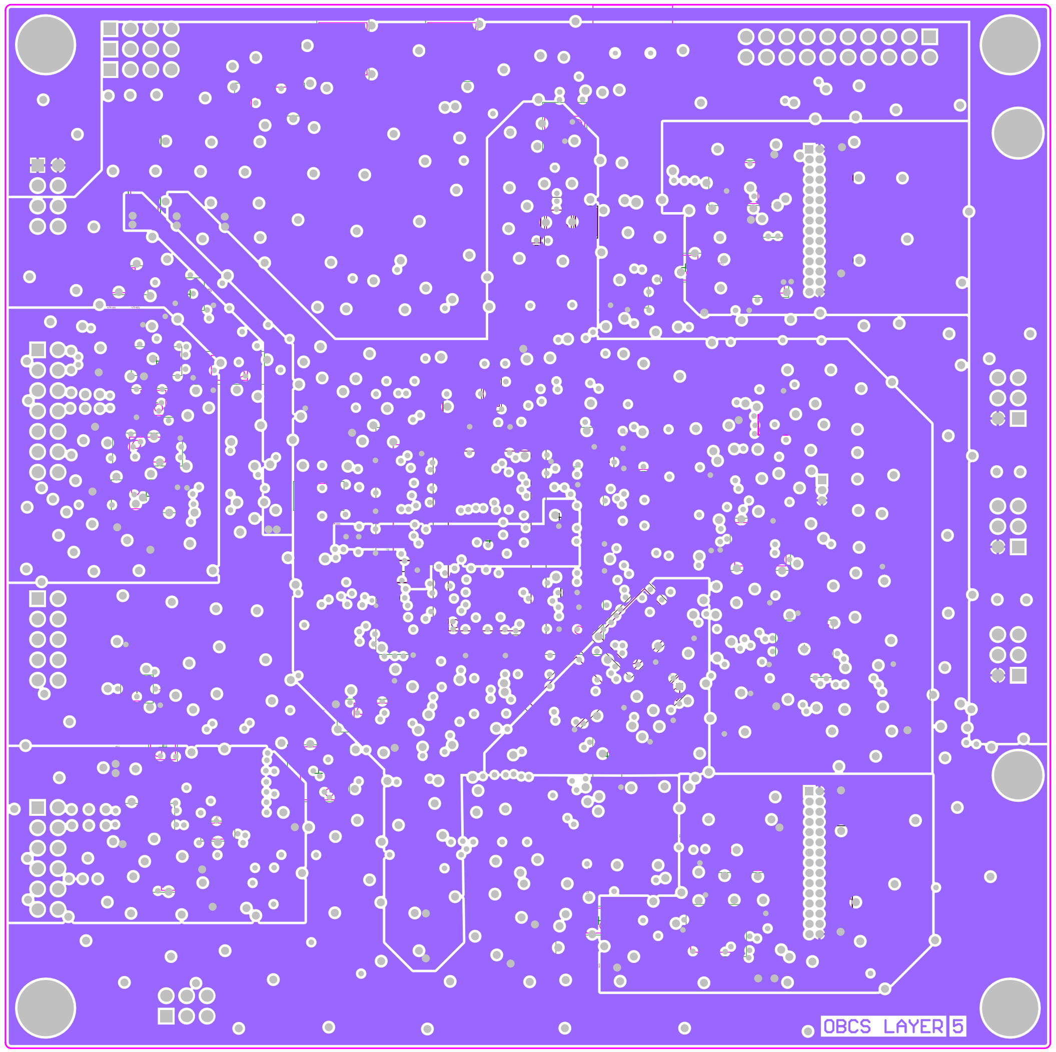

Figure 4.31: On-board computer system's printed circuit board layer 5 - power plane.

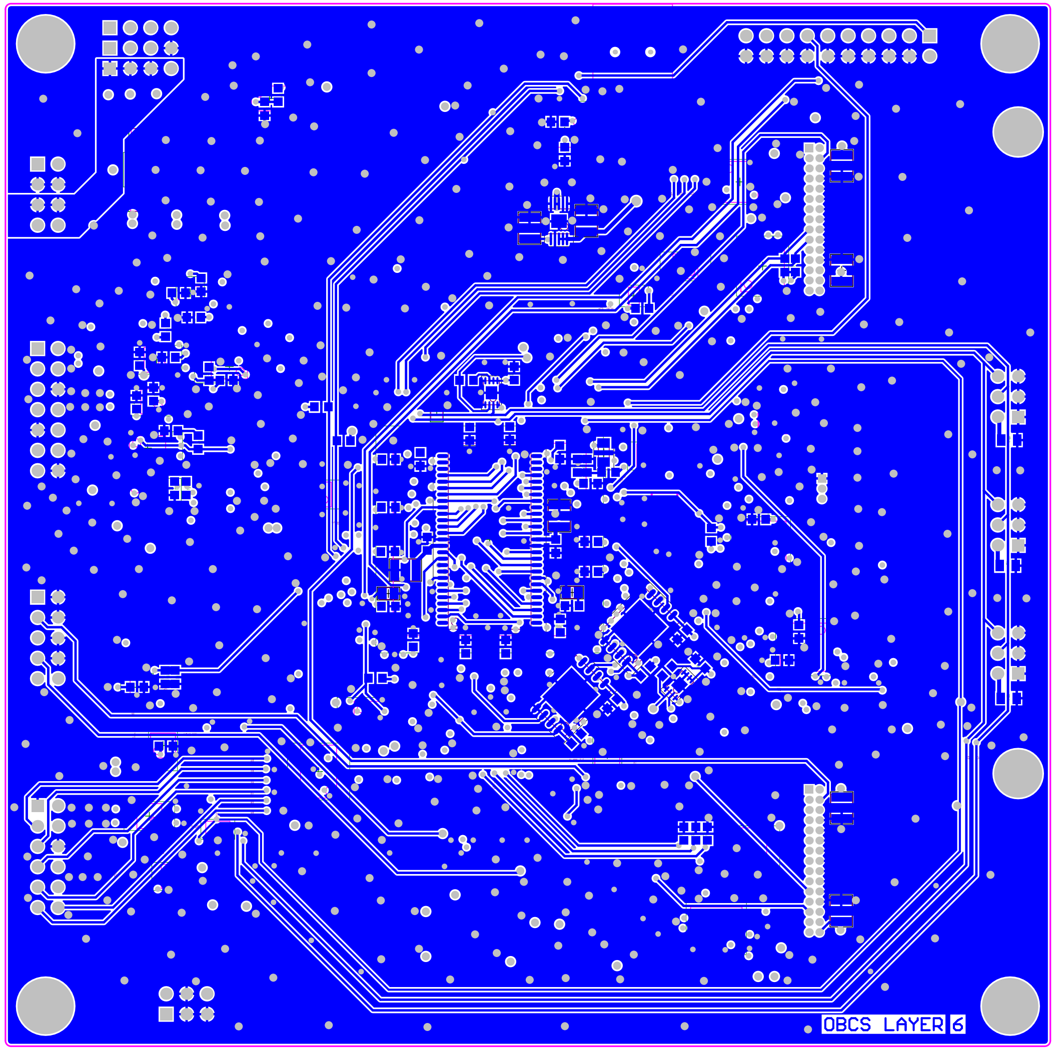

Figure 4.32: On-board computer system's printed circuit board layer 6 - component and signal plane.

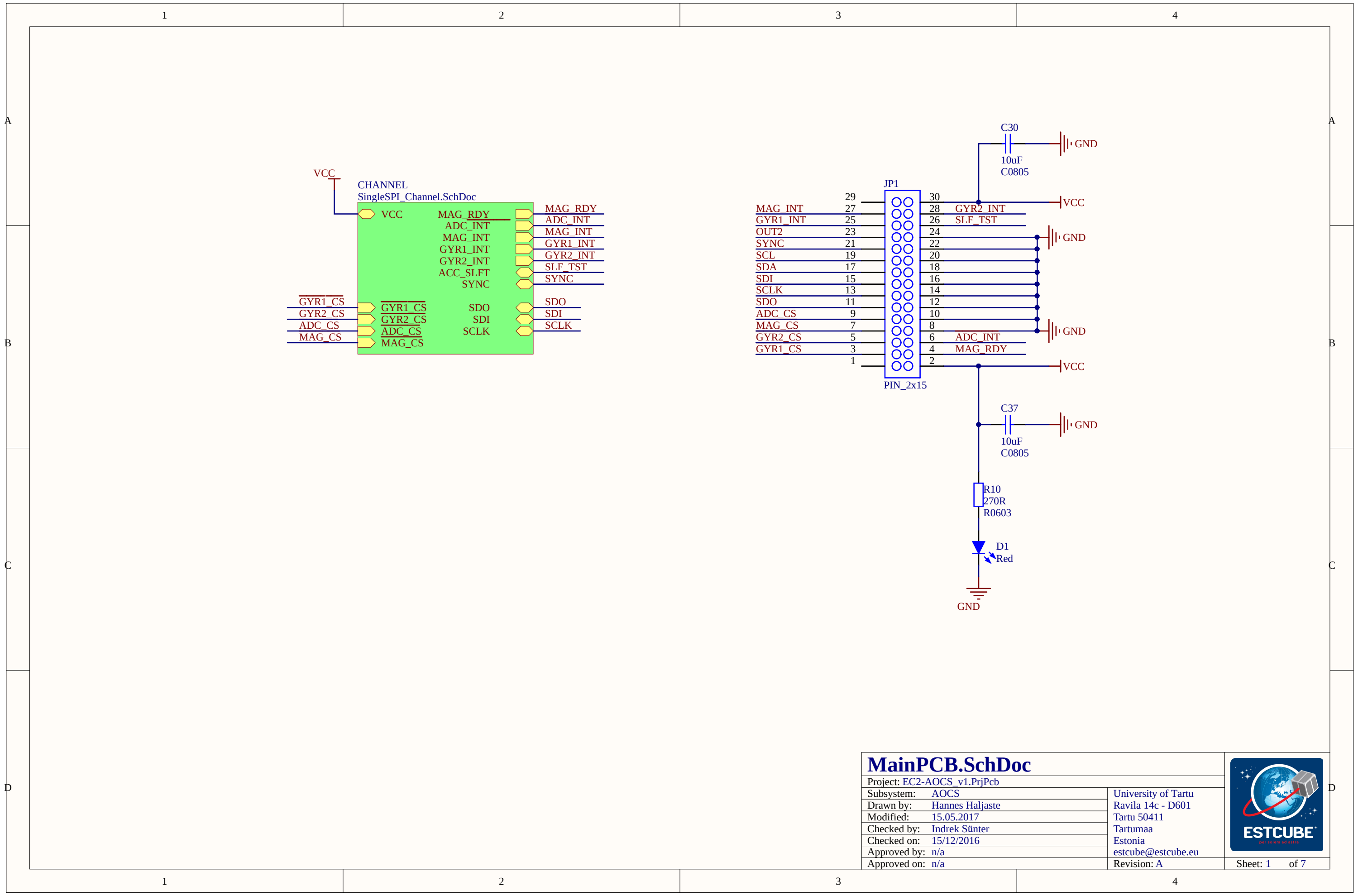

Figure 4.33: Attitude and orbit control system and its connector schematic.

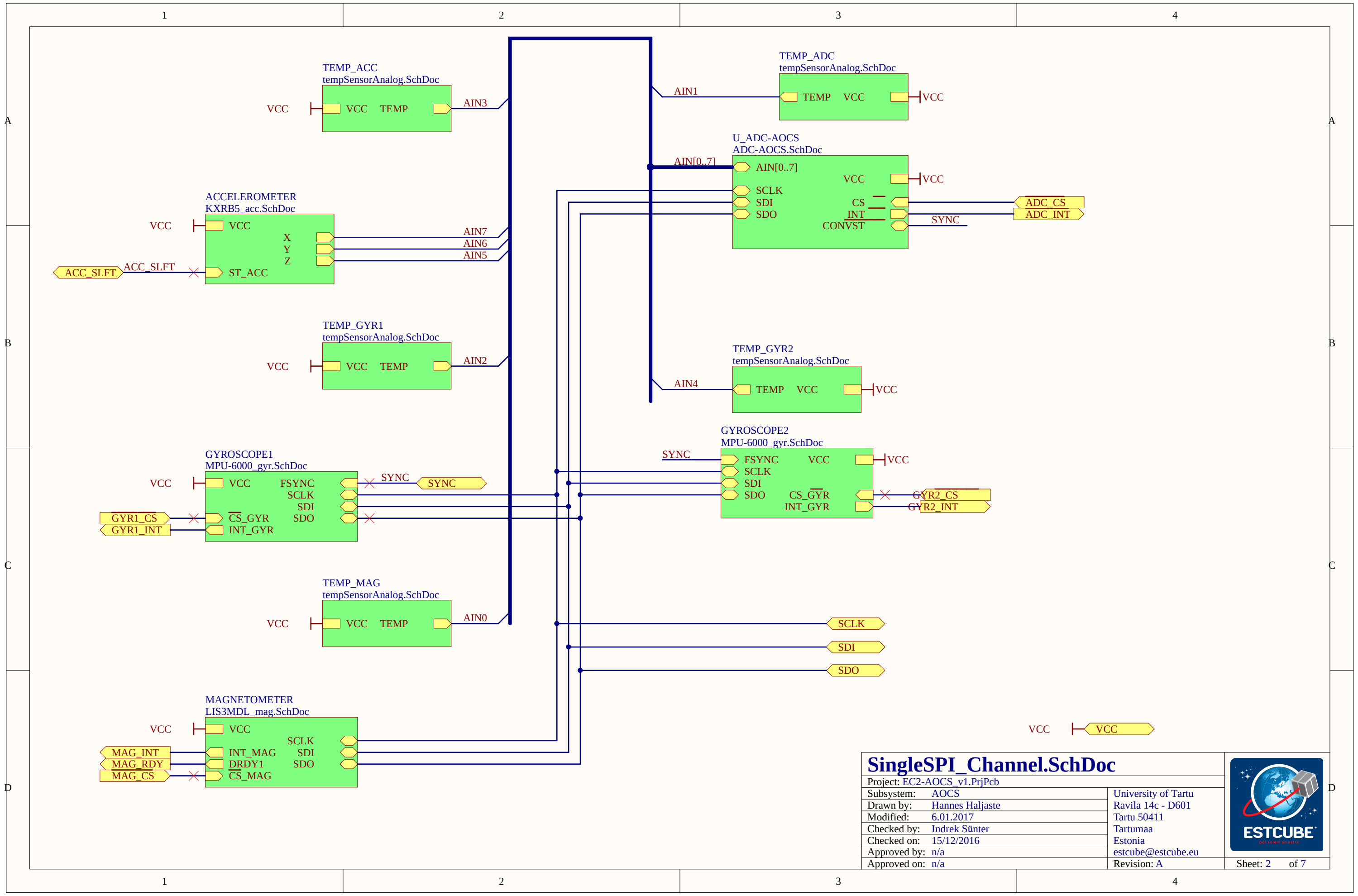

Figure 4.34: Attitude and orbit control system's connections schematic.

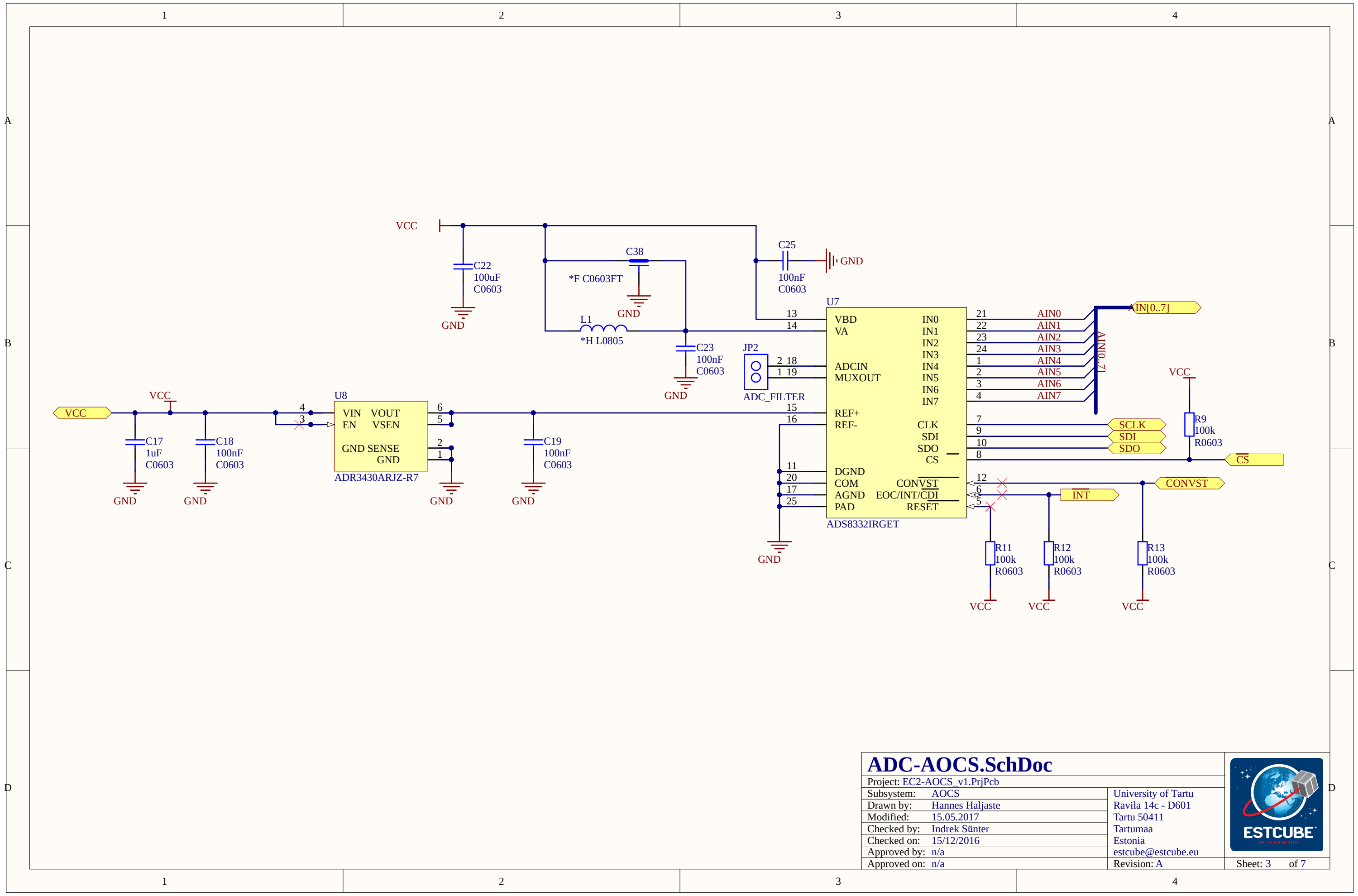

Figure 4.35: Analog to digital converter's schematic.

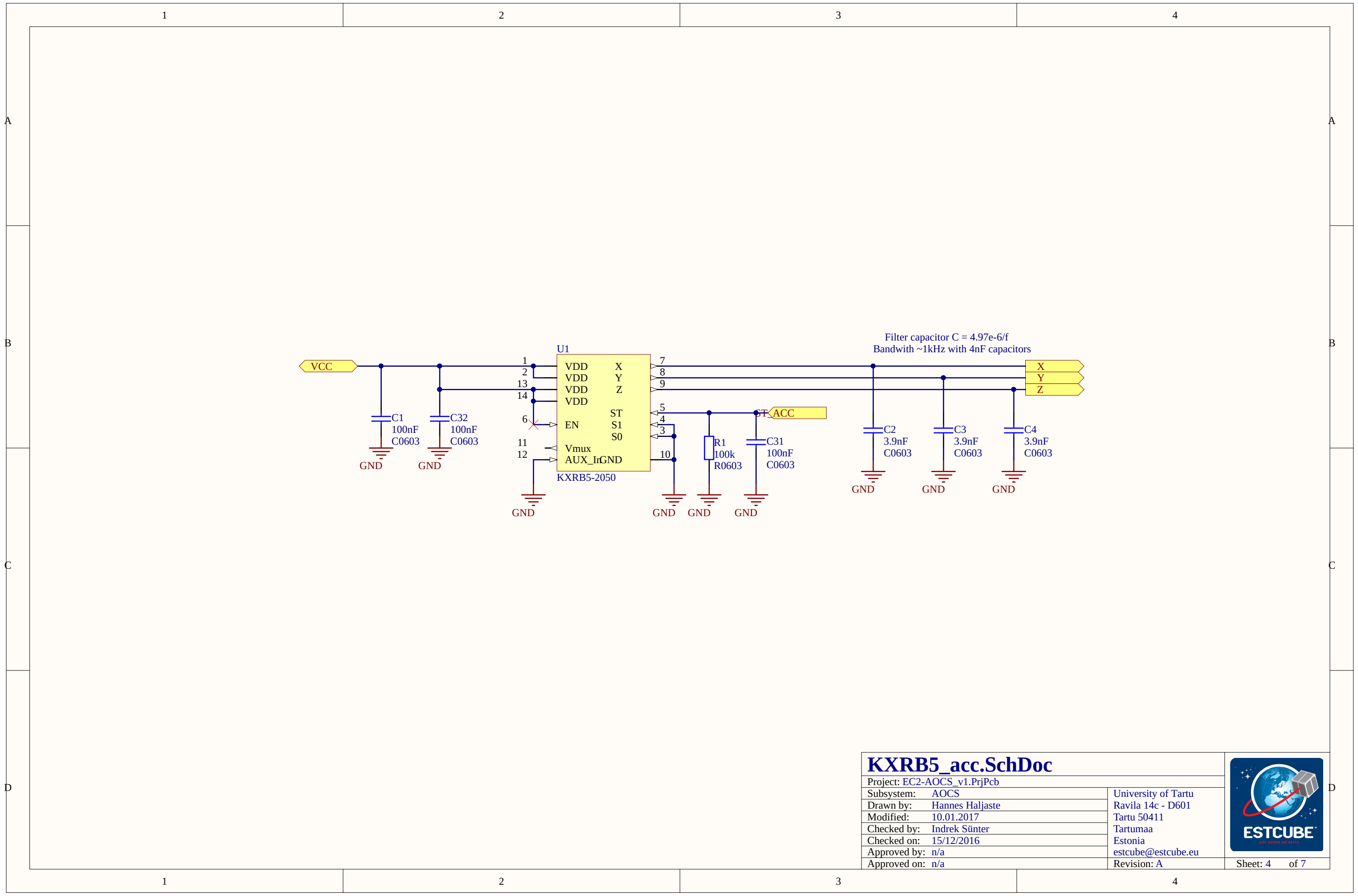

Figure 4.36: Accelerometer schematic.

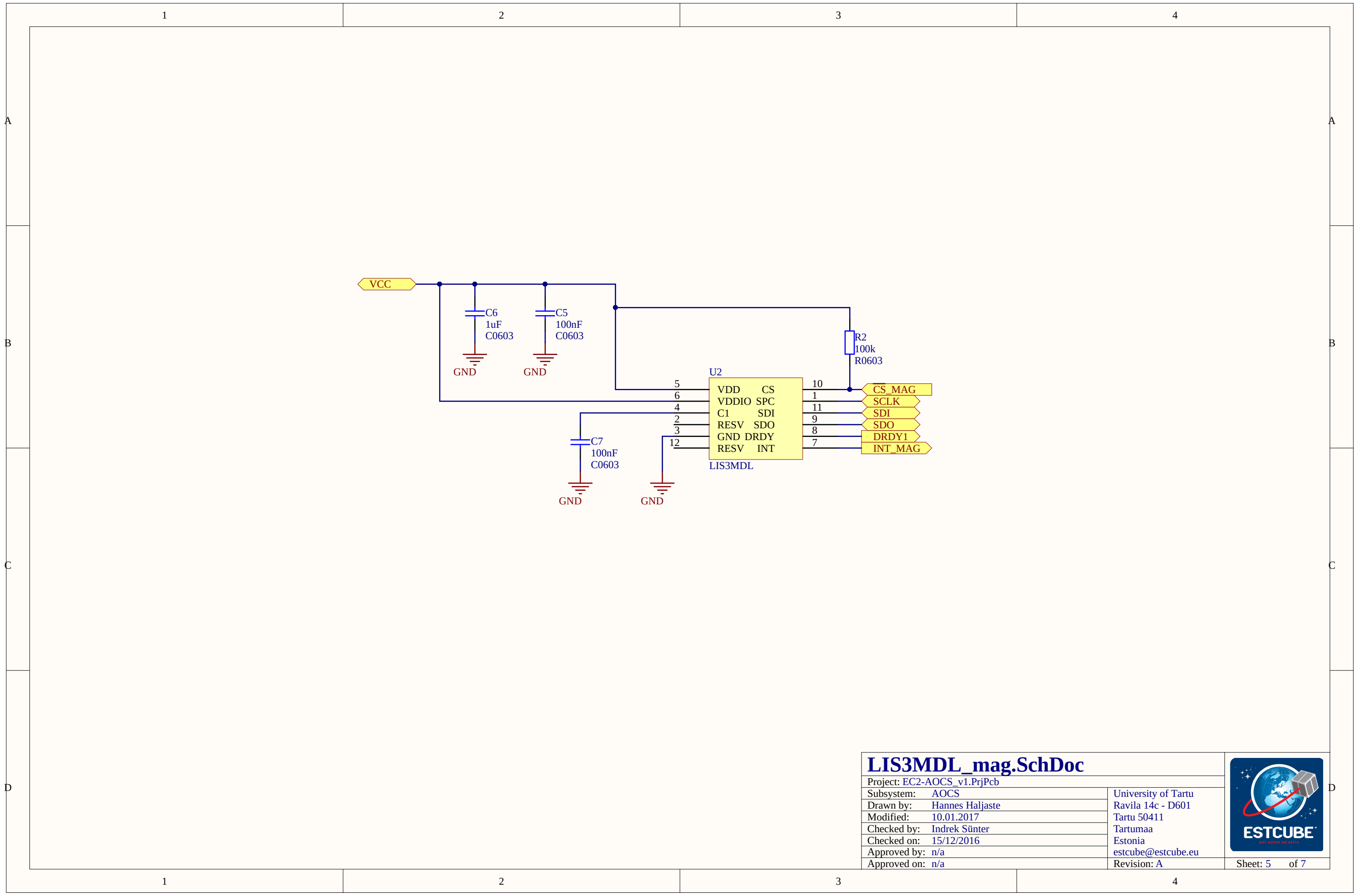

Figure 4.37: Magnetometer schematic.

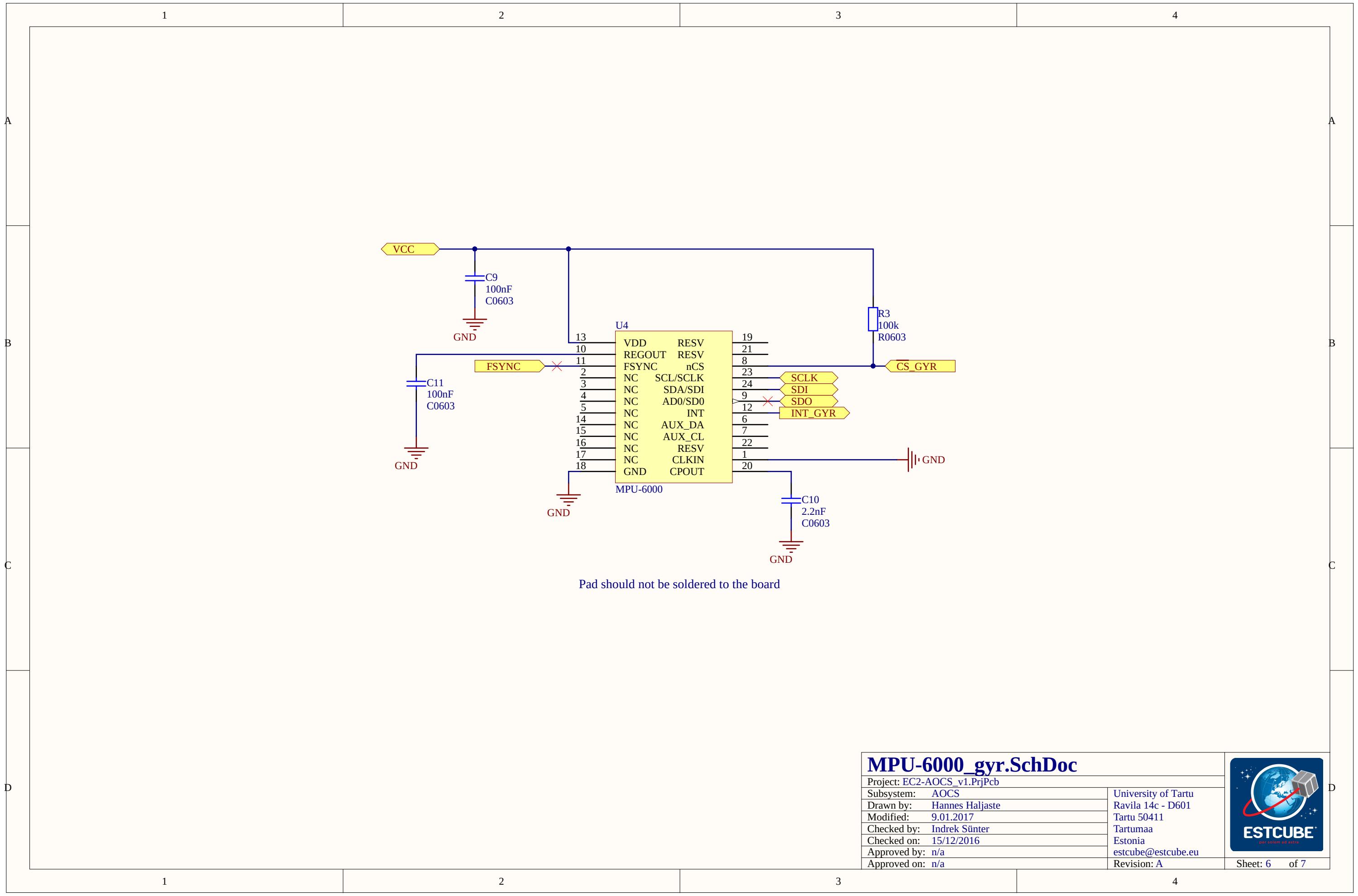

Figure 4.38: Gyroscope schematic.

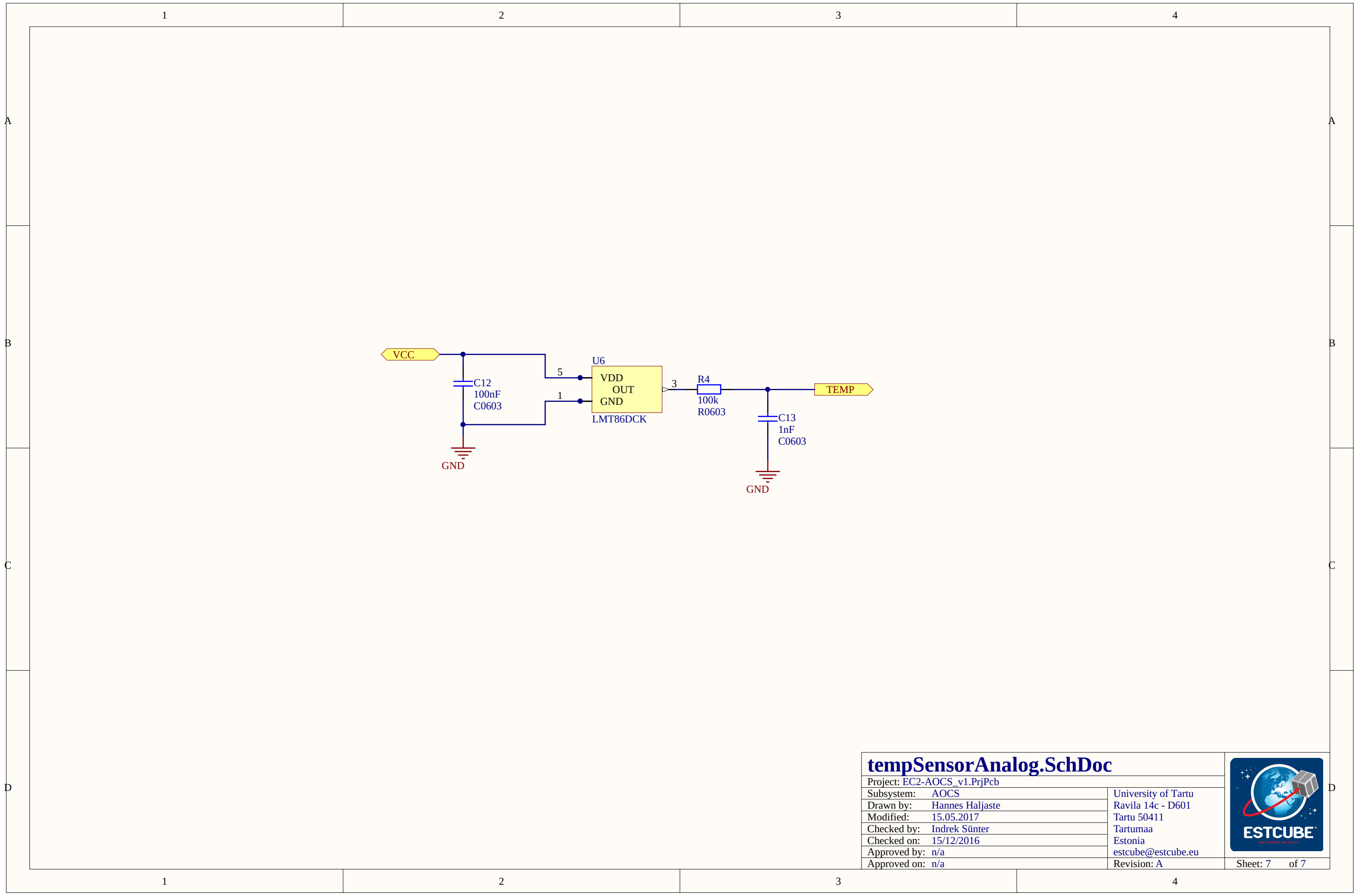

Figure 4.39: Attitude and orbit control system’s temperature sensor schematic.

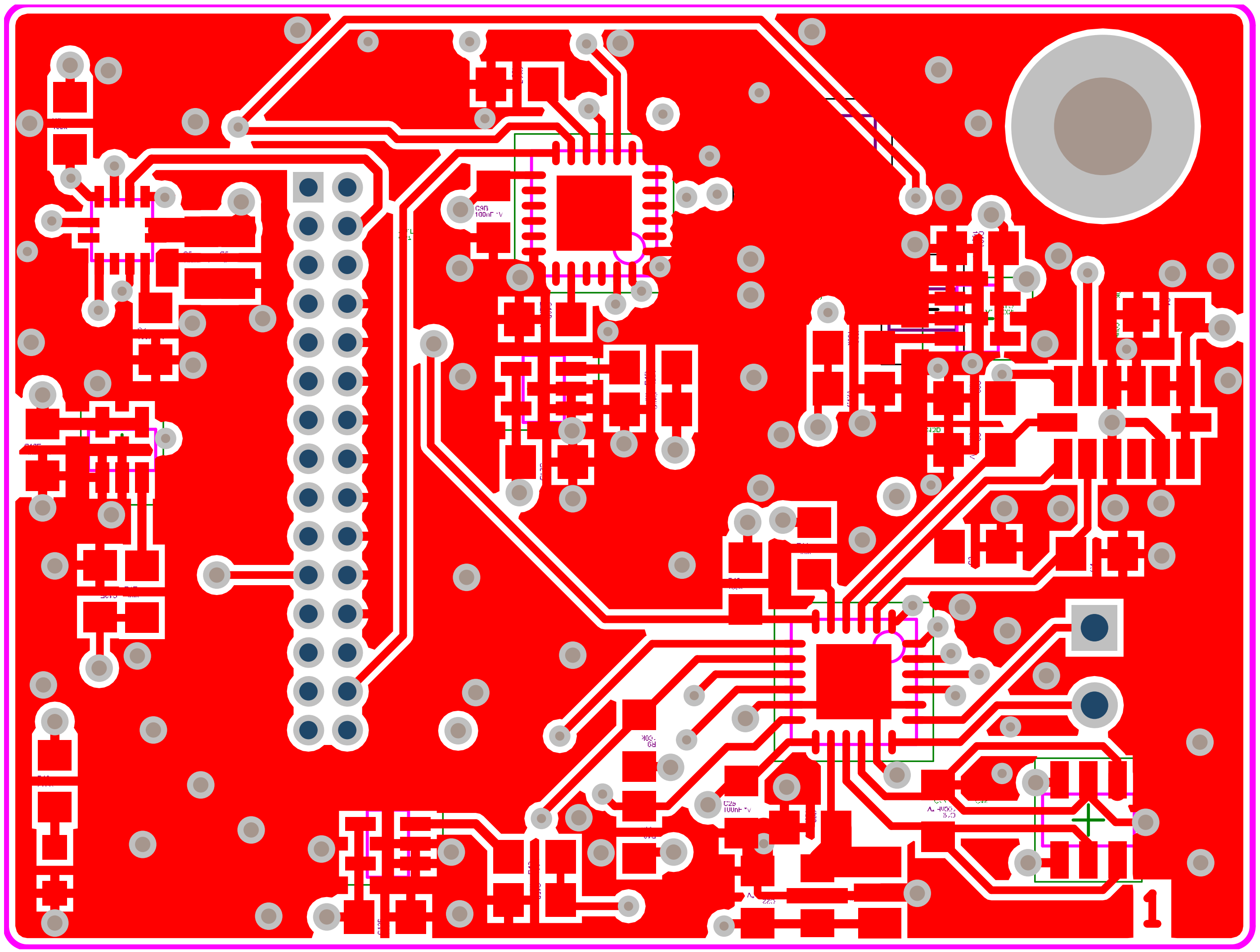

Figure 4.40: Attitude and orbit control system's printed circuit board layer 1 - component and signal plane.

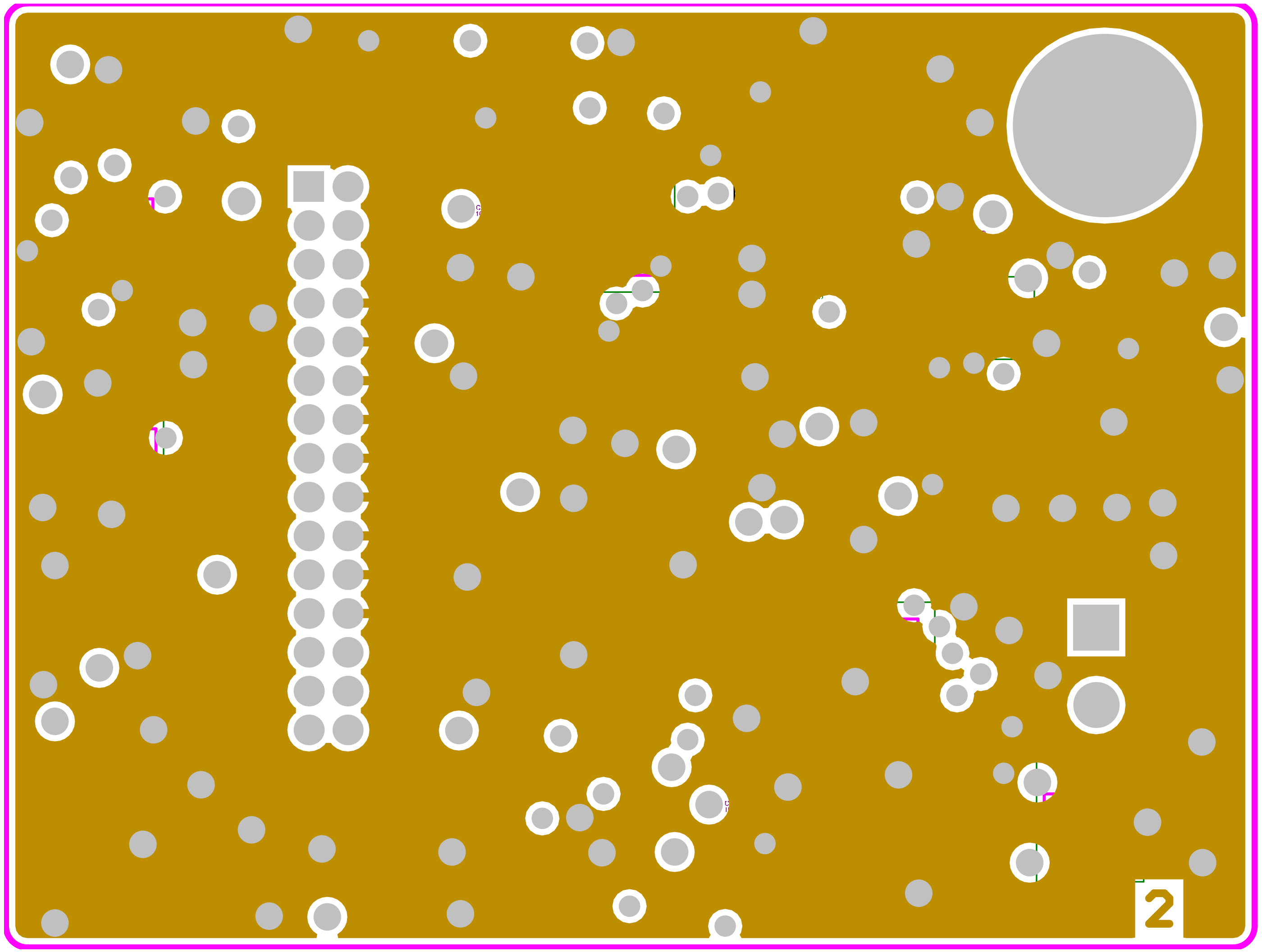

Figure 4.41: Attitude and orbit control system's printed circuit board layer 2 - ground plane.

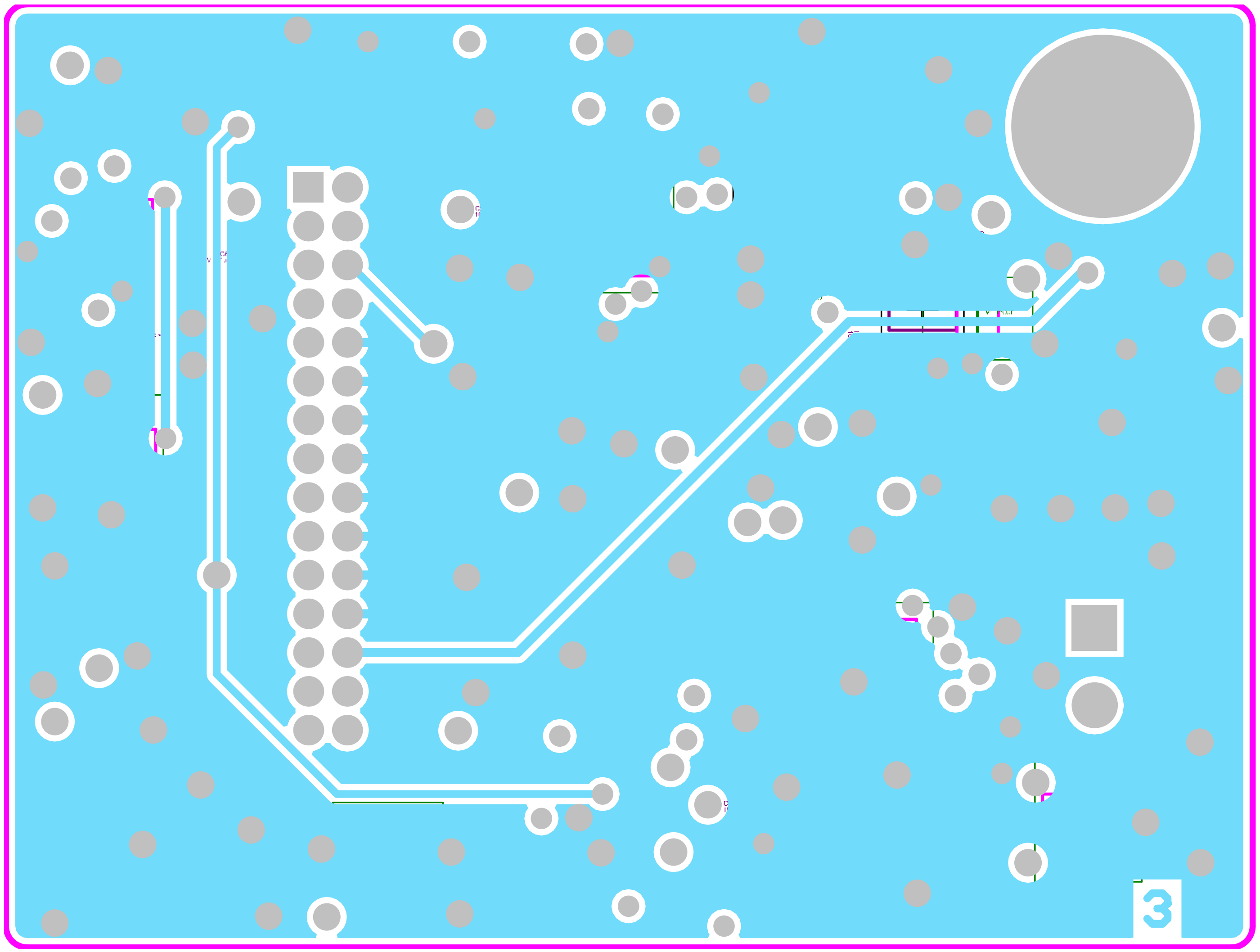

Figure 4.42: Attitude and orbit control system's printed circuit board layer 3 - signal plane.

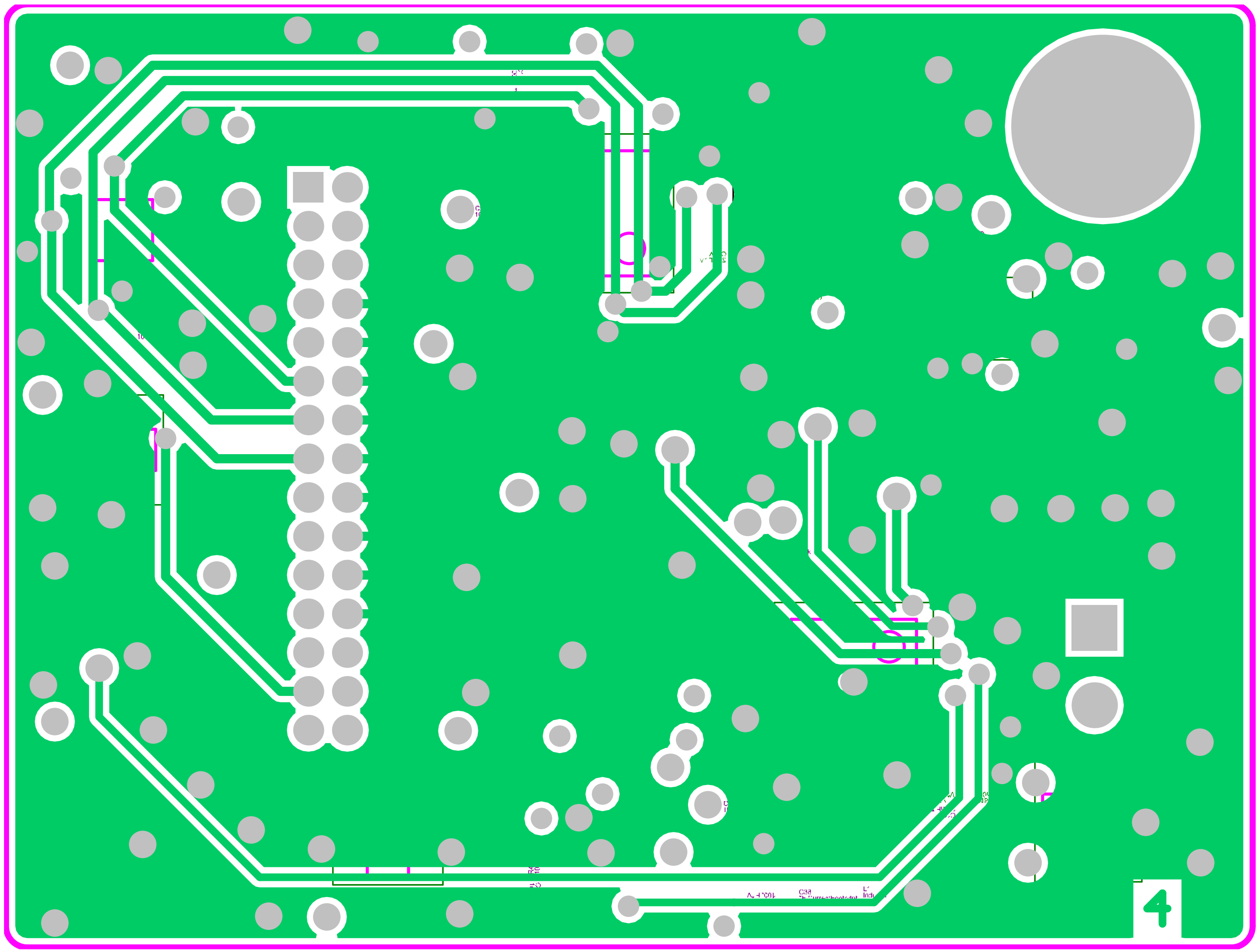

Figure 4.43: Attitude and orbit control system's printed circuit board layer 4 - signal plane.

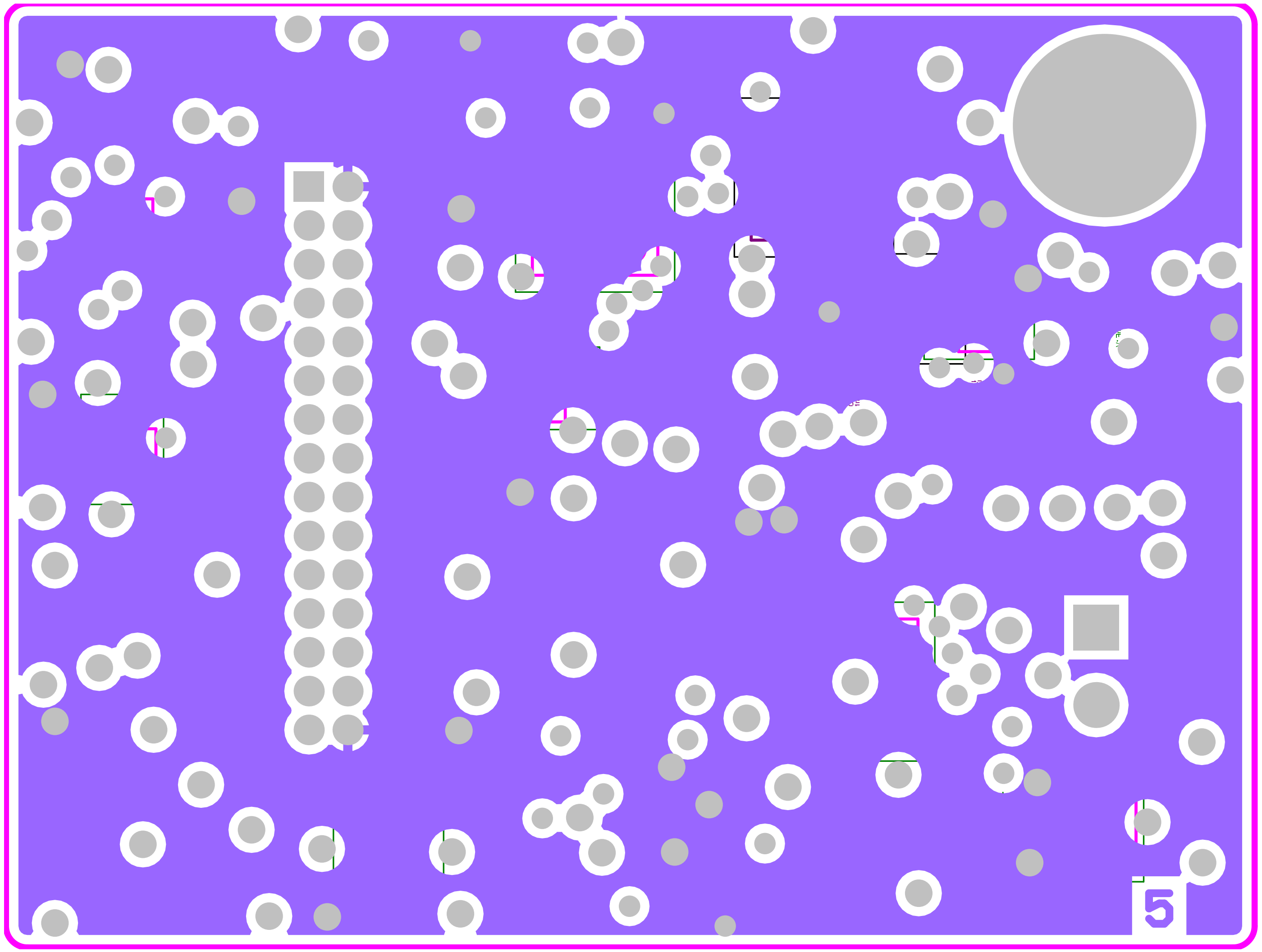

Figure 4.44: Attitude and orbit control system's printed circuit board layer 5 - power plane.

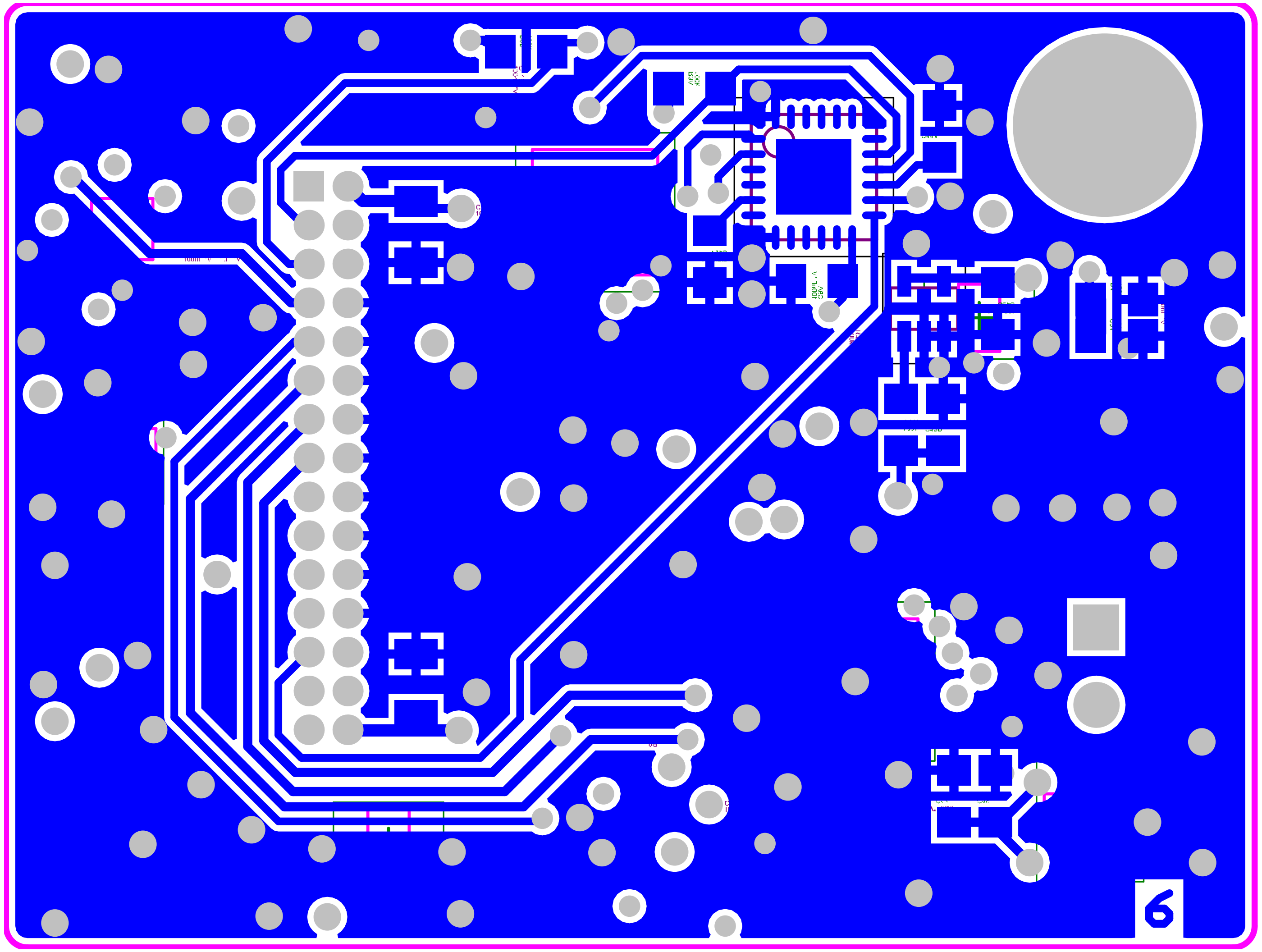

Figure 4.45: Attitude and orbit control system's printed circuit board layer 6 - component and signal plane.

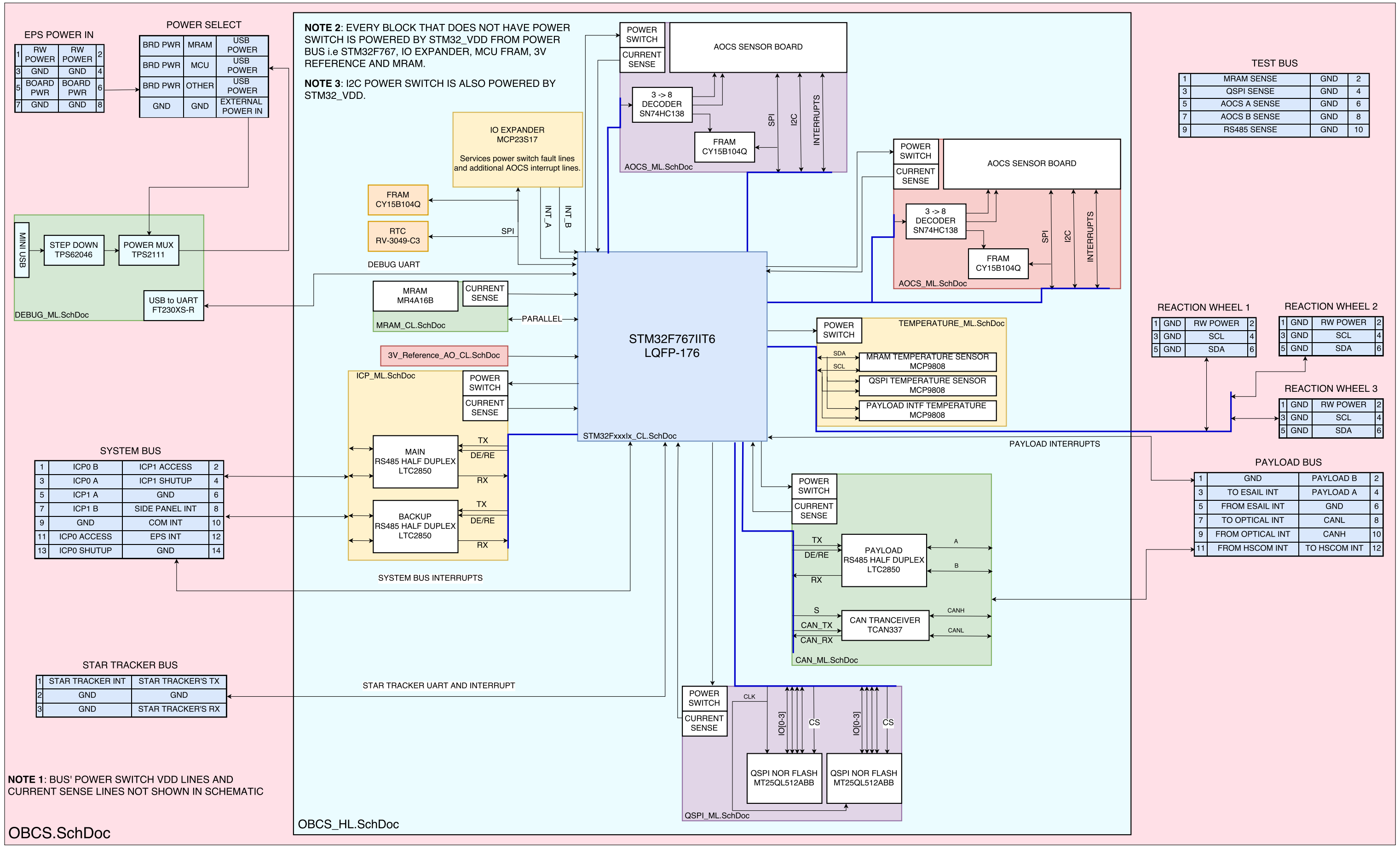

Figure 4.46: On-board computer system block diagram.

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ELECTRONICS DESIGN AND TESTING FOR ESTCUBE-2 ONBOARD COMPUTER SYSTEM WITH SENSORS FOR ATTITUDE DETERMINATION

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