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THE FACULTY OF POWER AND AERONAUTICAL ENGINEERING
WARSAW UNIVERSITY OF TECHNOLOGY



CRITICAL DESIGN REVIEW

Sun Sensor

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	PW-Sat2	Critical Design Review	
	2016-11-30	Sun Sensor	
	Phase C		

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Abbreviated terms

ADCS Attitude Determination and Control System

COMM Communication subsystem

DT Deployment Team

EM Engineering Model

EPS Electrical Power System

ESA European Space Agency

FM Flight Model

GS Ground Station

LEO Low Earth Orbit

MA Mission Analysis

MCU Mission Controller Unit

MDR Mission Definition Review

PDR Preliminary Design Review

PV Photovoltaic cell

RTD Resistance Thermal Detector

SC Spacecraft

SKA Studenckie Koło Astronautyczne (Students' Space Association)

Sps Samples per second

SSO Sun-Synchronous Orbit

SW Software

TBC To Be Continued

TBD To Be Defined

TCS Thermal Control System

WUT Warsaw University of Technology

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1 INTRODUCTION

1.1 PURPOSE AND SCOPE

The aim of the Sun Sensor experiment, as it was in the earlier phases, is to build and to test the performance of the Sun Sensor working on board of the satellite. The Sun Sensor will be two-axis device, with possibly small dimensions and sufficient accuracy (better than photodiodes), in order to create a low-cost sensor for CubeSat missions.

1.2 DOCUMENT STRUCTURE

Chapter 1 introduces the document and its structure.

Chapter 2 describes the Sun Sensor (SunS) from the system point of view.

Chapter 3 summarizes mechanical design of the SunS.

Chapter 4 presents electronics design of the SunS.

Chapter 5 describes computing algorithm of the sensor.

Chapter 6 describes embedded software on Mission Controller Unit of SunS.

Chapter 7 presents the SunS prototypes.

Chapter 8 presents the tests philosophy of the SunS.

1.3 PROJECT DOCUMENTATION STRUCTURE

See section 1.3 in [PW-Sat2-C-00.00-Overview-CDR].

1.4 REFERENCE DOCUMENTS

Internal project documents are referred by its name according to the [PW-Sat2-C-00.00-Overview-CDR].

1.5 DOCUMENT CONTRIBUTORS

This document and any results described were prepared solely by PW-Sat2 project team members.

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2 SYSTEM DESCRIPTION

2.1 SYSTEM REQUIREMENTS

The system requirements are the same as prepared in the phase B:

- Small dimensions – less than 1U wall with depth <20mm;
- Relatively wide field of view – 120°-160° on two axes;
- Sensor accuracy – as good, as it is possible, 0.1°-5°;
- Sensor structure easy to produce and relatively cheap;
- Using commercial off-the-shelf components;
- Low power consumption – less than 0.5W.

This is how a Table should look like. It may have horizontal lines in the table body, but you can do them also like in Table B-1.

2.2 LAST CHANGES

In the earlier phase there was considered design based on photovoltaic cells, fully analog devices. Due to many issues discussed later in this chapter (some of them were also mentioned in phase B document [PW-Sat2-B-06.00-SunS-PDR]), a decision was made to replace them with the digital components, the ALS (Ambient Light Sensors), which are smaller and easier for signal measurement than photovoltaic cells and photodiodes.

There were many problems with the photovoltaic cells. First of all, cutting of the cells to their final size was hard and only the diamond wire cutting gave sufficient results. Mounting cells to the PCB boards, due to their fragility, wasn't reliable and cells could be easily broken during the subsequent use of the sensor. Also the electronics required for the analog signals reading was quite extended. Still the readings have depended on the temperature changes. Such device based on the photovoltaic cells required a lot of additional work to do and the expected results could not be sufficient. Due to the described causes, there were made a decision to replace the cells with the Ambient Light Sensors. Such sensors are similar to the photodiodes, but they have a built-in current-integrating amplifier and analog to digital converter (ADC). This gives the possibility to achieve better performance than with photodiodes, as well as with solar cells. There were chosen the BH1730 sensors.

One of the important objectives part of the project was the size of the detector. With the selection of the digital BH1730 in the role of solar light sensor, it is possible to place 12 of these elements in the device, instead of four solar cells, giving the redundancy of the measurement. And still the final size of the device allows for mounting on the Cubesat wall.

The system consisting of the BH1730 will be made at low cost. There is expected correct operation of the whole device based of the angle tests and temperature tests. Performance of the photovoltaic has also been defined as correct, however, the requirement for small usable space, the need for make precisely cutting the solar cells and the need to implement an extended electronic system with temperature compensation algorithm, the design with the photovoltaic cells has been replaced.

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New design of the SunSensor is based on the examination of digital integrated light sensors, which feature a simple communication with the microcontroller and easy mechanical implementation. There were tested three sensors: TSL2561T, BH1751FVI, BH1730FVC. Basing on the test results, BH1730FVC was selected to work in the SunSensor. The small dimensions of the sensor and the surface provided for mounting the photocell enable to mount three such sensors and a temperature sensor. This provides redundancy and greater reliability of results than in the case of photovoltaic cells.

Although the ALS sensors still exhibit significant temperature dependence on light readings, there is enough space on the SunSensor board to equip the device with platinum resistance thermometers to compensate unwanted temperature influence.

The selected sensors show a sufficiently high angular resolution, and thanks to the digital form of data will be possible to quickly obtain information about the orientation of the expected accuracy of the location close to 1 °. Systems have a temperature compensation, but it's functionality is not ideal. The system selected have the temperature compensation function the closest to the linear over the entire range, so that it will be possible to eliminate additional control system.

The activities carried out, which resulted in the choice are presented in the thesis under the title 'Project of detector of optimal position to solar radiation in satellite PW-Sat2', whose author is a member of the PW-Sat2 team.

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3 MECHANICAL DESIGN

Sun Sensor's mechanical design needs to fulfill all space requirements and provide proper angular alignment of sensors. Selected materials, connections and dimensions shall ensure resistance to vibration loads during launch.

In this section there are presented the mechanical aspects - mainly sensors mounting and integration.



3.1 CASE DESIGN

Sun Sensor's case design is based on a pyramid shape. Four PCB's with sensors are placed separately, perpendicularly to each other. Electronics mounting is simple and tilted 20 degrees so there is no shadow caused by screening elements that could affect sensor read-outs. Sun Sensor's design is compact (56x56x8 mm) and ensures enough space for other subsystems. Case geometric shape is to reduce the number of elements. Device consists of 28 parts presented in table 3-1. All external surfaces of aluminum parts are anodized.

Table 3-1 Sun Sensor part list.

No	Name	Quantity	Material	Comments
1	Case	1	Aluminium 7075	Anodized
2	Cover	1	Aluminium 7075	Anodized
3	Spacer	4	Delrin/PEEK	
4	Screw ISO 10642 M2x8	4	A4	
5	Screw ISO 10642 M1,6x4	8	A4	
6	Nut ISO 4035 M2	4	A4	
7	Mainboard	1	FR4+electronics	
8	Sensor PCBs with 9 cables	4	FR4+electronics	
9	Cables with connector	1x4wires		
		28		

There are few things, that decided about the design of the case. The idea is to have the easy mounting of the electronic boards. The case is an aluminum milled part and PCB boards with sensors can be fixed with proper angle, without shadowing of the sensor's detector area. The Main Board is in the center of the system, to have a short connection with the sensors. Creating the one piece element for mounting the boards simplifies the integration process and ensures the proper alignment. The height of the system is to be low, to fit the Cubesat standard to have elements at maximum of 6.5mm distance over the Cubesat rails surface and not to disturb in the space inside of the satellite with placing other standard components. The design pictures are presented below.

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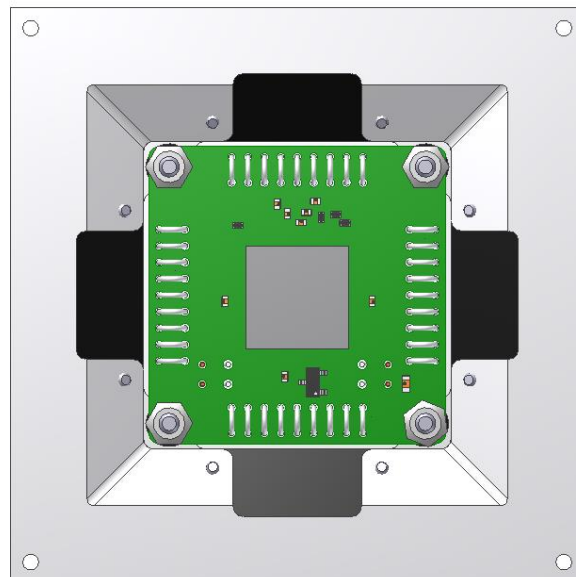
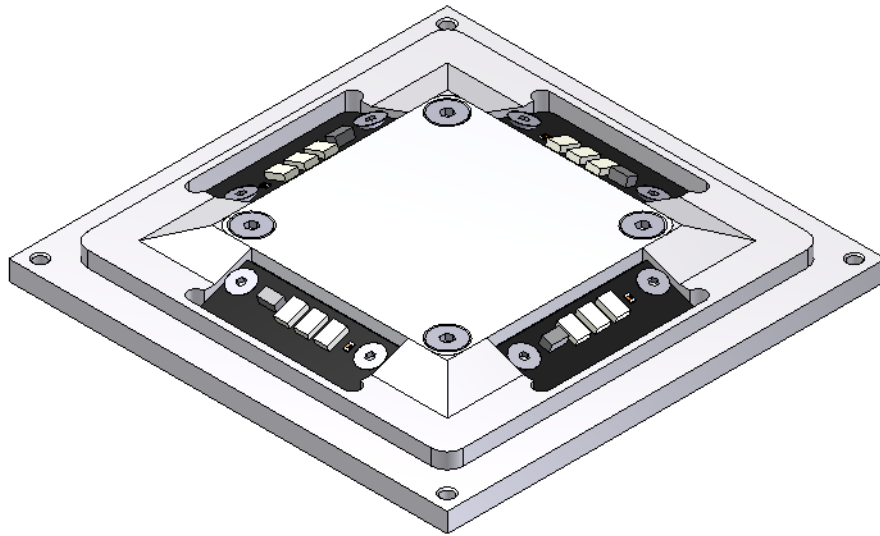


Figure 3-1 Sun Sensor case design.

3.2 INTEGRATION PROCESS

The design enables to mount and screw together already integrated electronic boards to the case.

Sun Sensor's assembly process consists of following steps:

1. Soldering cables between PCB's with sensors and Mainboard;
2. Placing electronics in the Case;
3. Mounting sensors' PCB's to the Case with 8x ISO10642 M1,6x4;
4. Placing four Spacers between Mainboard and threaded holes in the Case;
5. Mounting Cover to Case with 4x ISO10642 M2x8 screws, through the Spacers and Mainboard;
6. Mounting 4x ISO4035 M2 nuts on the screws.

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An additional document describing the process of integration will be provided. (TBD)

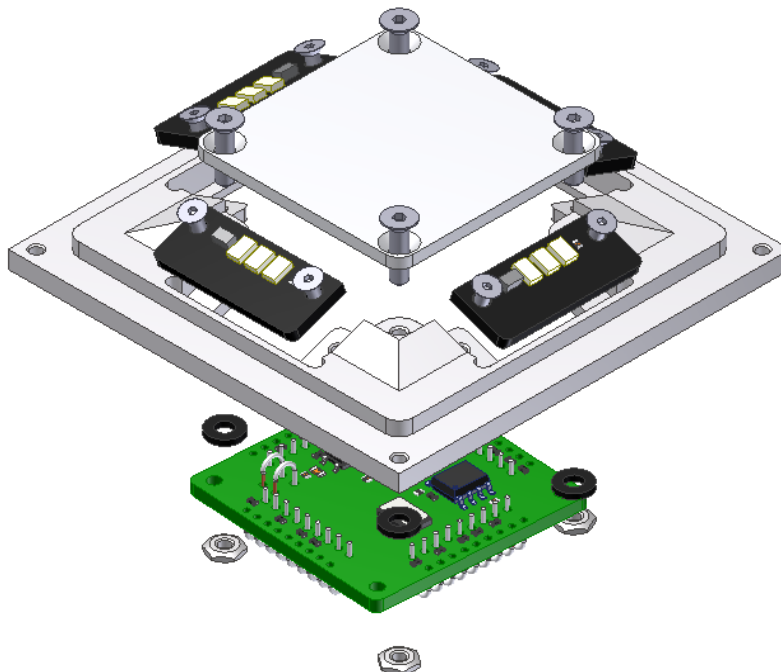




Figure 3-2 Sun Sensor case assembly

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4 ELECTRONICS DESIGN

4.1 CHANGES DESCRIPTION

Since Phase B, several changes were introduced in the design of electronic circuits in order to fulfil new requirements (space limits, integration issues and problems with photovoltaic cells fabrication) - for more details on this topic see chapter 2.2.

4.1.1 DIGITAL LIGHT INTENSITY SENSORS

The main change, affecting rest of the electronics of the Sun Sensor, is a new type of light intensity sensor. In a previous models to sense intensity of light, photovoltaic cells (PV) were utilized. As a purely analog device, a PV cell demands bias and readout circuits consisting of analog and analog-to-digital interfaces. In order to simplify whole system and get rid of a huge part of analog, noise susceptible and space-consuming electronics, a new type of sensor was selected. Digital ambient light sensor BH1730FVC from ROHM Semiconductor is a highly integrated circuit. It consists of two photodiodes (for visible light and infrared), programmable gain amplifiers, analog-to-digital converters and control logics. The sensor has digital, I²C interface, allowing easy and reliable way of communication with any microcontroller unit.

Three digital sensors are placed on every of four, small PCBs resembling a photovoltaic panel used in earlier models of the Sun Sensor.

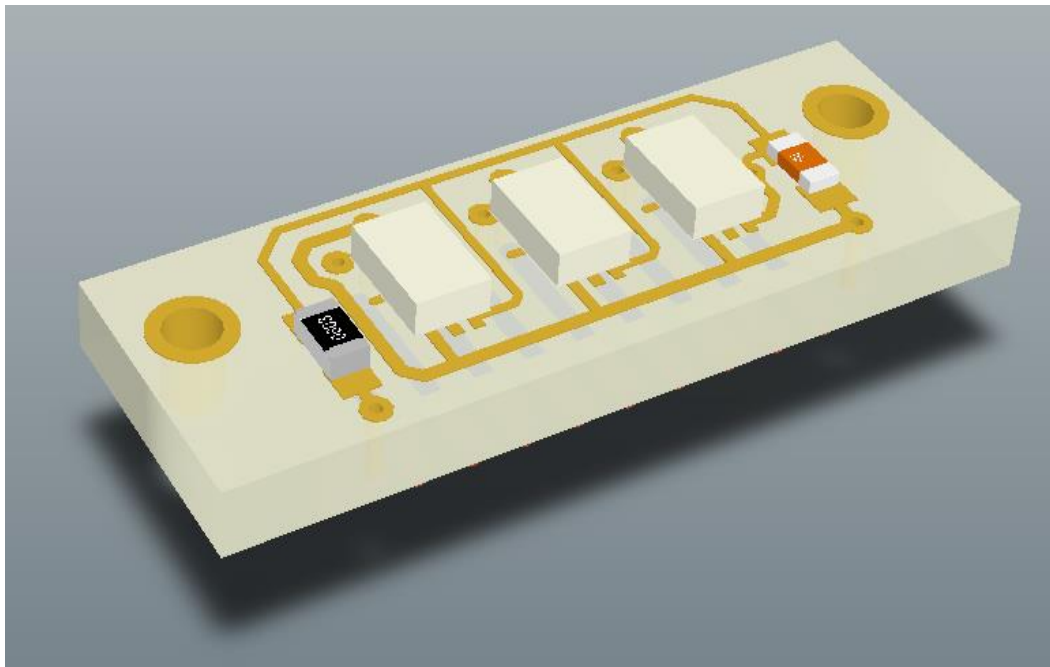
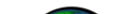



Figure 4-1 Module (a small PCB) with three digital ALS replacing an analog photovoltaic panel.

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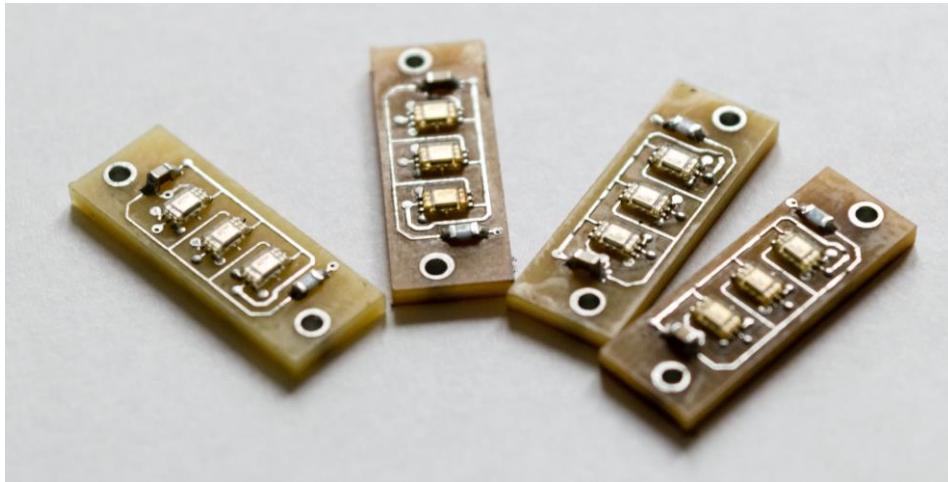


Figure 4-2 Panels with ALS sensors and RTD thermometers.

4.1.2 COMPACT MAIN BOARD

Thanks to changes introduced in light sensing elements, a number of parts that are necessary to be put on the main board of the Sun Sensor was dramatically reduced. Now, light intensity data are acquired by the main board in purely digital form, so the analog interface is no longer needed. Simplified and reduced analog part is present only for temperature sensing. Thanks to these changes, the main board is as small as a 29 mm – edge square – see Figure 4-3.

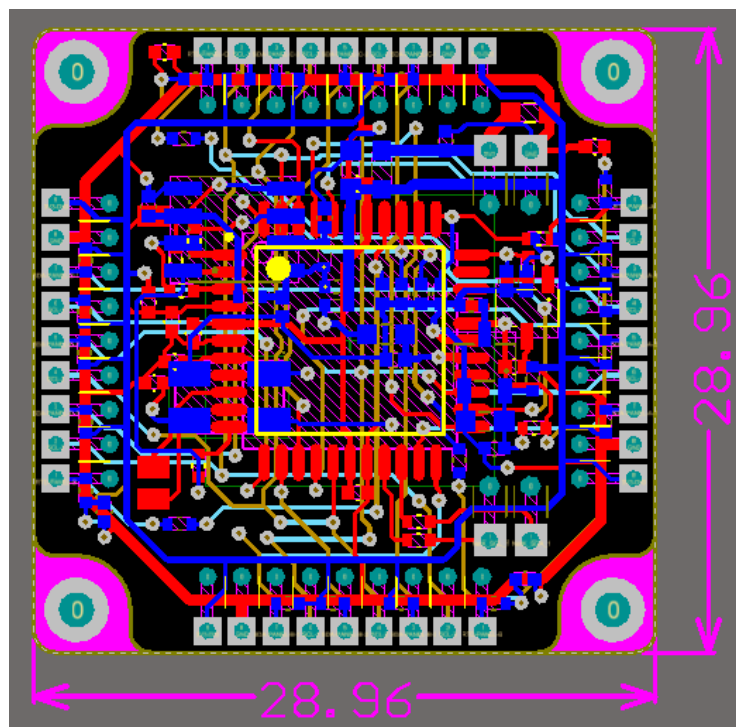


Figure 4-3 Main, 4-layer printed circuit board with dimensions.

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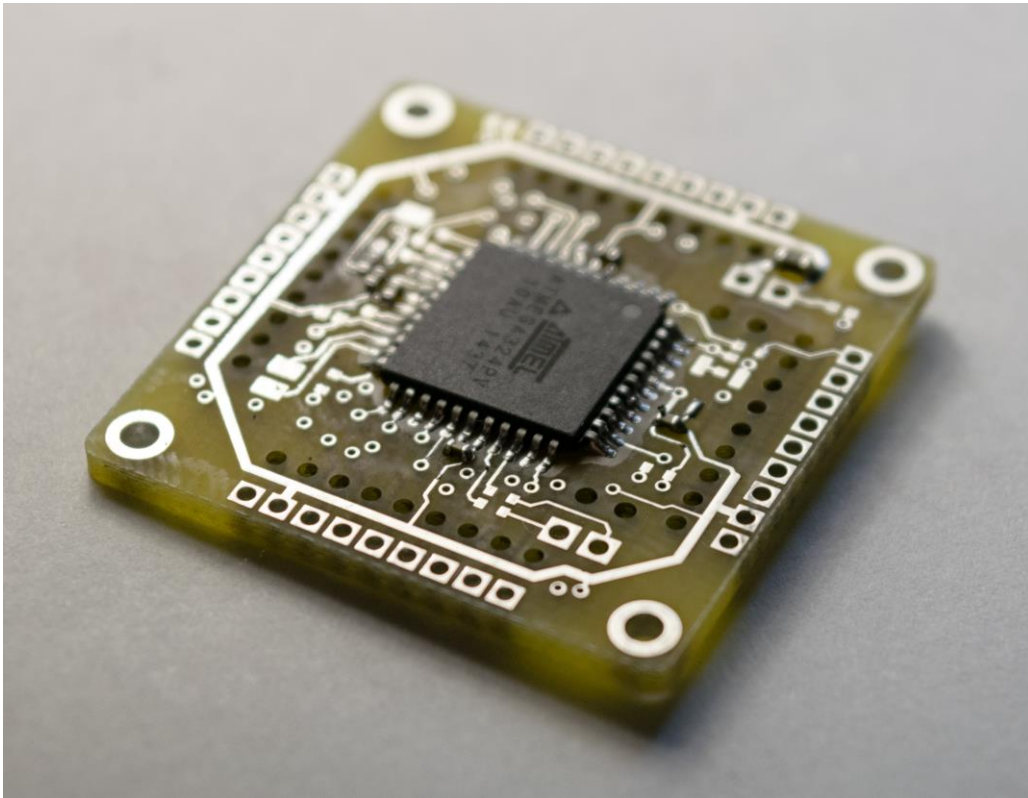


Figure 4-4 The main board of the SunSensor.

4.2 SYSTEM DIAGRAM

Sun Sensor's structure may be divided into two general parts: four PCBs ("panels") containing ALS and temperature sensor (RTD), and another PCB ("main board") containing readout circuits and microcontroller unit.

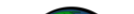
Every of four panels consists of:

- 3 x ambient light sensors connected via I²C-like interface
- 1 x platinum PT1000 resistance thermometer (RTD)

Main board contains:

- local power supply unit (PSU)
- microcontroller unit
- FRAM memory
- integrated temperature sensor

Interconnection between subsystems are shown in Figure 4-5.

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SunS architecture diagram

PW-Sat2 Team 2016-11

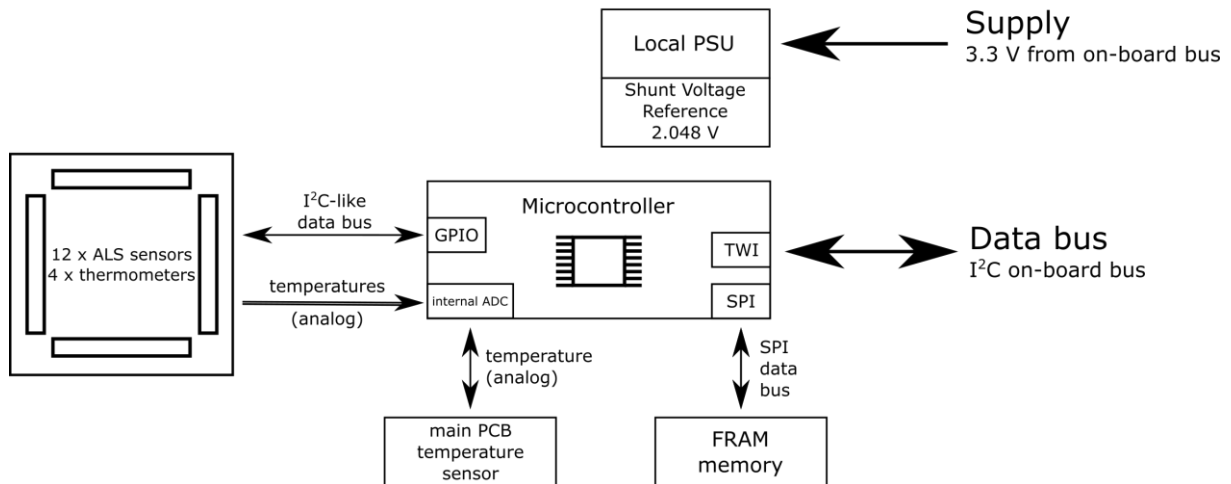


Figure 4-5 Sun Sensor architecture diagram.

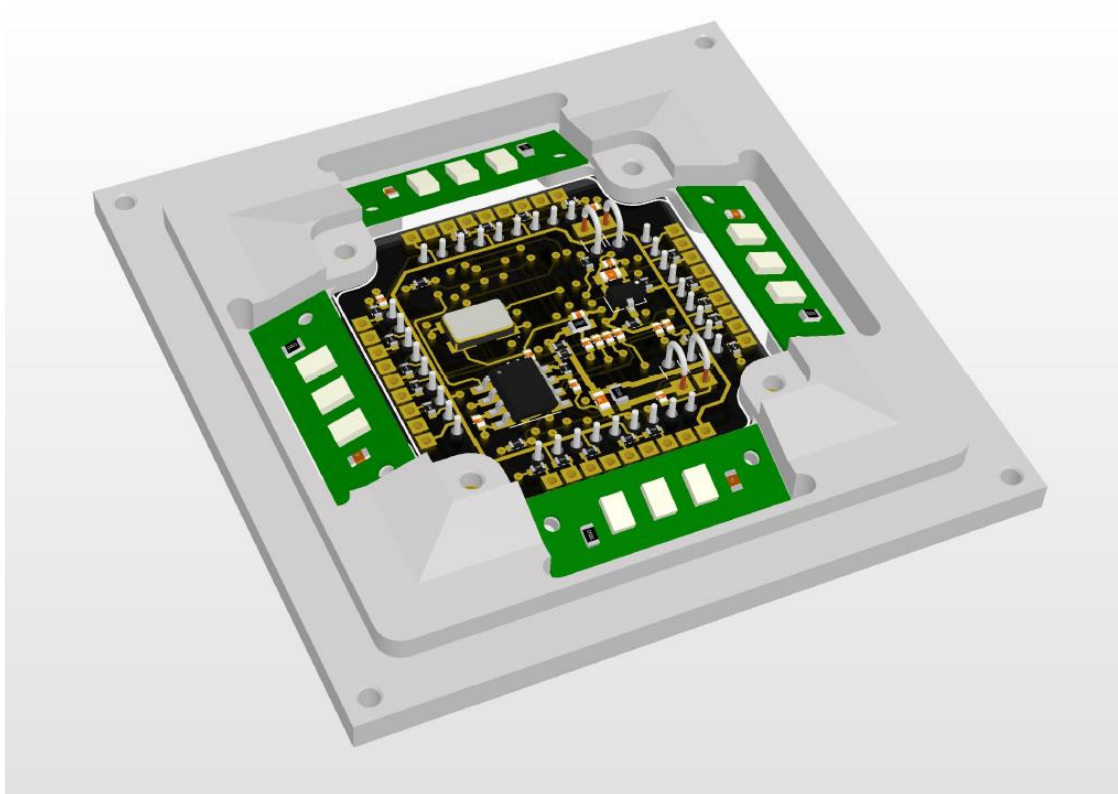


Figure 4-6 Render of the Sun Sensor.

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4.3 DESCRIPTION OF OPERATION

4.3.1 LIGHT INTENSITY MEASUREMENT

Sun Sensor has three sets of four light sensors to measure intensity of incident light. To proper operation the Sun Sensor needs only one set of light sensors. Other sets are used to average a measurement (to increase accuracy). They can be also considered as redundant ones.

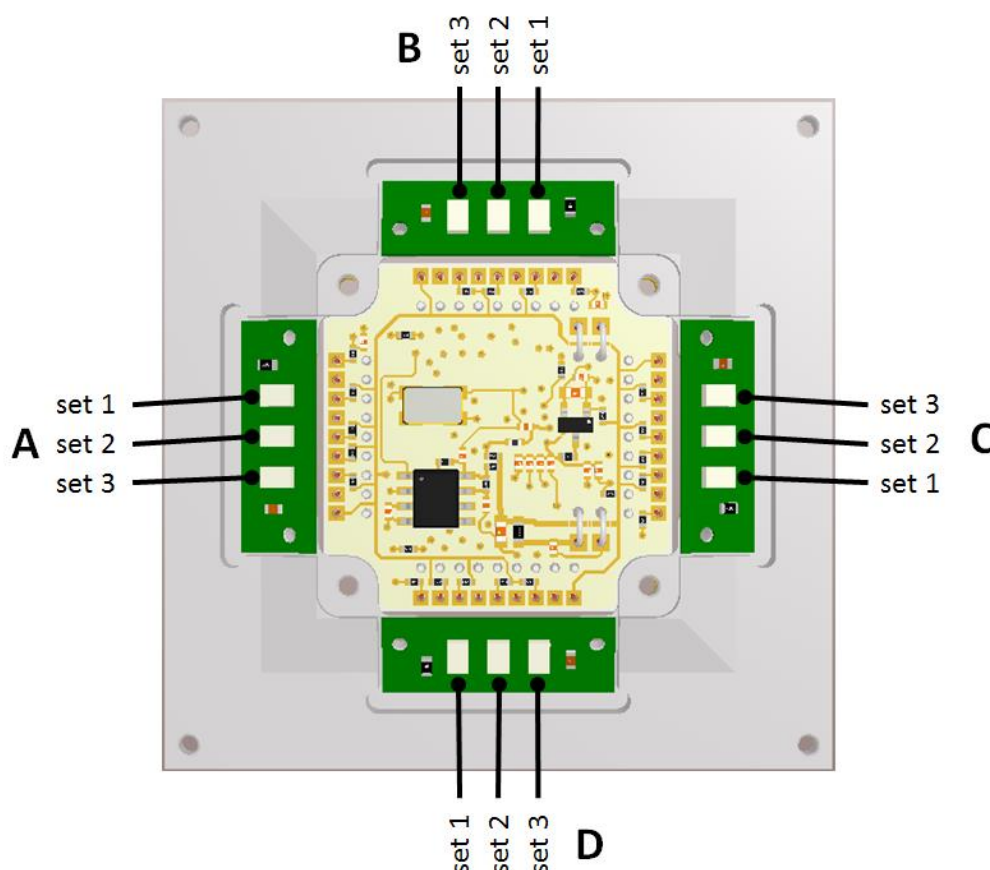


Figure 4-7 Light sensors grouped into three sets of four.

Digital ambient light sensor BH1730FVC from ROHM Semiconductor is able to measure visible light and infrared by separate photodiodes and ADCs. Thanks to built-in PGA and selectable ADC integration time the sensor can detect light in very wide range up to 65535 lx with resolution of 1 lx (16 bit). In some circumstances, resolution might be increased by use of PGA, but then range of the sensor is affected. Output decimal code is linearly proportional to the light intensity. Communication with sensor take place via I²C bus. Each sensor has the same slave address. Internal architecture of BH1730FVC is shown in Figure 4-8, whereas Table 4-1 summarizes the most important parameters of the light sensor.

The sensor has two 16-bit registers storing last result of conversion, one for visible light and IR. Conversion start may be configured in free-running mode or triggered by a command transferred via I²C.

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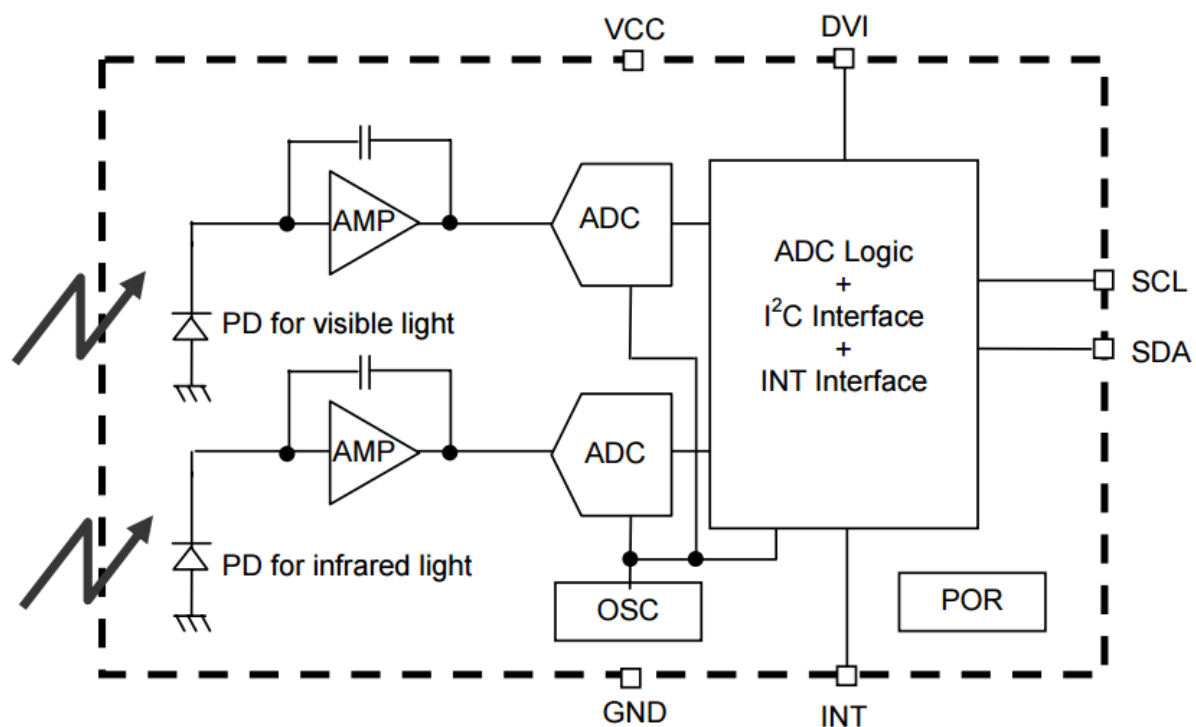


Figure 4-8 BH1730FVC ALS internal architecture.


Table 4-1 BH1730FVC sensor specification.

No	Parameter	Value	Units
1	Supply voltage	2.4 - 3.6	V
2	Supply power	0.6	mW
3	Measurement range	0.008 - 65535	lx
4	Integration time	2.7 - 688.5	ms
5	Communication interface	I ² C, one slave address	-
6	Dimensions	3.0 x 1.6 x 0.75	mm

Simultaneous light intensity measurements

To work properly, Sun Sensor needs light intensity data from all sensors in a set measured at the same time. When satellite is in non-stationary state (it has some angular velocity), time shift between measurements introduces an error in final output. To minimize this negative effect, conversion is triggered in all sensors exactly at the time. In order to do this, all four sensors in a set are connected in a special way.

All SCL lines are tied together, thus the clock is common for whole set of sensors. However, data lines (SDA) are connected to MCU independently - see Figure 4-9.

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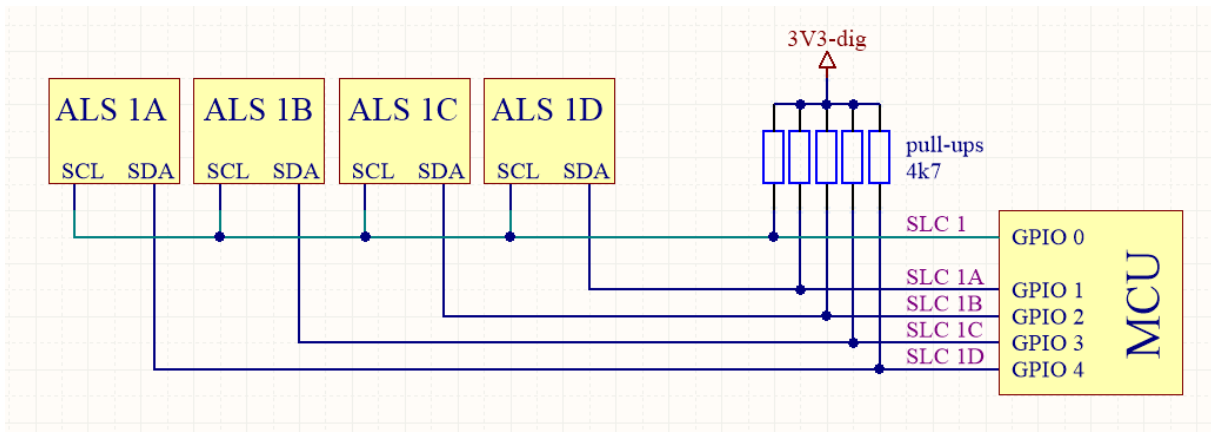


Figure 4-9 Connection of four sensors to microcontroller (one 'set').

An I²C interface is emulated using MCU's GPIOs (bit banging). Bytes are read and written to the sensor by following manner:

Write byte:

1. generate start bit (according to I²C specification standard)
2. set proper states at SDA lines according to *i-th* bit
3. generate clock pulse
4. jump to 2. if there are bits left in a byte
5. generate stop bit (according to I²C specification standard)


Read byte:

1. generate start bit (according to I²C specification standard)
2. set all SDA GPIOs as input
3. acquire state of each SDA line
4. generate clock pulse
5. jump to 3. if there are left bits in a byte
6. generate stop bit (according to I²C specification standard)

Typical scenario of data acquisition from 12 sensors:

- write proper bytes to settings registers of all 12 light sensors
- write byte triggering light conversion (at the same time to set of four sensors), then do the same for next group of 4 sensor, and finally for the last set of four sensors
- when conversion is completed, read data registers from the first group of four sensors, then for second and finally third groups.

Because each set of sensors is driven by separate clock, it's not possible to trigger conversion for all groups at once, but with properly written driver for AVR microcontroller the delay is negligible.

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Measurement reliability and redundancy

In order to provide a high level of reliability of angle measurement and immunity to failures, redundant ALS sensors are present in the Sun Sensor.

Ambient Light Sensors are one of the most intensively exposed to cosmic radiation electronic parts of the entire satellite. They have to operate in a wider temperature range than e.g. electronics on main board of the Sun Sensor. Because of that, triple-mode redundancy of ALS sensors was implemented in the Sun Sensor.

Each set consisting of 4 sensors can deliver full data needed for angle determination. Taking measurement by three sets of sensors with a very short time gap between them, then using voting algorithm allow to detect sensors malfunctions. In the worst case, with proper calibration and software, Sun Sensor should work (i.e. return proper angle with respect to the Sun) even if case of failure of one light sensor in each group (A-D) - see Figure 4-10.

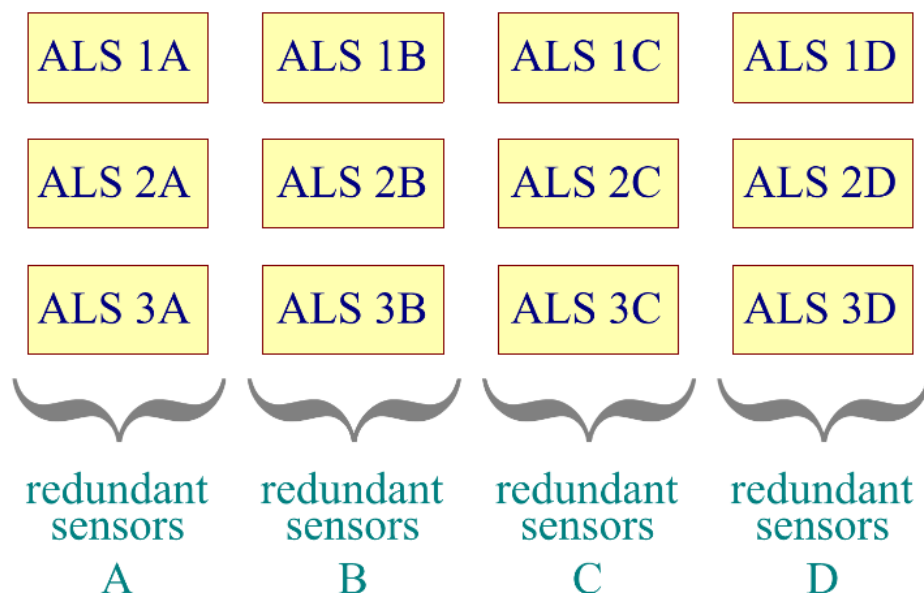



Figure 4-10 Groups of redundant ambient light sensors.

Temperature influence on BH1730FVC light measurement

As mentioned in previous chapters, the ALS light sensors exhibit non-zero temperature dependence on both visible and infrared light measurements. In order to compensate response of the sensors a calibration curves were measured.

Two sensors placed close to each other were lit with a constant intensity, white light from a halogen lamp powered by a DC voltage source. Temperature of the device was changed in range starting from 30 up to 100 °C. Obtained characteristics are shown in Figure 4-11 and Figure 4-12.

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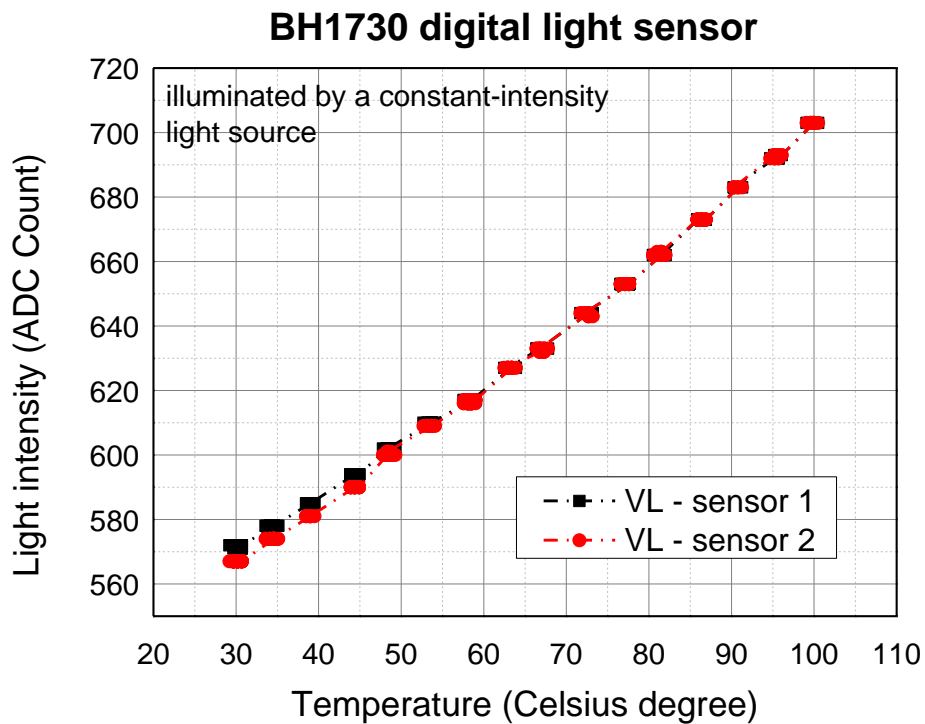


Figure 4-11 Calibration characteristic for visible light photodiode in the ALS.

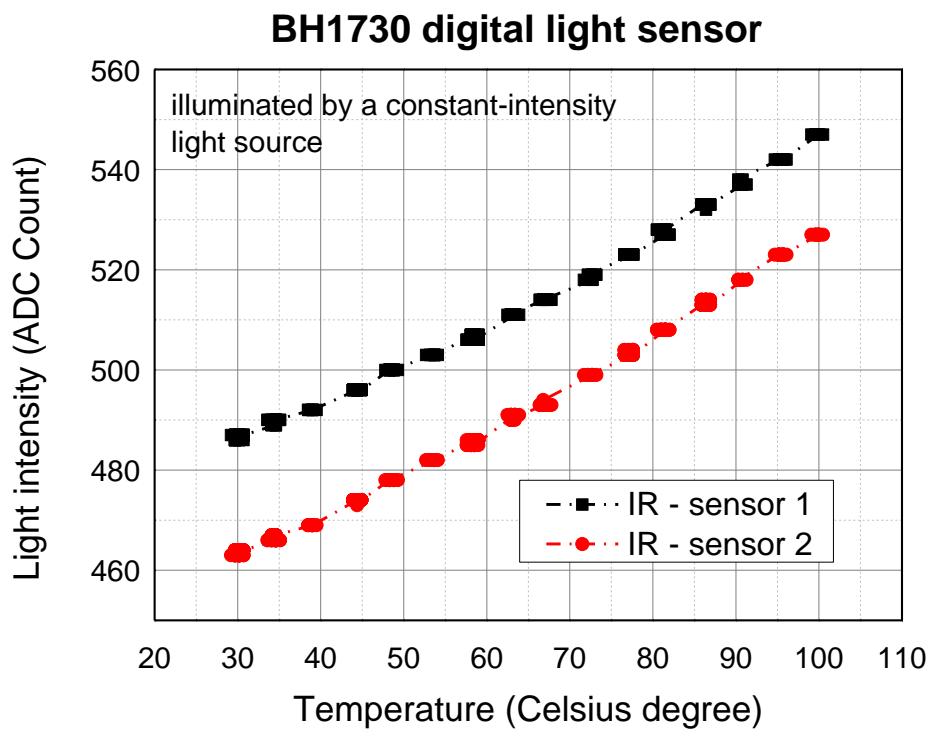


Figure 4-12 Calibration characteristic for infrared photodiode in the ALS.

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4.3.2 TEMPERATURE MEASUREMENT

There are five thermometers in the Sun Sensor, but only four of them, RTDs mounted on panels close to the light sensors have significant relevance for measurement correctness and accuracy. The fifth sensor (analog integrated circuit, LM60) is mounted on the main board and its intention is measurement of general temperature of the Sun Sensor. Nonetheless if temperature is kept within the operating range of electronic components, its indication has little or no effect on the Sun Sensor measurements, thus its accuracy is not critical.

4.3.2.1 Platinum Resistive Temperature Sensors - PT1000

Requirements

- measurement range: -55 °C - 150 °C
- resolution: at least 1 °C
- channels: 4
- sample rate: at least 1 Sps

The resistance of PT1000 RTD in given interval of the temperatures varies from 783.19 Ω up to 1573.1 Ω . Temperature dependence on resistance is described by IEC751 / ITS-90 standards.

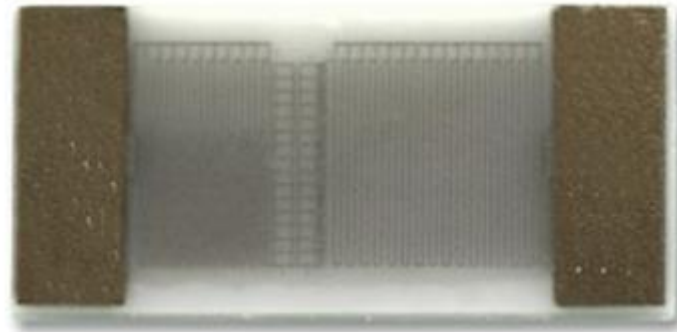
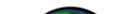



Figure 4-13 PT1000 RTD platinum sensor in SMD 0805 package.

In order to convert resistance changes of RTDs to a voltage, a simple circuit of voltage divider was implemented. Then, the output voltage passes through passive low-pass filter cutting all high frequency noise components. Filtered signal is sampled by built-in AVR microcontroller 10-bit analog-to-digital converter. Thanks to oversampling technique, a resolution of measurement is increased to 12 bit. Block diagram of RTD interface is presented in Figure 4-14, while schematic implementation is shown in Figure 4-15. In turn, Figure 4-16 shows a theoretical simulation of RTD resolution vs. temperature. Results show that resolution better than 1 °C is achievable over the whole range.

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SunS RTD architecture diagram

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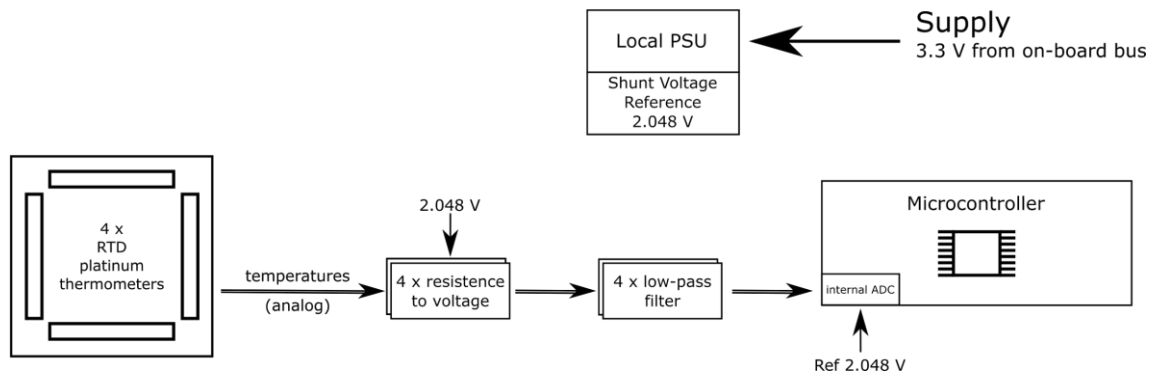


Figure 4-14 RTD platinum sensor readout circuit architecture.

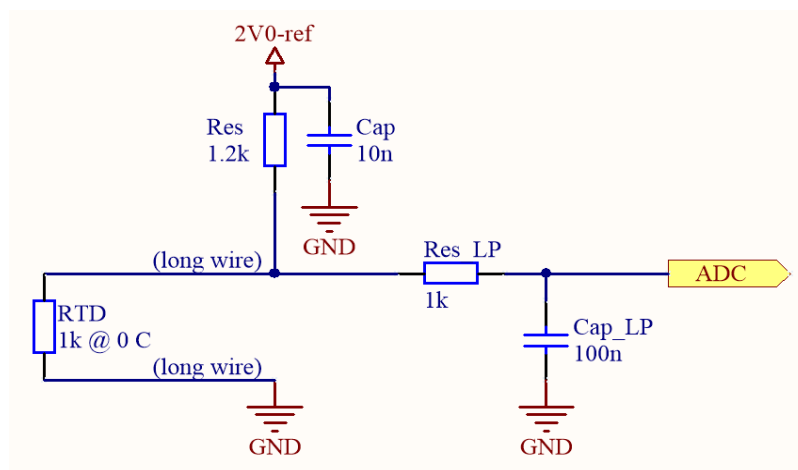
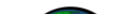



Figure 4-15 Analog interface for RTDs.

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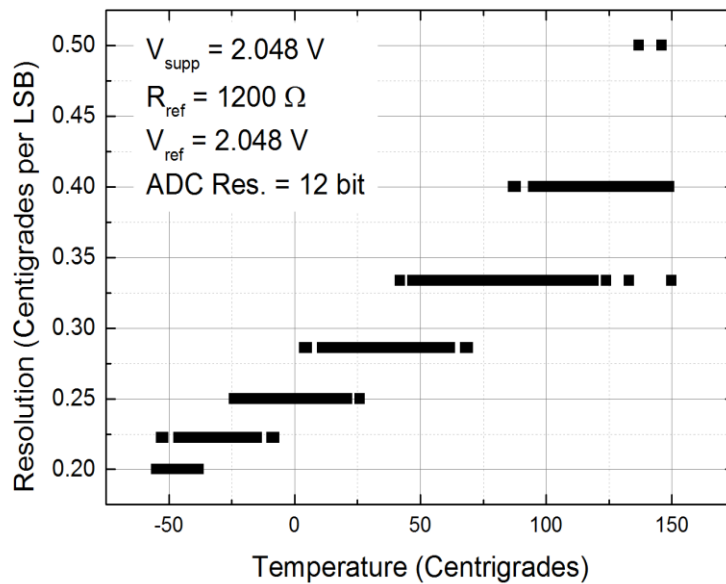


Figure 4-16 Resolution of temperature measurement with PT1000 RTDs.

4.3.2.2 Main board temperature sensor - LM60

The analog output of integrated temperature sensor LM60 placed on the main board is proportional to the actual temperature. The characteristic of the sensor is described in the manufacturer's datasheet. Output of the sensor passes through a passive low-pass filter and then it is connected to internal AVR's analog-to-digital converter. A 10-bit ADC with 2.048 V results in 0.3125 °C/LSB. This result may be improved by oversampling.

4.3.3 MICROCONTROLLER UNIT

Microcontroller tasks in the SunSensor are:

- taking measurements (ALS data exchange, temperatures with built-in ADC, telemetry),
- angle calculations,
- communication with OBC.

Due to chosen ADC the microcontroller must have following interfaces:


- I²C bus – satellite bus,
- Sufficient number of GPIOs – to connect ALS sensors
- Sufficient number of ADC channels – to connect 5 analog thermometers
- ISP/JTAG for first-time bootloader burning,
- UART for programming and debugging in development phase.

As a microcontroller that fulfils all mentioned needs AVR MCU from Atmel - ATmega324P-15AT1 was chosen.

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4.3.4 FRAM MEMORY

Ferromagnetic Random Access Memory (FRAM) is optional and may be used to store calibration coefficients for the sensor.

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5 SENSOR COMPUTING ALGORITHM

The algorithm working on the sensor will use the signals gathered from the ALS sensors and calculate the Sun Vector value, based on the model of the half sphere expected measurements.

5.1 GENERAL ASSUMPTIONS

First and most critical assumption for light sensor is to have algorithm which will run relatively fast. Next thing is limitation of memory, so the algorithm must work fast and be efficient in term of memory usage.

5.2 DESCRIPTION

Algorithm designed for light sensor is based on Neural Network. Neural network developed for this task got structure shown on Figure 5-1. Network got two hidden layers, this structure helps with approximation of highly nonlinear function of dependent signals from sensors.

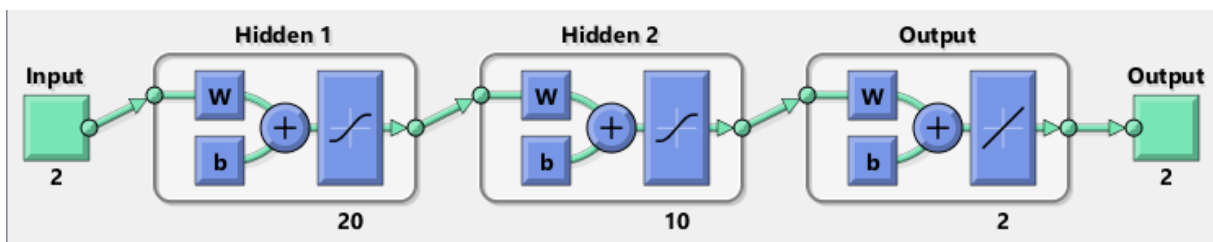



Figure 5-1: Structure of neural network used for approximation.

5.2.1 DEPENDENT SIGNALS

In process of designing algorithms there was a need for become independent from change of amplitude of signal. Shift of amplitude can occur due to various factors , and we are not able to determine signals level on the orbit, but we can determine correlation between them. Let's assume we got four signals I1,I2,I3,I4 from four sensor's sides. In satellite coordinate frame, in comparison to the Figure 4-3, I1 is on the A side, I2 is on the D side, I3 – C side and I4 – B side. With such order defined we can define Relative signals R1 and R2 which are as defined below:

$$R1 = (I1-I3)/(I1+I3)$$

$$R2 = (I2-I4)/(I2+I4)$$

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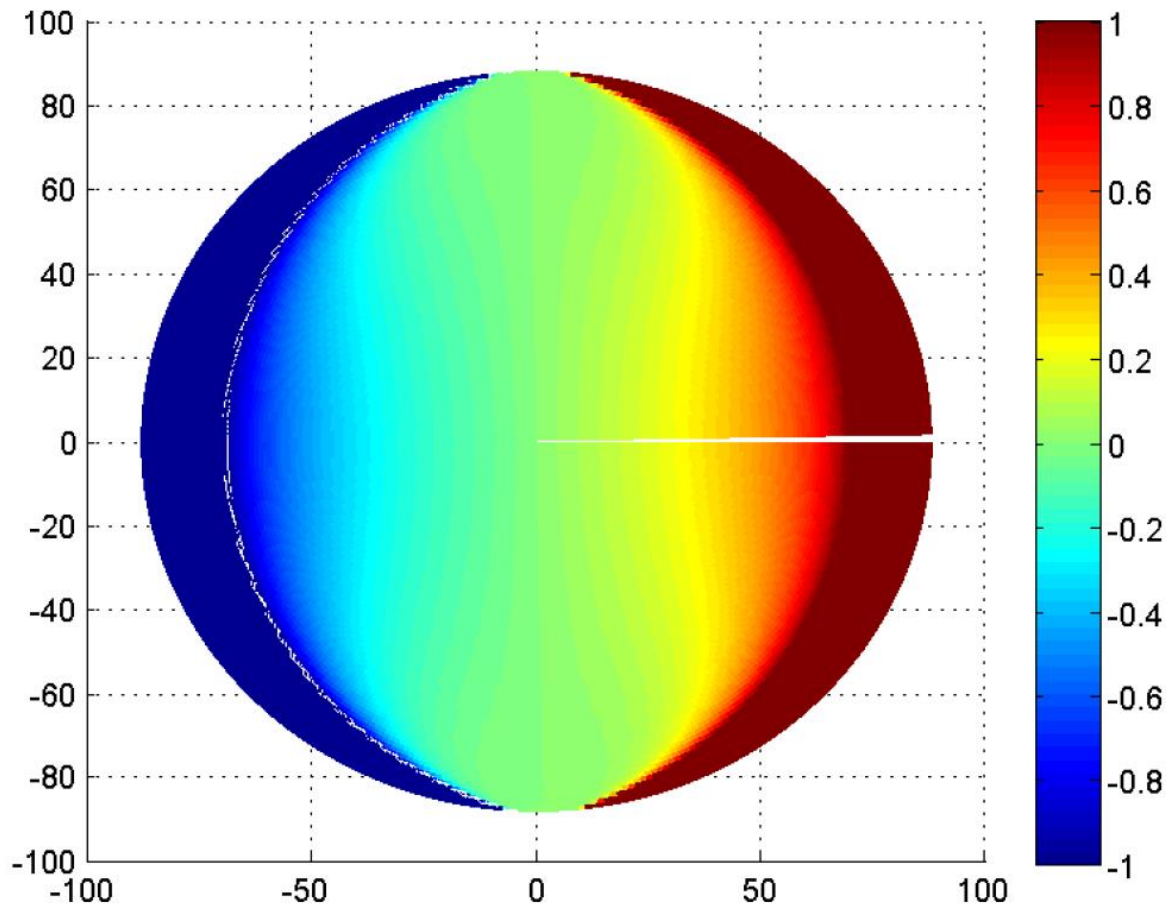


Figure 5-2: presentation of R1 in polar coordinates.

Signal R1 is dependent on orientation of the Sun relative to sensor. In the Figure 5-2 we can see signal in polar coordinates (where radius is 90° – elevation of sun, and angle is rotation of sun relative to satellite coordinate system). Signal R2 differs from R1 only by 90° rotation.

5.2.2 TRAINING NETWORK

Because signals R1 and R2 are symmetric, network can operate on first quarter of the circle. (Elevation from 20° to 90° and rotation from 0° to 90°). For other 270° of rotation first signal must be brought to first quarter of a circle (change signal sign to be positive and remember its original form to rotate outputs from network). Training of the network is performed on the extended set of data. This set is defined from -10 to 100° in rotation axis and from 20 to 90° in elevation axis (points in this set are located every 1° in both axis). This approach gives two advantages. Firstly, function is continuous on 0 and 90° rotation. Secondly, if noise is added (for example when measurement is made) it can suggest that rotation is smaller than 0 or bigger than 90° .

Training neural network is done with MATLAB toolbox tools. Training algorithm which is used is named Levenberg-Marquardt.

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5.2.3 EXPORT CODE

After saving neural network as MATLAB function it is exported by internal exporter to c code.

5.3 THEORETICAL RESULTS

Testing data set was set from 0 to 90° in rotation axis and 20 to 90° in sun elevation. This dataset is denser than Training set (points are located every 0.1° in both axis).

Values visualized on figures 5-3 and 5-4 are an error of elevation measured as difference between elevation from network output and this in test point. Error of this approximation is about from 1.3° to -2.1° in elevation axis and from 1.9° to -2.23° in rotation axis everywhere but on 90° rotation. In this case function (R1, R2->rot, elev) is non-injective and this error cannot be eliminated. On figures 5-5 and 5-6 there is presented error of rotation. Again values of this error are low everywhere but for 90° rotation. Tests showed that this algorithm is executed in less than 10ms on Arduino Uno (which has almost identical microcontroller like the one in used in the sensor).

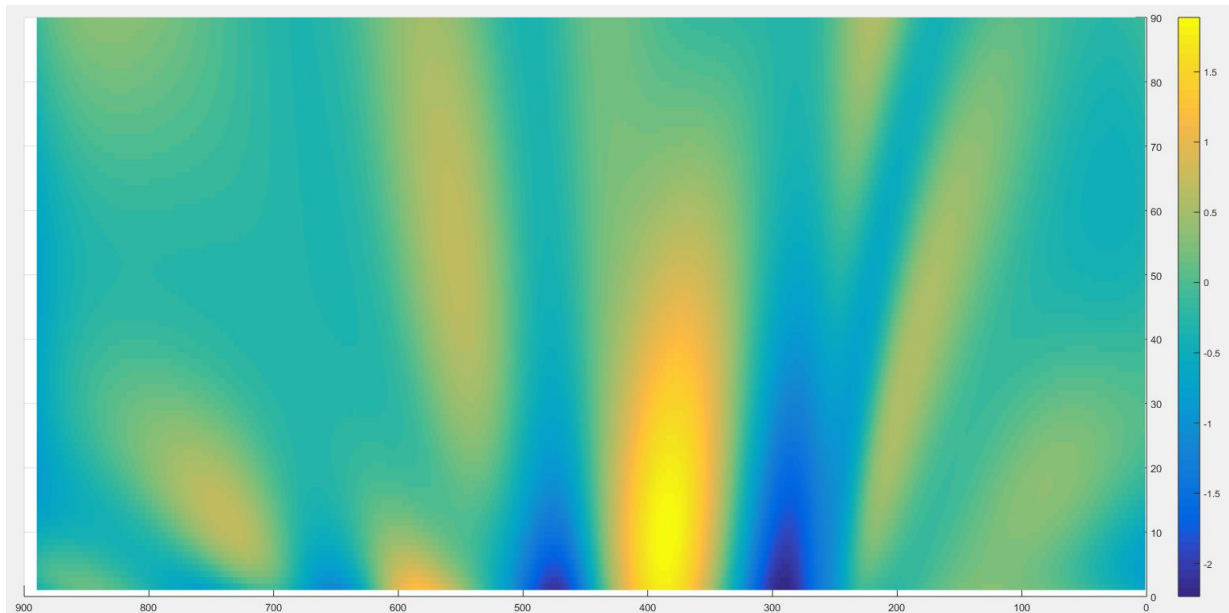


Figure 5-3: Error for elevation determining in every test point.

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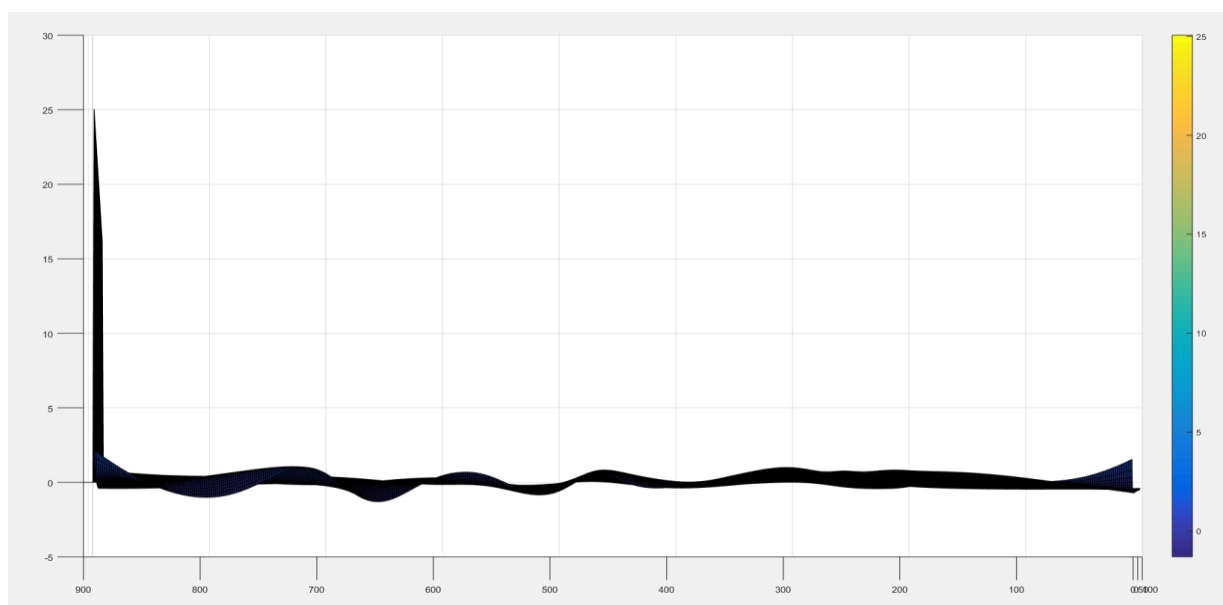


Figure 5-4: Error for elevation determining in every test point.

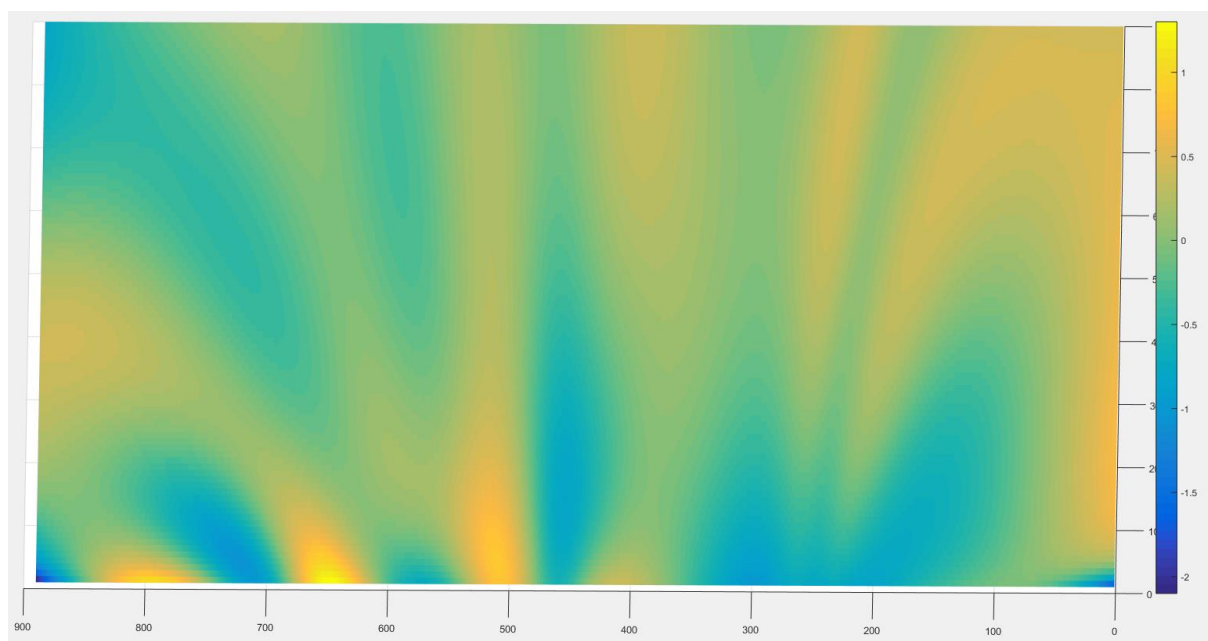


Figure 5-5: Error for rotation determining in every test point.

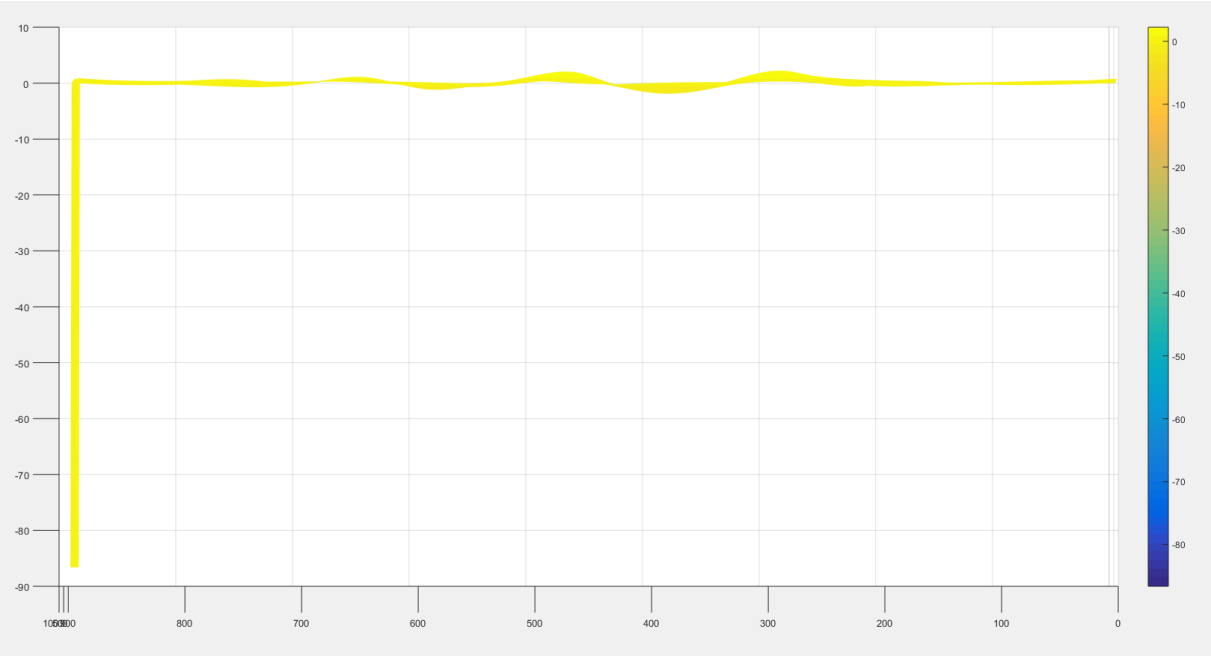


Figure 5-6: Error for rotation determining in every test point.

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6 MCU EMBEDDED SOFTWARE

This section describes software that runs on Sun Sensor's AVR microcontroller.

6.1 GENERAL DESCRIPTION

A software for the SunSensor's AVR microcontroller is written in C++ programming language utilizing AVR-HAL library developed by the PW-Sat2 Team, that provides hardware abstraction layer. The library is used in order to speed-up development process and improve its reliability. The AVR-HAL library is responsible for low-level functions of the MCU and was tested separately to the whole SunSensor application in automated, hardware-in-the-loop tests.

6.2 COMMUNICATIONS VIA I²C

The SunSensor communicates with a master device by an I²C bus. Standard communication procedure is described below:

1. Set trigger bit in Control and Status register (see Table 6-1) to request a new measurement.
2. Check Control and Status register for "new data" flag. The flag is usually set within 100 ms after new data request.
3. If the flag "new data" is set, data registers (0x01 – 0x2F) are up to date. Now it is possible to read registers with data that are demanded.

Several registers can be read in one I²C transaction. The register pointer within the SunSensor increments to the next address always after reading a byte.

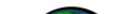
6.3 COMMANDS AND REGISTERS

Table 6-1 Register map of the SunS

Address	Name	Description	Data type	Type	Physical interpretation
0x00	Control and Status	bit 0: error state	bit field	RW	-
		bit 1: trigger	8 bit		
		bit 2: new data			
0x01	Azimuth angle		uint16_t	R	degrees
0x03	Elevation angle		uint16_t	R	degrees
0x05	Temperature A		int16_t	R	Centigrades
0x07	Temperature B		int16_t	R	Centigrades
0x09	Temperature C		int16_t	R	Centigrades
0x0B	Temperature D		int16_t	R	Centigrades

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Address	Name	Description	Data type	Type	Physical interpretation
0x0D	Temperature structure		int16_t	R	Centigrades
0x0F	ALS 1A RAW		uint16_t	R	raw
0x11	ALS 1B RAW		uint16_t	R	raw
0x13	ALS 1C RAW		uint16_t	R	raw
0x15	ALS 1D RAW		uint16_t	R	raw
0x17	ALS 2A RAW		uint16_t	R	raw
0x19	ALS 2B RAW		uint16_t	R	raw
0x1B	ALS 2C RAW		uint16_t	R	raw
0x1D	ALS 2D RAW		uint16_t	R	raw
0x1F	ALS 3A RAW		uint16_t	R	raw
0x21	ALS 3B RAW		uint16_t	R	raw
0x23	ALS 3C RAW		uint16_t	R	raw
0x25	ALS 3D RAW		uint16_t	R	raw
0x27	Temperature A		uint16_t	R	raw
0x29	Temperature B		uint16_t	R	raw
0x2B	Temperature C		uint16_t	R	raw
0x2D	Temperature D		uint16_t	R	raw
0x2F	Temperature structure		uint16_t	R	raw

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7 SUN SENSOR PROTOTYPE

A Sun Sensor prototype in the metal case is to be built during writing of this documentation. First integration of the electronics with the aluminum case structure will verify the integration process and accuracy of the alignment of the sensors. Earlier testing with 3d printed parts gave basic information about predicted performance (see fig. Figure 7-1). The prototype model will be used to gather the measurements from the sensors for the whole field of view of the sensor and compared with the theoretical predictions. Based on this measurements, there will be prepared the final version of the angles processing algorithm. Then the prototype will be tested in the functional tests.

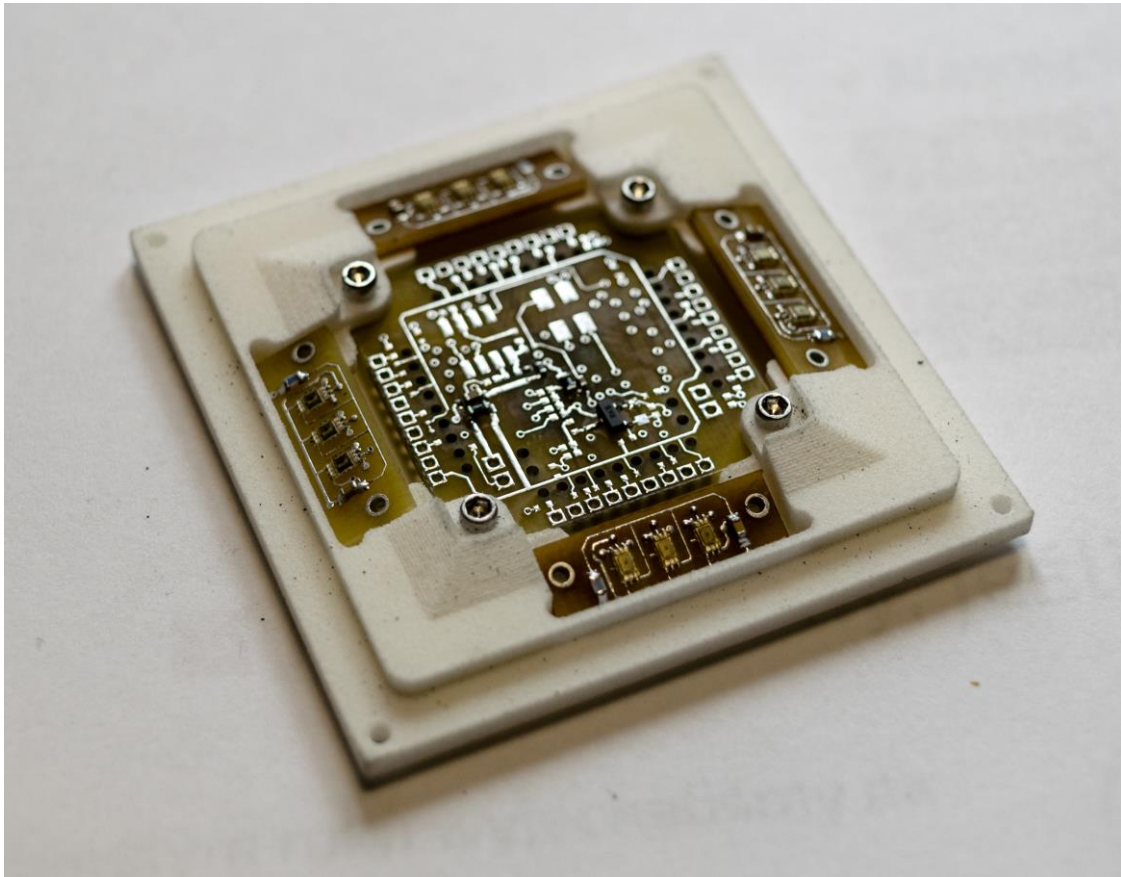


Figure 7-1 A picture of the SunSensor prototype during assembly.

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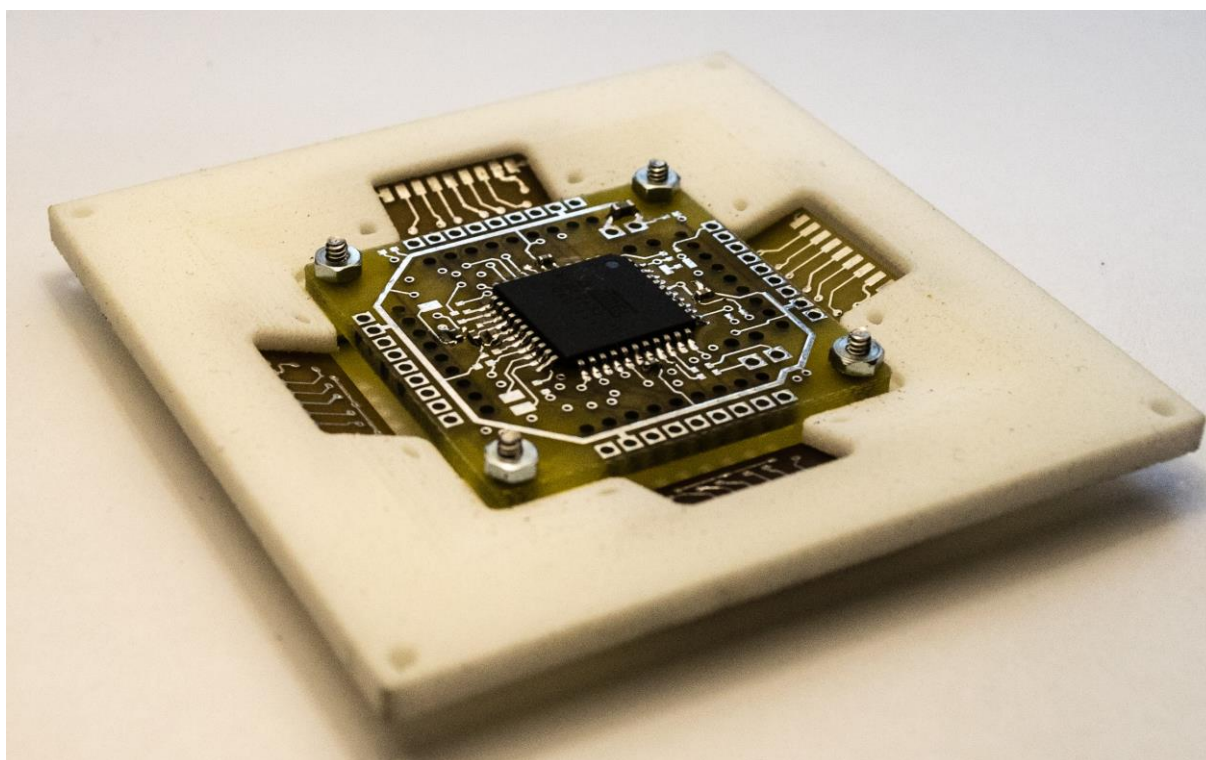


Figure 7-2 A picture of the SunSensor prototype during assembly.

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8 TESTING

To ensure that the instrument can work properly in low Earth orbit, there must be carried out a test campaign. In this chapter there is presented the idea for the final functional and qualification tests.

8.1 TEST STAND

Sun Sensor Test Stand is a system used for the performance tests. It consists of:

- light source: metal - halide lamp mounted on reflector or halogen;
- diaphragm: it allows only collimated beam reach Sun Sensor;
- rotating table: with two stepper motors, it provides rotation of the Sun Sensor within two axis.

8.1.1 LIGHT SOURCE

For light source there have been chosen two solutions: halogen and metal halide lamp. Both lamps has different light characteristics. Halogen lamp is an incandescent light source with less light power and is used without any additional system. Second lamp is a discharge lamp, prepared in another project in the SKA, named Słonecznik. It has collimated light, but because of the passive electric ballast, there are oscillations in the lighting. This lamp gives very good approximation of the Sun spectrum expected on the orbit.

In the Słonecznik, PHILIPS MSR1200 lamp (model 245514) has been chosen. Lamp characteristics and spectral range are presented below.

Table 8-1 Philips MSR 1200 1CT characteristics

Light Technical Characteristics	
Color Rendering Index	80 Ra8
Color Temperature	5900 K
Color Temperature Technical	5900 K
Chromaticity Coordinate X	325 -
Chromaticity Coordinate Y	320 -
Luminous Flux Lamp EM	94000 (min), 110000 (nom) Lm
Luminous Efficacy Lamp EM	91 Lm/W
Electrical Characteristics	
Watts	1200 W
Lamp Wattage Technical	1200 W

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Lamp Current	13.8 A
Ignition Supply Voltage	207 (min) V
Dimmable	No

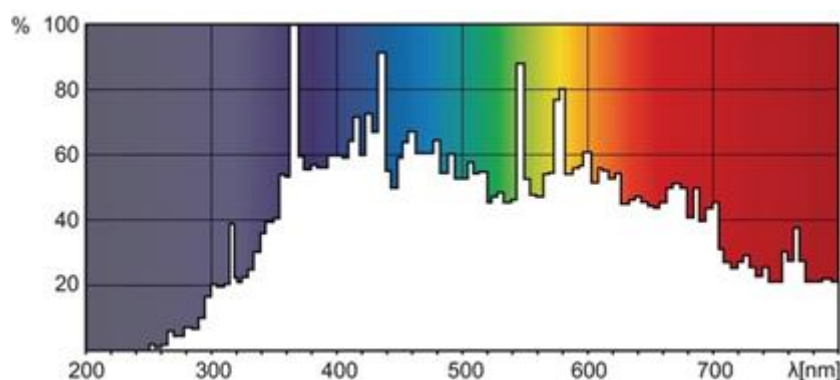


Figure 8-1 Philips MSR lamp spectral range

Reflector used in the test stand is aluminum parabolic Edmund Optics with a diameter of 300 mm. The focal length of the reflector is 75 mm. The thickness of the aluminum is 1 mm. The reflector is surrounded by a reinforcement ring in addition to which the overall diameter is 308 mm. The reflective surface is polished aluminum which reflects radiation over a wide frequency range.

8.1.2 ROTATING TABLE

Rotating table construction consists of two stepper motors and gives the ability to rotate on two axes. It enables to measure accuracy of Sun Sensor in half-sphere space. Test stand configuration is presented below. Stepper motors gives the control accuracy less than 0.1° . After the Test Stand calibration there is possible to know precisely the angular position of the mounted Sun Sensor from the positions of the motors.

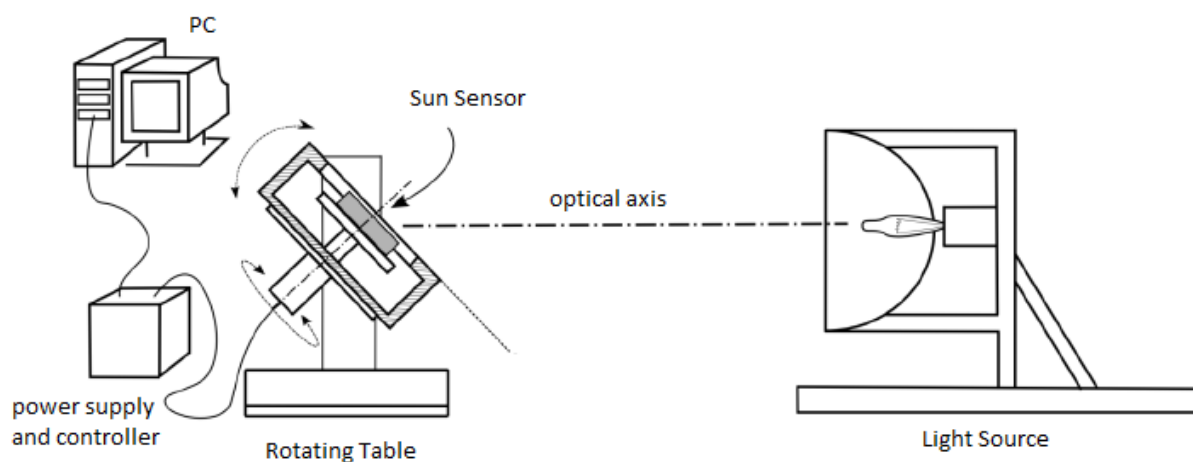


Figure 8-2 Test Stand configuration

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8.2 REQUIRED TESTS DESCRIPTION

8.2.1 FUNCTIONAL TESTS

The foundations of testing campaign are functional tests, which are the verification of the Sun Sensor's system performance, proper alignment and accuracy. For the accuracy testing, the Rotary Table is used to achieve all the angles from the field of view of the Sun Sensor with proper sampling. The signals gathered from the ALS sensors are used for the angular characteristics verification, noise verification, then used as an input for the neural network and angles calculations.

Because of the time required for the full test, it was proposed to introduce simplified functional test, which is faster full test, with different angles sampling in full field of view.

The functional tests require:

4. Dark room;
5. SunS Test Stand;
6. SunSensor;
7. PC;
8. Payload Board;
9. OBC evaluation module.

8.2.1.1 Full functional test

The functional tests should be performed for as much position angles as possible. To measure accuracy of Sun Sensor, it will be positioned in half-sphere angles using test stand described in chapter 8.1. The positioning accuracy will be checked for every 0.5° . All of the data will give two dimensional characteristics of signals from the ALS sensors. There will be checked differences between the sensors readouts as well as the algorithm performance. The Rotary Table will achieve the azimuth angle 0° - 360° and the elevation angle 20° - 90° . The results will be compared with the same results for the reference sun sensor, NSS Cubesat Sun Sensor, used for the ADCS system, which has the accuracy $<0.5^\circ$ after its calibration.

8.2.1.2 Simplified functional test

Performing full functional test will need a lot of time because of achieving every assumed angle. Thus the full test will be performed less times, to do more rough test, with sampling of 1° - 5° (TBD), with a few denser regions, with sampling 0.5° , where the angular calculations can sensitive. The size of the regions will be $5^\circ \times 5^\circ$ (TBD).

8.2.2 THERMAL TEST

The temperature cycle shall verify operational performance of the unit exposed to lower and upper temperature in the thermal chamber. The Sun Sensor must operate correctly at all operating conditions and it will be subjected to the minimum and maximum non - operating temperatures to verify that no degradation occurs. After several cycles of temperature change, simplified functional test of the Sun Sensor inside the thermal chamber will be performed and the simple light source will be used, because of the chamber limitations.

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8.2.3 VACUUM TEST

The purpose of the test in a vacuum chamber is to check all requirements regarding vacuum environment. All of the mechanical and electrical elements need to operate correctly and cannot degrade after being exposed to vacuum. Functional test after vacuum chamber testing should achieve the same results as in previous functional tests.

8.2.4 VIBRATION TEST

Vibration test is prepared for checking and verification of the technical concepts of the Sun Sensor. High qualification vibration tests level force will be performed to carefully check and verify the mechanical design and proposed solutions. In order to check Sun Sensor's resistance to vibrations resonance search, sine vibration and random vibration will be performed. Functional tests will be repeated to check if vibration affect the performance of the Sun Sensor.

8.3 TEST PLAN

Test plan described below will be performed on the same Sun Sensor model, one by one, to ensure us, that it is capable of survive tough environment on Low Earth Orbit.

0. Pre-functional tests;
1. Functional test - full.
2. Vibration test.
3. Functional test - (simplified).
4. Vacuum test.
5. Functional test (simplified).
6. Thermal cycles test.
7. Thermal - functional (simplified) test.
8. Functional test - full.

If our instrument will not pass full testing campaign flawlessly, we will focus to improve its reliability and robustness.

8.4 TEST RESULTS AND SYSTEM VERIFICATION

Correct operation of the device can be identified when all functional tests give the same results. After the vibration test Sun Sensor structure should be intact and resonance answer of the device should be the same for each test. Vacuum and thermal tests should prove that electrical and mechanical elements of the Sun Sensor operate correctly in space environment.

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9 ON ORBIT OPERATION

Because the Sun Sensor is an experimental device, it is not part of the satellite's bus and is not used by the ADCS subsystem. The main satellite's sun sensor (named NSS CubeSat Sun Sensor) is placed on the same wall of the satellite and is required for the spin Sun Pointing mode. This sensor will be the reference for the designed Sun Sensor. The Sun Sensor experiments will be conducted during the experiments phase.

9.1 OPERATING PLAN

The Sun Sensor will operate in a few modes: a single Sun's Vector reading and constant work with determined frequency.

1. Single SunS position reading - the OBC asks to get the single measurement. The readings of the Sun's Vector can be send in raw format (as a current readings from ALS sensors and thermometers) or processed format (angles and temperatures). The OBC can access all data at the time or just one register.
2. Constant operation - In the constant operating mode the chosen data will be send to the OBC with the frequency of the ADCS algorithm operation or any other determined. The OBC will use the looped command as for the single position reading mode. The constant operation mode sessions will last for the time determined by the telecommand (TBD).



At the same time of the SunS readings, the OBC will gather the same data from the reference sensor. The data will be saved as angle measurement and difference between the sensors measurements or the raw data, with a timestamp for every data package.

The Sun Sensor experiment will be conducted by the ground control. Satellite operation do not assume the additional attitude path control, thus the Sun Sensor performance will be checked during the sessions determined by the telecommands. The Sun Sensor will be turned on during the experiments phase. There is assumed the Sun Sensor will be turned on for 10-30 mins, starting from the telecommand reception or the time determined by the telecommand. Experiment will be ordered at least one time per communication session during the experiments phase of the Sun Sensor. During the next ground session the data will to be sent to the ground station. In case of good health of the satellite and good communication, the Sun Sensor will be turned on for full 2-3 days of the experiments phase of the Sun Sensor. Additionally the Detumbling or Sun Pointing ADCS modes may be used.

9.2 REQUIRED DATA AND DATA RATE

Sun Sensor will gather the raw data of currents on the ALS sensors and thermometers. Based on them it will calculate angular position data. All of the data can be acquired by the OBC. Sun Sensor will operate in a single mode i.e. acquisition must be triggered by the OBC each time.

In the most demanding case of acquiring the raw Sun Sensor data with a sampling 1/s, from all 12 ALS sensors and 5 values from the thermometers for the time of 10 minutes, there will be required about 20kB of free memory on board. The more typical cases assumes 10s sampling for 30 minutes of SunS calculated readings with temperatures and reference sensor readings and requires about 4kB. (TBD)

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9.3 ON ORBIT SYSTEM VERIFICATION DESCRIPTION

Below there is presented exemplary procedure of the Sun Sensor experimental measurement (TBD):

- command from the ground: [duration of the acquisition] [sample rate];
- ADCS turns off Detumbling;
- acquisition of data from experimental Sun Sensor, reference Sun Sensor and gyros to some space in memory;
- end of the experiment after given time;
- command from the ground to download data from last experiment.