Delfi-Twin Radiation Payload Development

By

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Space Systems Engineering Thesis Report

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Preface

This Master thesis report contains the development of a radiation payload for the newest PocketQube satellite of the TU Delft, The Delfi-Twin. This report is made as part of the Space Systems Engineering Master Track at the TU Delft. The project is developed as part of the Delfi-group, a satellite development team at the TU Delft.

I would like to thank my supervisor Alessandra Menicucci for guiding me through the thesis project. I would also like to thank the Delfi-Twin project heads Stefano Speretta and Sevket Uludag for their assistance and guidance.

This project is mostly related to the design, build and test of embedded systems, a topic which I personally have had little experience in. Despite the project taking longer than expected, I am grateful for getting the opportunity to learn more about embedded systems and how to approach such projects. I hope I will be able to utilize the many learning experiences I have had throughout this project in my future career.

Anthony Bats
Delft, May 2025.

Summary

Space radiation brings hazardous effects to hardware and humans in space [1]. In order to better understand and avoid these space radiation anomalies, the Delfi-group at the TU Delft decided to add a radiation measuring payload to their newest, in-development, satellite, the Delfi-Twin. The focus of this master thesis project was to design, build and test the radiation payload for the Delfi-Twin.

The project started with a literature study. At first, the space environment hazards of the satellite were identified. The development of the Delfi-Twin and its predecessor were looked into afterwards. The radiation sensor (FGD-03F [2]), MCU (STM32L476RG [3]), and housekeeping sensors had already been selected for the payload design by the Delfi-group. The Lunar Zebro, a TU Delft rover, was investigated as well as it uses the same FGD-03F sensor [4]. The literature study concluded with a project planning which resulted in the main research question stating: "What hardware and firmware designs need to be developed in order for the radiation payload to meet the mission requirements for the Delfi-Twin?".

The concept phase of the project used a system engineering approach to design the radiation payload. At first, the need and mission statements were made based on the research question. Afterwards, the stakeholder and system requirements were identified based on the needs of the Delfi-group. The requirements allowed for the creation of a break-down structure, dividing the radiation payload into multiple subsystems that adhered to the requirements. These were related to measurements (radiation, temperature, power), mechanical (radiation and temperature resistance), command data handling (data storage and distribution), power (power regulation and distribution), and housekeeping (checking anomalies within system). These were used to develop concept firmware and hardware designs of the radiation payload.

The detailed design focused on the development of a prototype PCB of the radiation payload. Due to time constraints, the prototype did not include all flight model components. Based on the concept designs made earlier, the components for the payload PCB were chosen. The data signal and power connections for each component were then identified and made into a schematic. The schematic was then used to create a PCB design. This PCB design, together with the chosen components, was ordered and soldered together via a soldering oven.

The firmware was created on the basis of the earlier described concept. The firmware was written within the MCU IDE in C++. The initial configurations of all components on the PCB, the main loop, command handling, and mode changes were written for the prototype PCB version. The main loop consisted of initializing all components, reading radiation measurements in a loop, and checking commands from the satellite. The firmware was uploaded to the manufactured prototype PCB for testing and debugging.

Verification and validation focused on the integration of both the hardware and firmware developed in the previous section. The verification focused on testing whether the prototype PCB could run basic functions. This showed a correct power distribution, MCU and FGD-03F initialization and command handling. The validation focused on testing the system with mission scenarios like reading radiation data and sending it to the MCU for a consecutive time. Unfortunately, due to time constraints and anomalies within certain modes, it did not become possible to fully complete the validation. Suggestions for further tests were made based on the remaining results.

As the tests showed the functionality of the hardware and firmware of the radiation payload while adhering to most requirements, it was seen as a conclusive answer to the research question of this project. It is recommended to further look into radiation tests of the prototype PCB and to expand the hardware and firmware into the completed flight model of the radiation payload.

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List of Abbreviations

ADCS	Attitude Determination and Control System
CDHS	Command and Data Handling System
CK	Clock
CLK	Clock
CME	Coronal Mass Ejections
COMMS	Communication System
CON	Connector
COTS	Commercial Off-The-Shelf
DD	Displacement Damage
ENWR	Enable Write
EPS	Electrical Power System
ESA	European Space Agency
ESD	Electrostatic Discharge
FGD	Floating Gate Dosimeter
FRAM	Ferroelectric Random Access Memory
GEO	Geostationary Earth Orbit
GNSS	Global Navigation Satellite System
GPIO	General Purpose Input/Output
GPS	Global Positioning System
HPTC	High Performance Telecommand Computer
HSE	High Speed External
IC	Integrated Circuit
IDE	Integrated Development Environment
IMU	Inertial Measurement Unit
LED	Light Emitting Diode
LEO	Low Earth Orbit
LDO	Low Dropout Regulator
LSE	Low Speed External
LSB	Least Significant Bit
LSI	Low Speed Internal
MCU	Microcontroller Unit
MEO	Medium Earth Orbit
MISO	Master In Slave Out
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
MOSI	Master Out Slave In
MPPT	Maximum Power Point Tracking
MSB	Most Significant Bit
NCS	Not Chip Select (same as NSS)
NIRQ	Not Interrupt Request
NSS	Not Slave Select
NSTBY	Not Standby
OAP	Optical Aperture Panel
OBC	On-Board Computer
PCB	Printed Circuit Board
PPU	Power Processing Unit
RMS	Root Mean Square
RXD	Receive Data
SCK	Serial Clock
SEB	Single Event Burnout

SEFI	Single Event Functional Interrupt
SEGR	Single Event Gate Rupture
SEE	Single Event Effects
SEL	Single Event Latchup
SET	Single Event Transient
SEU	Single Event Upset
SRAM	Static Random Access Memory
SWCLK	Serial Wire Clock
SWD	Serial Wire Debug
SWDIO	Serial Wire Debug Input/Output
SWO	Serial Wire Output
TID	Total Ionizing Dose
TU	Technical University
TXD	Transmit Data
UHF	Ultra High Frequency
VHF	Very High Frequency
V/I/P	Voltage / Current / Power
VLT	Voltage Level Translator

1 Introduction

The TU Delft Aerospace faculty has developed several satellites within its Delfi Program which have been sent to space. The Delfi program has consisted of three satellites so far: Delfi-C3 from 2008, Delfi-n3xt from 2013, and most recently the Delfi-PQ which launched in 2022 [5]. These satellites are mostly created via COTS components and are created to give students at the TU Delft the opportunity to develop and learn about small satellites [6].

As the Delfi-PQ was launched more than 3 years ago, the next satellite in the Delfi series is in development, the Delfi-Twin. This next satellite will use a PocketQube 3P form factor, the same as used by the Delfi-PQ [7]. What makes this successor to the Delfi-PQ unique will be its ability to split up into two separate satellites after launch, making it in total 6P in size with two detachable 3P configurations. This separation mechanic will be a demonstration on a potential swarm of PocketQube satellites working together. A swarm of PocketQubes would be able to make multiple measurements of any kind of information simultaneously at different locations, making it ideal to potentially better understand our space environment.

One area which would benefit in an increase of research would be space radiation. Space radiation comes from many sources: The van Allen Belts, our Sun, or even from outside of our solar system [8]. On Earth we are mostly well protected from these types of radiation due to our atmosphere. Satellites and astronauts are however directly impacted by space radiation, which can have hazardous consequences. Satellite electronics may fail from space radiation due to it causing bit flips, current overloading, solder joint failure and other types of anomalies. Astronauts have a higher chance of experiencing cellular damage, causing great health risks. More research in space radiation can potentially create better space radiation mitigation techniques, lowering the risk of satellite damage or astronaut health hazards [9].

The Delfi-Twin with its swarm technology is therefore the ideal system to research space radiation. One of the payloads that the Delfi-Twin carries is a radiation payload. It requires to make radiation measurements in Earth orbit to better understand potential hazards radiation can create for future missions and how to mitigate them. The radiation sensor integrated in the radiation payload is the FGD-03F [2], the same radiation sensor used by the TU Delft Lunar Zebro rover [4]. The conducted research for the Lunar Zebro radiation payload will be helpful in the development of the Delfi-Twin variant.

The topic of this thesis project will be the development of a radiation payload for the Delfi-twin satellite. The goal is to create a physical payload which can be tested and configured to better understand the FGD-03F radiation sensor. The project starts with a literature study in chapter 2 which focuses on understanding the space radiation hazards, current Delfi-Twin development, previous TU Delft satellites like the Delfi-PQ, and the Lunar Zebro radiation payload configuration. After the literature study, the system engineering/concept design phase of the radiation payload starts in chapter 3. This defines the project requirements and starts with creating concept designs of the payload hardware and firmware. In chapter 4, the detailed design phase, the specific components of the payload are chosen and a physical model of the payload is made. The firmware is written and uploaded onto the system for testing. Lastly, chapter 5 will discuss the verification and validation of this project by integrating the hardware and firmware and performing debug and functional tests on the system to see if it adheres to the project requirements. Conclusion and recommendations, chapter 6, will conclude the project by stating whether the research questions have been met. The recommendations are afterwards given which states the steps required to further develop the project.

2 Literature study

2.1. Introduction Literature study

At the start of the project a literature study was conducted. This literature study had the purpose of understanding the current state of the Delfi-Twin project and how to develop the radiation payload. Research was conducted on the following topics:

- **Environmental hazards:** Reasoning behind the radiation payload requirement and potential design criteria
- **Delfi-Twin:** Understanding the project hardware
- **Delfi-PQ:** Generally understanding the development of the Delfi-satellites
- **Lunar Zebro radiation payload:** TU Delft project that has already designed a radiation payload.

Together, these topics lay the basis necessary to further develop the radiation payload for the Delfi-Twin satellite. The problem description and project plannings are made starting from section 2.7. The development of the radiation payload can be read in chapter 3, chapter 4 and chapter 5.

2.2. Environmental hazards

2.2.1. Types of radiation

Measuring space radiation is of importance for future space missions as it can have hazardous consequences on satellite functionality and astronauts. Radiation which has a high frequency can have ionizing effects, causing atoms to lose electrons and become positively charged. This can cause anomalies within electrical circuits by for example overcharging [9], damaging the electrical components. Radiation is also able to change bits in stored memory. This is called a bit-flip and can cause errors in measurements or different commands. To humans, ionizing radiation can lead to cell damage and even cancer, making it detrimental for the safety of astronauts to understand radiation [1].

The effect of radiation is dependent on the type of radiation. In Table 2.1 a table can be seen which shows the most common sources of radiation a satellite can expect, including the particle type and how it affects the satellite. The effects are discussed in subsection 2.2.2.

Table 2.1: Space radiation sources, particle types, and their effects

Source	Type	Effect
Radiation Belts	Electrons Protons	TID, DD
Solar Events	Electrons Protons Heavy ions	TID, SEE, DD
Galactic Cosmic Rays	Protons Heavy ions	SEE

There are three main radiation sources in space near Earth [9] [8]:

1. Radiation Belts: Charged particles trapped in the magnetic field of Earth. Two of these radiation belts exist called the Van Allen belts, having an inner and an outer belt. The outer belt (13000-60000 km altitude) mainly consists of electrons while the inner belt (1000- 6000 km altitude) consists of protons.

2. Solar Events: The Sun has multiple ways to release radiation. Solar Flares are a sudden burst of charged particles on the surface of the Sun which consist of predominantly protons and heavy ions. In addition, CME (Coronal Mass Ejections) also occur at the Sun. These are bursts of solar wind which mainly exist of electrons and protons. Magnetic fields and plasma are released via these CME's which have a large impact on surrounding space weather.
3. Galactic Cosmic Rays: The hit rate of Galactic Cosmic Ray radiation is lower compared to the other two types, but the energy and penetration of the radiation is much higher. The radiation comes from outside of our solar system and consist of mainly alpha and proton particles with sometimes heavy ions with significant impact.

2.2.2. Introduction of space hazards

Space is a hazardous environment for any type of technology due to its exposure to extreme varying temperatures [10] and radiation [11]. The downsizing of satellites brings even more challenges to these two phenomena. As the size constraints increase, there will be less space for radiation shielding. This together with the use of non-space verified COTS (Commercial Off-The-Shelf) components can increase the risk of radiation anomalies [12]. The smaller size also gives less lineage in the distribution of heat, causing higher concentrations of heat on the satellite and its hardware [13]. As of this, it is of importance to be aware of the possible anomalies that could occur due to these hazardous environments and how these can be mitigated.

There are three general types of radiation effects that can occur within electronic devices [14]:

1. TID, Total Ionizing Doses
2. SEE, Single Event Effects
3. DD, Displacement Damage

2.2.3. Total Ionizing Dose (TID)

TID is the accumulated ionizing radiation absorbed by a component or material. This may cause an increase and leakage in supply current, timing changes, and voltage threshold shifts which can cause functional failures. TID anomalies can be mitigated by means of using radiation hardened components or radiation shielding [15]. Redundancy in susceptible components and fault tolerant/error detecting firmware can also mitigate or at least detect when errors occur. The amount of TID is dependent on the mission location. LEO missions tend to have less TID than missions which are further from Earth like MEO, GEO or deep space [16]. Trapped electrons, trapped protons and solar protons are often found in environments which cause TID. Solar events and radiation belts are therefore seen as environments with increased chances of TID [17] [18].

2.2.4. Single Event Effects (SEE)

SEE's are anomalies caused by single energetic particles. In contrast to TID, these anomalies are not building up due to prolonged radiation exposure, but are rather single hits of energy which can cause an anomaly on their own. Several types of SEE's exist, some of these being destructive to the hardware it may hit. Environments with heavy ions often cause SEE's as these can strike the materials and effect devices [17] [18]. This means Solar Events and Galactic Cosmic Rays can be seen as primary sources of SEE's.

The non-destructive SEE's consist of Single Event Upsets (SEU), Single Event Functional Interrupts (SEFI) and Single Event Transients (SET). SEU's cause stored data to change, for example by means of bit flips. This can be recovered by means of soft reboots. SEFI's cause non-functionality in certain hardware, caused by anomalies within control registers like processors. This can be recovered by means of a soft reboot (firmware reboot) or a hard reboot (power cycle). SET's cause voltage transients within control lines of the satellite. This could result in the loading of incorrect data if certain flip-flops are affected, but the result could also be similar to an SEU [19].

Destructive SEE's are described as Single Event Lachtups (SEL), Single Event Gate Ruptures (SEGR) and Single Event Burnouts (SEB). SEL's cause high current to travel through devices, potentially making them lose their functionality. Power must be removed quickly to prevent overheating. SEGR's cause gate leakage in MOSFETS, potentially degrading or destroying the connected devices. SEB's are similar to SEL's, but the burnout effect is to a greater extent. Thermal runaway can occur if the power is not quickly removed from the device [15].

Radiation shielding is the best solution to mitigate these hazards. However, as explained at the start of this section, this is not always a possibility with smaller satellites. The firmware design must therefore play a more prominent role in the mitigation of these anomalies. The firmware must be able to detect and take action when an anomaly caused by radiation occurs. For non-destructive SEE's a soft or hard reboot would be suffice, but destructive SEE's may require certain hardware to be shut-off to prevent overheating. How quickly the detection firmware can detect these anomalies will determine the damage taken [20] [21].

2.2.5. Displacement Damage (DD)

DD is caused by non-ionizing radiation which moves atoms from their lattice location to a different one, changing the properties of a material. For electronic hardware like transistors or diodes this can have a major effect on their performance and can change the way they should operate. The anomaly is often caused by trapped protons and electrons, meaning the radiation belts and solar events can be seen as primary sources [17] [18]. It is difficult to remove displacement damage once it has occurred, especially for hardware operating in space. To mitigate, it is often recommended to use radiation graded hardware and shielding. This is however difficult to achieve with the limited space of the PocketQube and the use of COTS for the radiation payload, meaning more focus must be set on components with flight heritage [22] [15].

2.2.6. Temperature hazards

The temperature cycling in space can cause stress and degradation to electrical components [23]. The solder joints of electrical components can be weakened due to thermal cycling, potentially breaking circuits and therefore potentially the whole payload [24]. In addition to radiation based damages, thermal cycling can have a great affect on the lifespan of the satellite and its payloads [25].

The most common mitigation strategy for thermal anomalies is to install thermal coatings and heat sinks onto the satellite [26]. Size constraints of small satellites makes this however difficult to install. Instead, picking electrical components and solder paste with a large temperature range can lower the risk of thermal anomalies [27]. The cycling stress can be lowered as well by using an ADCS system which can counteract the temperature swings by orienting the satellite differently. Temperature sensors should therefore be installed to detect thermal cycling. It is recommended to perform heat cycling tests onto the satellite and its payloads to see how they react to thermal swings.

2.2.7. Vacuum hazards

Another type of space environmental hazard is the vacuum of space. A vacuum removes the possibility of convective heat dissipation, meaning the satellite must mostly rely on radiating for its heat release [27]. Moreover, some components can release trapped gases when operating in vacuum, causing damage to the system [28]. Space heritage in components can help in mitigating the potential hazards caused by operating in vacuum.

2.2.8. Conclusion Environmental hazards

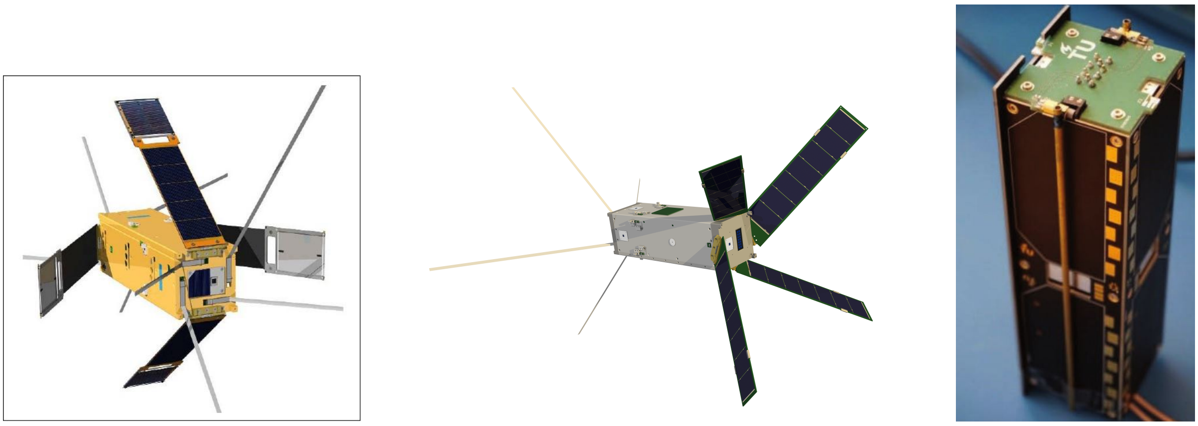
Based on the literature research it was found that there are multiple radiation sources which can potentially cause hazards to satellites and humans. This shows the need for more research into radiation in space to potentially mitigate these hazards. Moreover, it shows what needs to be taken into account when designing the radiation payload from a mechanical perspective. It needs to be able to mitigate as much of the radiation, heat and vacuum anomalies caused by the space environment. This will be discussed in the concept design section of chapter 3.

2.3. Delfi-Twin research

2.3.1. Objective Delfi-Twin

The Delfi-Twin project is a satellite project curated by the TU Delft. Previously, the TU Delft has worked on three other satellite projects [5]:

1. Delfi-C3, Figure 2.1a: This is the first satellite launched by the TU Delft in 2008. The satellite has a triple-unit CubeSat form factor and demonstrated the use of autonomous sun sensors, an electrical power subsystem and a radio including a linear transponder.
2. Delfi-n3xt, Figure 2.1b: This is the second satellite made by the TU Delft launched in 2013. The satellite has a triple-unit Cubesat form factor and demonstrates the use of a micropropulsion system, a new radio platform, an ADCS and more.
3. Delfi-PQ, Figure 2.1c: This is the most recent satellite launched in 2022. The Delfi-PQ is a triple-unit PocketQube developed to test the ability of developing a satellite in a smaller form-factor, potentially using it as a steppingstone for a swarm development.



(a) Delfi-C3 [29] **(b)** Delfi-n3xt [30] **(c)** Delfi-PQ [31]

Figure 2.1: Three most recent TU-Delft Delfi-satellite projects

The Delfi-Twin can be seen as the follow-up of the Delfi-PQ as it will use the same form factor as the Delfi-PQ, namely a triple-unit PocketQube. Similarly to the Delfi-PQ, the Delfi-Twin aims to demonstrate the potential of a swarm formation for triple-unit PocketQubes. The difference between the PQ and the Twin lies in the Twins ability to split itself up into two satellites once it is in orbit, having two operational satellites working from space. The Delfi-Twin will consist of two triple-unit PocketQubes attached to each other, identical in hardware. They will both perform the same tasks in space and communicate to Earth. The separation mechanism and the control of two satellites is seen as the next step for a swarm formation of satellites. The tracking of the Twin formation is an important task within the project as it will only become more difficult to track satellites the more you add to the swarm. The satellites themselves also have the mission to track their surroundings for space debris and each other. Research into space debris can lower the chances of collisions in space, which is especially important for a swarm formation of satellites. The Delfi-Twin satellite must be mostly created by means of COTS components. This brings its challenges in not using space graded components, but will lower costs and make manufacturing easier if the components are widely available.

To summarize, the mission goals of the Delfi-Twin satellite are [32]:

1. Tracking multiple operational satellites from Earth
2. Tracking surrounding objects in space through the satellites
3. Tracking multiple operational satellites from space via the satellites themselves

Tracking is one of the most important mission criteria of the Delfi-Twin as it is essential for further developing the swarm formation. The Delfi-Twin will however also contain other types of payloads on board, see subsection 2.3.3.

2.3.2. Mission design Delfi-Twin

Research regarding the mission design of the Delfi-Twin was performed in the master thesis of Mariana Centrella called "Mission and System Design of a Formation-Flying Picosatellites Cluster: A Technology Demonstration Mission for Space Situational Awareness Improvement" [32]. The mission design was not fully determined during this report and is of yet still unknown. No other information regarding the mission is known however, as for why it will be used for the radiation payload project.

According to the thesis, two extreme mission types were considered for the Delfi-Twin satellite:

- **Mission A:** Two identical triple-unit PocketQubes are used which are docked together during launch and detach once in LEO.
- **Mission B:** Comprehends one major satellite, likely a triple-unit CubeSat, which deploys a cluster of satellites. The size of the clusters is debatable.

The report went into greater detail regarding mission type A and suggests mission type B to be covered at a later date. Mission type A covers the basics of the Delfi-Twin as there are two identical PocketQubes which will be launched and which will communicate with each other. Several sequences for mission A were investigated, ultimately considering a sequence in which both the maximum distance and relative velocity play a role in the stopping conditions of the Delfi-Twin.

In terms of general knowledge regarding the mission design, the PocketQubes will orbit in a (for now assumed) circular orbit at 500 km altitude with a Sun synchronous orbit. The launch is expected at around the first quarter of 2027.

2.3.3. Hardware development

The Delfi-Twin is at the moment of this report still in its early stage development. Little is known about the high level mechanical or electrical architecture of the satellite, except that it will take close reference to the Delfi-PQ. According to a report related to the mission development of the Delfi-twin [32] and the Delfi-Team themselves, the Delfi-Twin will contain the payloads seen in Table 2.2. These components are still subject to change.

Table 2.2: List of currently known subsystems of the Delfi-Twin [33]

Payload	Objective
LED's	To maximize visibility and improve detectability
Miniaturized GNSS Receiver	To determine the satellite position and velocity
Camera	For space surveillance and tracking
Radiation Sensors	For on-board radiation monitoring
Laser Retro-Reflectors	To enhance laser ranging systems traceability
Optical Coating	To maximize visibility and improve detectability
Satellite License Plate	For satellite optical identification
OBC	Main MCU of the satellite controlling data flow through all payloads
EPS	Electrical power system, regulates and distributes power for all systems on board of the Delfi-twin
Battery	Power savings of solar panels
ADCS	Control system of satellite, currently provided purely though shifting positions of the solar panels. No thrusters are used.
COMMS	Satellite communication payload for communication to Earth
RABSII	Radiation amateur beacon for investigations of the ionosphere

As noticed in Table 2.2, most of the currently known payloads of the Delfi-Twin are related to tracking the satellite itself or its surroundings. This is to be expected when reading the previously mentioned mission goals in subsection 2.3.1. In Figure 2.2 a concept design can be seen of the payload layout. This design is still subject to change.

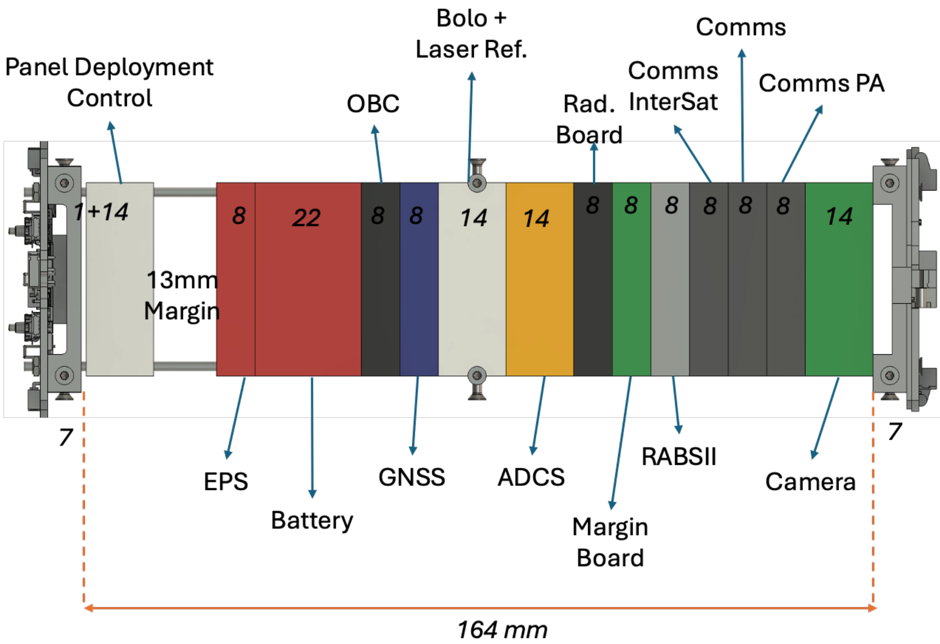


Figure 2.2: Concept design of the Delfi-Twin payload distribution [33]

The tracking payloads will however not be further discussed in this report. The main focus of this report is the development of the radiation payload seen in Table 2.2. The swarm formation is ideal to perform radiation tests as multiple measurements can be taken from different locations simultaneously. As space radiation can have damaging affects to satellites as discussed in subsection 2.2.2, it is of interest to the Delfi-group to further discover the space environment to potentially mitigate these hazards.

The only other ”payload” which will be mentioned of the satellite is the On-Board Computer (OBC) [34]. The OBC is essentially the main brain of the satellite and determines the activities of the payloads connected to it. Uplinked data will first go through the OBC before it is send to any payload, vice versa for downlinking data. The radiation payload will require to send data to the OBC when commanded and change its settings when commanded. Without the interactions between the radiation payload and the OBC, it becomes impossible to control the radiation payload and send radiation measurements to Earth, making this connection essential for the development of the radiation payload.

2.3.4. Delfi-Twin radiation payload

The development of the radiation payload is the main subject of this project. The radiation payload its goal is to make radiation measurements and to send these to the OBC. The payload consists out of a printed circuit board (PCB) which includes the required integrated components (IC’s) in order for the radiation payload to operate. Necessary components are for example a radiation sensor to take the radiation measurements, an MCU to interpret the raw data, a power supply bus, and a communication bus to the OBC. The exact details are reviewed and discussed in chapter 3, but the Delfi-Group has already demanded several components to be integrated into the PCB design. These are researched to better understand their integration into the radiation payload.

Radiation sensor: FGD-03F

The most important component of the radiation payload is the radiation sensor itself. This component takes the radiation measurements which require to be down-linked to Earth. When the radiation ”payload" is mentioned, it means all components working with the radiation sensor to make measurements like external memory, a microcontroller, other types of sensors etc. The radiation "sensor" is the chip which only makes the radiation measurements.

The radiation sensor used in this project is the FGD-03F (Figure 2.3 and Table 2.3), created by the company Sealicon [35]. The FGD-03F is also used in another project of the TU-Delft, the Lunar Zebro rover. This is a moon rover which has two FGD-03F's installed, one inside of the rover and one outside of the rover. The design, build and test of the radiation payload for the Lunar Zebro has been performed and is discussed in section 2.5. As the TU Delft has already had experience with building a radiation payload with the FGD-03F for the Lunar Zebro, the sensor will again be used for the Delfi-Twin project.

Table 2.3: Specifications FGD-03F radiation sensor [2]

Specification	Value	Unit
Size	5 x 5	mm^2
Temperature range	-45 until 85	C
Communication mode	SPI	-
Supply Voltage	5	V
Total TID to	500	Gy
Internal charge pump Voltage	+18	V

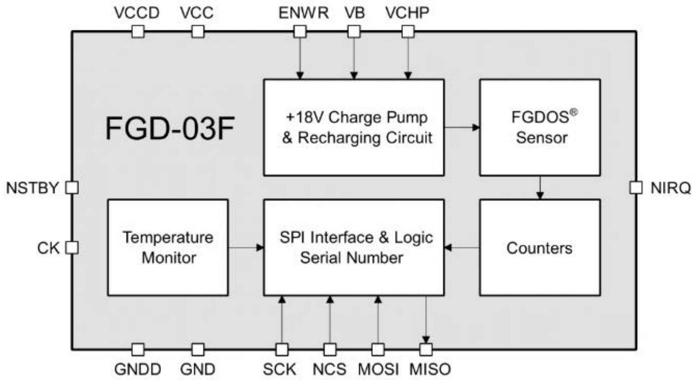


Figure 2.3: Simple schematic of FGD-03F. Keep in mind that there are two sensors per FGD-03F [2]

FGD stands for Floating Gate Dosimeter. Radiation can be measured by means of the floating gate capacitor installed into the dosimeter. Charge is applied onto the capacitor until it has reached its 'Target' value seen in Figure 2.4. The charge wont change as long as no ionizing radiation is applied onto the capacitor. Once this does happen the charge will drop in a linear trend until the lower 'Threshold' value has been met. Afterwards, the capacitor will recharge again until it has met its upper 'Target' level and will discharge if ionizing radiation is still applied. Once no radiation is applied the charge will remain constant.

The recharging and discharging of the floating gate must stay within the Target and Threshold value as the discharge between these will be linear. Outside of these values, the drop will not be linear, making it more difficult to interpret the radiation measurements. The values of Target and Threshold are dependent on the sensitivity configuration of the radiation sensor. The linear trend of the radiation measurements can be seen in Figure 2.4 between every Target and Threshold value. The measurement values of the radiation sensor are encoded as a frequency, meaning you obtain frequency values when you take radiation measurements. These can be post-processed into more common radiation units like Gray (Gy).

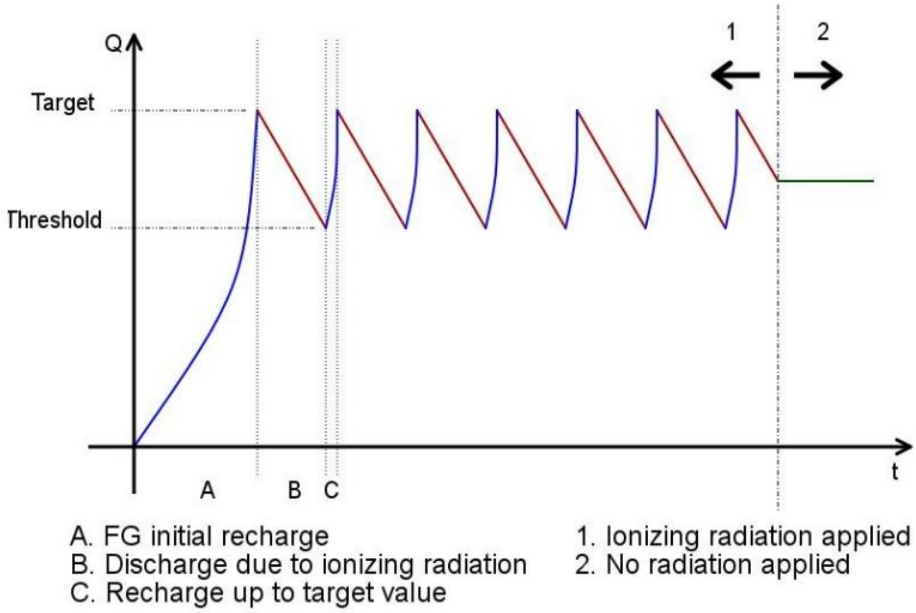


Figure 2.4: Example of FGD-03F measurement. The Threshold and Target values specify the linear range in which discharge may take place to easily measure the radiation intake [2]

Each FGD-03F radiation sensor chip contains two radiation sensors inside. These can take measurements one after another as a redundant component. Each radiation sensor takes two types of radiation measurements: A reference value and a sensor value. The reference value is a radiation measurement not affected by radiation dose, the sensor value is. Whenever no large temperature variations take place in the measurement environment, only the sensor value will be enough for accurate radiation reads. However, in space there will be many thermal cycles, causing vast temperature changes over time. These will have an effect on the radiation measurements, making them less accurate. The reference value can be used to compensate for these temperature anomalies in the measurements, making the radiation reads more accurate. The temperature compensation requires to be added in post-processing.

A general use case of the FGD-03F look as follows:

- Apply a clock signal of 32.768 kHz to the sensor, either via an external clock or via a microcontroller.
- Apply 5V of voltage to the radiation sensor and wait 100 microseconds to boot it up.
- Configure the radiation sensor by sending bits via the SPI connection made with a microcontroller.
- Read the reference and sensor measurement values of the radiation sensor for sensor 1, do the same for sensor 2.
- Send the measurements to a microcontroller and add post-processing.
- Wait 2.2 seconds for new values to be read and repeat.

The radiation sensor has multiple configuration which are able to be changed before or during operations. The most notable configurations are the following:

- Sensitivity: This determines how precise the measurements will be. There is a high sensitivity mode with 70 kHz/Gy and a low sensitivity mode with 10 kHz/Gy. These sensitivities also change where the linear range, and therefore the values Target and Threshold, of the radiation measurement is on Figure 2.4. For high sensitivity these values are between 50 and 90 kHz and for low sensitivity 140 and 180 kHz.
- Window: Determines the measurement window of the radiation sensor. It has four possible values: 32,768 CK pulses per window, 16,384, 8,192 or 4,096. The lower the value, the faster the measurement window. Lower values also mean that more measurements can be taken in a period of time, but it also affects the accuracy.

- Automatic recharge: Makes the recharging go automatically once the threshold value has been reached.
- Manual recharge: Makes the user manually make the recharging happen. This can be helpful for debugging.
- Standby Mode: Reduces power consumption to a minimum. The sensor core can still record radiation dose, but sending is only possible in normal mode.
- Passive Mode: Reduces power consumption to a minimum or even 0 when the voltage supply is removed. The sensor core can still record radiation dose, but sending is only possible in normal mode. The difference between Standby and passive is difficult to tell from the manual, but only Standby can be turned on via a dedicated GPIO signal. Passive requires the voltage supply to be removed. Both can be used to save power during operation by calculating an optimum duty cycle.

In addition to these modes, the radiation sensor is able to discharge itself by means of applying between 18V (internally) or higher (externally) onto the sensor, without the need of any radiation. This self-discharging mode is used to debug the system and to test whether the sensor operates as expected before any real radiation tests or missions are performed. The discharge can either be handled by an external power supply or an internal discharge.

Microcontroller unit: STM32L476RG
The microcontroller unit (MCU) of the radiation payload can be seen as the brain of the system. Firmware is uploaded onto the MCU to control data transfers. Measurements, commands, housekeeping data, and more are controlled by the MCU. The MCU chosen for the radiation payload is the STM32L476RG. This model is used as it is still regularly updated and manufactured, meaning future spacecraft can also potentially use an STM32 controller. The specifications of the system can be found in Table 2.4 and Figure 2.5. The MCU runs on 3.3V, is able to communicate via multiple SPI, I2C and UART connections, has multiple GPIO pins and can be configured via its own Integrated Development Environment (IDE), STM32CUBEMX. This IDE makes it possible to easily configure the MCU without the need for writing firmware. Firmware not related to pin configurations does have to be written. The language used in the IDE is C or C++, but C++ will be used throughout the project. More information regarding the pin configurations can be found in Appendix B.

Table 2.4: Specifications STM32L476RG MCU [3]

Specification	Value	Unit
Core	ARM Cortex-M4	–
Core Frequency	80	MHz
Flash Memory	1	MB
SRAM	128	KB
Operating Voltage	1.71 to 3.6	V
I/Os	Up to 51 GPIOs	–
Timers	13 timers	–
USART/UART	5	–
SPI Interfaces	3	–
I2C Interfaces	3	–
Operating Temp Range	-40 to +85	°C

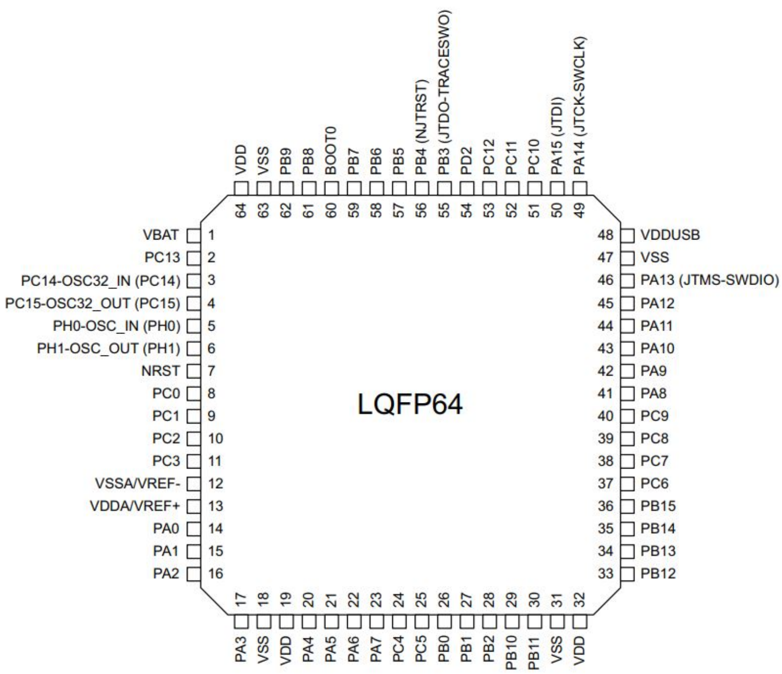


Figure 2.5: Simplified schematic STM32L476RG [3]

Temperature sensor: TMP100

The temperature sensors are required in order to keep track of the satellite temperature and potentially mitigate overheating or thermal cycling anomalies. The TMP100 temperature sensor will be used for the radiation payload due to its space heritage in the Delfi-PQ. Firmware and configurations used for the Delfi-PQ can be reused for the Delfi-Twin. How many and where these sensors will be installed is yet unknown and will be defined in a later stage of the Delfi-Twin project. The schematic of the sensor can be seen in Figure 2.6. In Table 2.5 the most relevant characteristics/specifications of the sensor can be found [36].

Table 2.5: Specifications TMP100 Temperature sensor [36]

Specification	Value	Unit
Size	2.90 x 1.60	mm^2
Temperature range	-55 until 125	C
Accuracy	+/-1	C
Supply Voltage range	2.7 - 5.5	V

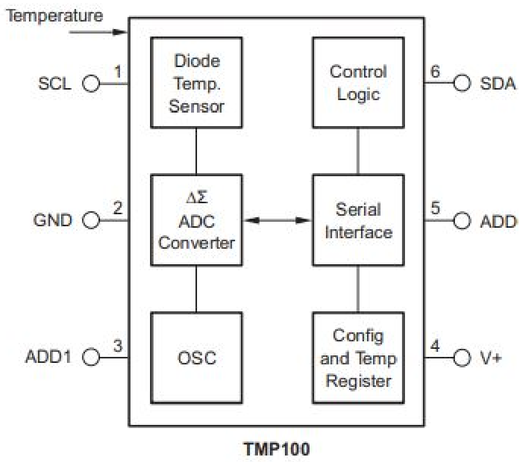


Figure 2.6: Simplified schematic TMP100 [36]

Voltage/current sensor: INA 226

The Voltage, Current and Power sensors (V/I/P) are required in order to keep track of the satellite voltage, current and power consumption. Firmware can be written which reads the sensor data and checks for anomalies to mitigate. The INA 226 V/I/P sensor will be used, similarly to the temperature sensor, for its space heritage in the Delfi-PQ. In Figure 2.7 a schematic of the sensor can be seen. In Table 2.6 the most relevant characteristics/specifications of the sensor are stated [37].

Table 2.6: Specifications INA226 Voltage, Current and Power sensor [37]

Specification	Value	Unit
Size	3.00 x 3.00	mm^2
Sensing Voltage	0 until 36	V
Accuracy, gain error	0.1	%
Accuracy, offset	10	muV
Supply Voltage range	2.7 - 5.5	V

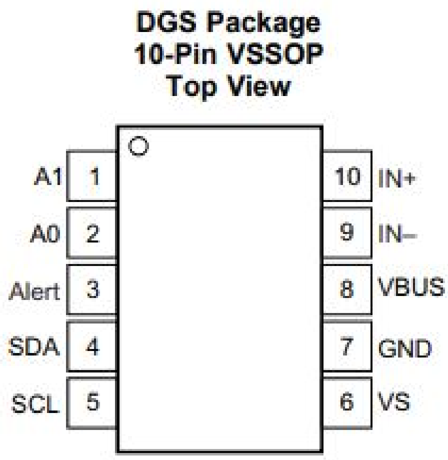


Figure 2.7: Simplified schematic INA 226 [37]

Bus connector: FSI-105-03-G-D-AD

The connector used to connect the OBC with the radiation payload is the FSI-105-03-G-D-AD. This is the same connector used in all other payloads of the Delfi-Twin, making it easier to install. The connector is able to connect 10 pins. See Table 2.7 for the specifications and Figure 2.8 for a 3D render [38].

Table 2.7: Specifications FSI-105 [38]

Specification	Value	Unit
Pins	10	-
Temperature range	-55 until 125	C
Height on PCB	3.00	mm

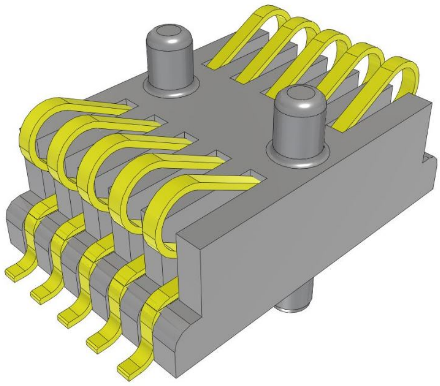


Figure 2.8: 3D design of the FSI-105 connector [38]

2.3.5. Conclusion Delfi-Twin research

The following conclusions can be taken regarding the Delfi-Twin literature study:

- The Delfi-Twin is still in development and many subsystem still require to be fully developed.
- The Delfi-Twin will have a separation mechanism splitting the satellite up in two. This means each payload needs to be integrated at least twice.
- The radiation sensor has already been chosen (the FGD-03F) and developed in a previous project of the TU Delft.
- The MCU chosen for this payload is an STM32L476RG.
- The TMP100 temperature sensor and the INA226 voltage, current and power sensor are requested to be integrated within the system in order to have regular check ups on the status of the system.
- The FSI-105-03-G-D-AD is used as bus connector as every other payload uses the same bus connector, simplifying the design of the OBC integration.
- Further hardware and firmware developments require to be made in order to finish the radiation payload system design.

2.4. Delfi-PQ research

The TU Delft has developed multiple satellites before the Delfi-Twin. The one most recent being the Delfi-PQ, a triple-unit PocketQube launched in 2022, see Figure 2.9. As aspects of the Delfi-PQ design will be similar to that of the Delfi-Twin, research was conducted on the design of the Delfi-PQ.

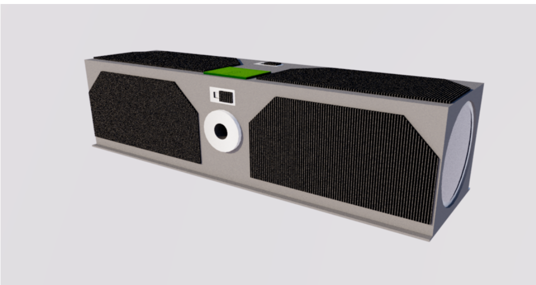


Figure 2.9: Delfi-PQ outside render [39]

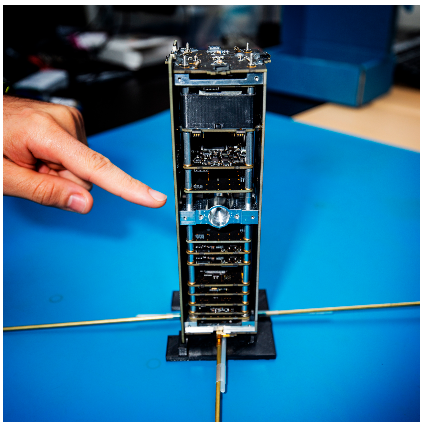


Figure 2.10: Delfi-PQ payload integration [40]

Figure 2.11: Delfi-PQ satellite, launched in 2022

2.4.1. Delfi-PQ mission

The primary goal of the satellite mission is education. Similarly to all other Delfi satellites, they are partially developed by students in order to gain hands-on experience in space hardware/firmware development and system engineering. The technical goal of the Delfi-PQ was to demonstrate an even smaller form factor of their satellite line-up than the previous versions. The Delfi-PQ is a triple-unit PocketQube, making it smaller than the Delfi-n3xt being a triple-unit CubeSat. The smaller size limits available power and therefore constraints payload, communication, ADCS and thrusting subsystems. Due to these constraints in power and size, these subsystems had to be designed by the TU Delft themselves in order to facilitate the size. This demonstrated a technical leap in the shrinkage of satellites [41].

2.4.2. Delfi-PQ hardware

The Delfi-PQ makes use of a 1-stack design, stacking the subsystems in the longitudinal direction, see Figure 2.10. The following components are integrated [41]:

- Antenna: The antenna's operate in UHF and VHF. A dipole with linear polarization configuration is used for two deployable antennas.
- Radio (communication): Is able to communicate in duplex via UHF (downlink) and VHF (uplink) as bands. This subsystem consists of a main board which can host the (de)modulation components, and a component which hosts the power and low-noise amplifier.
- Electrical power system (EPS): Consists of a battery board, a main EPS board, and solar panels. The MPPTs (Maximum Power Point Tracking) are placed on each solar panel due to the limited amount of space on the EPS board.
- OBC: Uses a MSP432 MCU.
- Attitude determination and control system (ADCS): Consists of three magnetorquers and two IMU (Inertial Measurement Unit) in order to stabilize a maximum rotational speed of 180 degrees/second.
- Payload: Thermal payload in order to measure the heat on several locations, micro-propulsion system using resistojets in order to steer the satellite and lastly a GPS system in order to track the satellite with its small size.

2.4.3. Delfi-PQ firmware

The operational modes of the satellite are controlled by the OBC and consist of 6 different modes. The following modes are used [7]:

- OFF mode: The satellite is turned off. The satellite stays within this mode until the kill switch is unpressed.
- Activation mode: Is used whenever the satellite needs to be activated again from OFF mode. Only the EPS, OBC and COMMs are activated during this mode.
- Deployment mode: Is used to determine whether the antennas are deployed. If not, the antennas will be deployed.
- Safe mode: Will be turned on in the case of a certain threshold or failure is noticed. This can for example occur when a certain voltage drop is noticed. The safe mode will turn off non-essential subsystems in order for the satellite to recover again.
- ADCS mode: Is turned on whenever an ADCS subsystem requires to be used. Examples are the magneto-torques whenever the satellite reaches high rotational speeds.
- Nominal mode: This mode is activated once the ADCS mode has finished and all health checks have been made. Only during this mode will the payloads be turned on. During nominal mode, tasks like checking and executing commands, collecting telemetry, sending telemetry, ADCS sensing and payload looping are performed.

2.4.4. Conclusion Delfi-PQ

Based on the information found regarding the Delfi-PQ, the following can be stated related to the Delfi-Twin project:

1. The Delfi-PQ uses a similar form factor to the Delfi-Twin, being a 3P PocketQube. This can help in integrating new payload systems into the Delfi-Twin as the PQ can be taken as reference.
2. The payloads and subsystems onboard of the Delfi-Twin seem to be different compared to the Delfi-PQ. Until now, the ADCS in the Delfi-Twin only uses its adjustable solar panel for orientation changes. In addition, more emphasis is given to tracking and navigational subsystems. No radiation measurement payload is present in the Delfi-PQ meaning no payload reference can be taken.

2.5. Lunar Zebro radiation payload

The following section will be regarding the Lunar Zebro, a mini rover developed by students from the TU Delft which utilizes the same FGD-03F radiation sensor as the Delfi-Twin. As the Delfi-PQ did not use any radiation payload, it is helpful to have a reference on how such a subsystem could be integrated, despite it being for a rover instead of a satellite. All findings in this section are based on the report 'REDMOON: Radiation Environment and Dose Monitoring On-board a Nano-Rover, The Science Payload for the Lunar Zebro' by Abhimanyu Shanbhag Abhimanyu [4].

2.5.1. Initial hardware design

The Radiation payload used in the Lunar Zebro is split up into multiple subsystems, see Figure 2.12.

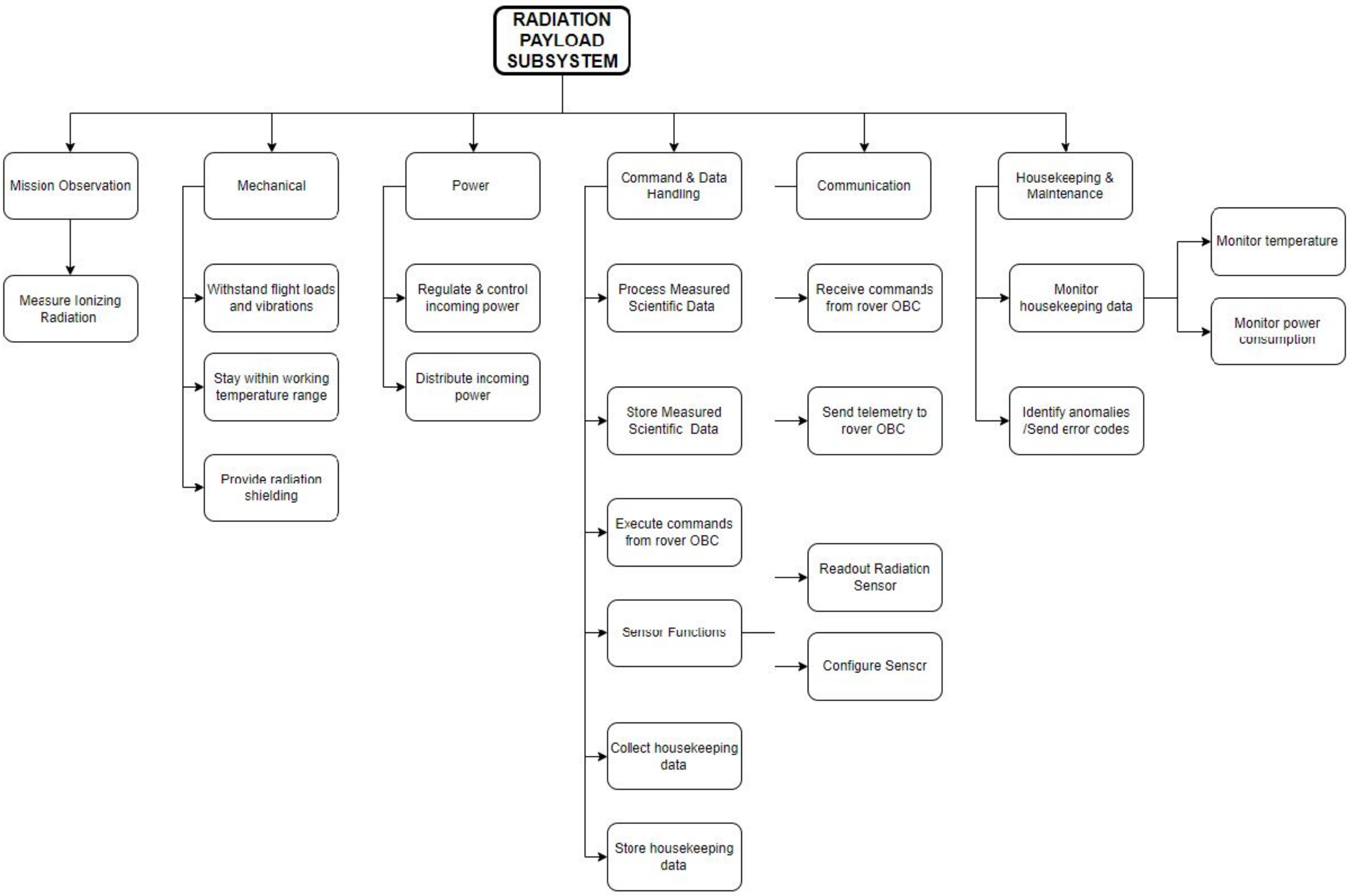


Figure 2.12: Functional breakdown radiation payload Lunar Zebro [4]

The subsystems are divided in several categories:

- Mission Observation: The main goal of the radiation payload is to measure radiation. This is performed by the radiation sensor, which can send the measurements to the payload MCU.
- Mechanical: The space environment hazards discussed in subsection 2.2.2 should be mitigated as much as possible. The mechanical section focuses on the detection and prevention/mitigation of these anomalies.
- Power: Most components installed onto the payload require power to operate. In addition, not all components require the same amount power. This creates respectively the need for power distribution and power regulation within the radiation payload.
- Command and Data Handling: These tasks are performed by the MCU and are crucial to the radiation payload. This subsystem focuses on the distribution of data, whether it is measurements, commands or housekeeping data.
- Communication: Communication delves into data transfer between the OBC and the radiation payload. The OBC gives commands to the payload, but the payload can also give requests to the OBC. These commands can be related to sending measurement data or changing the configuration of the payload.
- Housekeeping and Maintenance: The housekeeping and maintenance subsystem is necessary in order to monitor temperature, power and other types of factors within the radiation payload. This subsystem must spot anomalies and take appropriate action if required. As little can be done for the satellite once it is in space, this subsystem is crucial to the autonomy of the system.

In Figure 2.13 a flow diagram can be seen which shows the basic functionality of the radiation payload and how the measurements are brought to the OBC and are afterwards downlinked to Earth. It can be expected the Delfi-Twin will follow a similar path towards downlinking data.

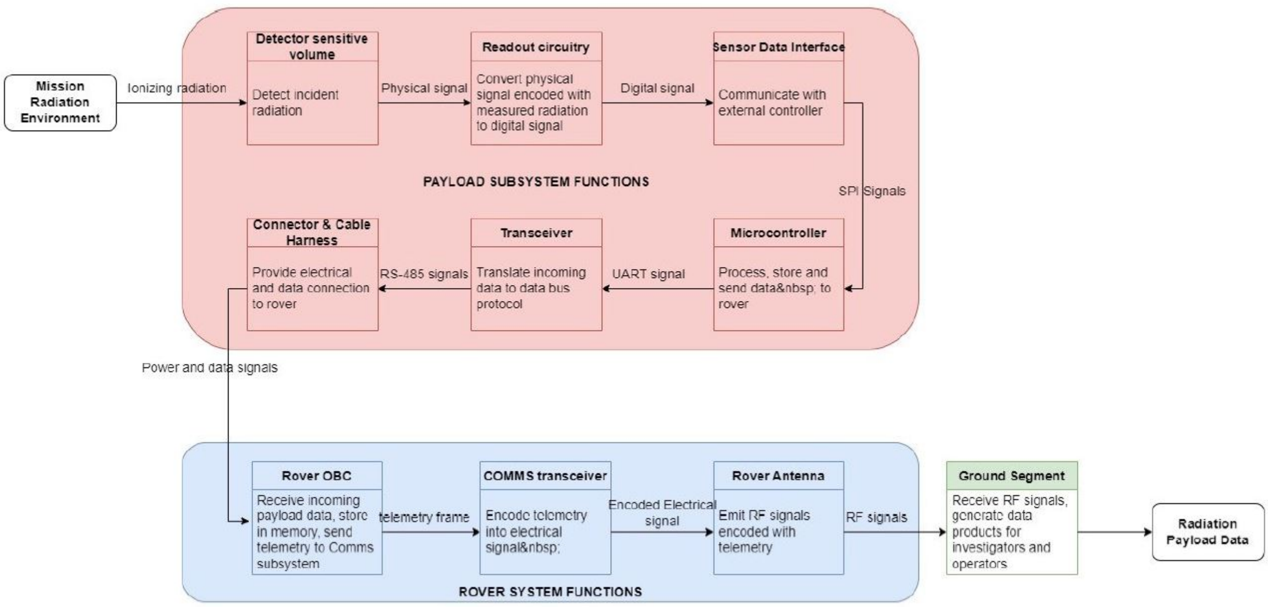


Figure 2.13: Functional Flow Diagram Lunar Zebro Radiation Payload [4]

In essence, if no parallel communication is assumed, the system must read the radiation environment, transmit it to the MCU, and send this signal to the rover OBC. The OBC will send the data to the antenna when commanded and downlink it to Earth.

In Figure 2.14 an architecture of the radiation payload can be seen. Figure 2.13 predominantly showed components necessary to measure data and downlink it to Earth, while the architecture also shows other components necessary to complete the payload design of the Lunar Zebro. The Onboard memory to store data and daughterboard are also included into the payload. The daugherboard serves as an extra radiation sensor placed outside of the Lunar Zebro's fuselage. This will bring different measurements, but is not relevant to the Delfi-Twin as it would not fit the triple-unit PocketQube form factor.

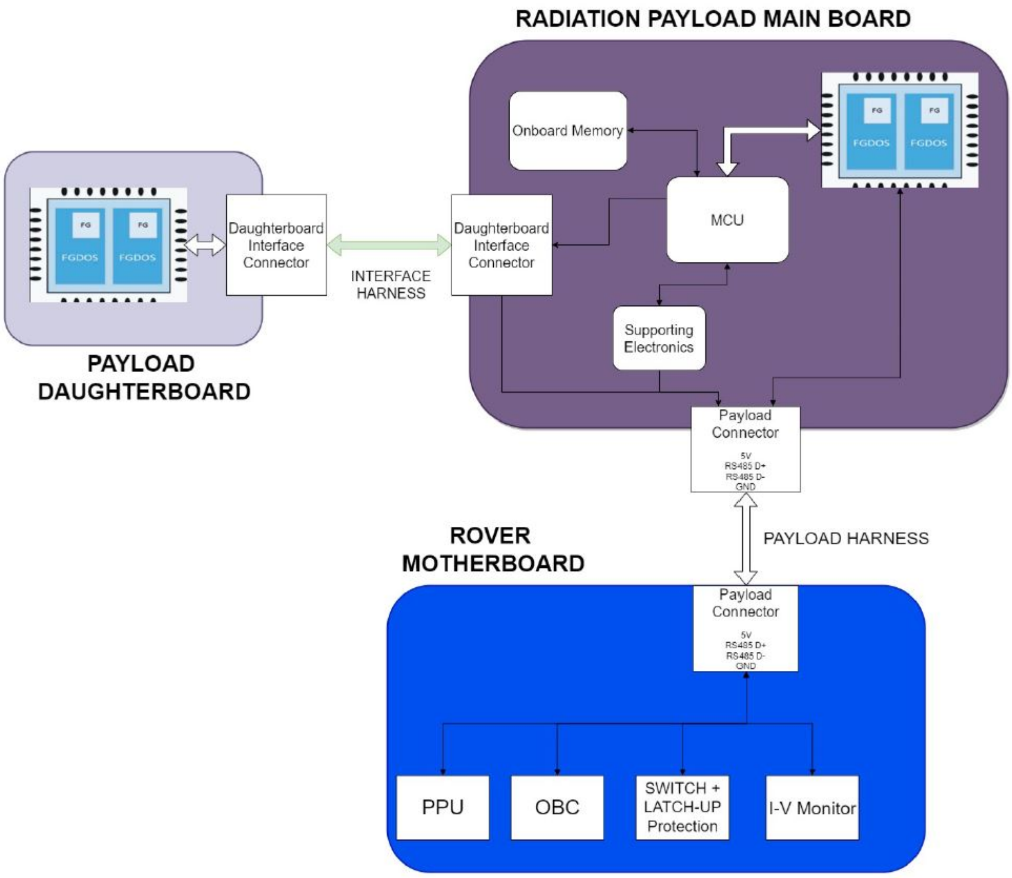


Figure 2.14: Radiation payload Architecture Lunar Zebro + rover motherboard [4]

After the high level subsystems were identified, a block diagram was created which identifies all IC's, their communication method, their required voltage and their connections to other IC's. See Figure 2.15 for the schematic.

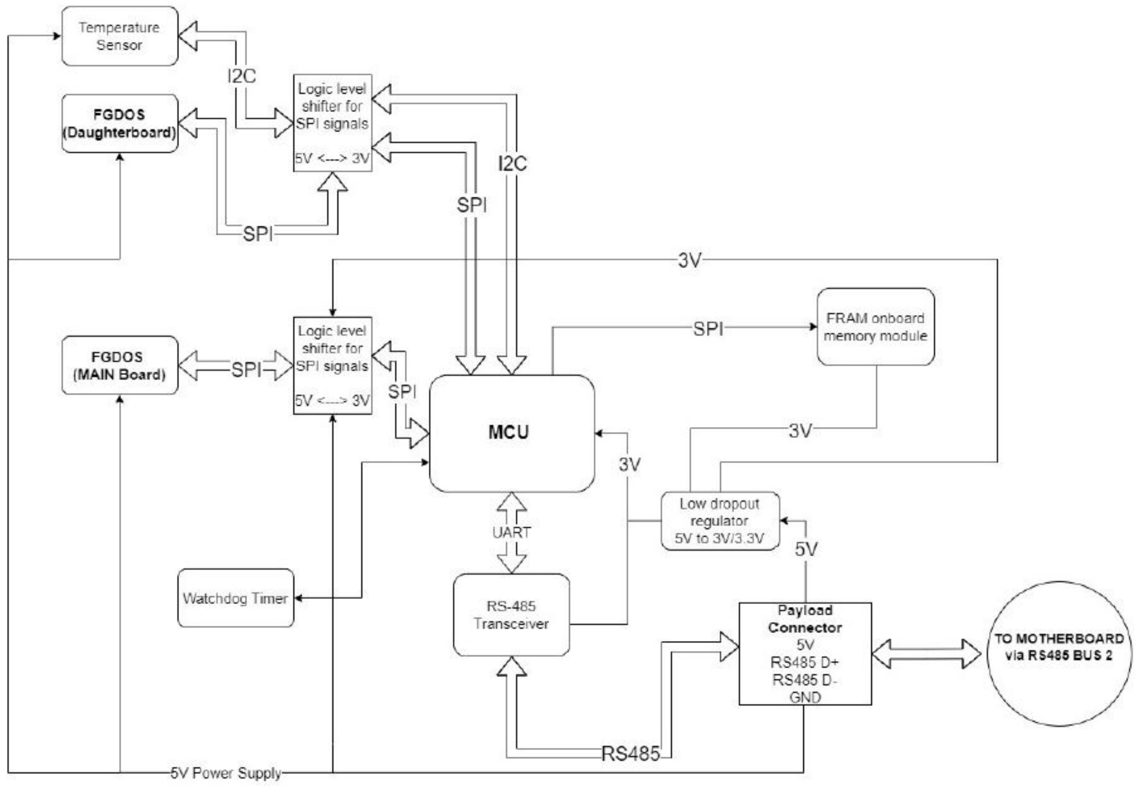


Figure 2.15: Radiation payload block diagram Lunar Zebro [4]

As the MCU, FRAM memory and RS-485 transceiver operate on 3V, a Low dropout regulator (LDO) was used to lower the voltage from 5V to 3.3/3V for these systems. The FGD-03F and temperature sensor operate on 5V and therefore bypass the LDO. The FGD-03F communicates via a SPI signal. As the MCU operates with 3V and the FGDOS with 5V, it becomes necessary to add a logic level shifter (also known as a voltage translator) to allow communication between the two systems. Two are used in this system for both the main board and daugtherboard. 3V components were chosen over 5V components as otherwise more logic level shifters had to be used, especially if the MCU would operate with 5V.

The following components were used specifically for this block diagram, see Table 2.8.

Table 2.8: Block diagram component usage Radiation Payload Lunar Zebro [4]

Component:	Name:
MCU	MPS430FR969
FGDOS	FGD-03F
Onboard Memory	CY15B104QN-50SXI FRAM
Level Shifter	MAX3001EEUP+
Voltage Regulator	LP2981
Watchdog timer	TPS538131580BVT
Transceiver	MAX3078EESA+T
Bus connector	DF13 4P 1.25H 76

2.5.2. Initial firmware design

The firmware required for the CDHS (Command data handling system) for the radiation payload were split up into two parts: One focused on handling radiation payload commands only, and one focused on transmitting data between the radiation payload and Lunar Zebro OBC. They are respectively called the ”payload firmware” and the ”payload app”. The payload app interacts with the real-time operating system of the Lunar Zebro called ”TRON”. In Figure 2.16 the CHDS architecture can be seen which displays the interactions between the controllers, memory, and its corresponding firmware.

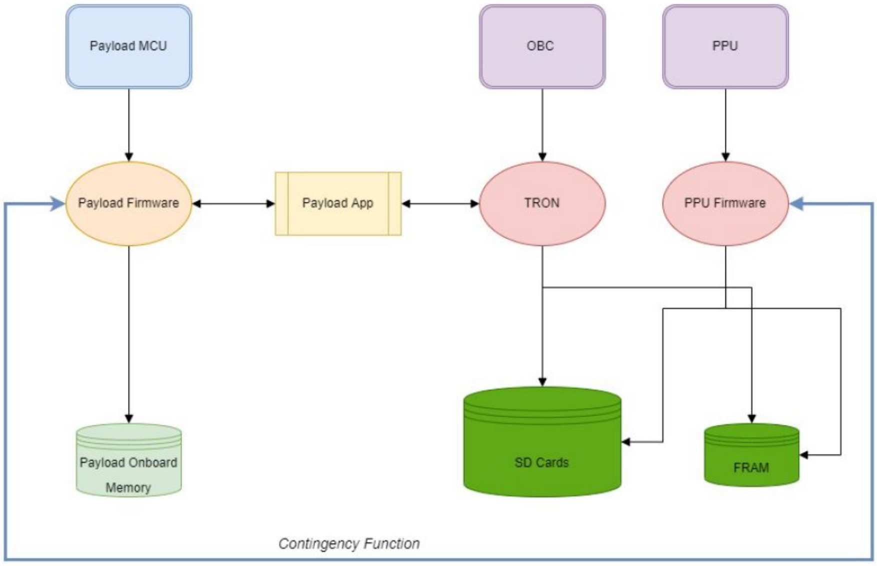


Figure 2.16: CDHS architecture Lunar Zebro [4]

The payload MCU is controlled via the payload firmware and interacts with the onboard memory, radiation sensors (main or daughterboard), housekeeping sensors and the OBC, similar to what can be seen in Figure 2.14. The rover OBC runs on TRON and interacts with the radiation payload via the payload app, stores the data in the rover SD card memory, or transmits/receives data through the OBC towards/from a telemetry and telecommands subsystem. In this configuration, the PPU (Power Processing Unit) serves as a back-up of the OBC in case of a malfunction. As for this, the PPU is connected to all rover memory (the SD-card and FRAM) and the payload firmware.

The payload firmware is considered to have four main tasks:

1. Task one, radiation sensing, consists of reading, checking, and processing the received data from the radiation payload. The settings for the radiation payload like sensitivity, mode configuration and sampling rate also require to be handled within this task.
2. The second task, Data storage and processing, consist of allocating the received data to the correct memory, storing this data, deleting data, and retrieving data from the memory.
3. The third task, telemetry and commands, consist of sending and receiving data from the OBC or PPU whenever the OBC malfunctions. Sending data could be regarding sending radiation payload data, error codes or a request for a power cycle. Receiving data could be related to a request for radiation payload data or a mode change.
4. The fourth task, Housekeeping and maintenance, consists of collecting housekeeping data like temperatures of sensors or MCU, monitoring this data by comparing it to nominal values and identifying or collecting error messages.

The payload app is considered to have four tasks as well, similar to the payload firmware:

1. The first task, payload control, is regarding the request of switching the payload on or off and changing its mode.
2. The second task, data storage, is regarding storing payload data in the rover onboard memory.
3. The third task, telemetry and telecommunication, is regarding receiving and sending payload data.

4. The fourth task, housekeeping and maintenance, is regarding collecting housekeeping data like power consumption from the PPU, monitoring this data by comparing it to nominal values and identifying and sending error codes.

The mode changes mentioned are related to the four modes of operations in which the radiation payload will be working in:

1. Re-initialization mode: This mode deals with the start-up and initialization of the radiation payload when it reboots from hibernation. This mode can convert to the nominal mode
2. Nominal mode: This mode consist of the nominal operations of the rover when it requires to read, send and retrieve data from or to the OBC. This mode can convert to either the safe mode or the decommissioning mode.
3. Safe mode: This mode is activated from the nominal mode whenever a critical error or failure is noticed within the payload. This mode can convert back to nominal mode when all issues have been mitigated.
4. Decommissioning mode: This mode is activated whenever the rover has met the end of its science mission and can be hibernated. This is done by offloading the payload, memory, and downlinking all available data. Afterwards the payload is turned off. It is still possible to bring the payload back to re-initialization mode if required.

A corresponding state transition diagram had been made to visualize the conversion of modes, see Figure 2.17.

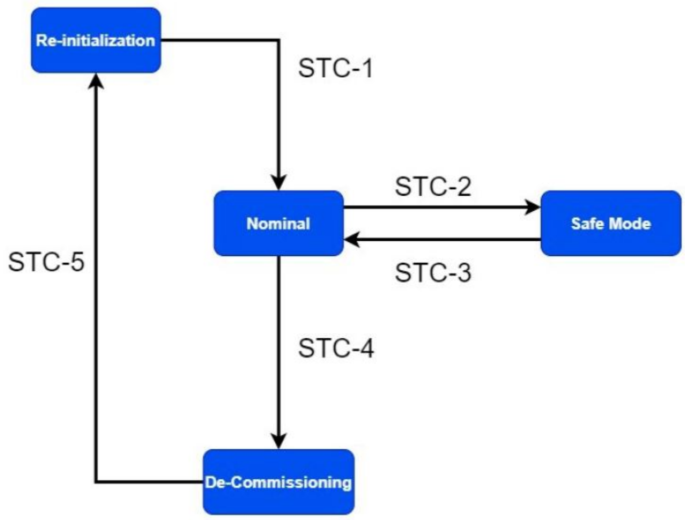


Figure 2.17: State transition diagram Lunar Zebro [4]

This concludes the hardware and firmware sections of the radiation payload designed for the Lunar Zebro. The thesis [4] regarding the development goes into further detail on how the physical test design is created and how the firmware operates. As these designs are made for the Lunar Zebro environment they are of less interest to the Delfi-Twin development. The concept design sections which have been discussed are however of interest as references to the Delfi-Twin radiation payload development.

2.5.3. Testing phase

The radiation payload has also been tested for various applications. Tests were performed regarding radiation measurements and the affect radiation has on the system. Temperature tests were conducted to see how it affected the power consumption of the radiation sensor. Lastly, combined radiation and temperature tests were conducted to see what affect temperature changes have on the radiation readings.

Radiation tests

The radiation tests consisted of using proton beam irradiation tests. The configuration used for these tests can be found in Table 2.9. The trends found during these tests are explained below.

Table 2.9: Radiation sensor configuration during testing [4]

Attribute	Value
Supply	5V – from Arduino Regulator via power adapter and HPTC socket
Readout interface	SPI through Arduino
Sensor Mode	Active / Passive
Sensitivity Modes	HI SENS / LOW SENS
Window Clock Frequency	31250 Hz
Window Pulses	4096
Window factor	7.63
Recharge Mode	Auto recharge from internal pump
Recharge voltage	16.5 V
SPI Frequency	5 MHz
Recharge Target Frequency - HI SENS	90000 Hz (85937.5)
Recharge Threshold Frequency - HI SENS	50000 Hz (46875)
Recharge Target Frequency - LOW SENS	180000 Hz (179687.5)
Recharge Threshold Frequency - LOW SENS	140000 Hz (132812.5)

The first trend seen with the radiation tests was the increase in radiation sensor sensitivity with increasing radiation beam energy. This was a consistent trend expected during the tests. See Figure 2.18 for two example plots.

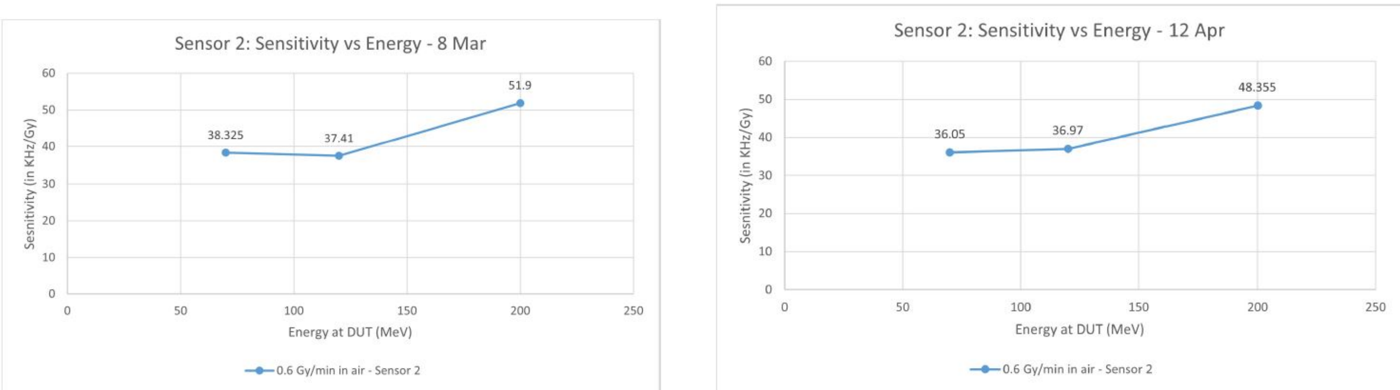
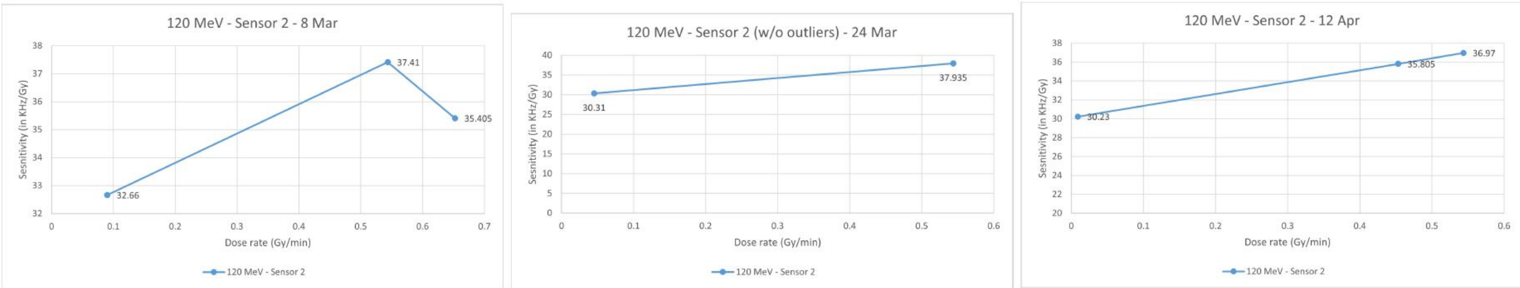


Figure 2.18: Plot which shows the increase in sensor sensitivity [KHz/Gy] with an increase in radiation beam energy [MeV] [4]

The second trend seen was a change in radiation sensor sensitivity with increasing Dose rate. This trend was however inconsistent, changing sensitivity from higher to lower and vice versa unexpectedly, see Figure 2.19. The reasoning was not fully found, but is to be expected due to potentially the test setup, beam characteristics or the data collecting method.



(a) *8 March* **(b)** *24 March* **(c)** *12 March*

Figure 2.19: Unclear trend in sensitivity change [KHz/Gy] with Dose Rate [Gy/min] of Lunar Zebro radiation payload [4]

A phenomenon called "Rapid Recovery Rate" was noticed when a certain amount of TID was accumulated. Rapid recovery rate is seen as a sudden rise in frequency measurements whenever the irradiation stops. Eventually the frequency levels off to a constant value. If irradiation is resumed, the frequency drops off again similar to pre-recovery values. The most plausible cause for this phenomenon is according to the research due to the readout circuitry, but this is not for certain. This is an unwanted anomaly as it changes the radiation measurements unnecessarily. An example can be found in Figure 2.20.

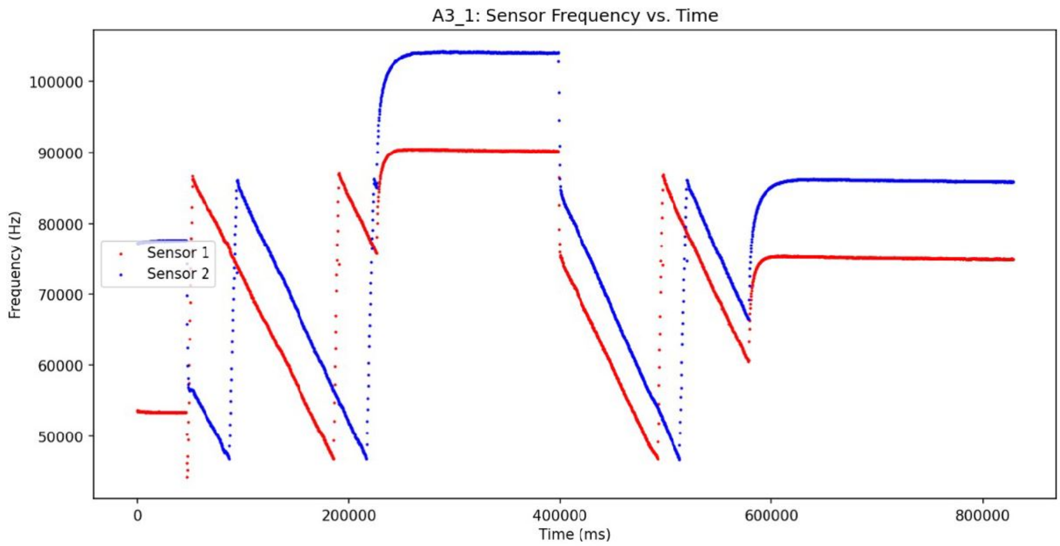


Figure 2.20: Example of Rapid Recovery Rate in radiation measurements of Lunar Zebro radiation payload [4]

Other forms of TID degradation on the radiation payload can be seen in Figure 2.21 and Figure 2.22. In Figure 2.21 it can be seen the sensitivity goes down with TID, but it does not always happen linearly. The 24th of March and 12th of April measurements even go up at certain sections. Figure 2.22 shows the increase in power consumption with the increase in TID. The increase remained over the several days it was measured. The changes are expected due to deterioration of the readout circuitry, DD anomalies (see subsection 2.2.2), or trapping of charge carriers in the radiation sensor.

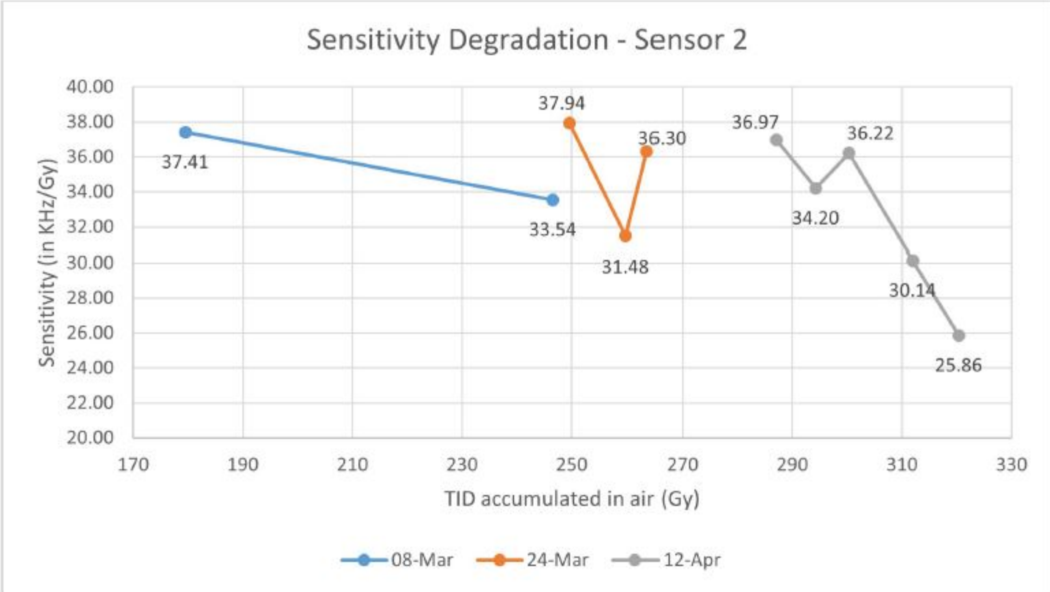


Figure 2.21: Degradation of sensitivity with increasing TID in Lunar Zebro radiation payload [4]

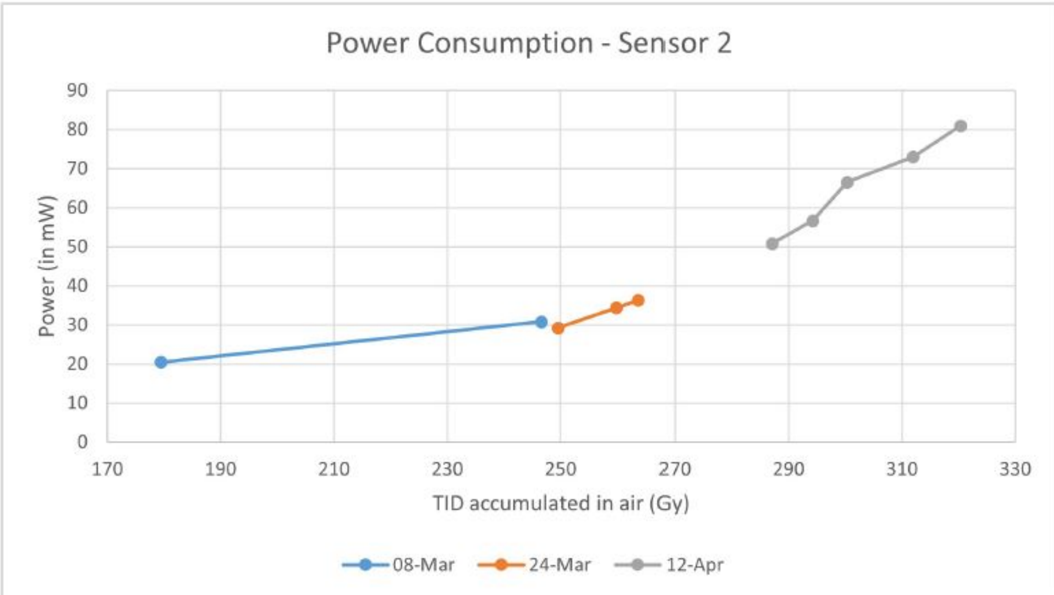


Figure 2.22: Increase in power consumption with increasing TID in Lunar Zebro radiation payload [4]

No latch-ups were seen during testing, but multiple SEE's did occur. Examples of such an SEE can be seen in Figure 2.23. No definitive answer could be found regarding the origin of the SEE's, even when taking into account temperature dip effects or general noise. However, the non-destructive nature of the observed SEEs made them of no concern due to readouts being refreshed each cycle.

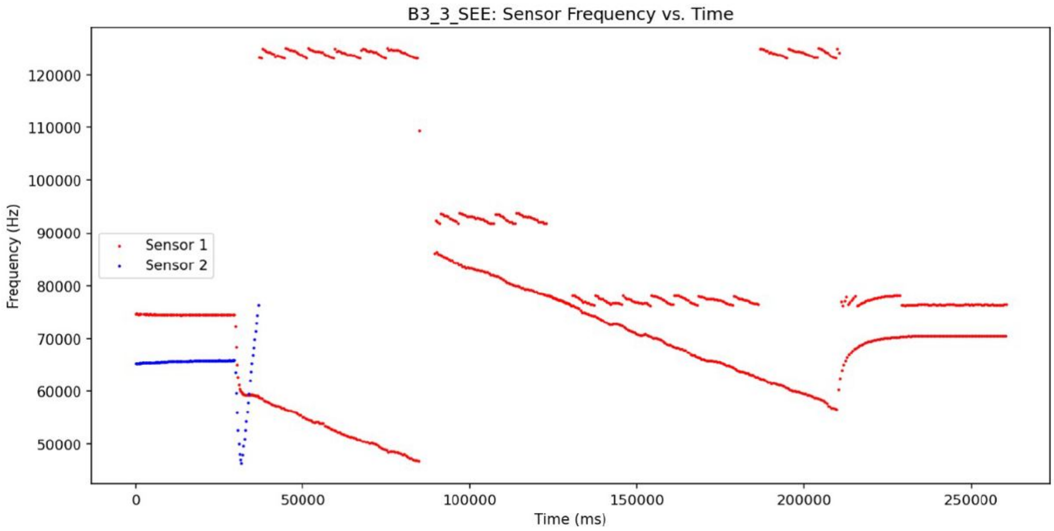


Figure 2.23: Example of SEE's in radiation measurements of Lunar Zebro radiation payload [4]

One other observation found was that the FGD-03F should be set to high sensitivity mode for any space application. This due to the low dose rates and fluxes observed in space, making it difficult for low sensitivity readings to pick up the difference between an actual drop in frequency and basic noise. This makes the measurements almost unusable, meaning a higher sensitivity is required to distinguish the radiation readings from noise.

Temperature tests

A thermocouple was attached to the radiation payload to make temperature measurements of the payload surface. An infrared heater was used to change the temperature on the payload. The temperature range the payload was subjected to was between 22 and 107 degrees Celsius. Once the temperature rose, the sensor frequency and reference frequency both went down.

The power consumption increase with the increase in temperature was negligible according to the measurements, see Figure 2.24.

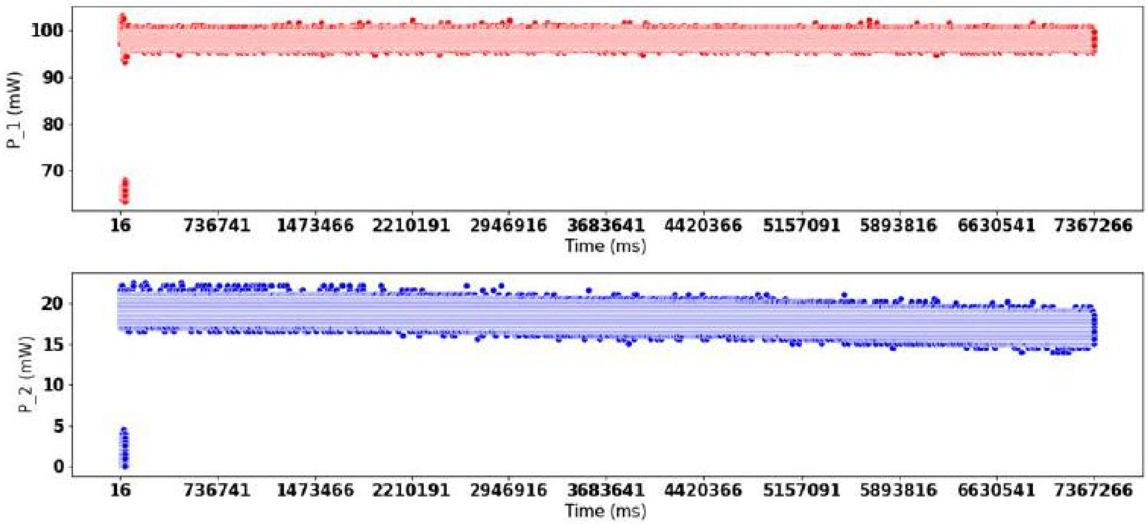


Figure 2.24: Change in power consumption with change in temperature for the Lunar Zerbo radiation payload [4]

The test set-up allowed for quick cycles between hot and cold temperatures, something which is expected to be more gradual during the Lunar Zebro mission. The extremes tackled by the Lunar Zebro are however expected to be larger than the temperature range tested for the payload. Further testing to see how the payload would react to these extremes are suggested to be performed at a later date.

Combined heating and radiation tests

To have a more realistic scenario akin to the Lunar Zebro mission, the payload was tested with the proton beam in addition to being subjected to heat cycles. During these tests, the frequency of the radiation measurements could be seen to be affected by the temperature rise. Once the temperature had risen, the frequency went down in similar fashion to how the temperature would change. This can be seen in Figure 2.25 and Figure 2.26 where the frequency takes an opposite shape to the change in temperature. The reaction from the temperature increase makes it relatively easy to separate the two effects from each other once the measurements are post processed.

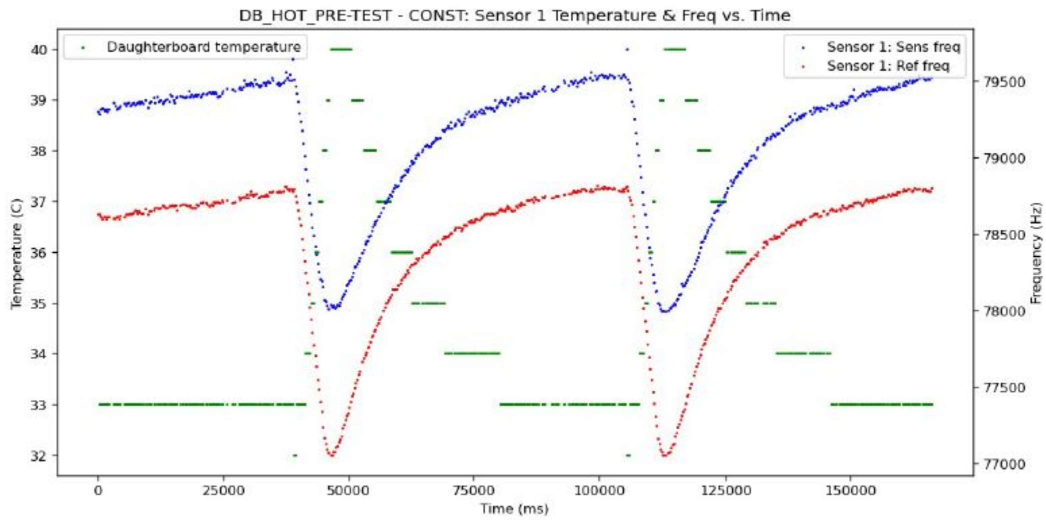


Figure 2.25: Change in radiation measurement sensitivity with change in temperature, example 1 [4]

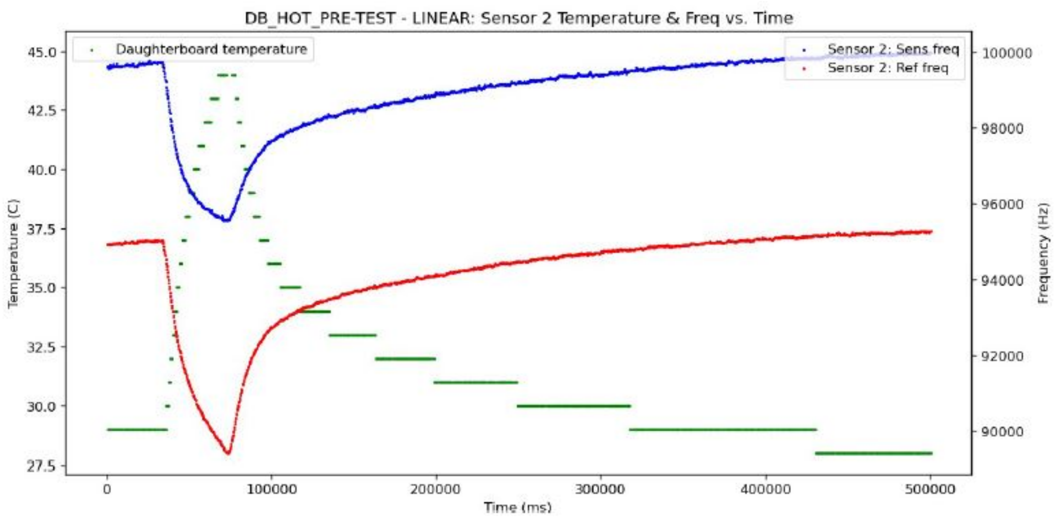


Figure 2.26: Change in radiation measurement sensitivity with change in temperature, example 2 [4]

2.5.4. Recommendations and further development

Several recommendations were given by the end of the radiation payload integration project thesis of the Lunar Zebro. The suggestions are most interesting to the Delfi-Twin development:

- Inclusion of an SRAM memory bank in order to store thermal neutron detections. This does however require changes in the allowed power usage, weight and size of the Lunar Zebro.
- Research into hardware with better radiation resistance.
- More redundancy and fault tolerance in the hardware architecture.
- More modularity to the firmware design
- Payload data compression methods may be necessary to safe storage space when saving data.
- Encryption methods in order to make the telemetry more secure.
- More radiation type tests as only proton beam tests have been performed.
- The use of an external oscillator for the MCU and radiation sensor to obtain a more stabilized clock signal.

2.5.5. Conclusion Lunar Zebro development

Based on the Lunar Zebro research conducted, the following conclusions can be made:

- The Lunar Zebro uses the same radiation sensor as the Delfi-Twin will use, meaning references can be taken from their design strategies
- The subsystems, architecture and block diagram of the Lunar Zebro radiation payload are design strategies which can be useful for the Delfi-Twin radiation payload development.
- The payload app firmware tasks are divided in payload control, data storage, telemetry commands and housekeeping. It is expected that something similar will be defined for the Delfi-Twin.
- The radiation and temperature tests conducted showed several anomalies ranging from SEE's to an increase in power consumptions. The phenomena 'rapid recovery rate' due to an increase in TID was understood the least, making it important to take into account when tests for the Delfi-Twin radiation payload are conducted.
- Several recommendations were made by the Lunar Zebro radiation payload development which can be used for this project if applicable.

2.6. Conclusion and findings literature study

The literature study has shown several aspects which are useful for designing the radiation payload for the Delfi-Twin.

At first, research was conducted on the space environment. It showed several anomalies which can occur on electronic components due to radiation, showing the need to take this into account for the payload design. Moreover, it showed the need for further research into this topic as it may help future missions prepare better for the space environment.

The research into the current Delfi-Twin development showed the early design stages the satellite is still in. Throughout the radiation payload project it is however expected that other payloads will be further into development as well. The main goal of the Delfi-Twin is not to measure radiation, but more to better understand how to control a potential swarm formation of satellites. Several components for the Delfi-Twin radiation payload have been chosen beforehand, namely the radiation sensor FGD-03F, the MCU STM32L476RG, the temperature sensor TMP100, the V/I/P sensor INA226 and the connector FSI-105-03-G-D-AD. The remaining hardware and firmware developments will be conducted within this development project.

The Delfi-PQ showed the Delfi-Twin will use the same form factor, but that the payloads will be different. No radiation payload had been installed for the Delfi-PQ, meaning no reference can be taken from this project. The Lunar Zebro project however does use the same radiation sensor as the Delfi-Twin, namely the FGD-03F. The hardware and firmware development made for the Lunar Zebro showed great potential to be used as reference. Moreover, the tests conducted on the radiation sensor showed anomalies discussed in the space environment literature study section, showing the affects radiation and temperature can have on measurements. This together with the recommendations made for the Lunar Zebro radiation payload development, can be used for the development for the Delfi-Twin payload.

This concludes the literature study section of this report. The sections starting from section 2.7 will focus on defining the project goals and scale, after which the development of the Delfi-Twin radiation payload will be discussed in chapter 3.

2.7. Problem description

The Delfi-Twin is the next generation of small satellites created by the TU Delft. This satellite will be unique to its predecessors by its ability to split up from a 6P PocketQube configuration to two 3P configurations. This two in one configuration is seen as the first step of a potential satellite swarm. Due to this configuration, the tracking and detecting of the satellite itself and its surroundings is of most importance in this project. In addition to detecting and tracking the payload, the satellite will include a radiation measuring payload. The sensor used for this payload is the FGD-03F, a sensor which has already been integrated into a small rover project by the TU-Delft called The Lunar Zebro.

The essence of this project is to integrate the FGD-03F into the Delfi-Twin satellite. The integration of the radiation payload will encumber the design of the mechanical, electrical and firmware design of this payload within the Delfi-Twin. The payload will afterwards require to be tested for its functionality. The end result of this project should be a physically testable radiation payload which is independently able to take radiation measurements, store these measurements and send them to the OBC for downlinking to Earth. The payload should also be able to take commands from Earth in order to change configuration whenever required. The radiation payload design of this project is not expected to be the flight model version due to time constraints, but it should be able to represent the essential tasks of the radiation payload.

2.8. Research questions/Design questions

The research/design questions for this project are based on the requests made by the Delfi-group. The previous research provided by the Lunar Zebro team is used as a reference [4].
The project consists out of three phases:

1. The system engineering phase
2. The detailed design phase
3. The verification and validation phase

Each one of these phases will have their own unique tasks to be completed, but all of them will have concepts within them related to the design of the mechanical hardware, electrical hardware and firmware of the radiation payload. Based on the general descriptions provided, the following research/design questions have been formulated, including the main research question of this report.

Main research question

What hardware and firmware designs need to be developed in order for the radiation payload to meet the mission requirements for the Delfi-Twin?

Sub research/design questions

The main research question is split-up into 6 sub research questions. These together will answer the main research question of this project. The research questions are split up in a system engineering phase, detailed design phase, and verification and validation phase in order to give structure to the project.

System engineering phase questions

- What stakeholder and system requirements are essential for the radiation payload project?
- Which hardware and firmware subsystems are critical to the operation of the radiation payload?

Detailed design phase questions

- Which components best meet the radiation payload's system requirements?
- What PCB design and layout best support the radiation payload's system requirements?
- What firmware design ensures autonomous and reliable operation of the radiation payload?

Verification and validation phase questions

- What tests are required to verify and validate that the radiation payload meets the stakeholder and system requirements?

In chapter 6, Conclusion and Recommendations, all proposed research questions are answered. If a research questions cannot be fully answered, an explanation will to be given regarding the deficiency.

2.9. Milestones and project goals

As stated earlier, the project will be split up into three phases consisting of a system engineering phase, a detailed design phase, and a verification and validation phase. All of these three phases can be seen as a milestone throughout the project and should all conclude a major section of the project. The milestones are all based on the research questions.

2.9.1. Phase 1: System engineering milestones

This phase will result in a high level conceptual design of both the mechanical, electrical and firmware integration of the radiation payload into the Delfi-Twin.

- The requirements list is the first milestone and consists of a stakeholder identification, stakeholder requirements and system requirements.
- The subsystems of the radiation payload are investigated to better understand which components are required during the detailed design phase. The subsystems are based of the requirements made previously.
- A breakdown structure, flowchart and architecture require to be made to better visualize radiation payload design. These steps will be taken for both the radiation payload hardware and firmware.

2.9.2. Phase 2: Detailed design milestones

This phase will result in a more detailed, physical representation of what had been made in the concept design. The radiation payload will be a physical PCB to which the developed firmware can be uploaded. This system must be able to test the radiation sensor and its surrounding IC's.

- At first the IC's for the PCB are selected based of the requirements and concept designs made in phase 1.
- A schematic will be made of all IC's and their connections with each other.
- If the integration of these IC's follow the system requirements and design rules, a PCB design will be made based of this schematic.
- When finished, the PCB and corresponding IC's are ordered and manufactured to become the radiation payload hardware design.
- The firmware design will be made simultaneously with the hardware design. The firmware will be made in the STM32CUBEMX IDE and will be based of the stakeholder requirements, system requirements and breakdown structure made in phase 1.

2.9.3. Phase 3: Verification and validation milestones

The verification and validation will require to test whether the integrated hardware and firmware designs are able to operate together and whether they can satisfy their mission design.

- Their functionality will be tested by means of debugging the payload and performing basic power and communication tests.
- Afterwards, the working system will perform radiation reads via the radiation sensor, which sends the data to the MCU and handles it according the commands given by the OBC. The measurements must be reevaluated to see whether any anomalies occur, similar to subsection 2.5.3 of the Lunar Zebro.
- The requirements made should in the end be reviewed to see which have passed and which have failed. Recommendations should be made based on these findings.

2.10. Project scope

The scope defines what activities lay within the boundary of the project and which do not. In Table 2.10 the scope list is shown.

Table 2.10: Scope List of Delfi-Twin radiation payload project

Scope list	
In scope	**Out of scope**
Examining the radiation payload components and their interactions with the OBC	Examining the OBC itself and the other payloads
Researching components which stay within the temperature, radiation and power requirements of the radiation payload	Calculating the structural integrity of the radiation payload
The PCB design of this project must showcase the capabilities of the radiation sensor	The PCB design of this project must be ready to be integrated into the satellite
The radiation payload firmware design must be able to receive and give commands to the OBC	Firmware written for the OBC to talk to the radiation payload
The radiation payload OBC will be built and tested for its basic functionalities and mission design	The PCB will be calibrated for specific radiation readings via radiation tests

2.11. Research approach

During the system engineering phase, literature research and interviews will be the predominant research approach. The interviews are necessary to obtain stakeholder and system requirements. The literature study is necessary to research the basic functions required to make the radiation payload operate. The Lunar Zebro design approach from the literature section 2.5 will be used as reference for the Delfi-Twin radiation payload design. This together with already existing payloads of the Delfi-Twin, will help in the conceptual design of the radiation payload.

The detailed design phase will at the start consist of more literature study related to the component selection of the radiation payload. In addition, more research will be performed regarding the firmware design and how the selected components will require to be activated and controlled. The hardware will be designed using Fusion 360, the firmware used for all payloads of the Delfi-Twin. This will incorporate an integration schematic of the selected components and a PCB drawing. Once the drawings are finished the PCB will be build and tested with the developed firmware. The firmware development will predominantly consist of code writing in STM32CUBEMX IDE.

The last phase, the testing phase, will predominantly be performed via debugging and testing the system. This is done via uploading test firmware to the hardware to see how the components react. Once this has been completed, actual radiation tests or simulations can be made. This section will focus on firmware writing and debugging.

2.12. Project planning

The project planning of this radiation payload project had to be changed due to the requirement of additional time. The planning can be seen in Figure 2.27 which shows the expected time and taken time for each phase of the project. The expected total amount of weeks the project would last was plus or minus 27 weeks. The weeks taken were around 47. This predominantly due to the detailed design phase which saw problems in the ordering of components and checking of the hardware and firmware designs. The PCB design was the biggest obstacle of the planning as it had to be fully correct and checked before it could have been ordered. If a mistake was made on the board it would require to be redesigned and reordered, costing money and time. Due to the lack of opportunities to get the PCB design checked, the PCB development kept being delayed and changed. The project was also on-going during the summer vacation, but this only stagnated progression as there was less opportunity to get work checked.

As an important note, the design of any component within a project should not be underestimated in time when it is dependent on the supervision of others. The supervision cannot always be granted, and must therefore be taken into account with the planning.

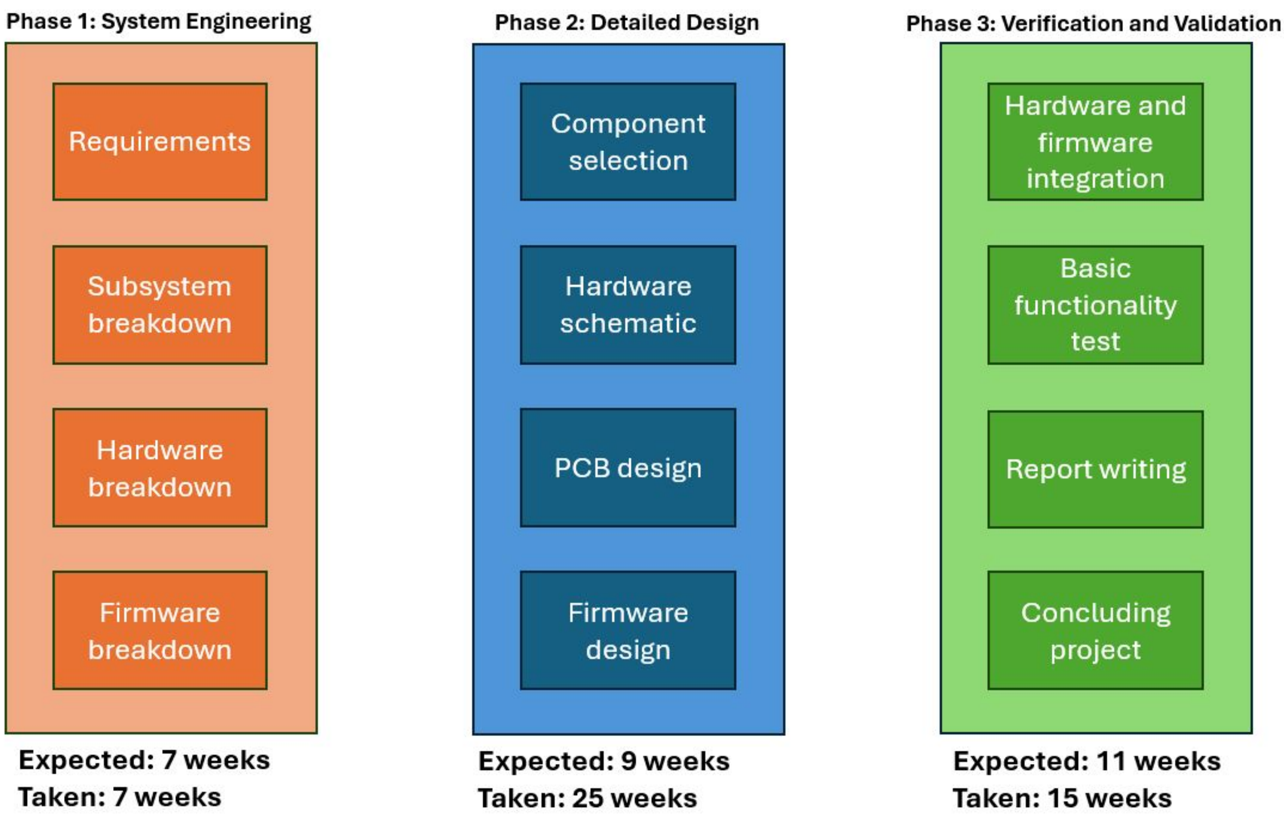


Figure 2.27: Project planning, expected vs actual time taken

3 System engineering

3.1. Introduction: System engineering

During the literature study, chapter 2, it could be concluded that the design of the Delfi-Twin is unique, as it consists of two triple unit PocketQubes that are able to split and work separately in space. In addition to this, the PocketQubes will each have a radiation payload which should be able to send radiation measurements to Earth. This is a unique mission design for the Delfi-Group, resulting in unique mission statements, stakeholders, requirements and overall architecture of the system. To give structure to the development process, a system engineering approach has been used to start this project.

The concept design phase of this project will predominantly follow the system engineering design approach based on the book 'Applied Space System Engineering' [42]. The result of this approach will be a conceptual hardware and firmware design of the radiation payload. These will identify which requirements, subsystems and type of components are required in order to develop a working radiation payload fitting to the mission criteria of the Delfi-Twin. After the conceptual design, a detailed, manufactured design of the radiation payload will be developed in chapter 4.

This section will focus on the identification of the need and mission statement and the stakeholder/system requirements. The approach seen in Figure 3.1 will be used from the book 'Applied Space System Engineering'.

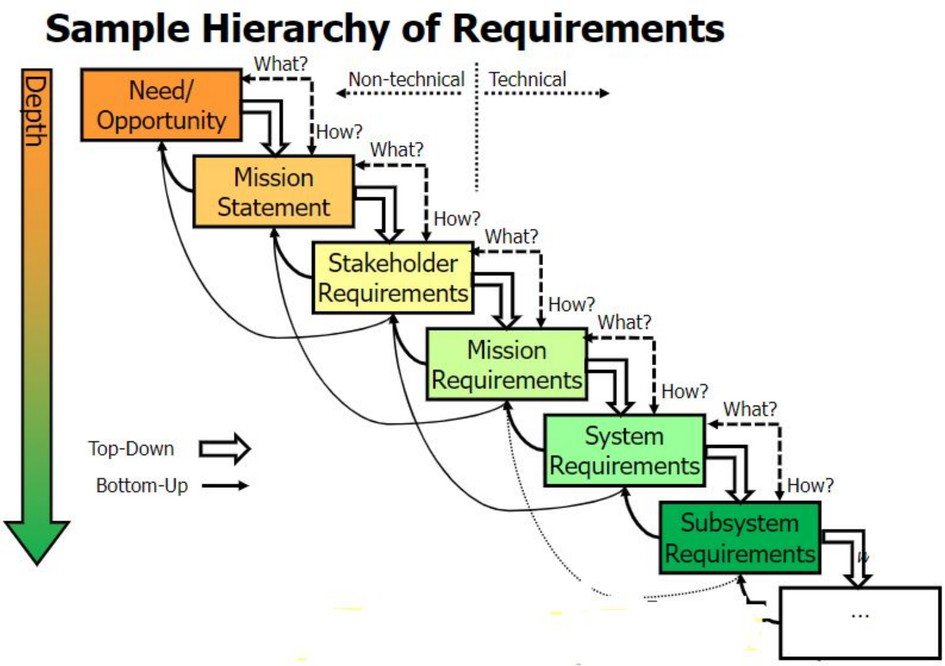


Figure 3.1: Sample Hierarchy of Requirements [42]

3.2. Need and mission statement

Before the requirements are set, a need and mission statement will be given to summarize the aim of this project. The need and mission statement are based of the literature study in chapter 2.

Need statement

"Space radiation causes anomalies within space hardware and health risks to astronauts. More accurate measurements of space radiation are needed to better understand and prevent radiation anomalies."

Mission statement

"The Delfi-group will integrate a floating gate dosimeter-based radiation measurement system into their newest developed satellite to monitor radiation activity in the mission environment."

3.3. Project requirements

3.3.1. Stakeholder requirements

The stakeholder requirements convey the need of the most relevant parties of this project. The stakeholder requirements must be followed as the stakeholders determine the success of the project.

At first the stakeholders themselves will be identified. The reason for their involvement and whether they are 'active (A)' (the stakeholder is directly involved) or 'passive (P)' (the stakeholder is indirectly involved). After the stakeholders are identified, each of their corresponding requirements are stated, including whether they are regarding a 'capability' (the system must have this function), 'characteristic' (the system is able to work within X and Y) or 'Constraint' (the system cannot be bigger or smaller than X and Y).

In addition, how critical a requirement is to the mission is stated as 'essential', 'conditional' or 'optional' [42]. The stakeholder identification can be found in Table 3.1 and its corresponding requirements can be seen in Table 3.2.

Table 3.1: Radiation payload stakeholder identification

Stakeholder	A/P	Explanation
TU Delft	A	Facilitates the working environment for the project to be developed at. Finances the project. Will use the development of the Delfi-Twin to promote the university and faculty.
Delfi-Group	A	Will directly work on the Delfi-Twin and are dependent on the radiation payload integration to finish the Delfi-Twin development.
ESA	A	Will play a role in the launch facility of the Delfi-Twin and make it yield to their requirements. Could potentially use the data obtained from the mission for its own space research.
Launch Providers	A	Will provide the launch facilities for the Delfi-Twin, making the satellite dependent on their involvement and vice versa.
Space Industry	P	Can utilize the data obtained from the mission. Vice versa, the Delfi-Twin can make use of previous data contributed by the space industry. No direct involvement is present unless ESA is seen as a contributor.
Sealicon	P	Provides the FGDOS-03F (radiation payload) for this project. Has no direct involvement with how the radiation payload will be used.
STMicroelectronics	P	Provides the hardware for the payload MCU and its firmware IDE. The company has no direct involvement with the satellite project.

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Stakeholder	A/P	Explanation
Hardware Manufacturer	P	Other hardware components like sensors, busses, Low Dropout Regulators, and more all contribute to the hardware realization of the project, but do not actively involve themselves with the project.
Testing Facility	P	Facilitates the testing of the radiation payload integration, but does not actively evolve with the project.

Table 3.2: Radiation payload stakeholder requirements list

Requirement Nr.	Stakeholder	Requirement	Capability/ Characteristic	Ess./ Con./ Opt.
Req.Def.1	Delfi-Group	The payload integration installment shall fit within the confined space of the Delfi-Twin	Char	E
Req.Def.2	Delfi-Group	The payload shall not exceed the power limit of the solar cells.	Char	E
Req.Def.3	Delfi-Group	The payload shall work within the operational temperatures similar to the Delfi-PQ	Char	E
Req.Def.4	Delfi-Group	The payload shall be radiation tolerable.	Cap	E
Req.Def.5	Delfi-Group	The payload shall only consist of COTS components.	Char	E
Req.Def.6	Delfi-Group	The payload integration hardware shall be operable within the vacuum of space.	Cap	E
Req.Def.7	Delfi-Group	The payload shall make use of the STM32L476 microcontroller to operate and communicate with the radiation payload and the OBC.	Cap	C
Req.Def.8	Delfi-Group	The payload integration shall make use of the TMP100 temperature sensor for internal temperature measurements.	Char	E
Req.Def.9	Delfi-Group	The payload integration shall make use of the INA226 voltage, current, and power consumption sensor for internal status measurements.	Char	E
Req.Def.10	Delfi-Group	The payload integration shall make use of a FSI-105-03-G-D-AD bus connector from the MCU towards the OBC.	Char	E
Req.Def.11	Delfi-Group	The payload integration shall use a separate voltage supervisor, not one that is integrated.	Char	E
Req.Def.12	Delfi-Group	The integrated payload must be able to survive the launch loads.	Cap	E
Req.Def.13	Delfi-Group	The radiation payload shall be able to measure radiation and send this data to the OBC.	Cap	E

Requirement Nr.	Stakeholder	Requirement	Capability/ Characteristic	Ess./ Con./ Opt.
Req.Def.14	Delfi-Group	The radiation payload shall be able to change modes depending on the circumstances of the mission	Cap	E
Req.Def.15	Delfi-Group	The payload system must be able to send and receive data to and from the OBC	Cap	E
Req.Def.16	Delfi-Group	The MCU must be able to send status measurements when requested from the OBC to the OBC.	Cap	E
Req.Def.17	Delfi-Group	The payload firmware must be made such that it is easy to use for outside users.	Char	E
Req.Def.18	Delfi-Group	The payload integration its power consumption should be as minimal as possible.	Cap	E
Req.ESA.1	ESA	The payload integration shall conform to the relevant ESA regulations.	Char	E
Req.Lau.1	Launcher provider	The payload integration shall conform to the launcher regulations.	Char	E
Req.TUDec.1	TU Delft	The payload integration project shall provide new data and developments to the space radiation measurement industry.	Cap	E
Req.TUDec.2	TU Delft	The payload integration project shall provide educational value to the TU Delft and its students.	Cap	C

3.3.2. System requirements

The system requirements are a more specified version of the stakeholder requirements which are more easily verified. The system requirements are split up in several subjects to organize the list. The following subjects are used:

1. Mission = States requirements regarding payload capabilities related to the mission objective.
2. Design = States requirements regarding design constraints.
3. Interface = States requirements regarding the interface with the OBC by means of data exchange or power.
4. Safety = States requirements regarding safety of the subsystem.

Similar to the stakeholder requirements, the system requirements will be categorized in capability, characteristic and constraint. In Table 3.3 the system requirements table can be found together with their type, rational and verification plan.

Table 3.3: System requirements list of radiation payload

Subject	Nr.	Requirement	Type	Rationale	Verification
Mission	MI-1	The payload should be able to measure radiation throughout the mission duration of at least 3 years.	Capability	This is the main science objective of the radiation sensor and must therefore be performed.	Testing
Mission	MI-2	The payload shall be able to give and receive commands from the OBC throughout the mission duration of at least 3 years.	Capability	This makes the radiation sensor able to change modes and send measurements. Without measurements being sent to the OBC, no data can be obtained and the mission shall fail.	Testing/ firmware design
Mission	MI-3	The payload shall be able to change modes depending on the OBC requests.	Capability	Survivability of the payload as shut-offs may be necessary when anomalies occur. It also allows the payload to potentially work more efficiently by changing modes suitable for the occasion.	Testing/ firmware design
Mission	MI-4	The payload shall be able to shut-off when requested by the OBC.	Capability	The shut-off should be a mode integrated into the payload as it can save the payload from destruction by anomalies as explained in MI-3.	Testing/ firmware design
Design	DE-1	The payload PCB design shall be confined within 42 by 42 mm (UPDATE: This has been changed to 45 x 47 x 8 mm)	Constraint	This is the allowed area of the PCB as it must be integrated into a PocketQube with multiple other payloads. The size constrictions are therefore of importance.	Hardware design
Design	DE-2	The payload PCB design shall use the same shape as the Delfi-PQ PCB. (UPDATE: The design has been changed, see DE-1)	Constraint	The Delfi-Twin payloads that use a PCB all follow the same format as given by the Delfi-PQ PCB's.	Hardware design
Design	DE-3	The payload shall use the FGD-03F as the radiation sensor.	Constraint	The radiation payload had been chosen beforehand by the Delfi-group. Previous research has already been done at TU Delft regarding the sensor, making it easier for the project not to use a different radiation sensor.	Hardware design
Design	DE-4	The payload shall use the STM32L476RG MCU as the main microcontroller.	Constraint	This MCU is still being manufactured and updated, making it a reliable system to use for the radiation payload.	Hardware design
Design	DE-5	The payload shall use the TMP100 as the temperature sensor.	Constraint	This IC is chosen as it has flown before in the Delfi-PQ, making it a reliable component to use according to the Delfi-group.	Hardware design

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Subject	Nr.	Requirement	Type	Rationale	Verification
Design	DE-6	The payload shall use the INA226 as the voltage, current, and power sensor.	Constraint	This IC is chosen as it has flown before in the Delfi-PQ, making it a reliable component to use according to the Delfi-group.	Hardware design
Design	DE-7	The payload shall use the FSI-105-03-G-D-AD connector to connect with the OBC.	Constraint	This connector to the OBC is used as the other payloads within the Delfi-Twin use the same connector. This keeps the designs consistent and integration of different payloads easier.	Hardware design
Design	DE-8	The payload shall use an external watchdog timer which does not have an integrated voltage supervisor.	Constraint	The Delfi-PQ had difficulties in using an external watchdog timer with an integrated voltage supervisor. To prevent these difficulties, it is requested to have both components separate for better design.	Hardware design
Design	DE-9	The payload shall, except for the radiation sensor, consist out of COTS components.	Constraint	To make the design cheaper and easier to order, the satellite should, except for the radiation sensor, consist out of components which can be bought at any time.	Hardware design
Design	DE-10	The components, except for the radiation sensor, shall be ordered from Mouser.	Constraint	To keep the component orders consistent, it is requested that all components, except for the radiation sensor, are ordered from Eurocircuits and Mouser.	Hardware design
Interface	IN-1	The payload firmware shall be written in C++.	Constraint	Other firmware of the payload are also written in C++. To keep consistency, it is recommended to keep the firmware language equal for all payloads.	Firmware design
Interface	IN-2	The payload firmware shall be able to send radiation, temperature and power data to the OBC.	Capability	Without being able to send the measured data to the OBC, it is not possible to downlink data and retrieve it on Earth. Without this functionality the radiation sensor would be useless.	Firmware design/ testing
Interface	IN-3	The payload firmware shall be designed such that no additional coding is required to change payload configurations.	Characteristic	It has been requested that the firmware is written such that a new person can easily modify radiation payload settings, change modes, and configurations.	Firmware design/ testing
Interface	IN-4	The payload shall be able to provide 5V, or other voltage levels, to components which require them.	Capability	The voltage given by the power supply of the satellite is 5V. The payload must be able to give components their necessary voltage, whether it is 5V or lower like 3.3V. Voltage converters would be required if lower voltages are needed.	Hardware design/ testing

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Subject	Nr.	Requirement	Type	Rationale	Verification
Safety	SA-1	The internal payloads shall be able to operate within temperatures of -35 to 35 degrees Celsius.	Characteristic	The Delfi-Group estimates the internal temperatures to be slightly higher than those of the Delfi-PQ (-25 to 25 degrees Celsius). The external payloads and solar panels have a higher temperature swing estimation.	Testing/ hardware design
Safety	SA-2	The payload shall be able to operate within vacuum.	Characteristic	The components must be able to withstand these hazards when installed.	Testing/ hardware design
Safety	SA-3	The payload shall be able to withstand the flight loads of 14.1 g RMS.	Characteristic	This is based on the launch provider manual given to the Delfi-Group.	Testing/ hardware design
Safety	SA-4	The payload shall operate withstanding around 3krad a year.	Characteristic	The mission environment inevitably causes radiation exposure which affects the payload components. This resistance is taken with considerable margin.	Testing/ hardware design
Safety	SA-5	The payload firmware shall detect anomalies within the measurements taken from the sensors.	Capability	The satellite must be able to autonomously survive in its mission environment.	Firmware design/testing
Safety	SA-6	The payload firmware shall be able to reboot or shut-off when anomalies are detected.	Capability	Rebooting or shutting off can prevent anomaly-based destruction in PCBs.	Firmware design/ testing
Safety	SA-7	The radiation payload shall not exceed a total maximum power consumption of 1.5 W.	Constraint	The Delfi-Group expects a power average of 2 Watts, 0.5 of which is used by the OAP. This means that, if all other payloads are shut off, a maximum of 1.5 W can be used. This number must however be lower as other systems must operate as well simultaneously.	Hardware design

3.4. Subsystem breakdown structure

As the system and stakeholder requirements are set, the design of the radiation payload can be discussed. Within subsection 2.3.3 of the literature study it became clear the Delfi-Twin has several tracking and detection payloads integrated. All payloads together give the system breakdown structure of the Delfi-Twin seen in Figure 3.2. As the Delfi-Twin is still in development, the subsystem table is most likely not fully representative of the final version.

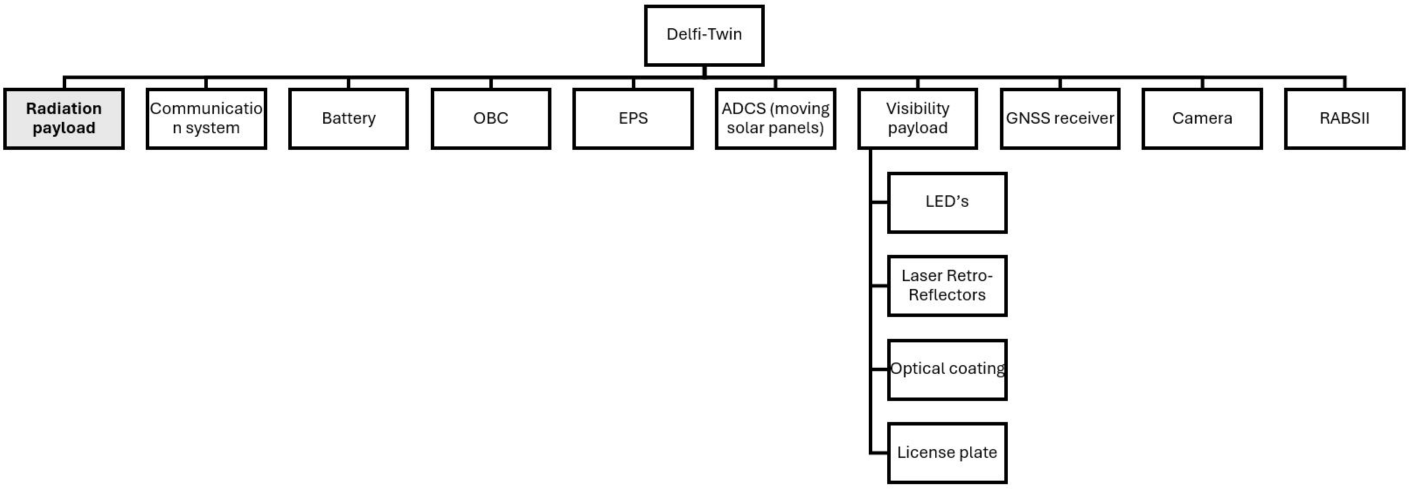


Figure 3.2: Delfi-Twin Breakdown structure

As introduced in subsection 2.3.3, the Delfi-Twin contains: A communication system, an On-board computer, an electrical power system, and an ADCS system. The Delfi-Twin also includes payloads for tracking the satellite: a GNSS receiver, a radio amateur beacon (RABSII) and the visibility payloads like LEDS. A camera is also installed to make Earth observations when in orbit.

The radiation payload is the last known payload which will be integrated into the Delfi-Twin. In Figure 3.3 a subsystem breakdown structure of the radiation subsystem can be seen that encompasses all the basic tasks that must be performed. These tasks are based of the literature study findings related to the Lunar Zebro radiation integration research (section 2.5) and requirements made by stakeholders (subsection 3.3.1).

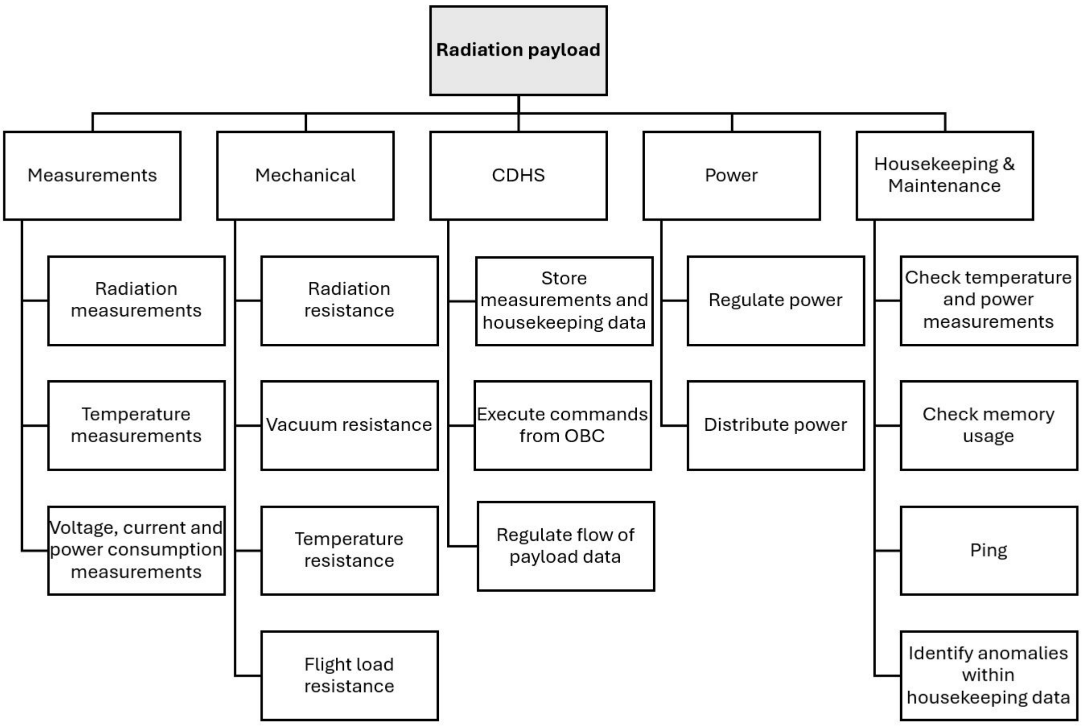


Figure 3.3: Radiation integration Breakdown Structure

Measurements
The most critical objective of the radiation payload is to make radiation measurements as seen on the far left. This will be provided by the FGDOS payload stated within subsection 2.3.4. This will however not be the only measurements made by this subsystem. As stated within the same section and in requirements DE-5 and DE-6, a temperature sensor and a V/I/P (voltage, current and power) sensor will be installed within the payload. These additional sensors are required as check-ups to detect overheating, overloading, or other types of anomalies.

Mechanical
The radiation payload must be able to withstand the environment discussed in subsection 2.2.2. Due to strict payload size requirements (see requirements DE-1 and DE-2), it becomes difficult to add shielding or other types of protection around the payload. The design of the outer layer of the satellite is out of scope of this project, meaning all resistance of the environment must come from the IC's themselves. The IC's chosen for the radiation payload must confine to the radiation and temperature requirements. They also must be operable in vacuum and must resist the flight loads. The temperature resistance are often mentioned in the data sheets of the IC's, making it easy to check for compliance to the requirements (requirement SA-1). The radiation and vacuum resistance are often only stated for specialized components which are often expensive and not COTS. Flight heritage can therefore be used for COTS components to check these two requirements. Little can be done for the flight loads as the payload size requirements are strict, meaning it is left to the structural design of the satellite to comply to these requirements. These mechanical requirements will be used for the trade-off of IC's in chapter 4.

CDHS
The CDHS (Command Data Handling System) encompasses all data transfer activity and storage within the radiation payload and towards other subsystems like the OBC. Radiation, temperature and power measurements will be send to either the on-board memory or OBC. Housekeeping data and requests from the OBC must also be collected and stored. The CDHS activities are all performed by the radiation payload MCU, see subsection 2.3.4 for more information regarding the MCU. The firmware written for the MCU will for one half exist out of CDHS commands. The other half is used for the housekeeping and maintenance of the payload.

Power
The power section regulates all power requirements of systems within the radiation subsystem. IC's within the payload can have different voltage requirements, requiring Low Dropout Regulators (LDO's) to convert voltages into higher or lower values [43]. IC's with different voltage levels that require to communicate with each other also have to use a voltage level translator [44]. Power is also regulated with anomaly detection and housekeeping. This can be done via V/I/P sensors or voltage supervisors [45]. These components and the distribution of the power itself encompass the power section of the subsystem. These will be discussed within the concept design architecture of the payload at section 3.6.

Housekeeping and Maintenance
Lastly, the housekeeping and maintenance encompasses all data check-ups, watchdog kicks, configurations, anomaly detection and pings. Whenever an anomaly occurs within the system, for example a sudden increase in temperature or voltage, the satellite must be able to detect and take affirmative action like powering-off the subsystem. The autonomy of the subsystem is based on the housekeeping and maintenance. The firmware design encompasses the housekeeping and maintenance design of the radiation payload.

To conclude, the breakdown structure encompasses all basic functionalities of the radiation subsystem which will be used for its initial concept design. The measurements are taken by the measurement sensors, the CDHS collects all data and sends or stores it, the housekeeping checks all data and makes the system more autonomous, the power regulates all power usage of the whole subsystem and the mechanical part looks into radiation, temperature and load stability.

3.5. Functional flow block diagram

The basic functionality of the radiation payload is visualized via a functional flow block diagram seen in Figure 3.4. This shows the actions required to take to go from measuring radiation via the sensor towards sending the radiation data towards the OBC.

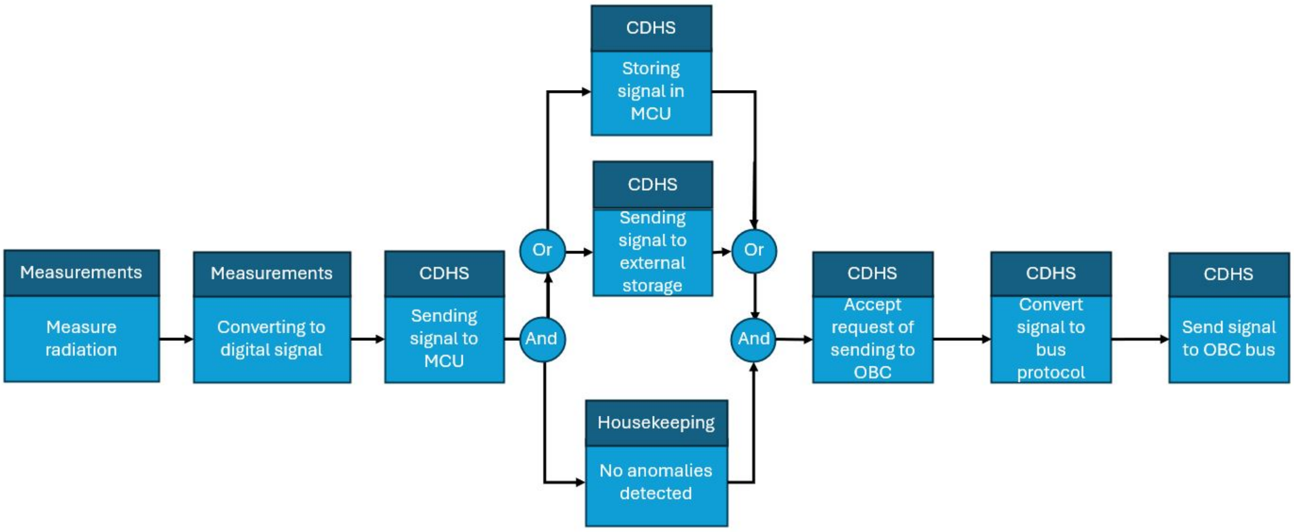


Figure 3.4: Flow diagram of the radiation payload

The radiation sensor will measure radiation and convert it to a digital format which can be transferred towards the MCU. This encompasses the measurement section of the breakdown structure seen in Figure 3.3. Once sent to the MCU it requires to be inspected for detectable anomalies which may consider the data unusable or state a warning regarding the condition of the hardware. This is provided by the housekeeping and maintenance firmware. Once anomalies are detected, immediate action requires to be taken by the MCU according to the housekeeping protocol programmed. If measurements are considered nominal, one can either send the data towards the onboard MCU memory or the external memory. The external memory should be chosen if no data requests are obtained from the OBC as the external memory is larger and can potentially have higher radiation resistance than the MCU memory.

If data requests are noticed, one should keep the data near the MCU hardware and send it towards the OBC. The handling of the data from the sensor towards the OBC is all performed by the MCU and therefore the CDHS. The MCU requires to send the measurements such that it corresponds to the OBC bus protocol to which it can read and interpret the values. The bus protocol has yet to be idealized by the Delfi-group, meaning the bus protocol will be kept to this projects own interpretation during development.

3.6. Hardware concept design architecture

Based on the requirements (section 3.3), breakdown structure (Figure 3.3) and functional flow block diagram (Figure 3.4), a first sketch of the hardware architecture can be made of the radiation payload. This consists out of the most essential hardware components without having the specific components chosen yet. Some of the components have already been chosen by the Delfi-Group, see subsection 2.3.4. For the remaining components, a trade-off is compiled in chapter 4. The concept hardware architect can be seen in Figure 3.5. The design is based of reference CubeSat/PocketQube missions [46] and the architecture made for the Lunar Zebro, Figure 2.15.

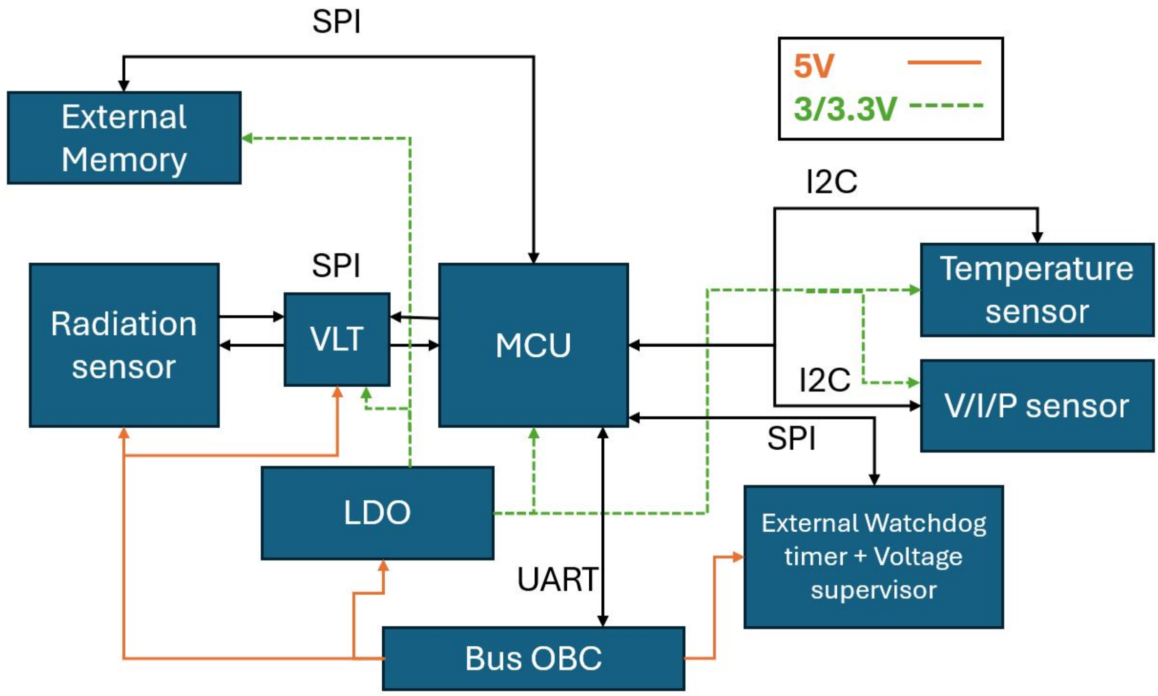


Figure 3.5: Concept hardware architecture radiation payload

The MCU is the main component of the CDHS and was chosen to be the STM32L476RG due to requirement DE-4. The MCU operates on 3.3V, but the power provided by the bus is 5V according to requirement IN-4. This leads to the need of an LDO (Low dropout regulator) which is able to convert the 5V supply to 3.3V, ensuring all components receive their power requirements.

Data communication for measurements is also performed by the MCU. Temperature, V/I/P and radiation data is read via the sensors discussed in section 2.3. These temperature sensor (TMP 100) and V/I/P sensor (INA 226) both operate on 3.3V and communicate via I2C. The MCU also operates on 3.3V and is able to read I2C, making a direct link between the MCU and sensors possible. The temperature and V/I/P sensors are both required to collect housekeeping data for the radiation payload.

The radiation sensor (FGD-03F) communicates via SPI and requires 5V. The MCU can read SPI, but due to the different voltage levels will require a Voltage Level Translator (VLT) in order for the MCU to "understand" the radiation sensor and vice versa. The VLT needs to be supplied with both 5V and 3.3V in order to make the translation.

The external watchdog + voltage supervisor are additions based of the Lunar Zebro mission and the previous Delfi-PQ mission design. The use of an external watchdog and voltage supervisor makes the system less dependent on the MCU. If the MCU experiences anomalies, the internal watchdog timer of the MCU may also be affected. This is prevented with both an external watchdog and voltage supervisor. The separation of the watchdog timer and voltage supervisor is due to requirement DE-8. The previous satellite, the Delfi-PQ, experienced anomalies during its mission when the watchdog timer and voltage supervisor were integrated in one IC. As of this, the two are designed to be separate IC's within the radiation payload.

An external memory is used within the architecture despite the MCU containing 1 Mbyte of Flash memory and 128 Kbytes of SRAM. SRAM and to a lesser extend flash memory are more susceptible to radiation anomalies than for example FRAM [47]. For redundancy and radiation protection reasons it is therefore suggested to implement an external memory storage which utilizes FRAM. During a radiation payload shut-off it is helpful to have reliable memory to store data until it can be sent to the OBC main memory.

The last component, the Bus OBC, is the connection between the radiation payload and the OBC of the satellite. The power supply of the radiation payload is given via the bus from the satellite EPS and data requests are send via UART to the MCU. Data going towards the OBC could be sensor measurements and housekeeping data. The OBC can sent housekeeping, payload configuration or measurement data requests. The bus used is the FSI-105-03-G-D-AD based on requirement DE-7. In addition to an OBC bus, a transceiver is a most likely required component as well. A transceiver is able to alter signals such that they are less susceptible to anomalies caused by long distance signal transfers. As the bus requires to transfer data between the payload and the OBC, it seems necessary for the integrity of the signals transfers [48].

The concept hardware architecture is the last step in the concept hardware design before the detailed design phase is started. The final design of the radiation payload will adhere to this architecture. The last part of the concept design consists of designing the concept firmware design.

3.7. Firmware breakdown structure

The concept firmware design is structured similarly to the hardware concept design. A breakdown structure and a flow diagram are made to convey the basic functionalities of the firmware. The firmware is known to be written via the MCU's IDE, the STM32CUBEMX. This firmware must be written in C/C++ as this is used within the IDE.

The firmware design is based on the system requirements in Table 3.3, the functionalities discussed in the payload breakdown structure, section 3.4, and the firmware written for the Lunar Zebro which uses the same radiation sensor [4]. The two most fundamental assignments for the firmware are:

1. Measurements and CDHS: Processing the measured data from the installed sensors. This can be the radiation measurements, temperature, or from the V/I/P. The data requires to be either stored or send towards the OBC for downlinking.
2. Housekeeping and Maintenance: Assuring the safety of the payload by checking for anomalies, frequent status updates, and taking appropriate actions once anomalies have been noticed.

As the firmware itself can be complicated in the amount of tasks it requires to perform, Figure 3.6 shows an initial breakdown of what it should perform. During the detailed design in chapter 4 these sections will be further discussed.

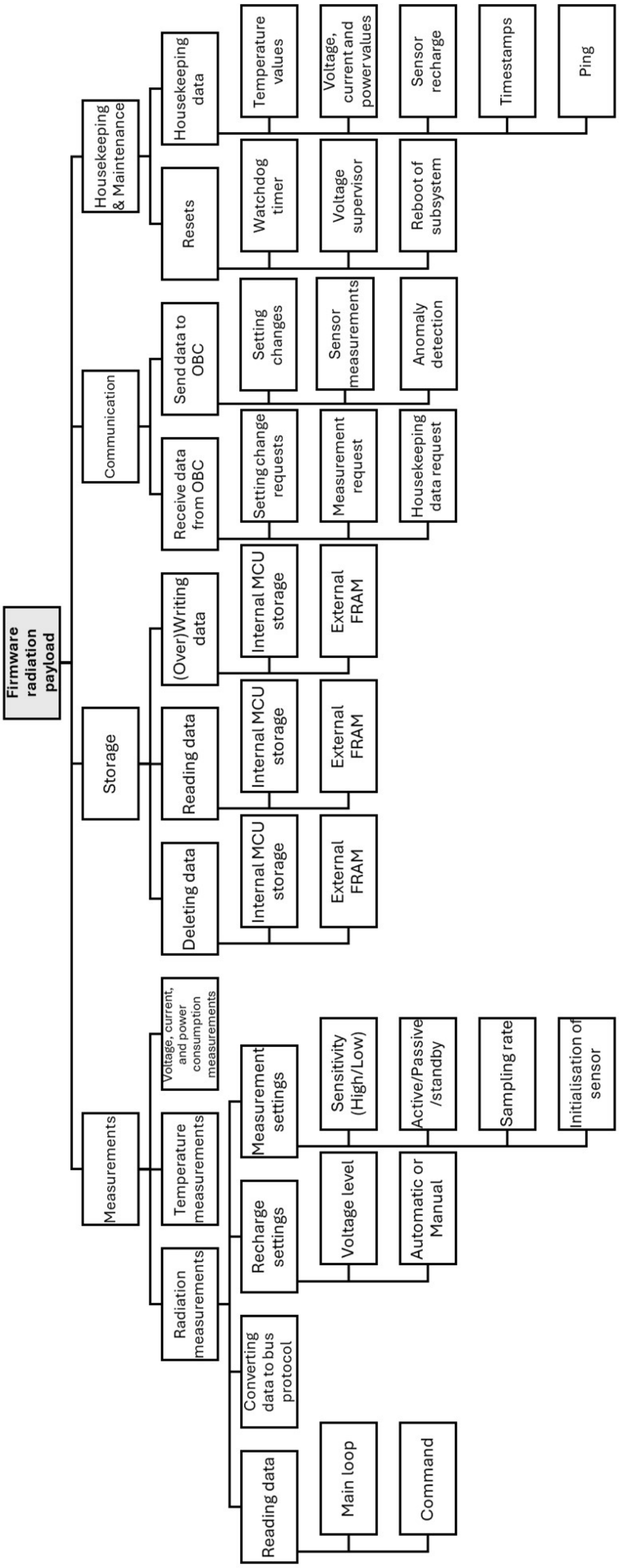


Figure 3.6: Firmware breakdown structure radiation payload

Measurements

Based on the literature study section regarding the radiation sensor, subsection 2.3.4, the basic principles of the measurement firmware can be found. The radiation data obtained by the sensor can be read via the MCU through SPI as seen in Figure 2.14. The radiation measurements are the main objective of the radiation subsystem and will therefore be included into the main loop of the firmware. This means every loop a measurement will be obtained from the sensor and send to the OBC or storage memory. Measurements may also be specifically commanded by the OBC if required. The sensor data obtained by the MCU requires to be send towards the OBC in the requested bus protocol.

The recharge system of the radiation sensor discussed in subsection 2.3.4 has several settings which must be configurable. The voltage level of the recharge can range from 14.5 V until 18 V, see subsection 2.3.4. The most optimal voltage level must be found via testing. The recharging itself can be configured to be done either automatically or manually. The automatic recharging mode is desired as otherwise commands require to be sent from the OBC to recharge the system in manual mode. The manual mode is however useful for debugging or testing.

The radiation sensor includes several other configurations which must be able to be switched via the firmware. All of the configurations mentioned in the breakdown structure have been previously explained in the mode section of subsection 2.3.4. The last type of setting is the initial configuration of the sensor which is made at the start of every boot-up of the system. The initial configuration will be configured in chapter 4. This configures all the settings mentioned into what is most beneficial for the subsystem at the start, after which they can be changed throughout the mission.

The temperature and V/I/P sensors are more simplistic than the radiation sensor as they contain less settings and are more used for housekeeping. Both sensor measurements will however be send via either the main loop or commands and also require to be send via the requested bus protocol of the OBC.

Storage

The data obtained from sensors, the OBC or MCU itself must be stored. This is performed by the firmware by deleting, reading or overwriting/relocating data to either the MCU memory, the external FRAM or the OBC main memory. The firmware must be designed such that it knows where to store data based on settings or commands.

Communication

The communication between the OBC and radiation payload is performed via the firmware of both systems. Both systems require a protocol through which they are both able to read what the other system is requesting or sending. The data send by the OBC must be interpretated at the MCU via the firmware. These are commands to either send measurements, send housekeeping data or change settings of the subsystem. Similarly, data send towards the OBC must be interpretated by the OBC as well. This can range from measurements from the sensors, housekeeping data and anomaly warnings.

Housekeeping and Maintenance

The firmware checks via the housekeeping data whether anomalies potentially occur in the system. This can be done by setting boundaries to measurements made by the temperature and V/I/P sensor and sending warnings whenever these are crossed. Adding timestamps to measurements can help in identifying where anomalies potentially occur by comparing it to the position of the satellite. Pings are used to check whether the IC's installed still operate correctly by checking if it responds correctly to a command.

The firmware must take action whenever an anomaly is detected which is identified to be dangerous to the system. Reboots of certain IC's or the whole subsystem can resolve many anomaly problems already as discussed in subsection 2.2.2 and requirements SA-6. The watchdog timer and voltage supervisor also help in the prevention of anomalies by resetting the MCU.

3.8. Firmware flow diagram

The firmware flow diagram shows the main tasks of the radiation payload sensors within the satellite, see Figure 3.7. Most housekeeping tasks seen in Figure 3.3 are not included in the flowchart as these are seen as the main task activities.

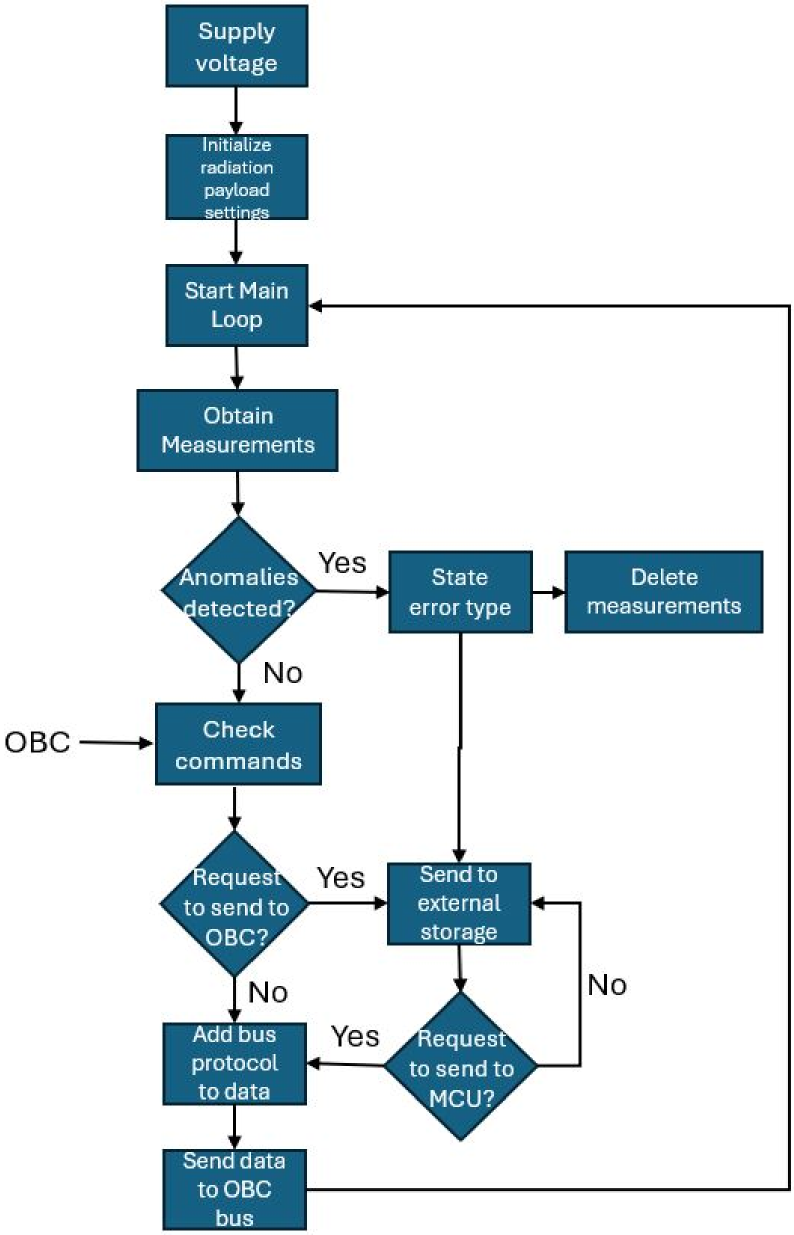


Figure 3.7: Firmware flow chart radiation payload

The flowchart contains the main tasks the radiation subsystem will perform which are based of the breakdown structure in Figure 3.6. After the initialization of the subsystem IC's settings, the main loop of the subsystem starts. Within this loop measurements are performed by the radiation, temperature and V/I/P sensor. These are checked for anomalies to which affirmative action is taken. Data requests commands are checked from the OBC, to which either the data is send to the OBC or stored until further notice. This flowchart only focuses on data commands, but setting changes are also a possible request.

With the breakdown structure and flowchart of the radiation subsystem firmware completed, the concept design of the firmware is finished. The hardware and firmware concept designs show a general concept of the radiation subsystem and how this can be operated. In chapter 4 the detailed designs of both the hardware and firmware are realized in order to manufacture and test the radiation subsystem.

3.9. Risk analysis

The risk analysis shows the most crucial identified risks which can occur during this project its development. By identifying the risks and ranking their severity, one can take into account these problems before full development has started. See Table 3.4 for the risk list, including mitigation strategies and Figure 3.8 for the risk severity matrix. The risks seen below were identified via the literature study in chapter 2 and with consultancy of the Delfi-group.

Table 3.4: Risk Assessment Table radiation payload

Category	Risk Nr	Risk	Criticality	Mitigation
Management	M.1	The project cannot be finished before the stated deadline	High	The thesis student will make a preliminary planning and will update this one depending on the progress of the project. In addition, regular meetings (every 2 weeks roughly) will be held in order to discuss project goals and what can be realistically finished on time.
	M.2	The project findings and the project requirements are not alike	High	Clearly discussed requirements and meetings during the project will lower the chance of creating alternative results.
	M.3	Project goals are postponed	High	The schedule and regular meetings should put enough pressure to reach goals on time if possible.
	M.4	Testing facility not available on time	High	The facilities necessary should be scheduled beforehand.
	M.5	Electrical components not available on time	High	Other COTS components should be considered if the ones required are not available.
Technical	T.1	The radiation sensor measurements will be affected by Total Ionizing Dose (TID) effects	High	Tests have been applied before this project onto the radiation payload related to TID effects. It was concluded that the radiation measurements changed with the TID and that these could be compensated via data post-processing.
	T.2	The radiation sensor will be affected by non-destructive SEE's	High	Most affects related to non-destructive SEE's were found to be solved by means of power-cycling the system.
	T.3	The radiation sensor will be affected by destructive SEE's	Extreme	Effects related to destructive SEE's need to be mitigated, but when occurring should be resolved by means of an immediate shut-off of the system.
	T.4	The radiation payload IC's will be affected by Total Ionizing Dose (TID) effects	High	As most COTS are not verified for radiation resistance, the best option is to look for IC's which have been used before in space to know how they react to radiation anomalies.
	T.5	The radiation payload IC's will be affected by non-destructive SEE's	High	Same answer as T.4

Continued on next page

Category	Risk Nr	Risk	Criticality	Mitigation
	T.6	The radiation payload IC's will be affected by destructive SEE's	Extreme	Same answer as T.4, but the results are expected to be severe. The IC's must be shut-off if such anomalies occur.
	T.7	The radiation payload measurements will be affected by temperature anomalies	High	This has been investigated before by means of testing, resulting that the specified temperature range of the payload can be reached without anomalies. The changes in measurements do have to be compensated within the measurement post-processing which is out of this scope.
	T.8	The integration hardware is affected by temperature anomalies	High	The hardware should be chosen such that it can handle the expected temperature range. If this cannot be complied to, other hardware shielding should be used.
	T.9	An easily susceptible hardware component fails during the mission, causing the radiation payload to malfunction	High	If space and costs allow, redundancies should be incorporated for components which play a crucial role within the system and have a relatively high chance of malfunctioning.
	T.10	A malfunctioning component causes harm to surrounding components	High	While not every situation can be mitigated, a reboot or safe mode should shut off all components (or only the least necessary ones) in order to potentially fix the malfunctioning component, or preventing it from doing more harm.
	T.11	Electrical discharge causes radiation payload charge to change	Moderate	Proper grounding should be incorporated in order to prevent overcharging.
	T.12	The internal memory of the radiation payload integration is overloaded	Moderate	A strategy regarding the communication and storage of data will be made beforehand to mitigate the chances of overloading.
	T.13	Mechanical damage to the satellite causes damage to the radiation payload	Moderate	The integrated radiation payload will be placed inside of the satellite bus, confining the most amount of structural protection it can obtain.
	T.14	Faulty commands are given or received from the OBC	High	The command history of the satellite will require to be downlinked to Earth for inspection to see whether anomalies have occurred.
Cost	C.1	The project itself goes over its estimated budget	Moderate	The project mainly consists out of COTS components, meaning most should not have a detrimental effect on the budget of the project. Only time can play a factor, which can only be mitigated by means of proper planning as discussed in the management risk category.
Safety	S.1	The radiation tests performed can be hazardous for the hardware and surrounding material or people	Moderate	The radiation tests will be performed within a dedicated area which must comply to all safety rules. A plan of approach will be made before the actual radiation testing is performed in order to prevent potential damage.
	S.2	The hardware tests may result in malfunctioning which could be hazardous for the surrounding material and people	Moderate	Potential harmful electronic tests will be performed within the clean room where a controlled area is provided. A plan of approach is made beforehand to circumvent potential hazards.

		Consequence						
		1. Negligible	2. Minor	3. Moderate	4. Major	5. Catastrophic		
Likelihood	5. Almost certain						Color	Meaning
	4. Likely		M.3, T.2, T.4, T.5, T.14	T.1, T.9	T.3, T.6			Extreme
	3. Possible		T.12, T.13	M.1, T.7, T.8	M.2, T.10, M.5			High
	2. Unlikely		C.1, S1, S.2, T.11		M.4			Moderate
	1. Rare							Low

Figure 3.8: Risk matrix radiation payload

Based on the risk severity matrix, the risk of experiencing destructible SEE's for both the radiation sensor and surrounding IC's is considered the highest. As destructible SEE's have the capability to destroy the payload hardware, their consequences are considered major. As the presence of larger amounts of radiation is unavoidable above the Earth's atmosphere, it also becomes likely to occur if no mitigation strategies are followed. The hardware chosen must be checked for its radiation resistance and/or flight heritage. Hardware redundancies and housekeeping firmware are also strategies which require to be used. The radiation sensor has already been tested on radiation anomalies which could be seen in the literature study subsection 2.3.4. The affects seen need to be compensated for by means of calibrations and reboots if deemed necessary.

The lowest risks are identified to be the budget of the project and the hazards which could occur during electrical and radiation tests. As the hardware components used are COTS (except for the radiation sensor itself) and are expected to be relatively cheap, it is not expected that this project will exceed this limit. The highest costs are in the radiation sensor as this is the most expensive IC which, if broken, can increase costs relatively high. The radiation sensor will however be bought in bulks of 10, meaning there is room for mistakes. The ordering of the radiation sensor also takes longer than other IC's as it is not COTS, meaning it can also affect the schedule of the project if more require to be ordered. The other lower risks are considered within the electrical and radiation tests. As both radiation and electrical tests will be performed in specialized rooms with supervision, no high risk of damage is expected to the test performer or the payload itself.

3.10. Conclusion: System engineering

The system engineering section of the project followed the sample hierarchy of requirements system engineering approach (Figure 3.1). At first the need and mission statements were identified, summarizing the project objectives. The essence came to designing, building and testing a radiation payload for the Delfi-Twin to make radiation measurements during the mission. To meet this goal, stakeholder and system requirements were identified which respectively state the needs of all stakeholders and the technical needs of the design.

From these requirements an early breakdown structure (Figure 3.3) of the radiation payload with all its needs to operate was created. This split the radiation payload up in multiple subsystems named measurements (radiation, temperature, power), mechanical (radiation and temperature resistance), CDHS (data storage and distribution), power (power distribution and regulation) and Housekeeping & maintenance (Data and component check-ups). The breakdown structure made the design principles of the radiation payload more organized, making it easier to identify the required hardware components and firmware design requirements. An early concept hardware architect (Figure 3.5) and firmware flowchart (Figure 3.7) was created based on the breakdown structure and requirements, creating the concept designs of the radiation payload.

Lastly, as more had been identified of the radiation payload design, a risk matrix was created to state the possible risks regarding the continuing development of the radiation payload project from a technical perspective and a project management perspective. This showed the biggest risks in measurements anomalies due to radiation affects as discussed in subsection 2.2.2. Mitigation suggestions were to choose components with flight heritage, perform radiation tests if possible, and to have firmware which is able to shut-off IC's when anomalies occur.

As the requirements, hardware and firmware concept designs, and risks have been identified, the system engineering section of the project is completed. In chapter 4 the physical test version of the radiation payload is designed based on the progress made in this chapter.

4 Detailed design

4.1. Introduction: Detailed design

The results from the concept phase in chapter 3 were breakdown structures, flow charts and architectures of both the firmware and hardware of the radiation payload. These were developed based on the requirements stated in subsection 3.3.1 and subsection 3.3.2. These concept designs are further developed in this chapter into a physical payload model which can be tested for its functionalities. The detailed design phase will delve into the hardware selection, radiation payload PCB development and the firmware development. The result of the detailed design development will be tested in the next phase, verification and validation, in chapter 5.

4.2. Component main criteria

The IC selection is based on the stakeholder and system requirements of chapter 3. Below Figure 3.3 it was stated the mechanical side of the radiation payload criteria must be mostly met by means of the IC selection. This means the most important criteria for every IC is its temperature resistance (requirement SA-1), radiation resistance (requirement SA-4), vacuum resistance (requirement SA-2) and flight load resistance (requirement SA-3). Flight load requirement is difficult to accomplish within this project as the shape and size of the radiation payload PCB cannot be changed. Temperature is a criterion which is stated within IC data sheets. Vacuum and radiation resistance are also difficult criteria to meet, but flight heritage of a component can already proof it works in space. Another, lesser important, criteria is cost. This has a lower value as no component is expected to be more expensive than the radiation sensor itself as they all will be COTS. The budget is therefore not expected to become a problem, but is still a criteria which will be compared when necessary.

Based on these criteria, the IC's which will be chosen are based on three options:

- IC's used in the Delfi-PQ
- IC's used in the Lunar Zebro
- IC's found based on research

An IC used in the Delfi-PQ means the IC has flight heritage, making it adhere to the mechanical criteria. This is a large advantage compared to other components, meaning they will always be used for comparison with similar IC's. IC's from the Lunar Zebro are also helpful, as the Lunar Zebro has undergone radiation tests, meaning radiation resistance can be claimed for such components. These are therefore also used for comparison. Lastly, IC's found by research are added if both the Delfi-PQ or Lunar Zebro IC do not adhere to other criteria of the IC. It is technically possible to have 10+ options for each IC based on research, but only a few are chosen to simplify the selection. The amount of IC's available are also an important criteria as new prototypes may want to be made in the future, relying on the availability of the components. If three or more options are possible for a certain IC, a trade-off table is used to better visualize the selection.

4.3. Component configuration

According to requirements DE-3, DE-4, DE-5, DE-6 and DE-7, several components for the radiation payload are chosen beforehand. These were already discussed at subsection 2.3.4, but are summarized:

Known components:

- MCU = STM32L476RG
- The V/I/P sensor = INA 226

- The temperature sensor = TMP100
- Radiation sensor = FGDOS-03F
- Bus connector = FSI-105-03-G-D-AD

The remaining components of Figure 3.5 require to be selected. The selection criteria are based on the stakeholder and system requirements list seen in Table 3.2 and Table 3.3. The unknown components are:

Unknown components:

- External FRAM
- External Watchdog timer
- External Voltage Supervisor
- Voltage regulator
- Translator
- Transceiver

In addition to these components, external oscillators will be introduced which have the potential to stabilize the clock signals even better than previous iterations of the radiation payload, for example the Lunar Zebro. The introduction of external oscillators comes from the recommendation made by the radiation payload development [4] seen in subsection 2.5.4. The MCU has an internal clock which can be used for all timing based operations in the radiation payload. An external clock will however be used in order to see if it is beneficial to the radiation payload. Similarly, the radiation sensor is able to obtain a clock signal from the MCU, but instead an external clock will be used to see what affect this has on the stabilization of the clock. This results in the addition of two extra components on the radiation payload.

- MCU external oscillator
- Radiation sensor external oscillator

The selection of components is based on the Mouser website collection [49]. The Delfi-group orders most of their components from Mouser, which is why only this distributor is used.

4.3.1. External FRAM: MB85RS1MTPNF

Use:
An external memory is required to store measurements made by the sensors or housekeeping data before they are sent to the main storage system near the OBC. The MCU memory is more susceptible to radiation, which makes the use of an external storage device that is less susceptible needed. As FRAM complies with these criteria, it is chosen as the external memory type [47].

Specifications of selected option (Table 4.1, Figure 4.1):

Table 4.1: Specification table of the MB85RS1MTPNF [50]

Name	MB85RS1MTPNF
Memory Type	Non-Volatile
Memory Size	1Mb
Organization	128K x 8
Interface	SPI
Voltage Supply	3.3V
Operating Temperature	-40 ∼85 C
Clock Frequency	40 MHz

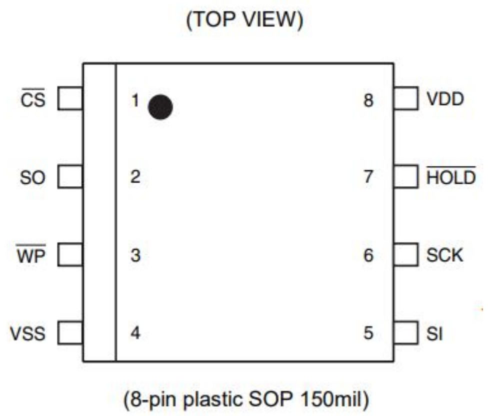


Figure 4.1: Schematic of MB85RS1MTPNF with pin configurations [50]

Choice description:
Memory size, costs, temperature range and heritage are seen as the main criteria to be taken into account. All need to fall within the ranges given by the system requirements list (see requirement topics design and safety). The following FRAM components were considered with their main reason of consideration:

- C15B108QN-40SXI [51]: Used by the Lunar Zebro
- MB85RS1MTPNF [50]: Used by the Delfi-PQ
- MB85RS4MTYPFGBCE1 [52]: Filtered in Mouser, has a slightly higher temperature range compared to others
- MB85RS2MTAPNF-G-BDERE1 [52]: Filtered in Mouser, is similar to option 2 except for having double the memory size

With the criteria mentioned earlier, a trade-off table was made to choose between the memory options. See Table 4.2.

Table 4.2: Trade-off Comparison of FRAM

		FRAM				**Rates**
Category	**Weight**	C15B108QN-405XI	MB85R-S1MTPNF	MB85RS4M-TYPFGBCE1	MB85RS2MT-APNF-G-BDERE1	
Memory	2	8 Mbit	1 Mbit	4 Mbit	2 Mbit	4
Cost	1	35.27 euro	5.78 euro	8.73 euro	6.16 euro	3
Temperature	2	85 C	85 C	125 C	85 C	2
Heritage	3	No	Yes	No	No	1
Score		21	**28**	23	23	

The costs is considered the least important criteria as the costs are low compared to other components like the radiation sensor. The memory size and temperature range are medium in weight as they must be conformed to the given requirements. Only the heritage is given a higher weight as knowing whether a component can work within space or not is of large importance to preventing unexpected errors from occurring during the mission.

According to requirement SA-1, the temperature range the IC's must confine to is between -35 and 35 degrees Celsius. This makes the use of a component which is higher than 85 C, which is a usual value used for FRAM, unnecessary. The amount of memory required according to members of the Delfi-group would be not more than 1 Mbit. The Lunar Zebro however estimated 8 Mbit to be necessary, making it necessary to conduct further memory calculations. Due to time constraints this could not be reviewed, but it is recommended to be performed for future research. The heritage of the second option, due to it being used in the Delfi-PQ, makes it the most interesting choice for this configuration. Further research regarding the measurement memory requirements will have to be performed in order to give a definitive answer regarding this payload.

4.3.2. External watchdog timer: MAX6371KA+T

Use:
An external watchdog timer is used in order to have confirmation whether the MCU is still nominally operating. This is performed by the MCU "petting" (or sending heartbeats) to the watchdog repeatedly. If the watchdog is not "pet", it assumes something has gone wrong with the MCU, making it reset the MCU. The MCU itself also includes a watchdog timer, but one is also necessary to check the MCU itself [53].

An important requirement for the watchdog timer (Requirement DE-8) is that it should not have an Incorporated voltage supervisor. According to the project leads of the Delfi-PQ, the integrated voltage supervisor inside of the external watchdog caused malfunctions. Instead, the voltage supervisor must be installed separately from the watchdog timer within this system.

Specifications of selected option (Table 4.3, Figure 4.2):

Table 4.3: Specification table of the MAX6371KA+T [54]

Name	**MAX6371KA+T**
Reset	Active Low
Nr. of Voltage Monitored	1
Output	Open Drain
Voltage Supply	5V
Operating Temperature	-40 ~125 C

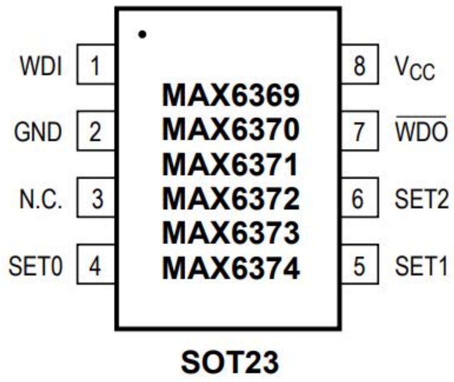


Figure 4.2: Schematic of MAX6371KA+T with pin configurations [54]

Choice description:
A trade-off had to be used again in order to determine which watchdog timer would be most suitable for the system. The following were considered:

- TPS3813I50DBVT [55]: Used in the Lunar Zebro
- MAX6371KA+T [54]: Suggestion made by Delfi-Twin project lead
- STWD100NYWY3F [56]: Filtered in Mouser, has similar specifications as previous options, but is from another brand

The first option has an integrated voltage supervisor, making fail requirement DE-8. The other two options are predominantly different in cost, power consumption and versatility in reset options. See Table 4.4 for the trade-off table.

Table 4.4: Trade-off Comparison of Watchdog ICs

		WATCHDOG			**Rates**
Category	**Weight**	TPS381350DBVT	MAX6371KA-T	STWD100NYWY3F	
Includes V supervisor	3	Yes	No	No	4
Heritage	3	Yes	No	No	3
High or Low reset	2	Low	Low	Low	2
Cost	1	2.31 euro	3.98 euro	1.15 euro	1
Power consumption	2	9 picoampere	1.3 picoampere	3 picoampere	
Score		28	**33**	31	

The cost is due to similar reasons as at the external memory seen as a lesser important criteria. There is also no need for multiple reset options, making this criteria also less of an importance. The power consumption is the only more notable criteria as the satellite systems require to consume as low amount of power as possible (see requirement SA-7). As for this the second options, the MAX6371KA+T, is seen as the most suiting option.

4.3.3. External voltage supervisor: TPS3838K33DBVR

Use:
The external voltage supervisor works different from the INA 226 as it resets the system when a voltage is detected which is over or under the allowed threshold. This can be integrated into the watchdog timer, but due to problems with the Delfi-PQ it is required to have them as separate systems (Requirements DE-8).

Specifications of selected option (Table 4.5, Figure 4.3):

Table 4.5: Specification table of the TPS3838K33DBVR [57]

Name	TPS3838K33DBVR
Supply Voltage	3.3V
Reset type	Open Drain
Temperature range	-40 ∼ 85 C
Threshold Voltage	2.93V

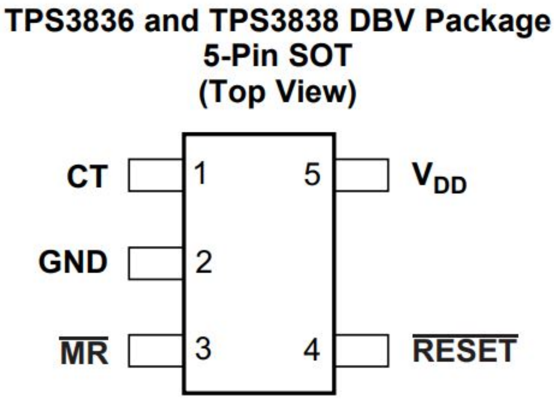


Figure 4.3: Schematic of TPS3838K33DBVR with pin configurations [57]

Choice description:
Radiation hardened voltage supervisors like the TL7700-SEP are available for purchase, but the prices are much higher compared to the regular versions. The TL7700-SEP costs roughly 75 euros per single piece compared to 3.57 euros for a regular version [58]. This makes using a radiation hardened voltage supervisor unattractive for this system. The TL7700 without the radiation hardening would fit within the design, but another option was taken, the TPS3838K33, as it complies to the voltage thresholds it needs to read (requirement IN-4) and has a relatively low power consumption compared to the TL7700. No trade-off had to be made for this selection as the Delfi-PQ and Lunar Zebro do not contain separate voltage supervisors which could have been used for comparison.

4.3.4. Voltage regulator: LTC3531

Use:
The radiation sensor uses 5V and the MCU 3.3V. The bus delivers 5V to the radiation payload, which means a voltage regulator is needed to transform 5V into 3.3V. The voltage each component uses can be seen in Figure 4.9.

Specifications of selected option (Table 4.6, Figure 4.4):

Table 4.6: Specification table of the LTC3531 [59]

Name	LTC3531
Topology	Buck-Boost
Output	Fixed
Output	Open Drain
Voltage Supply	5V
Voltage Output	3.3V
Operating Temperature	-40 ∼ 125 C

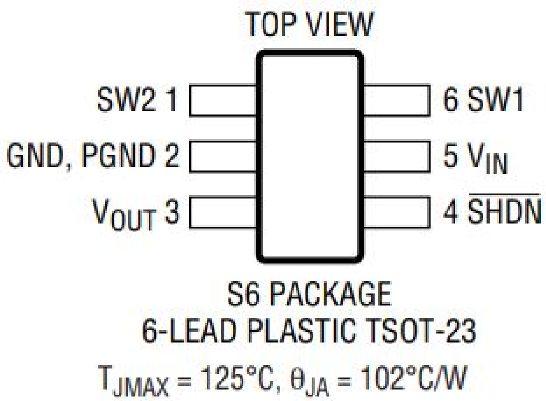


Figure 4.4: Schematic of LTC3531 with pin configurations [59]

Choice description:
The amount of options for the voltage regulator are vast, while each requires to perform the same action of reducing the 5V supply to 3.3V. As the fundamentals of the component are straight forward, the same voltage regulator (LTC3531) was chosen as used for the Delfi-PQ. This comes with its flight heritage which guarantees it is operable in the space environment.

4.3.5. Translator: MAX3001EEUP+

Use:
As some components use 5V and others 3.3V, communication between these components requires a translator.

Specifications of selected option (Table 4.7, Table 4.5):

Table 4.7: Specification table of the MAX3001EEUP+ [60]

Name	MAX3001EEUP+
Nr. Circuits	1
Channels per Circuit	8
Data Speed	4Mbps
VCCA	1.2 ∼ 5.5V
VCCB	1.65 ∼ 5.5V
Operating Temperature	-40 ∼ 85 C

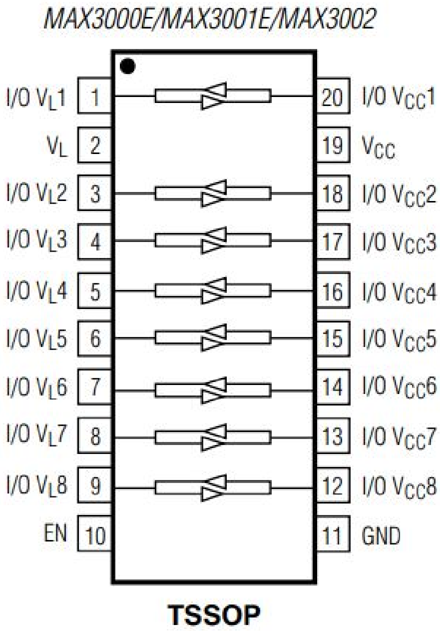


Figure 4.5: Schematic of MAX3001EEUP+ with pin configurations [60]

Choice description:
Similar to the voltage regulator, there are too many options to choose from while the functionality all stays the same. As for this it was chosen to stick to the translator which was chosen for the Lunar Zebro. No translator was used during the Delfi-PQ, making it not possible to use a system with a known flight heritage.

4.3.6. Transceiver (RS-485): LTC2850

Use:
The communication between the radiation payload and the OBC is performed via RS-485 transceiver. The transceiver changes the digital data to a robust signal which can more easily be transferred over long distances, in this case the OBC [48].

Specifications of selected option (Table 4.8, Table 4.6):

Table 4.8: Specification table of the LTC2850 [61]

Name	LTC2850
Protocol	RS422, RS485
Data Rate	20 Mbps
Voltage Supply	3.3V
Operating Temperature	-40 $\sim$ 85 C

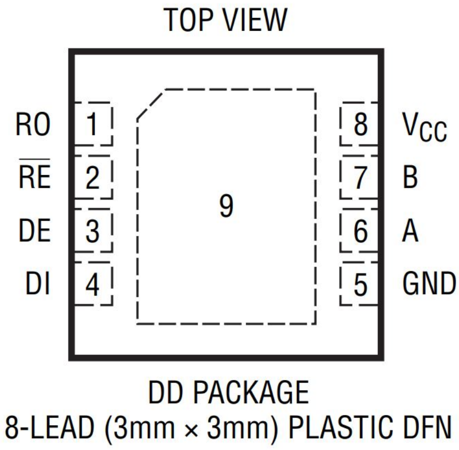


Figure 4.6: Schematic of LTC2850 with pin configurations [61]

Choice description:
The LTC2850 was chosen as the transceiver as it has been used in the Delfi-PQ before and contains flight heritage. Other options were disregarded as the LTC2850 is relatively cheap and stays within the temperature criteria, meaning no other options were required to be researched.

4.3.7. External oscillators: [8 MHz] - ASDMB and [32.768 kHz] - SIT1533-AI

Use:
The external oscillators are used to give a more stable clock signal than otherwise the MCU would give to both itself and the radiation sensor.

Specifications of selected option (Table 4.9, Table 4.7, Table 4.10, Table 4.8):

Table 4.9: Specification table of the ASDMB [62]

Name	ASDMB
Frequency	8 MHz
Voltage Supply	3.3V
Operating Temperature	-40 $\sim$ 85 C

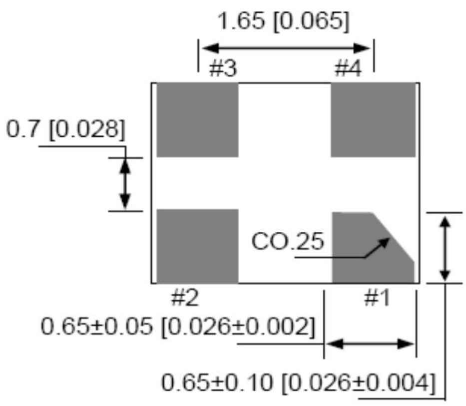


Figure 4.7: Schematic of ASDMB with pin configurations [62]

Table 4.10: Specification table of the SiT1533 [63]

Name	SiT1533
Frequency	32.768 kHz
Voltage Supply	3.3V
Operating Temperature	-40 ~ 85 C

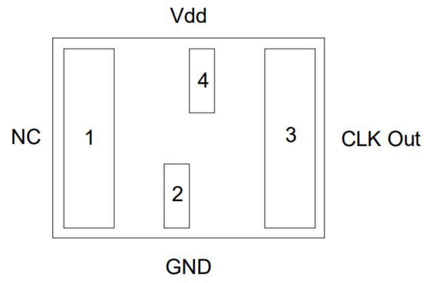


Figure 4.8: Schematic of SiT1533 with pin configurations [63]

Choice description:
The oscillators were chosen based of research on Mouser. There were no oscillator modules which could have been used as examples from the Lunar Zebro or Delfi-PQ as these work with crystals. The temperature range, voltage supply, frequency and amount available were the most important criteria. The radiation sensor requires 32.768 kHz, and based on the amount of oscillators available the SiT1533 was seen as the most suitable option. The MCU is able to use both a high speed external (HSE) oscillator and a low speed external oscillator (LSE). For simplicity reasoning only the HSE is installed. The criteria are the exact same as for the radiation sensor external oscillator, except that the STM32L476RG requires a 8MHz signal from the clock for HSE. Based on the Mouser results and the availability of the IC, the ASDMB was seen as the best option.

4.3.8. Final architecture schematic

Based on the chosen IC's and the concept architecture made in Figure 3.5, a finalized architecture can be made that can be seen in Figure 4.9.

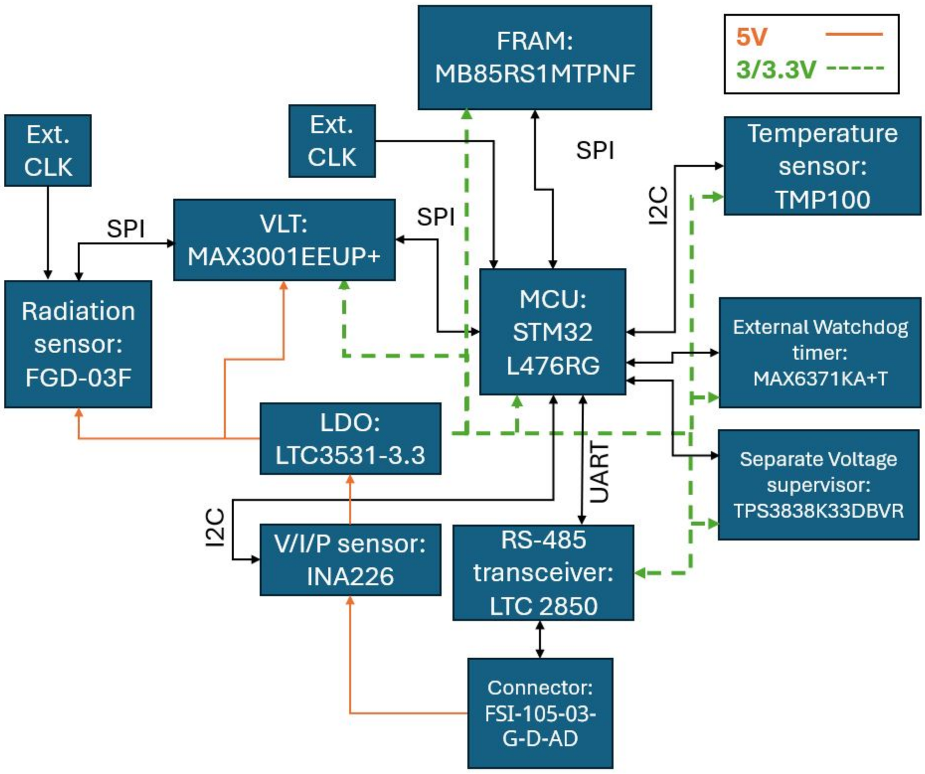


Figure 4.9: Finalized concept hardware architecture radiation payload

The final selection of main IC's of the radiation payload can be seen below.

- MCU: STM32L475L476RG [3]
- FRAM: MB85RS1MTPNF [50]
- Radiation Payload: FGD-03F [2]
- Temperature Sensor: TMP100 [36]
- Voltage/Current/Power sensor: INA226 [37]
- External Watchdog Timer (excluding voltage supervisor): MAX6371KA+T [54]
- Separate External Voltage Supervisor: TPS3838K33DBVR [57]
- Voltage Regulator: LTC3531-3.3 [59]
- RS-485 Transceiver: LTC-2850 [61]
- Translator: MAX3001EEUP+ [60]
- Bus Connector: FSI-105-03-G-D-AD [64]
- MCU External Oscillator: [8 MHz] - ASDMB [62]
- Radiation Sensor External Oscillator: [32.768 Hz] - SIT1533-AI [63]

4.3.9. Power budget

The power usage of the components must be checked in order to check whether they stay within the allowed limits of the power requirements (requirement SA-7) of max 1.5 Watts. For power budget calculation, the components maximum usage for their applicable configuration was chosen to see whether they can withstand this scenario. See Table 4.11 for the power budget table.

Table 4.11: IC Power Consumption calculations radiation payload

Component	Name	Amount	Voltage [V]	max Current [A]	max Power [W]
MCU	STM32L476RGT	1	3.3	0.0163	0.05379
T sensor	TMP100	1	3.3	0.0001	0.00033
V/I/P sensor	INA226	1	3.3	0.00042	0.001386
Rad sensor	FGD-03F	1	5	0.004	0.02
Translator	MAX3001EEUP+	1	5	0.00005	0.00025
FRAM	MB85RS1MTPNF	1	3.3	0.0095	0.03135
V Regulator	LTC3531	1	3.3	0.000016	0.0000528
Watchdog	MAX6371KA+T	1	3.3	0.000008	0.0000264
V supervisor	TPS3838K33DBVR	1	3.3	0.00000045	0.000001485
RS-485 transceiver	LTC2850	1	3.3	0.00025	0.000825
MCU Oscillator	ASDMB-8.000MHZ-LC-T	1	3.3	0.015	0.0495
Rad Oscillator	SIT1533-AI	1	3.3	0.0000014	0.00000462
				Total:	0.157395285

The result of the calculation is that the radiation payload is expected to consume 0.16 W of power, lower than the absolute maximum of 1.5 W. The 1.5 W is however within the scenario that every other payload is turned off, meaning a much lower power consumption is expected. The payload takes therefore around 10% of the allowed payload power, leaving room for other payloads to be power on as well. How much each payload consumes is as of now unknown.

The addition of redundant components has not been taken into account for these calculations as it is of now unknown. Components as the TMP-100 and INA-226 can however be expected to have multiple installed, but their power consumption is of no concern. In subsection 2.5.3, it was seen that TID can increase the power consumption of IC's. It is recommended to further test these affects to see how the payload power consumption potentially could increase over the mission lifetime.

4.4. Prototype PCB design

4.4.1. Build explanation prototype

The schematic seen in Figure 4.9 represents the final build of the radiation payload. A physical model of the radiation payload had to be created in order to test the functionality of the system. This model needed to consist out of a PCB with the build in footprints and connections of all chosen IC's from the final architecture.

The main component of the radiation payload, and most difficult to configure, is the radiation sensor. Being able to operate this sensor is the most important task in this project. Due to complexity and time constrain reasons, it has therefore been decided not all components from Figure 4.9 will be installed onto the PCB physical model. Instead, only the IC's necessary to operate the radiation sensor and send data to the OBC have been selected. This results in a prototype PCB architecture which can be seen in Figure 4.10. The removal of several IC's does not make them any less important for the completed radiation payload. In a follow-up project the prototype needs to be upgraded to the version seen in Figure 4.9.

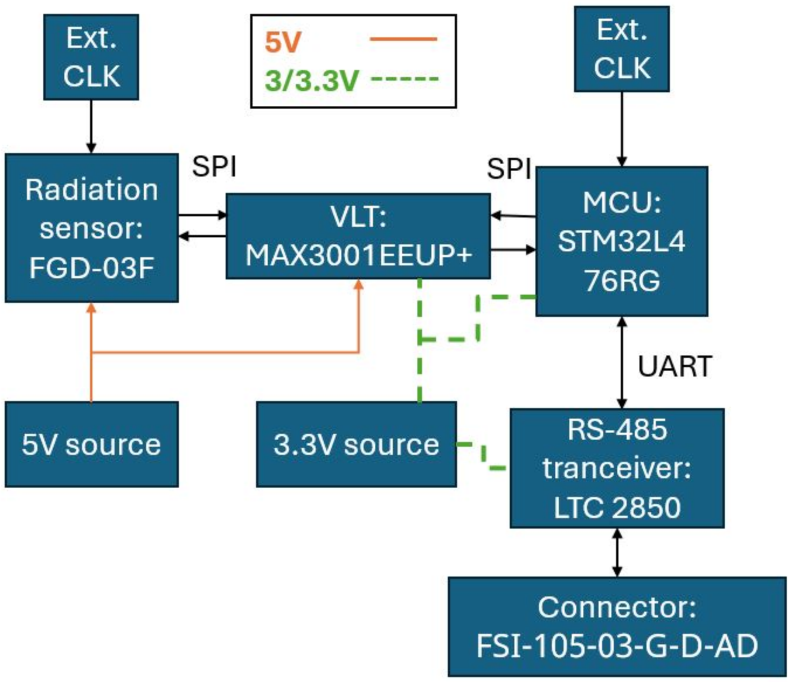


Figure 4.10: Prototype concept hardware architecture radiation payload for testing

This results in a prototype architecture and PCB consisting of:

1. The radiation sensor, FGD-03F
2. The MCU, STM32L476RG
3. The voltage translator, MAX3001EEUP+
4. The RS-485 transceiver. LTC2850
5. The bus connector FSI-105-03-G-D-AD
6. MCU External Oscillator: [8 MHz] - ASDMB
7. Radiation Sensor External Oscillator: [32.768 Hz] - SIT1533-AI

These components make it possible for the MCU to read and write to the radiation sensor for configurations and data handling. The translator makes sure the communication between the MCU and sensor is possible despite their differences in voltages. The transceiver will read and write data from the MCU to the OBC, making it possible to send commands and transferring data. This all is suffice for the radiation payload fundamental operations.

The components omitted of this prototype version are the following:

1. The temperature sensor, TMP100
2. The Voltage/Current/Power sensor, INA226
3. The external watchdog timer, MAX6371KA+T
4. The external Voltage supervisor, TPS3838K33DBVR
5. The Voltage regulator, LTC3531
6. The external FRAM, MB85RS1MTPNF

The TMP100, INA226, MAX6371, and TPS3838 are seen as extra components which are not required in order to make the radiation sensor operational. Their small size makes them relatively easy to integrate into the prototype PCB at a later stage and their lack of configurations makes them easier to implement into the MCU firmware. For these reasons they are seen as omitable for the prototype. These components are however fundamental for the housekeeping and maintenance of the full radiation payload, and must therefore not be forgotten in the final version.

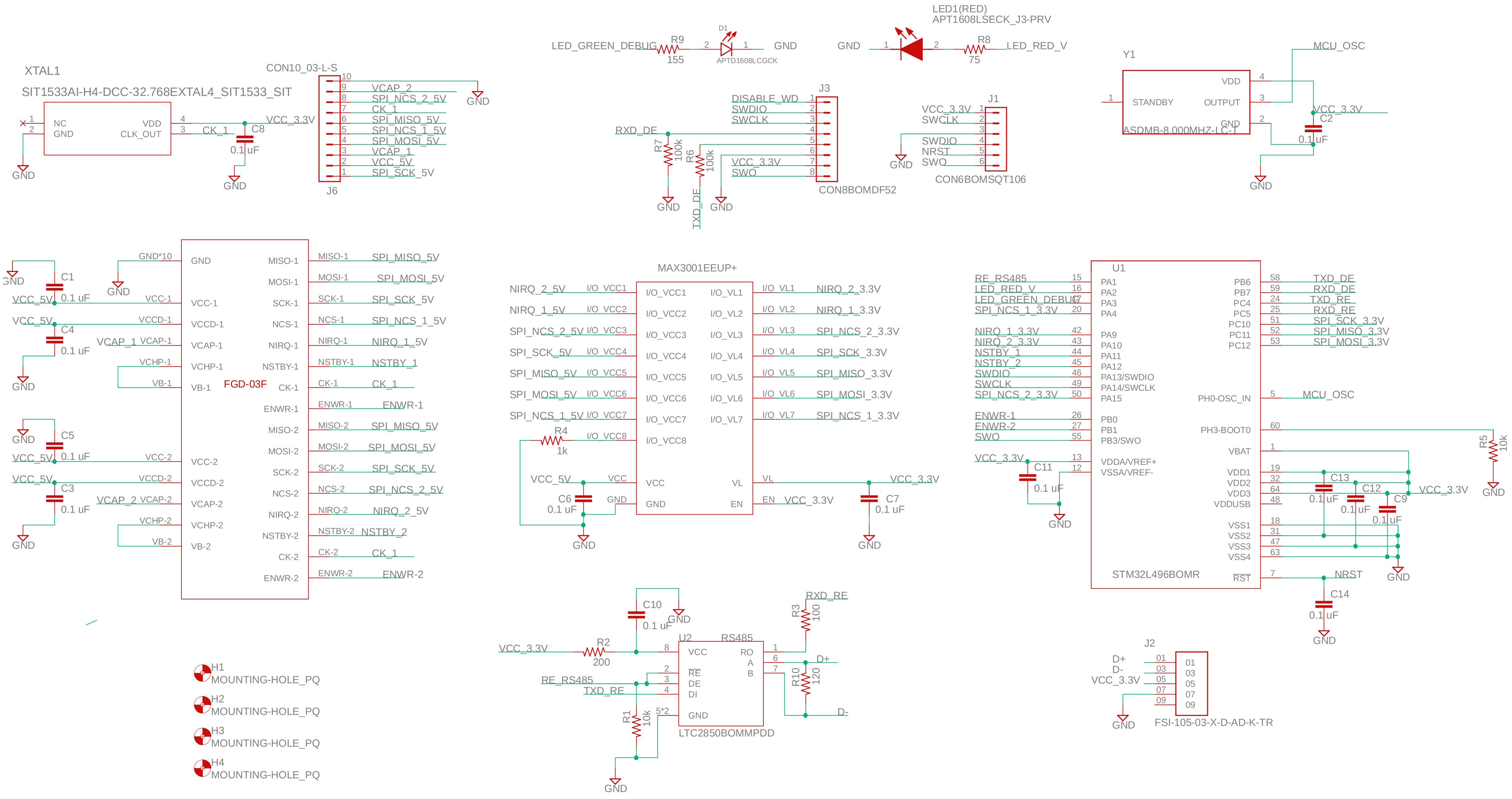
The voltage regulator is an integral piece of hardware to the system as the sensor works with 5V and the MCU and surrounding components with 3.3V. However, the regulator is easily replaced by providing separate connections for a 5V and 3.3V signal onto the PCB. This reduces the complexity of the PCB and reduces the chances of anomalies when testing the radiation sensor as there is no voltage regulator IC which can be affected. As of this, it is also omitted for the prototype version of the radiation payload.

Lastly, the external FRAM is omitted from the prototype radiation payload. The data obtained can be stored in the MCU or immediately sent via the connector to the OBC or testing computer, removing the need for external memory for basic testing.

In addition to the IC's seen in Figure 4.10, several debugging IC's are included onto the board in order to ease the debugging process. These consist of several additional connectors and LEDS. The connectors will directly supply the PCB with 5V and 3.3V as seen in Figure 4.10, in addition to allowing several pins of the radiation sensor to be directly connected to the connectors. This will make signal measurements from the radiation sensor more easy and can help in removing anomalies. Another task of the additional connectors is to upload firmware to the MCU. The LED's will be used as visual support for debugging firmware anomalies.

4.4.2. Prototype PCB schematic

In order to develop a prototype PCB, Figure 4.10 needs to be configured into a schematic showing all IC connections. These connections will be traced onto the PCB to provide the necessary communication structure and power supply to all components. The full schematic of the prototype PCB can be seen below. A description of the most important connections are made below in order to understand the design choices. The description of all pin connections can be found in Appendix C .


XTAL1
SIT1533AI-H4-DCC-32.768EXTAL4_SIT1533_SIT
CON10_03-L-S
J6
LED_GREEN_DEBUG
R9
155
D1
APTD1608LCGCK
LED1(RED)
APT1608LSECK_J3-PRV
R8
75
LED_RED_V
Y1
ASDMB-8.000MHZ-LC-T
J3
CON8BOMDF52
J1
CON6BOMSQT106
FGD-03F
MAX3001EEUP+
U1
STM32L496BOMR
U2
RS485
LTC2850BOMMPDD
J2
FSI-105-03-X-D-AD-K-TR
H1
MOUNTING-HOLE_PQ
H2
MOUNTING-HOLE_PQ
H3
MOUNTING-HOLE_PQ
H4
MOUNTING-HOLE_PQ

MCU - STM32L476RG

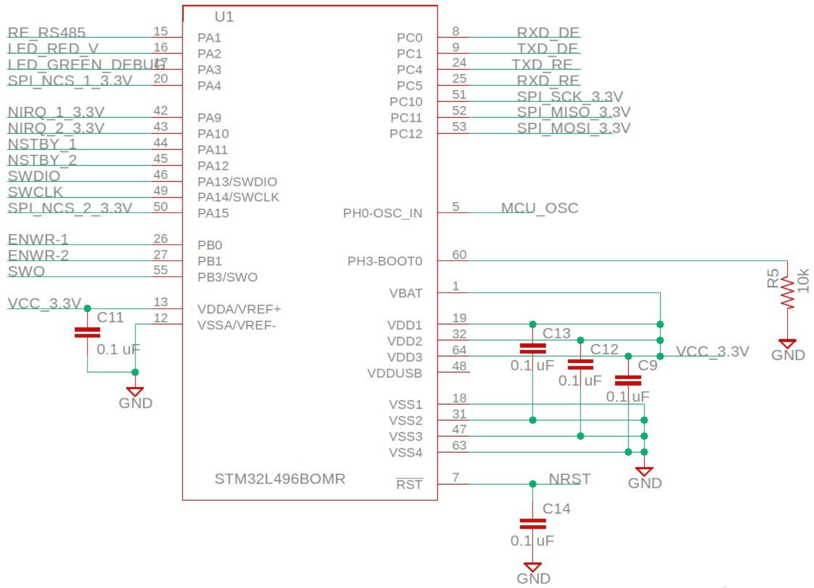


Figure 4.11: Schematic of prototype PCB MCU

Only the used pins can be seen in the schematic Figure 4.11, all other pins which are not used are neglected. Most pins on the MCU can be configured as GPIO pins, but some of them are dedicated for either communication or debugging. The position for the SPI and UART (TXD and RXD) pins are therefore specifically chosen. The same reason goes behind the SWD, SWDIO and SWCLK pins which are used for debugging and uploading firmware onto the MCU. Most of the remaining connections, like the LED, RS485, NSTBY and ENWR are arbitrary GPIO pins. All pins their function and connection can be read in Appendix C, Table C.1. For a general overview of the MCU pin abilities, see Appendix B.

RADIATION SENSOR - FGD-03F

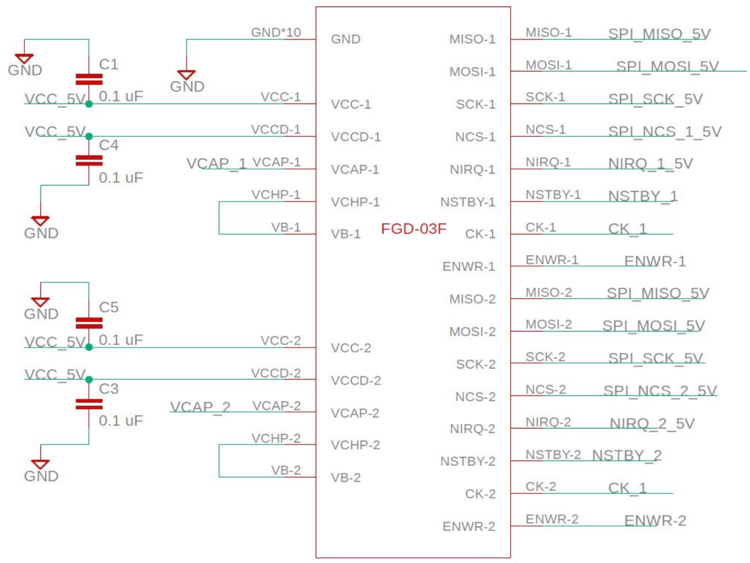


Figure 4.12: Schematic of prototype PCB radiation sensor

The radiation sensor has 30 pins confined in the schematic Figure 4.12. In the schematic, the left pins are confined to different kinds of voltage supplies and ground pins, while the right side consists of remaining inputs and outputs. The radiation chip consists of two identical sensors which will both be used in the prototype version. As for this, each pin name is seen twice in the schematic. The two sensors will work one after another and not simultaneously.

The pins used for SPI communication are MISO, MOSI, SCK and the slave select NCS. The clock signal needed for the radiation sensor is provided via CK. NIRQ, NSTBY and ENWR are GPIO signals controlled by the MCU. Please see Appendix C, Table C.2 for more details regarding the pin connections.

TRANSLATOR - MAX3001EEUP+

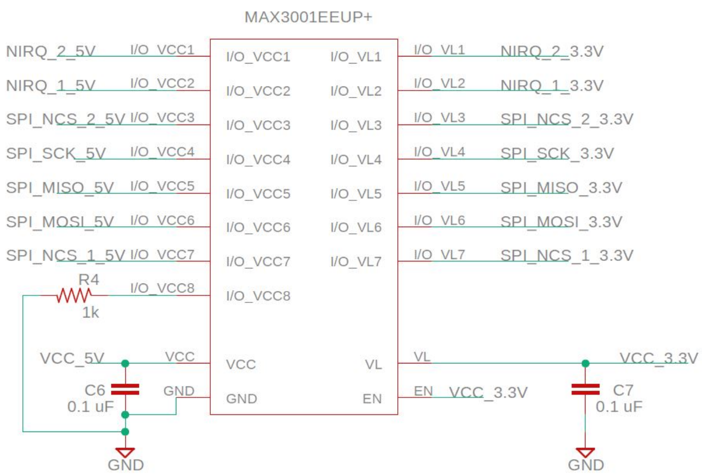


Figure 4.13: Schematic of prototype PCB translator

The translator translates the 5V signal from the radiation sensor into a 3.3V signal which can be read at the MCU, and vice versa. The translator therefore requires both voltages to be connected, see Figure 4.13. The translator used, the MAX3001EEUP+, consists of 20 pins, 16 of which are used to translate between the radiation sensor and the MCU. All pin connections can be read in Appendix C, Table C.4.

The pins which require translation are the SPI signals (both for sensor 1 and 2) and the interrupt GPIO signal NIRQ. The GPIO pins NSTBY and ENWR, both one and two, of the radiation sensor are directly connected to the MCU and not attached to the translator. This can be done as these two pins can operate within the 3.3V range according to the manual of the radiation sensor [2].

TRANSCEIVER - LTC2850

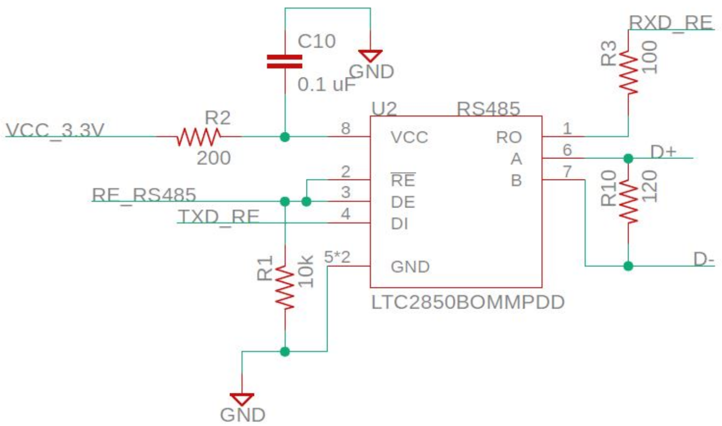


Figure 4.14: Schematic of prototype PCB tranceiver

The transceiver receives or transmits data from the MCU to the OBC of the satellite. The signals from the MCU are in UART (TXD and RXD) send to the transceiver which then sends it in RS485 format to the OBC (D+ and D-), see Figure 4.14. The RE and DE pins determine whether the signals can be transmitted, received, or both. To avoid accidental transmissions as much as possible, the RE and DE are connected to each other, meaning they will either be set in the receive or transmission mode. These modes are further discussed in Appendix F. All pin connections can be read in Appendix C, Table C.5.

EXTERNAL CLOCK RAD SENSOR [32.768 kHz] - SIT1533-AI

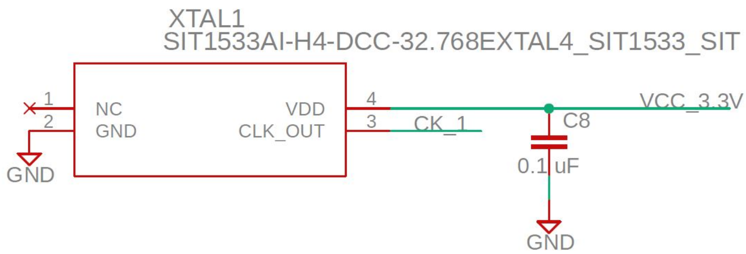


Figure 4.15: Schematic of prototype PCB radiation sensor external oscillator

The external clock with a frequency of 32.768 kHz is used to provide a stable clock signal to the radiation sensor, instead of relying on the MCU for a clock signal. The clock is directly connected to the radiation sensor, see Figure 4.15. All pin connections can be read in Appendix C, Table C.6.

EXTERNAL CLOCK MCU [8 MHz] - ASDMB

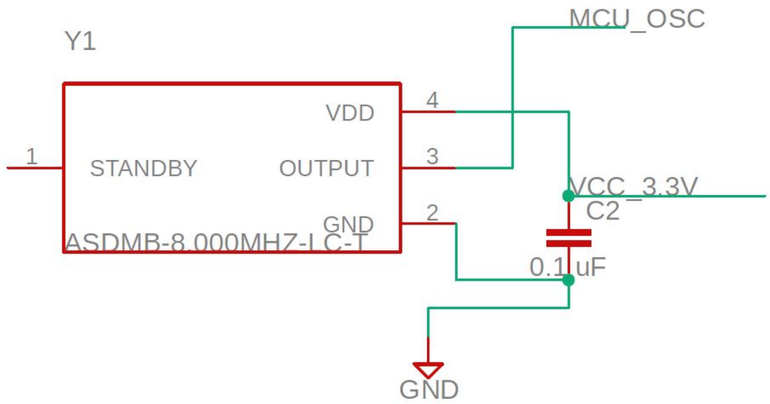


Figure 4.16: Schematic of prototype PCB MCU external oscillator

The external clock with a frequency of 8 MHz is used to provide a stable clock signal to the MCU, instead of relying on the internal clock of the MCU. This clock is directly connected to the MCU, see Figure 4.16. All pin connections can be read in Appendix C, Table C.3.

CONNECTORS

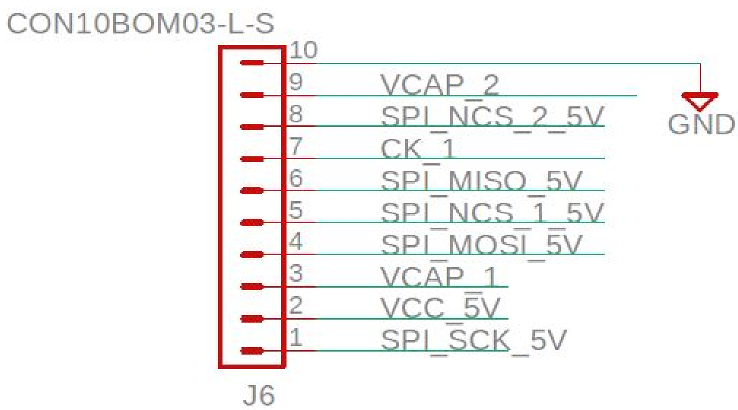


Figure 4.17: Schematic of prototype PCB radiation sensor debugging connector (10 pins)

There are four connectors installed on the prototype board. The connector with 10 pins next to the radiation sensor is meant to directly communicate with the radiation sensor, without interference of the translator. This is used as a potential check-up to see whether the signals send and received to the radiation sensor are correct during debugging. The connector also provides the VCAP and 5V supply to the radiation sensor, see Figure 4.17. All pin connections can be read in Appendix C, Table C.7.

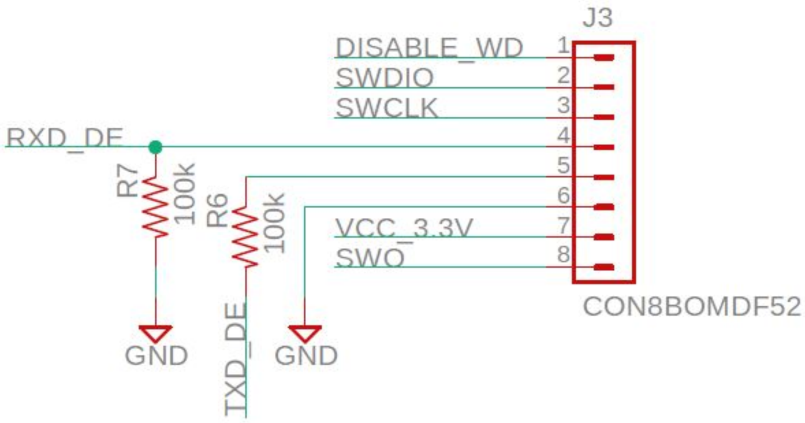


Figure 4.18: Schematic of prototype PCB MCU debugging connector (8 pins)

The connector with 8 pins is used to upload firmware and read data from the MCU for debugging purposes, see Figure 4.18. The connector is the same connector other Delfi-Twin payloads use for debugging. All pin connections can be read in Appendix C, Table C.8.

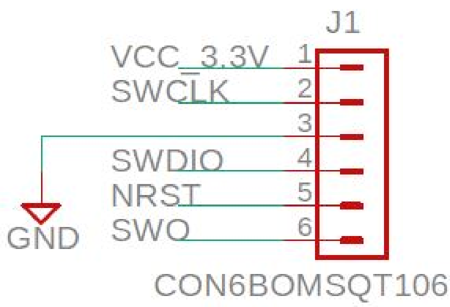


Figure 4.19: Schematic of prototype PCB MCU debugging connector (6 pins)

The connector with 6 pins is used as a debugging device as well, but is placed as redundant connector. This connector is also able to provide 3.3 V directly to the system without using the FSI-105-03-G-D-AD connector if needed, see Figure 4.19. All pin connections can be read in Appendix C, Table C.9.

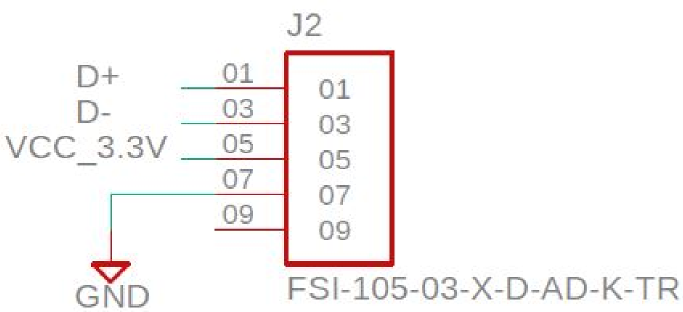


Figure 4.20: Schematic of prototype PCB MCU main connector (10 pins)

The 10 connector FSI-105 is used as the main connector between the transceiver and the OBC. It is not used directly for debugging, but can be used to simulate the transmitting and receiving of data between the OBC and the MCU, see Figure 4.20. All pin connections can be read in Appendix C, Table C.10.

LEDS

Figure 4.21: Schematic of prototype PCB MCU debugging LED's

There are two LEDS on the PCB which help in debugging, see Figure 4.21. The LEDS can be activated via the MCU to visually indicate when certain actions are activated. It can be used in between firmware functions to visually indicate a certain milestone is reached. This is more intuitive than sending messages via UART to imply a certain action has been taken. The number of LEDS are arbitrarily chosen as more could have potentially been used, but would take up more space of the PCB.

DECOUPLING CAPACITORS

The capacitors seen at every IC their voltage supply pin is used as a decoupling capacitor [65]. A decoupling capacitor is able to compensate for voltage dips at the particular IC it is connected to, stabilizing the voltage supply. This can occur once an IC suddenly uses more current. IC's which handle communication or require a certain clock accuracy are especially in need of such decoupling capacitors to reduce anomalies in those signals. The value for every capacitor is taken as 0.1 microFarad as this is the most often used value for such decoupling capacitors. Capacitor values may need to increase once anomalies are spotted at certain IC's.

4.4.3. Prototype PCB routing

The schematic seen at the start of subsection 4.4.2 shows all the IC's and signals required for the radiation payload prototype to function. A PCB design of this schematic has been designed to physically test the radiation payload. The PCB size and shape constraints are the same for every Delfi-Twin payload and are the same as the ones used in the Delfi-PQ, see Figure 4.22. No changes were therefore allowed to be made to the PCB shape and its four assembly holes, see requirement DE-2. The PCB design is made with the tool Fusion 360 and manufactured via the company Euro-circuits. The exact same process is followed for every other PCB within the Delfi-Twin.

After the development of the PCB, a new design of the Delfi-Twin PCB had been made by the Delfi-Group which is slightly larger, see Figure 4.23. This changes requirement DE-2, but as it is larger it has no effect on the developed prototype PCB. The new PCB design is therefore not used, but should be taken into account when designing a next iteration of the radiation payload.

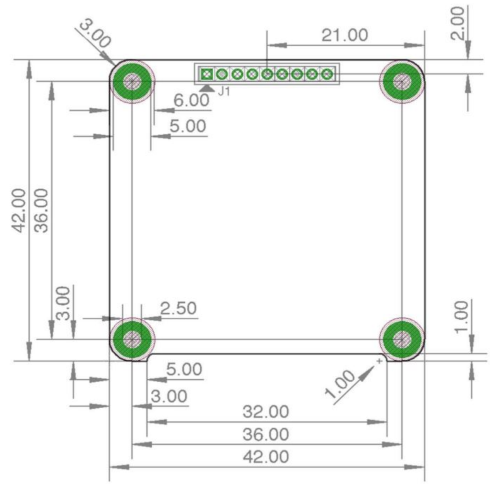


Figure 4.22: PCB size constraints based on the Delfi-PQ requirements [66]

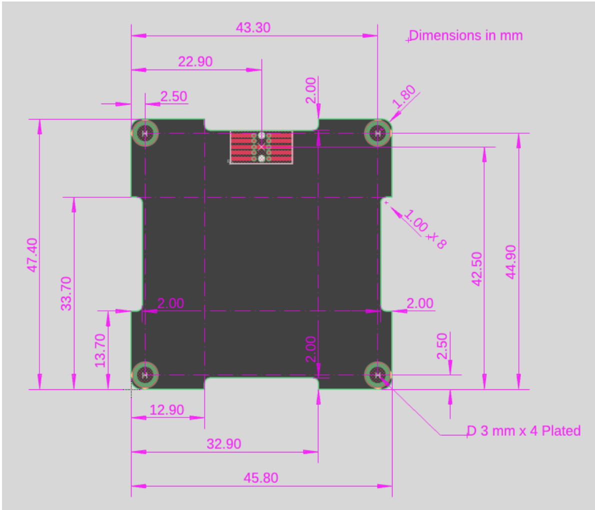


Figure 4.23: Updated PCB design. This design is not used within the current model

Figure 4.24: Left: Old PCB design which was also used in the Delfi PQ. Right: New, larger design of the PCB. Not used in this project

The PCB and its signal routing is split up into four layers:

1. Top route layer
2. Ground layer
3. Power layer
4. Bottom route layer

In Figure 4.25 the PCB design can be seen, including the placement of each IC. Below the signal routes for each layer is explained.

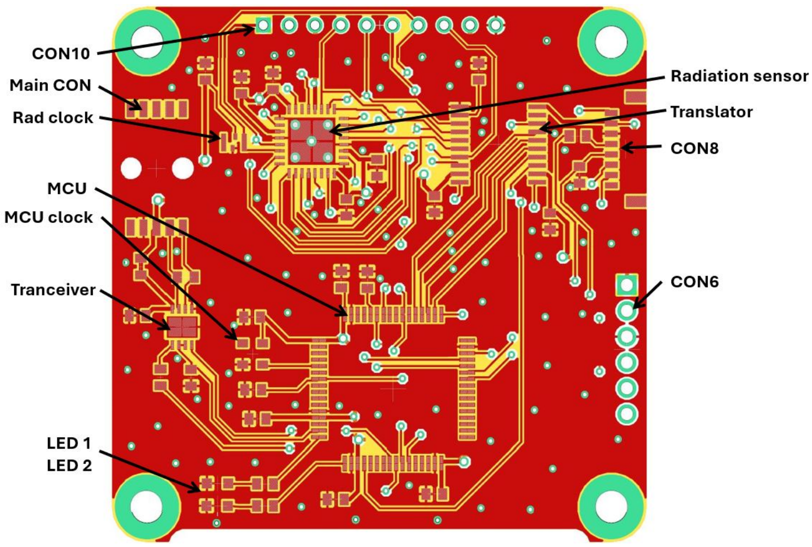


Figure 4.25: Full design PCB based on radiation payload schematic, IC placement shown

Top Route

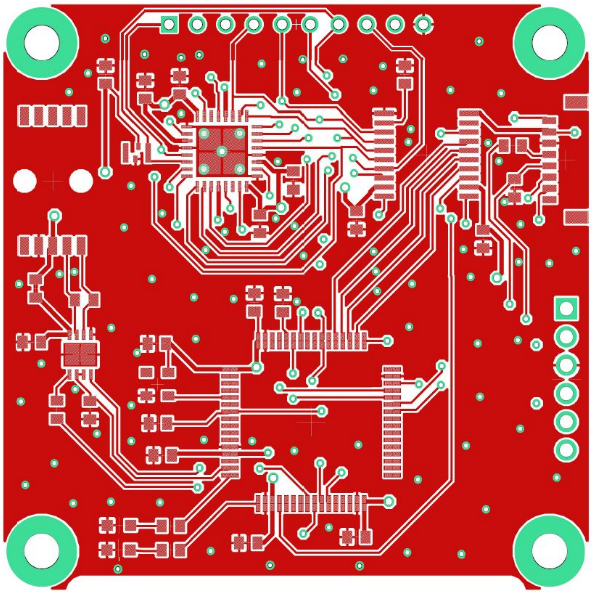


Figure 4.26: Top layer of the radiation payload PCB prototype

The top route consists of all IC's and its high speed or sensitive signals, see Figure 4.26. These are commonly [67] the I2C/UART/SPI signals and the clock signals. In the prototype no I2C signals are used, but can be expected from the temperature and V/I/P sensors on the final version. UART signals or SPI signals which run parallel are separated with an arbitrary distance to lower the chances of crosstalk [68]; see Figure 4.27. Another design strategy for the top layer is to have short connections for the high-speed/sensitive signals to lower interference/noise [68]. The use of vias for these signals is also kept to a minimum to avoid noise. Improvements can be made in shortening the signals routing for the SPI signals in Figure 4.28. This can be achieved by reorienting the IC components on the PCB board, but should be done once the full version of the PCB with all missing components is designed.

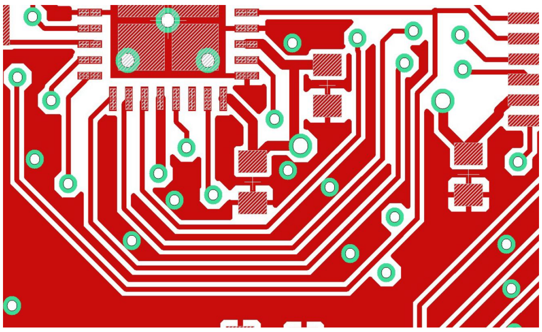


Figure 4.27: Space in PCB routing to prevent crosstalk

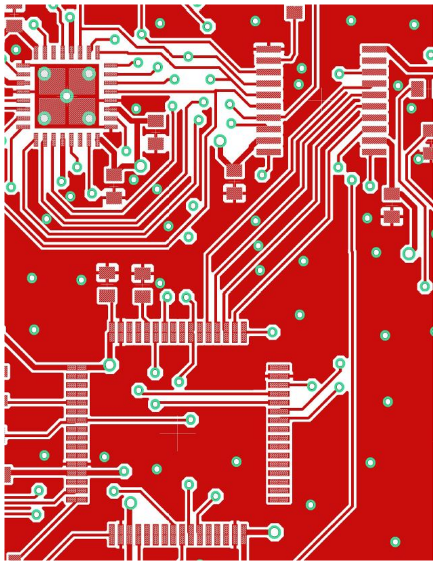


Figure 4.28: Distance between Translator and MCU signals is too long

Figure 4.29: Design recommendations to PCB

Remaining signals which are less sensitive or have a lower speed are usually routed to the bottom layer via vias in order to give extra space to the top layer signals. These are GPIO pins or debugger pins as these do not fall into the category of high-speed/sensitive signals. The capacitors and external clocks are also placed as close to their respectable IC's as possible in order to decrease potential noise [68].

Ground layer

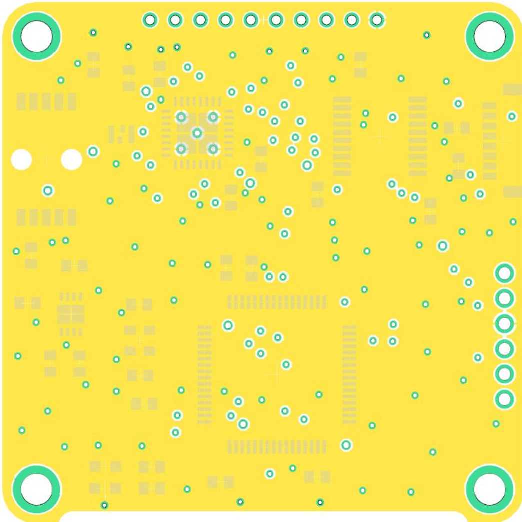


Figure 4.30: Ground layer of the radiation payload PCB prototype

The ground layer has two purposes. First is to provide ground to the other layers by means of via stitching. Vias can then be placed near IC's which require a ground connection by simply being connected to the ground plane. Signal routings are not placed on the ground layer. Secondly, it is used to shield the bottom and top signals from each other to prevent crosstalk [69]. See Figure 4.30 for the second layer PCB routing design.

Power layer

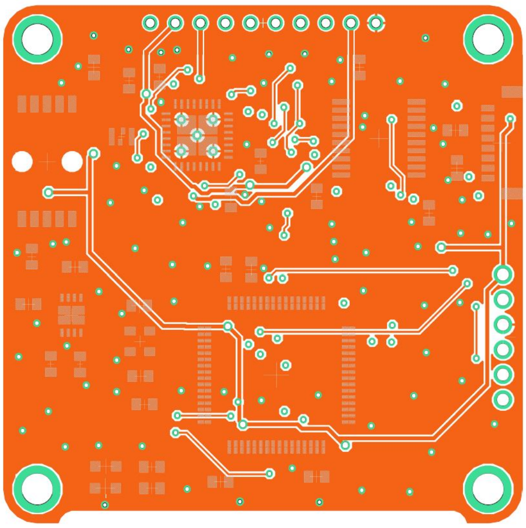


Figure 4.31: Power layer of the radiation payload PCB prototype

Power layers are usually used in a similar matter as ground planes where the full plane is used as a voltage source [70]. As there are two main voltages at use, 3.3V and 5V, the plain could be split up into separate sections for each voltage level. The VCAP 1 and 2 would however still need their separate routing to provide 18V+ to the sensor for manual discharging; see subsection 2.3.4 and Appendix C for its use case.

This design technique is for the prototype version however not applied, see Figure 4.31. This mainly as the power layer serves a second purpose except giving power to all systems. It also serves as a side routing for both the bottom and top layer. Whenever one of the two layers cannot reach a certain routing directly, a via is used to side-route the signal by means of the power layer. This gives more space to the bottom and top layer without having two interfering with each other. In the final version more IC's will be used on the board, meaning more space is needed for the additional signals. By means of using the power layer as an extra routing, the top and bottom layers will reserve more space for the additional IC's.

Bottom Route

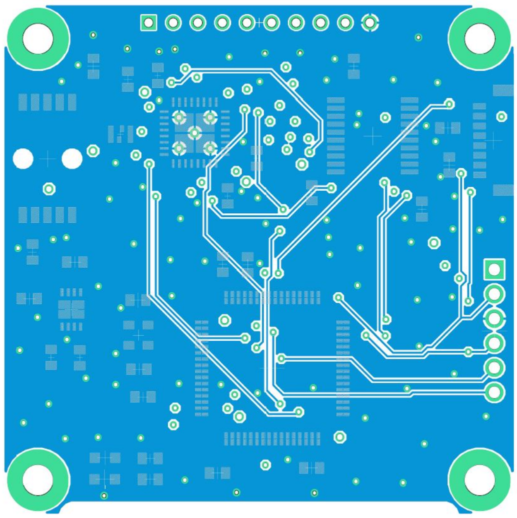


Figure 4.32: Bottom layer of the radiation payload PCB prototype

The bottom layer consists of GPIO and debugger routing, no IC's are installed on the bottom as of now, see Figure 4.32. As explained in the top routing, the GPIO and debugger routing are not as speed and sensitivity crucial as for example communication or clock signals. As of this they can use more vias to complete the routing. The side-routing of the bottom layer is performed with the power layer.

Copper layer and ground stitching
A last detail which is added to all layers of the PCB is a ground copper layer. The colors in each layer which are not signal traces (red, yellow, orange and blue respectively for the four above layers) are all large ground traces. This provides ground to all IC's without the need for traces. The second layer, the ground plane, serves also as a distributed ground source which can connect to other layers to provide a more stable ground connection. This is done with via stitching [71] which are the green dots on the board without a signal trace attached. These stitches are spread across board, but are predominantly placed near IC ground connections for stability.

4.4.4. PCB manufacturing

As the IC's have been selected and the PCB design is finished, the PCB and IC's can be ordered and manufactured. The full components list can be found in Appendix A. All components were ordered via Mouser [72] as the Delfi-group buys mostly all of their components from this distributor. The PCB is ordered via Euro-Circuits. In Figure 4.33 the empty PCB can be seen before the IC's have been installed. The 2 x 2 PCB layout is not for any particular reason ordered.

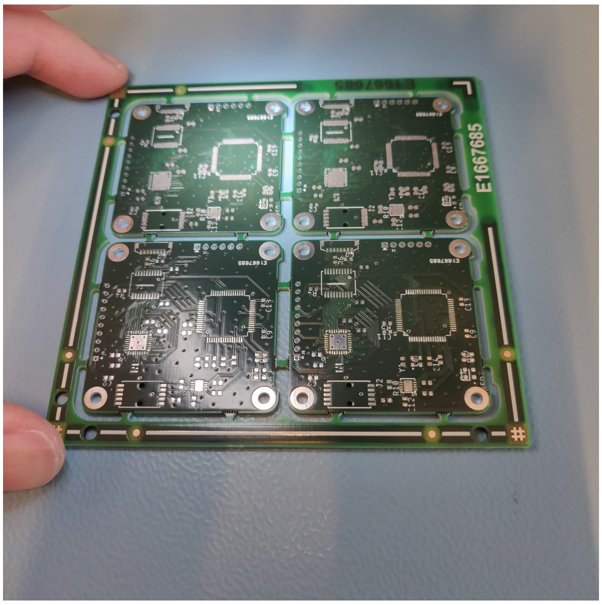


Figure 4.33: Empty prototype PCB of radiation payload

When the assembly takes place, ESD (electrostatic discharge) safety measures must be taken to prevent the potential destruction of the IC's. A basic ESD safety measurement recommended is wearing a bracelet connected to ground to lower the chances of ESD [73].

The PCB is assembled by means of reflow soldering [74]. A stencil is ordered together with the PCB which aligns with the IC placements, see Figure 4.34. The stencil is layed on top of the PCB and soldering paste, Figure 4.35, is spread across the stencil. The IC holes will be filled with the soldering paste, leaving the remaining sections of the PCB empty. A stencil thickness of 100 micrometers is recommended for these PCB sizes in order to prevent the overuse of paste which could lead to short circuits. The stencil is removed and the IC's are manually placed onto the PCB. As the PCB and the IC's sizes are in the range of millimeters to micrometers, it is necessary to use a microscope and ESD verified tweezers for the manual assembly, see Figure 4.39.

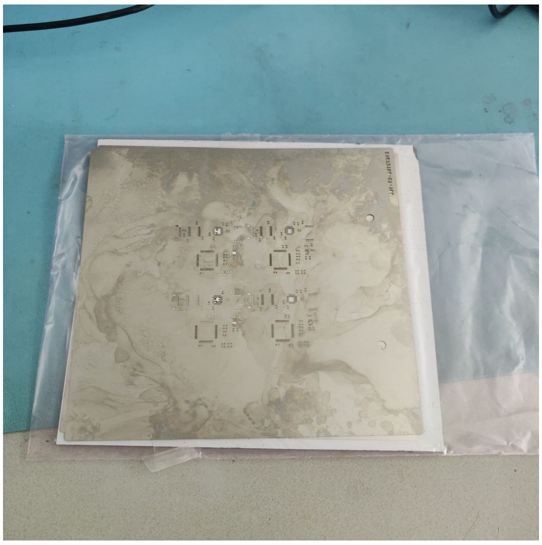


Figure 4.34: Soldering sheet for the PCB

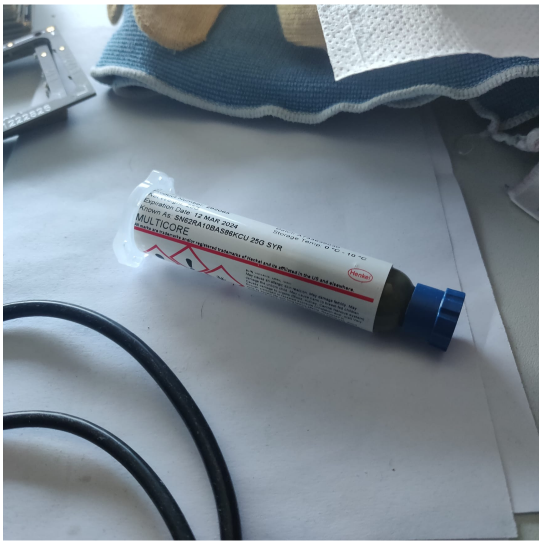


Figure 4.35: Soldering paste used on top of the sheet.

Figure 4.36: Sheet and paste to solder PCB IC components

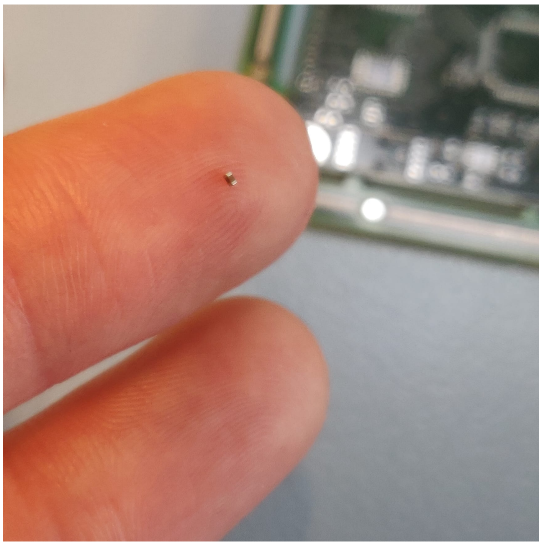


Figure 4.37: Size of capacitor on the PCB

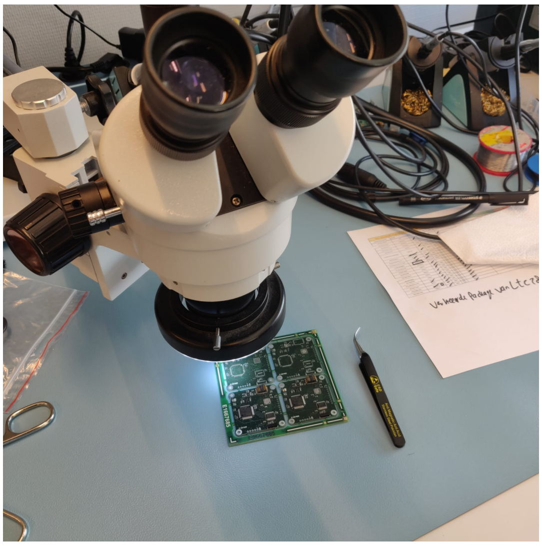


Figure 4.38: Microscope used for PCB assembly

Figure 4.39: Assembly of PCB

The PCB with soldered pasted IC's now requires to be heated within a special oven which attaches the IC's onto the PCB. For this PCB the oven in the LR clean room is used, see Figure 4.40. Once the PCB has cooled down it is ready for inspection. In Figure 4.41 the PCB with all IC's soldered can be seen which will be used for testing the radiation sensor throughout this project. Two have been soldered to test whether certain debugs are exclusive to one board or to both. This says something about anomalies potentially being a soldering mistake or whether the design itself is faulty.

Figure 4.40: Soldering oven

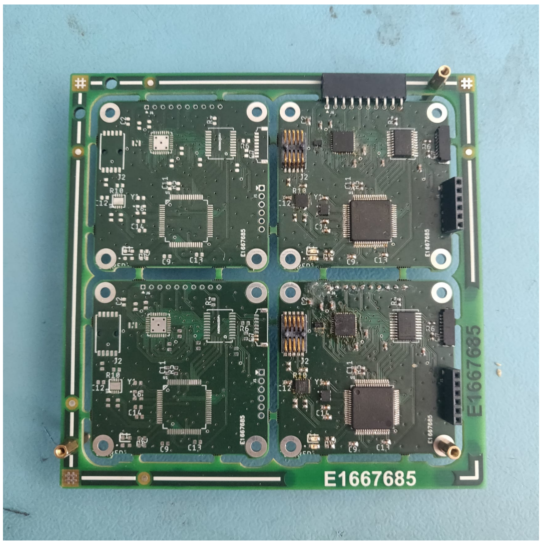


Figure 4.41: Radiation payload prototype PCB including IC's

Figure 4.42: PCB assembly finished

4.4.5. Hardware conclusion

The hardware development for the detailed design phase has concluded. The result is a prototype PCB, Figure 4.41, which includes the most essential IC's in order to test the radiation sensor of the radiation payload. In a future project the remaining components will require to be designed and installed onto a final PCB design. The hardware design includes:

- The FGD-03F radiation sensor, which is the most important IC which requires to be tested in this project.
- The STM32L476RG MCU, the brain of the PCB which will handle all signal transfers.
- The LTC2850 transceiver, which determines whether signals will be send or received by the MCU from the OBC. Also transforms the UART data into rigid data which is easier send over long distances towards the OBC.
- The MAX3001EEUP+ Translator to make communication between 5V and 3.3V IC's possible. In this case between the MCU and the radiation sensor.
- The ASDMB MCU external oscillator and SIT1533-AI radiation payload external oscillator.
- Connectors, used for debugging, uploading firmware or providing power to the system.

This results in a PCB to which firmware can be uploaded. This will create a radiation payload prototype which can be tested for its functionality. The firmware design is discussed in section 4.5.

4.5. Firmware/IC configurations

4.5.1. Introduction firmware configurations

The firmware concept design was completed in chapter 3, which resulted in a flow chart, Figure 3.7, showing a simplistic representation of the firmware main loop. In this section the concept loop designed in Figure 3.7 will be developed into an actual firmware code which can be uploaded onto the prototype PCB seen in Figure 4.41. The prototype PCB board has been developed with less components than the expected flight model. For this reason, only firmware will be developed which is relevant to these prototype PCB board components. Firmware for missing components will require to be developed in a follow-up project.

In subsection 2.3.4 it had already been stated that the firmware will be written in de STM32CUBEMX IDE in the language C++. This development environment makes it easy to configure the STM32 MCU used in the prototype PCB, and to add additional configuration code for the additional components like the radiation sensor and transceiver. The pins of the MCU can directly be configured via an interface installed in the IDE, requiring no additional code to be written, see Figure 4.43.

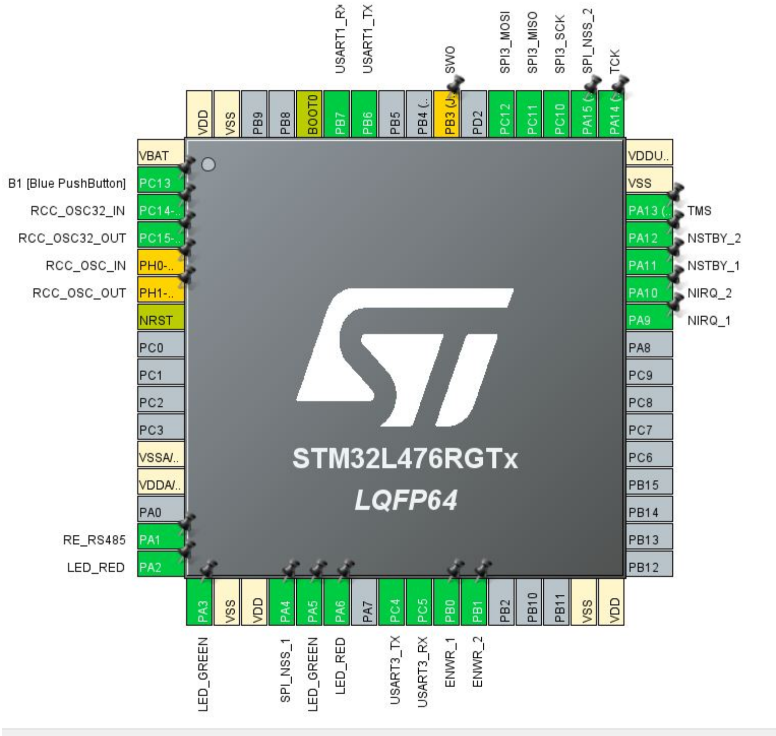


Figure 4.43: Pin configuration of MCU via STM32CUBEMX

The following topics are discussed regarding the firmware development of the radiation payload:

- MCU configuration: The initial configuration for the MCU when power is turned on.
- Radiation sensor configuration: The initial configuration for the radiation sensor when power is turned on.
- Transceiver configuration: Has not been implemented in the code due to time constraints. Appendix F does state the necessary configurations necessary to implement it into the firmware.
- Radiation sensor mode: Different configurations of the radiation sensor which can be changed via commands.
- Firmware main loop: Main actions the radiation payload will perform during a mission.
- Post-processing: Post-processing of radiation measurements.

4.5.2. MCU Firmware configuration

The MCU is configured via the STM32CUBEMX IDE. In Table 4.12 the configuration for the MCU can be seen. The configurations not mentioned but are available in CUBEMX are kept at their default values. The configurations altered are regarding the connection types (UART and SPI), clock, GPIO, and debugging.

Table 4.12: System and Communication Configuration Settings

Configuration	Setting
SPI Configurations	
Data Size	8 Bits
First Bit	MSB First
Prescaler	16
Baud Rate	5.0 Mbits/s
Clock Polarity	Low
Clock Phase	1 Edge
Hardware NSS	Disable
UART Configurations	
Word length	8 Bits
Baud Rate	115200 Bits/s
Stop Bits	1
Clock Configurations	
HSE	BYPASS Clock Source
LSE	Disable
Debug Configurations	
Debug	Serial Wire

SPI configuration

The data size of the SPI is set to 8 bits as this is equal to the size of the radiation sensor read/write registers as seen later in Figure 4.47. Increasing or decreasing the size would unnecessarily make the readings more difficult to decipher. MSB first, clock polarity low and clock phase at the first edge are default settings which are kept as changes will not benefit the communication. The prescaler is set to 16, causing the baud rate to be equal to 5.0 Mbits/s as this is the maximum allowed speed for the SPI according to the sensor manual [2]. The hardware NSS (slave selects) are disabled as more than one slave select is required which cannot be configured via the build-in hardware NSS configuration of the STM32 board. Instead, general GPIO's are used as output in order to disable or enable the slave select pins necessary to control the two radiation sensors integrated in the FGD-03F.

UART configuration
The UART is configured with a word length of 8 bits. This again to accommodate the 8 bit register map size which is used by the sensor. The baud rate is set to 115200 Bits/s as this is a common value used in these applications which balances between speed and reliability. The stop bits is set to 1 as it has yet to be seen if a stop bit of 2 or more is of necessity to the system reliability.

Clock configuration
The high speed clock of the MCU is activated by an external high speed clock as explained in section 4.3. This HSE (High speed external) gives an 8 MHz clock cycle to the MCU which gives a more stable clock signal than the internal one of the MCU [75].

No LSE (Low speed external) is used for this prototype PCB, but is recommended when a final version is created. As the LSE, similar to the HSE, will give a more stable clock signal than the LSI (Low speed Internal) [75]. The LSI used is kept at its standard configuration, meaning a signal of 32.768 kHz.

Lastly, an external clock is also used for the FGD-03F radiation sensor. This external clock runs on 32.768 kHz as this is the clock speed the sensor runs on according to the FGD-03F manual [2].

Debugging configuration
For the debugging and uploading the firmware onto the PCB's MCU (the STM32L476RG), a J-link is connected (Figure 4.44) to the 8 PIN connector (Figure 4.18). The other possible SWO connector (Figure 4.19) will not be used as it mostly served as spare connector. As the J-LINK connection is the recommended debugging connection of the Delfi-group, it will be used for this configuration. See Figure 4.45 for how the J-link connection is made with the PCB.

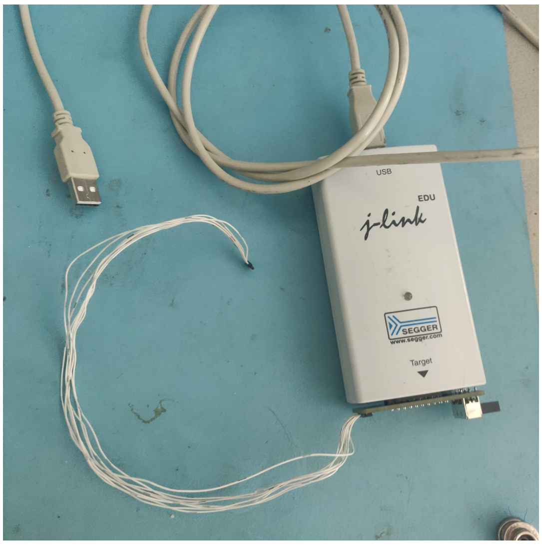


Figure 4.44: J-link connector

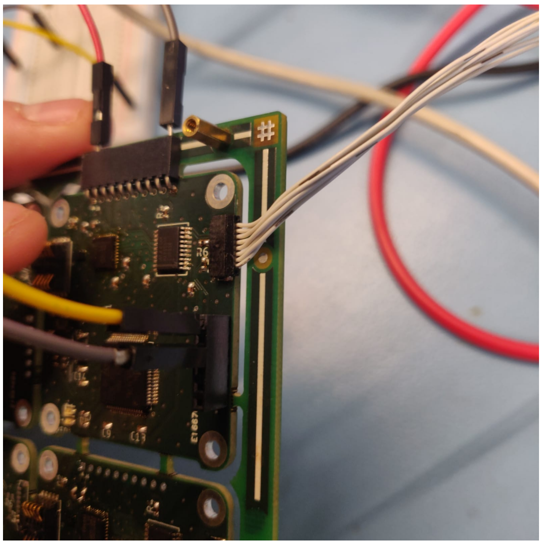


Figure 4.45: J-link connection with PCB CON8 to upload firmware and read direct data

Figure 4.46: J-link connection PCB

The STM32CUBEMX 'Run Configurations' settings for debugging require to be set onto a SEGGER J-LINK debug probe with an SWD interface. This allows the J-link connection to work for uploading and reading code from the STM32 MCU.

4.5.3. Radiation sensor firmware configuration

The radiation sensor can be configured by means of changing values inside its register map, see Figure 4.47. The register map consists of addresses, 0x00 until 0x14, each consisting of an 8 bit register. Each bit can be toggled to a 0 or a 1 and has a specific function. By means of changing the bits inside of the addresses, the configuration is changed. The desired changes to the registers are send via SPI through the MCU. At first the address is send, after which the desired 8 bit configuration is send. Similar to writing configurations to the registers, the registers themselves are also able to be read.

REGISTER MAP

OVERVIEW

<table>
<tr><th>Addr</th><th>Bit 7</th><th>Bit 6</th><th>Bit 5</th><th>Bit 4</th><th>Bit 3</th><th>Bit 2</th><th>Bit 1</th><th>Bit 0</th></tr>
<tr><td>0x00 R</td><td colspan="8">TEMP(7:0)</td></tr>
<tr><td>0x01 R</td><td>RECHEV</td><td colspan="7">RCHCNT(6:0)</td></tr>
<tr><td>0x02</td><td colspan="8">Not implemented</td></tr>
<tr><td>0x03 R</td><td colspan="8">F1R(7:0)</td></tr>
<tr><td>0x04 R</td><td colspan="8">F1R(15:8)</td></tr>
<tr><td>0x05 R</td><td>0</td><td>0</td><td>0</td><td>0</td><td>DNEWR</td><td>F1ROVF</td><td colspan="2">F1R(17:16)</td></tr>
<tr><td>0x06 R</td><td colspan="8">F1S(7:0)</td></tr>
<tr><td>0x07 R</td><td colspan="8">F1S(15:8)</td></tr>
<tr><td>0x08 R</td><td>0</td><td>0</td><td>0</td><td>0</td><td>DNEWS</td><td>F1SOVF</td><td colspan="2">F1S(17:16)</td></tr>
<tr><td>0x09</td><td>0*</td><td>0*</td><td>0*</td><td colspan="5">TARGET(4:0)</td></tr>
<tr><td>0x0A</td><td>0*</td><td>0*</td><td>0*</td><td colspan="5">THRESHOLD(4:0)</td></tr>
<tr><td>0x0B</td><td>EAWR</td><td>EVBCHP</td><td>NCHP</td><td>ENDCH (**)</td><td colspan="2">WINDOW(1:0)</td><td>0</td><td>TDIV</td></tr>
<tr><td>0x0C</td><td>FCH</td><td>1*</td><td>1*</td><td>1*</td><td>1*</td><td colspan="3">SENS(2:0)</td></tr>
<tr><td>0x0D</td><td>0*</td><td>ECH</td><td>EPWR</td><td>NEASNR (**)</td><td>E2V</td><td colspan="3">SET(2:0)</td></tr>
<tr><td>0x0E</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0*</td><td>EDIRT</td><td>NIRQOC</td><td>ENGATE</td></tr>
<tr><td>0x0F</td><td colspan="8">Not implemented</td></tr>
<tr><td>0x10</td><td colspan="8">SN(7:0)</td></tr>
<tr><td>0x11</td><td colspan="8">SN(15:8)</td></tr>
<tr><td>0x12</td><td colspan="8">SN(23:15)</td></tr>
<tr><td>0x13 R</td><td colspan="8">CHIPID(7:0)</td></tr>
<tr><td>0x14</td><td>0</td><td>0</td><td>0</td><td>0</td><td colspan="4">Reserved</td></tr>
</table>

R: Read-only register
(*) : Reserved. Must be set to specified value
(**) : ENDCH and NEASNR are internal debugging bits and must be set to 0.

Figure 4.47: Register map FGD-03F radiation sensor [2]

When the radiation sensor is powered on, it requires to obtain an initial configuration of the register maps in order for it to perform actions which are desired. The addresses 0x00 until 0x08 are READ addresses, meaning they can only be read by the MCU and are not used for configure purposes. These are used to obtain measurement values like temperature values (address 0x00) or radiation measurement values (addresses 0x03, 04, 05, 06, 07 and 08). 0x09 until 0x0E are the addresses which will be used for the radiation sensor configurations as they are both READ and WRITE.

In Table 4.13 and Table 4.14 the function of each bit seen in Figure 4.47 is explained. This helps in understanding the differences between the read and write addresses and what configurations are possible from the READ/WRITE registers. There are other bits which could be used for configuration purposes (see Appendix D), but for the general use case these are not required to alter and will therefore not be explained. If necessary, read subsection 2.3.4 again to understand the basic principles of the FGD-03F system. Keep in mind that the explanations given Table 4.13 and Table 4.14 are based on the FGD-03F manual [2]. The manual however is not always clear in the description of every register, meaning these are partially based on self-interpretation. To be fully convinced on their use, contact Sealicon when needed.

Table 4.13: Sensor Register Details of Radiation Sensor FGD-03F part 1

Address	Bit Length	Function	Details
0x00	8	TEMP	Gives 8-bit temperature reads from the built-in temperature sensor in the radiation sensor. This is implemented to calculate the compensation required for the radiation data measurements as these are affected by temperature.
0x01	1	RECHEV	Shows whether the radiation sensor is recharging (1) or not (0). Radiation measurements during recharging should be disregarded due to inaccuracies.
0x01	7	RCHCNT	Counts the amount of recharges made by the radiation sensor. Can go from clear (0x00) to a maximum of 127 (0x7F). To reset the counter, one requires to manually WRITE a 0x00 once the maximum is reached. This is the only address within the READ addresses that also requires a WRITE.
0x02	8	Not Implemented	Not implemented.
0x03	8	F1R	Gives 8-bit radiation reads as a reference for the sensor radiation reads. The full radiation read consists of F1R from 0x03, 0x04, and 0x05, making it 18 bits long. These data signals require to be assembled into one measurement read in post-processing of data.
0x04	8	F1R	Part 2 of radiation reference measurement data.
0x05	1	DNEWR	Shows whether there is no new reference data ready (0) or is (1). Is cleared automatically.
0x05	1	F1ROVF	States whether there is no overflow in the reference measured data (0) or is (1). Can occur when the measurement window is too long or the sensor recharging value is too high. Overflowed data should be disregarded.
0x05	2	F1R	Part 3 of radiation reference measurement data.
0x06	8	F1S	Gives 8-bit radiation reads for the sensor radiation readings. The full radiation read consists of F1S from 0x06, 0x07, and 0x08, making it 18 bits long. These data signals require to be assembled into one measurement read in post-processing of data. Together with F1R, the reference measurements, these two measurements can be used to compensate for the temperature effects on the radiation data.
0x07	8	F1S	Part 2 of radiation sensor measurement data.
0x08	1	DNEWS	Shows whether there is no new sensor data ready (0) or is (1). Is cleared automatically.
0x08	1	F1SOVF	States whether there is no overflow in the sensor measured data (0) or is (1). Can occur when the measurement window is too long or the sensor recharging value is too high. Overflowed data should be disregarded.
0x08	2	F1S	Part 3 of radiation sensor measurement data.

Table 4.14: Sensor Register Details of Radiation Sensor FGD-03F part 2

Register	Bit	Bit Length	Function
0x09	TARGET	5	States the linear frequency range the radiation sensor operates in. This is dependent on whether the sensor is configured in Low sensitivity mode (180 kHz) or High sensitivity mode (90 kHz). The value for TARGET must be calculated and written to the sensor where it must be as close as possible to either the HS value of 90 kHz or the LS value of 180 kHz. The calculation method depends on the state of ENGATE in 0x0E and TDIV in 0x0B.
0x0A	THRESHOLD	5	States the linear frequency range the radiation sensor operates in. This is dependent on whether the sensor is configured in Low sensitivity mode (140 kHz) or High sensitivity mode (50 kHz). The value for THRESHOLD must be calculated and written to the sensor where it must be as close as possible to either the HS value of 50 kHz or the LS value of 140 kHz. The calculation method depends on the state of ENGATE in 0x0E and TDIV in 0x0B.
0x0B	EAWR	1	Determines whether automatic recharging of the radiation sensor is disabled (0) or enabled (1). If it is disabled, manual recharging is performed.
	EVBCHP	1	Internal charge pump connection to VB. Either not at VB pin (0) or at VB pin (1). If one uses the internal charge pump system of the radiation sensor, EVBCHP must be set to 1.
	NCHP	1	Determines the source of recharging the radiation sensor. Either done by the internal charge pump of the sensor (0) or an external voltage at pin VB (1).
	ENDCH	1	Must be set correctly, whether the VB pin is not connected to VCAP (0) or is (1). Used when one does not want to use an external voltage supply at the VCAP pin.
	WINDOW	2	Determines window length of radiation measurements. Either 32,768 CK pulses per window (00), 16,384 CK pulses per window (01), 8,192 CK pulses per window (10), or 4,096 CK pulses per window (11).
	TDIV	1	Determines, together with ENGATE, how the radiation measurements at F1R and F1S can be calculated. 13 Least significant bits (LSB) are used when 0 and 10 LSB when 1.
0x0C	FCH	1	Determines force charging in manual recharging mode. Either stopped (0) or started (1).
	SENS	3	Sets the sensor in low sensitivity mode with 10 kHz/Gy (linear range: 140 kHz to 180 kHz, 100) or high sensitivity mode with 70 kHz/Gy (linear range: 50 kHz to 90 kHz, 001). Remaining bits (000, 010, 111) are reserved.
0x0D	ECH	1	Determines if recharging is not allowed (0) or allowed (1). Applicable for both manual and automatic recharging.
	EPWR	1	If internal discharger is used, it must be set to 0. If manual recharging is used, it must be set to 1.
	NEASNR	1	Internal debugging bit; must be set to 0.
	E2V	1	Determines reference frequency configuration. Either high (0) or low (1).
	SET	3	Determines charge pump output voltage. Can be between 14.5 V (000) and 18 V (111). Needs to be calibrated during testing to prevent overcharging.
0x0E	EDIRT	1	Determines whether measurements are allowed during SPI communication between the sensor and the MCU. Either allowed (0) or discarded (1).
	NIRQOC	1	Determines NIRQ interruption of radiation sensor being push-pull (0) or open collector (1).
	ENGATE	1	Determines measurement window by a specific number of CK pin pulses (0) or by the duration of an external pulse at CK pin (1). Works with TDIV to calculate F1R and F1S (the radiation measurements).

For the initial configuration of the radiation sensor, the following configurations are made:

- High sensitivity
- Automatic recharging
- Window clock at 4,096 CK
- Charge pump output of 14.5 V

Based on the recommendations made in section 2.5, it was recommended to always configure the high sensitivity mode of the radiation sensor. As of this, the initial configuration will be kept at high. The automatic recharge is enabled as it would be unrealistic to ask for recharges manually via the OBC as the amount of recharges would be too much to handle.

The window clock is initially set to 4,096 CK pulses per window, which is the fastest setting the radiation sensor can make readings. The chances of errors and noise however do increase with an increase in read speed. During the testing phase the accuracy of the readings needs to be checked to see if a longer measuring window is required for potentially more accurate results. The charge pump output voltage for the recharging of the radiation sensor is set to its lowest value at the start of 14.5 V. During the testing phase it is checked upon whether a higher value is required for the functionality of the system.

How to configure these initial configurations by means of changing the register maps is explained below. These initial configurations are still able to be changed via commands from the OBC. This implementation will be discussed in subsection 4.5.4.

For address 0x0B the following is sent:

Table 4.15: Register configuration for address 0x0B.

0x0B							
EAWR	**EVBCHP**	**NCHP**	**ENDCH**	**WINDOW**		**0**	**TDIV**
1	1	0	0	1	1	0	1

- Automatic recharging will be enabled, meaning EAWR needs to be 1.
- No external charge pump is used for the radiation sensor as it would not fit the PCB design, meaning the internal one will be used. EVBCHP therefore requires to be 1.
- The use of the internal charge pump also makes NCHP 0.
- For VCAP an internal source will be used as this will be used for debugging. This pin will not be used during the satellite mission, meaning ENDCH can be 0.
- The measurement window was chosen to be the shortest of 4,096 CK pulses per window, meaning a WINDOW signal of 1 1.
- TDIV is set at 1 as a WINDOW time of 4,096 CK is chosen. This is relevant for the linear range calculation of address 0x09 and 0x0A. These are explained at their respective sections of the initial configuration. In the testing phase it is seen what effect it has on the radiation measurements.

These configurations result in a signal of 11001101, or 0xCD in hexadecimal, being sent to address 0x0B.

For address 0x0C, the following is sent:

Table 4.16: Register configuration for address 0x0C.

0x0C							
FCH	**1**	**1**	**1**	**1**	**SENS**		
0	1	1	1	1	0	0	1

- As no use of the manual recharging is initially used, the FCH pin stays at 0.
- The high sensitivity mode is used, meaning SENS is set at 001.

These configurations result in a signal of 01111001, or 0x79 in hexadecimal, being sent to address 0x0C.

For address 0x0E, the following is sent:

Table 4.17: Register configuration for address 0x0E.

0x0E							
0	**0**	**0**	**0**	**0**	**EDIRT**	**NIRQOC**	**ENGATE**
0	0	0	0	0	1	0	0

- To minimize the noise in the measurements, no measurements will be kept during the SPI transmissions. EDIRT is therefore 1 [2].
- NIRQOC is kept at 0 as push-pull interruptions will work with the current set-up of the radiation sensor. Using open collector sees no direct benefit.
- ENGATE is set to 0 as working with 1 will require the user to control the external clock to control the measurement window.

These configurations result in a signal of 00000100, or 0x04 in hexadecimal, being sent to address 0x0E.

For address 0x0D, the following is sent:

Table 4.18: Register configuration for address 0x0D.

0x0D							
0	**ECH**	**EPWR**	**NEASNR**	**E2V**	**SET**		
0	0	0	0	0	0	0	0

- At the start of the configuration the recharging is kept to a halt as other addresses still require to be configured. Therefore the ECH will be set to 0 at first
- EPWR must be set to 1 when working with the manual recharging system. As the automatic recharging is initially configured, the EPWR must be 0.
- NEASNR is used for internal debugging and must according to the manual be set to 0.
- E2V is set by default at 0. This meaning the reference frequency is set high.
- he charge pump voltage is as earlier explained set to its lowest value of 14.5 V, meaning a signal of 0 0 0.

These configurations result in a signal of 00000000, or 0x00 in hexadecimal, being sent to address 0x0D.

For address 0x09, the following is sent:

Table 4.19: Register configuration for address 0x09.

0x09							
0	**0**	**0**	**TARGET**				
0	0	0	0	1	0	1	1

The 0x09 and 0x0A addresses are not the ones which are first covered, despite their order in address, due to their configuration being dependent on multiple other addresses. As a high sensitivity was configured in address 0x0C, the linear range of the radiation sensor for measurements will be 50 kHz to 90 kHz. This means the value of TARGET requires to be 90 kHz, or 01011 for the signal. This value is however not simply send to the address, but must be obtained from calculations which need to be as close as possible to this number. The same steps need to be taken for the THRESHOLD signal at 0x0A. The formulas can be found in Figure 4.48.

	TDIV = 0	TDIV = 1
ENGATE = 0	$FS_T \times \frac{WINDOW(1:0)}{F_{CK} \cdot 8192}$	$FS_T \times \frac{WINDOW(1:0)}{F_{CK} \cdot 1024}$
ENGATE = 1	$FS_T \times \frac{T_{CK}}{8192}$	$FS_T \times \frac{T_{CK}}{1024}$

Figure 4.48: Formulas used to calculate TARGET or THRESHOLD, depending on the state of TDIV and ENGATE [2]

What can be noted is that the formulas are dependent on ENGATE and TDIV, two more signals which have an affect on what TARGET and THRESHOLD must be. ENGATE is set to 0 and TDIV to 1 to obtain the correct linear range for the WINDOW value chosen.

TARGET requires to be 90 kHz, which is obtained by having the values 01011 as the signal. The binary signal 01011 equals 11 in decimals, meaning 11 needs to be obtained from the formulas in Figure 4.48. If ENGATE = 0 and TDIV = 1 one can calculate with the following formula.

$$TARGET = F_{St} * \frac{WINDOW}{F_{ck} * 1024} \tag{4.1}$$

WINDOW was set at 4,096 at address 0x0B, Fck represents the frequency of the external clock which is 32.768 kHz and Fst is the target sensor frequency in Hz, which currently is 90000 Hz. Filling these values in gives the following.

$$TARGET = 90000 * \frac{4096}{32.768 * 10^3 * 1024} = 10.986 \approx 11 \tag{4.2}$$

If TDIV would equal 0 and 8192 would be used instead of 1024 in Equation 4.2, it would not result in 11, meaning choosing the correct TDIV is crucial to obtaining the required linear range. If TDIV would equal to 0 but WINDOW would be put at 32,768 instead of 4,096, it would result in the correct value of 11, see Equation 4.3.

$$TARGET = 90000 * \frac{32768}{32.768 * 10^3 * 8192} = 10.986 \approx 11 \tag{4.3}$$

With this it becomes clear that when choosing a specific WINDOW, one must change TDIV in order to approximate the linear range as closely as possible. For the use case of WINDOW = 4,096, TDIV must be 1 and ENGATE 0.

For address 0x0A, the following is sent:

Table 4.20: Register configuration for address 0x0A.

0x0A							
0	**0**	**0**	**THRESHOLD**				
0	0	0	0	0	1	1	0

Similar to TARGET, THRESHOLD needs to be within the high sensitivity linear range as configured in address 0x0C. THRESHOLD must equal 50 kHz which is obtained with the binary signal of 00110. In decimals this equals 6, meaning the formulas of Figure 4.48 need to be used again. ENGATE = 0 and TDIV = 1 with WINDOW = 4,096. The external clock still uses 32.768 kHz and the target frequency of the sensor is 50000 Hz (50 kHz). Filling this in gives the following formula.

$$THRESHOLD = 50000 * \frac{4096}{32.768 * 10^3 * 1024} = 6.1035 \approx 6 \tag{4.4}$$

Similarly to TARGET, the TDIV must be chosen correctly based on the WINDOW selected to obtain the best approximation to the linear range fitting to the sensitivity chosen.

For address 0x0D, the following is sent:

Table 4.21: Register configuration for address 0x0D.

0x0D							
0	**ECH**	**EPWR**	**NEASNR**	**E2V**	**SET**		
0	1	0	0	0	0	0	0

- ECH is set to 1 as every address is configured, meaning the automatic recharging is turned on.

These configurations result in a signal of 01000000, or 0x40 in hexadecimal, being sent to address 0x0D.

Summarized, the following configuration is set for the radiation sensor once the power of the payload is turned on:

- Address 0x0B: signal 0xCD
- Address 0x0C: signal 0x79
- Address 0x0E: signal 0x04
- Address 0x0D: signal 0x00
- Address 0x09: signal 0x0B
- Address 0x0A: signal 0x06
- Address 0x0D: signal 0x40

These configurations represent what has been used for this design. Changes are still allowed to be made to the initial configuration, but can also be made during the main loop of the firmware itself by means of commands.

4.5.4. Radiation sensor modes

The radiation sensor has several modes which can be altered, see subsection 2.3.4 for a review of these modes. Using the command system integrated in the main loop, it will be possible to change these modes while the satellite is operating. The initial configurations explained in subsection 4.5.3 will therefore be altered in order to activate these modes. Keep in mind that the FGD-03F chip has two radiation sensors integrated, meaning every mode command must be performed twice with different slave selects activated. The following modes are currently integrated in to the command system.

- NSTBY
- Manual recharge
- Automatic recharge
- Forced discharge
- High sensitivity
- Low sensitivity
- Window settings

NSTBY

The NSTBY corresponds to the standby mode of the radiation sensor in which the sensor will be turned off. The NSTBY mode can be controlled via the NSTBY pin which is directly connected to the MCU, see Figure 4.11. The NSTBY has two pins, NSTBY-1 and NSTBY-2, which both correspond to one of the two sensors installed in the FGD-03F chip. The NSTBY is turned OFF. when the pin is set high and turned ON when the pin is set low. If both sensors require to be put into NSTBY, both have to be set low.

An important note, when the radiation sensor is used for the first time the NSTBY is automatically set low/floating. This means that the radiation sensor will not work until you actively pull both NSTBY pins high via the firmware. This must be implemented in the code before any other actions are taken as otherwise you are not able to make any readings or configure any registers.

Manual recharge
The manual recharging mode can be used for debugging the radiation sensor or testing the sensor properties. It can also be used as a replacement of the automatic recharging mode if this experiences anomalies.

In order to activate the manual recharging mode, the EAWR register must always be 0 at address 0x0B. EAWR enables the automatic recharging which is currently not required.

Table 4.22: Register configuration for address 0x0B when changing to manual mode.

0x0B							
EAWR	**EVBCHP**	**NCHP**	**ENDCH**	**WINDOW**		**0**	**TDIV**
0	1	0	0	1	1	0	1

In order to activate the manual recharging, the ECH and EPWR in 0x0D must be set to 1 and FCH in 0x0C must also be set to 1. The recharging will activate and must be stopped when the required frequency is met. This is either 90000 Hz for high sensitivity or 180000 Hz for low sensitivity. The recharge is deactivated once the ECH, EPWR and FCH are set to 0.

Table 4.23: Register configuration for address 0x0D.

0x0D							
0	**ECH**	**EPWR**	**NEASNR**	**E2V**	**SET**		
0	**1**	**1**	0	0	0	0	0

Table 4.24: Register configuration for address 0x0C when changing to manual mode.

0x0C							
FCH	**1**	**1**	**1**	**1**	**SENS**		
1	1	1	1	1	0	0	1

Automatic recharge
Automatic recharging is used for the standard configuration as it performs the recharges automatically. This is most useful for the satellite as sending commands for manual recharging is undesirable for such an autonomous system.

Before the automatic recharging is activated it must be checked whether the manual recharging registers are deactivated. Once this is completed the automatic recharging can be activated by setting FCH to 0, EAWR to 1 and ECH to 1. It is deactivated by setting EAWR and ECH to 0.

Table 4.25: Register configuration for address 0x0C when changing to automatic mode.

0x0C							
FCH	**1**	**1**	**1**	**1**	**SENS**		
0	1	1	1	1	0	0	1

Table 4.26: Register configuration for address 0x0B when changing to automatic mode.

0x0B							
EAWR	EVBCHP	NCHP	ENDCH	WINDOW		0	TDIV
1	1	0	0	1	1	0	1

Table 4.27: Register configuration for address 0x0D when changing to automatic mode.

0x0D							
0	ECH	EPWR	NEASNR	E2V	SET		
0	**1**	0	0	0	0	0	0

Forced discharge
The forced discharge is used to emulate radiation discharge. This is helpful during debugging to test whether the sensor operates accordingly.

In order to activate the forced discharge created by the radiation sensor itself, it is important to leave VCAP floating. The SET register in 0x0D must be set to 18V by means of the setting 1 1 1 and EPWR must be set to 0. After this the EVBCHP and ENDCH must be set to 0 in 0x0B.

Table 4.28: Register configuration for address 0x0D when changing to forced discharge mode.

0x0D							
0	ECH	EPWR	NEASNR	E2V	SET		
0	0	**0**	0	0	**1**	**1**	**1**

Table 4.29: Register configuration for address 0x0B when changing to forced discharge mode.

0x0B							
EAWR	EVBCHP	NCHP	ENDCH	WINDOW		0	TDIV
1	**0**	0	**0**	1	1	0	1

The discharge can be activated by setting ECH in 0x0D to 1 and can be turned off when ECH is set to 0.

Table 4.30: Register configuration for address 0x0D when changing to forced discharge mode.

0x0D							
0	ECH	EPWR	NEASNR	E2V	SET		
0	**0/1**	**0**	0	0	**1**	**1**	**1**

High sensitivity
The High sensitivity mode is used when a 70 kHz/Gy read configuration is desired. The linear range for the radiation reads is between 50 kHz and 90 kHz in this mode. This is used as the initial configuration for the radiation sensor as the low sensitivity was found to be unuseful for radiation readings for the Lunar Zebro, see subsection 2.5.4.

The high sensitivity mode can be activated by setting SENS to 0 0 1 for address 0x0C.

Table 4.31: Register configuration for address 0x0C when changing to high sensitivity mode.

0x0C							
FCH	1	1	1	1	SENS		
0	1	1	1	1	**0**	**0**	**1**

Low sensitivity
The Low sensitivity mode is used when a 10 kHz/Gy read configuration is desired. The linear range for the radiation reads is between 140 kHz and 180 kHz in this mode.

The Low sensitivity mode can be activated by setting SENS to 1 0 0 for address 0x0C.

Table 4.32: Register configuration for address 0x0C when changing to low sensitivity mode.

0x0C							
FCH	**1**	**1**	**1**	**1**	**SENS**		
0	1	1	1	1	**1**	**0**	**0**

4.5.5. Firmware main loop

After the initial configurations for all IC's on the radiation payload have been completed, the main loop of the firmware can be initiated. Within this loop, all necessary measurements and commands must be integrated which the PCB requires to perform throughout the mission. The functions necessary within the firmware were already discussed in section 3.7 via a breakdown structure and a flow chart, see Figure 3.6 and Figure 3.7. These figures focused on the completed version of the radiation payload, while this section will focus on the prototype version. This resulted predominantly in the lack of housekeeping firmware being written as this requires temperature and power sensors to be installed, both of which are not in the prototype PCB.

The firmware used for the PCB prototype can be found at **the Delfi-Group GitLab**. It consists of three files to make the firmware operate. The Library sensor.c file serves to define all functions which are used within the main loop. The Library Sensor.h file serves to define all macros and initialize all functions and libraries used in the main loop. Finally, the Main.c file contains the configurations and main loop of the firmware which includes all the functions, definitions and libraries earlier mentioned in Library Sensor.c and Library Sensor.h. All these files are required in order for the firmware to operate.

The main loop can be summarized by means of Figure 4.49. Keep in mind that every initialization, read and command has to be performed twice in order to have both sensors in the FGD-03F used. The main loop is based on the quick set-up recommendations made by the FGD-03F manual [2].

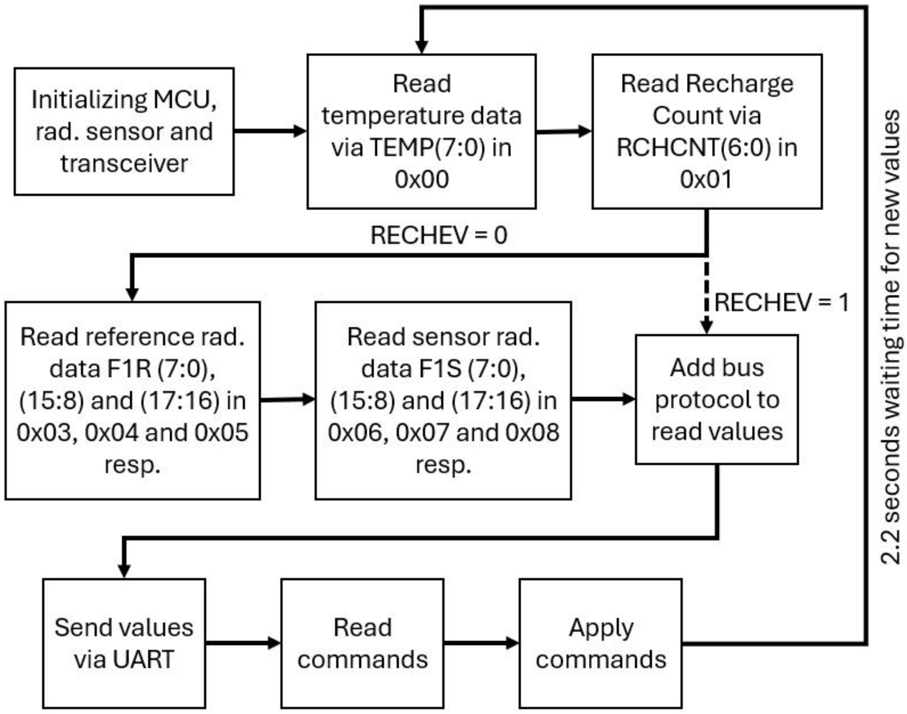


Figure 4.49: Firmware loop of the prototype radiation payload

The sensor selection is performed via the Slave Select line seen in Figure 4.12. The radiation sensor is able to measure three types of data: the temperature, the sensor frequency (an interpretation of the radiation measurements) and the recharge count. The temperature measurements are used to compensate for temperature affects on the radiation measurements. As no temperature tests have been performed in this project due to time constraints, no temperature post-processing firmware has been written. The calculations according to the FGD-03F manual are however explained in Appendix F. As explained in Table 4.13, address 0x00 allows one to read the temperature data by means of signal TEMP(7:0).

The measured frequency represents the radiation measurements taken by the sensor. These are split up into two measurements: one which is not affected by radiation dose (signal F1R), and ones who is affected by radiation dose (signal F1S). Both signals are longer than 8 bits and require to be read over multiple addresses (18 bits in total). For F1R this is performed at 0x03 (8 bits), 0x04 (8 bits) and the last two bits of 0x05 (2 bits). For F1S this is performed at 0x06 (8 bits), 0x07 (8 bits) and the last two bits of 0x08 (2 bits). In subsection 4.5.6 it is explained how one goes from the measured frequency to the actual radiation measurements.

The recharge count allows one to perform measurements over longer periods as it is made clear when the last measurement had taken place. The recharge count needs to be manually reset as explained in Table 4.13, meaning a function is set which will reset the value once it hits the maximum of 127 recharges (0x7F in Hexadecimal).

According to the FGD-03F manual, it is not recommended to keep radiation measurement values while the sensor is recharging as the measurements will become inaccurate. Once the sensor recharges, the register RECHEV in address 0x01 will become 1. This means that whenever RECHEV = 1, the radiation measurements must be discarded. This is shown in the firmware loop Figure 4.49 via the dotted line.

The collected data requires to be changed into the bus protocol used by the OBC. This is unknown at this point, but a simple protocol was used to read data for testing. The following protocol was defined: State either 'S1' or 'S2', 'Temperature:' Temperature value, 'Recharge count:' Recharge count value, 'Reference Radiation frequency:' frequency value, 'Sensor Radiation frequency:' frequency value. The statement of S1 or S2 defines which sensor reads are taken. By means of the protocol the OBC or computer firmware can detect what is considered to be the temperature, recharge count and frequencies.

The command function is used to receive commands from the OBC to alter configurations or receive measurement data from the sensor. The command function uses polling to be activated, similar to what has been used in the Lunar Zebro firmware. This means that every loop the status of the command function is checked to see if a new command is given by the OBC. The other option would be to receive commands via interrupts, removing the constant check-ups from the code. As the firmware for the prototype PCB is kept simplistic to prevent the project from overextending, the polling method is used. It is however recommended to look into interrupts for the full version of the radiation PCB to make the firmware more efficient.

The following commands are used to operate the command function. All commands are used twice as they are separately used for the two sensors which are integrated into the FGD-03F. Some of these commands have already been introduced in subsection 4.5.4:

1. Collect all data: Collects all data measured within the same loop. This includes the sensor frequencies, reference frequencies, temperature and recharge count.
2. Collect Target and Threshold: Collects the Target and threshold frequencies calculated. This is necessary to see if the linear range (whether set to high or low sensitivity) is met.
3. Change NSTBY: Used if standby mode is wished to be activated.
4. Change sensitivity: Changes the sensitivity between low or high if required.
5. Manual Recharging: Used for the manual recharging mode of the radiation sensor.
6. Automatic recharging: Used for automatic recharging of the radiation sensor.
7. Discharging: Used for simulating radiation measurements for debugging. Discharging can be stopped or started via this command.
8. Reset: Resets the whole system if required. Can be helpful in debugging or removing anomalies in the system.
9. Change initial configuration: Changes the initial configurations of the system the next time it is reset. This helps when a certain configuration must be set at the start of the first measurement after a reset.

4.5.6. Post-processing data

Calculating sensor frequency and radiation

The data send via UART is collected via a Python script (Appendix E) which organizes it into an Excel file. These contain for each sensor the timestamp of the UART read, the temperature, sensor recharge count, reference frequency, sensor frequency, the configurations of the sensor (window pulses, but could be expanded with for example TDIV setting, NSTBY setting), and additional comments regarding any mode changes. An example of such readings can be found in Figure 4.50.

Timestamp	Sensor	Temperature (Â°C)	Recharge Count	g_window_pulses	Reference	Sensor Radiation
16/04/2025 16:34	NSS 1	86	0	4096	66436	293548
16/04/2025 16:34	NSS 2	88	0	4096	74264	266929
16/04/2025 16:34	NSS 1	86	0	4096	66360	293685
16/04/2025 16:34	NSS 2	88	0	4096	74295	266807
16/04/2025 16:34	NSS 1	86	0	4096	66360	293655
16/04/2025 16:34	NSS 2	88	0	4096	74249	266891
16/04/2025 16:38	NSS 2	88	0	4096	74272	266738
16/04/2025 16:38	NSS 1	86	0	4096	66413	293418
16/04/2025 16:38	NSS 2	88	0	4096	74302	266746
16/04/2025 16:38	NSS 1	86	0	4096	66398	293495
16/04/2025 16:39	NSS 2	88	0	4096	74241	266731
16/04/2025 16:39	NSS 1	86	0	4096	66452	293396

Figure 4.50: Example of capturing UART data via Python script to Excel, see Appendix E for an example script.

The radiation measurements are read as frequencies. These can be converted to a more traditional unit 'Gray' (Gy) via Equation 4.5 given by the FGD-03F manual [2].

$$Radiation(Gy) = \frac{(F(sensor)_n - F(sensor)_{n-1})(Hz)}{SENSITIVITY(Hz/Gy)} \tag{4.5}$$

The sensor frequency data is obtained from the sensor via the SPI and UART transmissions. If no temperature compensation wishes to be performed, the sensor frequency will be equal to the sensor register data from F1S (17:0) multiplied by the clock frequency, divided by the window pulses. See Equation 4.6 for the equation:

$$Sensorfrequency(F_n) = \frac{F1S(17:0)}{WINDOWPULSES} * f_{ck} \tag{4.6}$$

In which fck is 32.768 kHz as this is equal to the frequency given by the external clock. WINDOW PULSES is chosen via register WINDOW in address 0x0B of the sensor. This can either be 32768 CK, 16384 CK, 8192 CK or 4096 CK. For the readings performed in this thesis the 4096 CK is used as this gives the quickest transmissions possible from the sensor. Equation 4.6 is performed within the firmware of the MCU while Equation 4.5 is performed within the Python script.

Important to the calculations is the definition of F1S (and therefore automatically also F1R). The F1S consists of 18 bits as described by the "(17:0)" description. The order is defined as to start with bit 17 and ending with bit 0. This means that the bits at the front are the bits from the last register read related to the F1S values. F1S is read through addresses 0x06, 0x07 and 0x08. Both 0x06 and 0x07 have 8 bits of data of F1S, while 0x08 has only 2 bits. The order (17:0) states that the 2 bits of 0x08 must be in the front, afterwards the 8 bits of 0x07 and lastly the 8 bits of 0x06. This may seem obvious to some, but to prevent mistakes it is still mentioned.

The SENSITIVITY is obtained from the sensitivity configuration taken from SENS at address 0x0C. If High sensitivity is chosen, 70 kHz/Gy is enabled. If low sensitivity is chosen, 10 kHz/Gy is enabled. The Fn and Fn-1, respectively, represent the present and previous reading of the sensor frequency. The difference between these two represent the discharge created by the radiation intake of the sensor.

4.5.7. Firmware conclusion

The firmware development for the detailed design phase has concluded. The result is a firmware written in C++ for the STM32CUBEMX IDE which can be uploaded onto the radiation payload PCB prototype of subsection 4.4.4, Figure 4.41. The firmware is able to:

- Initialize all IC's installed onto the prototype PCB
- Run a loop which reads radiation, temperature and recharge count data of the radiation sensor. See Figure 4.49 for a visualization.
- Send the data via the main connector or J-link to another device (either a computer or OBC)
- Retrieve and act upon preconfigured commands

This results in firmware which can be uploaded onto the prototype PCB to examine and test the capabilities of the radiation sensor. Debugging of the firmware can mostly be performed once the firmware is uploaded onto the PCB. As both the hardware and firmware of the prototype are completed, the debugging and testing phase can be entered.

4.6. Conclusion: Detailed design

The concept design phase,chapter 3, ended in a concept design of both the hardware and firmware of the radiation payload. These were both represented by means of a breakdown structure and a flow chart, to which the hardware also included a concept architecture, Figure 3.5. The goal of chapter 4 was to create a detailed, testable version of this concept design. Due to time constraints it was however not possible to create a test design which fully represented the radiation payload, including all expected IC's. For this reason the detailed design phase was split up into two sections:

1. The completed hardware selection and architecture radiation payload design.
2. The prototype PCB and firmware development radiation payload design.

At first, all required components for the completed radiation payload design were selected. This was performed by means of trade-offs or simpler selections based on set requirements, see section 4.3. This resulted in a hardware selection and completed hardware architecture seen in Figure 4.9. The component selection also adhered to the power requirements, see Table 4.11.

As the radiation sensor is the most important and complex IC within the payload, it was decided that only IC's will be installed onto the prototype PCB which are necessary for the radiation sensor to operate. This concluded in the architect seen in Figure 4.10. Based on this design, a detailed architecture and PCB schematic were developed. These designs also included several debugging tools like LEDS and connectors to make debugging and testing easier. The PCB design and IC's were ordered and soldered, resulting in the completed PCB prototype seen in Figure 4.41.

Firmware has been written to initialize all IC's of the prototype PCB and to configure the main loop of the radiation measurements. The firmware is made to work with the prototype, but can be used for the completed version if further developed. The firmware is uploaded via a J-link connection to the PCB, see Figure 4.46. The firmware at first initializes all IC's after which it starts the main loop. The main loop collects radiation, temperature and recharge count measurements from the radiation sensor and sends them to the OBC (or computer). The firmware also allows the payload to receive commands from the OBC to change modes or send measurements.

The hardware and firmware together form the testable version of the prototype radiation payload. These tests are performed in chapter 5 and will conclude the radiation payload design for this project.

5 Verification and validation

5.1. Introduction verification and validation

The developments made in chapter 3 and chapter 4 resulted in the creation of a prototype PCB radiation payload with corresponding firmware. The functionality of this PCB has not been confirmed yet, as well as whether it adheres to the set requirements made in section 3.3. In this chapter, Verification and Validation, the adherence to the requirements and functionality of the prototype radiation payload are tested. If certain aspects of the project cannot be verified or validated, an explanation will be given regarding this anomaly together with a recommendation on the required actions needed to take. This is the final radiation payload development chapter of this report after which a conclusion and recommendations are made in chapter 6.

5.2. Verification

5.2.1. Definition of verification

Verification can be defined as a quality control process [76]. Verification is used to evaluate whether a system is able to operate from a technical point of view. The verification of the radiation payload will focus on testing the basic working principles of the system. The end result should be an integrated hardware and firmware design of the radiation payload which is able to be configured for mission tests. These mission tests are required to be performed in the validation section.
The verification tests are the following:

- Hardware and firmware integration debugging
- Power distribution tests
- Basic GPIO and UART communication tests of the MCU
- Clock signal tests
- SPI communication tests of the radiation sensor
- Configuration tests via SPI of the radiation sensor
- Command functionality tests

5.2.2. Hardware and firmware integration

During the verification process, many anomalies are able to occur. During the integration of the hardware and the firmware it often becomes the questions whether the anomaly is caused by a hardware issue or a firmware issue. A firmware issue is most of the time easier to solve as code can be re-uploaded during this design phase. A hardware issue is more problematic as this may require re-soldering or even redesigning the PCB. Redesigning is undesired as this will require a new PCB to be ordered which costs time and budget.

To prevent anomalies caused by hardware as much as possible, a check-up should be performed on the soldered PCB. Any manufacturing mistake should be removed before firmware check-ups are performed. Below are the most common hardware anomalies found within this project examined. After the hardware anomalies, a few common firmware anomalies are shared as well.

Solder Bridges: Excess solder shorting two adjacent pads
Solder bridges, Figure 5.1, can be visibly inspected via a microscope, but are still difficult to detect as the short circuits can also arise under the IC's. The best preventive action is to use a stencil that is not too thick (100 micrometers or less) with a stencil area which is slightly smaller than physically possible for the IC pins. This decreases the solder paste on the board, preventing excess solder paste to create solder bridges. Even if the paste bridges over from pin to pin, the likelihood of a short circuit is still not guaranteed, as the paste most of the time is not fully conductive. Removing excess solder

paste can be done with a copper solder braid, which when heated, can absorb bits of paste. If the IC lays correctly on top of the PCB layout, the copper braid should not absorb much underneath the IC connection. Scratching short circuits off of the PCB between pins may also be necessary if the area is too small for the copper solder braid to work. This must be performed under a microscope as otherwise damage may be done to the board.

Components with most solder bridges anomalies were the MCU, translator, FGD-03F and the FGD-03F external oscillator. This predominantly because of the small pin spaces between most of these components, creating a solder bridge with only slight misalignment.

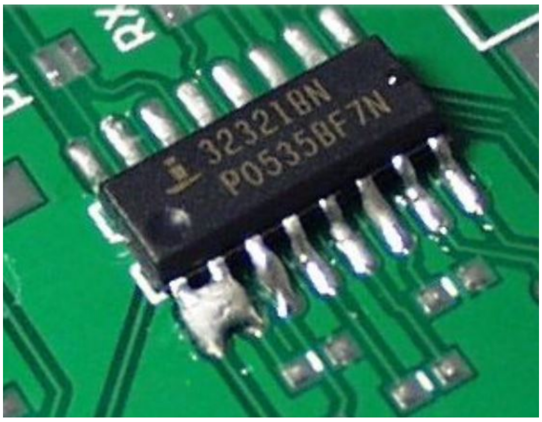


Figure 5.1: Example of solder bridge at IC [77]

Tombstoning: Small components standing upright due to uneven heating
Tombstoning, Figure 5.2, occurs when either the solder paste or the IC is incorrectly placed onto the PCB solder print. It must also be checked whether the packaging of the IC is the same as the one used for the PCB design. If these are different, the paste will not align and tombstoning will occur, causing the IC to not be connected onto the PCB. Tombstoning can be prevented by using the minimum required amount of paste, aligning the IC's correctly with the board and double checking whether the correct packaging is used compared to the PCB print. Tombstoned IC's can be reheated and removed from the PCB when necessary.

Tombstoning can most easily occur in small components like capacitors as these are lightweight and can have difficulty sticking to the solder paste.

Figure 5.2: Example of tombstoning at a capacitor [78]

Misaligned Components: Placement errors
This can be prevented by looking at the alignment marks on the IC's, often marked as a circle, see Figure 5.3. These alignment marks should also be designed onto the PCB itself in order to lower the chances of misalignment. Components like the LED's also have a specific direction they should be aligned to which is marked on the backside of the IC. The IC's manual should be used when it is unsure which direction the IC should be aligned with respect to the IC.

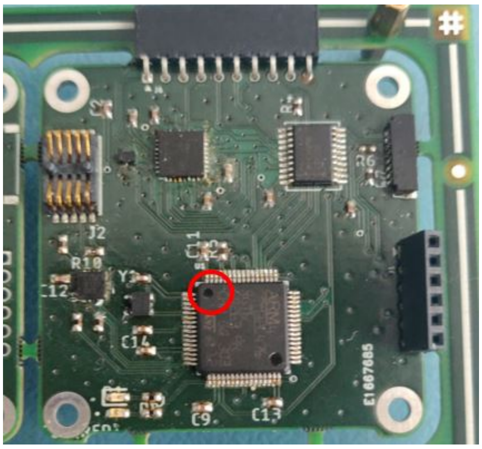


Figure 5.3: Orientation mark of IC. Other IC's also include this mark

Firmware errors and pin configurations

The firmware check-ups are in itself more simplistic as most debugging will be done when the firmware is integrated with the hardware. In general, all errors statements within the firmware design must be removed as otherwise the firmware is not able to be uploaded onto the hardware. Whether the firmware functions as expected cannot be seen, but a firmware language error cannot be present during the integration. In addition, the most common firmware error found during the validation phase was regarding incorrect pin definitions for the MCU. Within the PCB design, the MCU is connected to several IC's which it requires to exchange data with. The pin connections made on the PCB must coincide with the connections made on the STM32CUBEMX IDE pin configurator, see Figure 5.4. As the configuration of the pins is made so easy within the IDE, it is also easy to make mistakes in defining the pins.

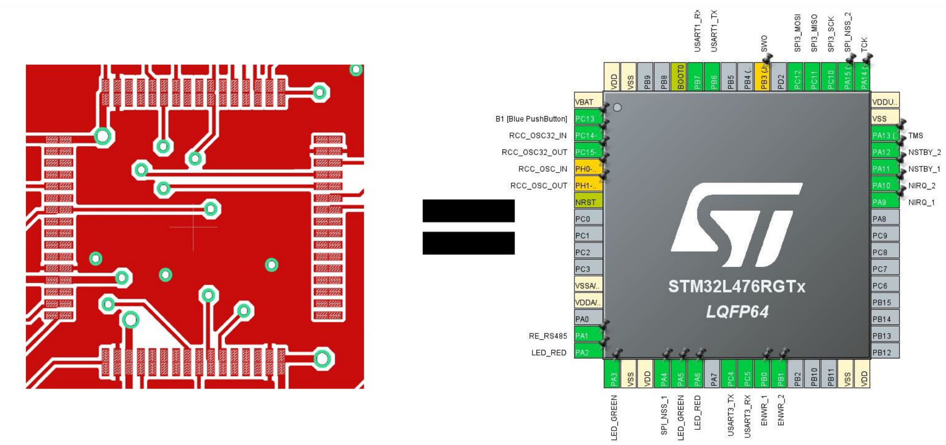


Figure 5.4: The PCB design pin configuration should be equal to the configuration made in STM32CUBEMX

Once the hardware and firmware have both been checked individually, they can be integrated together. The firmware is uploaded via the J-link, Figure 4.46. Once this is done, the radiation payload can be tested for its basic functionalities. This will be performed in steps, starting with easy tasks and building it up to its eventual design requirements.

5.2.3. Power tests

As stated in Figure 4.10, some of the radiation payload components require 5V to operate, others 3.3V. The prototype PCB model is made such that the 5V and 3.3V are given separately to the system without the need of an LDO. As the FGD-03F is the only major component on the PCB which uses 5V, the power tests can be separated in a 3.3V test and a 3.3V + 5V test. The 3.3V is given first, giving power to the MCU, clocks, transceiver and LED's. The 3.3V is provided via STM32L476RG NUCLEO board, see Figure 5.5 for the setup.

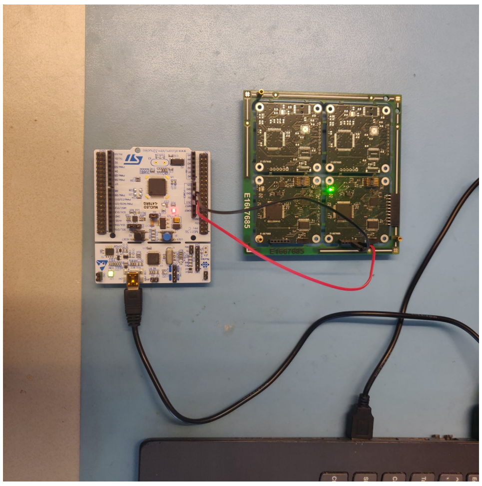


Figure 5.5: STM32 NUCLEO board providing 3.3V and ground to the prototype PCB

The power is tested in three ways:

- Measuring the voltage level on the PCB
- Measuring the temperature on the PCB
- Activating components on the PCB

Measuring the voltage levels on the PCB can be tricky if there is no dedicated connections through which this can be measured. Other techniques are to probe conductive sections of the PCB with a multimeter or oscilloscope which are connected to power lines. This was performed on the CON6 connector which showed a stable 3.3V signal. This however did not confirm every IC received its required 3.3V. This had to be checked by means of a thermal camera, see Figure 5.8.

Figure 5.6: Thermal camera used for power inspections

Figure 5.7: Thermal camera used to display heat concentrations

Figure 5.8: Thermal camera usage

The thermal camera is able to show hot spots on the PCB. Whenever a short circuits occurs the IC will most likely heat up. This was noticed with the external clock of the radiation sensor which also uses 3.3V. Due to its small size it becomes prone for short circuits. After resoldering the external clock the hot spot was removed, removing all hot spots from the PCB.

The last step of testing the power distribution is to activate the IC's to see whether they work. The MCU is the easiest to confirm as firmware is directly uploaded onto it. An LED attached to the MCU was activated by sending a command to pull its pins up. This resulted in the activation of the LED, see Figure 5.9, confirming the MCU is able to receive firmware and obtains its 3.3V.

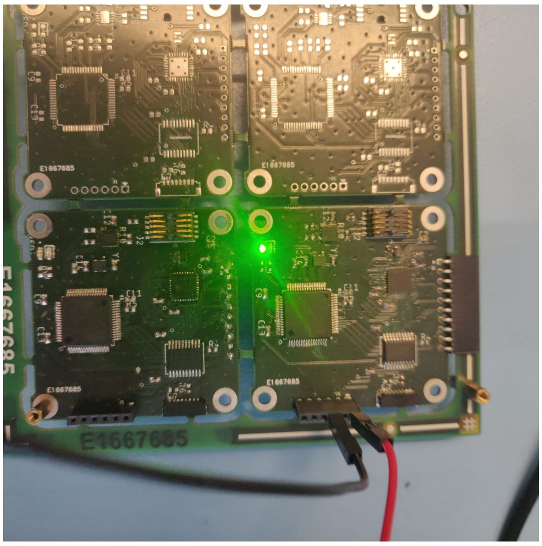


Figure 5.9: LED turned on to check MCU response. Power distribution to MCU can be confirmed

The 5V power supply is reviewed in the same way.The 5V is supplied by the CON10 connector seen in Figure 5.10. The 5V supply is measured via a multimeter to be around 5V. The thermal camera is used to check the hotspots of the board.

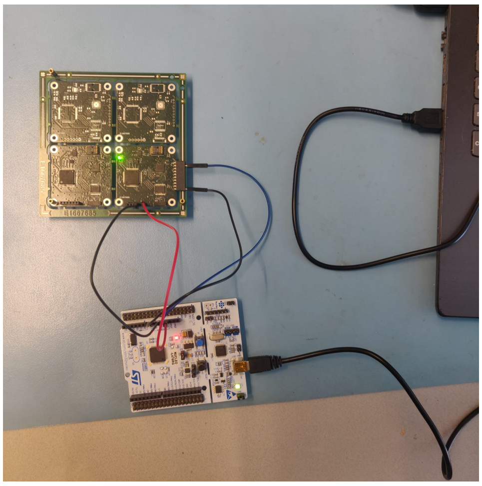


Figure 5.10: Both 3.3V (red) and 5V (blue) provided to radiation payload via STM32 NUCLEO board

In order to test the functionality of the components that use the 5V supply, in this case only the FGD-03F, the MCU must be turned on as well in order to initialize the FGD-03F. Before this is done however, the GPIO pins and UART communication need to be tested of the MCU.

5.2.4. GPIO and UART functionality MCU

The GPIO of the MCU can be most easily tested by means of toggling the LEDs. A loop code must be uploaded via the J-link connection which turns the pin connected to the two LED's on and off, showing the MCU its ability to toggle GPIO's. The LED's serve as a visual indicator. If the LED's do not respond, the MCU must be checked whether the correct pin is configured and toggled or whether hardware anomalies exist, see subsection 5.2.2.

The next step is to test whether the MCU can correctly send signals via UART to the OBC (or computer for this testing phase). The UART signals have for these tests been received via the J-link, Figure 5.11, instead of the transceiver and bus connector as the firmware related to these were not completed yet as explained in section 4.5. A code is send to the MCU which commands it to send arbitrary messages via UART to the computer. If everything is setup correctly, the message should be visible via a UART reading program like PuTTy [79] or Python on the computer, see Figure 5.12.

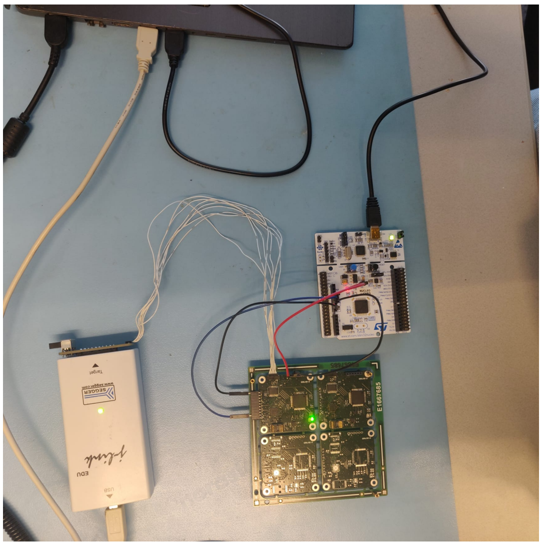


Figure 5.11: J-link connection to radiation payload to upload firmware and read UART data

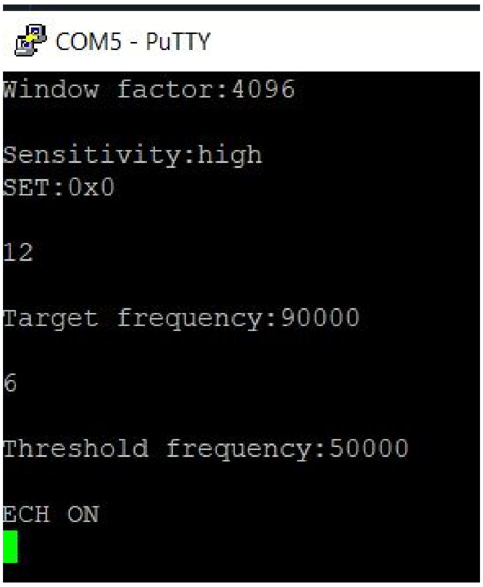


Figure 5.12: Arbitrary UART messages send to PuTTy. Can be used to potentially send measurements or mode status

Figure 5.13: J-link connection PCB

5.2.5. External clock testing

The external clock for both the MCU and the FGD-03F need to be checked whether their signals give a fitting clock frequency. This must be measured via an oscilloscope probing the clock outputs from the PCB. For the FGD-03F external clock this can be done via CON10 as the CK line is attached to the 7th pin, see Figure 5.14. The conductive material below can also be probed to measure the clock signal.

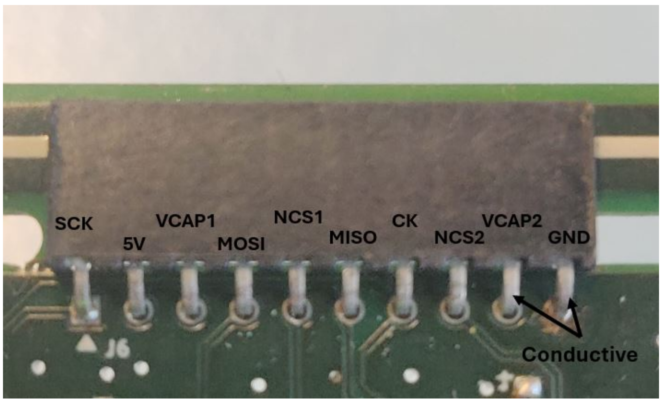


Figure 5.14: Connections of CON10 to be used for debugging

The MCU has already shown no anomalies within its operations so far, meaning either the external clock works as expected, or the internal MCU clock is used. The external clock of the FGD-03F did show anomalies in its first time use, see Figure 5.15. It was later found that a pull down resistor to ground of around 18 kOhm is required in order to obtain the correct clock signal. Nothing could be found in the external clock manual [63] which states this requirement, but this must be taken into account for a flight version of the radiation payload PCB. It has been fixed by connecting the resistor to the output clock connector towards ground, see Figure 5.16, Figure 5.18 and Figure 5.20 for a visualization of the fix and measurement process respectively.

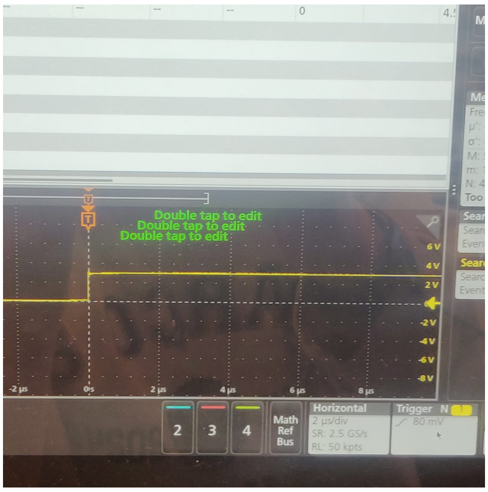


Figure 5.15: Initial reading clock frequency. No frequency readings

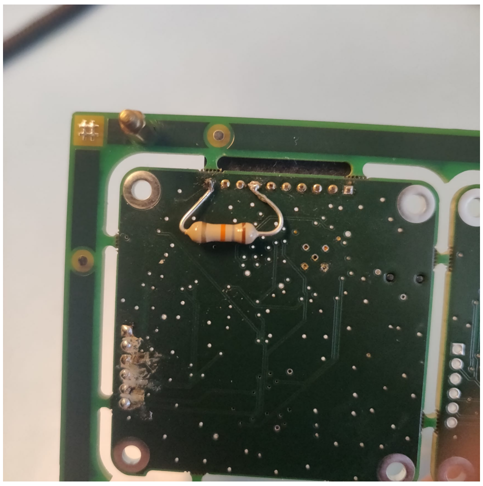


Figure 5.16: Addition of pull-down resistor between CK and ground. Fixes clock frequency

Figure 5.17: Anomalies in FD-03F external clock. Requires pull-down resistor

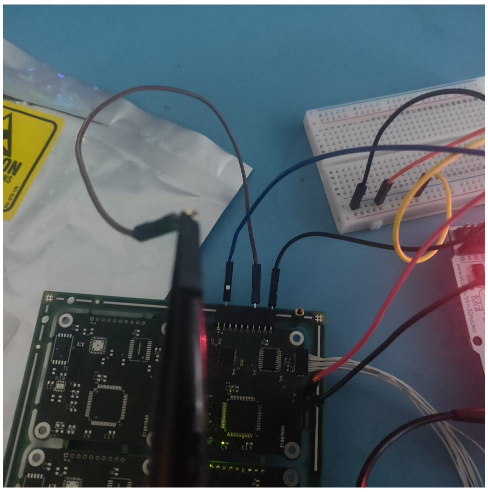


Figure 5.18: Measuring the CK signal via CON10 with the additional fix

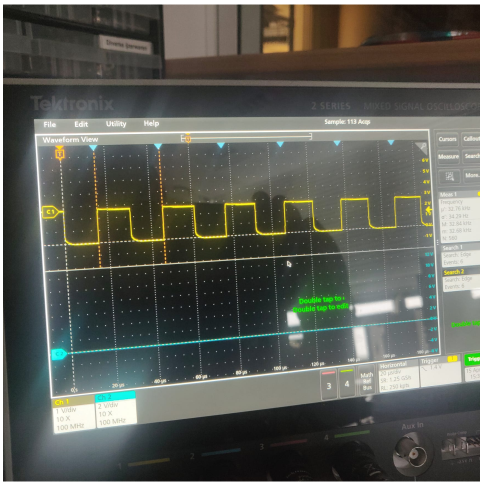


Figure 5.19: CK measurement shows clear frequency

Figure 5.20: Fixing of CK anomaly

If the 18k Ohm pull-down resistor is taken into account for the next iteration, the schematic of Figure 4.15 changes into Figure 5.21. This alters the PCB design slightly, but can for now be fixed by means of the hot fix seen in Figure 5.16.

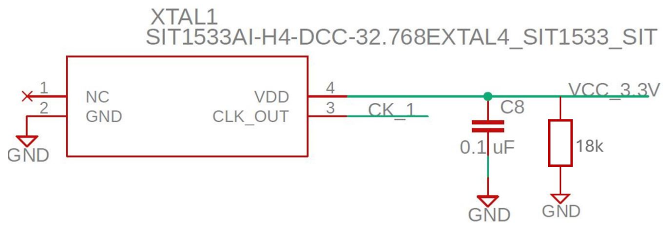


Figure 5.21: Altered schematic of external clock for FGD-03F. 18K Ohm resistor to ground added.

5.2.6. Reading data from FGD-03F

The radiation sensor basic functionalities were tested first via reading the registers from Table 4.13. This is accomplished by uploading firmware to the MCU which asks through SPI communication to send each address and register data to the MCU. The MCU will then send the data via UART through the J-link to the PuTTy software to be read on a computer. The FGD-03F consists out of two build-in radiation sensors which can be selected via the slave select. If the sensor is not used, the slave select pins are set high. If one does need to be used (for reading or sending SPI data) it requires to be set low. Before any measurements are taken, the MCU must specify which radiation sensor it would like to read by pulling one slave select low. The slave selection is checked via an oscilloscope to see if they are both pulled correctly during operation. If this can be confirmed, the SPI communication should work. The SCK, MISO and MOSI lines can also be double checked with the oscilloscope to see whether they correspond to the data sending request. All SPI lines can be measured via CON10 as shown before in Figure 5.14.

The register request is now able to be completed. The firmware written for the data request results in an array of data, stating the register address and the corresponding register values, see Figure 5.22. Whether the registers are read correctly can be checked via register address 0x13, which states the chipID. This is a standard value, being 0x81 for the version used in this project [2]. If 0x81 is not read, the firmware related to the register readout should be double checked.

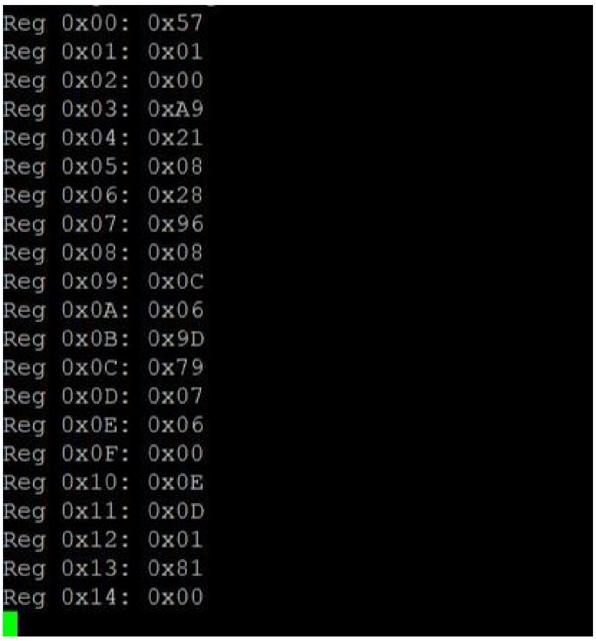


Figure 5.22: Reading FGD-03F sensor register data (sensor 1 of the 2). This is before any configuration is made via the firmware, meaning the configuration seen in the figure is arbitrary. Data is send via UART and read with PuTTy

5.2.7. Changing data from FGD-03F

The second step is to change the registers mentioned in Table 4.13. Only a few of these are able to be changed, namely 0x09 until 0x12 as the others are only read registers. As stated in subsection 4.5.4, the registers are changed in order to configure the radiation sensor into a certain mode. As of this, the initial configuration mentioned in subsection 4.5.3 is send via SPI through a new firmware upload. This results in Figure 5.23 which shows the change compared to Figure 5.22, showing the ability to change data.

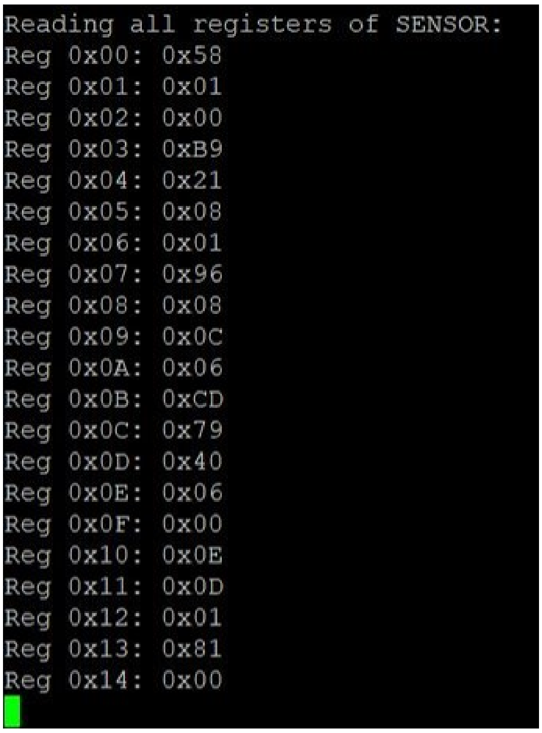


Figure 5.23: Initial configuration of the radiation payload. 0X0E should however initially be 0x04, not 0x06.

With this it can be seen whether these changes can also be made via a command, instead of uploading a new initial configuration constantly. This allows for mode changes during the mission.

5.2.8. Command tests

The prototype PCB has shown until now it is able to send and receive data to the FGD-03F. This means a loop can be created in which the sensor data is read, obtaining the basic functionality of the radiation sensor. The last functionality which will be checked is its ability to handle commands. Changing commands is of importance to change modes and to handle data requests. The possible mode changes are covered in subsection 4.5.4. These are integrated into the command firmware together with data requests. The OBC functionality is unclear of this moment yet, as for why the command system is made such that by pressing a single button on the computer, a command is send which either changes the registers or receives data from the registers.

In Figure 5.24 a simple command toggle can be seen between turning two LED's on and off one after the other. This shows the basic concept of the commands. Figure 5.25 shows a more practical command by retrieving all basic information the radiation sensor measures. As can be seen, it is possible to toggle between the two sensors build into the FGD-03F.

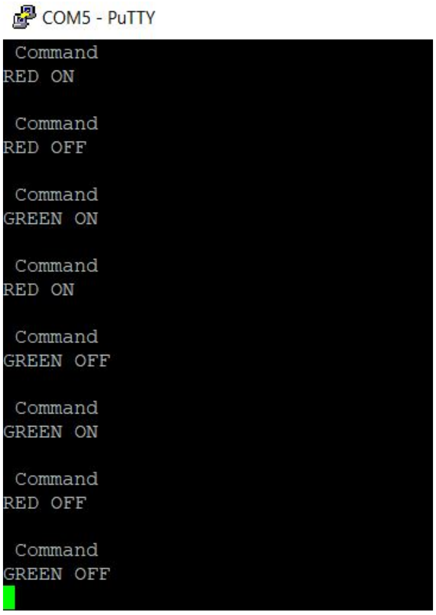


Figure 5.24: Simplistic LED command including UART communication of command

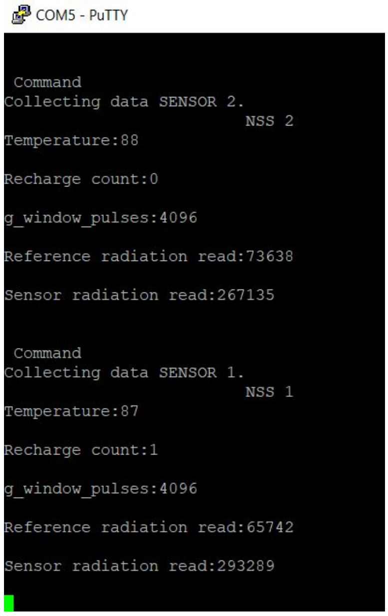


Figure 5.25: Measurement command which takes measurements, converts them to readable values, and sends them via UART to the computer

Figure 5.26: Different ways to utilize the commands for the radiation payload.

The commands can also be used for changing modes. The initial configuration of the FGD-03F can be seen in Figure 5.23. After sending the command to change it to manual recharging, Figure 5.27, the registers will look as in Figure 5.28. The changes in Address 0x0B, 0x0C and 0x0D are due to the mode change.

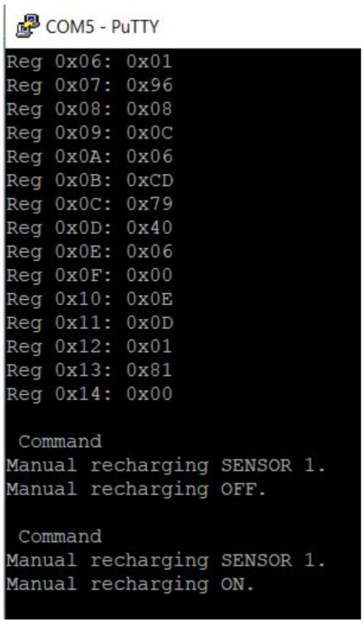


Figure 5.27: Command activated to turn on manual recharging mode

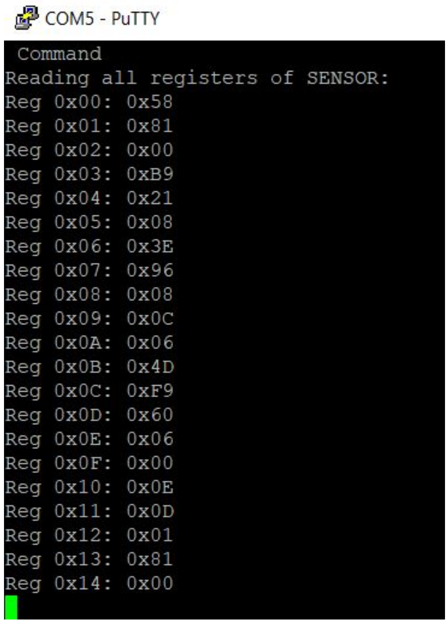


Figure 5.28: Changes in registers due to change in mode. See addresses 0x0B, 0x0C and 0x0D.

Figure 5.29: Activation of manual recharging command

5.2.9. Conclusion verification

The hardware and firmware for the prototype PCB have been integrated. Throughout the tests shown through the verification, it can be confirmed the radiation payload is able to control the basic functionalities of the radiation sensor. As the prototype PCB is able to read and write to the radiation sensor and is able to change its configurations via commands, the verification is considered completed for this prototype. More however will require to be tested in order to fully grasp the functionality of the created payload prototype. In the validation phase it will be validated whether the system is build such that it can satisfy the mission goals by satisfying the stakeholder and system requirements from section 3.3.

5.3. Validation

5.3.1. Definition of validation

The validation will focus on validating whether the produced system, in this case the prototype radiation payload, is able to achieve its missions goals. In literature [76] the validation part is often summarized as "the right system being build". This refers to the system following the requirements and achieving the mission goals stated in chapter 3. The verification portion only verified whether the system works, but not if the working system follows the requirements. In this section it is seen how the radiation payload can be validated and if the current version can be validated.

5.3.2. Automatic recharging and anomalies

To validate the radiation payload design, the firmware loop of Figure 4.49 is build with the working pieces from the verification. The radiation payload will first initialize every component according to the ones suggested in subsection 4.5.3, the measurements will be read for both radiation sensors inside of the FGD-03F, the data is send via the J-link to the computer and the commands are checked/executed.

Due to time constraints no real radiation tests could be used for this section. In subsection 4.5.4 it was explained a build-in discharger can be used to mimic the radiation discharge. This has been used for the validation instead of real radiation tests. The radiation sensor is first initialized to the configuration shown in subsection 4.5.3. Within this initialization the automatic recharging function is turned on. Afterwards, the radiation sensor is reconfigured through a command to activate the forced discharging mode seen in subsection 4.5.4. By means of ECH in address 0x0D, the discharge can be turned on and off.

The activation of the radiation discharge did unfortunately not result in a discharge of the radiation sensor as the radiation frequency readings kept being stable. This was confirmed by reading the VCAP pin in CON10 (Figure 5.14) which should result in an 18V read when the discharge is activated [2]. This however showed 0V, meaning the discharge is not activated. Longer discharging times were taken, but this did not result in any change. The FGD-03F developer, Sealicon, has been contacted, but this has not yet resulted in a solution.

The second option is to create a forced discharge is via an external power supply. The power supply must be attached to the VCAP pin (either 1 or 2 depending on the sensor) and give a voltage between 18V and 25V. A larger discharge could be able to activate the discharging capabilities of the sensor. Due to time constraints it however became unfortunately not possible to further test the discharge possibilities of the radiation sensor. This leaves the radiation payload design unclear whether it is possible to automatically recharge the system for radiation readings. This is a crucial activity of the radiation payload as without, it is not possible to make readings. The testing of the automatic recharging has to be continued either by fixing the discharge function of the prototype PCB, or to use actual radiation to enable a discharge. From that point it becomes possible to examine the automatic discharging capabilities of the radiation payload.

The anomalies noticed in the discharging mechanism are unfortunate as testing the automatic recharging would be of interest to the Lunar Zebro team as well. The Lunar Zebro development team shared information that their automatic recharging mode did not work properly. It is important to the Delfi-Twin mission to know whether this anomaly can be fixed as otherwise other methods require to be researched.

To circumvent the inability to automatically recharge, the Lunar Zebro team has created firmware which changes the manual recharging mode, see subsection 4.5.4, into an automatic recharging mode. The average of an X amount of radiation measurements are taken and seen whether it reaches the threshold value (discussed in subsection 2.3.4). If this is the case, the manual recharging will activate until the average value reaches the target value. Manual charging will be stopped and the cycle repeats. There will be some overshoot with the threshold and target values, but according to the Lunar Zebro team this is not a problem for the radiation readings. When further tests are performed on the prototype PCB for the Delfi-Twin and the automatic recharging mode does not work as well, similar steps akin to the Lunar Zebro must be taken to circumvent the problem. It is however undesirable to not have the automatic recharging mode work once the satellite will operate in space, meaning contact must be held with Sealicon regarding this anomaly.

5.3.3. Further suggestions validation

The validation could unfortunately not be completed due to anomalies in the Discharging mode and time constraints of the project. Instead, further recommendations are given regarding the verification steps required to take in order to satisfy the completion of the prototype PCB for the radiation payload.

- Look into potential firmware anomalies for activating the internal discharge mode. Recheck the FGD-03F manual [2] for possible solutions.
- Examine short circuits or mistakes in the VCAP routing on the PCB.
- If none of these options fixes the internal discharge mode, contact Sealicon for further assistance. In the meantime, try to operate the discharge mode via an external power supply instead of using the internal discharger. The external voltage supply should start at 18V and can be gradually increased in steps if no discharge is seen. The maximum allowed voltage to be supplied is 25V according to the FGD-03F manual [2].
- If the discharger cannot be fixed with a power supply or contact with Sealicon, try real radiation tests to discharge the radiation payload. Previous projects have performed proton beam radiation tests (see subsection 2.5.3), but other methods are also possible.
- Initialize the firmware as suggested in subsection 4.5.3 and examine whether the automatic recharging works. If it does not, and no obvious fault can be found within the hardware or firmware design, contact Sealicon for further assistance. In the meantime, try to see if the manual recharging does work.
- If no solution can be found for the automatic recharging, try automating the manual recharge mode as suggested in chapter 5. This makes it possible to perform longer radiation tests without the need for automatic recharging.
- Contact with Sealicon is required in order to potentially fix the automatic recharging problem.

Once readings are able to be made with automatic recharging, the following tests will require to be performed:

- Basic radiation measurement loop test: Test the firmware loop seen in Figure 4.49 and search for anomalies to debug.
- Change modes throughout the radiation measurements and see how the data reacts
- Perform real radiation measurements and search for radiation anomalies akin to subsection 2.2.2.
- Test temperature variations on the radiation payload and research how the measurements change. Implement the temperature compensation of Appendix F if necessary.
- Check if readings are possible via the transceiver to see how this can be implemented in the firmware. The transceiver should be implemented such as explained in Appendix F.

This summarizes the steps required to consider the prototype of the radiation payload both verified and validated. The next step is to look into the stakeholder and system requirements to see whether they have been met.

5.3.4. Requirements checklist

Despite the difficulties in validating the radiation PCB design, the requirements can be checked to have a full list of what has been passed, partially passed or failed the requirements. Failings in the requirements will be further elaborated in how to solve them. At first the system requirements, Table 5.1, will be answered as these are more specific and easier to refer to in the report. Afterwards the stakeholder requirements are answered which will partially overlap with the system requirements.

Table 5.1: System requirements list of radiation payload (Updated)

Subject	Nr.	Requirement	Verification	Status	Discussion
Mission	MI-1	The payload should be able to measure radiation throughout the mission duration of at least 3 years.	Testing	Fail	No radiation tests were able to be completed in this report, see chapter 5. Due to this, nothing can be stated regarding the longevity of the radiation reads. The recommendations made for the validation must be followed in order to start with the radiation tests.
Mission	MI-2	The payload shall be able to give and receive commands from the OBC throughout the mission duration of at least 3 years.	Testing/ firmware design	Partial	Actual OBC tests have not been performed as no full integration tests can be done yet. Command testing has however worked via a computer, see chapter 5.
Mission	MI-3	The payload shall be able to change modes depending on the OBC requests.	Testing/ firmware design	Partial	Similar reasoning to MI-2. Modes were able to be changed via the commands, see chapter 5.
Mission	MI-4	The payload shall be able to shut-off when requested by the OBC.	Testing/ firmware design	Partial	Similar reasoning as MI-2 and MI-3. Via commands it is possible to turn on NSTBY mode which switches off the radiation sensor. The whole payload must be switched off via the PPU which is unclear as of this point.
Design	DE-1	The payload PCB design shall be confined within 42 by 42 mm (UPDATE: This has been changed to 45 x 47 x 8 mm).	Hardware design	Pass	This has been taken into account in subsection 4.4.3.
Design	DE-2	The payload PCB design shall use the same shape as the Delfi-PQ PCB (UPDATE: The design has been changed, see DE-1).	Hardware design	Pass	This has been taken into account in subsection 4.4.3.
Design	DE-3	The payload shall use the FGD-03F as the radiation sensor.	Hardware design	Pass	It has been designed in subsection 2.3.4 and partially tested in chapter 5.

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Subject	Nr.	Requirement	Verification	Status	Discussion
Design	DE-4	The payload shall use the STM32L476RG MCU as the main microcontroller.	Hardware design	Pass	It has been designed in subsection 2.3.4 and partially tested in chapter 5.
Design	DE-5	The payload shall use the TMP100 as the temperature sensor.	Hardware design	Partial	It has been taken into account for the flight model version in subsection 2.3.4, but has not been implemented in the prototype PCB. Making it a partial pass. After the radiation sensor has been tested a flight model should be build with the sensor included.
Design	DE-6	The payload shall use the INA226 as the voltage, current, and power sensor.	Hardware design	Partial	Similar answer as DE-5.
Design	DE-7	The payload shall use the FSI-105-03-G-D-AD connector to connect with the OBC.	Hardware design	Partial	This has been implemented in subsection 2.3.4 but could not be tested due to time constraints. The bus + transceiver should be tested on the prototype board.
Design	DE-8	The payload shall use an external watchdog timer which does not have an integrated voltage supervisor.	Hardware design	Partial	Similar answer as DE-5.
Design	DE-9	The payload shall, except for the radiation sensor, consist out of COTS components.	Hardware design	Pass	This has been proved in section 4.3 by only picking components from Mouser.
Design	DE-10	The components, except for the radiation sensor, shall be ordered from Mouser.	Hardware design	Pass	See section 4.3.
Interface	IN-1	The payload firmware shall be written in C++.	Firmware design	Pass	The STM32CUBEMx IDE only allows C or C++, as to why C++ is used for the firmware development. See subsection 2.3.4.
Interface	IN-2	The payload firmware shall be able to send radiation, temperature and power data to the OBC.	Firmware design/testing	Partial	Figure 5.25 showed that measurement data can be send via the prototype radiation board. As the temperature and power sensor are not implemented in the prototype version, it is only partially passed. The flight model version should by means of I2C connections send the sensor data to the MCU and send it similarly to what is seen in Figure 5.25.

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Subject	Nr.	Requirement	Verification	Status	Discussion
Interface	IN-3	The payload firmware shall be designed such that no additional coding is required to change payload configurations.	Firmware design/testing	Pass	As long as the commands are used, not additional steps require to be taken in order to change configurations. Adding additional commands does require code to be changed.
Interface	IN-4	The payload shall be able to provide 5V, or other voltage levels, to components which require them.	Hardware design/testing	Partial	In chapter 5 it was shown how the power is distributed through the payload and how the IC's respond. Because the LDO is not implemented in the prototype, this requirement is only partially passed. Tests regarding the LDO should clear whether the voltage distribution fully works on the payload.
Safety	SA-1	1 The internal payloads shall be able to operate within temperatures of -35 to 35 degrees Celsius	Partial	Partial	The components chosen in section 4.3 all have a temperature range equal or higher than the one required. It has however not been tested how the PCB will react to these temperature swings, meaning it is only considered partially passed. Tests similar to the ones for the Lunar Zebro, see subsection 2.5.3, are suggested to further understand the temperature resistance.
Safety	SA-2	The payload shall be able to operate within vacuum.	Testing/ hardware design	Partial	In section 4.3 it was noted some components were chosen based on their flight heritage. Vacuum chamber tests are for example recommended later in the development of the Delfi-Twin when all other payloads can be tested as well [80].
Safety	SA-3	The payload shall be able to withstand the flight loads of 14.1 g RMS.	Testing/ hardware design	Fail	No flight loads have been mentioned by the Delfi-group, and it is expected these flight loads must be withstood by the chassis of the satellite. The PCB structure itself will have to be predesigned on how to withstand the loads.
Safety	SA-4	The payload shall withstand around 3krad a year during operation.	Testing/ hardware design	Fail	Similar to MI-1, no radiation tests have been performed yet, meaning nothing can be said about this requirement.

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Subject	Nr.	Requirement	Verification	Status	Discussion
Safety	SA-5	The payload firmware shall detect anomalies within the measurements taken from the sensors.	Firmware design/ testing	Fail	The absence of temperature and power sensors make it difficult to develop firmware to detect anomalies surrounding these measurements. Once the flight model is developed, the readings of these two measurements must be used as key anomaly checkers.
Safety	SA-6	The payload firmware shall be able to reboot or shut-off when anomalies are detected.	Firmware design/ testing	Fail	Similar answer to SA-5. Shut offs are possible with requirement MI-4
Safety	SA-7	The radiation payload shall not exceed a total maximum power consumption of 1.5 W.	Hardware design	Pass	Table 4.11 shows the flight model power usage. Even with a safety factor, or if redundant components are added, the power supply will not exceed the limit. What is interesting is to test the phenomena seen in subsection 2.5.3 where the power increased with TID. It must be seen how much effect this has on the power supply.

Table 5.2: Radiation payload stakeholder requirements list

Requirement Nr.	Stakeholder	Requirement	Status	Description
Req.Def.1	TU Delft Team	The payload integration installment shall fit within the confined space of the Delfi-Twin.	Pass	Related Sys.Req: DE-1, DE-2. The requirements related to the PCB shape are made to fit inside of the Delfi-Twin, just as any payload which uses the same PCB shape.
Req.Def.2	TU Delft Team	The payload shall not exceed the power limit of the solar cells	Pass	Related Sys.Req: SA-7. Similar reasoning as related system requirement.
Req.Def.3	TU Delft Team	The payload shall work within the operational temperatures similar to the Delfi-PQ.	Partial	Related Sys.Req: SA-1. Similar reasoning as related system requirement.

Requirement Nr.	Stakeholder	Requirement	Status	Description
Req.Def.4	TU Delft Team	The payload shall be radiation tolerable.	Partial	Related Sys.Req: M-1, M-2, SA-4. Components chosen in section 4.3 are sometimes from previous space missions, meaning they have been exposed to space radiation before and have a higher chance of surviving. Radiation tests have however not been made yet, meaning these will still require to be performed to fully understand the potential anomalies, see chapter 5.
Req.Def.5	TU Delft Team	The payload shall only consist of COTS components.	Pass	Related Sys.Req: DE-9. Similar reasoning as related system requirement.
Req.Def.6	TU Delft Team	The payload integration hardware shall be operable within the vacuum of space.	Partial	Related Sys.Req: SA-2. Similar reasoning as related system requirement.
Req.Def.7	TU Delft Team	The payload shall make use of the STM32L476 microcontroller to operate and communicate with the radiation payload and the OBC.	Pass	Related Sys.Req: DE-4. Similar reasoning as related system requirement.
Req.Def.8	TU Delft Team	The payload integration shall make use of the TMP100 temperature sensor for internal temperature measurements.	Pass	Related Sys.Req: DE-5. Similar reasoning as related system requirement.
Req.Def.9	TU Delft Team	The payload integration shall make use of the INA226 voltage, current, and power consumption sensor for internal status measurements.	Pass	Related Sys.Req: DE-6. Similar reasoning as related system requirement.
Req.Def.10	TU Delft Team	The payload integration shall make use of a FSI-105-03-G-DAD bus connector from the MCU towards the OBC.	Pass	Related Sys.Req: DE-7. Similar reasoning as related system requirement.
Req.Def.11	TU Delft Team	The payload integration shall use a separate voltage supervisor, not one that is integrated.	Partial	Related Sys.Req: DE-8. Similar reasoning as related system requirement.
Req.Def.12	TU Delft Team	The integrated payload must be able to survive the launch loads.	Fail	Related Sys.Req: SA-3. Similar reasoning as related system requirement.

Requirement Nr.	Stakeholder	Requirement	Status	Description
Req.Def.13	TU Delft Team	The radiation payload shall be able to measure radiation and send this data to the OBC.	Partial	Related Sys.Req: MI-1, M-2, DE-3, IN-2. The payload is able to read the registers of the radiation sensors and send them to a computer, but it has not been checked whether these values are correct and whether the automatic recharging operates accordingly. This is the next step according to validation.
Req.Def.14	TU Delft Team	The radiation payload shall be able to change modes depending on the circumstances of the mission.	Pass	Related Sys.Req: MI-3, M-4, SA-5, SA-6. The commands explained in chapter 5 are able to change the modes discussed in subsection 4.5.4.
Req.Def.15	TU Delft Team	The payload system must be able to send and receive data to and from the OBC.	Partial	Related Sys.Req: MI-2, IN-2. Not much is known about the OBC, but commands are able to be perceived by the radiation payload via a computer.
Req.Def.16	TU Delft Team	The MCU must be able to send status measurements when requested from the OBC to the OBC.	Fail	Related Sys.Req: SA-5. The housekeeping firmware has not been developed yet as there are no temperature or power sensors installed onto the prototype PCB. This must be performed in the flight version.
Req.Def.17	TU Delft Team	The payload firmware must be made such that it is easy to use for outside users.	Pass	Related Sys.Req: IN-3. This has been interprated as making the radiation payload understand commands. Only the commands need to be activated in order for a mode change or measurement request for example, making the payload easy to use when activated.
Req.Def.18	TU Delft Team	The payload integration its power consumption should be as minimal as possible.	Partial	Related Sys.Req: SA-7
Req.ESA.1	ESA	The payload integration shall conform to the relevant ESA regulations.	Partial	Related Sys.Req: none. The ESA regulations should be integrated already into the Delfi-group requirements. Other requirements are not of importance to this project.
Req.Lau.1	Launcher provider	The payload integration shall conform to the launcher regulations.	Pass	Related Sys.Req: DE-1, DE-2. The Delfi-Twin must fit the launcher specifications. The size of the Delfi-Twin cannot be changed through this project, meaning as long as the payload fits inside the Delfi-Twin, it should also fit the launcher.

Requirement Nr.	Stakeholder	Requirement	Status	Description
Req.TUDec.1	TU Delft	The payload integration project shall provide new data and developments to the space radiation measurement industry.	Partial	Related Sys.Req: none. As the FGD-03F is already being developed for the Lunar Zebro, it is not a totally new development. However, the use inside of a PocketQube satellite with the size and power limitations given, makes it a new development in the integration of radiation payloads for PocketQubes. Because of this it is seen as partially passed.
Req.TUDec.2	TU Delft	The payload integration project shall provide educational value to the TU Delft and its students.	Pass	Related Sys.Req: none. The project helps in the development of the Delfi-Twin, resulting in a new PocketQube the TU-Delft will be able to launch. The Delfi-Twin creates new projects and opportunities for future students to work and develop on.

5.3.5. Conclusion validation

The validation of the prototype PCB radiation payload could not be fully satisfied due to anomalies in the discharging firmware, and most predominantly due to time constraints. Several suggestions have been given to further validate the radiation readings of the payload by means of using external power supplies, or using the manual recharging mode. The FGD-03F developer Sealicon should be contacted for further assistance regarding the setup of the radiation sensor configurations.

The review of the system and stakeholder requirements have shown that the radiation payload has adhered to most component, firmware and safety requirements. Additional tests related to temperature, vacuum and flight loads are however suggested further in the Delfi-Twin development. The requirements related to radiation tests and housekeeping data are the least adhered requirements. This due to the lacking validation and the removal of the temperature and power sensor of the prototype board. These sensors are required to create housekeeping firmware and should be further developed once the flight model is build.

5.4. Conclusion Verification and Validation

The verification and validation were used to confirm respectively whether the system works from a technical standpoint, and to confirm whether it is build such that it can accomplish the mission goals of the Delfi-Twin.

The verification showed the basic integration of the hardware and firmware components discussed in chapter 4. Common debugging techniques and anomalies were discussed in order for future builds to prevent them. The power tests showed the 3.3V and 5V supply being provided to all components. The GPIO and UART tests showed the basic functionalities of the MCU. The basic FGD-03F read and write tests showed how to configure the suggested initializations from section 4.5 and how to read data. During the debugging of the FGD-03F it was found that a pull-down resistor is needed for the external clock of the FGD-03F, this must be added to the next iteration of the PCB. Commands to change modes or request measurements were shown to operate via a computer, but could not confirm yet how the OBC would use this function. Concluding, the firmware and hardware developments have so far shown that they are verified to work and integrate together.

The validation was unfortunately halted due to anomalies and time constraints. The radiation payload was shown to work from a technical aspect in the verification portion, meaning with additional time it would be possible for the PCB to configure the radiation sensor such it would be flight ready. The main problem however was the inability to discharge the sensor to see whether the automatic recharging of the radiation sensor operated properly. The internal discharges could not be turned on and the remaining options of using an external power supply or using actual radiation were not possible due to time constraints. Suggestions have been made instead, requesting further research into the discharger to see whether an automatic recharge can be triggered by the radiation sensor. If not, contact needs to be made with the radiation developer as the automatic recharger is known for having problems in the Lunar Zebro project.

When reviewing the requirements made in section 3.3, it became clear most requirements related to hardware reviews, firmware development and safety were passed or partially passed. These were mostly also discussed within the verification portion of the report. The requirements related to radiation tests and housekeeping of the system were not met most of the time due to the lack of validation tests and additional sensors on the prototype PCB respectively. The prototype model should be tested until the full operation of the radiation sensor can be confirmed, after which a flight model can be made which adds the additional components of Figure 4.9 and focuses on housekeeping and maintenance within the firmware.

This concludes the verification and validation section of this report. The next section will conclude the findings of this report and recommend further developments to the radiation payload of the Delfi-Twin.

6 Conclusion and recommendations

6.1. Conclusion

The objective of the radiation payload design project had been summarized by means of the main research question which had been defined after the literature study. The answer to the main research question is to be considered the conclusion of this report. The following main research question had been made:

"What hardware and firmware designs need to be developed in order for the radiation payload to meet the mission requirements for the Delfi-Twin?".

To answer this question in an organized method, the main research question was split up into six sub research questions. All sub research question answers together are the answer to the main research question.

Sub research question 1: "What stakeholder and system requirements are essential for the radiation payload project?"

The main stakeholder during the project was the Delfi-group. The key stakeholder and system requirements were related to the mechanical constraints/tolerances of the radiation payload and the mission design goals.

- The mechanical payload requirements consisted of size constraints to fit the Delfi-Twin, power constraints to minimize power usage, radiation and temperature tolerances to operate within the space environment, and component constraints as the payload must be made by means of COTS components.
- The mission payload requirements were regarding the payloads ability to make radiation measurements and send these to Earth, and requirements related to the housekeeping and maintenance of the payload. The housekeeping is of importance to the autonomy of the satellite as it is estimated to operate for at least 3 years, requiring self-sustenance by means of detecting and preventing anomalies via the housekeeping system.

The requirements have been the main design focus of the radiation payload and have helped in organizing the system into multiple subsystems which helped in the development of the concept designs.

Sub research question 2: "Which hardware and firmware subsystems are critical to the operation of the radiation payload?"

For the hardware and firmware, the following subsystems were identified: Measurements, mechanical, command data handling, power and housekeeping.

- Measurements are directed to the mission requirements of being able to send radiation data to Earth. This must be achieved via a radiation sensor.
- Mechanical is related to the tolerance requirements. The payload must be able to tolerate radiation, vacuum, temperature and flight loads. This had to be done mostly via component selection, redundancies and firmware design as the size constraints did not allow for additional shielding to be installed.

- Command data handling is regarding the collection, storage and transfer of data within the payload. Without this system, no radiation data, or any kind of data, can be transferred through the system.
- Power relates to distribution and regulation of the power required for every subsystem component within the payload.
- Housekeeping relates to the mission goal of the satellite operating independently. Without much interaction from Earth, the satellite must be able to spot anomalies and take affirmative action via housekeeping firmware to prevent technical hazards for the satellite.

Based on the above, these subsystems represent the most important radiation payload hardware/-firmware subsystems. These were used to define a hardware and firmware concept architecture and flow diagram, representing an early concept design of the radiation payload.

Sub research question 3: "Which components best meet the radiation payload's system requirements?"

This questions further delves into the hardware design development of the radiation payload. Based on the subsystems made for question 2, the general components required for a working radiation payload could be identified.

- The measurements subsystem require a radiation sensor to achieve the mission goal. In addition, a temperature and power sensor are installed for housekeeping data management. If anomalies occur due to power consumption or temperature extremes, they will be able to be detected.
- The mechanical subsystem does not specify a certain component, but was seen as a requirement necessary for each component. The criteria of a chosen component should be partially based on its radiation, temperature, vacuum and flight load resistance.
- The command data and handling subsystem requires a microcontroller (MCU) to upload firmware which can configure all components and transfer data to their required location. In addition, a transceiver to communicate with the on board computer (OBC) of the satellite is needed in order to send measurements to the OBC and receive commands. Lastly, an external memory had been added to the design in order to store measurement data whenever they cannot be send to the OBC directly.
- The power subsystem requires a low dropout regulator in order to provide different voltage levels to components which requires them. The radiation sensor (FGD-03F) and MCU (STM32L467RG) respectively operate on 5V and 3.3V. As 5V is given by the satellite power unit, the dropout regulator is required to be installed. Moreover, in order to communicate between two voltage levels, a voltage translator is needed.
- Lastly, the housekeeping subsystem requires the installment of an external watchdog timer and a voltage supervisor. The watchdog timer checks whether the MCU still operates accordingly and gives a reset whenever this is not the case. The voltage supervisor does this as well, but only performs this action whenever a certain voltage level is crossed due to an anomaly. These two are needed in order for the MCU to work independently.

This summarizes all components installed onto the radiation payload, based on the subsystems and requirements found in question 1 and 2.

Sub research question 4: "What PCB design and layout best support the radiation payload's system requirements?"

The radiation payload concept design was designed into a PCB prototype in order to perform tests. Only the components that operate the FGD-03F radiation sensor were installed onto the prototype in order to save development time. This meant that only the radiation sensor, translator, MCU, transceiver and debugging devices were installed onto the prototype.

- A PCB schematic was made which determined all communication, power and ground connections of the prototype components.

- Once this had been defined, the schematic could be transferred into a PCB design in which the connections are physically made on the board. The PCB is designed with four layers. The top layer is used for quick signals like SPI and clocks, the second layer for purely ground, the third layer for power and the fourth layer for less fast connections.
- The PCB and its selected components were ordered and assembled by means of a soldering oven.

This concluded the prototype PCB design of the radiation payload. The development of the firmware makes it possible to configure and command the PCB prototype for testing.

Sub research question 5: ”What firmware design ensures autonomous and reliable operation of the radiation payload?”

The firmware design for the prototype PCB requires to independently take radiation measurements and send these to the OBC. The firmware development had to be divided into three sections: The configurations, the main loop and the commands.

- The configurations are related to configuring every component chosen for the prototype PCB via the firmware. The components are configured via the MCU and are activated once the power is provided to the PCB.
- After the components are configured, the main loop of the radiation payload firmware is activated. The main loop works as follows: the radiation sensor is read for radiation data. After the data is obtained, it is send to the MCU to check for anomalies. If the OBC commands the data, the data will be send to the oBC. If no commands are given, the data must be stored.
- After the data has been sent, the commands are checked. These tell the MCU to take a certain action and are given via the OBC. These can be to change initial configurations, change modes, or to give specific measurement or housekeeping data.

The detailed designs of both the hardware and firmware of the radiation payload have been completed. The integration of both systems and testing will determine whether the radiation payload is able to adhere to the requirements developed in question 1.

Sub research question 6: ”What tests are required to verify and validate that the radiation payload meets the stakeholder and system requirements?”

The verification and validation of the system have shown which tests are required to confirm the stated requirements.

- The verification focused on the testing of the basic functionality of the prototype PCB. The firmware was uploaded onto the PCB, after which power tests were conducted. These showed the PCB’s ability to give 3.3V and 5V to all components required. Afterwards, the basic response of the MCU was tested via basic GPIO and UART tests. The FGD-03F was tested on its SPI communication and initialization via the MCU as well. This resulted in the ability to read the payload registers and changing its configuration.
- Validation tests were used to show how the working prototype PCB is able to confirm to mission goals. This was tested via discharging the PCB to see if it is able to read the radiation measurements, charge automatically and send the measurements to the MCU for further analysis. The measurements were however not able to be taken due to anomalies in the discharging mechanism. Due to time constraints it was not possible to fully validate the system, and instead recommendations were made for future tests.
- Reviewing the requirements set at the start of the project, it became clear the requirements related to hardware selection, firmware, and safety are mostly satisfied due to the verification steps and design strategy. The requirements related to radiation measurements and housekeeping of the payload were mostly not satisfied due to the lack of radiation tests and housekeeping firmware development. The prototype PCB does not include temperature or power sensors, or watchdogs timers which can aid in the housekeeping firmware. As for this these are not satisfied.

Concluding:
The sub research questions together have summarized and answered the main research question of the radiation payload design project. The result of this project is a radiation payload prototype PCB design which includes firmware to operate its basic functionalities like taking measurements and retrieving commands. Tests to see if the radiation payload would work within a mission environment have not been performed unfortunately due to time constraints, limiting the validation of this project.

As the validation could not be completely performed and as this PCB does not represent the flight model of the radiation payload, recommendations are made to further develop this payload. These recommendations are made in section 6.2.

6.2. Recommendations

As the radiation payload PCB is not far enough in development to consider it the flight model, more research and work requires to be put into this design. Based on the findings of this report, the following recommendations are made for further development on the radiation payload for the Delfi-Twin. The recommendations are ordered on importance for the next development.

Most significant: Validation steps

- As the validation steps could not have been completed due to anomalies in the forced discharging mode, further debugging tests require to be made in order to fix the anomaly. The first option would be to use an external power supply attached to the VCAP connection to activate the discharging mode. The steps are similar to the internal discharging mode, but all steps are also explained in the FGD-03F manual [2] to activate this mode. Via the external discharging method it is possible to give a voltage supply up to 25 V to the system. According to Sealicon, the FGD-03F developer, the lower voltage supply of the internal discharge could have caused the problem
- If the discharging mode cannot be fixed, real radiation tests are recommended to be performed in order to see if the radiation sensor is able to read a discharge. Moreover, the automatic recharging mode configured must be validated as the Lunar Zebro tests have shown anomalies in this configuration. If radiation tests also do not cause a discharge in the system, contact with Sealicon is again required to find the anomaly.
- If discharging does occur, but no automatic recharging occurs, Sealicon should again be contacted to see if the radiation sensor is correctly configured.
- To circumvent the inability to use the automatic recharging mode, the manual recharging mode can be used via the commands. By taking a certain sampling size of the measured frequencies, a target and threshold value for the linear range of the radiation sensor can be stated to which the manual recharging must be activated. This creates an automatic recharging by means of using the manual recharging mode.
- If it is possible to send radiation measurements (whether from the discharging mode or actual radiation) automatically to the OBC, the prototype PCB will be considered validated.

Significant: Further testing of prototype PCB

- The transceiver firmware should be developed into the existing firmware of the radiation payload, akin to what is stated in Appendix F.
- Real radiation tests have to be conducted to test the radiation measurements for radiation anomalies. TID, SEE's and DD phenomena must be researched to see whether anomalies occur and how to mitigate them.
- Temperature tests should afterwards be performed to see how the measurements and power consumption change with an increase or cycle of temperature. Combined radiation and temperature tests are also recommended.
- Based on the results of the temperature tests, the post-processing of the radiation measurements must be developed akin to what is stated in Appendix F.
- Based on the radiation tests, further research must be conducted in necessary housekeeping firmware and redundancies of components.

Remaining: development of flight model

System engineering:

- As the Delfi-Twin development in all areas progresses, more will be known regarding the constraints which the radiation payload needs to apply too. Revise the power consumption, flight loads, and radiation tolerance requirements.
- Progress in the Delfi-Twin development will also allow more information regarding the mission design. Specify the mission duration and set requirements for how long the radiation payload must last within the mission environment.
- Update the mission orbit to the final version to see whether this has affect on the space environment requirements.
- Update the breakdown structure of the Delfi-Twin with the additional payloads.
- Revisit the risk matrix and change it depending on the amount of changes within the system engineering section.

Detailed design:

- Based on further calculations performed on the prototype PCB radiation payload, calculate the estimated external FRAM size to confirm whether the chosen external memory, the MB85RS1MTPNF with 1MB of memory, is sufficient for the mission goals.
- Add an external LSE clock to the MCU. Until now only a HSE has been implemented, but an LSE could also provide a more stable clock for clock signals which require a lower frequency.
- Check the addition of redundant components to the radiation payload. The FGD-03F radiation sensor has a second radiation sensor build in already, so no redundant system would be required. Temperature sensors, V/I/P sensors, watchdog timers or low dropout regualtors could be of interest.
- Recalculate power requirements. The addition of a LSE or redundant components should not increase the power by much, but development in the Delfi-Twin itself may change the power requirements themselves.
- All components chosen within the section 4.3 must be implemented in the component schematic. This will define the full flight model of the radiation payload, not the prototype version. The debug connections and LED's can be moved or removed to make space for the additional components.
- The PCB design for the flight model should make use of the new shape the Delfi-Group uses, Figure 4.23.
- The PCB design requires to be redesigned to accommodate the components which have not been installed yet. It is suggested to keep the four layer routing as this allows for more space and separates high speed signals from other signals. When the redesign is made, make sure the routing on the top layer are as short as possible with as little vias as possible. If this is not applied it may cause anomalies within the high speed signals.
- As the J-link connection has shown no problems, the other connector used, CON 6, can be removed from the debugging interface. The 3.3V port does have to be relocated.
- In chapter 5 it was concluded that the external oscillator used at the radiation sensor requires a pull-down resistor of 18 kOhm to ground in order to prevent the clock from floating. This has to be added to the schematic if the same clock will be used.
- Make the 100 micrometer soldering sheet holes slightly smaller than necessary to prevent over use of paste which causes short circuits.
- Firmware initializations and configurations require to be made for each newly added component which requires such procedures.
- If known, the OBC bus protocol needs to be added whenever data is send to the OBC or vice versa. As of yet this is unknown.
- Firmware related to the storage of the measurement data requires to be written. The firmware must decide based on certain criteria whether the measurements are send to the OBC or stored in the external memory.

- The housekeeping and maintenance firmware needs to be updated in including the temperature and power measurements. These need to correspond to anomaly thresholds which trigger either a reboot or a shut-off of a component.
- The efficiency of the radiation payload can potentially be increased by switching between normal mode and passive/standby mode. The optimal duty cycle needs to be determined which balances between the minimum amount of data readings necessary and the energy savings.
- Radiation simulations can be made once more is known regarding the mission orbit the satellite will take. With these simulations using for example SPENVIS [81], it is possible acquire a rough idea on what radiation dose can be expected during the mission and of what type. The radiation tests can afterwards be based on these simulations to see whether the radiation payload (and the whole satellite itself) are capable of withstanding the environmental hazards.

6.3. Future look on the project

The project has resulted in a prototype radiation payload which is able to perform its basic tasks, but has not yet been validated for its main mission purposes. As of the lack of validation and the fact that this is not the flight model, a lot of work still requires to be done in order to fully complete this payload for the Delfi-Twin mission. The work performed however does show potential as the prototype does work for its most fundamental communication components. The radiation sensor its malfunctions are unfortunate, but nothing shows yet that this is due to a fundamental mistake in the design. The time constraints and therefore lack of additional testing is the key reason this validation has not been completed yet. There is confidence that with future developments that follow the recommendations made in this chapter, a solution can be found for the radiation sensor anomalies.

In addition to the developments in this project, the Lunar Zebro has also further developed their radiation payload using the FGD-03F. These developments should be followed for this payloads future development as they show the potential benefits and also downsides of using this radiation sensor. Keep in mind that the Lunar Zebro is developed for a Moon mission, meaning it will have different environmental criteria than the Delfi-Twin. Despite this, the development of the Lunar Zebro radiation payload looks positive as multiple radiation tests have been made which shows the capabilities of the radiation payload.

Concluding, despite the lack of validation, the current state of the prototype payload and current development of the Lunar Zebro radiation payload both show a positive outlook for the use of the FGD-03F radiation sensor for space radiation measurements. The further development of the radiation payload are eagerly anticipated for a potential integration in the Delfi-Twin for a 2027 launch. It is hoped that the radiation payload integration will be able to increase our current understanding of space radiation and potentially mitigate anomalies for future space mission for both satellites and humans.

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A Component list prototype PCB

How many boards are going to be manufactured					5	BOARD NAME AND VERSION		Programming Board v1		Board Price for Electronics (rougly)					203.46
Manufacturer Part No	Element	Value	Package Size	Project	System/ Device	Reference Designator	Purpose	Relation with another component	Provider	Provider Order Code	Quantity Per Board	Total Quantity	Unit Price (EURO)	Min Order	Price Sum (BTW inc.)
STM32L476RGT6	MCU		LQFP-64	Delfi-twin	Rad sensor	MCU:U1			Mouser	511-STM32L476RGT6	1	5	10.02	5	50.1
DF52-8S-0.8H (21)	Connector	8 pin		Delfi-twin		MCU:J1			Mouser	798-DF52-8S-0.8H21	1	5	0.525	5	2.625
SQT-106-01-L-S	Connector	6 pin		Delfi-twin		MCU:J2			Mouser	200-SQT10601LS	1	5	1.87	5	9.35
SQT-110-01-L-S-RA	Connector	10 pin		Delfi-twin		MCU:J3			Mouser	200-SQT11001LSRA	1	5	2.33	5	11.65
ERA2AED103X	Resistor	10k	0402	Delfi-twin		MCU:R1, RS4:R1			Mouser	667-ERA-2AED103X	2	10	0.054	30	1.62
CGA2B3X7R1E104K050BB	Capacitor	0.1u	0402	Delfi-twin		MCU:C1, MCU:C2, MCU:C3, MCU:C4, MCU:C5, TRAN:C1, TRAN:C2, RAD:C1, RAD:C2, RAD:C3, RAD:C4, OSC1:C1, OSC2:C1, RS4:C1			Mouser	810-CGA2B3X7R1E104K	14	70	0.027	100	2.7
MAX3001EEUP+	Voltage translator	8 pin	TSSOP-20	Delfi-twin		TRAN:U1			Mouser	700-MAX3001EEUP	1	5	8.01	5	40.05
ASDMB-8.000MHZ-LC-T	Oscillator	8 MHz	QFN-4	Delfi-twin		OSC1:U1			Mouser	815-ASDMB-8MHZ-LC	1	5	2.4	5	12
SiT1533AI-H4-DCC-32.768E	Oscillator	32.768 kHz	2 mm x 1.2 mm	Delfi-twin		OSC2:U1			Mouser	788-1533AIH4DCC32.76	1	5	0.818	5	4.09
LTC2850IDD#PBF	RRS485 TRX	Half Dublex	DFN-8	Delfi-twin		RS4:U1			Mouser	584-LTC2850IDD#PBF	1	5	6.35	5	31.75
FSI-105-03-G-D-AD	Connector	10 pin		Delfi-twin		RS4:J1			Mouser	200-FSI10503GDAD	1	5	5.5	5	27.5
ERJ2RKF1000X	Resistor	100	0402	Delfi-twin		RS4:R2			Mouser	667-ERJ-2RKF1000X	1	5	0.015	15	0.225
ERJ2RKF2000X	Resistor	200	0402	Delfi-twin		RS4:R3			Mouser	667-ERJ-2RKF2000X	1	5	0.015	15	0.225
ERJ-2RKF1001X	Resistor	1k	0402	Delfi-twin		TRAN:R1			Mouser	667-ERJ-2RKF1001X	1	5	0.015	15	0.225
ERJ-2RKF1003X	Resistor	100k	0402	Delfi-twin		MCU:R2, MCU:R3			Mouser	667-ERJ-2RKF1003X	2	10	0.015	30	0.45
ERA-2AEB750X	Resistor	75	0402	Delfi-twin		MCU:R4			Mouser	667-ERA-2AEB750X	1	5	0.095	10	0.95
APT1608LSECK/J3-PRV	Red LED		0603	Delfi-twin		MCU:L1			Mouser	604-APT1608LSECKJ3RV	1	5	0.363	10	3.63
ERJ-2RKF1540X	Resistor	155	0402	Delfi-twin		MCU:R5			Mouser	667-ERJ-2RKF1540X	1	5	0.015	10	0.15
APTD1608LCGCK	Green LED		0603	Delfi-twin		MCU:L2			Mouser	604-APTD1608LCGCK	1	5	0.286	10	2.86
ERJ-PA2D1200X	Resistor	120	0402	Delfi-twin		RS4:R4			Mouser	667-ERJ-PA2D1200X	1	5	0.131	10	1.31

Figure A.1: Order list of prototype radiation payload. Does not include PCB or FGD-03F order as these were not bought separately

B STM32L476RG NUCLEO pin configuration list

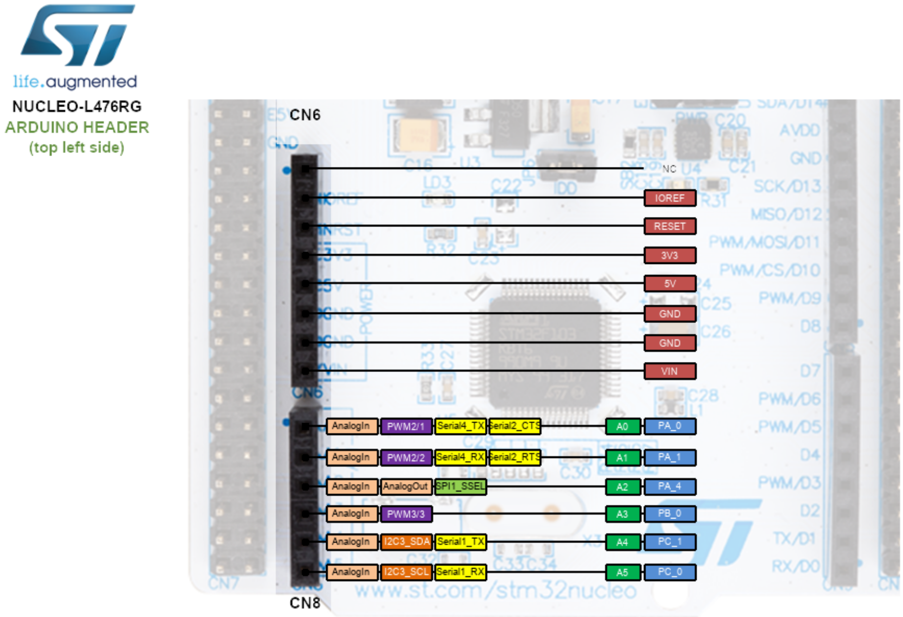

Figure B.1: Part 1.1 [82]

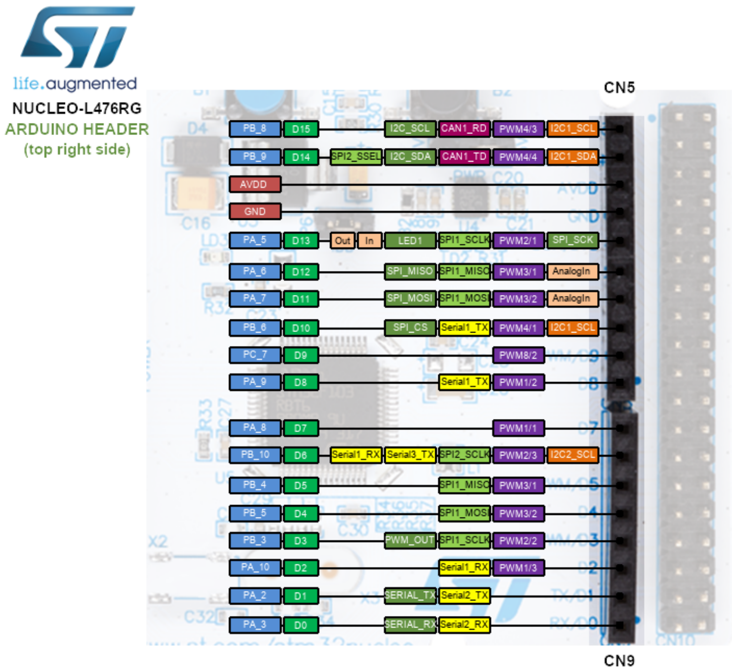

Figure B.2: Part 1.2 [82]

Figure B.3: Pin configurations of the STM32L467RG NUCLEO. Can be used for the STM32L476RG if the pin numbers are followed, Part 1.

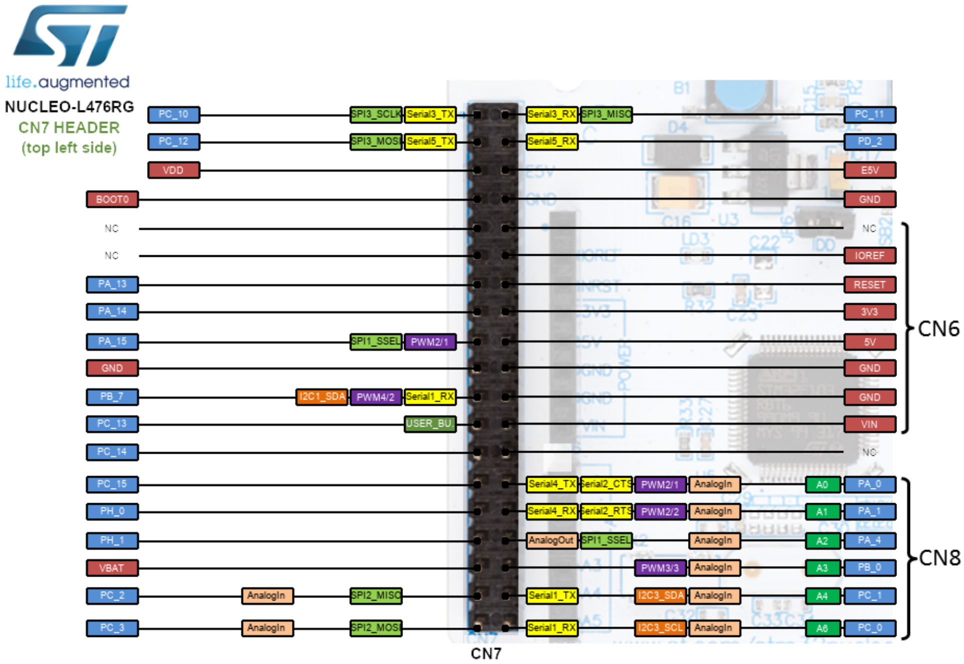

Figure B.4: Part 2.1 [82]

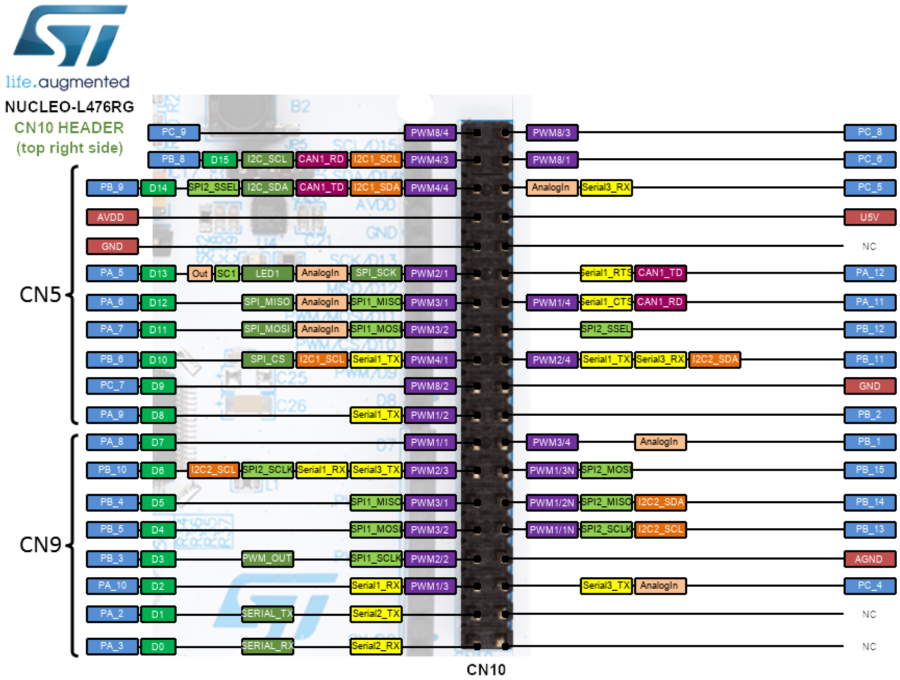

Figure B.5: Part 2.2 [82]

Figure B.6: Pin configurations of the STM32L467RG NUCLEO. Can be used for the STM32L476RG if the pin numbers are followed, Part 2.

C Prototype PCB radiation payload pin definitions

Table C.1: Pin configurations for STM32L476RG

Pin	Function	Connection
VSSA	Analog ground connections, used for ADC, DAC and other analog peripherals on the MCU	General ground
VDDA	Analog voltage connections, used for ADC, DAC and other analog peripherals on the MCU	3.3 V supply
VBAT	Provides via a battery power to essential pins. Due to it not being used it is connected to the general 3.3V supply	3.3 V supply
VDDX	Digital voltage connections, used for GPIO and other digital peripherals on the MCU	3.3 V supply
VSSX	Digital ground connections, used for GPIO and other digital peripherals on the MCU	General ground
NRST	Reset pin which can be used for debugging. Is connected to the CON6 to help with debugging during prototype phase.	Debugger connector
PA1	General GPIO, used for RE_RS485 signal in transceiver	Transceiver
PA2	General GPIO, used for external LED_GREEN	Green LED
PA3	General GPIO, used for external LED_RED	Red LED
PA4	General GPIO, used for SPI Slave Select 1 (NSS1)	Translator 3.3V $\rightarrow$ 5V
PA9	General GPIO, used for NIRQ_1_3.3V in radiation sensor	Translator 3.3V $\rightarrow$ 5V
PA10	General GPIO, used for NIRQ_2_3.3V in radiation sensor	Translator 3.3V $\rightarrow$ 5V
PA11	General GPIO, used for NSTBY_1 in radiation sensor	Directly to radiation sensor
PA12	General GPIO, used for NSTBY_2 in radiation sensor	Directly to radiation sensor
PA13	Used for SWD (Serial Wire Debugging). SWDIO pin is connected for transferring and receiving inputs and outputs via debugging to the MCU.	Debugger connector
PA14	Used for SWD (Serial Wire Debugging). SWCLK pin is connected for giving a clock signal to the input and output of the debugging signal to the MCU.	Debugger connector
PA15	General GPIO, used for SPI Slave Select 2 (NSS2)	Translator 3.3V $\rightarrow$ 5V
PB0	General GPIO, used for ENWR_1 in radiation sensor	Directly to radiation sensor
PB1	General GPIO, used for ENWR_2 in radiation sensor	Directly to radiation sensor
PB3	Used for SWD (Serial Wire Debugging). SWO pin is connected for real-time tracing and debugging of the MCU. Is an optional connection for debugging to work	Debugger connector

Pin	Function	Connection
PC0	RXD dedicated pin, is able to easily configure UART communication between MCU and the debugger connector	Debugger connector
PC1	TXD dedicated pin, is able to easily configure UART communication between MCU and the debugger connector	Debugger connector
PC4	TXD dedicated pin, is able to easily configure UART communication between MCU and transceiver	Transceiver
PC5	RXD dedicated pin, is able to easily configure UART communication between MCU and transceiver	Transceiver
PC10	SPI_SCK dedicated pin, is able to easily configure SPI communication between MCU and radiation sensor	Translator 3.3V $\rightarrow$ 5V
PC11	SPI_MISO dedicated pin, is able to easily configure SPI communication between MCU and radiation sensor	Translator 3.3V $\rightarrow$ 5V
PC12	SPI_MOSI dedicated pin, is able to easily configure SPI communication between MCU and radiation sensor	Translator 3.3V $\rightarrow$ 5V
PH0	External oscillator pin which is used for the high frequency clocks.	External MCU clock
PH3	Is connected to a 10k resistor to ground to ensure it is always low. The pin must be pulled low to turn off the built-in bootloader. The bootloader makes it possible to upload firmware via USART or USB, but is not relevant as SWD is used for uploading firmware	Ground with pulldown resistor

Table C.2: FGD-03F Pinout Description

Pin	Function	Connection
GND	Providing ground to the system.	General ground
VCC	Providing 5V voltage supply to the system.	5V supply CON10
VCCD	Stands for digital voltage supply. Is used to determine what is seen as a 1 and 0 in binary. Needs to be supplied with 5V.	5V supply CON11
GNDD	Similar to VCCD, this provides a digital ground. Needs to be supplied with a ground connection.	General ground
VCAP	Can be provided with external 18V to 25V in order to simulate a radiation reading. Helpful for testing and debugging.	VCAP supply CON10
VCHP	Together with VB used for enabling an external charge pump for charging the radiation sensor for measurements. As the internal charge is sufficient for the PCB prototype, VCHP requires to be short circuited with VB according to the FGD-03F manual.	VB
VB	Needs to be short circuited with VCHP, see VCHP function explanation.	VCHP
MISO	Provides Master In Slave Out (MISO) line for SPI communication.	Translator 5V $\rightarrow$ 3.3V
MOSI	Provides Master Out Slave In (MOSI) line for SPI communication.	Translator 5V $\rightarrow$ 3.3V
SCK	Provides the Serial Clock (SCK) line for SPI communication.	Translator 5V $\rightarrow$ 3.3V
NCS	Provides the Slave Select line for SPI communication. Will be used to switch between the two radiation sensors in the chip.	Translator 5V $\rightarrow$ 3.3V
NIRQ	Allows for interrupts within the radiation sensor. Important for configuring the sensor after initialization or when other orders are given from the OBC.	Translator 5V $\rightarrow$ 3.3V
NSTBY	Standby pin which when activated (pulled low) the radiation sensor will go into standby mode, resulting in minimum power consumption. This is not the same as passive mode.	MCU GPIO
CK	Clock pin which requires to either be regulated by the MCU or an external clock. Is partially responsible for determining the measurement frequency of the radiation sensor. Previous experiments, subsection 2.5.3, on the radiation sensor have suggested using an external clock would provide a more stable frequency.	External clock 32.768 Hz
ENWR	Stands for Enable Write. Is used to control the manual recharging of the radiation sensor when measuring. Needs to be connected in the case the automatic recharging is not working.	MCU GPIO

Table C.3: Pin configurations for ASDMB

Pin	Function	Connection
GND	Providing ground to the system.	General ground
VDD	Providing 3.3V voltage supply to the system.	3.3V supply
OUTPUT	Outputs the clock signal to the MCU of 8 MHz.	MCU
STANDBY	Can set oscillator on low power consumption mode. Is not used, so can be left open according to the manual.	Floating

Table C.4: MAX3001EEUP+ Pin Descriptions

Pin	Function	Connection
GND	Providing ground to the system.	General ground
VCC	Providing 5V voltage supply to the system.	5V supply
VL	Providing 3.3V voltage supply to the system.	3.3V supply
EN	Enables the translator on and off. The translator will not be shutdown as it always needs to translate the signals between the MCU and radiation sensor. Therefore it is connected to a 3.3V supply, meaning it will always be high and stays on.	3.3V supply
I/O VCCX	Connection between radiation sensor and MCU which needs to be translated from 5V to 3.3V or vice versa. While only MISO and NIRQ require the translator, for consistency in the SPI signal the remaining SPI signals NCS, SCK and MOSI are included as well.	NIRQ, NCS, SCK, MISO, MOSI
I/O VLX	Connection between radiation sensor and MCU which needs to be translated from 5V to 3.3V or vice versa.	NIRQ, NCS, SCK, MISO, MOSI
I/O VCC8	I would connect one of the floating pins on the device (either I/O_VCC_8 or I/O_VL_8 but not both) to ground with a 1kOhm resistor. Leaving the pin floating will confuse the internal logic detecting the pin direction while forcing one of the two low will tell the internal logic this is an output and force the other pin (the floating one) to a low value too.	General ground

Table C.5: LTC2850 Pin Descriptions

Pin	Function	Connection
GND	Providing ground to the system.	General ground
VCC	Providing 3.3V voltage supply to the system.	3.3V supply
RE	Together with DE used for configuring the transceiver. As only transmitting (both pins high) and receiving (both pins low) is used and not the shutdown or transceive function, both pins are connected to each other so they both receive the same low and high via the RE_RS485 signal through the MCU.	DE on the transceiver and together to the MCU GPIO pin
DE	Similar function as RE.	RE on the transceiver and together to the MCU GPIO pin
DI	Transmit pin for MCU to transceiver via RS485. Signal changed in transceiver to a differential signal of D- and D+.	TXD pin on MCU
RO	Receive pin for MCU to transceiver via RS485. Signal changed in transceiver to a differential signal of D- and D+.	RXD pin on MCU
A	Differential signal of the RS485. Signal is more robust against noise, making it ideal to transmit to the OBC.	Connector to OBC
B	Differential signal of the RS485. Signal is more robust against noise, making it ideal to transmit to the OBC.	Connector to OBC

Table C.6: Pin configurations for XTAL1 SIT1533AI

Pin	Function	Connection
GND	Providing ground to the system.	General ground
VDD	Providing 3.3V voltage supply to the system.	3.3V supply
CLK_OUT	Outputs the clock signal to the radiation sensor of 32.768 Hz.	Radiation sensor
NC	Not Connected (NC).	Floating

Table C.7: Pin configurations for CON10

Pin	Function	Connection
PIN 10	GND connection	General ground
PIN 9	VCAP_2 connection, must provide between 14.5 and 18V in order to simulate the radiation measurements on the sensor	Radiation sensor
PIN 8	SPI_NCS_2_5V connection, used to read the SPI signal directly from the sensor instead of via the MCU	Radiation sensor
PIN 7	CK_1, used to read the CK signal on the sensor directly	External radiation sensor clock
PIN 6	SPI_MISO_5V, used to read the SPI signal directly from the sensor instead of via the MCU	Radiation sensor
PIN 5	SPI_NCS_1_5V, used to read the SPI signal directly from the sensor instead of via the MCU	Radiation sensor
PIN 4	SPI_MOSI_5V, used to read the SPI signal directly from the sensor instead of via the MCU	Radiation sensor
PIN 3	VCAP_1, must provide between 14.5 and 18V in order to simulate the radiation measurements on the sensor	Radiation sensor
PIN 2	VCC_5V, provides 5V to the PCB for all necessary ICs	5V supply
PIN 1	SPI_SCK_5V, used to read the SPI signal directly from the sensor instead of via the MCU	Radiation sensor

Table C.8: Pin configurations for CON8

Pin	Function	Connection
PIN 8	SWO connection, needed for debugging	MCU
PIN 7	VCC_3.3V, supplies 3.3V via the debugger	3.3V supply
PIN 6	GND, provides ground	General ground
PIN 5	TXD, separate from the one used for the transceiver at the MCU. This TXD, together with RXD, is used for debugging	MCU
PIN 4	RXD, separate from the one used for the transceiver at the MCU. This RXD, together with TXD, is used for debugging	MCU
PIN 3	SWCLK connection, needed for debugging	MCU
PIN 2	SWDIO connection, needed for debugging	MCU
PIN 1	DISABLE_WD, not used but part of the standard debugger configuration of Delfi-Twin. Used for regulating the external watchdog to not interrupt while debugging. Relevant once the external watchdog is installed in the completed version	Floating

Table C.9: Pin configurations for CON6

Pin	Function	Connection
PIN 6	SWO connection, needed for debugging	MCU
PIN 5	NRST connection, used to reset MCU via debugger	MCU
PIN 4	SWDIO connection, needed for debugging	MCU
PIN 3	GND, provides ground	General ground
PIN 2	SWCLK connection, needed for debugging	MCU
PIN 1	VCC_3.3V, supplies 3.3V via the debugger	3.3V supply

Table C.10: Pin configurations for FSI-105-03

Pin	Function	Connection
PIN 1	D+ connection, sends differential signal of MCU to OBC	Transceiver
PIN 3	D- connection, sends differential signal of MCU to OBC	Transceiver
PIN 5	VCC_3.3V connection, is the general supply of 3.3V in the system	3.3V supply
PIN 7	GND, ground	General ground

D FGD-03F register map including all configurations

EXTENDED BIT REGISTER MAP								
Addr	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
0x00 R	TEMP(7:0)							
0x01 R	RECHEV	RCHCNT(6:0)						
0x02	Not implemented							
0x03 R	F1R(7:0)							
0x04 R	F1R(15:8)							
0x05 R	0	0	0	0	DNEWR	F1ROVF	F1R(17:16)	
0x06 R	F1S(7:0)							
0x07 R	F1S(15:8)							
0x08 R	0	0	0	0	DNEWS	F1SOVF	F1S(17:16)	
0x09	0*	0*	0*	TARGET(4:0)				
0x0A	0*	0*	0*	THRESHOLD(4:0)				
0x0B	EAWR	EVBCHP	NCHP	ENDCH	WINDOW(1:0)		0	TDIV
0x0C	FCH	NEBUF	ENTEMP	NELF	ENOSC	NEIDCM	SNRF	E9S
0x0D	ENMC	ECH	EPWR	NEASNR	E2V	SET(2:0)		
0x0E	0	0	0	0	LOWN	EDIRT	NIRQOC	ENGATE
0x0F	Not implemented							
0x10	SN(7:0)							
0x11	SN(15:8)							
0x12	SN(23:15)							
0x13 R	CHIPID(7:0)							
0x14	0	0	0	0	Reserved			

R: Read-only register

Figure D.1: Additional register map valuse. Not used for general use of FGD-03F [2]

E Python code for managing radiation payload measurements

```python
import serial
import pandas as pd
import datetime

ser = serial.Serial('COM5', 115200, timeout=1)

#File name
csv_filename = "sensor_data4.csv"

#Excel header
columns = ["Timestamp", "Sensor", "Temperature (°C)", "Recharge Count", "g_window_pulses", "Reference Radiation", "Sensor Radiation"]

try:
    df = pd.read_csv(csv_filename)
except FileNotFoundError:
    df = pd.DataFrame(columns=columns)
    df.to_csv(csv_filename, index=False)

print("press Ctrl+C to stop")

#Splits data so it knows what is a value
def parse_line(line):
    parts = line.split(":")
    if len(parts) == 2:
        key = parts[0].strip().lower()
        value = parts[1].strip()
        return key, value
    return None, None

#Accumalating data
data_dict = {}

try:
    while True:
        line = ser.readline().decode(errors="ignore").strip()
        if not line:
            continue

        print(f"Received: {line}")

        if "Sensor:NSS" in line:
            sensor_id = line.split(":")[-1].strip()
            data_dict['sensor'] = sensor_id

        elif any(keyword in line for keyword in [
            "Temperature:", "Recharge count:", "g_window_pulses:",
            "Reference radiation", "Sensor radiation"
        ]):
            key, value = parse_line(line)
            if key and value:
                data_dict[key] = value

#Write to excel file
        if all(k in data_dict for k in [
            'sensor', 'temperature', 'recharge count', 'g_window_pulses',
            'reference radiation', 'sensor radiation'
        ]):
```

```
            timestamp = datetime.datetime.now().strftime("%Y-%m-%d %H:%M:%S")
            data_dict['timestamp'] = timestamp

#Arrange values
            new_data = pd.DataFrame([{
                "Timestamp": timestamp,
                "Sensor": data_dict['sensor'],
                "Temperature (°C)": data_dict['temperature'],
                "Recharge Count": data_dict['recharge count'],
                "g_window_pulses": data_dict['g_window_pulses'],
                "Reference Radiation": data_dict['reference radiation'],
                "Sensor Radiation": data_dict['sensor radiation']
            }])

            new_data.to_csv(csv_filename, mode="a", header=False, index=False)
            print("Data saved to CSV.")

            data_dict.clear()

except KeyboardInterrupt:
    print("\nStopping data logging...")

ser.close()
print(f"Final data saved to {csv_filename}")
```

F Firmware additional notes: Transceiver firmware and temperature post-processing

F.1. Transceiver Firmware configuration

The RE and DE pins visible in Figure 4.14 are used to configure the transceiver, see Figure F.1.

LTC2850

Logic Inputs		Mode	A, B	RO
DE	$\overline{RE}$			
0	0	Receive	R_{IN}	Driven
0	1	Shutdown	R_{IN}	Hi-Z
1	0	Transceive	Driven	Driven
1	1	Transmit	Driven	Hi-Z

Figure F.1: Configurations LTC2850 transceiver [61]

The DE and RE pins are connected to each other, making them only able to send [0 0] (receive) or [1 1] (transmit) to DE and RE respectively. This makes the distinction between the two actions more clear and prevents accidental transmissions or receptions. As a starting configuration the transceiver will be set on the 'receive' setting, meaning a 0 is send to both DE and RE. This in order to obtain orders from the satellite OBC. Measurements or other types of data has yet to be made, meaning the 'transmit' setting would have no use as an initial configuration. Once the OBC demands measurements or other types of data from the radiation PCB, the transceiver must be set to 'transmit' and a 1 needs to be send to DE and RE.

F.2. Adding temperature effect compensation

The space environment in which the satellite will operate will bring about severe temperature changes. This has already been discussed in subsection 2.2.2 and has been stated as a requirement in requirement SA-1. Temperature has an affect on the radiation measurements of the FGD-03F, causing them to become less accurate. See Figure 2.25 and Figure 2.26 in the literature study for examples of radiation measurement anomalies caused by increasing temperatures. This can however be compensated for by means of the reference frequency readings made by the radiation sensor. The compensation technique used comes from the FGD-03F user manual [2].

As the temperature compensation must be performed when increasing temperatures are noticed, temperature tests require to be conducted in order to calibrate these compensation techniques, similar to the ones shown in section 2.5 for the Lunar Zebro. Due to time constraints these have not been performed, but they are recommended as temperature affects are inevitable for space missions. The explanation given for these compensations are therefore solely for future usage and are not found within the current firmware development.

The relation between the reference frequency and sensor frequency is linear with temperature variation according to the FGD-03F manual. This creates a linear function between the two frequencies, namely.

$$FS_{rad0} = m * FR_{rad0} + a \tag{F.1}$$

The values m and a are kept undefined. The rad0 in the formula states that for this linear equation, it is assumed no radiation is put onto the system. Figure F.2 shows the linear relation between the two frequency values taking frequencies at room temperature (TRT) and an arbitrary temperature (T1).

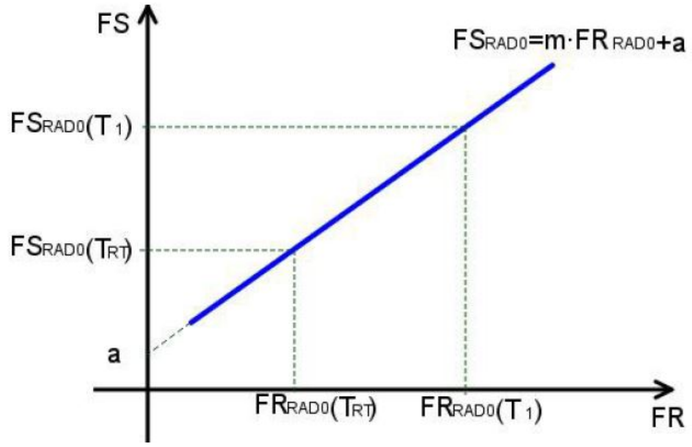

Figure F.2: Linear relation between F1R and F1S with no radiation at different temperatures [2]

If radiation would be applied, the slope is according to the manual allowed to be assumed constant, meaning the linear line will only move left or right. If at one arbitrary temperature value (T3) frequency measurements are made when radiation is applied (rad1), a new line can be created as the slope stays the same. See Figure F.3 for an example.

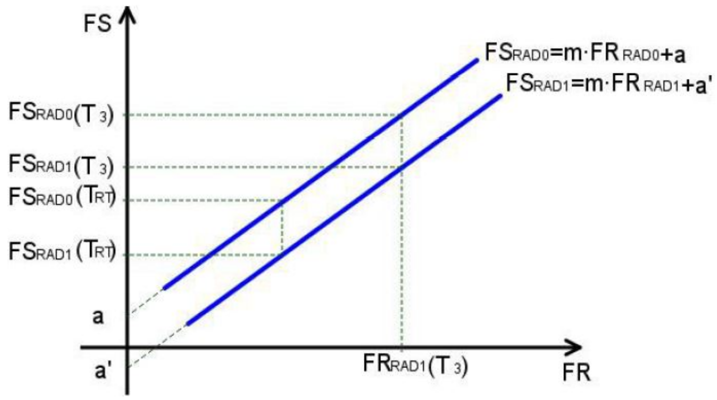

Figure F.3: Linear relation between F1R and F1S with no radiation and with radiation at different temperatures [2]

From these two graphs. Equation F.2 can be made.

$$FS_{rad0}(T3) - FS_{rad0}(TRT) = FR_{rad1}(T3) - FS_{rad1}(TRT) \tag{F.2}$$

This equation can be rewritten to Equation F.3.

$$FS_{rad1}(TRT) = FR_{rad1}(T3) - FS_{rad0}(T3) \tag{F.3}$$

Equation F.3 states that the sensor frequency measurement made when an arbitrary amount of radiation is applied at room temperature (meaning no temperature interferences are created), can be obtained by subtracting the sensor frequency value made at a particular temperature without radiation from the reference frequency value with radiation and the particular temperature value as well. The reference value is obtained by reading F1R(17:0) during the operation as it will include the temperature effects and will occur when radiation is applied. The sensor frequency without radiation and that same temperature is however more difficult to obtain as these values have to be obtained beforehand. A look up table can be created via tests to see what sensor frequency values occur at particular temperatures with no radiation.