

Propulse NTNU - Project Birkeland

Team 60 Project Technical Report 2022 Spaceport America Cup

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Propulse NTNU presents the rocket Birkeland scheduled to participate in Spaceport America Cup 2022. The team is aiming for a target apogee of 30 000 ft, powered with a Cesaroni Pro 98 solid rocket motor. Birkeland is highly influenced by our previous flight-proven rocket, Stetind. The development of Birkeland has been an pivotal step for Propulse's long-term goal of reaching the Kármán line. The objective of this project is to develop a reliable and capable rocket, and to enable members to enrich their engineering capabilities alongside their studies. Birkeland's airframe is constructed of two filament wound fiber composite sections that are optimized for low drag at supersonic speeds, by replicating the Von-Kármán shape towards both the rocket's nose and the tail. The recovery system includes both commercial and student-developed parachute deployment systems for redundancy. The avionics system controls the recovery system, and monitors the flight trajectory using barometers, inertial measurement units, a magnetometer, GNSS, thermometers, and five cameras. The avionics system transmits all data to the ground station in real time throughout the flight. Meanwhile, Birkeland's experimental payload measures the in-flight oscillations and compares the recorded vibrational noise from sensor measurements for a damped versus undamped set of electronics. The software and the majority of PCBs on-board the rocket are student-researched and developed. The technical details and validation methods for the systems that constitute the rocket Birkeland are covered in this report.

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PROJECT BIRKELAND



Abbreviations

SA Cup	–	Spaceport America Cup
COTS	–	Commercial Off The Shelf
SRAD	–	Student Researched and Developed
DTEG	–	Design, test and evaluation guide [4]
R&R	–	Rules and requirements [5]
FEA	–	Finite element analysis
PV	–	Pressure vessel
CFD	–	Computational fluid dynamics
PCB	–	Printed circuit board
GNSS	–	Global Navigation Satellite System
NTNU	–	Norwegian University of Science and Technology
PBSS	–	Pressure based separation system
EuRoC	–	European Rocketry Challenge
OR	–	Open Rocket
FSM	–	Finite state machine
AoA	–	Angle of Attack
MEKF	–	Multiplicative Extended Kalman Filter
CNC	–	Computer numerical control

Nomenclature

A	–	Area
A_p	–	Projected Area
a	–	Average Attraction Between Particles
b	–	Volume Excluded by a Mole of Particles
C_D	–	Drag Coefficient
CG	–	Center of Gravity
CP	–	Center of Pressure
D	–	Maximum Diameter
d_i	–	Distance Between the Component's Centre of Gravity and the Nose Tip
F	–	Force
F_D	–	Drag
$F_{D, aft}$	–	Drag on aft
$F_{D, forward}$	–	Drag on forward
g	–	Gravitational Acceleration
m	–	Mass
P	–	Pressure
q_∞	–	Dynamic Pressure
R	–	Universal Gas Constant
ρ	–	Density
ρ_∞	–	Freestream Density
α	–	Angle of Attack
β	–	Oblique Shock-wave Angle
σ	–	Stress
T	–	Temperature
V	–	Volume
V_∞	–	Freestream Velocity
v	–	Velocity
W_t	–	Total Rocket Weight
W_i	–	Component Weight

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I. Introduction

A. Organization

Propulse NTNU is a volunteer student organization with the goal of providing students with knowledge and engineering experience through design, production, and launch of sounding rockets. The organization is currently working on three technical projects: Project Birkeland, the engine development project, and a flight trajectory simulator. These projects are the necessary steps toward our long term goal of reaching the Kármán line. Other functional areas in the organization are business, marketing and administration. There are 58 members in total, from 17 different fields of studies, supported by 14 mentors. Members working on the main project are split between system-related groups.

B. Project Birkeland

Project Birkeland is currently the main project of Propulse NTNU. The objective is to develop a sounding rocket capable of carrying a 4kg payload to 30000ft, with a commercial off-the-shelf (COTS) solid propulsion system. These are the underlying project goals:

1. Ensure economic viability
2. Create a good environment for learning and social interaction
3. Perform a successful flight
4. Push boundaries and further development
5. Achieve exemplary results

As a result, the underlying requirements set by the team for the rocket are related to cost and production, reliability, and validation through analysis and tests. The planning and management of the project is grounded in the experiences and lessons learned from previous projects, stated in G. The rocket is a comprehensive multidisciplinary system, so the different subsystems must follow strict engineering principles. Testing of such systems has been a major focus, with the intent of improving the rocket's performance significantly. The system requirements can be found in Appendix V.H. To find solutions fulfilling these requirements, the members are encouraged to compare new ideas to the existing methods and technologies. The solutions are evaluated through design reviews, where professors, sponsors, alumni and team members participate. New designs and solutions are made iteratively based on feedback from the reviews, test results, analysis, risk assessment and production constraints. The main technical challenges of the project have been on designing and validating high performing aerodynamic structures for the rocket, developing our own separation and parachute release systems, and developing the software on embedded systems.

C. Stakeholders

The primary stakeholders in the project are the team members. Spaceport America Cup (SA Cup) establishes several requirements for the project, while our sponsors and the Norwegian University of Science and Technology (NTNU) have contributed to the project in the form of expertise, production and funding. Kongsberg Defense & Aerospace is the main sponsor. The organization is also sponsored by Radionor Communications, the Faculty of Information Technology and Electrical Engineering at NTNU, the Faculty of Engineering at NTNU, NCAB Group, NORBIT, Altium, Innision Løkken, 4Test Instrument, Norwegian Defense Research Establishment (FFI), Eidel, Swagelok Norway, WindTec, Nammo and Eidsvoll Electronics.

II. System Architecture

A. System Overview

The Birkeland rocket consists of four main systems: Structure, recovery, avionics and payload. The rocket structure is divided into outer structure and inner structure.

Outer structure comprises two fiber-composite airframe sections, a nose tip, coupling tube, boat tail, and four symmetric trapezoidal fins. It is through the boat tail and aft airframe that the motor force is transferred to the rest of the rocket. The forward airframe is made out of radio transparent fiberglass, whereas the aft airframe is made out of carbon fiber. Both sections are tapered, following a Von-Kármán ogive. The four fins are made of carbon fiber, and mounted to the bottom of the aft airframe with aluminum fin brackets. The inner structure of the forward airframe is modular and hosts the payload, avionics and recovery systems. The latter two share the same architecture, where rails and ring modules ensure structural integrity, and serve as mounting points for the housed components. The payload module is tubular and allows for quick and easy removal. The aft airframe houses the commercial off the shelf (COTS) Cesaroni pro 98 6GXL solid rocket motor, as well as a camera facing the fins. Birkelands parachutes are contained within the coupling tube, hereby referred to as the coupler. Figure 1 shows the rocket Birkeland from the outside, and Figure 2 the inner structure.

Birkeland employs a two-stage recovery system. The first stage separates the rocket into two halves at the coupler, pulling out the drogue parachute. The separation is triggered by a surge of gas from either the COTS or the student researched and developed (SRAD) pressure based separation systems (PBSS) on board. The gas pressurizes the volume within the coupler, breaking the shear screws holding the coupler and forward airframe together, separating the rocket into two halves such that the drogue parachute is deployed. The SRAD PBSS is designed to be fully reusable, unlike the COTS PBSS, which consumes a CO2 canister for each use. The second stage of recovery is the SRAD mechanical release system, hereby referred to as the Main Chute Release System (MCRS). The MCRS stage is programmed to initiate at a preset altitude of 450 m Above Ground Level (AGL).

The main function of the avionics systems is to activate the two stages of recovery. This function can be fulfilled by either the SRAD Flight Computer, or the redundant COTS system. The SRAD system also has a function of collecting, storing and transmitting sensor data. There are two cameras which record the exterior surroundings of the rocket, whereas a third and fourth camera record the inside of the coupler section containing the parachutes and the MCRS. The requirements for all the systems are listed in Appendix V.I, which provides further details on the design choices. Table 1 shows key physical and performance parameters for Birkeland.

Table 1: Key parameters for Birkeland

Parameter	Value
Launch weight [kg]	39.6
Total length [mm]	3302
Predicted apogee [m]	9162
Max velocity [m/s]	502
Max acceleration [m/s^2]	123



Fig. 1. The Birkeland rocket



Fig. 2. Inner structure of the Birkeland rocket

B. Propulsion System

The Cesaroni Pro98 6GXL motor with the 2106203400-P fuel grain was chosen early in the concept phase. This resulted in the rocket being designed based on the performance and size properties of the motor. This particular motor was chosen because it is a high power motor at an acceptable price for our organization. Additionally, it has a high impulse to diameter ratio, which makes reaching the 30000 ft altitude target feasible, albeit a challenge, with the 21062 Ns of impulse the motor provides. The interface between the motor and the mechanical structure of the rocket is described in II.D.

C. Trajectory calculations

The trajectory calculation consists of two steps. The first is to analyze the flight data from team 2021's rocket Stetind, which flew at the European Rocketry Challenge (EuRoC) in 2021. The goal is to adjust the simulation parameters to fit the flight data from Stetind, determining which parameters had been set incorrectly in 2021, in order to improve the simulations for the rocket Birkeland. In the second part, OpenRocket and RocketPy are used to calculate the flight trajectory of Birkeland.

1. Flight analysis Stetind

The results of the flight analysis of Stetind are shown in Figure 3. In the left figure, the C_d -values are plotted for the coasting phase (Power-Off). The drag coefficient of the CFD (orange) follows the flight data best (for a more detailed analysis and explanation see V.L. Trajectory and CFD). OpenRocket and RasAero II both have large discrepancies in the subsonic/transonic regime. These deviations have an influence on flight trajectory (Figure 3b). RasAero II underestimates the flight path significantly. For the simulation with the CFD data the python library RocketPy was used. The fact that the simulation with the CFD data is so accurate is probably because the CFD curve is between Power Off and Power On, and so coincidentally balance each other out. The detailed analysis (see V.L. Trajectory and CFD) showed that OpenRocket predicts the flight parameters precisely and is therefore primarily used for the flight simulation for Birkeland. RasAero II, on the other hand, has shown some flaws and is therefore not used. The data from OpenRocket are complemented with the RocketPy - CFD simulation.

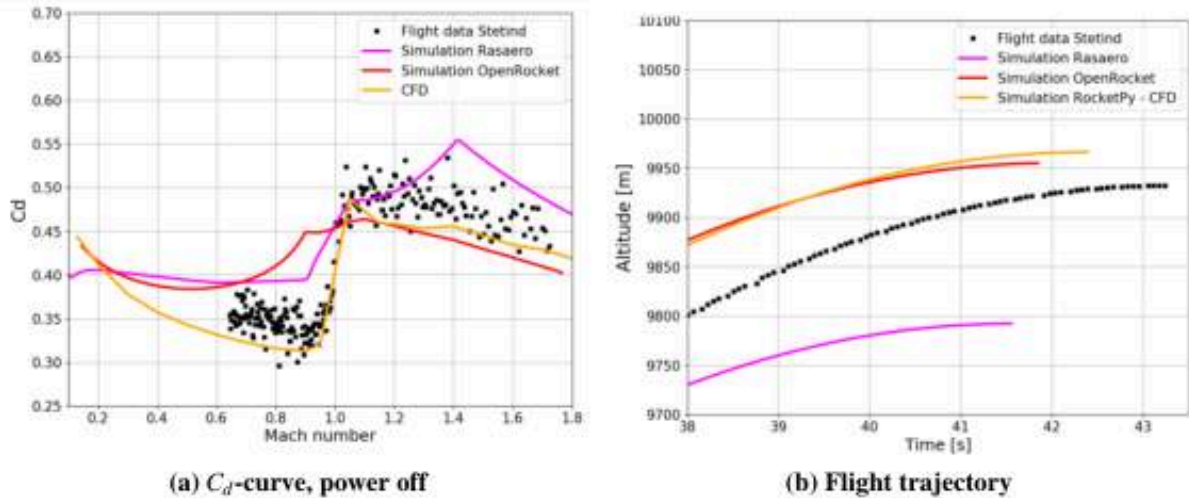


Fig. 3. Comparison of OpenRocket, RasAero II and CFD with the flight data.

2. Flight profile Birkeland

The calculated flight trajectory with Open Rocket is shown in Figure 4. We expect a 6 second burn phase, followed by a 36 second coast phase, resulting in a 42 second total ascent duration. The predicted apogee is 9162 meters (30 059 ft). The velocity and acceleration profile are pictured in Fig. 5. The powered flight in the first 6 seconds results in a maximum velocity of 507 m/s. The maximum acceleration 123 m/s^2 is experienced slightly before the burn-out. At the main chute deployment, the acceleration reaches a peak value of 149 m/s^2 .

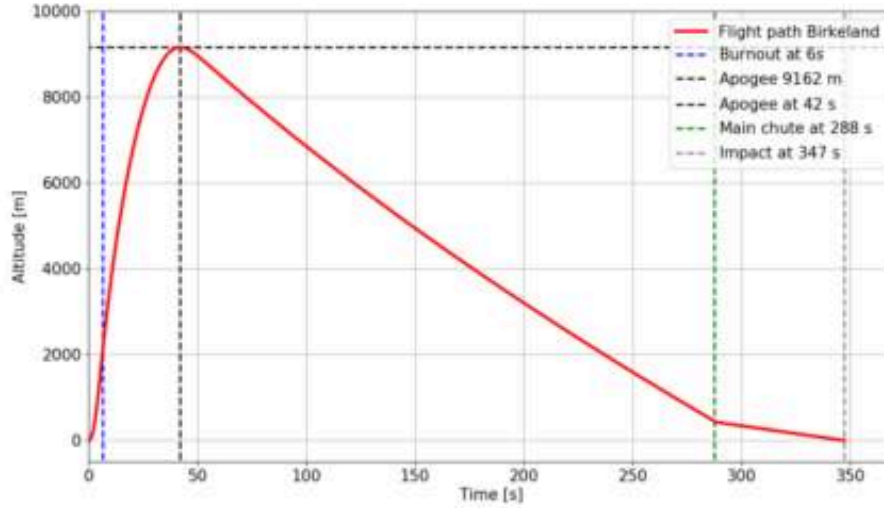


Fig. 4. Simulated Birkeland flight profile with flight phases highlighted.

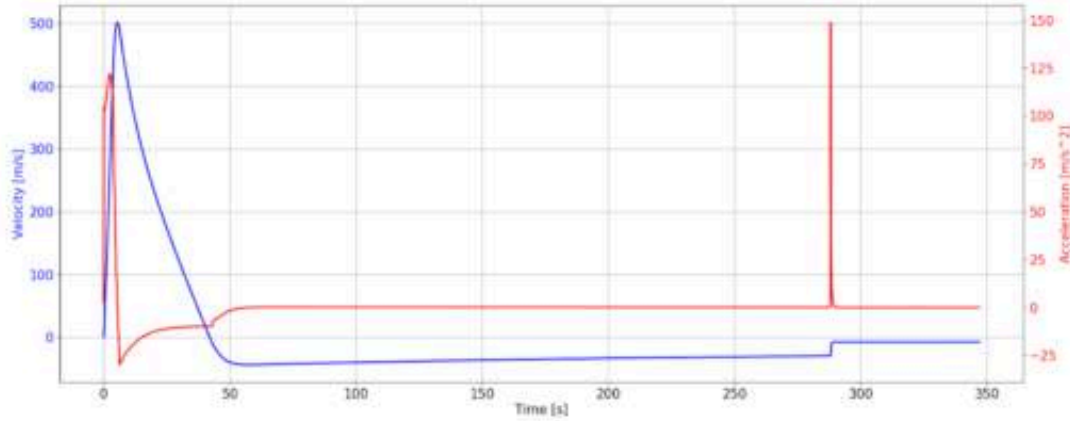


Fig. 5. Predicted velocity and acceleration during flight. The rapid change in acceleration at around 340 s is due to the main parachute being deployed.

The C_d curves were also calculated for Birkeland (see V.L. Trajectory and CFD). These have been modified to use them for RocketPy. With RocketPy, a Monte Carlo analysis was performed (see V.L. Trajectory and CFD). The result of 6500 simulations is shown in Figure 6a. The mean apogee is 9205 meters with a standard deviation of 51 meters. Thus the OpenRocket result is in the standard deviation of the Monte Carlo analysis.

3. $MaxQ$ / Mach number

The maximum dynamic pressure is found by extracting the air density ρ and velocity v values from OpenRocket, where equation (1) is used to then calculate the dynamic pressure q .

$$q = \frac{1}{2} * \rho * v^2 \quad (1)$$

In Figure 6b the dynamic pressure is plotted over time. The maximum can be found 1 second before burn-out and has a value of 133 k Pa. The dynamic pressure allows locating the time where the rocket experience the highest aerodynamic loads. The resulting drag force on the rocket is 642 N.

4. Stability

Examining the stability of the rocket is crucial for a safe flight. The stability margin (SM) presented in Eq. 2 is a way to measure the rocket's stability. It depends on Center of Pressure (CP) and Center of Gravity (CG). The

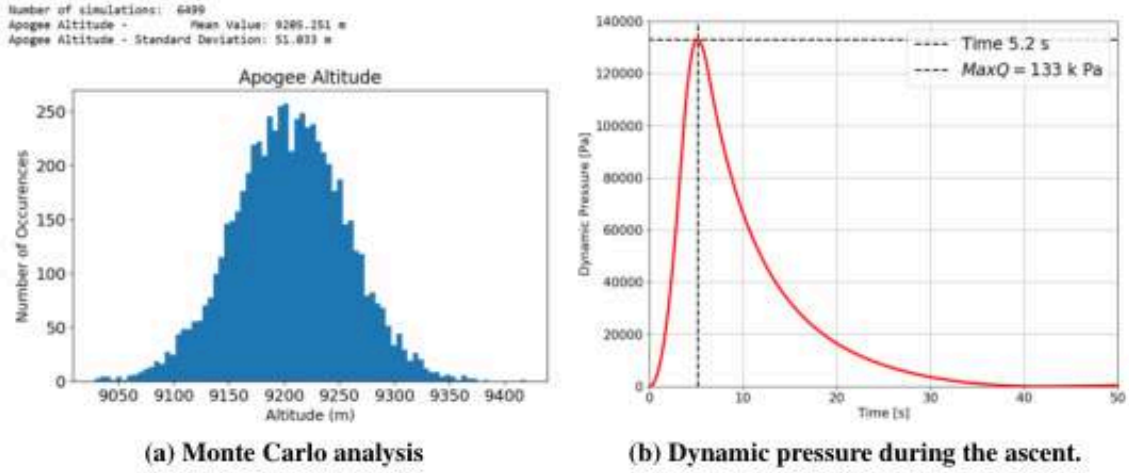


Fig. 6. Monte Carlo and dynamic pressure

stability is given by the distance between CG and CP, measured in calibers (body tube diameters):

$$SM = \frac{CP - CG}{d} \quad (2)$$

Where CG is the center of gravity, CP is the center of pressure. It is expected that the stability margin will change significantly during flight. This is on the one hand due to depleting fuel in the motor, moving the CG further forward. On the other hand, as the rocket passes through the transonic and into the supersonic regime, wave drag from shockwaves act on the nose tip and fins. The wave drag is at its greatest when the rocket passes through $M = 1$. The net result of the wave drag is a movement of the CP towards the aft. Therefore, after burnout, when the rocket decelerates back down through the transonic regime, the stability margin will be at its greatest. As can be seen in Figure 7, the stability at Rail-Off is lowest with 1.78 and short after burn-out with 5.84 calibers the highest. These parameters fulfill the SACup requirements for the stability since the stability is between 1.5 and 6 during the ascent. With a Off-Rail velocity of 33.7 m/s, the target of 30.5 m/s is also met.

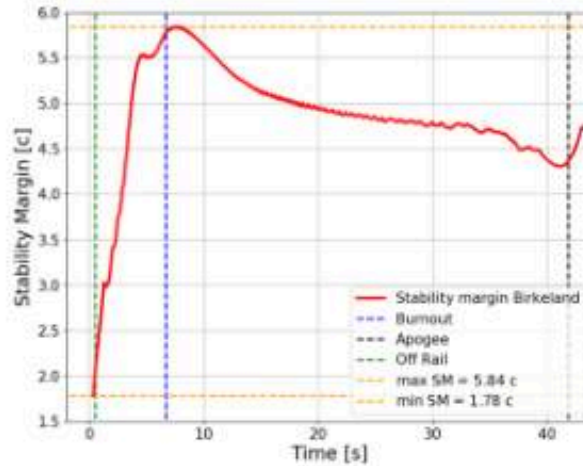


Fig. 7. Stability of the rocket from Off-Rail to separation.

D. Outer structure

1. System function and system overview

The fundamental task of the outer structure is to provide structural integrity, and to ensure a stable flight [V.L]. The airframe is optimized to minimize drag in supersonic flight, featuring a von Kármán nose-cone and boat-tail, a small cross section, and four wedged trapezoidal fins. The goal for all parts is a safety factor of 2, and whenever it is much greater, it is usually due to manufacturing constraints. The components are made to balance weight, structural integrity and aerodynamics.

2. Components and dimensioning forces

Table 2: Overview of Outer Structure components

Component	Reference	Material	Production	Validation	Functions			
					Load bearing	Fastening point	Drag reduction	Flight stabilization
Nose tip	O.NT	Aluminum 7021-T6	CNC machining	CFD, Flight proven				
Forward Airframe	O.FA	Glass Fiber	Filament winding	FEM, CFD, Compression test				
Coupler	OC	Aluminium 6082-T6	Turning	FEA				
Aft Airframe	O.AA	Carbon fiber	Filament winding	FEA, CFD, Compression test				
Fins	O.F	Carbon Fiber HexPly 8552 Woven Carbon Prepregs	Carbon fiber prepreg lay-up	FEM, CFD, Bending test				
Fin brackets	O.FB	Aluminum 6082-T6	CNC milling	FEA, CFD, Flight proven				
Boattail	O.BT	Aluminum 6082-T6	CNC machining	FEA				
Camera shell	O.CS			FEA, CFD, Integration test	Provides fin view during flight			

3. Nose Tip

Function

The nose tip functions as an aerodynamic continuation of the upper airframe. It has to withstand the high temperatures and pressures through super sonic flight, as well as the mechanical load from touch down. The nose tip middle and lower part serves as a mounting point for the inner structure.

Design

The nose tip is divided into a lower, middle and upper part as seen in Figure 8. The lower and middle part provide a permanent structural interface between the inner structure and the nose cone. The lower part is glued

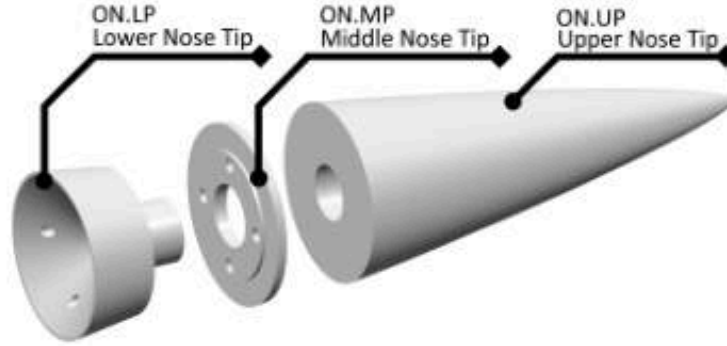


Fig. 8. Exploded view of the nose tip assembly

inside the uppermost part of the nose cone, and the middle part is glued and fastened to the lower part using four M4 countersunk screws. The middle part interfaces with the front of the nose cone, so that the forces acting on the nose tip are transferred through the airframe, not the inner structure. A M8 threaded rod from the inner structure slides through the lower and middle nose tip upon assembly, and is fastened with a nut. The upper part screws onto the protruding threaded section on the lower part.

Manufacturing decisions

To be able to withstand high temperatures, the nose tip has been made out of aluminum 7021-T6. Aluminum is easy to machine, and is well suited for components of such geometries. All of the three parts have been CNC machined.

4. Forward Airframe

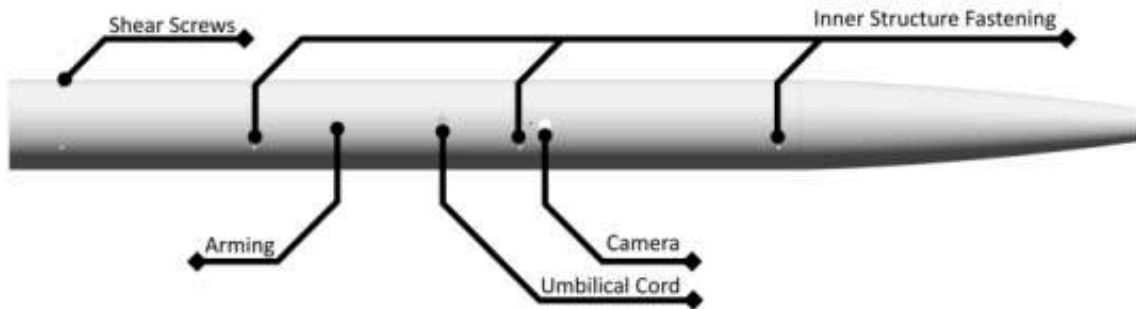


Fig. 9. Forward Airframe including holes for fastening: shear screws (4 holes), inner structure (3 rows of 3 each), camera (2 holes) as well as arming (2 holes) and an umbilical cord hole.

Function

The functions of the forward airframe are as follows:

- Load bearing
- Shield the inner structure from external disturbances
- Minimize aerodynamic drag
- Improve dynamic stability
- Be radio transparent
- Provide storage for the recovery system, avionics and payload

Design

The forward airframe is made of zentron 758 S-2 glass fibers and UF3369 epoxy. It has a total length of 1620 mm of which the first 488.5 mm follows the Von-Kármán shape. This shape is mathematically derived to achieve the theoretical lowest coefficient of drag possible [30]. A longer nose cone will reduce generation of expansion waves. The total length of 1620 mm was subsequently chosen as a compromise between manufacturing and aerodynamics. The 124 mm inner diameter for the straight section was chosen as a compromise between aerodynamics, and giving the inner structure team enough room to house all components. The wall thickness of the forward airframe is 2.5 mm, due to the layup and thickness of the fibers. This gives an outer diameter of 129 mm in the straight section. The forward airframe overlaps with the coupler by one body caliber, and is retained using four nylon M4 shear screws. The forward airframe is made out of fiberglass for its high strength to weight ratio, as well as to comply with the requirement of radio transparency (subsection H). There are three rings of three equally spaced Ø4 holes running along the airframe. These holes will be used to fasten the inner structure of the rocket to the airframe. This will reduce vibrations during flight, not to mention the opportunity to access elements of the inner structure while the rocket is on the launch rail. There are two Ø10 holes for two outward facing cameras, two Ø14 holes for arming the PBSSs, and one Ø16 hole for the umbilical cord Table 18.

Manufacturing decisions

The forward airframe is manufactured with filament winding. Making the airframe out of only two parts yields a high stiffness, and simplifies manufacturing. A 55/45% mix of zentron 758 S-2 glass fibers and UF3369 epoxy was wound around a mandrel with varying speed and rotation to achieve a specific layup. The fiber layup is -10+10+45-45+85+45-45-85 in accordance with the principles stated in ESA PSS-03-203 issue 1 structural materials handbook [22]. After winding, the airframe and mandrel is cured at a temperature of 120°C for approximately 2 hours. An additional layer of epoxy is added and sanded to achieve a smooth surface finish.

5. Aft Airframe

Function

The functions of the aft airframe are as follows:

- Be load bearing
- Shield the inner structure from external disturbances
- Mounting point for fins and boat tail
- Minimize aerodynamic drag

Design

The aft airframe is made out of Toray T700S carbon fiber with UF3369 epoxy, like the forward airframe, consists of a Von-Kármán section and a cylindrical tube. It has a total length of 1409 mm with the last 175 mm being tapered. By tapering in both ends (forward and aft airframe) the wave and wake drag is reduced at transonic speeds. The inner diameter is the same as in the forward airframe, 124 mm. At the end of the aft airframe the boat tail is fastened with 4xM4 bolts together with the four fins who are fastened to the airframe with 8xM4 bolts each. The coupler is glued inside the aft using epoxy glue. The aft airframe also has a hole for the camera shell tasked with recording the fins.

The aft airframe does not have to be radio-transparent and therefore carbon fiber is chosen due to its high specific strength to weight ratio.

Manufacturing decisions

The aft airframe is produced with the same mandrel and production technique as the forward airframe. The same mandrel is used as tapering the aft airframe makes it more aerodynamic. Moreover the mandrel is a big and costly tool so only needing one is a great benefit. The material used is a 58/42% mix of Toray T-700s carbon fiber and UF3369 epoxy. The carbon fiber reinforced composite is thicker than the glass fiber reinforced composite, to compensate for this only one hoop layer of 85 degrees is used. This results in the final aft airframe layup being -10+10+45-45+85+45-45

6. Coupler

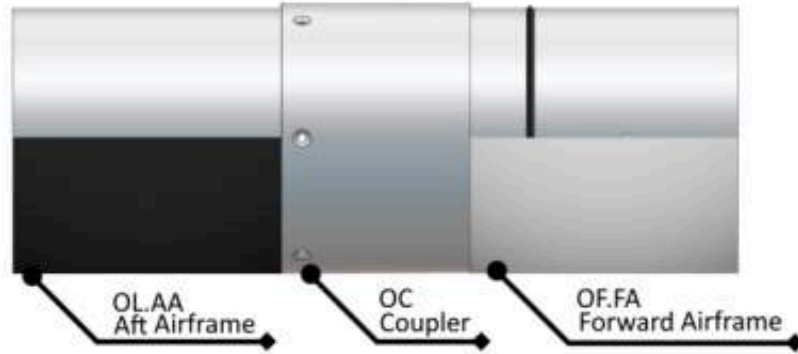


Fig. 10. Coupler connecting both airframe halves

Function

The function of the coupler is to act as a stiff interface between the airframe sections, and to allow for separation of the rocket into two halves for parachute deployment.

Design

The coupler is a cylindrical tube in the middle of the rocket that is fastened to the forward airframe with 4 M4 shear screws, and fastened permanently to the aft airframe using epoxy adhesive. Both airframe sections overlap the outside of the coupler by one caliper. Due to the different thicknesses of the forward and aft airframe, the bridging section between the airframes is slightly conical to maintain the prevent excessive drag. The motor bulkhead is fastened on the inside of the coupler. This bulkhead is a mounting point for the U-bolt connecting the aft airframe to the parachutes. It also prevents gas from the separation sequence to escape into the motor bay within the aft airframe. An O-ring groove is machined into the section where the coupler overlaps with the forward airframe. The O-ring prevents gas from the separation event from escaping through the coupling. It also adds to the stiffness of the joint, by making it a tight fit. A venting hole is drilled in the conical part of the coupler, to allow for equalization of the pressure to the decreasing ambient air pressure as the rocket ascends. The venting hole is too small to interfere with the intended pressure build up, and subsequent separation, that the coupler is made to facilitate. The coupler has no inside features or required surface roughness, simplifying the machining process.

Manufacturing decisions

The coupler is CNC machined by turning, and the raw material was shaped as a tube, reducing the amount of wasted material and time consumed during machining. The thickness of the coupler exceeds the required value to achieve a sufficient FoS, but was chosen to minimize the risk of ovality from retainment in the lathe.

7. Camera Shell

Function

The functions of the camera shell is to allow for a camera to get a view of the fins, exhaust plume and ground during the flight, through the aft airframe.

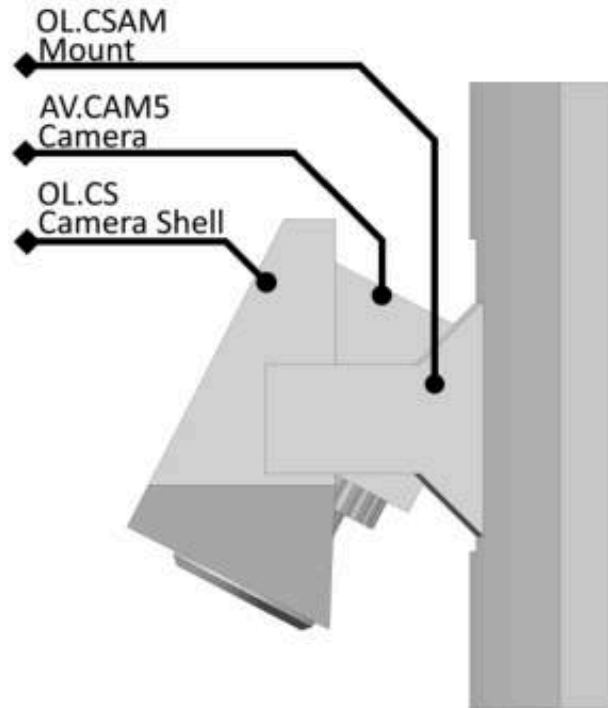


Fig. 11. The camera shell with the RunCam Split 4 attached. The camera shell will be on the outside of the airframe, whilst the mount plate is on the inside of the airframe.

Design

The camera shell houses an independent camera system in the aft airframe above the motor. It has its own battery, circuit board and SD-card to be completely independent from the rest of the avionics system. The camera is oriented so that the fins are in its field of view (FOV). The camera used is a RunCam Split 4 with a low FOV around 60° . The camera and mount will go through a hole in the airframe with a radius of 12 mm. The camera shell will stick out 12 mm from the airframe. This is the same as the launch lugs, and is from experience assumed to have a negligible effect on apogee and stability. The camera shell will be glued to the airframe, and the camera will be fastened to a mount inside the airframe.

Manufacturing decisions

The camera shell will be 3D printed out of PETG. 3D printing allows for quick, easy and cheap production. Calculations on the structural integrity of the aft airframe were performed to ensure that the aft airframe can still handle the forces with the significantly large camera hole [V.I.2A].

8. Fins

Function

The functions of the fins are:

- Provide an aerodynamic self-stabilizing force
- Place center of pressure downstream center of mass to ensure appropriate/required stability
- Reduce unintentional roll movement
- Withstand operating forces

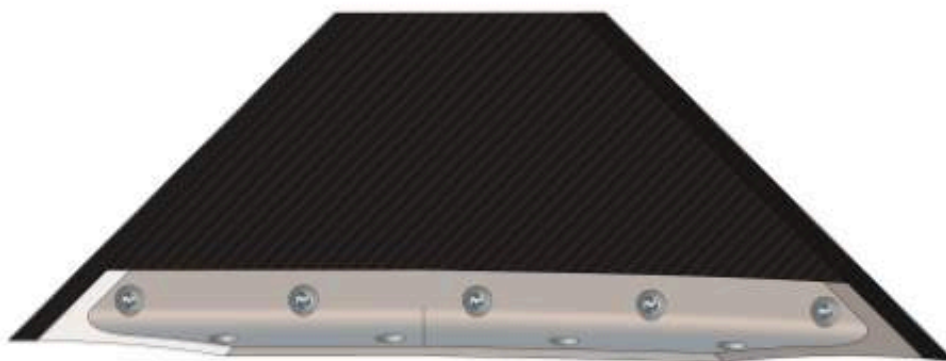


Fig. 12. The fin assembly

Design

Each fin consists of three parts, one fin blade and two mounting brackets. The fin blades are 97 mm high and trapezoidal with a sweep angle of 45° . For supersonic flight, the trapezoidal shape has the lowest drag.

The fins have a wedge angle of 30° on both leading and trailing edge. 30 degrees was chosen as a reasonable compromise between aerodynamic purposes, namely low wave-drag at supersonic flight, and the structural integrity of the material. The root chord has a length of 279 mm and the tip chord 80 mm. Their width has been set to 4.5 mm, as a compromise between required strength and the cross-sectional area (reduced drag). They will be mounted to the brackets with 5 screws and the brackets will in turn be mounted to the airframe with screws. This design was chosen since it is easy to manufacture, and because it allows fins to be swapped out easily in case of damage during for example handling. The latter is an important feature if a relaunch is to be performed, since the fins are prone to damage during touchdown. Both the carbon fiber fins and the attachment method is a flight-proven design previously used on Stetind.

The fins have been placed as far backwards on the aft airframe as possible. This will increase the stability margin and in turn allow us to make them smaller and more aerodynamic without sacrificing stability characteristics.

Manufacturing decisions

The fin blades are machined out of a carbon fiber plate of 21 0.2 mm thick layers made with manual prepreg layup. This allows them to be thin and light while still being stiff and strong. Calculations on the material properties of the composite together with FEA can be found in "VI.2A".

9. Fin Brackets

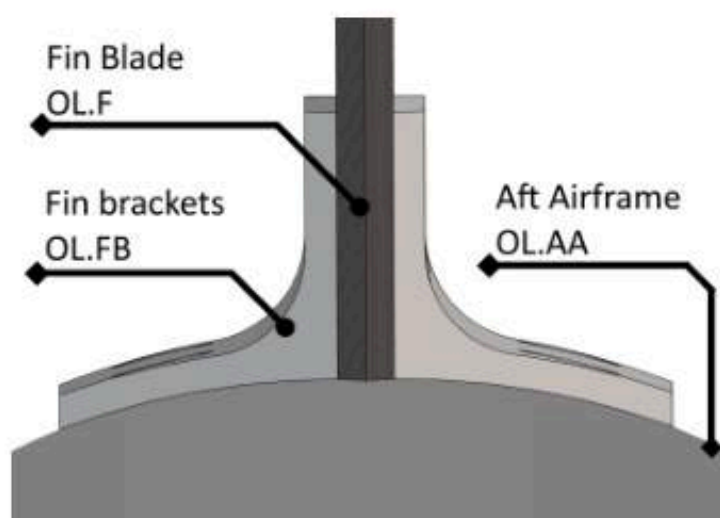


Fig. 13. Front view of the fin brackets assembly

Function

The functions of the fin brackets are as follows:

- Fasten the fin blades to airframe
- Withstand operating forces

Design

The brackets are made to follow the tapered airframe. They have a thickness of 2.5 mm. The brackets are glued and bolted to the airframe in order to distribute the forces as evenly as possible.

Manufacturing decisions

The brackets are machined out of 7021-T6 aluminum, as it has a high strength to weight ratio while being easy to machine. Since the fin brackets have a double curved surface in order to fit the Von-Kármán shape of the aft airframe, CNC machining is needed for manufacturing.

10. Boat Tail

Function

The boat tails functions are to:

- Retain the motor
- Reduce wake drag behind the rocket
- Transfer motorforce to aft airframe
- Protect the fins and airframe from the ground impact

Design

The boat tail has a conical shape and a continuous transition to the aft airframe. This gives an angle of 8° that tangents the airframe. In order to handle the force transfer from motor to airframe, the boat tail assembly consists of three parts: The boat tail is a metal part with threads that will be screwed on to the threaded part of the boat tail centering ring. The boat tail centering ring will handle the force transfer and also be a mounting point for the boat tail. The wedge will be screwed with the centering ring into the airframe and thereby fasten the boat tail assembly to the airframe. The wedge ensures secure fit between the motor - boat tail - airframe. A layer of thermal insulation will be adhered to the inside of the boat tail to shield from thermal loads during powered ascent.

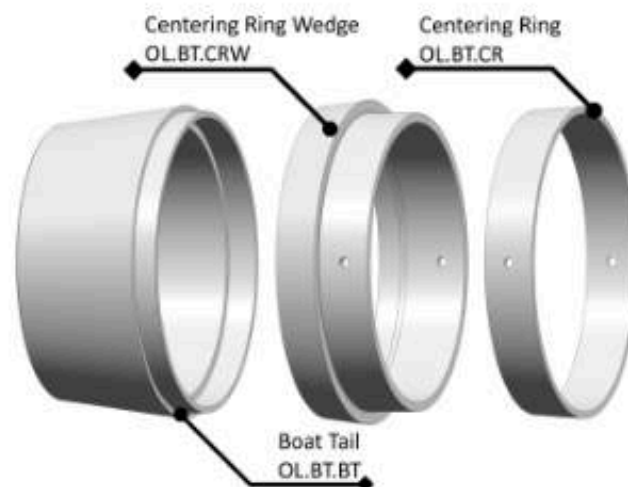


Fig. 14. Exploded view of the boat tail assembly

Manufacturing decisions

The boat tail is CNC machined out of 6082-T6 aluminum. Aluminum has a high strength to weight ratio and is easy to machine.

11. Validation

CFD

Computational Fluid Dynamics (CFD) was used to investigate the forces expected to act upon the rocket, and numerically determine the coefficient of drag (C_d) to more accurately predict the apogee together with Open-Rocket. The process involved using flight data from previous projects to estimate the velocity of the rocket at different altitudes. Then calculations were run using standard atmospheric conditions.

Simulations were run for a range of Mach numbers between $M_\infty = 0.3$ to $M_\infty = 1.55$, with a step of 0.05, for a total of 30 simulations. To calculate the highest aerodynamic forces acting on the rocket, 3D simulations were run at an expected maximum Mach number of 1.5. The results of the drag forces on the different parts can be found in Table 3. The total drag force at the highest Mach number was found to be 642N.

The analysis was performed on a simplified version of the Birkeland rocket geometry, where holes, screws, mounting lugs for launch, and other details were neglected. Therefore, the geometry analyzed is smoother than the real rocket, leading to a lower computed drag coefficient than in real life. A plot of pathlines showing the velocity magnitude of the flow around the aft of the rocket is shown in Figure 16. In Figure 15 the Mach waves propagating off of the rocket body at Mach 1.5 can be seen. Further discussion of the setup and results obtained using CFD is included in V.L.

Table 3: Maximum experienced forces on the different components with its calculated safety factor.

Component	Forces	Maximal expected force [N]	Safety factor	Validation method
Forward Airframe	Aerodynamic drag Inertial force of the load.	CFD result at highest Mach number: 191 N Inertial force: <4698 N	8	FEA, Compressiontest,
Aft Airframe	Aerodynamic drag Inertial force of the load.	CFD result at highest Mach number: 92 N Inertial force: <4698 N	20	FEA, Compression test, Wind tunnel test
Fins	Aerodynamic drag	CFD result at highest Mach number: Moment: 24.4 Nm (7° AoA) Shear, azimuth: 622 N @7° Shear, axial: 92 N Shear, total: 628 N @7°	7	FEA, Bending test
Boat tail	Thrust	Inertial force: 4698 N	29.6	FEA

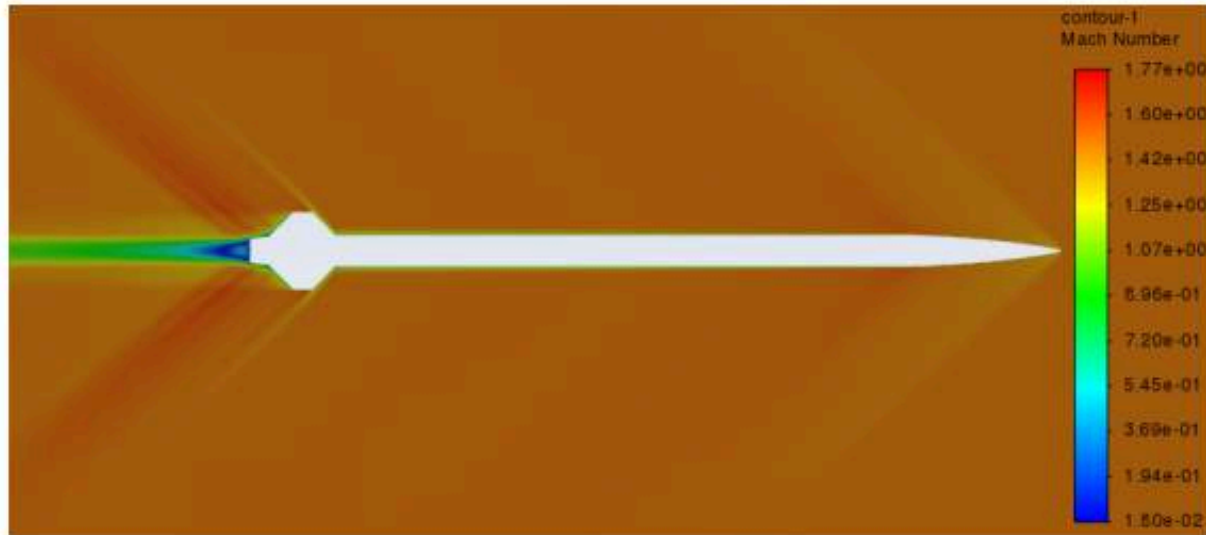


Fig. 15. A contour plot of Mach numbers at Mach 1.5.

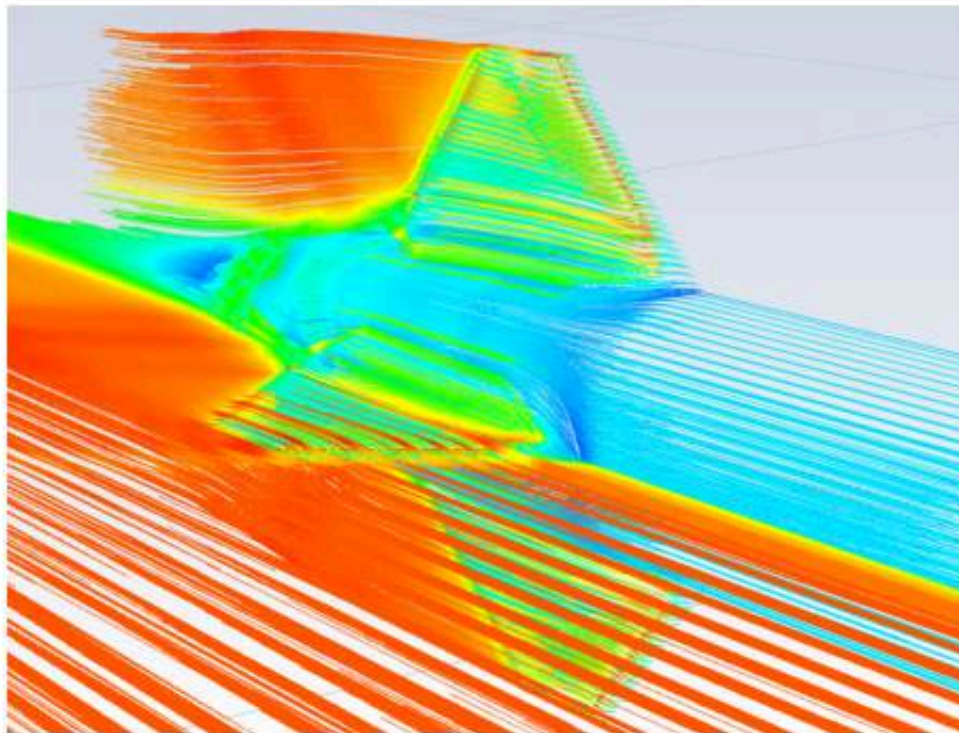


Fig. 16. A plot of pathlines showing the velocity magnitude around the fins at Mach 1.5.

Forward & Aft Airframe validation

For the entire Aft and Forward Airframe, FEA analyses were performed. The detailed description of the analytical calculations and the assumptions made can be found in appendix V.I

To safely launch Birkeland and have a safe flight it is preferable to know how much stress and strain the airframe can handle, at the very least figure out how many holes the airframe safely can handle. The properties of Toray T700s, Zentron 758 S-2 and UF3369 can be used with formulas given by ESA structural material handbook [22] to calculate a few mechanical properties of both the carbon and glass fiber reinforced composites.

Using ansys it is possible to get an approximation of how strong the material is. Since composites are brittle materials you can expect a deviation between each similar part, composites are also orthotropic which makes it difficult to predict the material properties analytically. Therefore a compression test was performed on test pieces of both the forward and aft airframe to validate finite element analysis. The second glass fiber test piece

delaminated at approximately 98 kN of compression force, while FEA predicted failure at 100 kN. The carbon fiber test piece delaminated at 190 kN while FEA predicted failure at 180 kN. These are preferable results however the safety factor is awfully high. It is however required to do an extensive amount of testing to accurately predict the material properties of composites, and these results give a good approximation.

Boat tail validation

The boat tail was validated with FEA. A force of 5 kN (maximum thrust of the motor is 4696 N) was applied to the surface pushed by the engine lip and a clamp was applied to where the boat tail meets the airframe. A maximum Von Mises stress of 9 MPa was observed. This gives a safety factor of 29.

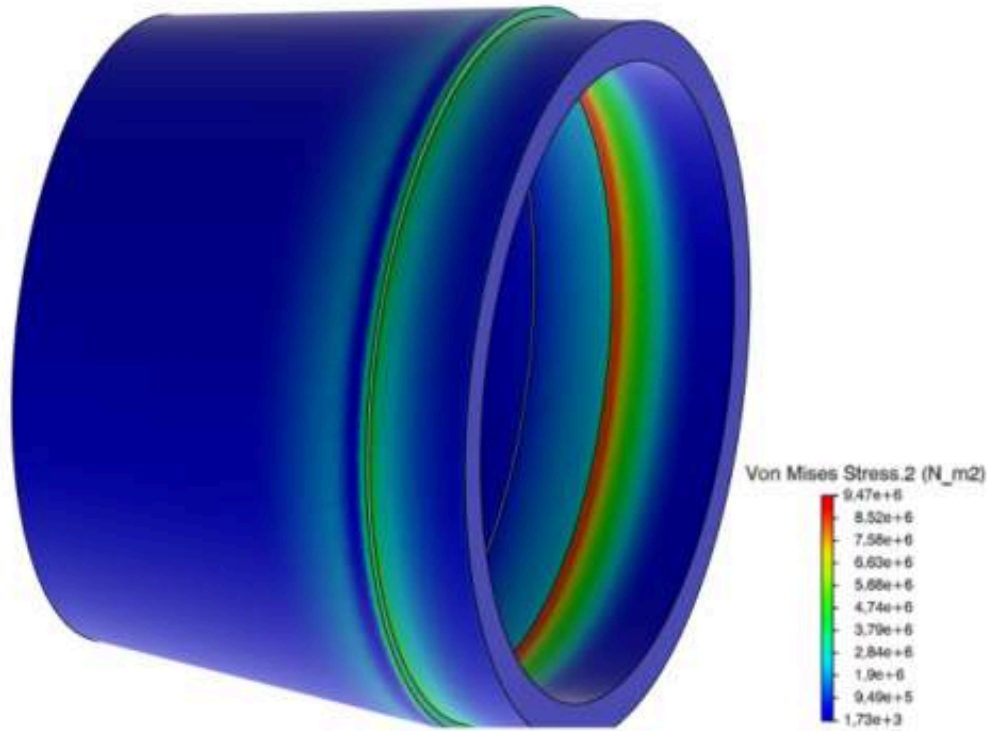


Fig. 17. FEA done on the boat tail.

E. Inner structure

1. System function and system overview

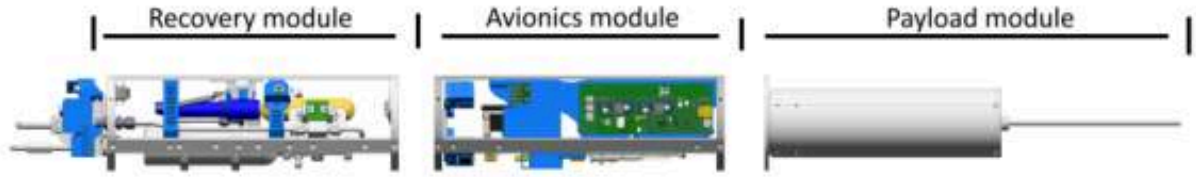


Fig. 18. An overview of the subsystems of the inner structure.

The main function of the inner structure is to provide a framework and mounting points for the internal components of the rocket Birkeland, while incorporating modularity and ease of assembly. The structure inside the upper half of the rocket is module-based, housing the payload, avionics and recovery modules as shown in figure 18. This architecture is chosen to allow for parallel, independent, and thus faster assembly of the payload, avionics and recovery sub-systems. The structural components within the lower half of the rocket are related to the motor, the camera shell, and recovery of the lower half.

Table 4: Overview of the Inner Structure components and their function.

Component	Reference	Material	Validation method	Functions		
				Fastening point	Modularity	Stiffness
Upper Cap	IP.UC	6082-T6 Aluminum	FEA, Integration test			
Payload Tube	IP.T	6061-T6 Aluminum	FEA, Integration test			
Plate Top	IP.PT	S235JRH grade steel	FEA, Integration test			
Payload Plate	IP.PP	S235JRH grade steel	FEA, Integration test			
Lower Cap	IP.LC	6082-T6 Aluminum	FEA, Integration test			
Upper/ Lower Module Ring	IA.UB/ IA.LB	6082-T6 Aluminum	FEA, Integration test			
Avionics Rail (x3)	IA.R	6082-T6 Aluminum	FEA, Integration test			
Mounting Plate	IA.MP	PA12/ PA2200 Nylon	FEA, Integration test			
COTS Battery Casing/Lid	IA.CBC/ IA.CBL	PETG	Integration test			
Video Encoder Casing/Lid	IA.VEC/ IA.VEL	PETG	Integration test			

SRAD Battery Pack Casing/ Lid/ Bottom	IA.SBC/ IA.SBL/ IA.SBB	PETG	Integration test			
Recovery Module Ring	IR.MR	6082-T6 Aluminum	FEA, Integration test			
Recovery Rail A/B/C	IR.RA/ IR.RB/ IR.RC	6082-T6 Aluminum	FEA, Integration test			
Recovery Plate	IR.RP	6082-T6 Aluminum	FEA, Integration test			
Hawk Plate	IR.HP	6082-T6 Aluminum	FEA, Integration test			
PV Brackets	IR.PB	6082-T6 Aluminum	FEA, Integration test			
Camera Mount	IR.CM	6082-T6 Aluminum	Integration test			
Coupler	IAE.C	7075-T6 Aluminum	FEA, Ground test			
Motor Bulkhead	IAE.MB	5754-H11 Aluminum	FEA			
Motor Centering Ring	IAE.MCR	6082-T6 Aluminum	FEA, Flight Proven			

2. Component interfaces

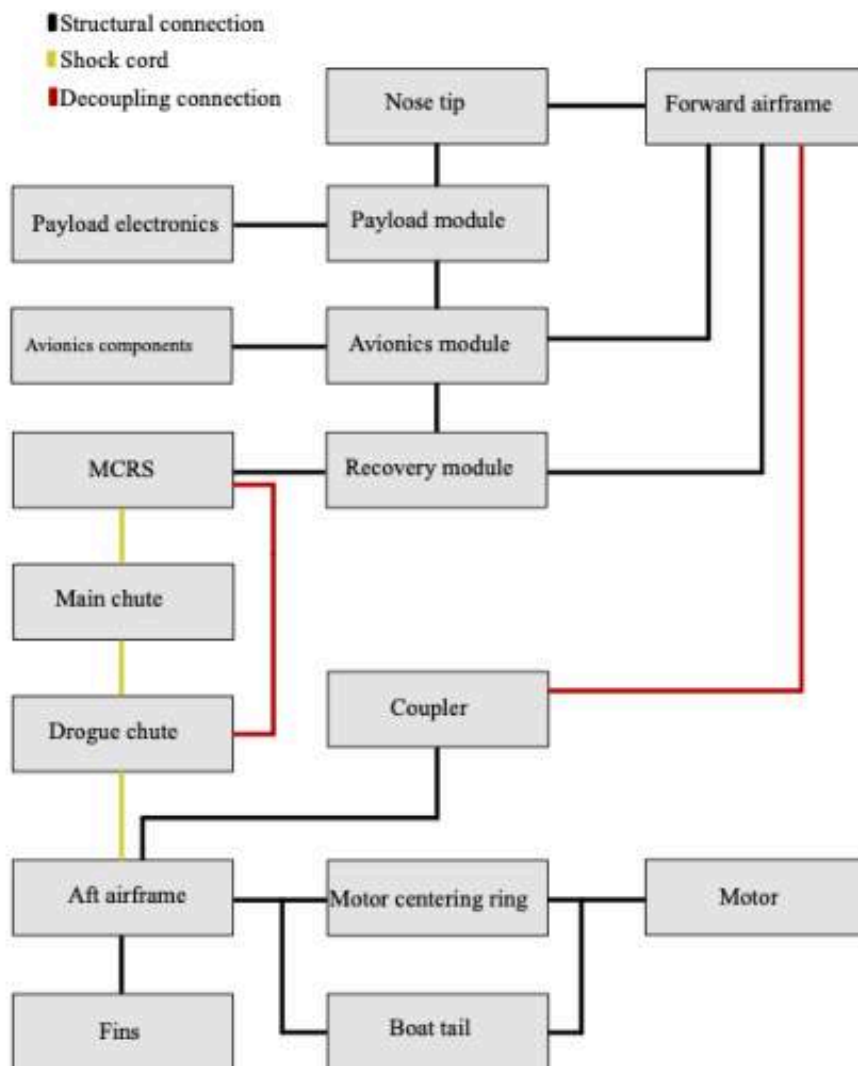


Fig. 19. System diagram.

3. Payload module

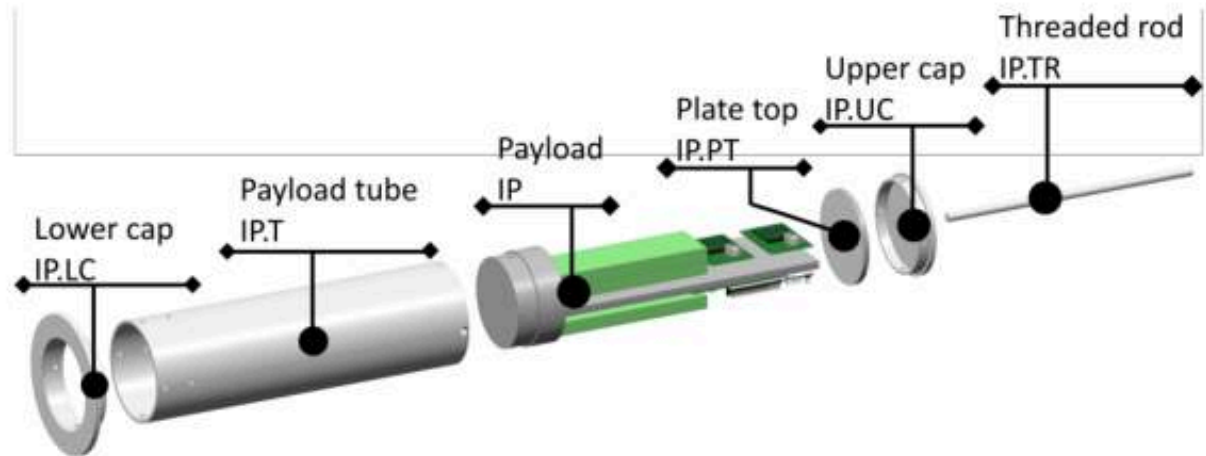


Fig. 20. Exploded view of the Payload module.

Function

The functions of the payload module are as follows:

- Houses the payload experiment
- Fastens the inner structure to the nose tip
- Allows the payload to be removed, such that it can be worked on independently
- Allows the module to be detached from the avionics module

Design

The payload module is designed with ease of production and ease of assembly in mind. The upper cap has a chamfer, allowing it to fit snugly against the airframe and thus preventing excessive vibrational loads on the inner structure. The lower cap has a flanged base, in order to interface with the avionics module below it. Mounting and dismounting of both the payload structures and payload experiment can easily be done at all stages of the assembly process, prior to the insertion of the inner structure into the airframe, by removing four screws in the lower part of the payload tube.

Payload mounting plate

The payload mounting plate is designed to allow the payload experiment and electronics to be mounted securely. See "II.H" for details.

Payload casing

The payload casing consists of three parts: the upper cap, payload tube and lower cap. This design allows for easy insertion and removal of the payload from either the top or the bottom of the payload tube. When the inner structure is fully assembled, the easy removal of the lower cap allows for the payload electronics and mount to be inserted dead last. This allows the payload team to work on their system all the way up until the final steps of assembly. The design also allows for the rocket Birkeland to launch without the payload electronics. Instead, a cylindrical dummy weight could be integrated.

Manufacturing decisions

The components comprising the payload module are manufactured either by plasma cutting or by turning. These manufacturing methods are simple and easy to utilize, making for cheap and quick production. The payload tube is made from a standardized tube, cut to length. The payload mounting plate is plasma cut, and ground to

sufficient tolerances before being welded to a steel puck in one end. The steel puck is turned from a piece of cold rolled round bar. The threaded rod is COTS, and cut to length. The main support structure of the module is made from 6082-T6 aluminum, while the payload mounting plate is made from S235JRH grade steel.

4. Avionics module



Fig. 21. Avionics module.

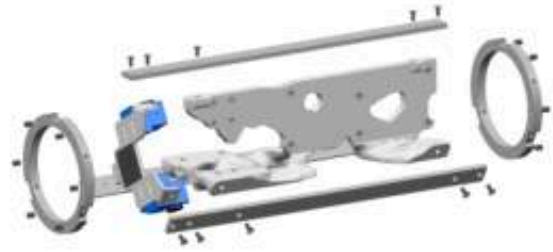


Fig. 22. Exploded view of Avionics module.

Function

The functions of the avionics module are as follows:

- Organizes avionics components in a space efficient way
- Fastens electrical cables in an organized manner
- Allows for easy removal of individual avionics components
- Independent of the other modules up until final assembly

Design

The skeleton structure consists of rails and module rings as seen in figure 21 and 22, and make up the basis for the avionics module. The modules are fastened together by six bolts through the module rings. The rails have countersunk holes to allow the bolts to lie flush with the airframe. The skeleton structure allows for easy removal of the avionics mounting plate, by removing one of the rails (i.e. five bolts). The outer diameter of the module rings is equal to the inner diameter of the airframe and interfaces with the airframe by use of three bolts per module ring. This is a measure to increase the stiffness of the structure, thereby reducing the vibrational loads on the inner structure during flight.

Mounting plate

The T-shaped cross-sectional design creates flat surfaces to mount components inside the available circular space. To reduce weight and volume, the mounting plate has been iterated upon using topology optimization (see appendix V.I). The part is subsequently analyzed to verify that it meets the structural requirements. To allow the avionics components to be removed from the outside individually, threaded inserts are used as mounting points.

Component fastening

Some avionics components do not have fastening points. To resolve this, casings are 3D-printed to allow mounting of these components as shown in figure 23. The SRAD Battery Pack features fastening for PCBs monitoring temperature and voltage on the underside.

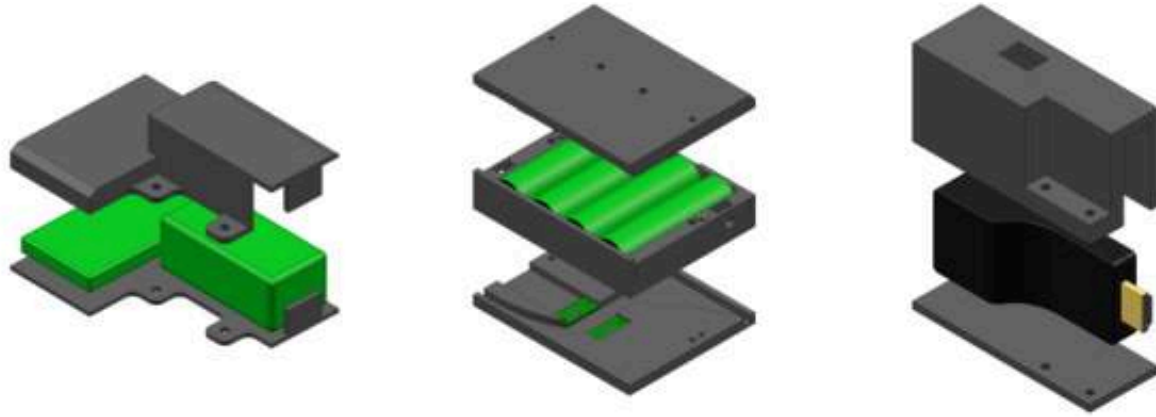


Fig. 23. From left to right: COTS Battery Casing, SRAD Battery Pack and Video Encoder Casing.

Camera mount

The camera mount, shown to the left in figure 21 and 22, holds two opposing cameras used to view out of the airframe. The mount features three fastening points which fasten to the avionics rails and incorporates mounting for camera PCBs and circuit protection PCBs needed for the cameras to operate safely.

Manufacturing decisions

The structure needs to be light, strong, and easy to manufacture. Therefore, laser cut aluminum was chosen for most metal components. The mounting plate is manufactured using SLS 3D-printing, eliminating the need for support structure when printing.

The material used is PA12/PA2200 nylon, chosen for its 48 MPa tensile strength, 930 kg/m³ density and high heat deflection temperature (175°C @ 0.45 MPa). The material also has holes built into the mounting plate allowing heated threaded inserts of sizes M2-M4 to be installed using a soldering iron. Heated inserts are good for use in thermoplastics like PA12 nylon as the plastic melts momentarily and stiffens around the insert, resulting in a strong thread in a plastic part.

The smaller plates, casings FDM 3D-printed, as this is cheaper. Here, PETG is used because of its adequate 50 MPa yield strength and heat deflection temperature (68°C @ 0.45 MPa). The camera mount is made of laser cut and bent 6082-T6 aluminum together with 3D-printed brackets in PETG. The metal acts as a heatsink for the camera PCBs.

Repeated use of threaded holes in aluminum can result in damaged threads. The holes in the module rings are therefore tapped and strengthened using helical inserts. Assembly of the module is explained in detail in Appendix V.E.

5. Recovery module

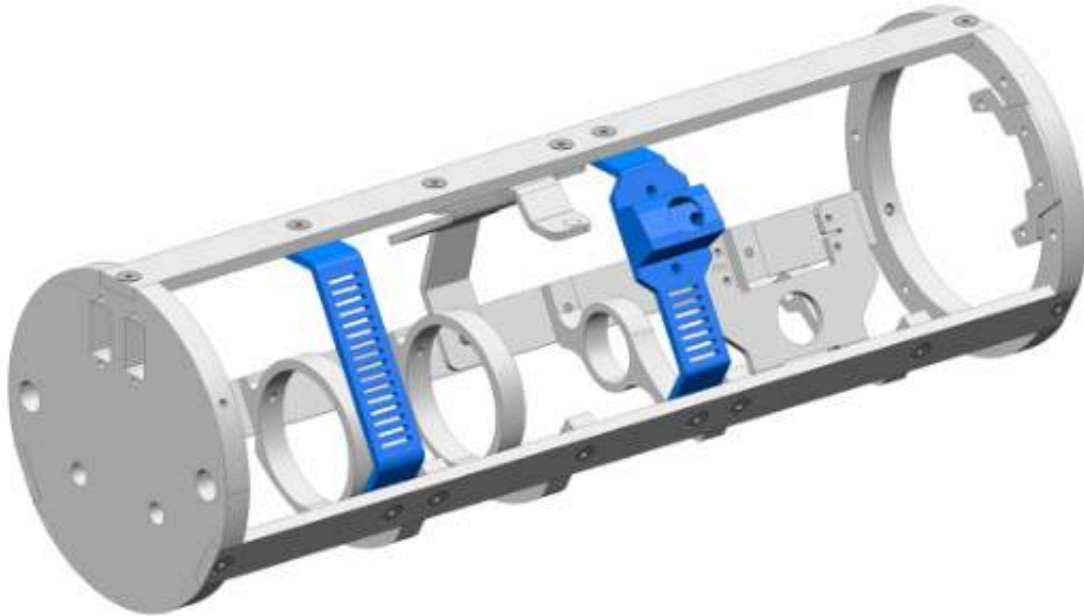


Fig. 24. Recovery module.

Function

The recovery module incorporates the following functions:

- Housing the recovery components
- Ease of assembly/disassembly
- Fastens wires in an organized manner

Design

The recovery module has a skeleton structure which is similar to the avionics module, but slightly altered. There is only one module ring, which is not connected to the outer structure. The rails are of the same length, but have three different configurations for hole placement to fit the plates and brackets in the module. The lower side of the rails is connected to the recovery plate.

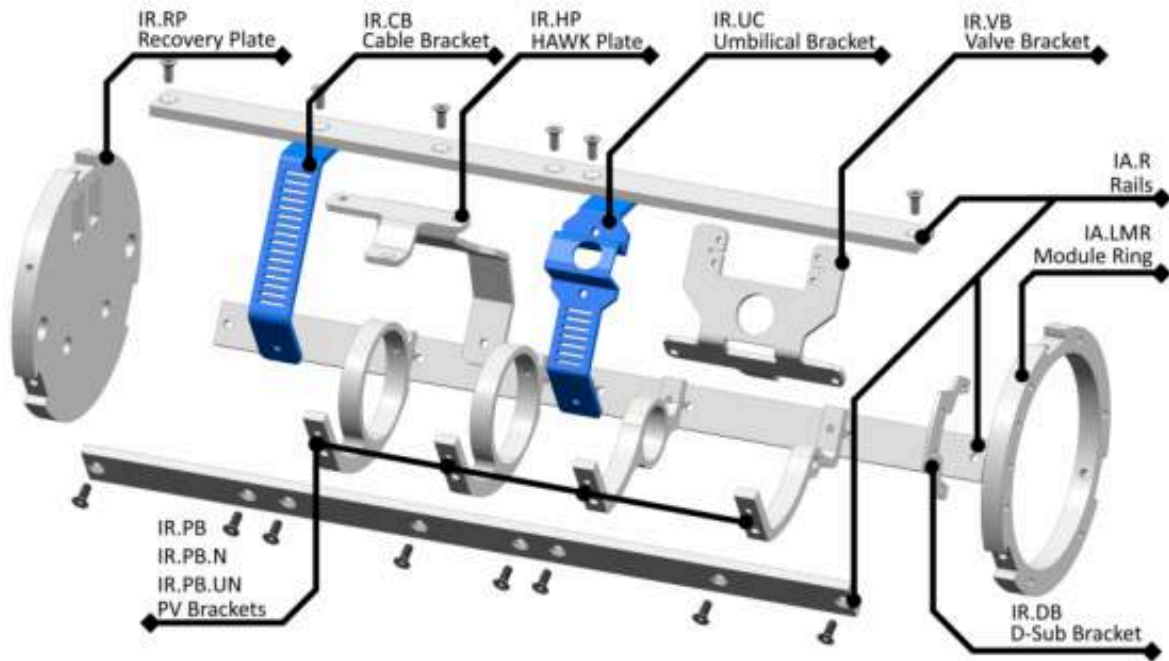


Fig. 25. Exploded view of the Recovery module.

Mounting components

The PV brackets hold the PV in place and are coincident with the airframe for added stability. The HAWK plate provides mounting points for the COTS PBSS and is bolted to the rails. The simple design makes it easy and cheap to produce. The valve bracket is designed to keep the ball valve and tubing for the SRAD PBSS in place, lining up a safety pin with a hole in the airframe.

Recovery plate

The recovery plate is located at the bottom of the module and acts as a lower module ring. The is nearly airtight, in order to not interfere with the intended pressure build up, and subsequent separation, in the recovery bay. There are a total of 6 holes in the recovery plate. Two holes are meant for the hose/piping for the two PBSS, two holes are for D-sub connectors which will provide better cable management. The last two holes are used to mount the MCRS. The recovery plate has three radial holes for fastening it to the airframe using bolts.

Cable management

Cable brackets are used for easier cable management, and the umbilical bracket lines up a magnetic umbilical connector with the airframe providing constant power to the avionics until launch. The D-sub bracket allows all connections between the recovery and avionics module to go through one D-sub connector. The cables will be assembled prior to installation in the module for efficiency.

Manufacturing decisions

The rails and module ring will be produced using laser cutting. All the structural components are made of aluminum 6082-T6. All fasteners will be made out of 18.8 stainless steel. Material for the cable brackets and umbilical bracket is PETG filament. This filament retains strength better than most filaments as temperature rises. All metal components are mostly laser-cut and bent. The reasoning for this is that the rails, module ring and recovery plate are cost effective with laser cutting. The HAWK-plate and the valve bracket were designed with laser cutting and plate bending in mind. All holes in the rails are countersunk, allowing the module to lie flush with the airframe.

6. Aft end



Fig. 26. Motor centering ring and Motor bulkhead.

Function

The inner structure of the aft end consists of the motor centering ring and the motor bulkhead. The functions of an aft end are as follows:

Motor centering ring

- Keeps the motor centered, hindering radial movement
- Makes assembly of the aft end easier.

Motor bulkhead

- Separates the recovery bay from the motor bay
- Provides fastening points for the U-bolt used for recovery

Design

The motor centering ring sits between the motor and the aft airframe, and is fastened permanently to the aft airframe using adhesive and four screws. It has an angled inner edge, to make assembly easier. The motor bulkhead sits in the coupler, fastened with six radial screws. It contains two axial holes used to fasten the U-bolt, which is used for recovery.

Manufacturing decisions

Both the motor centering ring and the motor bulkhead are circularly symmetric, making them optimal for turning. The motor centering ring is made of 6082-T6 Aluminum. The motor bulkhead is made of 5754-H11 Aluminum.

7. Validation

Integration testing and Finite Element Analysis (FEA) allows for validation that the components can perform their intended functions. Dassault Systemes Simulia 3DEXperience was used for all FEAs. For a complete list of the validation methods, see table 4.

The individual components of the inner structure have been validated using FEA, see appendix V.I. The inner structure is not load bearing, and therefore a total system FEA is not necessary. The majority of the forces present will be applied to the airframe.

F. Recovery

1. System function and overview

The recovery system utilizes a dual-event parachute recovery [DTEG 6.1 Dual-Event Parachute and Parafoil Recovery], which consists of a drogue and a main parachute. The drogue chute is to be deployed shortly after reaching apogee using a pressure-based separation system (PBSS). Birkeland has one SRAD PBSS, as well as a redundant COTS system. The SRAD PBSS is activated first, and then 2 seconds later the COTS PBSS is activated. The main chute is deployed at an altitude of 450 meters above the ground level using a SRAD main chute release system (MCRS).

An overview of the system is shown in Figure 27. The two PBSS are housed inside the recovery module. The recovery plate is connected at the bottom of the recovery module, separating it from the parachute bay where the parachutes are located. It also serves as a mounting base for the MCRS. The parachute bay is the compartment within the coupler section of the rocket, and will be pressurized for separation.

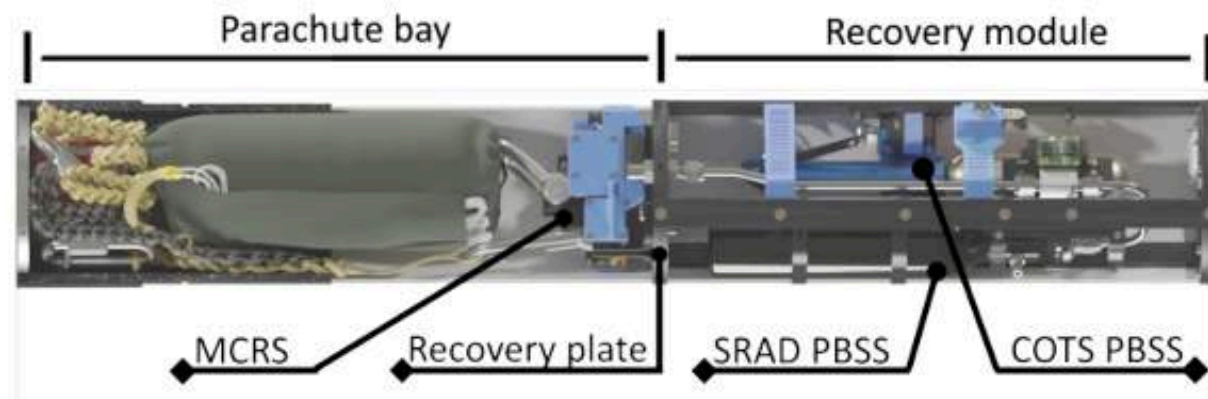


Fig. 27. Recovery overview

Table 5: Recovery function diagram

Component	Reference	Production	Validation	Functions			
				Energetic device	Load bearing	Drogue deployment	Main deployment
Pressure based separation system	RH	Commercial off-the-shelf	Ground test				
	RSP	Commercial off-the-shelf Laser-cut Machined parts	Pressure test Ground test Drop test				
Main chute release system	RM	Laser-cut Machined parts Metal sheet bending	FEA Function test				
Parachute system	RC	Commercial off-the-shelf	Rated load from supplier compared to parachute calculations* Drop test Wind tunnel test Car test				

* Calculations performed analytically and also with python.

2. SRAD PBSS

Function

The function of the SRAD PBSS is to separate the rocket at apogee using compressed air.

The SRAD-system utilizes a valve-operated pressure vessel in order to pressurize the parachute bay. The actuated valve is triggered by the SRAD flight computer upon apogee detection, allowing the stored gas to expand into the parachute bay. The pressure build up is enough to break the shear screws that hold the coupler and forward airframe together, resulting in separation of the rocket and deployment of the drogue parachute.

Design

The SRAD PBSS consists of the following components:

- Pressure Vessel (PV)
- Actuated valve that is operated by a servo motor with gears
- Gear safety pin
- Pressure gauge
- Bent metal pipes
- Adapters between the components

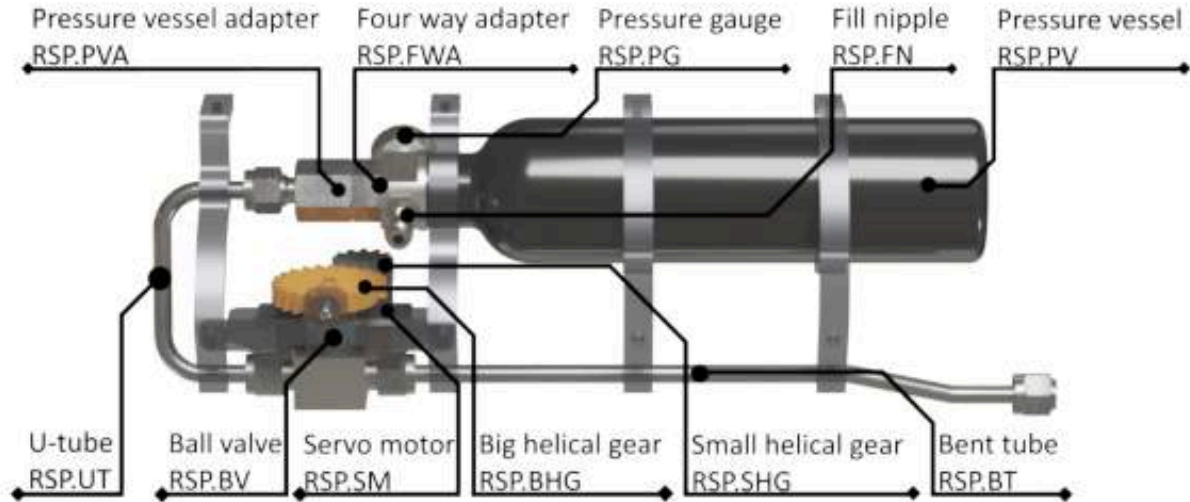


Fig. 28. SRAD PBSS

The PV has a volume of 0.22 L and is made to withstand 200 bars of pressure. The actuated valve assembly consists of a ball valve, a servo motor, two gears and a bracket. The servo moves the gears, which opens and closes the valve. The valve has an actuation time of 0.5s. Further, a safety pin is used to lock the gears in place when the system is energetic [DTEG 6.18 Stored-energy Devices - Energetic Device Safing and Arming]. The bent metal pipe routes the gas into the parachute bay. In addition the SRAD PBSS is designed to be a reusable system for rocket separation and can be filled manually with a hand-powered pump.

Manufacturing methods

The SRAD PBSS consists of SRAD and COTS parts. The PV, tubes and adapters are COTS. The valve is a swagelok manual ball valve modified to work with a servo and 3D-printed gears. The adapter between the PV and the tubing is SRAD, and machined out of a steel bolt. The gears are 3D-printed with carbon fiber reinforced nylon.

Shear screws

The shear screws function as a controlled structural weak point, meaning that they have to hold both rocket halves together during launch, and to break as intended when a PBSS is activated. Four M4x0.7 screws have been chosen, and validated in Appendix V.I. The pressure calculations show that the four screws combined break under a pressure of 2.22 bar. They have also been validated during ground tests, drop test and shear pin tests. In Table 6 the results from the calculations are presented with safety factors for separation:

Table 6: Separation safety factors

PBSS	Pressure from separation system [bar]	ISO metric thread	Number of screws	Safety factor separation
COTS(33g)	5.10	M4x0.7	4	2.30
SRAD(50g)	7.05	M4x0.7	4	3.18

The shear screws must be strong enough to handle the forces from flight and handling of the rocket. Pressure buildup can cause an unwanted early separation. It is therefore crucial to have a venting hole to prevent unintentional pressure from building up inside the rocket [8.1 Adequate venting]. Since the rocket is supposed to separate, it could be argued that it is not necessary to have a venting hole in the parachute bay. However, there will be one in order to eliminate the risk of early separation. Additionally, an O-ring is used in the coupler to ensure that the parachute bay is completely airtight elsewhere.

3. COTS PBBS

Function

The function of the COTS PBSS is to separate the rocket at apogee by releasing pressurized CO_2 into the parachute bay.

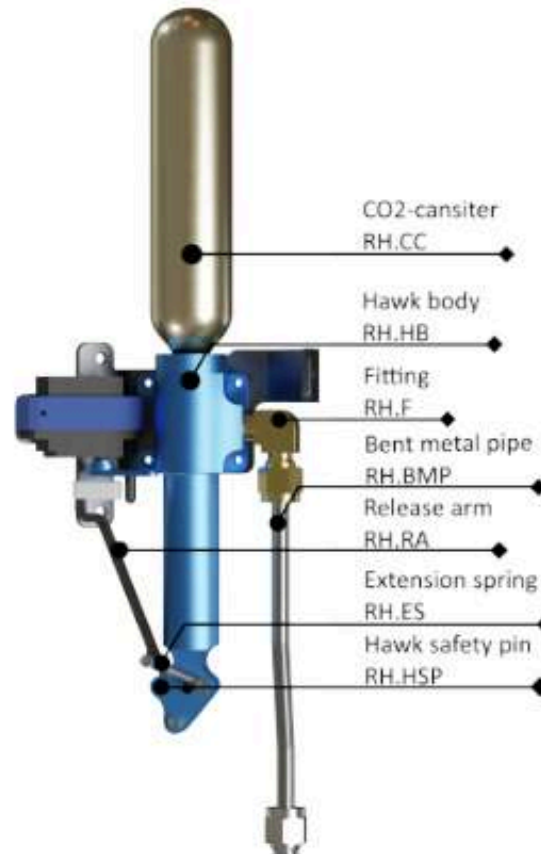


Fig. 29. COTS PBBS

Design

The COTS PBSS is designed to be a reliable and dissimilar back-up to the SRAD PBSS. While the SRAD PBSS is connected to the SRAD flight computer, the COTS PBSS is connected to the COTS flight computer in order to have electronic redundancy [DTEG 6.8. Redundant Electronics]. The system consists of a Hawk, a servo motor and a pressurized CO_2 -canister. The components are mounted to an aluminum backplate (see Figure 29.). The servo motor is angled on the backplate, but the servo arm rotates around the same axis. This is to save space in the recovery module. The Hawk is a COTS-system that features a spring-loaded piston that is held in place by a release arm. The motor rotates the release arm to unleash the piston. The CO_2 -canister is then punctured, and gas flows into the parachute bay. This results in separation of the rocket and deployment of the drogue chute. Note that the pressure systems are activated at different times in order to distinguish between them. The SRAD PBSS is activated first, and then 2 seconds later the COTS PBSS is activated.

The Hawk is considered an energetic device once the spring is loaded and must comply with the same energetics requirements as the SRAD PBSS [DTEG 6.18. Stored-energy Devices - Energetic Device Safing and Arming]. To accommodate this the Hawk features a safety pin that is installed once the system is loaded. The safety pin has a wire at its end that is led through an opening in the airframe, which allows the system to be armed externally at the launch pad.

Manufacturing decisions

The Hawk is a COTS system from Fruity Chutes Inc. [11]. The hawk plate is produced from a 3 mm thick aluminum plate that has been laser cut and bent into the desired shape. The ductile property of aluminum makes it suitable for bending.

4. Parachutes

Function

The function of the drogue chute is to:

- Control the descent from apogee until main chute release
- Slow down the descent velocity
- Reduce drifting
- Provide visual confirmation of deployment

Function

The function of the main chute is to:

- Decrease the descent velocity enough for a safe landing
- Limit impact stress on the structure
- Provide visual confirmation of deployment
- Ease recovery operation, improved visibility

Design

The descent velocity for the drogue chute shall be between 23 m/s and 46 m/s, whilst the main chute descent velocity shall be below 9m/s according to SA Cup [DTEG 6.2 Initial Deployment Event and 6.3. Main Deployment Event]. The chosen main parachute is Iris 96" compact parachute and the chosen drogue parachute is 30" elliptical. This selection of parachutes was based on the drag force equation solved for velocity. The calculations are detailed in section V.H. The drogue chute descent rate is expected to be 30.2 m/s at 450 m. In combination with OpenRocket, RocketPy and the python script, the different expected impact velocities were averaged. This gives an impact velocity of 7.3 m/s. The velocity profile is shown in Figure 30.

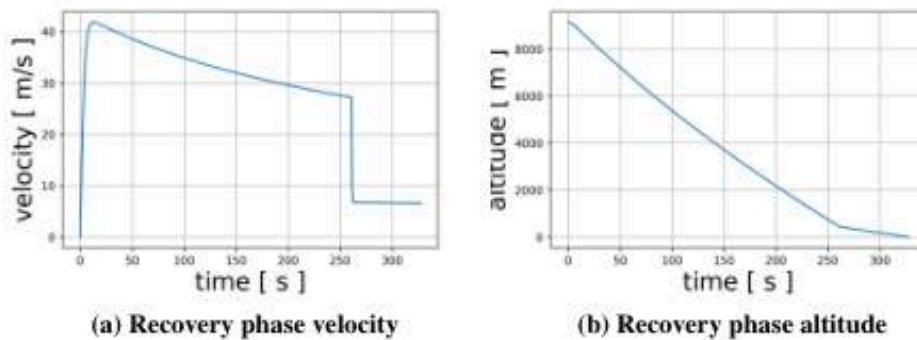


Fig. 30. Descent profile of recovery phase.

Furthermore the parachutes have different colors to differentiate the parachute deployments [DTEG 6.6. Parachute Coloration and markings]. The drogue chute is white and red, while the main chute is black and orange.

Shock cords

The shock cord setup consists of a straight cord connected to the aft tube and drogue chute, and a Y-cord connected to the fore tube and parachutes. One leg of the Y-cord has a swivel added in the middle. This is the setup after the main chute is released and can be seen in Figure 31. This complies with apogee rocket's statement, that the shock cord connecting the aft and drogue chute should be about three times the length of the rocket. This setup is intentionally designed in such a way that the aft and forward airframe do not collide mid-air. The intention of having a longer cord attached to the aft is so that the aft touches the ground first. This is intended to cause a smoother landing of the forward airframe. The velocity on the forward airframe is then decreased to 5.4 m/s, see Appendix V.I.

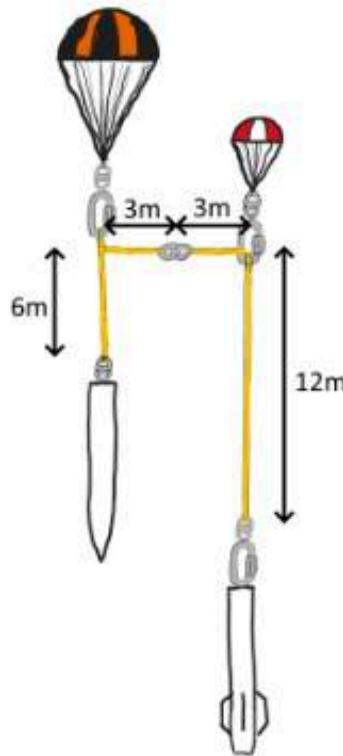


Fig. 31. Shock cords length

The main feature of the shock cords is to connect the airframe to the parachutes and to reduce the shock from the parachute's release force. However there are several risks associated with shock cords. The shock cords can cause zippering, tangle and snap. Five swivel links are distributed in the parachute system to lower the risk of tangling [DTEG 6.5. Parachute Swivel Links]. In order to mitigate the chance of zippering the shock cord features a surface extender. The surface extender is installed where the shock cord meets the airframe when the shock cord is fully stretched. The solution increases the contact area with the airframe and relieves the pressure on the cord. This reduces the chance of zippering of the fuselage as well as cutting of the shock cord.

5. Deployment forces

The deployment forces was calculated using the drag force equation,

$$F_D = \frac{1}{2} \rho v^2 C_D A. \quad (3)$$

The resulting maximum deployment force is found to be approximately 1.6 kN and 4.5 kN during drogue and main chute deployment respectively. The force distribution for these events are shown in Figure 32.

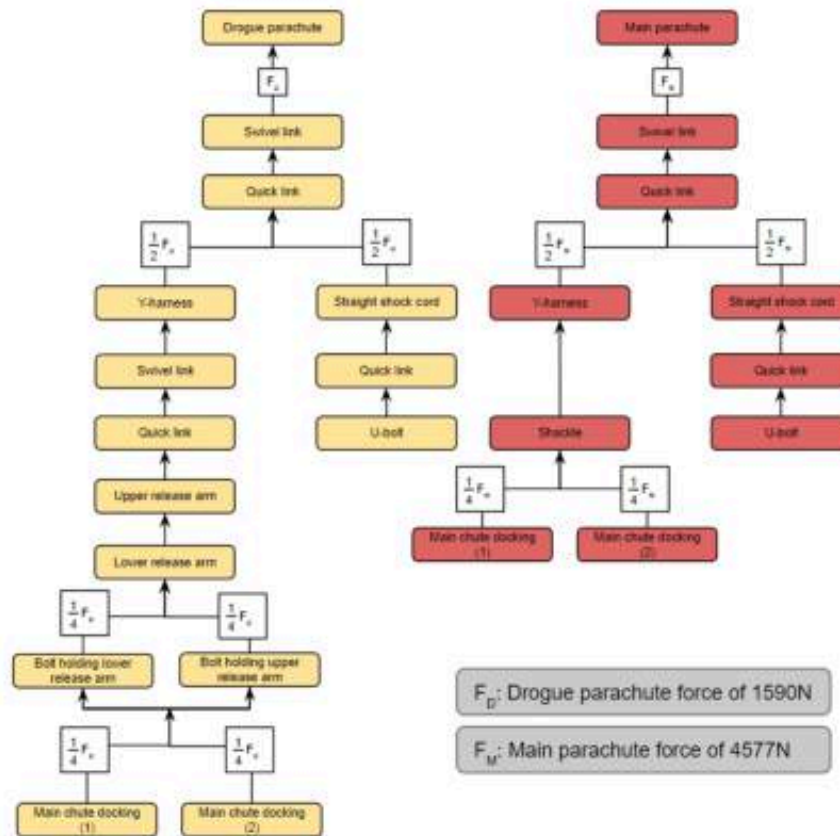


Fig. 32. Force flow during initial and main deployment stage

The calculations have been calculated with a python script that uses the equations mentioned above. The python script and detailed calculations are given in Appendix V.I Chute Calculations and Parachute Trajectory Simulations. The python code can be found directly in Appendix V.I python chute calculations. The results and corresponding safety factors are shown in Table Table 7. A safety factor of minimum 2 was targeted.

Table 7: Overview COTS components and experienced load.

Component (material)	Reference	Deployment stage	Experienced load maximum [N]	Rated maximum load [N]	Safety Factor
Main parachute (nylon)	RC.MC	Main	4493	21365	4.8
Drogue chute (nylon)	RC.DC	Initial	1590	7828	4.9
Quick link (Stainless steel)	RC.QL	Initial	4493	9341	2.1
Swivel link (Stainless steel)	RC.SL	Initial	4493	13345	3.0
Straight shock chords (Nylon)	RC.SCD	Initial	4493	9786	2.2
Y Harness (Kevlar)	RC.SCY	Initial	4493	9786	2.2
U-bolt	RC.U	Initial	2098	8896	4.2
Shackle	RM.S	Initial	2395	8829	3.7

6. Main chute release system

Function

The main functions of the MCRS are as follows:

- Releasing the main chute at 450 m altitude
- Serve as a load bearing fastening point during both deployment phases

Design

The MCRS consists of two different rotating arms, held in place by two bent steel plates. The system is powered by two independently controlled servo motors. One of the servos is connected to the SRAD flight computer, while the other servo is connected to the COTS flight computer. This is done to add a layer of redundancy as of the requirements from SA Cup [DTEG 6.8 Redundant Electronics]. When one of the servos rotates its servo horn, it pushes on the lower release arm (see Figure 33). This will in turn allow the upper release arm to rotate and consequently release a quick link. It is this quick link that connects the main chute to the drogue chute. When the quicklink is released, the drogue chute will pull the main chute out of its deployment bag, allowing it to deploy. Moreover, at 450 m the servo receives a signal from the SRAD flight-computer to activate, then at 430 m the other servo is activated by the COTS. The servos are activated at different altitudes to differentiate when each system is activated. Both systems act independently, adding redundancy and reliability.



Fig. 33. MCRS overview (left), MCRS locked position (middle) and MCRS open position (right). Note that one of the two servos are hidden to display the mechanism more clearly.

When load from the drogue chute is applied to the system, rotation of the upper release arm is prevented by the lower release arm. The system is self locking, meaning a higher load implies that a higher force is needed to rotate the lower release arm in order to deploy the parachute. This reduces the risk of early deployment and allows it to function as a fastening point for the aforementioned quick link during drogue descent. During main chute descent the parachutes are attached to a shackle at the top of MCRS. This saves space and makes assembly of the system easier compared to having a separate u-bolt or eye-bolt.

Manufacturing decisions

The system is designed to be easy to manufacture. The basis for production is 6 mm thick steel sheets (S650MC), laser cut into the desired shapes. To achieve the final shape, the main chute dockings are bent by 90 degrees. The yield strength of this product is 650 MPa, and the components have been verified by using FEA. The results are shown in table Table 8

Table 8: FEA results of the components of the MCRS

Part	Reference	Worst case load [N]	Experienced stress [MPa]	FoS
Upper release arm	RM.URA	966.2*	74.9	8.7
Lower release arm	RM.LRA	966.2*	180	3.6
Main chute docking	RM.MCD	1177.5*	71.1	9.1

*These simulations use an earlier calculated drogue deployment force and main chute force that is greater than the expected one from the new calculations.

Design

7. Validation

The recovery system has been validated by calculations, FEA and physical testing. Calculation was done to give an analytic validation of the system. FEA was used in order to validate the strength of the components. Furthermore because of Norwegian law and heavy restrictions it is not possible to do a flight test. Instead, several ground tests of key subsystems have been done to accommodate SA cup's requirement of recovery system testing [DTEG 6.16 Ground tests demonstration]. Some of these tests include a function test of the separation system, parachute and main deployment mechanism test in a wind tunnel and a helicopter drop test. The results from these tests conclude that the recovery system functions as intended and is ready for launch at SA-cup. Table Table 9 presents an overview of the conducted tests, while detailed test reports can be found in Appendix V.B

Table 9: Recovery validation overview.

Subsystem	Validation purpose	Status	Reference
MCRS	FEA of the MCRS to validate the strength of its components.	Success	Appendix V.B MCRS and Recovery Plate Calculations and analysis
MCRS, main chute and drogue chute	To see if the main chute deployed prematurely under different conditions.	Success	Appendix V.B Car test
SRAD PBSS	To see if the SRAD PBSS can withstand a pressure of 180 bar	Success	Appendix V.B Hydrostatic test report
MCRS, main chute and drogue chute	To test parachute deployment systems behavior in realistic conditions	Success	Appendix V.B Voss wind
COTS PBSS and SRAD PBSS	To determine if both the COTS and the SRAD PBSS are able to separate a representation of the rocket.	Success	Appendix V.B Ground test
All recovery subsystems	The drop-test aims to test the recovery system's behavior in its designed operating conditions	Complimentary Success	Appendix V.B Drop test

8. Validation Remark

As can be seen from table Table 9, project Birkeland had a complimentary successful drop test. The results were as follows: The SRAD PBSS was successfully activated and able to separate the rocket. Both parachutes were able to deploy, allowing the rocket model to land in a safe and controlled manner. However the drop test

unveiled some issues with both the recovery and avionic systems. The MCRS was unable to retain the main chute after the separation. This was caused by an unfavorable geometry on the release arms, combined with the use of too loose retainment springs. The avionics system experienced a loss of power, preventing it from activating the MCRS and the COTS PBSS. Read more about the test in the test report appendix V.B Drop test.

A thoroughly validated recovery system is very important for the success of a flight. Iterations have been made to the mechanical design of the MCRS, and additional testing is planned to be performed. The latter will not be conducted until after the submission deadline for this report. Therefore, remaining reports will be available in time to the competition for the judges to review.

G. Avionics

1. System overview

The rocket will contain two completely independent sets of avionics. One set will be SRAD, the other a COTS solution for redundancy. The SRAD solution is based around a self developed flight computer carrying two IMUs, a barometer, a magnetometer, and a GNSS-reciever. This sensor data is passed through a multiplicative extended kalman filter (MEKF) and then used in a finite state machine (FSM) which controls when to deploy recovery systems. All collected data onboard the rocket, as well as one of five captured video streams, will be sent live down to our ground station. The system is powered by four li-ion batteries in a 2S2P configuration. The ground station, in addition to storing telemetry, is also used as an independent and redundant tracking method for the rocket. Both system's main functions are tabulated in Table 10 below.

Table 10: Required avionics functions

Function number	COTS system functions	SRAD system functions
1.	Activate recovery systems	Activate recovery systems
2.	Collect and store data	Collect and store data
3.	Location tracking using GPS for recovery after landing	Location tracking using GPS for recovery after landing
4.		Additional functionality (discussed later)

2. COTS avionics system

COTS avionics is included in the rocket to ensure that there is a proven redundant set of electronics onboard the rocket. It has to fulfill requirements from SA cup [DTEG 2.6, DTEG 6.8, DTEG 6.9, DTEG 4] as well as requirements from other systems [S.4.3 V.H]. A list of the general functionality the COTS avionics fulfills, as well as the chosen COTS solution, is listed below in Table 11. A diagram of all connections in the COTS system can be found in Figure 34.

Table 11: Required COTS avionics functions

Function	Description	Solution chosen
Redundant Recovery flight computer	Redundant avionics for activating the Hawk pressure-based separation system, and MCRS.	Altimax G4 (AV.AM)
COTS GPS tracker	COTS solution for GPS tracking of rockets.	Featherweight GPS tracker (AV.FW)

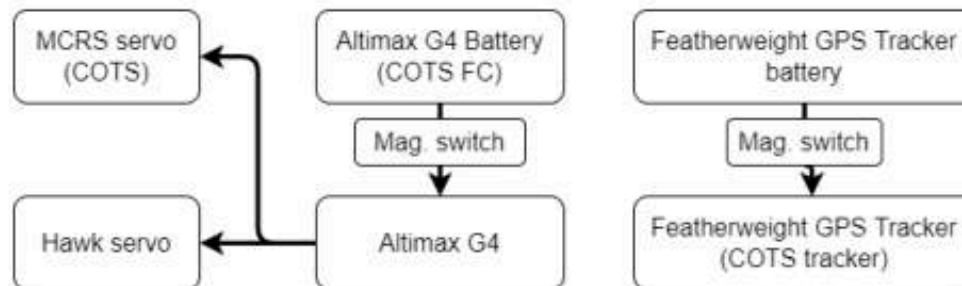


Fig. 34. Diagram of COTS system connections.

The Altimax G4 flight computer was chosen because of its sensor suite and ability to activate the recovery system. The system can use both a barometer and accelerometer, making it suitable for detecting apogee in a supersonic flight. It was also chosen because it has the capability to activate servo motors, which is needed for both stages of recovery.

The Featherweight GPS tracking system was chosen because of its ease of use, effectiveness, small size, operating radio frequency, and previous teams' experience with it. Because it operates in the 915 MHz band, it can be used without any HAM radio license in the US.

Another important design choice for the COTS avionics is having it all be independent. The COTS systems each run on their own battery, making them completely independent from each other and the SRAD system. This way if one system fails, it should not affect the others. The battery specifications and estimated on-time for the COTS systems are listed in Table 12 below.

Table 12: COTS battery life overview

Battery features	Altimax G4	Featherweight GPS tracker
Battery setup	2S1P LiPo	1S1P LiPo
Nominal battery voltage	7.2 V	3.6 V
Minimum battery capacity	800 mAh	650 mAh
Estimated battery life	4+ hours	24+ hours

For arming the COTS electronics, a magnetic switch is utilized. This switch lets us power the systems at the launch pad via a magnet from outside the airframe, meaning no holes are needed in the rocket for this purpose. The featherweight magnetic switch (AV.MS2) is the magnetic switch which will be used.

3. SRAD avionics system

The SRAD avionics system is self developed in nearly all aspects, from PCBs to embedded software both onboard the rocket and on the ground station. Only the radio transceivers and camera solutions used in the SRAD system are COTS parts.

Requirements & function

The SRAD system fulfills the functions listed in Table 10. Additional functionality beyond what is required from SA cup rules are listed in Table 13. The functions are performed to improve technical expertise amongst members and to research, develop and validate new solutions for later projects.

Table 13: Additional SRAD functionality

Additional function number	SRAD Avionics additional functions
1	Live telemetry of all collected data during flight.
2	Live videofeed during flight.
3	Multiple layers of circuit protection against electrical faults on all electronics.
4	Blackbox for safe data storage.
5	Location tracking using radio (no-GPS fix required).

The SRAD system has to fulfill the SA cup requirements, which are mentioned in IREC. In addition to these, requirements from the mechanical and recovery systems have to be followed. Lastly, there are some practical guidelines in the SA cup DTEG that the system has to follow. These are DTEG appendix V.B, safety critical wiring guidelines.

4. SRAD electronics

The SRAD flight computer (AV.FC) consists of two stacked PCBs, with various smaller PCBs for peripheral use located throughout the rocket. An image of the SRAD flight computer is seen in Figure 35, and an overview of all connections in the SRAD system can be seen in Figure 36.



Fig. 35. PCBs used in the avionics module. The KB3 microcontroller board is on the bottom, while the power delivery board (PDB) sits on top.

Flight computer specifications

The top and bottom PCB in the flight computer PCB stack are named PDB (AV.PDB) (Power Delivery Board) and KB3 (AV.KB3) (Kristian Birkeland Brain Board) respectively. The KB3 is based around a STM32H753 microcontroller, which runs the software performing all of avionics' main tasks onboard the rocket. The PDB houses a battery management system built around the BQ20z655-R1 battery gauging IC. It is used to monitor battery State of Charge (SoC) and provide protection for a GPS receiver, in addition there are the power management ICs used to control power delivery to external peripherals.

Sensor solutions

Onboard the SRAD flight computer are a suite of sensors chosen for collecting critical flight data which will be used for performing the avionics' main tasks, as well as for post flight analysis. In Table 14 below, all sensors used are listed with relevant specifications. Note that the magnetometer will not be mounted on the PCBs, but instead housed further up in the nose cone to avoid any magnetic interference.

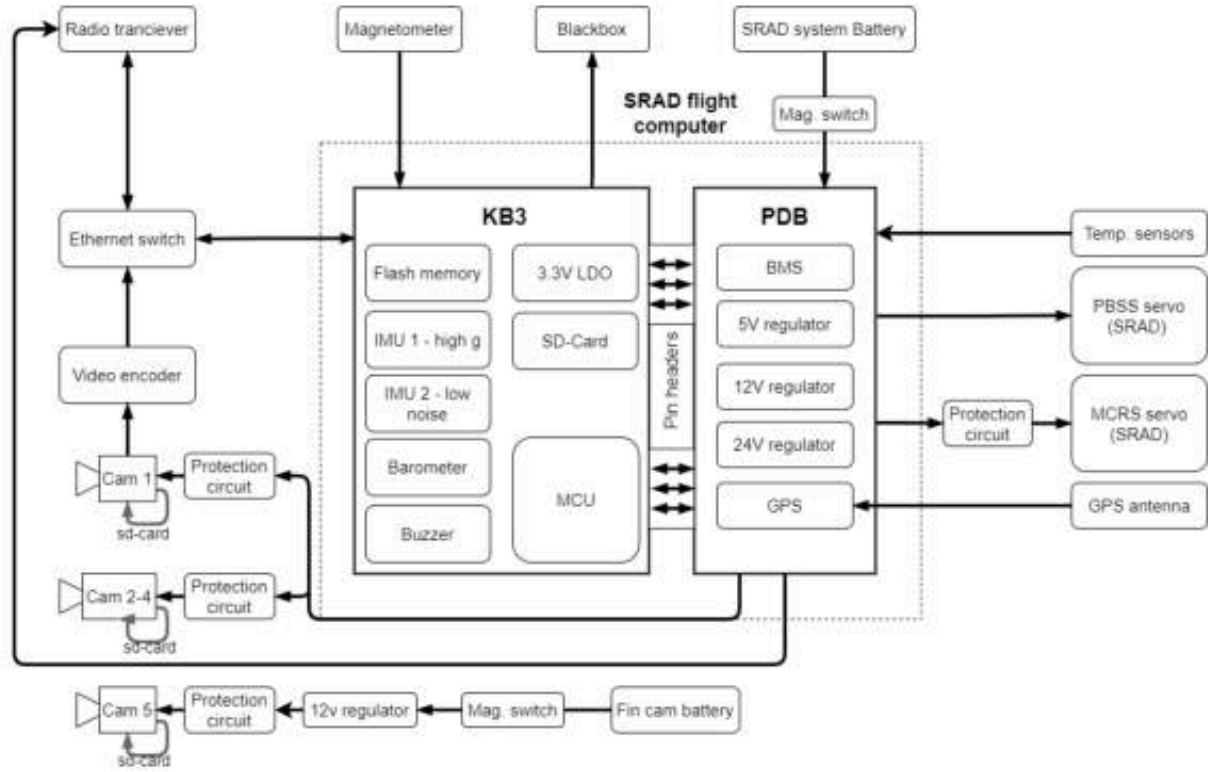


Fig. 36. Diagram displaying all connections of the SRAD avionics.

Table 14: Sensor Models and Specifications

Sensor type	Sensor model	Comms. protocol	Relevant specifications
Barometer	MS5607-02BA03	SPI	Reads at max. and min. pressure: 120 kPa, 1 kPa.
6Dof-IMU (accel+gyro)	LSM-6DSO32	SPI	Reads upto 32 Gs of acceleration, with a max. data output rate of 6.7 kHz.
6Dof-IMU (accel+gyro)	IIM-42652	SPI	Reads upto 16 Gs of acceleration, with a max. Data output rate of 32 kHz.
Magnetometer	LIS3MDL	SPI	Max. data output rate of 100 Hz, with readings ± 1.6 mT.
GPS	U-Blox NEO M9N	UART	Concurrent reception of 4 GNSS, max update rate of 25 Hz, vertical velocity limit of 20 km/s.

Storage solution

A flash chip and an SD card will be used to store data onboard the rocket. After conservative calculations for the required amount of data were made, it was found that 144 Mb of data would be stored in a 30 minute long flight, calculation can be found in appendix V.I. The actual flight is expected to last closer to 15 minutes, and the storage capacity is 256 Mb giving us a good safety margin for storage. The specifications for the chosen flash memory chip can be seen in Table 15.

Table 15: Flash Chip characteristics

Storage type	Flash
Component name	W25Q256JVF1Q
Communication protocol	Quad SPI (enables high write speeds)
PCB footprint	16 SOIC (common footprint, changes of chip can be done with ease if needed)
Storage capacity	256 Mb/32 MB

Battery solution

The battery solution is based around a 2S2P configuration of Li-ion batteries. The Battery Pack (IA.SBC) will power all of the SRAD system. Note that this system is completely electrically independent from both of the COTS systems. In subsection O, an overview of the avionics' electrical characteristics are outlined.

Table 16: Avionics Electrical Characteristics

Electrical Characteristics	System Characteristics		
	Avionics Module		2S2P Battery
	Nominal	Maximum	Critical*
Power (W)	37	54.2	72
Voltage (V)	3.3 - 24	3.3 - 24	5**
Current (A)	7.4	10.86	14.55***

* The values listed values on the table correspond to operating conditions under the highest possible current draw and lowest possible voltage of the battery, the critical state.

** The value listed is the battery's lowest possible voltage. The battery's nominal voltage is rated at 7.2 V, and its maximum voltage is rated at 8.4 V.

*** The current rating here is the maximum amount of current that can be delivered from the battery.

Umbilical cord solution

To avoid draining the battery while the rocket is idle at the launch pad, an umbilical cord (AV.CORD) to provide power is utilized. This cord connects a smart charging IC BQ24800 to the BMS. By charging the battery pack with constant voltage, the batteries of the rocket will be kept fully charged, and power to the rest of the avionics system will be provided by the charging IC.

The umbilical cord is connected to the rocket with a magnetic plug through which power is provided, as well as an SMBus communication signal to ensure the correct charging voltage is provided. Upon launch, the magnetic plug of the umbilical cord will automatically disconnect, and the system will run on its battery pack.

Cameras

Four cameras are directly connected to the avionics module; two cameras are positioned in the recovery bay and avionics module each. The purpose of these cameras is to monitor and record the activation of the MCRS servo, record parachute deployment, as well as to capture video from the outside of the rocket. These recordings will be useful in the event of an investigation into any problems encountered during flight upon successful retrieval of the Avionics module. The camera placements can be seen in Figure 37.

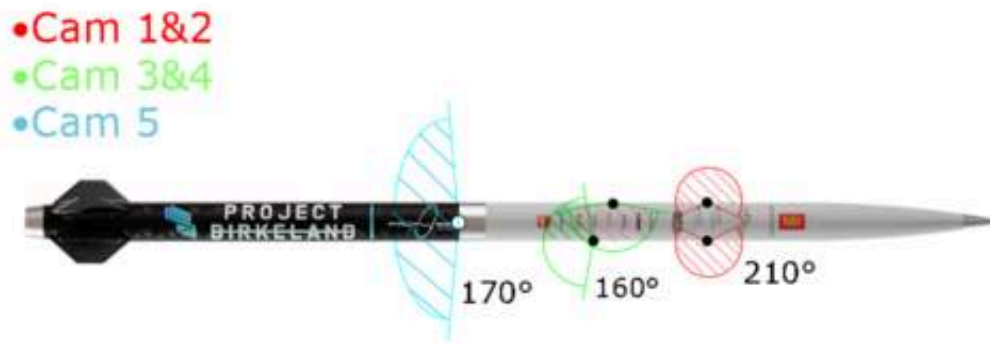


Fig. 37. Camera placements in the rocket.

Table 17: Onboard camera specifications.

Camera	Camera model	Component ID	Resolution	Framerate	Field of view	Live stream
1	Firefly split 4k	AV.1	3840 x 2160	30 FPS	210° or 185°	Yes
2	Firefly split 4k	AV.2	3840 x 2160	30 FPS	210° or 185°	No
3	Runcam split 3 lite	AV.3	1920 x 1080	60 FPS	160°	No
4	Runcam split 3 lite	AV.4	1920 x 1080	60 FPS	160°	No
5	Runcam split 4	AV.5	3840 x 2160	30 FPS	170°	No

Additional hardware included

Additional PCBs designed for the system and their purpose can be seen in Table 18.

Table 18: Overview of additional PCBs for the SRAD system.

PCB name	Component ID.	Purpose
Circuit protection PCBs	(AV.PC1-4)	A small circuit which holds an eFuse. This adds multiple forms of electrical protection to ensure that the system will be safe in case of incorrect assembly. This PCB will be attached to servo motors and cameras in the rocket. Can be seen in Figure 38.
Mag switch PCB	(AV.MS1-3)	A small PCB on which the magnetic switch used for arming is placed to attach plugs in a proper manner. Can be seen in Figure 38.
Mag plug PCB	(AV.MP)	A small PCB to which the magnetic plug used for the umbilical cord is attached for practical use. Can be seen in Figure 38.



Fig. 38. From left to right, Mag. plug PCB, Circuit protection PCB and Mag. switch PCB.

Thermal evaluation of module

Given the thermal conditions expected in the desert, a thermal evaluation of the avionics stack has been conducted. This is to ensure that all our components are rated for the given temperature expected when the rocket is waiting on the pad in the sun with all systems turned on. The calculation is found in appendix V.I. A maximum allowed inner temperature of 60°C has been set as a requirement based on our components [V.H S4.4.3]. High heat emission from key components are expected, and the components in question have been designed with heat sinks as required. Additionally, an 12V air fan is attached at the bottom of the avionics module to help local heat dissipation. Consequently, uniform heating inside the module is expected. The calculation assumes that the rocket is in direct sunlight, an ambient temperature of 36°C and a worst-case heat emission from the avionics of 34 W. The simulations shows that the expected temperature within the module will reach a steady-state of 48.5°C within 15 minutes, which is below our maximum limit.

5. SRAD software

The SRAD software's main task is to sample sensor data, filter it, estimate states, and then use these estimations as inputs to the Finite State Machine (FSM) in order to activate the recovery systems at the optimal points during flight. The software's secondary task is to store all raw and filtered sensor data both onboard the system's flash memory and send it to the ground station over radio. After apogee, the data from the flash is also copied to the SD card for redundancy in saving the data multiple places.

Real Time Operating System

The software uses a Real-Time Operating System (RTOS), as this is a real-time system that can be structured into largely independent tasks. The tasks themselves are based on the major system components, which are shown in Figure 39. Separating the device interface of the embedded system this way makes it simpler, and it's possible to achieve higher update frequencies in each task. Furthermore, the data is stored in shared variables in critical sections, where they can be accessed by one task at a time. More details about the function and update frequency of each task, and which shared data they use, can be found in appendix V.N.

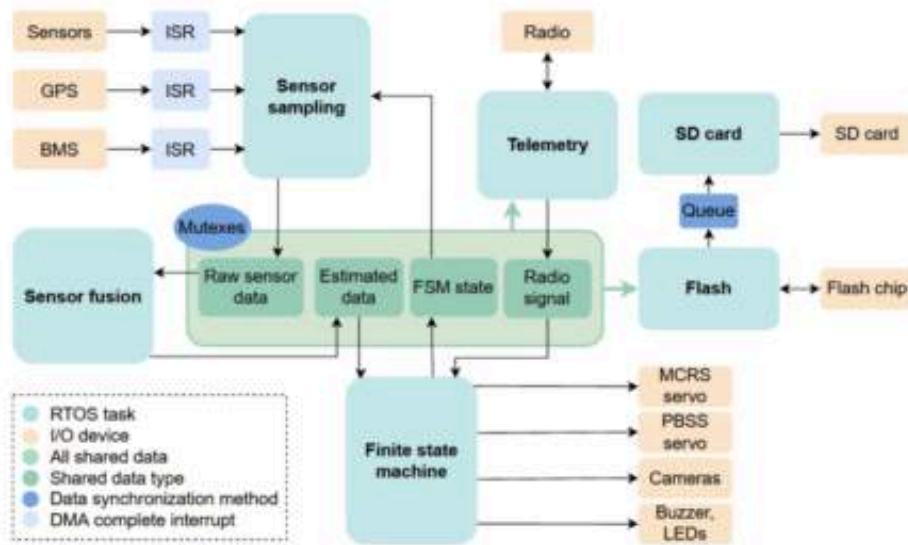


Fig. 39. Software architecture, with overview of RTOS tasks and data flow.

Finite state machine

The FSM is class based, and the states and transitions are designed to have unique purposes and are necessary for the flight. This ensures that certain systems are active only at the right time, like the deployment of the parachutes, changing the sensor sampling rates, and storage of data. Each transition is dependent on sensor data and the previous state, ensuring no loops in the transitions, as shown in Figure 40. A mach delay is also implemented as precaution to make sure that the recovery system cannot activate before a defined amount of seconds. Table 19 gives an overview of the states, their triggers and their functionality. More details about the FSM implementation and apogee detection can be found in appendix V.N.

Table 19: Finite State Machine state and triggers.

State	Trigger	Rocket state	Function
Idle	Powered on / Disarming signal from GS	Initial state when the rocket is first powered.	Microcontrollers and the radio transmitter turn on. Power to the cameras is turned off, live stream is stopped and sampling rate is slow.
Armed	Arming signal from GS	Rocket is on the launchpad.	Cameras are powered up, live stream begins and logging of data starts with a fast sampling rate.
Powered	Acceleration > 3 g	Rocket engine burning.	Sets start time for the mach delay.
Coast	Acceleration < 0	Motor no longer burning.	Apogee detection begins.
Drouge	Apogee detected	After apogee.	On entering this state, the SRAD PBSS servo is activated and the rocket will separate and the drogue chute will deploy. Slows down the sensor sampling rate, and starts storing data on the SD card.
Main Chute	Altitude < 1500 ft/450 m	Below 1500 ft/450 m.	MCRS servo is activated and the main parachute is released upon entering this state.
Retrieval	Altitude constant	When the rocket has landed.	Increase the sound of the buzzer. Cameras will turn off after some time to save power.

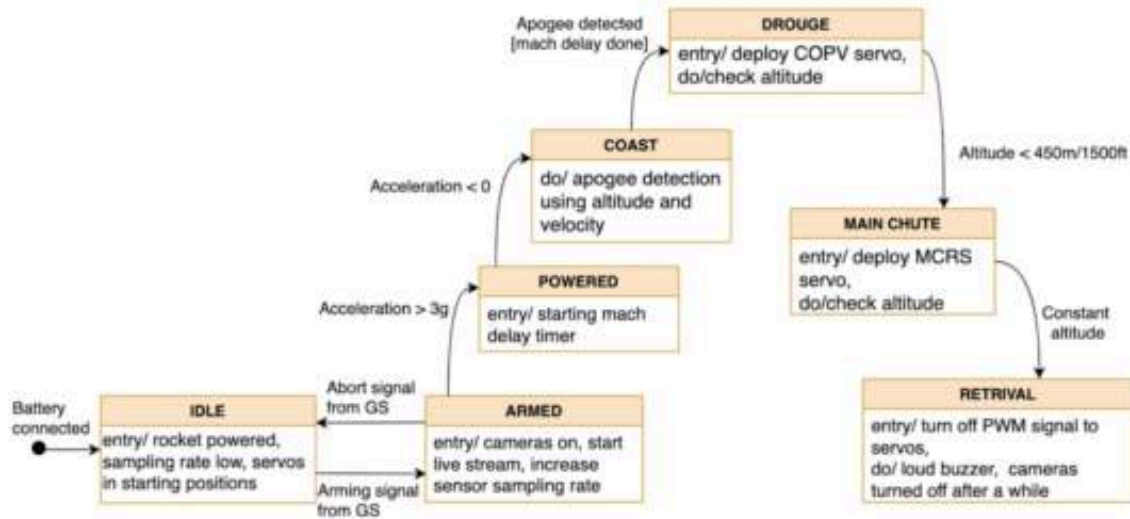


Fig. 40. Overview of FSM states and transitions during normal flight.

Navigation / filter system

The navigation system used is part of a master thesis written in collaboration with Propulse NTNU. The system uses sensor data and models to determine the rocket's position, attitude and speed in 6 degrees of freedom.

The system is based around a Multiplicative Extended Kalman Filter (MEKF). The first due to the use of quaternions as attitude parameters and the latter due to the nonlinear system and measurement models needed to represent the system.

MEKF works in two loops, see Figure 41. One loop uses one of the IMUs to produce an estimated navigation solution on its own in the 'INS-module'. This loop can run as fast as the IMU outputs data. The second loop takes the estimated solution as input to the Kalman filter and combines it with the other sensor data to produce a more accurate solution. The error is then fed back to the 'INS-module' to correct bias and noise errors.

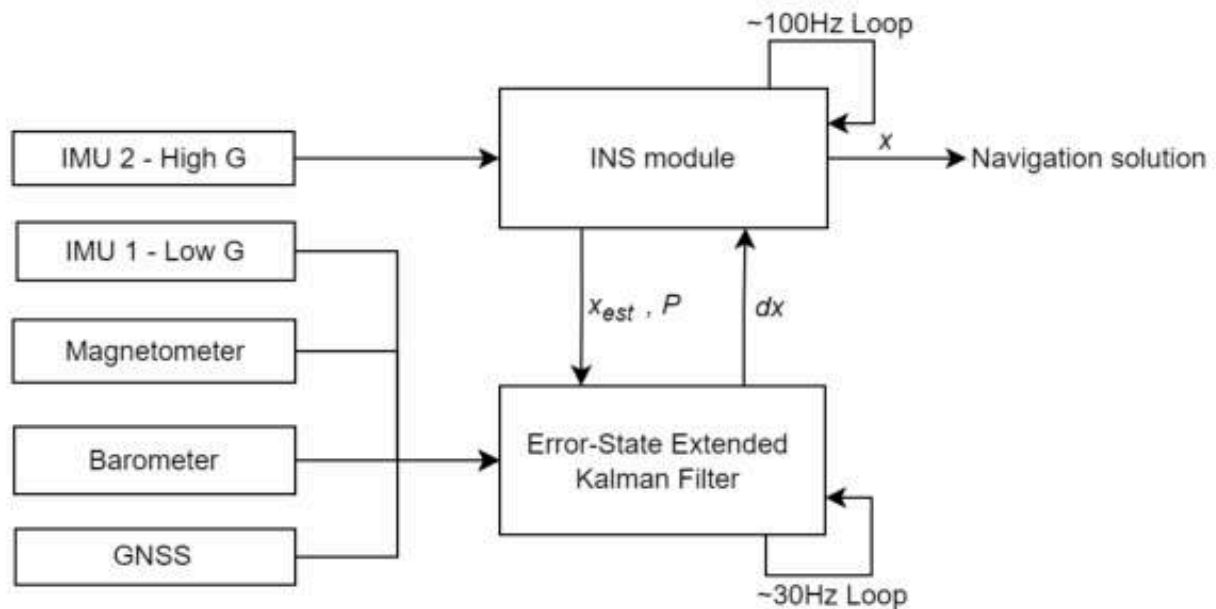


Fig. 41. Kalman Filter architecture.

MEKF also allows for much higher frequency updates of flight states since the IMU can run as an Inertial Navigation System even when no other sensor data and state corrections are available. This, combined with RTOS, gives us the possibility to achieve the sample frequencies seen in Table 20.

A number of fault checks will be done in real-time to detect abnormalities within the sensor measurements or the filter system. This includes validity checks, innovation filtering and innovation sequence monitoring. Lastly,

Table 20: Sample frequencies for filter.

Function	Frequency
IMU Supersampling	32 kHz
IMU dead-reckoning navigation solution	100 Hz
Sensor-fused, filter corrected navigation solution	30 Hz

when the rocket is going supersonic, the barometer readings will be erroneous. This was observed at the Stetind flight. To prevent these readings from interfering with the system, context-adaptive modeling is used to disable the barometer while going above mach 0.8. Read more about the system in Appendix V.P.

6. SRAD Ground station

Requirements & function

The ground station and telemetry system has a multitude of functions, which can be seen in a prioritized order in Table 21.

Table 21: Ground station and telemetry function.

Priority	Function	Description
Main	Send arm/disarm signal	Arming or disarming the rocket.
Main	Receive and store telemetry	Store all telemetry data for later use.
Secondary	Track rocket	Reliably track the rocket with the radio itself.
Secondary	Display telemetry	Display telemetry with OpenMCT at the ground station computer.
Tertiary	Video stream	Display the video stream on the ground station.

Hardware

The radio system used for the ground station is the CRE2 system from Radionor. This radio system operates in the 5 GHz band and is rated for transceiving signals at over 20 km distance with a data rate up to 7 Mbps, which allows transmission of a high-definition video stream in addition to telemetry data. The radio models which are used are the CRE2-144-LW (AV.R) in the rocket, and the CRE2-189 (AG.R) on the ground station. AV.R is an omnidirectional radio connected to the flight computer (AV.KB3) and an encoder (AV.ENC) through an ethernet switch (AV.ETH). AG.R is a high gain planar phased array antenna that is mounted on a tracking mount (AG.TRC), which will attempt to actively point the antenna towards the rocket. An overview of the data flow and connections can be seen in Figure 42. Everything communicates through ethernet except the radiolink.

Ground station software

Transmission Control Protocol (TCP) is used for transmitting telemetry data, and Real Time Streaming Protocol (RTSP) for live streaming an onboard camera. The data is handled using a python script on the ground where it is stored in a JavaScript Object Notation (JSON) format, and passed on to Open MCT (Mission Control Technologies) in order to visualize the telemetry data in several customized displays. Open MCT is an open-source framework made by NASA Ames to visualize data. Lastly, the arming signal is sent with a python script from the ground station computer.

Ground station tracking

The radio tracking system uses two stepper motors (AG.TRC.VS) and (AG.TRC.HS), powered by two stepper drivers (AG.TRC.VD) and (AG.TRC.HD) in order to track the rocket on the vertical and horizontal axis. The required performance of the tracker can be seen in Table 22. This requirement is set according to the model with a safety margin to avoid the tracker moving too slowly and errors, such as the stepper motor skipping steps.

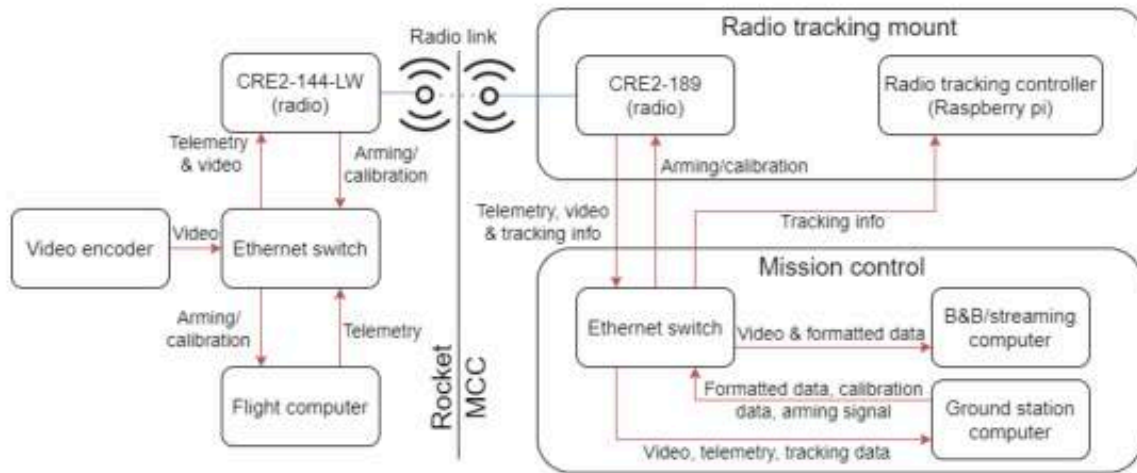


Fig. 42. Telemetry data flow.

Table 22: Radio transceiver tracking system requirements.

Function	Requirement	Description
Vertical axis rotation	30° per second	Able to track the rocket according to model and radio signal vector.
Horizontal axis rotation	10° per second	Able to track the rocket according to model and radio signal vector.
Tracking accuracy	$\pm 0.36^\circ$	Tracking accuracy according to model and radio signal vector.

The tracking software is based on a finite state machine, and is controlled from a raspberry pi (AG.RP) mounted to the system. A model for the rocket's flight trajectory is used to track the rocket during the ascent. After ascent, the tracking software will base the rocket's position on the radio signal vector. If the tracker malfunctions, the ground station crew will be able to manually control it via the computer. More information on the tracking algorithm can be found in appendix V.M.

7. Validation

Most of avionics' functionality can be verified by simply running the code as it's created, but to actually validate the functionality of the software and electronics put together larger tests have been performed. These tests can be seen below in Table 23.

Table 23: Lists of tests to validate the avionics system.

Test	Purpose	Results
Medium scale rocket launch	To use the SRAD electronics to collect a test dataset which will be used for tuning the MEKF as well as logic parameters for the FSM.	Electronics flew successfully onboard the rocket, reached an apogee of 1500 meters, and landed safely with collected data.
Small scale rocket launch.	To use the final SRAD electronics to collect a test dataset which will be used for tuning the MEKF as well as logic parameters for the FSM.	To be performed at the start in June.
Vibration testing	To validate the system can handle vibrations and shock without failing.	To be performed at the start in June..

H. Payload

1. Introduction

The main purpose of the payload experiment is to measure the vibrations of the rocket and find ways to dampen them. It consists of an STM32 NUCLEO-F411RE microcontroller and two IMUs in parallel; one mounted with a dampening material, moongel, and one without. The data from these will be compared in order to study the effects of moongel as a vibration dampener.

2. Requirements

The payload has to fulfill the requirements in the IREC rules section 2.3. To fulfill these requirements the payload is functional with an experiment, completely independent, weighs 4 kg and contains no hazardous materials. The exception from this is that it does not fulfill section 2.3.5 in the IREC, to fit inside the payload tube of the rocket, the payload is constrained to a cylinder with a diameter of 84 mm, and height of 290 mm.

3. Payload structure

Figure 43 shows an overview of the components in the payload. In Figure 44 it is shown how the two IMUs used are mounted. One is rigidly attached to the payload mounting plate, while the other is clamped down onto the moongel.



Fig. 43. Render of Payload with components marked.

4. Software

The IMU used for the experiment is a IIM42652, it has a maximum data output rate at 32 kHz, which would theoretically allow us to measure vibrations up to 16 kHz. However, the software is likely not able to handle such high sampling rates. Thus far non-optimised code has allowed us to sample up to only 200 Hz. In order to increase this rate the FIFO (First in, First out) buffer on the IIM42652 sensor will be used in combination with the DMA

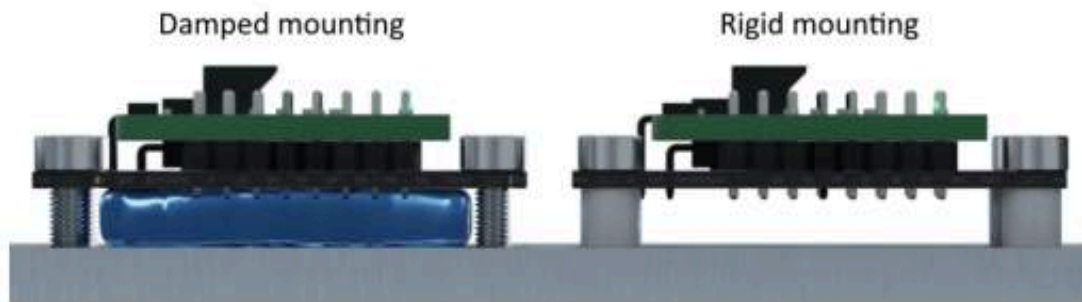


Fig. 44. Render the Payload IMU attachment methods.

(Direct Memory Access) on the microcontroller to attain sensor data at its maximum output rate. This should make it possible to achieve a sampling rate of approximately 9.0 kHz with this sensor.

5. *Data storage*

All information obtained from the flight will be stored in a flash with a backup SD card. The challenges relating to this are further elaborated upon in the appendix V.J.

6. *Battery capacity*

To power the payload three LiPo 7.4 V 3450 mAh batteries will be connected in series and power the system through an efficient 5 V regulator. At maximum power consumption, the microcontroller, together with the other components, draws a maximum of 50 mA at 5.0 V. With the LiPo batteries in use, this gives it more than enough battery runtime required for the process (24 hrs +). More details can be found in appendix V.J.

7. *Testing and validation*

The payload will undergo a vibration test alongside the rest of the rocket. The readings from this test will be compared to the actual vibrations it is subjected to during the test in order to evaluate its accuracy.

III. Mission concept overview of operations

The rocket's flight is arranged in eight phases, shown in Figure 45. In each phase it is indicated what criteria must be fulfilled for operations to be nominal. Risks to mission success, during each phase, are stated in appendix V.D.

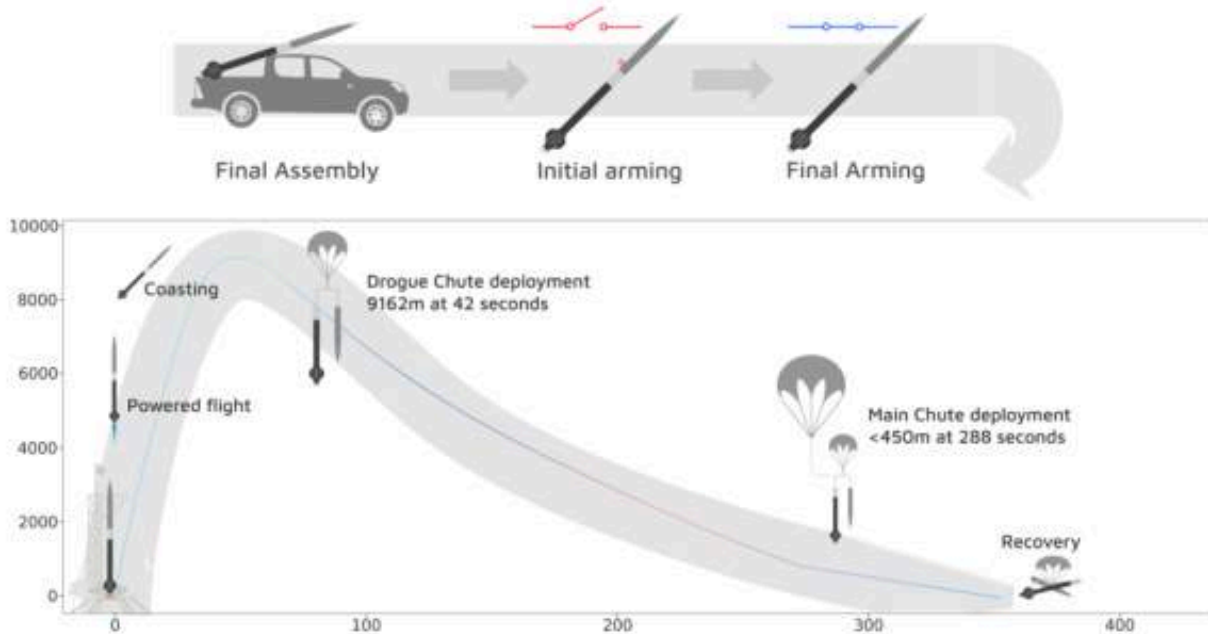


Fig. 45. Visualization of mission concept of operations.

Phase 1: Initial arming

The initial arming phase starts when the rocket is attached to the launch rail. The rocket will stay on the launch pad for an undefined amount of time, waiting for launch approval.

Pass criteria:

- Pre launch procedures have been completed correctly according to checklists found in appendix V.E.
- Ground control has established a connection with the avionics system.
- Ground station tracker has been calibrated.
- Received a "Go for launch" signal.

Phase 2: Final Arming

The final arming phase starts when an arming signal is sent from the ground station to the avionics system.

Pass criteria:

- The avionics system is armed.
- The payload is activated and logging data.
- Ground control receives and displays sensor data from avionics.
- All sensors are deemed nominal.

Phase 3: Lift off

Lift off is initiated when a "FIRE" signal is sent to the igniter.

Pass criteria:

- The avionics system detects acceleration above 9 g, and thus enters the “Powered” state of the FSM [V.N].
- The rocket obtains a minimum velocity of 30.5 m/s before clearing the launch rail, in accordance to DTEG 10.2.

Phase 4: Powered flight

Powered flight starts when the rocket leaves the launch rail. Max Q occurs during this phase.

Pass criteria:

- The structure withstands forces at Max Q.
- The rocket remains stable [V.I.2A].
- Successful propulsion completed.

Phase 5: Coasting

Coasting starts when the motor has burned out, expected at 6.16 s. The rocket will coast upwards until it reaches apogee. Apogee is estimated to be 9162 m above ground level and occur at 42 s.

Pass criteria:

- The rocket remains stable [V.I.2A].
- The avionics system detects apogee [V.N].

Phase 6: Drogue chute deployment

The drogue chute deployment is initiated when apogee is detected. The drogue chute is first deployed near apogee, and is estimated to descend with a velocity of 42 m/s. As the atmosphere gets thicker it is estimated to slow down to 30.16 m/s at 450 m above ground level.

Pass criteria:

- Drogue chute deployed.
- The MCRS system does not deform [V.I.2C].
- The structure withstands the release force [V.I.2].
- The rocket slows down to a velocity between 23 m/s and 46 m/s in accordance with DTEG 6.2.
- The avionics system detects a pressure altitude below 457 m above ground level [V.M].

Phase 7: Main Chute deployment

The Main chute deployment phase is initiated when the avionics system detects an altitude below 457 m above ground level based on barometric readings.

Pass criteria:

- Main chute is deployed.
- The structure absorbs the release force.
- The rocket slows down to a velocity lower than 9 m/s in accordance with DTEG 6.3.

Phase 8: Recovery

The recovery phase starts when the lower part of the rocket hits the ground with a velocity of 7.3 m/s. The rocket will be collected and inspected for damage, following the post flight checklist in appendix V.E.

Pass criteria:

- The structure withstand the landing impact without permanent damage.
- Sensor data is intact.
- Successfully tracked down the rocket using GNSS receiver.
- Rocket is successfully collected.

IV. Conclusions and lessons learned

Propulse NTNU's Team 2022 has developed a rocket that they judge to fulfill the requirements set by ESRA. Therefore, Team 2022 are confident it will be a successful flight. The rocket Birkeland is based on the flight-proven rocket Stetind, which won the 30 000 ft COTS solid class in both Spaceport America Cup and the European Rocketry Challenge. Since then, the team has improved the design, testing and production procedures of the rocket. This has been achieved through a greater degree of calculations, simulations and testing which has resulted in frequent iterations on the already existing design. Ease of assembly has gotten a lot of attention based on the experiences working on the rocket Stetind at EuRoC. Furthermore, the continuous improvement of project management and systems engineering has led to dependable production and testing regimes.

Throughout the project year, there has been an emphasis on developing both the members' knowledge, but also the organization's knowledge as a whole. With a focus on more SRAD components in Birkeland, we are one step closer to our vision, which is to reach the Karman line with an SRAD rocket. The project has put tight constraints on both time and budget, and the members have learned how to use the scarcity of resources at our disposal in an efficient manner. Lessons learned during the 9 month project period are stated below:

- Design
 - Multiple groups experienced that advanced solutions are not necessarily good, especially while on a strict timeline.
 - Designs passed over from previous projects need special care with regards to documentation and transfer of knowledge, in order for new members to be able to understand and iterate on the legacy components and systems.
 - The fact that the rocket shares design with previous projects has resulted in a lower degree of ownership to the project for new members.
- Validation
 - Some systems have been harder to validate than others, e.g. strength of composite structures.
 - Comprehensive CFD course at the start of the project is not ideal and should be implemented later in the timeline, when the members would have gained a greater understanding of the ways and uses of the tool.
 - FEA of the entire assembly could have further validated the structure, but the complexity of achieving this was beyond the members abilities, and the time boundaries of the project.
- Production
 - Supply issues with electronic components have placed challenges on the team's progression.
 - Sourcing raw materials took time, which halted the production process for our mechanical subsystems.
 - Production partners can be unreliable, in terms of not responding to mails or and/or not producing our planned components. In Birkelands case it has halted the fin production.
 - Take holidays of the production company into account when ordering components.

To make sure the knowledge stays in the organization we have several strategies for the corporate knowledge transfer. The board of the new team participates in the current board's meetings. They also, along with all the other members in the organization, will receive a document which includes the lessons learned from the past year, written specifically for their role. The first months of the coming project year will in fact be used solely to educate the new members. In this process the members from the last year serve as mentors, and thereby teach the new members the basics of how to make a rocket. The main objective of this, is to give them a foundation upon which to build the further knowledge required to complete their project as well.

V. Appendix

SYSTEM WEIGHTS, MEASURES, AND PERFORMANCE DATA APPENDIX

Rocket information

Number of stages	1
Vehicle Length (inches)	130
Airframe Diameter (inches)	5.10
Number of fins	4
Fin Semi-span (inches)	3.82
Fin attachment	Aluminium fin brackets
Fin flutter analysis	The fins have been validated through FEA and iterated from flight proven components. See in appendix V.H for detailed fin flutter analysis
Vehicle Weight (pounds)	87.3
Empty motor case/structure (pounds)	12.4
Propellant weight (pounds)	24.8
Payload weight (pounds)	8.82
Liftoff weight (pounds)	87.3
Center of Pressure (inches)	88.8
Center of Gravity (inches)	75.8 (Look at sheet below for detailed CG calculations with origin at the nose-tip)

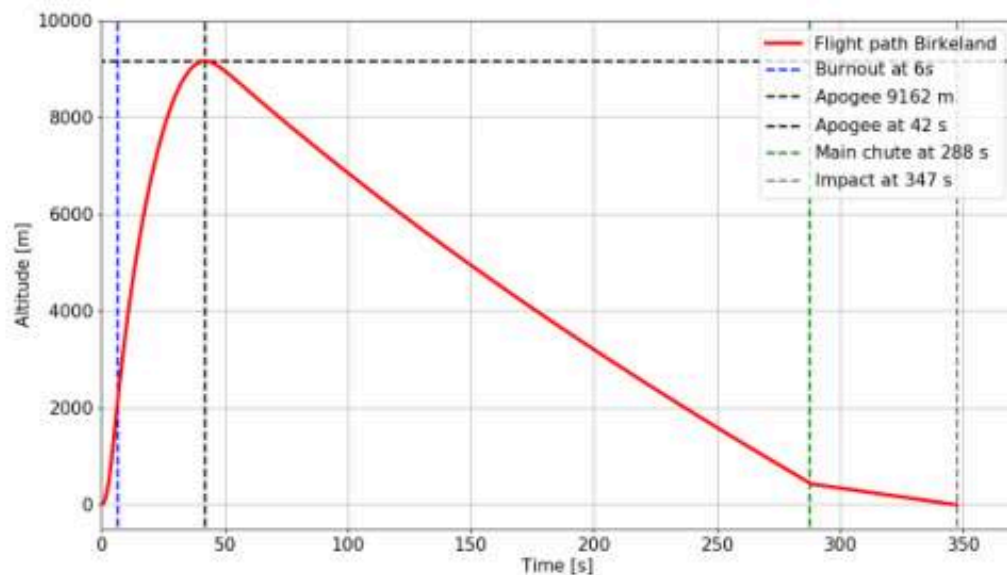
Propulsion information

Motor cluster	N/A
Propulsion Type	Solid
COTS, SRAD, or Combination	COTS
Propulsion Manufacturer	Cesaroni
COTS Motor - Manufacturers Designation	CTI Pro98 6GXL 21062 O3400-IM P
Motor Letter Classification	O

Average Thrust (N)	3416.7
Total Impulse of all Motors (Ns)	21062.2 Ns
Motor Burn Time (s)	6.16 s

Predicted Flight Data and Analysis

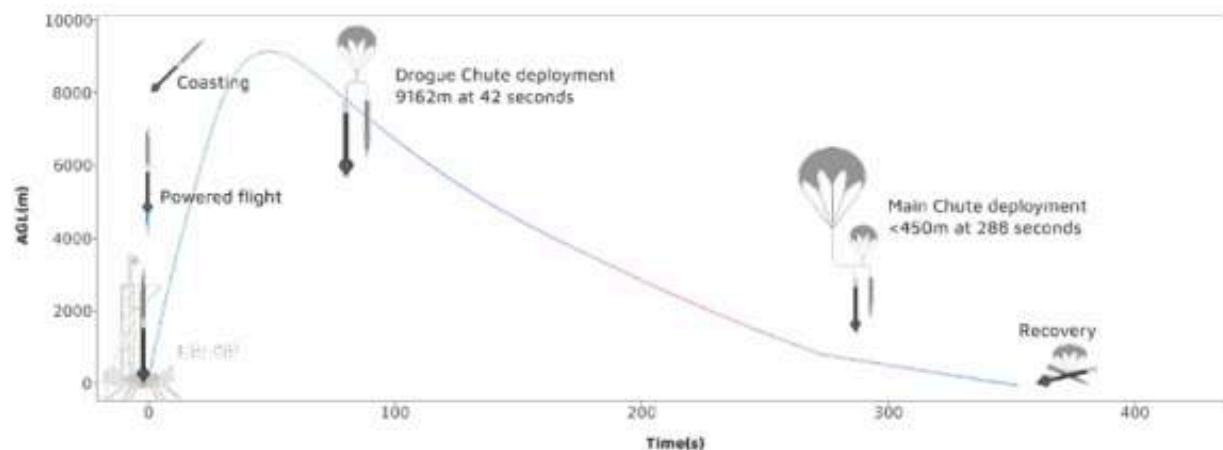
Launch Rail	ESRA Provided Rail
Rail Length (feet)	17
Liftoff Thrust-Weight Ratio (X:1)	12:1
Launch Rail Departure Velocity (feet/second)	111
Minimum Static Margin During Boost	1.78
Maximum Acceleration (G)	12.3
Maximum Velocity (feet/second)	1663
Target Apogee (feet AGL)	30,000
Predicted Apogee (feet AGL)	30,059

**Fig.1: Flight profile graph, for more information & .ork file**

<https://drive.google.com/drive/folders/11vN1-htmJ8fSEXAgQIDxMTiz7e-U0QwW?ths=true>

Recovery information

COTS Altimeter	Altimax G4
Drogue Deployment Charges - Primary & Backup (g)	21 g of air in primary, 33 g CO ₂ in secondary
Main Deployment Charges - Primary & Backup (g)	N/A
Drogue Deployment Altitude (feet)	29902
Drogue Decent Rate (feet/second)	99.1
Main Deployment Altitude (feet)	1476
Main Decent Rate (feet/second)	24.0
Shock Cords and Mechanical Links	Kevlar Y-harness - rated for 2200 lb, Nylon shock cord - rated for 2200 lb, Forged steel swivel links - rated for 3000 lb, Forged quicks link - rated for 2100 lb, Forged U-bolt - rated for 2000 lb, Forged shackle - rated for 1985 lb

**Fig.2: Flight profile graphic**



Thanks for submitting your entry for the Spaceport America Cup 2022, we've got it safe and sound.

Good luck!



Submission

[Return to editing](#)



Introduction

title

PropulseNTNU | Project Birkeland | 3rd Progress report

Short description

Propulse NTNU's supersonic rocket Birkeland.

Eligibility

Choose Your Team

60 Norwegian university of science and technology

Category

30k - COTS - All Propulsion Types

Category Change

No

Student Lead

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Alternate Student Lead

Steven Xu / steven.xu@propulsentnu.no / +47 91311636

Faculty Advisor

Tore Børvik / tore.borvik@ntnu.no / +47 73594647

Alternate Faculty Advisor

N/A

Team Mentor(s) & Flyer of Record

Team Mentor(s)

Arve Tokheim / 4test Instrument AS / arvetok@online.no / +47 40280994 / TRA Cert. Level 3.

- Joins our reviews, and looks through and gives feedback on our documentation.

Mariusz Grøtte / Phd Research Fellow at NTNU / mariusz.eivind.grotte@ntnu.no

- Joins our reviews and gives feedback in terms of aerodynamics and the avionics.

Tore Børvik / Professor at NTNU / tore.borvik@ntnu.no / +47 73594647

- Serves as our faculty advisor. Is a communication link between us in Propulse NTNU and the University (NTNU).

Flyer of Record (FoR)

Arve Tokheim, TRA #10246, TRA 3, arvetok@online.no, +47 402 80 994

FoR will be in attendance

Yes

FoR Discussion

Our Flyer of Record, Arve Tokheim, is a Tripoli Rocketry Association Level 3 certified member since 2009. His TRA member number is #10246, and he obtained his L1 from Tripoli West Palm in Florida, L2 from Tripoli San Diego, and L3 from ROC, also in California. Tokheim is Norway's first TRA L2 and L3, and has been flying commercial and experimental solid motors. As well as being our mentor in 2021, he also acted as the Launch Readiness Review (LRR) officer at EuRoC, the European Rocketry Challenge in Portugal. Tokheim will be having the same role for Portugal Space also in 2022, in addition to being a mentor and FoR for Propulse NTNU.

Team Demographic Data

This is all members working with your project including those not attending the event. This will help ESRA and Spaceport America promote the event and get more sponsorships and grants to help the teams and improve the event.

Number of Undergraduate Team Members

31

Number of Masters Team Members

7

Number of PhD Team Members

0

Number of Male Team Members

29

Number of Female Team Members

9

Number of Veterans

13 (former members)

How many team members will be attending SAC 2022 in person?

44

List of Attendees

Harald Bjerkeli

Erlend Lokna

Johanne Andersen

Tea C. Rasmussen

Einar Bergslid

Trond Steinagard

Steven Xu

Sandra L Pettersen

Sverre Ose

Emil Fylling

Stian Alseth

Robert Kalrud

Anders I Hestad

Simen Flåtter Flo

Kacper Zajac

Henrik S. Roestad
Hege grytten
Even Drugli
Pelle Traalum Okkenhaug
Mikkel Gisleberg
Rizqi Fairuz Wahyudin
Ola V. Flaata
Ahmet Emre Güzey
Ingrid Hjelle
Ane K.H.Morkemo
Sheikha Al-Nasser
Amira Khalil
Saad Rahman
William Mikal Ruud Schmidt
Vilhjalmur Arnar Vilhjalmsson
Tobias Heinz
Henrik R. Baumann
Erik Trydal
Viljar Engesæt
Magnus Røsstad
Tobias R. Thrane
Marcus S. Young
Mikael Bertheussen
Jessica Husby
Svein Jostein Husa
Trygve Nummedal Os
Andreas Fanebust
Ask Hovik
Arve Tokheim (#10246)

Describe any activities that your team leads or participates in that helps your local community with Science, Technology, Engineering or Math enrichment.

STEM Outreach Events

Propulse NTNU together with Andøya Space Education, have presented space and engineering related topics to junior and senior high school students. With the goal of presenting STEM and relating it to our experiences towards space related studies and activities.

The organization has also taken part in arranging a fully booked case competition and space conference together with Start NTNU, Space NTNU, NASA JPL, and Andøya Space Center, where former members of Propulse NTNU won the NASA JPL case.

In addition, we are collaborating with the local science museum and do technology related pop-ups, stands and talks to promote STEM to a younger audience. Furthermore, the team has visited high schools and a handful of innovation events; where members have held presentations and stands. We have also hosted executives from the Kongsberg group, local and foreign high schoolers, and students at our office.

Safety Updates

Safety Remediation

Our ERSA safety reviewer wanted to verify that our recovery components are rated to withstand up to 30X the rocket's weight. Our u-bolt which was the component of concern was changed after the 2nd progress report with a safety rating of 2000lbs and is within the aforementioned margin

There have not been any further issues identified by our team's ESRA safety reviewer.

Testing

Test Flight

No

Test Flight Discussion

N/A

Ejection Charge Testing Discussion

To validate the separation system for the rocket Birkeland, several ground tests were performed on the 3rd of April. Once for the SRAD and once for the COTS pressure

based separation system (PBSS). The test article is comprised of a highly accurate representation of the upper half of the rocket, and a mass simulator of the lower half of the rocket. The upper half was made out of components with the same design, the same material and the same production methods as the flight hardware, whilst the lower half was a steel mass simulator bolted to the aluminium coupler tube connecting the two halves together. By having the test article manufactured in this way, it allowed the members to train on the actual assembly and arming procedures that they will be following during the competition. The test article was mounted to a rig that secured it to the ground during the test, fixing the upper half to the ground when the lower half flies away after separation.

The tests validated that both the SRAD and the COTS PBSS worked as intended, pressurizing the volume within the recovery bay enough to share the 6 M6 nylon shear pins, separating the two halves. The test also showed that the venting hole on the coupler tube surrounding the recovery bay, did not impair the PBSS's functionality.

The COTS PBSS is based on a HAWK-system, and will not change between now and the competition. The SRAD PBSS will be optimized, in the sense of reducing total size and number of parts. **This system will therefore be tested once more following the same test procedures on the 10th of May**, to verify that the design iterations does not worsen the functionality of the system.

Recovery System Testing Discussion

Performed tests:

Wind tunnel test, 7th of February:

This test was meant to validate the main chute release system under realistic conditions. Parachute deployment and parachute deployment mechanisms were tested in a vertical wind tunnel. The test article was mounted in the middle of the wind tunnel. The test did not involve a ejection/separation event, and was only meant to test the recovery phase after separation until main chute deployment.

The drogue chute was deployed by hand, letting go when the tunnel was up to speed. The recovery system is designed to deploy the main chute when the main chute release system (MCRS) lets it go, and the drogue chute pulls it out. When the drogue is deployed, the main chute is stowed inside the body tube of the upper half of the rocket, within its retainment bag. The test would see if the MCRS was able to retain the main chute until receiving the release signal.

The test validated that the MCRS was able to retain the main chute when the drogue chute was deployed. It also validated that the MCRS was able to release the main chute on command, and that the drogue chute was able to successfully pull out the main chute for deployment.

Car test, 4th of April:

This test was meant to validate our corrective measures for premature main chute deployment. Propulse's last rocket suffered a premature main chute deployment during EuRoC 2021, this happened because the parachute bag was unable to retain the main chute in the windy environment after separation at (apogee). This resulted in the main chute escaping from the bag and deployed, while still retained in the MCRS. The thought reason for the premature deployment, was the surge of gas from the PBSS passing by the packed chute, dragging it out (coupled with surrounding wind).

The proposed solution to this was to add rubber bands around the packed chute bag, giving it a tighter grip around the main chute.

The same test article used in the ground separation testing was mounted to the roof rack of a car, with the drogue chute out, and the main chute packed within its bag. Then the car proceeded to drive at a speed of around 80 km/h (22 m/s) for several runs, simulating the conditions the rocket would encounter after separation, with and without the rubber bands. The COTS PBSS was activated on a run to see if the rubber bands was able to retain the main chute.

The test validated that the two rubber bands would retain the main chute inside its bag during all runs, even with ejection of the COTS PBSS. The test also uncovered that the drogue was still able to pull out and deploy the main chute when released from the MCRS, even with the two rubber bands applied.

Helicopter drop test, 7th of april:

This test was meant to validate that all recovery related systems were able to work together, meaning avionics, PBSSs and the MCRS, in a realistic environment. The test article was dropped from an altitude of ~500 meters (~1600 ft) AGL by a helicopter, then all recovery events would be triggered in order by the avionics system. The avionics activated the systems using simple timers, everything started when a pinned got pulled out when the article dropped. The recovery sequence went as follows:

One of the PBSS separates the test article, drogue chute gets pulled out and deploys; MCRS lets go of the main chute, allowing it to get pulled out by the drogue for deployment. This last step was set to happen 4 seconds after triggering the separation event.

After dropping, the avionics were able to successfully activate the SRAD PBSS, separating the test article and deploying the drogue chute. But, an anomaly occurred with the avionics where it restarted, so that the COTS PBSS nor the MCRS got the signal to activate. We believe this was caused by a strange voltage drop which we had observed across the servo motors a day before which had lasted a few ms. This did not cause any problems during pre-testing, but if this drop had been long enough then this would presumably cause the observed issue. Another problem that was

uncovered was that when the drogue deployed, the shock made the MCRS let go of the main chute prematurely, deploying it. In other words, separation, drogue deployment and main chute deployment occurred with only activation of the SRAD PBSS.

Solutions to the problems, and subsequent testing of said solutions, have already been planned. The solution to the mechanical issues with the MCRS are to use tighter (and therefore more "shock-resistant") springs on one of the release arms, as well as to alter the shape of the intersection of the systems two release arms, making the mechanism passively stable, meaning unable to release the main chute prematurely as long as the drogue pulls on it. The solution to the avionics systems are to use a more powerful 5v PSU, and add a bulk capacitor on the board.

Shock testing on the iterated MCRS will be performed on the 8th of may, to verify that the MCRS is able to retain the main chute when subjected to severe shocks.

Electronics Testing Discussion

The SRAD electronics are continually being tested for functionality as its been developed.

To test sensors, storage of data, and the logic of the flight computer a rocket with just the SRAD Flight computer has been launched. This rocket carried the avionics in a 2U cansat format to an altitude of ~1500 meters (~5000 feet).

This test validated that our sensors worked, and also provided us with a test data-set which we will use to tune our Extended Multiplicative Kalman Filter.

Tests to be performed later:

As discussed in "recovery testing discussion" the avionics restarted during flight. We believe this has to do with the 5V PSU onboard being unable to keep up with power demands 100% of the time. To resolve this issue version 2 of the flight computer will house a much larger 5V PSU (one which handles 9A), and additionally a bulk capacitor if needed. This PSU should be able to handle a complete stall of both servo motors and power all electronics fine, but this will be thoroughly tested to ensure no voltage drop is observed anywhere in the system.

The avionics will at end of May undergo a vibration/shock test. It will be mounted on a vibration table and undergo vibrations derived from Falcon 9 payload test requirements. The goal is to verify that the system handles the vibrations without any critical issues.

Once version 2 of the flight computer PCB arrives at end of May, we will fly it on a smaller rocket to about ~400meters (~1300 feet), as a final validation that the electronics behaves as designed.

Payload Testing Discussion

The payload experiment is based on measuring vibrations with an Inertial Measurement Unit. The functionality of the payload is continually being tested for read-speed as its being developed.

We wish to mount the Payload (together with the rest of the inner structure of the rocket), on a vibration table and compare data from the testing partner with the collected data from the payload to validate its functionality.

Additional Comments

Additional Comments

Since the last progress report, a flaw in the pressure calculations have been uncovered. The pressure calculations were the basis for the dimensioning of the pressure vessel of the SRAD PBSS. The flaw made us believe that the 0.36 L pressure vessel needed to handle an operating pressure of about 120 bar. This resulted in us opting for a COPV rated for 300 bars of pressure.

Now that the flaw has been fixed, the needed pressure for a 0.36 L canister is half of the initial pressure of 120 bars, meaning 60 bars. Due to this fact, a new pressure vessel has been aquired. This pressure vessel is rated for 200 bars, and has a smaller volume of 0.2 L (and it is not wound in carbon fiber). This has allowed us to make the SRAD PBSS a lot more compact, which is highly beneficial for us since we only have a diameter of 124 mm at our disposal inside our rocket Birkeland.

The tank for the SRAD PBSS will in other words no longer be referred to as a COPV, but rather a PV (pressure vessel).

It is due to these changes that an another ground test will be performed on the 10th of May.

Birkeland Cg				
Component	Mass [kg]	Gx [mm]	Gy [mm]	Gz [mm]
<u>NoseTip</u>				
Upper nose tip	0,271	-90,3	0,0	0,0
M8 nut	0,007	-113	0,0	0,0
Middle nose tip	0,016	-131	0,0	0,0
Lower nose tip	0,064	-139	0,0	0,0
<u>Forward Airframe</u>				
Forward airframe	2,62	-996	0	0
<u>Payload</u>				
M8 threaded rod	0,093	-219	0	0
Payload upper cap	0,108	-340	0	0
Payload experiment	4,00	-492	0	0
Paylaod tube	0,665	-492	0	0
Payload lower cap	0,111	-643	0	0
<u>Avionics module</u>				
Altimax GPS	0,015	-909	11,1	17,6
Umbilical connector	0,050	-867	-3,90	-49,2
Altimax flight computer	0,013	-904	38,7	-11,1
COTS battery shell	0,016	-867	-3,90	-49,2
COTS battery lid	0,007	-866	-5,81	-38,1
Video encoder bracket	0,037	-902	-35,0	1,52
Video encoder lid	0,008	-899	-34,4	-19,9
Translator	0,010	-914	-14,4	37,5
Fan	0,164	-958	0,508	-7,32
GPS-antenna	0,173	-804	14,3	17,3
Avionics module ring	0,101	-972	0,0	0,0
Magnetic switch	0,015	-885	11,6	44,0
Magnetic switch	0,015	-717	44,6	10,0
Magnetic switch	0,015	-953	2,60	-45,8
Mounting plate	0,335	-813	-0,513	-4,62
Battery management system	0,173	-751	-31,4	10,8
Radion antenna	0,085	-775	2,51	-44,1
Radio voltage regulator	0,020	-876	30,0	-43,4
Avionics rail	0,088	-812	-3,33	58,6
Avionics rail	0,088	-812	52,4	-26,4
Avionics rail	0,088	-812	-49,1	-32,2
SRAD battery pack	0,431	-717	20,7	14,5
Avionics module ring	0,101	-652	0,0	0,0
Video	0,018	-896	-40,3	-2,29
<u>Recovery module</u>				
Test import.1	0,271	-1057	-5,33	12,4
PV bracket	0,028	-1128	-39,3	-36,9
COTS PBSS assembly	0,565	-1298	-27,9	5,01
Recovery module ring	0,103	-1262	0,00	0,00

Recovery rail	0,126	-1215	-49,1	-32,2
Recovery rail	0,126	-1215	-3,33	58,6
Recovery rail	0,126	-1215	52,4	-26,4
Recovery plate	0,964	-1476	1,08	1,17
SRAD PBSS assembly	1,02	-1145	18,3	-48,1
Recovery module ring	0,103	-982	0,00	0,00
<u>Coupler</u>				
Coupler	1,99	-1797	0,0	0,0
Drogue chute	0,088	-1825	0,0	0,0
Main chute	0,502	-1674	0,0	0,0
Motor bulkehad	0,218	-1832	0,0	0,0
<u>Aft Airframe</u>				
Aft airframe	2,32	-2542	0	0
Dummy weight	2,50	-1832	0	0
Motor centering ring	0,088	-2380	0	0
Motor casing	5,61	-2653	0	0
Propellant	11,2	-2653		
<u>Fins</u>				
Fin	0,284	-3092	0,0	-85,9
Fin	0,284	-3092	85,9	0,0
Fin	0,284	-3092	0,0	85,9
Fin	0,284	-3092	-85,9	0,0
<u>Boat tail</u>				
Boat tail assembly	0,316	-3268	0	0
Upper half	13,5			
Lower hald	26,0			
Total	39,5			
Center of Gravity total				
		-1925	0,175	-1,07

BIRKELAND TEST REPORTS

Dual redundancy:

The recovery system features dual redundancy in order to increase its reliability. The system has two separate power supplies, one for the COTS altimax flight computer and the other for the SRAD flight computer. The COTS flight computer is an Altimax G4, which is included to ensure that there is a proven set of electronics onboard the rocket. The SRAD flight computer consists of a Power Delivery Board (PDB) and the Kristian Birkeland Brain Board (KB3), with the SRAD software and separate recovery activation. The COTS Altimax G4 flight computer has the ability to activate the hawk servo and MCRS servo as seen in Fig. 1 below.

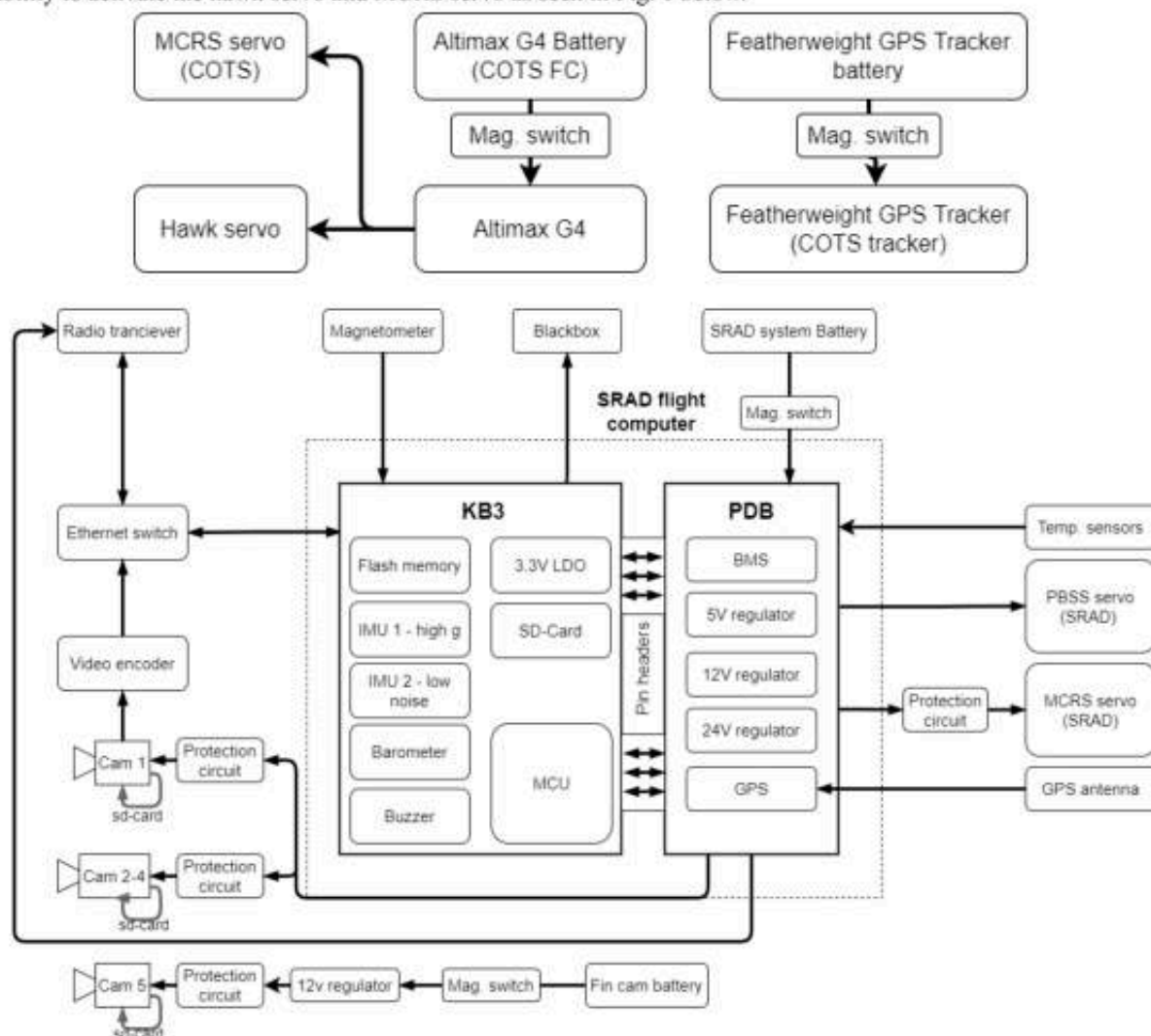


Fig 1: Diagram displaying all connections of the avionics

The flight computers are connected to two separate pressure based separation systems. One COTS PBSS and one SRAD PBSS. The systems have dissimilar designs, which increases the redundancy. With this redundancy, the rocket will still be able to separate, even if one of the flight computers fails to detect apogee or one of the PBSS is

malfunctioning. In the event that both the SRAD and COTS systems are activated, the rocket will still separate and the excessive gas will flow out to the surrounding air. Each of the flight computers are connected to two independent servo motors that activate the main chute release system. The main chute will be able to deploy with either of the servo motors activated. The systems are implemented to fulfill DTEG 6.8 and DTEG 6.9.



Ground test - Rocket separation

Date: dd/mm/yyyy

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Purpose:

The purpose of this test was to determine if both the COTS and the SRAD pressure based separation systems (PBSS) are able to pressurize the recovery bay sufficiently to break the 4 M4 shear pins, separating the test article, which is required to enable deployment of the drogue parachute.

Participants:

Hege Grytten, Simen Flåtter Flo, Einar Bergslid, Mikkel Gisleberg, Tobias Heinz, Robert Kalrud, Amira Khalil, Trond Steinagard, Pelle Okkenhaug, Sverre Ose Kristensen, Stian Alseth, Arthur Tjomsland

Test Equipment & Set-Up Description:

The test article was made to be as representative as possible to the flight hardware for the rocket Birkeland. This test article was also designed in such a way that it would be possible to use it in other tests, such as the Car Test and the Drop Test. A plywood test rig was made to retain the test article during testing. Parachutes and shock cords were included in the test, to see how they fit in the recovery bay.

Component overview:

- Filament wound fiberglass airframe
- M6 threaded rod
- 4 kg steel payload dummy weight
- Avionics module (structural rings and rails)
- 3D-printed avionics mount
- Flight computer rev. 1
- Batteries
- Electric cables
- Activation switch for SRAD PBSS
- Activation switch for COTS PBSS
- Recovery module (structural rings and rails)
- COTS PBSS (HAWK)
- HAWK arming pin
- 33 g CO₂-canister
- Hawk plate
- SRAD PBSS
- Valve bracket

- Recovery plate with O-ring
- Main chute release system (MCRS)
- Drogue parachute
- Main parachute in its bag
- Shock cords
- Test coupler with O-ring
- 4x M4x0.7 nylon shear pins
- 10 kg aft dummy weight
- Fasteners
- Tools
- Plywood test rig
- Ratchet straps
- Patent band
- Manual hand pump for SRAD PBSS



Fig 2: Fully assembled test article placed on the plywood test rig

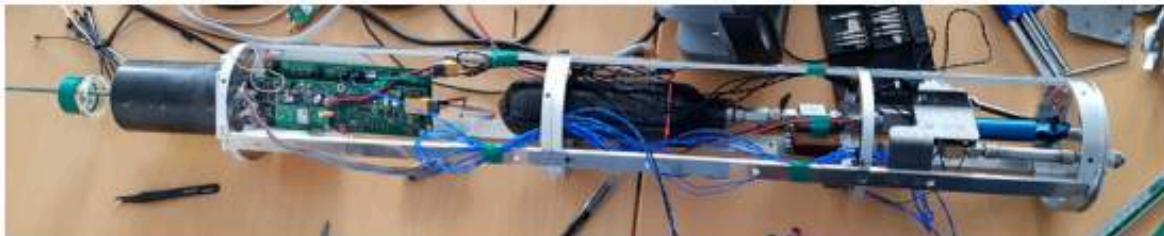


Fig 3: Inner structure of the test article, showing payload dummy weight and modules.

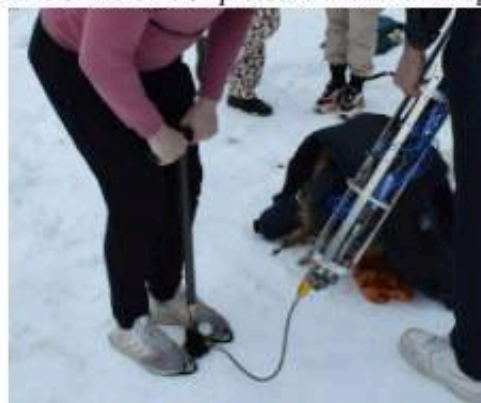
**Fig 4:** MCRS**Fig 5:** Parachutes and shock cords**Fig 6:** Test coupler

Safety concerns:

When separating, the coupler and dummy weight would become a projectile flying ballistically through the air. Therefore, everyone must keep away from the test couplers expected flight path. To allow this, the activation of the separations could be done from a distance, using two long cables with activation switches. The COTS PBSS is spring loaded. To prevent accidental and premature ejection, a safety pin was inserted when the CO₂-canister was installed. The SRAD PBSS was filled with both the manual and the actuated valve in the open position. To prevent accidental and premature ejection, the manual valve was closed when filling completed, and until right before testing. To ensure that these steps could happen as late in the process as possible, the arming for both systems was possible through the airframe. Safety goggles were used by test participants to prevent eye injury from potential flying shear pins.

As-Ran Test Procedure:

The inner structure was assembled in its entirety before heading to the testing grounds. The SRAD PBSS was filled with air to 120 bars of pressure with the handpump, as shown in figure 6.

**Fig 7:** Pumping air into the COPV

The COTS PBSS was loaded with a 33 g CO₂-canister. The inner structure was then inserted into the fiberglass airframe and fastened using M4 bolts, as shown in figure 7.



Fig 8: Insertion of inner structure into airframe

The parachutes got placed into the test coupler, and the test coupler got fitted to the forward airframe. Four M4 nylon shear screws were inserted into the coupler through the airframe, fastening the two parts together. The two cables with an activation switch for the PBSSs were pulled out through the airframe. This can be seen in figure 8.



Fig 9: Cables for activation running through the airframe

Test run #1:

After every test participant moved clear of the test article, one member armed the SRAD PBSS by turning the manual valve through the hole in the airframe.

The activation switch was then pressed to activate the separation system.

After separation, the chutes were packed into the test coupler once more, and the coupler mounted to the airframe. Four new shear pins were inserted.

Test run #2:

After every test participant moved clear of the test article, one member armed the COTS PBSS by pulling out the safety pin through the hole in the airframe.

The activation switch was then pressed to activate the separation system.

Test Criteria:

Pass criteria	Success/ Failure
The SRAD PBSS is able to fully separate the test article	Success
The COTS PBSS is able to fully separate the test article using a 33g-canister	Success
Predetermined fill and arming procedures for the SRAD PBSS can be executed without deviation	Success
Predetermined fill and arming procedures for the SRAD PBSS can be executed without deviation	Success
The time between activation and separation for the SRAD PBSS is below the indicative value of 5 seconds	Success
The time between activation and separation for the SRAD PBSS is below the indicative value of 5 seconds	Success

Test Results:

Test run 1#

The SRAD PBSS was able to break all shear screws, resulting in successful separation of the test article, as shown in figure 10.



Fig 10: Separation by means of the SRAD PBSS

From the video footage, it was determined that the time between activation and complete separation was approximately 2 seconds. The aftermath of the test can be seen in figure 11.



Fig 11: Test rig, chutes and test coupler after successful separation by the SRAD PBSS

Test run 2#

The COTS PBSS was able to break all shear screws, resulting in successful separation of the test article, as shown in figure 12.



Fig 12: Separation by means of the COTS PBSS

The time between activation and separation was approximately equal to that of the SRAD PBSS. The aftermath of the test can be seen in figure 13.



Fig 13: After COTS PBSS was activated and the coupler separated from the airframe

Discussion of Results:

The tests showed that both the SRAD and the COTS PBSS are able to fully separate the test article in a satisfactory time after activation by the avionics system. Due to the fact that the test article was very representative of the actual flight hardware, the results are considered to have a higher degree of confidence. The avionics system powering the activation of the separation systems was to a large degree preliminary, since the actual flight hardware and software was still under development. In other words, this test was only able to validate the recovery hardware that the rocket Birkeland will utilize during competition.

The indicative value for separation time of 5 seconds was set as an upper value for what could be considered a rapid separation. A rapid separation, or rather a rapid pressurization of the recovery is required for two reasons. Reason one is that the pressure has to build up faster than it escapes through the venting hole in the recovery bay. This could prevent reaching the adequate pressure for breaking the shear pins. The second reason is that minimizing the time between apogee and drogue chute deployment, reduces the probability of the drogue chute shredding due to high vertical speeds.

Some other takeouts from the tests are:

- The importance of assembly checklists as a means of reducing assembly time and ensuring correct assembly was underlined.
- There was a significant mismatch between the tolerances for the coinciding holes in the airframe and inner structure, making final assembly hard. The mismatch prevented us from fastening all the screws going through the airframe properly. The holes in both the airframe and the inner structure were both created manually, something that won't be the case for the flight hardware.

For videos and additional data and documents use this open folder:

<https://drive.google.com/drive/folders/1IvNI-htmJ8fSEXAgQIDxMTiz7e-U0QwW?ths=true>

Conclusion:

The test showed that both the SRAD and the COTS PBSS are able to fully separate the test article. Since the test article was very close to the actual flight hardware, the results from this test are considered to have high confidence. It was only a test of the recovery hardware and separation dynamics, and the avionics system supposed to activate these systems during flight remains to be tested.

V.B.2



Drop test

Date: dd/mm/yyyy

0	7	0	4	2	0	2	2
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Fig 14: Test participants posing in front of the helicopter with the test article after the test.

Purpose:

The purpose of the drop test was to validate the function of the recovery systems to be used in the rocket.

This includes validating if:

- The avionics system is able to activate the recovery systems
- The pressure based separation systems (PBSS) are able to separate the test article
- The main chute release system (MCRS) is able to release the main parachute
- The parachutes deploy without tangling.

Participants:

Hege Grytten, Simen Flåtter Flo, Einar Bergslid, Anders Hestad, Sverre Ose Kristensen, Kacper Zajac, Trond Steinagard, Tobias Heinz, Stian Alseth, Robert Kalrud, Steven Xu, Viljar Engesæt, Amira Khalil, Mikkel Gisleberg, Ola Flaata, Jessica Husby, Even Hugdal, Henrik Roestad, Pelle Traalum Okkenhaug, Vebjørn Bratlie, Johannes Mørkrid, Ask Hovik, Eivind Heggset, Pilot, Co-pilot

Test Equipment & Set-Up Description:

Test equipment:

- Fiberglass test airframe.
- 4 kg steel payload dummy weight
- Avionics module (structural rings and rails)
 - Flight computer rev. 1 (not flight hardware)
 - Batteries
 - Electric cables
- Recovery module (structural rings and rails)
 - COTS PBSS (HAWK)
 - 33 g CO₂-canister
- SRAD PBSS
 - Recovery plate with O-ring
- Main chute release system (MCRS)
- Recovery bay camera
- Drogue parachute
- Main parachute in its bag
- Straight cord and Y-harness
- Swivel links
- Quick links
- Test coupler with O-ring
- 4x M4x0.7 nylon shear pins
- 10 kg aft dummy weight
- GoPro
- Avionics triggering plug and harness
- Helicopter
- Helicopter connector harness

Figure 15 shows the inner structure of the test article.



Fig 15: The test article without the airframe

Safety concerns:

Use of energetic devices This was mitigated by standing on the safe side of the device.
Falling parts from the sky poses danger to people in the dropzone area.
These concerns were solved by having people standing guards on the perimeter of the dropzone. The perimeter guards were required to wear high visibility vests and instructed on how to act if such an event is to occur.

As-Ran Test Procedure:

The inner structure was assembled with avionics and recovery systems accordingly. The energetic devices were prepared and secured (MagSwitch, SRAD & COTS). The valves were opened and the SRAD system was filled with compressed air. The valves were then closed with the manual valve being the last one. The COTS system was loaded with a compressed CO2 cartridge and secured with a safety pin.

The parachutes were prepared and packed with the shroud lines secured and the cord ends connected to the swivel-links to minimize the risk of cord-tangling (see Figure 16). The parachutes were then connected to the MCRS with Quick-link.



Fig 16: Parachute packed, shroud lines z-folded

The inner structure was then inserted into the airframe and secured with fasteners and nylon shear-screws. The coupler section was then mounted and secured. The test article was then connected to the helicopter's release-mechanism (see Figure 17). Once connected, both the avionics and recovery systems were armed. The helicopter then elevated the test article to approximately 500 metres above the ground level. The article was then released from the helicopter.



Fig 17: Helicopter connection

The parachutes were then observed deploying. (See Figure 18). It was hard to determine when the chutes were deployed. After that the test article was recovered at the landing location.



Fig 18: Deployment of parachutes

Test Criteria:

Pass criteria	Success /Failure
The SRAD PBSS is able to fully separate the test article	Success
The COTS PBSS is able to fully separate the test article if the SRAD PBSS fails to separate	Inconclusive
The drogue parachute is pulled out and successfully deployed after separation.	Success
The MCRS retains the main parachute after drogue deployment	Failure
The MCRS activates, initiating main parachute deployment	Inconclusive
The main parachute deploys successfully during descend	Success
The test article survives the descent	Success
The avionics logs flight data	Success
The flight data is recovered	Success

Test Results:

When the test article was released, the avionic safety cable disconnected and initiated the timed sequence. The SRAD PBSS was activated, causing separation of the test article. The drogue was then deployed, but the main parachute was also pulled out during separation. There was little tangling of the chutes. The MCRS did not hold back the main chute as intended. Then the avionics experienced a power loss, which meant the COTS PBSS and MCRS servo were not activated. The test article had a soft landing and the

avionics data was logged and successfully recovered.

Discussion of Results:

The drop test revealed a few points of improvement in the current design as well as possible causes of premature parachute deployment and avionics failure. Additionally, the drop test further validated the SRAD PBSS design and functionality.

Discussion about MCRS:

The spring for the MCRS was too loose, there was some wiggle room and there was no interlocking between the upper and lower release arm. This contributed to the premature release of the main chute. From the camera feed it was observed that the MCRS was not activated by the avionics.

Firstly, the geometry of the lower release arm makes MCRS less effective at retaining the load as pictured in figure 19. This is because the contact area between the upper and lower release arms are rounded. Further explanation is given in figure 20. Here it is illustrated that a force acting normal to a horizontal surface will not have any force component. So the arm will not rotate. However if there is a slope, like the one on the arm in figure 19, then a force component will induce a rotation of the arm. Consequently the mechanism is subject to premature deployment.



Figure 19: Lower release arm geometry (note looks rounder due to camera angle)

Secondly, when examining the system after the test it was found that the springs, that help to hold the lower release arm in place during vibration and handling, were not pretensioned as shown in figure 20. Because of this the mechanism was vulnerable to any handling or vibrations, since the lower release arm could practically move freely. This vulnerability increases the risk for displacement of the lower release.

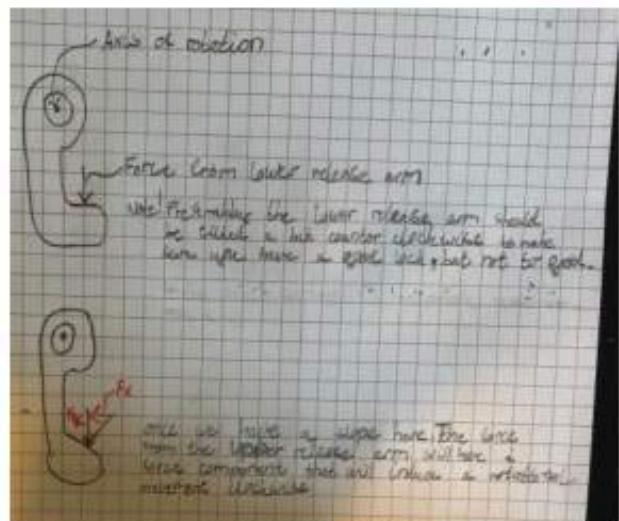


Figure 20: Mechanical explanation of force and rotation

Finally, the parachute bay was packed too compact, which caused the shock cords to be in contact with the MCRS's lower release arm. As the test article separated, the cords were dragged out. At this time the lower release arm's movement can be observed to happen in synchronization with the movement of the cords, according to the on-board camera feed. In case of contact between the cords and the arm, it could mean that the arm's movement is related to the displacement of the cords, which could result in premature parachute deployment.

To mitigate the risk of all three vulnerabilities affecting the parachute deployment in the actual rocket, design improvements will be implemented:

1. To improve the surface geometry between the release arms, the lower release arm's geometry will be changed so it can induce a restraining force.
2. To reduce the effect of vibrations on the MCRSs and the lower release arms freedom-of-movement, the springs will be pretensioned, increasing the lower release resistance to vibrations and restricting its movement so it remains undisturbed due to vibrations, additional shims will be used to fasten the release arms properly.
3. To reduce the risk of shock cords contributing to premature release, a protective shroud over the MCRS shall be implemented. Such a shroud will mitigate the possibility of shock cords coming in contact with the lower release arm, eliminating the risk of cords causing premature release. Additionally, the size of the parachute bay will be increased.



Figure 21: MCRS before launch. The springs are clearly not pretensioned

Discussion about avionics:

The reason the avionics only activated the SRAD PBSS, and not any of the latter recovery mechanisms, is likely due to a loss of power which occurred just after the SRAD PBSS was activated. A day prior to the test, during preparation of the electronics, the voltage across the servo motors was measured with an oscilloscope. Here the 5 V power to the servo motor was observed to drop to 2.5-3 V for very short bursts (a few hundred microseconds at most). This never caused any issues during preparation, but the theory is that during the actual test the experienced voltage drop was large/ lasted long enough that the 3.3 V regulator for the microcontroller was unable to provide enough power to the microcontroller for a short moment. Such a power loss would explain the reason that the microcontroller on board restarted during the test.

Further evidence that such power loss occurred is the reason for the camera error during the test, preventing them from restarting. The cameras ran off a 12 V regulator, which was not connected to the 5 V regulator that the servos and microcontroller was. Additionally the 5 V regulator used in the test is built to handle continuous 2.5 A at most, but with all four servo motors attached to the system during this test a maximum current of 6-7 A could theoretically be required if all servo motors were to be activated and stalled. During testing however, the largest current spike was measured at 1.25 A, which was thought to be well within the operating margins.

For videos and additional data and documents use this open folder:

<https://drive.google.com/drive/folders/1IvN1-htmJ8fSEXAgQlDxMTiz7e-U0QwW?ths=true>

Conclusion:

The SRAD pressure system was successfully activated and able to separate the rocket. Both parachutes were able to deploy, allowing the rocket model to land in a safe and controlled manner. However the drop test unveiled some issues with both the recovery and avionic systems. Two of the three onboard recovery systems failed. The MCRS failed to retain the main parachute due to mechanical errors. Namely change in geometry after doing manual modifications and faulty assembly. In addition the avionics system failed to activate MCRS and the COTS PBSS, due to a power loss.

In order to prevent premature release caused by MCRS the following changes will be done:

The lower release arm's geometry will be changed so it can induce a restraining force. The springs will be pretensioned so the release arms remain undisturbed due to vibrations, additional shims will be used to fasten the release arms properly. A protective shroud over the MCRS will be added which will mitigate the possibility of shock cords coming in contact with the release system, the size of the parachute bay will also be increased, allowing the cords to be stored more loosely.

In order to prevent power loss/restart of the avionics the following will be done:

A new 5 V regulator will be utilized, one which can handle 9 A continuously. A bulk capacitor across the 5 V power rail will be added to compensate for any voltage drops. Only two servo motors will be controlled by the SRAD system in the actual rocket launch, not four as in this test, this will reduce stress on the voltage regulator.

In order to validate the system after the changes mentioned above a new test will be conducted to ensure the successful and correct activation of the recovery system. This test will be a shock test where the model is dropped from a bridge or similar to simulate the shock MCRS will experience and see if it can retain the quick link holding the main parachute. All the electronics will be included in this test to simulate the same power draw as expected during launch and see if it is able to activate both the PBSS properly and MCRS.

V.B.3 SRAD propulsion system testing

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V.B.4 SRAD Pressure Vessel Testing

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V.B.5

Hydrostatic pressure test of SRAD PBSS



Date: dd/mm/yyyy

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Purpose:

The purpose of the Hydrostatic pressure test was to verify that the Student Researched and Developed Pressure Based Separation System (SRAD PBSS) can withstand a pressure of at least 1,5 times the system's operating pressure. The system's operating pressure is 120 bars, the test was therefore conducted at 180 bars of pressure. The transmission medium was water diluted with diesel.

Participants:

Viljar Engesæt, Mikkel Gisleberg

Test Equipment & Set-Up Description:

The equipment:

- Composite Overwrapped Pressure Vessel (COPV) (1)
- Main COPV adapter (2)
- Solenoid Valve (3)
- Solenoid adapter (4)
- Manual ball valve (5)
- Manual valve adapter (6)
- Flexible hose (7)
- Test rig adapter
- Power supply
- Cables
- An electrical switch

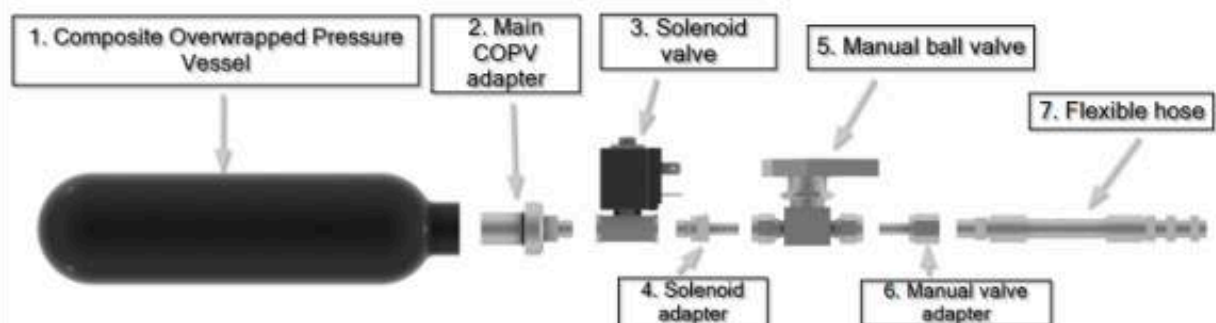


Fig 22: An overview of the SRAD PBSS

The figure above represents the components of the SRAD PBSS. An additional adapter was necessary in order to connect the system to the pump - Test rig adapter.

To the right is a picture of the SRAD PBSS and the electrical equipment we used to control the solenoid.

The electrical equipment consisted of a 24 V power supply, voltage regulator and an electrical switch.

The hydrostatic test was performed at ViaNor, Trondheim.

The set-up:

SRAD PBSS was assembled, opening both valves. The system is then filled with water, pressurized to the pressure of at least 180 bar.



Fig 23: Test setup

Safety concerns:

The main safety concern was the possible air pockets in the system during pressurization. The compressed air could expand rapidly, resulting in an injury if not handled with care.

As-Ran Test Procedure:

The set up of the test was as follows:

- Filled the SRAD PBSS with water component by component
- Had both valves closed and pressurize the system to 180 bar
 - It withstood the pressure with no problems
- Opened the manual valve
 - It withstood the pressure with no problems, but the pressure reduced slightly
 - Pressurized to 180 bar again and closed the manual valve
- Open the solenoid
 - It withstood the pressure, but the pressure fell down to 150 bar
- Depressurized the system. Test completed.

Test Criteria:

Pass criteria	Success/ Failure
The system withstands 180 bar of pressure without leaking.	Success

Test Results:

Despite some minor problems with the test rig adapter, the test was completed without any major problems and we were able to test what we set out to.

Results:

- All the components in the SRAD PBSS is able to withstand 1,5x working pressure
- There were no leaks between the manual adapter or solenoid when there were 180 bars of pressure on one side and almost none on the other.

Picture of the pressure gauge. Pressure can be read as slightly above 170 bar. That is because it was taken a brief while after pressurizing the system.



Fig 24: Pressure gauge shows 170 bar

Discussion of Results:

Two problems occurred during the test:

- 1.) As the system was filled, we noticed the test rig had some markings which caused it to leak. From there we proceeded to use turning to remove some material to avoid this problem
- 2.) Test rig adapters were leaking when the system was pressurized due to the threads. This happened because we forgot to bring thread tape which is needed for the system. But luckily the workshop had some spare we could use.

After this we cleaned out the system with water and then used pressurized air to get all of the remaining water and diesel solution out.

Discrepancies:

- the adapter had to be turned.
- -we didn't bring thread tape.

Conclusion:

The SRAD PBSS withstands 180 bars of pressure without leaks.

Since the test an update has been made to the SRAD PBSS with a new pressure vessel, which means this test does not verify our final system. Despite this, the test shows a way we can use in further testing of the system and contributes to the iterated design. It also shows that it is possible to create an SRAD PBSS and that it can be pressure validated and checked for leaks.

V.B.6

Pressurization test



Date: dd/mm/yyyy

2	7	0	3	2	0	2	2
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Purpose:

The purpose of this test was to fill the student researched and developed pressure based separation system (SRAD PBSS) with air to its design pressure, and to release the air to see how long the system takes to empty.

Participants:

Simen Flåtter Flo, Tobias Heinz, Kacper Zajac, Stian Alseth

Test Equipment & Set-Up Description:

Test equipment used is as follows:

- SRAD PBSS
- Plywood test rig
- Patent band
- M4 nuts
- M4 bolts
- Pump with integrated manometer
- Power cable
- Power supply



Fig 25 Test setup

Safety concerns:

The test involves a high pressure air system, and the safety concerns are related to this.

The main concern was injury from being in the path of the ejected air, and the debris that might follow. This was mitigated by all test participants being far away from the test rig when armed, and during testing.

Another concern was that improper assembly of the SRAD PBSS would result in it springing a leak when pressurized, and the leaking air injuring one of the participants. This was mitigated by being thorough when assembling, incorporating all seal rings and thread tape required to make it airtight.

As-Ran Test Procedure:

The system was tested a total of 4 times, with an increasing pressure for each test. The lowest pressure was

50 bars, and the highest pressure was 150 bars.

After the SRAD PBSS was assembled, mounted to the test rig, and the solenoid hooked up to the power supply, the procedure went as following for each test:

1. Solenoid was opened by turning on the power supply (24 V, 0.25 A)
2. Manual arming valve was opened
3. Pump got connected to the system, and filling commenced
4. When target pressure was reached, the solenoid and manual valve got closed
5. The relief valve on the pump was opened before disconnecting the pump from the SRAD PBSS
6. The system was armed by opening the manual valve
7. Air was released by turning on the power supply, opening the solenoid valve. A timer was used to get a value for the time it took to empty the system

Test Criteria:

Pass criteria	Fail/Success
Be able to fill the system	Success
Be able to empty the system	Success
No leaks when pressurized	Success
The time to empty the system matches with the calculated time of 0.3 seconds	Failure
Emptying the system takes no more than 2 seconds at 120 bars of pressure	Failure

Test Results:

It was possible to fill the system in an efficient manner, by use of a quick-connect solution between the pump and the system (as intended).

Arming of the system worked as intended, and no leaks were encountered.

It was possible to empty the system, but it took 30 seconds for the system to empty at 120 bars of pressure.

Discussion of Results:

The main takeaway from the test is that the system takes too long to empty for it to be effective as a mode of separating the rocket for parachute deployment. It took 30 seconds to empty it at the design pressure of 120 bars, which is above what is required.

The dangers of this system taking too long to empty is that separation gets delayed to the extent that the gain in vertical velocity of the rocket between apogee and separation results in shredding of the drogue chute on deployment. The other danger of a slow pressurization is that air will escape through the venting hole in the rocket so much so that target pressure needed for separation never gets reached.

The reason as to why ejection of the air took 30 seconds is because of the solenoid valve. It has an orifice size of 0.7 mm, choking the flow. The calculations done before the test showed that it would take 0.3 seconds, meaning that the calculations were wrong and misleading.

Otherwise, the rest of the system worked flawlessly, with quick and easy filling, as well as no leaks.

A solution to this issue has already been proposed. This solution makes use of a ball valve actuated by a servo motor. This valve has an orifice size of over 4 mm, and a straight flow pattern, increasing the mobility of the air moving through it compared to the solenoid. The calculations have also been improved, and now show a time of separation of around 31 seconds for the SRAD PBSS as tested.

Conclusion:

The test uncovered a major flaw in the SRAD PBSS and the calculations done to estimate time for emptying. The system took 30 seconds to empty, whilst the calculations predicted it would take 0.3 seconds. It was the solenoid valve that choked the flow, making for a prolonged time for emptying the system. The test showed that procedures for filling and emptying the system worked as intended, apart from the above mentioned issue. Improvements have been done to the calculations based on the test results, and an alternate solution for the solenoid valve is under design and will soon undergo testing.

Parachute deployment test



Date: dd/mm/yyyy

0	4	0	4	2	0	2	2
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Purpose:

To see if the main chute would deploy prematurely under different conditions, and to validate the main chute release system (MCRS).

Participants:

Amira Khalil, Hege Grytten, Kacper Zajac, Mikkell Gisleberg, Simen Flåtter Flo, Sverre Kristensen, Vebjørn Bratlie, Viljar Engesæt

Test Equipment & Set-Up Description:

With the test article mounted to the roof of the car, the drogue chute was left hanging outside the test article in the deployed configuration (not retained). The main chute was packed in its bag, stowed within the airframe tube, and retained in the MCRS.

- Car
- Shock chords
- Main parachute
- Drogue chute
- Airframe
- Quick links
- Swivel links
- Servo motor
- Safety pins
- CO2 canister
- Recovery module,
- Avionic module
- GoPro
- Test rig



Fig 26: Inner structure inserted into airframe mounted to the roof of the car

Safety concerns:

Ensuring nobody is close to the track where we drive. A simple solution was to have one person staying guard for the test location.
The test article could fly out with the main chute deployment. By strapping the test article tight on the car roof and using as many screws as possible we minimized this threat.

As-Ran Test Procedure:

The conducted tests wanted to show if the main parachute would stay within its bag when subjected to a dynamic environment with wind, vibrations and surging gas from the COTS PBSS passing by it. P

For each test, the car was to accelerate up to speeds close to 80 km/h, with the drogue chute deployed behind the car. Different parameters were changed for each test, such as moving velocity, the addition of securing rubber bands around the main chute bag, and ejection of gas from PBSS. The MCRS was also tested.

TEST 1: No rubber bands, 50 km/h

TEST 2: No rubber bands, 60 km/h

TEST 3: No rubber bands, 80km/h

TEST 4: Two rubber bands, PBSS ejection, 80 km/h

TEST 5: Two rubber bands, MCRS activation, 80 km/h

TEST 6: Two rubber bands, MCRS activation, 80 km/h

Test Criteria:

Pass criteria	Success/ Failure
The premature release of the main chute experienced by team 2021 at EuRoC is successfully recreated	Failure
The main chute stays within its bag during PBSS ejection when using two rubber bands	Success
The main chute is able to deploy when packed with two rubber bands	Success
The MCRS is able to release the main chute	Success

Test Results:

The testing failed to provoke a premature deployment of the main chute.
The test succeeded in uncovering that the main chute would remain in its bag at high speeds, during PBSS gas ejection, and with two retainment rubber bands around the main chute bag.
The main chute was able to deploy successfully even with the addition of two retainment rubber bands around the main chute bag.

Results from each test:

TEST 1: Main chute retained in its bag

TEST 2: Main chute retained in its bag, but main chute bag flap opened

TEST 3: Main chute retained in its bag with flap opened

TEST 4: Main chute retained in its bag with bag flap successfully retained by two rubber bands. Main chute shock chords got partially blown out by surging gas.

TEST 5: Avionics issue prevented main chute deployment

TEST 6: Successful main chute deploy

Figure 2 shows the view of the drogue chute from the GoPro mounted to the test article. The snapshot is taken from test run 1. Figure 3 shows a snapshot of from after successful main chute deployment.



Fig 27: Drogue chute during test 1



Fig 28: Main- and drogue chute released during test 6

Discussion of Results:

The fact that the initial three tests were unable to provoke premature main chute deployment made the subsequent test more uncertain. Test 4 sought to uncover whether or not the rubber bands would reduce the chance of premature deployment, but since premature deployment never happened, a key comparative result was lacking. Still, the test 4 was successful, since it uncovered that the rubber bands indeed would ensure that premature deployment won't happen when gas from the PBSS is surging past it (as it will in flight). This was one of the key hypotheses from team 2021, as to why the main chute deployed prematurely, and the proposed solution was rubber bands around the bag.

There was a concern that the implementation of two rubber bands for retainment of the main chute in its bag would prevent the main chute from escaping the bag when released from the MCRS. This was not the case, and the rubber bands will as a result be implemented onto the main chute bag of the rocket Birkeland on launch day.

The MCRS released the main chute successfully. The environments at which this was achieved was similar to that of actual flight, with the drogue deployed and resisting wind speeds of upto 80 km/h. It was a concern that the force that this would exert on the MCRS would prevent the servos from activating the mechanism. This was not the case, and the servos were able to activate, and the MCRS successfully released the main chute.

Conclusion:

The rubber bands were also to retain the main chute within its bag when activation of the COTS PBSS. The drogue chute was able to pull out the main chute efficiently when the MCRS released, even with two rubber bands over the main parachute bag. The test was unable to provoke the similar premature deployment of the main chute as seen at the launch of team 2021's rocket, disabling us from uncovering a possible root cause for the behavior..



Shear screw test

Date: dd/mm/yyyy

2	5	0	8	2	0	2	1
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Purpose:

The purpose of this test was to uncover the shear strength of the shear screws that will be used in the rocket. Another purpose of this test was to test the consistency of the shear strength in order to validate them.

Signature(s):

Vebjørn G. Bratlie, Johannes E. Mørkrid, Kristian Hope, Ane Morkemo, Ola Flaata, Svein J. Husa

Test Equipment & Set-Up Description:

The equipment:

- Compressor
- Test rig
- Test couplers
- O-ring
- 8 x Shear screws wrapped in PTFE tape
- Safety goggles and hearing protection.

The set-up:

The couplers were mounted onto the test rig, fastened, assembled and pressurized using the compressor.



Fig 29: Test set-up

As-Ran Test Procedure:

Checked that the valve was closed and the hose was at atmospheric pressure before connecting the hose to the test coupler nipple. After this we video recorded the manometer while slowly opening the valve until the shear screws sheared.

Safety concerns:

An aluminum part will fly with a high velocity. Mitigated by making sure the area in front is cleared before the test is conducted. Also making sure that no one was standing behind the test setup.

The separation will cause a lot of noise, mitigated by using hearing protection.
Parts of nylon screws can spread and hit the eyes of the test participants, mitigated by using safety goggles.

Test Criteria:

Pass criteria	Success/ Failure
Withstand pressure of 1.32 bar	Success
Measure pressure the shear screws withstands (Reason: High variety of shear strength for nylon screws)	Success
Consistent shear strength	Success

Test Results:

Attempt #1



Fig 30: Shear pressure: measured at 2.5 bar, consistent shear for all screws.

Attempt #2

Fig 31: Shear pressure: measured at 2.5 bar, consistent shear for all screws.

Attempt #3

Fig 32: Shear pressure: measured at 2.7 bar, consistent shear for all screws.

Discussion of Results:

The test showed a consistent result of 2.5 bar. On the last attempt we built the pressure up more rapidly. This can explain the deviation of 0.2 bar.

The build up pressure of 2.5 bar resulted in breaking the shear screws. This was a successful test and gives an estimate of the pressure needed to break 8 shear screws. From calculations this gives the screws a combined shear strength of 1590 N and each screw a shear strength of approximately 198 N.

We expected the ultimate tensile strength of the M3x0.5 nylon screw to be between 66.2-72.4 MPa and the force needed to break them to be between 346-378 N. The test showed that the screws only had a combined strength of 1590 N. The lack of strength could be caused by uneven shearing. By this we mean that the shear screws are sheared one by one, or four by four, rather than all at once.

Conclusion:**Old conclusion for the rocket Stetind:**

We expected the shear strength to be larger than the first test we conducted on April 24th 2021, but the shear strength was the same this time around. The reason we expected a larger strength was because we used 7 shear screws back then, and this time we used 8 shear screws. So either the shear screws are weaker than the first pair we used, or there is no difference between using 7 than 8 shear screws due to uneven shearing.

Still these screws passed the test of withstanding a pressure of 1.76 bar. And because they break at 2.5 bar, CO2 canisters of size 25g, 33g and 45g will suffice to break the shear pins (see appendix V.I *pressure calculations*), according to this test. And they can proceed to be used in the rocket and the drop test.

Preliminary functionality test - Main Chute Release System (MCRS)



Date: dd/mm/yyyy

1	8	0	1	2	0	2	2
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Purpose:

The purpose of this test is to confirm compatibility of the main chute release system components. Furthermore, the test aims to check the integrity of the load-bearing mechanism by manually operating the release arm.

Participants:

Mikkel Gisleberg, Kacper Zajac, Hege Grytten & Simen Flåtter Flo

Test Equipment & Set-Up Description:

The equipment:

- Main Chute Release docking, 2 pcs.
- Upper and Lower release arm.
- Quick link.
- Fasteners and spacers.
- Parachute bag (Empty).
- Mounting plate (Plank).
- Newtonmeter

The set-up:

The test set-up consisted of a mounting plate upon which the fully assembled main chute release system, hereby MCRS, was mounted with two bolts, an empty parachute bag with its cords attached and a newtonmeter to measure the applied forces.

Safety concerns:

No concerns for personal safety.

As-Ran Test Procedure:

The Main Chute Release System was first assembled where the integrity of its components was checked. It was then mounted to the mounting plate using two bolts. The Quick link, a carabiner to which the parachute shall be attached, was then inserted into the MCRS along with an empty parachute bag and the connecting nylon cord. The release mechanism was then manually operated to release the Quick link. After several completions, the test participants then applied force to the system by pulling the nylon cord and manually triggered the release mechanism. The force applied to the system was measured with a newtonmeter (force gauge).

Test Criteria:

Pass criteria:	Success/ Failure
The Upper and Lower release arms are locked when the mechanism is armed-to-release.	Success
The MCRS releases Quick link under low-to-no load.	Success
The MCRS releases Quick link under significant load (>20 - >40 kg load).	Partial success*

*Improvements necessary

Test Results:

Little-to-no load test:

MCRS works as it should. The arm is safely locked prior to release and the “locking mechanism” triggers successfully.

Test with significant load applied:

*MCRS triggered somewhat successfully, the load-bearing bolt collides one of the release-arms upon parachute release. Improvements are necessary to increase reliability of the mechanism.

Discussion of Results:

- The load-bearing screw, to which the parachute will be connected, is placed too close to the release arm and collides under parachute release. That reduces free space between the MCR-docking and the release arm which might complicate the parachute release. The space between the load-bearing screw and release arm must be increased.
- The equipment mounts on the bottom of MCRS are too close to its mounting screws, complicating the mount of servos that will ultimately operate the release system. The space between these fasteners must be increased.
- The load-bearing screw must be tested and validated prior to flight.
- A shock-absorbing solution could be beneficial for the load-bearing screw and spacer.

Conclusion:

The system completed the test runs rather successfully, although a few improvements must be made prior to the test in a wind tunnel in Voss. Placement improvements of the fasteners on the MCRS must be made to increase the space between the; Quick link and release arm, as well as bottom mounting fasteners with servo-mounting screws.

New FEM-analysis and functionality test is to be performed.



Compression test

Date: dd/mm/yyyy

0	4	1	1	2	0	2	1
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Purpose:

The purpose of this test is to uncover the relative strength loss of composite airframe segments with holes, compared to a control segment without holes.

Participants:

Simen Flåtter Flo, Robert Kalrud, Hege Grytten, Arthur Tjomsland

Test Equipment & Set-Up Description:

The equipment:

- 3x 15 cm long filament wound carbon fiber segments
- 2x 15 cm long filament wound fiberglass segments
- Hydraulic press
- 2x Polymer plates
- 2x Steel plates
- Acrylic blast shield
- Gloves

The set-up:

The cylindrical segments were compressed between two steel plates in a hydraulic press.

Safety concerns:

Gloves must be used when handling the segments, to prevent potentially hazardous splinters piercing the skin.

There must not be any body parts in the vicinity of the hydraulic press when it is actuated, this to prevent bodily damage from test operations.

A blast shield must be placed between the press and the participants to prevent bodily damage from failing segments.

As-Ran Test Procedure:

For all tests, the pressure gauge was recorded until just after the samples yielded.

TEST #1

The first test sample was a carbon fiber section without holes. Here, we used 2 plates of 2 cm thick plastic at the top and bottom of the carbon fiber sample. The 2 steel plates on the hydraulic press would then press against these plastic plates, instead of pressing directly on the carbon fiber. This was done to prevent shearing of the ends, and instead end up with breakage somewhere along the sample between the ends.

TEST #2

The second test sample was fiberglass without any holes. Here, there were no plastic plates between the steel plates on the press and the ends of the sample. The same goes for all subsequent tests.

TEST #3

The third test sample was carbon fiber without any holes. The reason we did this again was because we wanted to test the strength without the plastic plates for carbon fiber as well.

8 Ø4 holes were drilled into both a fiberglass and a carbon fiber sample. The holes were placed in the middle of each sample (between both ends), spaced 45 degrees apart.

TEST #4

The fourth test was done on the fiberglass sample with 8 holes, and the fifth and final test was done on the carbon fiber sample with 8 holes.

Test Criteria:

Pass criteria	Success/ Failure
Segments with holes break at the holes, and not at the ends.	Failure
The test participants are able to record the force at which the samples break.	Success
Get comparable results on the carbon fiber and the fiberglass composite sample.	Failure

Test Results:

Table below shows a summary of the test results for the carbon fiber (CF) and the fiberglass (GF) test samples.

Sample	Weight [kg]	Force [N]	Pressure [MPa]
3 (CF)	20000	196200	247
2 (GF)	19500	191295	241
1 (CF)	15000	147150	185
4 (GF), 5 (CF)	10000	98100	123

TEST #1: Solid Carbon fiber

The carbon fiber cut through both plastic plates and started to shred at the top the sample, in contact with the steel plates, at 15 metric tons of pressure. Test results inconclusive

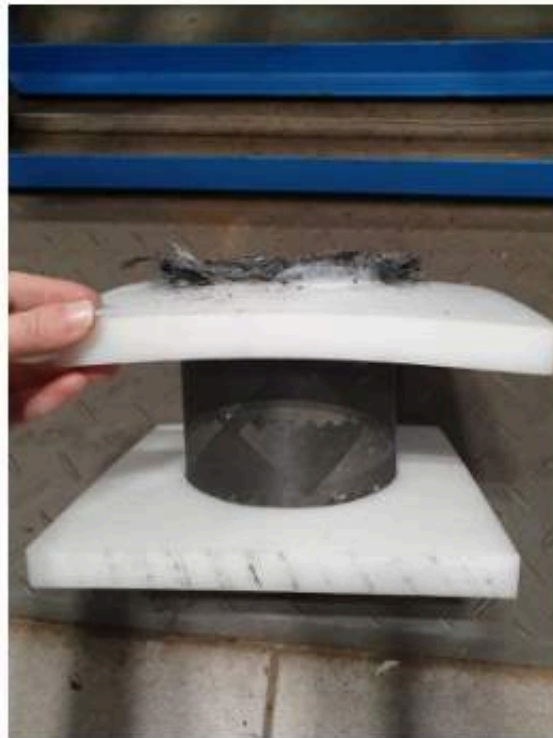


Fig 33: Carbon fiber section and polymer plates after test 1

TEST #2: Solid glass fiber

The glass fiber broke in the middle at 19.5 metric tons.

No shredding at the ends.



Fig 34: Fiberglass section after test 2



Fig 35: Force exerted on the test article when it yielded

TEST #3: Solid Carbon fiber

The carbon fiber started shearing at the top at around the same time as there was a break in the material 3-4 cm above the bottom edge. This happened at 20 metric tons.

The picture below shows the pressure gauge just before sample 3 broke. The innermost gauge shows 20 metric tons.



Fig 36: Force exerted on the test article when it yielded



Fig 37: Carbon fiber section after test 3

TEST #4: Glass Fiber with 8 holes
The sample started shredding, inconclusive results.
Held up at 10 metric tons



Fig 38: Fiberglass section with holes after test 4

Test #5: Carbon fiber with 8 equally spaced M4 holes

The sample shredded, inconclusive results.

Held up at 10 metric tons before starting shredding at the ends.

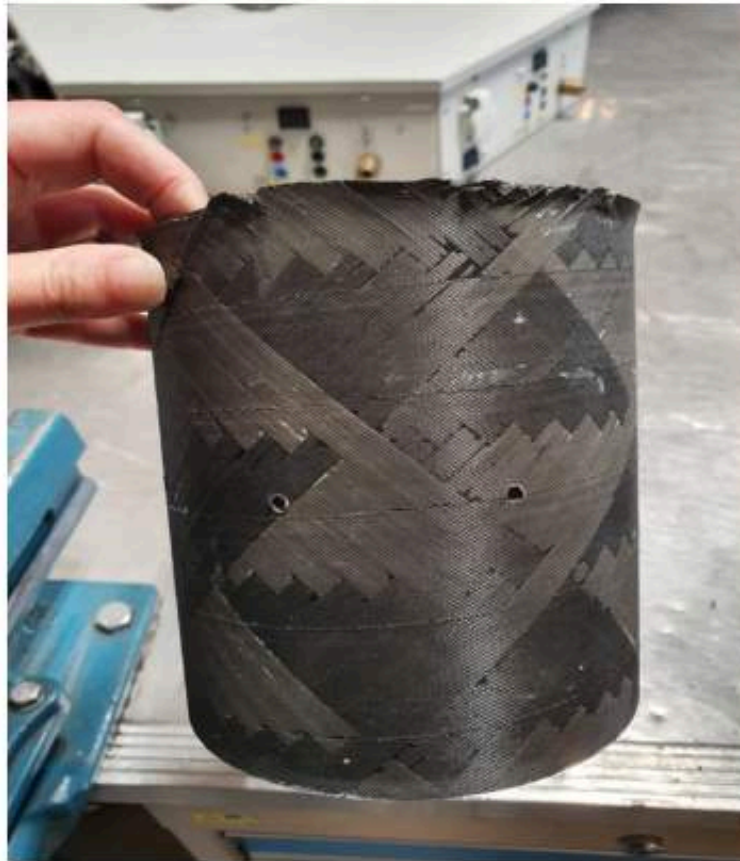


Fig 39: Carbon fiber section with holes after test 5

Discussion of Results:

- We uncovered that both of the test materials held up a minimum of 10 metric tons.
- We got satisfactory results for 2 of the test samples (one carbon fiber and one glass fiber)
- Of the 5 test samples, only 2 samples did not fail due to shredding at the ends. We were not able to directly observe a cause to why these two samples performed differently to the others.
- The failure of the test for 3 samples was likely due to the nature of the test setup.
- We need a better test setup to achieve reliable results.

Conclusion:

The successful results that we were able to get from the test was that glass fiber without any holes broke at 20 metric tons, and carbon fiber without any holes broke at 19.5 metric tons.

All the test samples with holes in them gave inconclusive answers, so if we want reliable results we need to perform a new test.

If a new test is performed then we need to use a test cap/flange to stop the edges from shredding, and use a

different method of cutting the sample pieces if possible to try and eliminate this risk. As discovered during this test, do not use an industrial saw with a hydraulic side press, this will compress the tube and break up the layers.

Integration test



Date: dd/mm/yyyy

1	2	0	3	2	0	2	2
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Purpose:

The purpose of this test was to assemble the internal structure of our rocket Birkeland, to see if everything fit together, and to get a notion of the process and steps needed to efficiently assemble the sub-systems.

Participants:

Simen Flåtter Flo, Robert Kalrud, Stian Alseth, Einar Bergslid, Trond Steinagard, Mikkel Gisleberg

Test Equipment & Set-Up Description:

The test was conducted using 3D-printed representations of the components, as well as actual purchased or produced components. Screws, tape and adhesive were used to mount many of the components together. Tools, such as screwdrivers, wrenches and drills, were used to aid the assembly process. The test was set up in a fashion of having components, tools and fasteners on a table, and working on assembly of different subsystems at different tables.

Safety concerns:

None

As-Ran Test Procedure:

The test procedure went as follows:

- All components were laid out and sorted by the subsystems.
- Groups of two worked on each subsystem, with one person doing assembly, and the other taking notes.
- The people doing the assembly, assembled the systems in the order they had thought up while designing the system. Each step was noted into an assembly checklist, and improvements were added under way.
- When the subsystems had been assembled, they were mated together to the final configuration.
- The final configuration of the inner structure was then inserted into the forward airframe, to check the fit.

Test Criteria:

Test criteria	Success/ Failure
All modules can be assembled separately.	Success
Modules are able to be connected together in a final configuration.	Success

Eventual design flaws identified.	Success
Solution to the design flaws and further improvements are applicable.	Success
The inner structure assembly fits into the outer structure.	Failure
Creation/ Improvement of assembly checklists for assembly in the future.	Success

Test Results:

Design flaws uncovered:

1. The CO2-cartridge in the HAWK crashed with the hawk plate.
2. Holes in the hawk plate were not compatible with the hawk mounting screws.
3. The hawk plate allowed for too much rotation of the hawk when tugging on the arming pin.
4. The slit in the COPV mounting brackets were too narrow to fit the 12 mm wide clamp bands through.
5. The lid for the SRAD Battery Pack did not fit after mounting the pack to the avionics mounting plate.
6. The altimax battery shell had one more hole than needed for assembly.
7. The altimax battery pack crashed with the radio voltage regulator
8. When mounted to the recovery plate, the rails in the recovery module made the module not fit inside the airframe. **(Figure 43)**
9. Two of the radioron antennas are unnecessarily long.
10. Cable management becomes more difficult after fastening the mounting plate to the rails.
11. Cables and antennas make it harder to fasten the mounting plate to bulkheads/rails.
12. The ends of the radioron antennas have no fastening method.
13. The screws for the MCRS crashed with the Hawk-body **(Figure 42)**
14. The recovery valve bracket does not reach all the way to the bulkhead
15. The holes in the recovery valve bracket are too close to the bending point
16. 6 holes/screws between bulkheads is unnecessary and may result in unwanted displacement.
17. The flexible hose in the SRAD PBSS was not oriented as intended.
18. The quick connect for the pump crashes with the 3d printed mount **(Figure 50)**
19. The recovery valve bracket hole had to be filed down to fit the valve
20. The servo motors on the MCRS crash with the holes for the PBSS
21. We are missing a clamp band that prevents up-and-down movement

Flaws in assembly procedures:

1. The SRAD PBSS is difficult to assemble part-by-part in the module
2. We can not tell which rails should have the COPV ears on them
3. Mounting direction of the avionics bulkheads is not obvious.

Each module, meaning payload, avionics and recovery module, were successfully assembled separately **(Figure 51, 52 and 53)**

The modules were successfully connected **(Figure 54)**

The inner structure was unable to fit inside the airframe in its entirety, due to the flaw mentioned in bullet point 8 above, together with known discrepancies on the dimensions of 3D-printed parts, compared with

their actual design dimensions.

Assembly checklists were made, and the final checklists for the competition will be heavily based on these.

Discussion of Results:

Improvements of design (numbering corresponds with test results):

1. Change design of the hawk plate (**Figure 41**)
2. Make the hawk mounting holes in the hawk plate countersunk
3. Change the design of the hawk plate (**Figure 41**)
4. Widen the slit in the COPV mounting brackets to 12 mm
5. Make room in the avionics mounting plate for removal of battery pack lid
6. Remove one hole from the altimax battery shell
7. Change the shape of the altimax battery pack to an L
8. Make the grooves in the recovery plate for the rails deeper
9. Use the shorter antennas for the radio transmitter
10. Implement solutions for cable management in avionics module
11. Implement solutions for cable management in avionics module
12. Implement fastening solutions for the radio antennas in the avionics module
13. Use shorter screw for mounting the MCRS to the recovery plate
14. Make valve bracket 2 mm longer
15. Move holes in valve bracket away from the bending point
16. Reduce the number of holes between bulkheads to 3, and make sure that these holes are drilled simultaneously during production to ensure the wanted alignment of the holes.
17. Fix the orientation of the flexible hose in the CAD to represent the orientation.
18. Move the hole of the hose closer towards the edge of the recovery plate
19. Increase the size of the hole by 5 mm
20. Move the holes for the SRAD PBSS closer to the edge of the recovery plate and machine down nuts on hoses.
21. Add a clamp band on the tapered part of the COPV

Improvements to assembly procedures (numbering corresponds with test results):

1. The entire SRAD PBSS should be assembled together before going in the main assembly
2. Mark the rails that should have the COPV ears in them
3. Mark the bulkheads to indicate correct configuration when assembled

Conclusion:

The test uncovered minor flaws to the design that is possible to improve, and that will make the design and the assembly process better. This test granted important experience and insight for the assembly crew for SA Cup, highlighting the importance of ease of assembly, and motivating the team to work on improving the design for this purpose.



Fig 40: Component overview

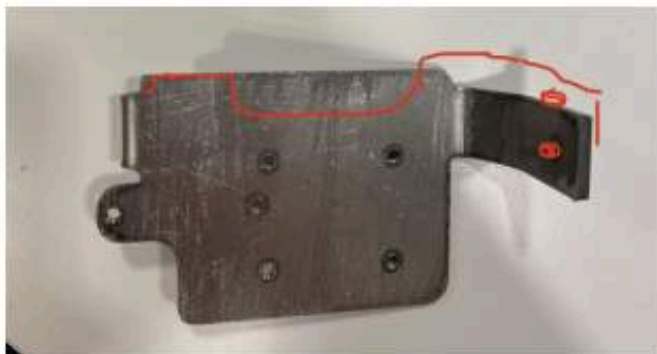


Fig 41: Suggested design improvements to hawk plate



Fig 42: Screw crashing with HAWK

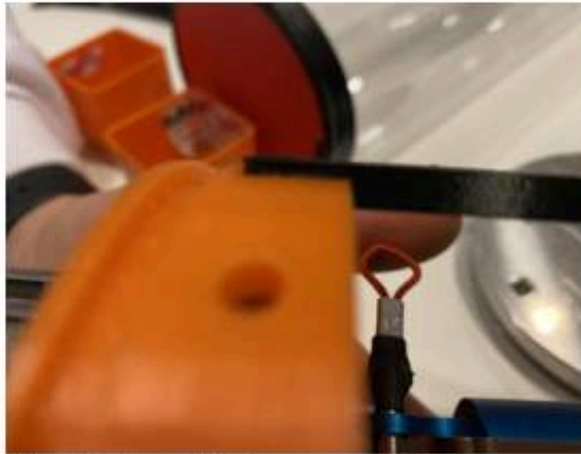


Fig 43: Rail outside the recovery plate

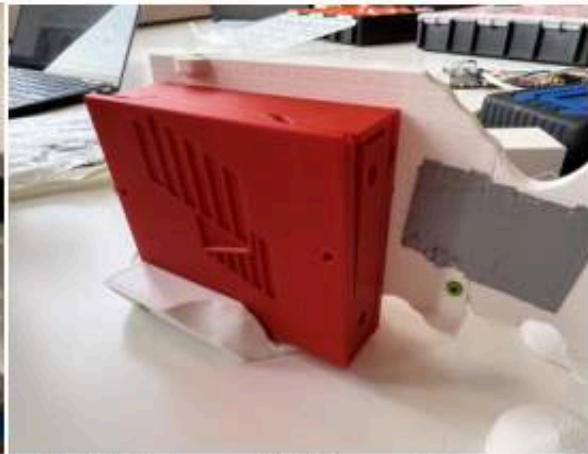


Fig 44: Battery pack lid does not fit



Fig 45: Radio antenna

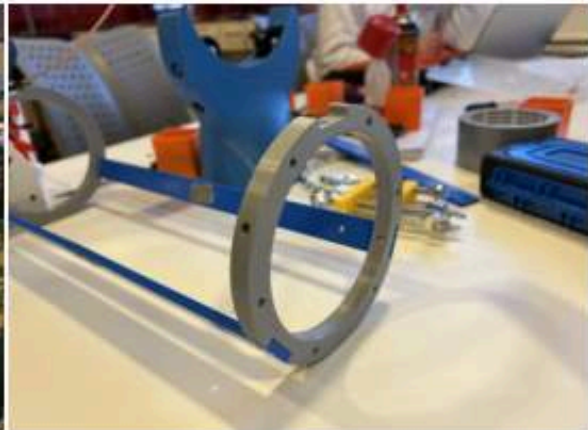


Fig 46: Bulkhead with no obvious orientation

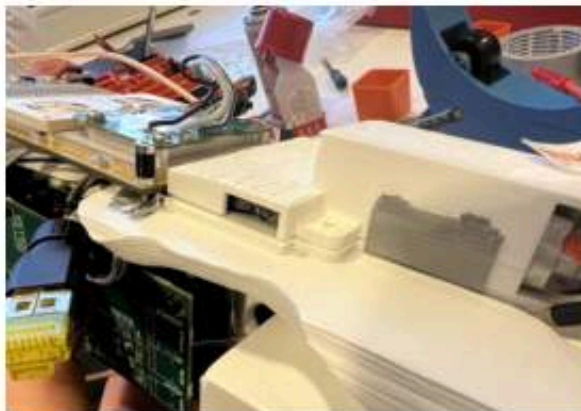


Fig 47: Unnecessary hole

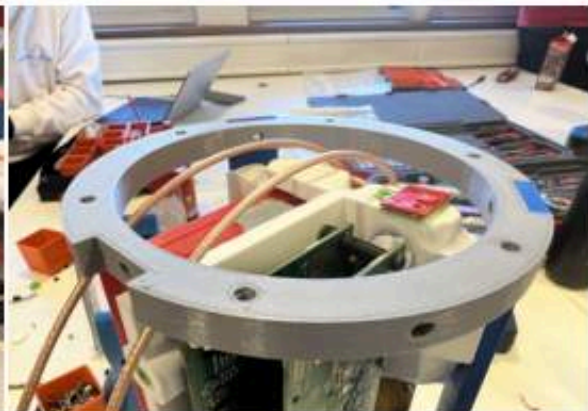
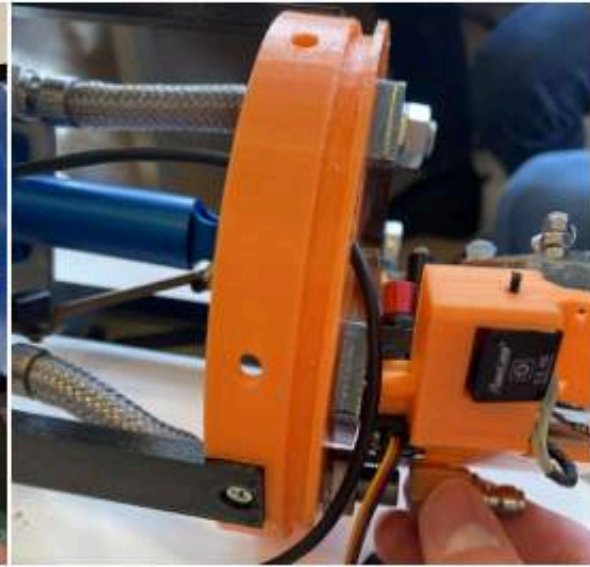


Fig 48: Hard to fasten plate with antennas present

**Fig 49:** flexible hose of SRAD PBSS**Fig 50:** Pump adapter crashing with camera holder**Fig 51:** Payload**Fig 52:** Avionics module**Fig 53:** Recovery module**Fig 54:** The Recovery, Avionics and Payload assembled



Avionics test flight - Andøya Space Center

Date: dd/mm/yyyy

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Purpose:

The purpose of this test was to determine if the avionics stack would reliably retrieve and store sensor data and send telemetry during a medium range rocket flight, in order to retrieve data to finalize the Kalman filter. We are looking to test a barometer, two IMUS, and a GPS, and a low-cost telemetry system, in addition to see if the FSM software would send the correct signals for the chute deployments. Another purpose was to test the ground station software, both backend and frontend.

User(s):

Ane K. H. Morkemo, Even Drugli, Ola Flaata, Rizqi F. Wahyudin, Sverre O. Kristensen

Test Equipment & Set-Up Description:



- KB3 PCB
- PDB PCB
- Main battery
- Wires
- Duct tape
- 2x Xbee Pro S3B radio transceiver with wire antenna (on both the payload and ground station)
- Computer with ground station software (OpenMCT)
- 3D printed casing for housing the components
- 2U CanSat rocket with parachutes & motor ([Cesaroni Pro38-6G](#))
- Parachute for our payload
- Other launch equipment and services provided by Andøya Space Center (ASC)

Fig 55: The payload.

Safety concerns:

Due to the risk of an anomaly with the rocket motors, a large safety perimeter should be set around the launch pad and the possible trajectory for the rocket. The safety of both the Propulse team and the general public was handled by the professionals at ASC, which minimized the potential risk. Every safety regulation from ASC should naturally be followed.

As-Ran Test Procedure:

We assembled the avionics payload and covered it in duct tape to make it as water-proof as possible. We also installed some weights to have the payload weigh about 700 gram. Furthermore we attached the parachute and turned on the power. Before we put the payload in we waited for confirmation on telemetry and GPS lock. From then on the professionals at ASC were in charge of handling the rocket launch. Returning from the launch site with a car we got line of sight of the other side of the mountain, which gave us telemetry again. The last coordinates that were given were used to locate and recover the payload.

Test Criteria:

Pass criteria	Success/ Failure
Successfully retrieve and store FSM state and sensor data from a barometer, IMUs and a GPS on a micro SD card.	Success
Successfully receiving data from flight computer using the Xbee radio	Success
FSM state switched correctly	Failure

Test Results:

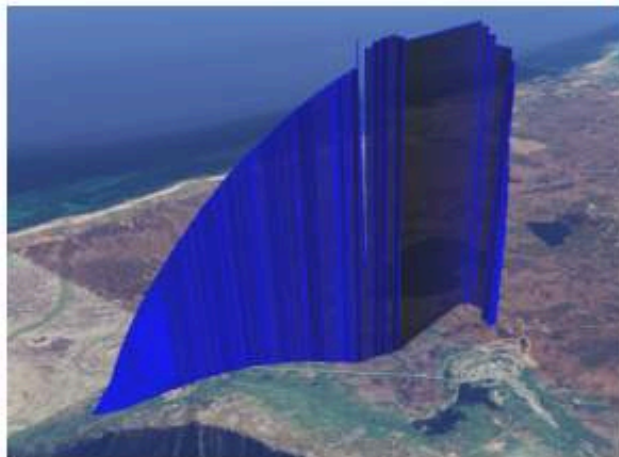


Figure 56: Longitude and latitude from GPS plotted with barometric height in Google Earth.

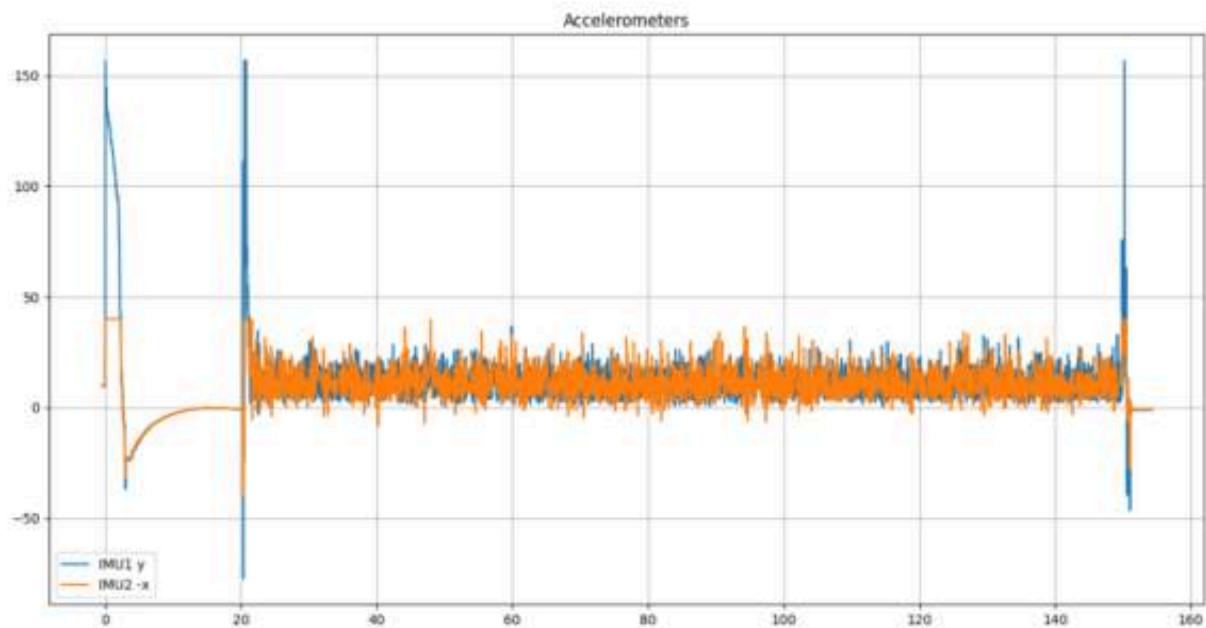


Fig 57: Acceleration data in flight direction, showing IMU maxing out at 4Gs.

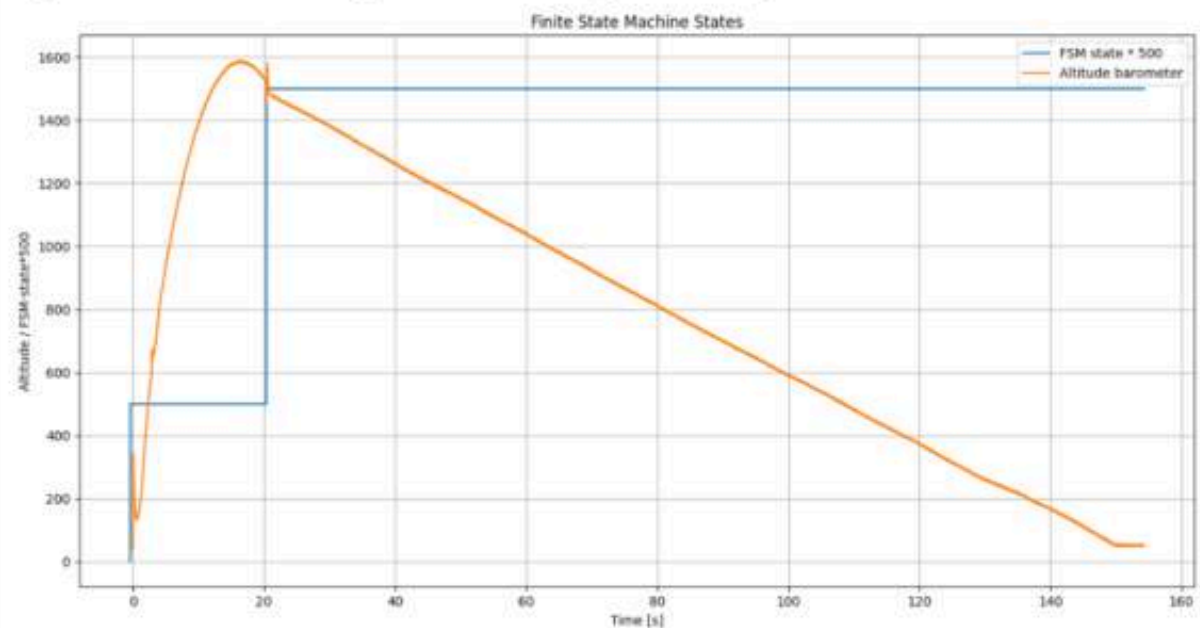


Fig 58: Barometric altitude and FSM flight states during the flight, shows the FSM stopped progressing after reaching "Coast" state.

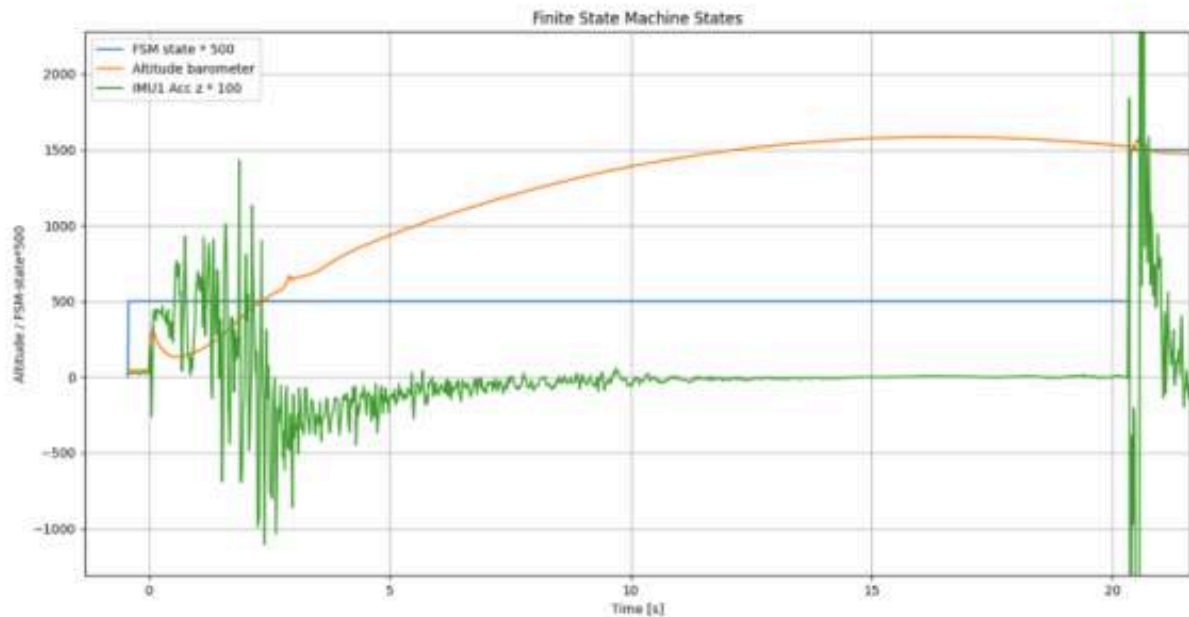


Fig 59: FSM state, barometric altitude, and acceleration used in the state machine.

We were able to successfully retrieve telemetry data live, including the GPS position. The SD card file was recovered without issues, but we discovered that all the data had been written twice.

Discussion of Results:

All the sensors worked as expected, sampling at 100Hz. We lost the GPS fix around apogee, see *Figure 1*, but quickly got it back. As the GPS antenna used was less powerful than the one on Birkeland, we don't see this as an issue, and consider it a success. The sampling rate of the GPS was only at around 1Hz, mainly due to issues using any other baud rates than 9600 bits/s, which slowed it down a lot. This is something we will try getting to 10 Hz.

SD card storage also worked mostly as expected. This was done at 50Hz due to some issues with buffer sizes that couldn't be fixed in time. This meant that only half of the sensor readings at 100 Hz were actually stored. However, due to another error in the code, every sensor reading was written to the SD card twice. The error was found, and the duplicates have been removed in the plots.

The Finite State Machine (FSM) didn't perform as expected, as it reached "Coast" too late and never continued from there. All the issues were due to mistakes made when implementing the code. Firstly, we used the z-value instead of y. This resulted in the FSM only reaching "Powered" at deployment, right after 20s, as the acceleration threshold was 30 m/s^2 . Directly thereafter, it detected negative acceleration and went into "Coast". Secondly, the altitude used in apogee detection was never updated, which made apogee detection. These issues were simply made because we didn't test the FSM software before launch, so we need to have more tests to further validate the FSM.

The telemetry system functioned as anticipated and the ground station received telemetry until the payload went past the mountain behind the launch site. There were some errors with the telemetry, which caused some data points to become corrupted. This error is guaranteed to not come from the payload, but rather the communication between the two xbee's.

The ground station software was tested during this flight, and all non-corrupted data that was sent to OpenMCT was visualized. Thus we had no errors with the frontend of the ground station software. The backend also worked well, but due to errors with the xbee's we had some problems with error handling. This is not critical as this is not the radio system we are using under competition.

Conclusion:

In conclusion, the test went very well, and resulted in a lot of data for tuning the kalman filter. We discovered bugs with the SD card writing and FSM implementation, but these didn't impact the rest of the system. The telemetry and ground station software also worked as expected.



Wind tunnel test

Date: dd/mm/yyyy

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Purpose:

The purpose of the wind tunnel test is to test parachute deployment systems behaviour in realistic conditions. The test aims to verify whether:

- The MCRS operates as intended, retaining the main parachute until signalled.
- The optimisation of MCRS is successful.

Participant(s):

Simen Flåtter Flo, Hege Grytten, Viljar Engesæt, Kacper Zajac and Mikkel Gisleberg

Test Equipment & Set-Up Description:

The media acquired during the wind tunnel test can be found here: [Link](#)

The test rig assembly consisted of following parts:

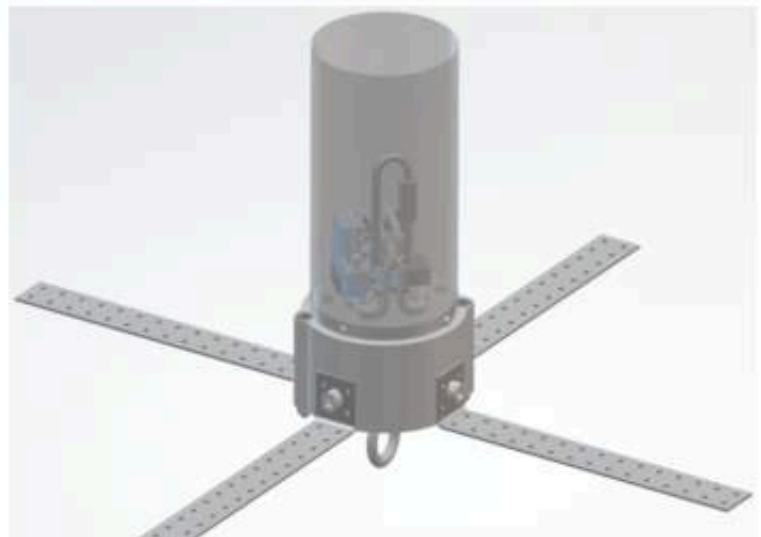
- An aluminium base.
- 4 aluminium brackets, strengthened with a steel threaded rod.
- A fastening rope.
- 3 Carabiner hooks.
- A plastic cylinder to mimic the airframe.
- A recovery plate test article.
- The Main Chute Release System (MCRS).
- Various fasteners.

Avionics setup:

- A camera and servo bracket.
- An activation button.
- A battery pack.
- Spare cables.
- Main printed circuit board (PCB).
- RunCam split 4 camera.
- LED - light strip.

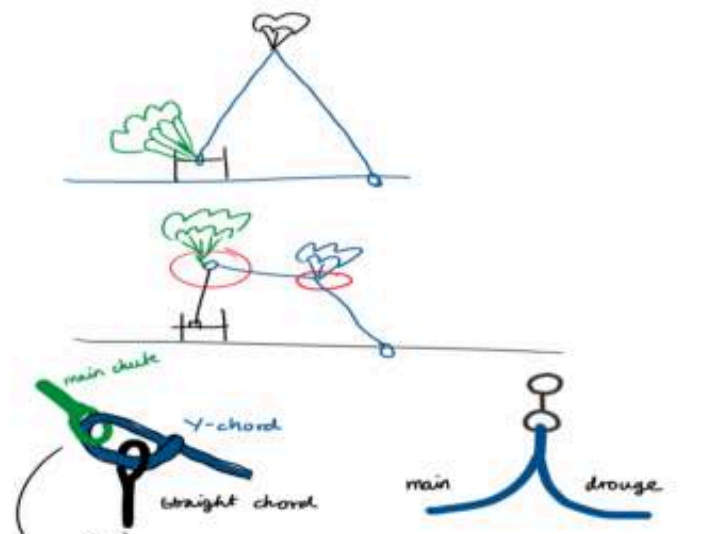
General information about the test rig assembly:

- The base assembly, hereby chonky base, consists of several aluminium plates fastened together with bolts and lock-nuts.
- The chonky base was produced at Byåsen using 500 series Aluminium.
- The tube simulating the airframe is made out of plastic and stiffened with gaffer tape.

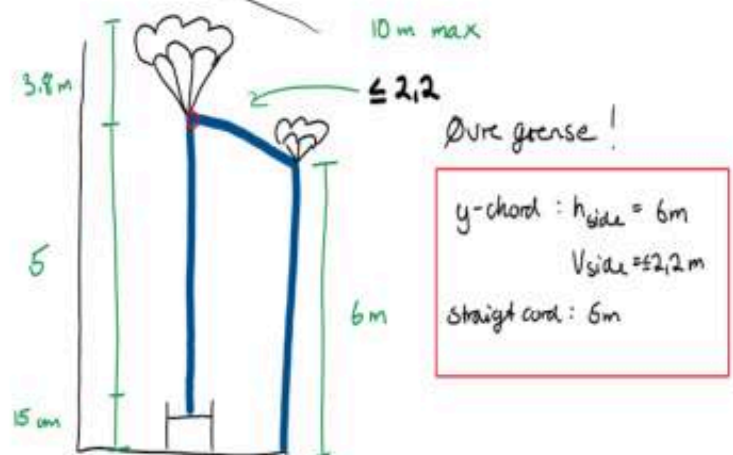


General information about the test environment:

- The ceiling of the wind tunnel was approximately 10 metres high.
- Every part of the test rig had to be fastened as loose parts would pose a risk to the personnel and the wind tunnel itself. This resulted in adjusted test set-up where the swivel links and quick links were removed. These were replaced with shock cords.
- The cords connecting the parachutes had to be reduced in length due to tunnel size limitations. This was solved by implementing knots in the cords to reduce length.



The pictures on the right aim to represent the composition of the cords and their respective fastening points. The parachutes were also connected to the wind tunnels "floor"/ base, consisting of strengthened steel wire rope, with a carabiner in case the system was unable to handle the loads it was subjected to during parachute deployment.



Safety concerns:

Health and safety of members

Precautions were taken in the wind tunnel as instructed by the employees there and we made sure the test rig was safely mounted with redundant systems.

Metal parts that hit the walls in the wind tunnel

Mitigation: The base was attached to the floor with two carabiner hooks for redundancy in case the test rig was to fail. The drogue chute was attached with a carabiner hook as well.

The integrity of the Base:

The base was made by us and so we were not certain of the strength/integrity of it.

We did a FEM-analysis to check this. There was done FEM-analysis on both docking part of the MCRS and the recovery ring. From the analysis we got promising results with Safety Factor of 2 for the recovery ring, and about 3 for the docking part. With these results we could conclude that it would be safe for us to proceed with the wind tunnel test.

As-Ran Test Procedure:**Problems during the preparation:**

The MCRS had too much friction between the ARMs and was unable to release with the servo motor.

Test number 1 (parachutes only):

The first test was to see how the parachutes would behave in the wind tunnel. The wind speed was set to 80km/h. The drogue chute was thrown out in the wind tunnel which pulled the main chute out. The chord holding the main chute then snapped.

Test number 2 (full test with avionics and the test rig):

The wind speed in the tunnel was set to 80km/h. The drogue chute was then thrown out and the button to activate the MCRS was pressed. The test was stopped after 5 seconds as the main chute was not pulled out.

Test number 3 (same setup as test number 2):

The test started like the previous one and the drogue chute was thrown out. The MCRS was activated and it took about 15 seconds for the main chute to fully deploy.

Test Criteria:

Pass criteria	Fail/Success
The MCRS deploys	success
The drogue- & main-chute deploy	success

Test Results:

The takeaways from the first test:

- Do not have knots in the cords as the forces increase there and they may snap. Have extra cords available or make sure not to have any knots.
- Redundancy is key - if we did not have the drogue chute attached to the carabiner hook the parachutes would have gone up to the ceiling, which we did not want.

Takeaways from the second test:

- We found out the MCRS did actually release, so we concluded that the main chute needed more time to deploy. This is what we aimed to check during the third test.

Takeaways from the third test:

The MCRS worked and the main chute was fully deployed after 15 seconds.

The brackets in the test rig were bent and almost all of the pink rope had torn apart. Having two carabiner hooks underneath for redundancy was key here.

We found out that the storage for the cameras was full so we missed out on video for two successful tests. .

We wanted to do a final test with the airframe shortened down, but since we rushed too much we were not able to perform the test in a safe manner

Results:

The MCRS did deploy and release the parachute successfully, although it can be attributed to the filed down "Lower Release Arm" which initially generated friction when the force was applied to the shock cords. The parachute testing, test number 1, showed how important it is not to have knots in the cord as the overall strength is reduced and the cord is more likely to snap. The further tests, number 2 and 3, validated the functionality and strength (as previously simulated and proven with Finite Element Method Analysis (FEM)) of Main Chute Release System (MCRS). Although the parachute may take as long as 15 seconds to fully deploy, the system can be seen as fully functional in its current state.

Test criteria satisfied and successful.

Discussion of Results:

The test shows that the MCRS works in realistic conditions and that the parachutes behave as intended with the load bearing attachment point. It uncovered a flaw with the lower release arm that has been iterated upon and improved. It also highlighted the importance of proper calculations in length of chords as they will not behave exactly as one would think in theory.

Conclusion:

In Conclusion the trip was a great success. We confirmed that the MCRS worked in realistic conditions and that the parachutes deployed.

We also got a real-life example of how important it is to have redundant systems

Lessons learned: (most of which can be useful to know for the helicopter drop test)

- Check the avionics setup early and not the day before as there can come up problems there
 - Update the CAD so we never have to file it again - also buy a automatic file
 - Check the video storage and the configuration of SD-cards in the cameras.

Hazard Analysis

Introduction

This appendix addresses the hazards that pose a potential danger to personnel related to material handling, pre-launch procedures, hazards in flight, and transportation and storage of propellant. Risks to mission success can be found in the Risk Assessment Appendix D.

The scale used here to indicate the risk level in this appendix consists of five levels: Very low - Low - Medium - High - Very high. Risk is the combination of perceived likelihood and consequence.

Category	Hazard	Possible cause	Initial risk	Mitigation approach	Residual risk
Material handling					
	Carbon Fiber - Can cause irritation to eye, skin, throat and nasal passages.	Incorrect handling	Low	Personnel will wear protective gloves and eyewear when handling the carbon fiber.	Very low
	CO₂-canisters - unexpected release can cause injury	Incorrect handling	Low	Canisters will be stored out of direct sunlight and away from other sources of direct heat. Will be stored in an appropriate container during transport.	Very low
	Epoxy - Can cause eye and skin irritation	Incorrect handling	Low	Personnel will wear protective gloves and eyewear when handling the epoxy	Very low
	Batteries - can explode due to close proximity with a heat source, or due to short circuiting, causing injury	Incorrect handling	Low	Will be stored dry and out of direct sunlight and away from other sources of direct heat. Will be stored in an appropriate container during transport.	Very low
	Propellant - can irritate eyes and the respiratory tract. Accidental ignition can cause serious	Incorrect handling	Low; higher risk due to the potential of serious injury, but the	The propellant will be stored in its original packaging until assembly. The propellant will be handled according to safety guidelines, manufacturer's	Very low

	injury		propellant is very stable and from a well known manufacturer. The probability of accidental ignition is very low	instructions for use, and pre launch checklist. It will not be stored with combustibles or close to heat sources that might cause an ignition.	
	Microwaves - Radio transceivers emit strong electromagnetic waves around them. Being too close can cause damage to the body in different ways.	Standing too close to strong radio equipment	Low	The transceiver in the rocket has a minimum safety distance at 0.5 meters when at max power. The ground station transceiver has a minimum safety distance of 3 meters in front of the transceiver, and 0.5 meters from the other sides. By keeping the correct safety distance from this equipment personnel should be completely safe.	Very low
Energetics handling	SRAD separation system- Premature separation during handling (e.g. under assembly or walking to launch rail) Standing in front or behind of the rocket during the incident will cause bodily harm.	Incorrect handling in addition to premature arming of the energetics after the pressurisation of the system. Or Incorrect assembly	Low; higher due to a self developed subsystem.	Make sure that the arming procedures are followed and proper assembly of the componentes.	Low
	Hawks- Premature separation during handling (e.g. under assembly or walking to launch rail) Standing in front or behind of the rocket during the incident	The arming pin comes loose in addition to premature arming of the flight computer.	Low	Make sure that the arming procedures are followed.	Vert low

	will cause bodily harm.				
Pre-launch	Rocket falls off launch rail and causes injury	Launch rail was not properly assembled or is damaged	Low	Launch rail will be inspected before launch to ensure everything is secured in place and there is no damage done that might cause the rail to let go of the rocket, tilt or fall over.	Very low
		Rocket was not properly secured to launch rail	Low	The rail and rocket will be inspected to ensure that the fasteners are in working order. After fastening the rocket, there will be a last check to ensure the rocket stays in place.	Very low
	Fuel grain ignites after the igniter is installed, causing injury to personnel	Personnel fails to check propellant for cracks and damage	Low: the propellant is very stable and from a well known manufacturer. The probability of accidental ignition is very low	A routine check of the fuel grain will be done before it's inserted in the rocket.	Very low
		The propellant comes in contact with a source of heat or static discharges		All handling of the propellant pre launch will be done according to safety guidelines, manufacturer's instructions for use, and the checklist. It will not be stored with combustibles or close to heat sources that might cause an ignition.	
		Igniter is not installed correctly	Medium; the combination of the igniter and propellant pose a higher risk than the propellant by itself	Correct handling and installation of igniter while following all safety regulations	Low
	Accidental firing of the Hawks during preparations causing injury	Safety pins have not been inserted properly	Low	The Hawks are to be armed at the last moment possible to minimize the risk of it accidentally going off. Double check the safety pin by several people on the team.	Very low
Storage and transportation of	Storage - potential of accidental ignition which can		Low	Storage will be handled by the vendor until the competition, and will be delivered on site.	Very low

propellants	lead to damage on property and/or personnel			It will be stored in its original packaging until assembly.	
	Transportation - potential of accidental ignition which can lead to damage on property and/or personnel		Low	Transportation will be handled by the vendor until the competition, and will be delivered on site.	Very low
Flight	The rocket touches the ground at a higher speed than anticipated, in one or multiple segments, and the debris causes injury to property and/or personnel	Scenarios mentioned below are further discussed in Appendix D Risk assessment. The drogue chute is not deployed	Low	Preflight checklist ensure that: i. Joints are tight before launch. ii. Batteries powering the avionics system are fully charged before launch.	Very low
		The main chute is not deployed	Medium	Preflight checklist ensure that: i. Joints are tight before launch. ii. Batteries powering the avionics system are fully charged before launch.	Low
		Cords and chutes are entangled.	Medium	Wrapping the chords with the "non-tied fishtail braid" is a way to ensure a clean unraveling of the chords and minimize the risk of entanglement. Packing the chutes in a protective deployment bag. Swivel link attached to the chords to rotate alongside the rotation of the rocket.	Low
		The rocket shreds	Medium	The rocket will not be launched if there is a lot of wind. The mechanical structure is dimensioned to withstand forces at max Q and the release forces	Low

				from parachutes.	
Rocket strays from nominal flight path and endangers property and/or personell	Unstable launch rail	Medium	Launch rail and rocket will be inspected before launch to ensure everything is secured in place and there is no damage done that might affect the rocket's trajectory. The rocket will not be launched if there is a lot of wind.	Low	
	Fins separate from rocket or flutters, causing the rocket to be unstable	Medium			
	Damage to the rocket body causing instability in flight	Medium			
The rocket explodes during launch or close to the ground, the debris causing damage to property and/or personnel	Cracks in the propellant	Medium; higher risk due to the potential of serious damage, but the propellant and casing is from a well known manufacturer and the probability of accidental ignition is low	Visual inspection of casing and fuel grain during final assembly to ensure there is no damage. Commercial casing and fuel grain with proven reliability, low probability of wrong installation if instructions are followed	Low	
	Damage to the casing				
	Propellant breaks off in chunks during flight, blocking nuzzle				
	Incorrect installation of casing and/or fuel grain				
	Motor mount failure				
	Overpressurization		Follow the instructions for motor assembly, inspect the motor casing threads for damage or wear, prior to assembly and adhere to the recommended safety distance during launch.		

Introduction

The following sections present the completed set of risks to mission success, as well as the mitigation approaches. Severity, and failure probability after mitigation, are evaluated for every risk on a scale from one to five. Critical rating is the resulting *product* of these two evaluations to a maximum rating of 25. The risks are sorted according to the phases described in Section III, Mission Concept Overview. Risks that are present in multiple phases, are only described in the first phase where it occurs. Several risks are mitigated by pre-launch procedures, which are described in detail in Appendix V.E Assembly, Preflight and Launch Checklists. Risks that are related to health and safety are stated in Appendix V.C Hazard analysis.

Propulse Risk Analysis and Mitigation						
Mission Phase	Failure Mode	Possible Cause	After mitigation		Mitigation approach	Critical rating 1-25
			Mishap Severity 1-5	Failure probability 1-5		
Initial Arming	Premature deployment of recovery systems	Faulty software logic with FSM or restart function, faulty sensor readings, or electrical anomaly in the avionics system.	2	1	FSM software is tested extensively, and should not deploy chutes before launch. Restart mechanism should not enable a jump to the wrong FSM state [Appendix V.B].	2
		Improper assembly and arming		1	Test and analysis of the recovery system. Ensure proper practice in assembly and arming procedures	2
	Failure to arm avionics system	Loss of radio connection or faulty arming in the flight computer.	1	1	Check wiring with voltmeter during assembly and ensure that the flight computer will arm on the arming signal.	1
	Loss of communication to ground station	Signal corruption due to loose/bad wiring.	2	1	Check wiring with voltmeter during assembly.	2
	Battery is low	Discharged battery	3	1	Charge all batteries ahead of launch day. Umbilical power cable at the launch rail.	3

	Components do not fit together	Poor assembly	2	1	Ensure fool-proof assembly checklists, and thorough assembly practice.	2
Final arming	Recovery systems deploy.	Avionics faulty software logic with FSM or restart function, faulty sensor readings, or electrical fault.	2	1	FSM software is tested extensively, and should not deploy chutes before launch [Appendix V.B].	2
		Avionics electrical fault		1	Check wiring during assembly.	2
		Recovery separation system fault or assembly error.		2	Follow the assembly checklists; Validate the separation system.	4
	Loss of communication to ground station	Signal corruption due to loose/bad wiring	3	1	Check wiring with voltmeter during assembly. When armed, the software works without radio connection, allowing the rocket to still perform its main functions.	3
	Loss of communication with COTS GPS	Low battery charge or loose/bad wiring to GPS payloads or tracker.	1	1	Testing systems and wiring beforehand, making sure batteries are charged.	1
	Payload system does not activate	Payload runs out of battery; Not enough batteries, power drain is too high	1; Is not critical to nominal flight	1	We will ensure that the batteries are fully charged, payload will last 24 hours+ at maximum power drain at max capacity.	1
		Payload does not receive or respond to launch signals; Due to bad wiring.	1; Is not critical to nominal flight	1	Testing wiring and the rest of the system beforehand.	1
Lift off	Motor (IAE.M) explodes during launch	Production failure from Cesaroni. Motor overpressurized.	5;	1;	Follow pre-launch procedures and ensure proper storage before use.	5

	Failure to ignite propellant	Production failure from Cesaroni or igniter.	1	1	Follow pre-launch procedures.	1
	Motor goes trough or destroys the rocket	Faulty motor rententon and structure.	5	1	Validating load bearing structures and ensure proper assembly.	
Powered flight	Recovery systems deploy.	Avionics faulty software logic, faulty sensor readings, or electrical fault.	5	1	FSM software is tested extensively [Appendix V.B]. FSM only uses accelerometer before Coasting, no barometer, and the Kalman filter minimizes the effect of faulty sensor data.	5
	Exposed conductive material on wires, PCB, or similar come in contact, possibly shorting or causing other damage to the electronics.	Loose wiring, dangerous exposed material, heavy vibrations further loosening stuff.	3	1	There aren't any loose components when assembly is finished, especially not with exposed material. Make sure all wires and PCBs are well isolated.	3
	Rocket is over-stable; Drastic change of trajectory.	Stability margin is too high at large velocities.	4	2	Make accurate simulations and analysis of center of gravity and center of pressure.	8
	One or more fins are severed.	The fins are not accurately aligned leading to high angle of attack, or are not sufficiently sturdy.	5	2	Assure correct alignment of fins and do thorough testing, flutter and FEM analysis.	10

	Coupler breaks during powered flight	Coupler is too weak and can not withstand loads applied during launch	4	1	Validate that the coupler can handle the operating forces.	4
Coasting	Recovery systems deploy early.	Avionics faulty software logic, faulty sensor readings, or electrical fault.	4	1	FSM software is tested extensively [Appendix V.B]. The Kalman filter minimizes the effect of faulty sensor data.	4
	Coupler does not separate after apogee	Too high friction between parts, or not enough pressure in the chamber.	4	2	Reduce friction between the parts. Check for airtightness.	8
Drogue chute deployment	Drogue chute does not deploy.	Avionics faulty software logic, faulty sensor readings, or electrical fault that causes a software restart.	5	1	FSM software is tested extensively [Appendix V.B]. The Kalman filter minimizes the effect of faulty sensor data. The software should handle a restart [Appendix V.M]	5
	Main chute deploys.	Avionics faulty software logic, faulty sensor readings, or electrical fault.	3	1	FSM software is tested extensively [Appendix V.B]. The Kalman filter minimizes the effect of faulty sensor data.	3
		High air pressure after separations leads to that the chute bag opens and the main chute deploys		3	Test extensively and make sure the drogue and main chute are properly separated.	9
Main Chute Deployment	Failure of airframe due to crack propagation from holes in composite material.	The structure does not	4	1	Ensure	4
	Main chute does not deploy.	Avionics faulty software logic, faulty sensor readings, or electrical fault with the servos or that causes a software	5; Main chute won't release, causing a	2	FSM software is tested extensively [Appendix V.B]. The Kalman filter minimizes the effect	10

		restart.	heavy impact		of faulty sensor data. The software should handle a restart [Appendix V.M]	
		Servo breaks down before execution on the MCRS: Too high voltage sent through the servo causing breakdown		2; We have two servo in case one of them break down	Test the circuit. Order servo from a company in Norway rather than foreign country to get a shorter and more reliable delivery.	10
	Main chute rips the internal components out of the airframe	Too high impact force from main chute deployment on the recovery module and/or bolts.	2	2	Control that the fasteners can handle the loads they are supposed to.	4
	Chute malfunctioning	Tangling of the chute and cords	5; Birkeland fails to land safely	2; This can happen i.e. if we pack the chutes wrong	Wrap the chutes in a certain way that ensures a clean unraveling of the chords and deployment of the chute. Use more swivel links	10
		Chords get torn or the eye bolt unscrews. Zippering		2;	Use a tennis ball or similar on the cord where the cords would get in contact with the coupler. Validate cord connections.	10
Landing	Avionics	Losing connection to the rocket	1	5	Will likely lose contact on landing since the radio is line-of-sight based. We will keep the radio pointed towards the rocket to maintain contact for as long as possible.	5
	Airframe breaks upon landing.	Airframe is not strong enough to withstand impact with the ground.	1	2	Make sure the airframe and fins are produced correctly.	2

	Blackbox breaks upon high impact	Bad design with poor shock absorption.	2	1	Sturdy construction to ensure the blackbox doesn't break even if falling at terminal velocity. All data is also sent simultaneously to the ground station, and should also be stored there. Possibly some backup data on the SD card as well.	2
	Rocket and components destroyed by landing impact.	The rocket exceeds a velocity of 9m/s. Wrong angle of attack for landing. Landing surface can also influence this (sand, rock, grass, concrete, etc.)	2	2	Validate that the components can handle a nominal impact; In addition to validating the parachute deployments and function.	2

Overview of all checklists							
Lvl.1.1 [Small parts: Mechanical]	Lvl.1.2 [Small parts: Avionics]	Lvl.2 [Modules]	Lvl.3 [Inner structure]	Lvl.4 [Final assembly]	Lvl.5 [Launch operations]	Preflight Checklist	Recovery checklist
MCRS Assembly	Avionics mount Assembly	Recovery plate assembly	Inner structure assembly	Hawk loading	Final assembly inspection - Launch site	Preflight Checklist	Recovery operations checklist
PBSS Assembly	Battery pack assembly	Recovery module assembly	Parachute packing	PBSS loading	Launch rail checklist		
Hawk plate Assembly	Payload	Avionics module assembly		Airframe integration	Scrub list		
Parachute preparation	Camera Assembly	Payload module assembly		Motor integration			
Shock chord preparation				Final parachute integration			

Preflight Checklist						
T-	Location	Action	Description	Nominal	If not nominal	Check
		1.1	Check batteries are fully charged		Charge batteries	
		1.2	Operational team	Members are present	Use backup members or scrap	
	Before Launch Site	2.1	Flight Safety reviews	Pass review	Resolve issues from safety personnel	
		2.2	Packing list	List is completed		
		2.3	SD-Cards	Formatted correctly	Format cards correctly	
	Vertical launch area/Launch Site	3.1	Unpack and run safety procedures	Completed and premises secured with proper safety procedures	Begin 3.1 again	
	Rocket assembly area	4.1				
		4.2	Assembly checklist	Completed		
		4.3	Arming pins	Check the pins are in security		
		4.4	Hawk and COPIV	Confirm fully loaded		
		4.5	Launch crew checklist	Action 2.2 completed	Return to lower level lists	
		4.6	Flight card	Acquired	Complete list of new issues	
		4.7	Ground station	Online		
		4.8	Ground station battery	Confirm battery lifespan	Charge ground station	
		4.9	Equipment and Launch crew checklist	Completed	Find components	
	Launch pad	5.1	Launch Area	Green Range status flag	Wait until the red status flag or further information from Range safety officer	
		5.2	Launch crew checklist	Proceed with the rest of the launch crew checklist from action	Redo actions from Launch crew checklist or consider scrub	

MCRS Assembly						
Step	Action	Description	If not nominal	Tool	Fasteners	Check
1	1	Assemble Main chute docking.	Use spare fasteners	Torx or Umbraco Adjustable wrench	2x Steel socket screw 2x 4mm Spacers 2x Socket lock nuts	☐
2	2	Mount the upper release arm to the main docking.	Use spare fasteners		1x Shoulder screw "dumppap" 1x "Dumppap" lock nut	☐
3	3.1	Attach the MRS push-arm and release arm springs.	Use spare fasteners		1x MRS Pom bolt & Lock nut 2x MRS Pom spacers 2x Spring attachments	☐
	3.2	Attach the lower release arm to the main docking.	Use spare fasteners		1x Release arm shoulder bolt (M6) & lock nut 2x Extension spring attachments	☐
4	4	Attach the preassembled* Servo & Camera mounts to the main docking	Use spare fasteners		4x Main mounting screws (M3)*	☐
5	5	Attach the parachute shackle to the main docking.	Use spare fasteners		1x Shackle lock nut 1x Shackle safety pin	☐
6	6	Check whether everything is fastened correctly.	Fasten correctly		All of the above	☐
7	7	Fasten with lock nuts to the recovery plate.			2x M6 lock nuts	☐
Checklist completed:						
Name:						
Timestamp:						

SRAD PBSS assembly						
Step	Action	Description	If not nominal	Tool	Fasteners	Check
1	1.1	Attach three PV brackets to the PV		Torx or Umbraco Adjustable wrench		☐
	1.2	Attach the PV to the four-way adapter			N/A	☐
	1.3	Attach the fill nipple to the four-way adapter				☐
	1.4	Attach the pressure gauge to the four-way adapter				☐
	1.5	Attach the PV adapter to the four-way adapter				☐
	1.6	Attach the PV bracket to the U-tube				☐
	1.7	Attach the U-tube to the PV adapter				☐
	1.8	Attach the big helical gear to the ball valve (make sure the orientation is correct for the safety pin)				☐
	1.9	Attach the small helical gear to the servo motor				☐
	1.1	Attach the servo motor and ball valve to the bracket				☐
	1.11	Attach the safety pin to the big helical gear				☐
	1.12	Attach the Servo bracket to the PV brackets				☐
	1.13	Attach the bent tube to the ball valve				☐
	1.14	Attach the bent tube to the PV brackets				☐
2	2.1	Connect the flexible hose to the pump		Manual air pump *Torx or Umbraco *Adjustable wrench		☐
	2.2	Fill the COPV gradually with pressure				☐
	2.3	Check whether the COPV leaks air	Check the connections Tighten loose connections			☐
Checklist completed:						
Name:						
Timestamp:						

COTS PBSS Assembly						
Step	Action	Description	If not nominal	Tool	Fasteners	Check
1.		Avionics starts setting up electronics for moving servo motors. Main battery, sensorboard (CAN bus and POWER) mainboard, hawks and mcrs needs to be connected. Also COTS battery, Altimax G3, hawks, mcrs.				
	1.1					
	1.2					
	1.3	Fasten hawk elbow-fitting with PTFE tape		Wrench + PTFE tape		
	1.4	Connect the Bent metal pipe to the fitting		Wrench		
	1.5	Connect the HAWK body to the hawk plate	Use spare fasteners	Phillips screwdriver M3 Umbraco	4x Hawk screws	
	1.6	Mount hawk to hawk plate	Screwdriver	Hawk screws x4		
	1.7	Mount servo arm to servo	Screwdriver + loctite			
	1.8	Mount servo to servo mount	Screwdriver	Servo screws x2		
	1.9	Mount servo mount to hawk plate	Screwdriver	Servo mount screws x2		
Checklist completed:						
Name:						
Timestamp:						

Shock chord preparation						
Step	Action	Description	If not nominal	Tool	Fasteners	Check
1	1.1	Install a surface extender on the straight shock cord				
	1.2	Braid the straight shock cord from one end all the way to the other				
	1.3	Close the loop so the shock cord doesn't unbraided itself during the rest of the assembly				
	1.4	Braid the Y-shock cord from one end to the middle				
	1.5	Close the loop so the shock cord doesn't unbraided itself during the rest of the assembly				
	1.6	Continue braiding from the middle to the other end				
	1.7	Close the loop so the shock cord doesn't unbraided itself during the rest of the assembly				
Checklist completed:						
Name:						
Timestamp:						

Parachutes preparation						
Step	Action	Description	If not nominal	Tool	Fasteners	Check
1	1.1	Verify that the main parachute shroud lines aren't entangled				
	1.2	Do a run with the chute and see that it is inflated properly				
	1.3	Place the parachute on a clean surface and stretch out the shroud lines. Make sure that all lines are of the same length.				
	1.4	Use a string to tie a knot where the shroud lines meet the canopy				
	1.5	Organize the canopy with 6 gores on each side. Have one person to hold the shroud lines while organizing the canopy				
	1.6	Straight out all the gores neatly				
	1.7	Pull each side, consisting of 6 neatly straighten gores, over so all gores are over one another and form a rectangle				
	1.8	Stuff the parachute in the deployment bag				
	1.9	Fold the shroud lines in 6 Z-folds: three within each column of rubber bands. Use only the upper two rows of rubber bands				
	1.10	Make sure that there is nothing on the shock cord that can catch the rubber bands				
	1.11	Untie the knot in step 1.4				
	1.12	Pull the cover from the recovery bag over the shroud lines				
	1.13					
	1.14					
Checklist completed						
Name:						
Timestamp:						

Avionics mount assembly						
Step	Action	Description	If not nominal	Tool	Fasteners	Check
1	1.1	Make sure avionics mounting plates are fastened sturdy.	Notify inner structure and/or tighten the plates.			☐
2	2.1	Assemble black-box by placing flash breakoutboard between the black-box upper and lower plates.				☐
	2.2	Mount the black box between KB3 and PDB. Use 12mm M3 spacers between PDB and KB3.		Tors	5x 25mm M3 flathead	☐
	2.3	Mount the PCB stack onto the avo. mounting plate.				☐
3	3.1	Fasten GNSS antenna to avo. mounting plate.			2x 15mm M3 flathead	☐
	3.2	Connect GNSS antenna cable to PDB.		8mm wrench		☐
4	4.1	Mount ethernet switch onto avo. mounting plate.				☐
	4.2	Attach red-black and green-black cables to switch.		Tors	2x M2 8mm flathead.	☐
	4.3	Connect green-black wire to KB3.				☐
	4.4	Place video encoder into encoder casing and connect red-black ethernet wire.				☐
	4.5	Mount encoder casing to avo. mounting plate.			2x 25mm M3 flathead	☐
5	5.1	Mount assembled battery pack to avo. mounting plate.			4x 35mm M3 flathead	☐
	5.2	Mount battery pack power cable to PDB.				☐
	5.3	Zip tie avo. bay cable snake to avo. mounting plate.				☐
	5.4	Attach all cable snake connectors to corresponding PCB connections.				☐
	5.5	Buddy-check ALL snake-PCB connections.	Connect correctly.			☐
6	6.1	Connect snake-connector to Altimax and attach Altimax to avo. mounting plate.			2x 25mm M3 flathead	☐
	6.2	Connect snake-connector to Featherweight and attach Featherweight to avo. mounting plate.				☐
	6.3	Mount Radiorc radio and attach ethernet to switch and power to PDB.				☐
7	7.1	Zip-tie all loose cabling.				☐
	7.2	Check all connectors are tight and all components and no components are loose.				☐
Checklist completed:						
Name:						
Timestamp:						

Recovery plate assembly						
Step	Action	Description	If not nominal	Tool	Fasteners	Check
2	2.1	Attach the MCRS to the recovery plate		Wrench for M8 screw and nut	2x M8 Screws and 2x M8 lock Nuts	
	2.2	Attach the 3d prints/brackets + attach the servos and the camera mount and camera to it.			M3 socket head screws. Dont need nuts because of threads	
	2.3	put the cables through the cable gland				
Recovery Module						
Step	Action	Description	If not nominal	Tool	Fasteners	Check
1	1.1	Fasten the rails to the recovery plate (make sure the location of each rail is correct)		screwdriver	3x M4 countersunk screws	
	1.2	Assemble the upper bulkhead to the rails		screwdriver	3x M4 countersunk screws	
2	2.1	Attach the lower bulkhead to the rails (check that the rail orientation is correct)		Wrench for M8 screw and nut	2x M8 Screws and 2x M8 lock Nuts	
	2.3	Attach the upper bulkhead to the rails		Wrench for M8 screw and nut	2x M8 Screws and 2x M8 lock Nuts	

Payload module assembly						
Step	Action	Description	If not nominal	Tool	Fasteners	Check
2	2.1	Attach the Payload Disk to the Payload Mounting plate		Wrench for M4 screw	2x Countersunk M4 Screws	
	2.3	Attach the Upper Cap to the Payload Tube		Wrench for M4 screw and nuts	4x Countersunk M4 Screws and 4x M4 lock Nuts	
	2.3	Place the Payload Mounting Plate on the Lower Cap				
	2.3	Slide the Payload tube over the mounting plate and disk				
	2.3	Attach the Payload Tube to the Payload Mounting Plate through holes in the Lower Cap		Wrench for M4 screw	4x M4 Screws	
	2.3	Attach the Threaded rod to the Upper Cap		Wrench for M8 nut	2x M8 Nuts	

Inner assembly						
Step	Action	Description	If not nominal	Tool	Fasteners	Check
1	1.1	Attach the recovery module to the Avionics module		Screwdriver	M4 Countersunk screws and nuts	
	1.2	Attach the Payload and threaded rods to the avionics module			2xM4 socket head screws, for the threaded rods 1xM6 lock nut and 2xM6 nuts	
	1.3					
2	2.1	Connect the Servos in the MCRS to the Avionics				
	2.2	Connect the Hawk servo to the avionics				
	2.3	Connect the Gear activated valve (SRAD PBSS) to the avionics				
	2.4	[connect the chute system-> quick link with cords and chute]				

Hawk loading

Hawk arming is to be done twice.

Hawk safety instructions. If there is time, read aloud to participating members.

NEVER put any part of your body over the parachute canister cap while there is a CO2 cartridge installed in the system.
NEVER put any part of your body in line with the open end of the Valve Body when the piston is in the armed position without a Cartridge Adapter threaded fully into place.

NEVER test any part of the system unless it is bolted firmly to an immovable object.

ALWAYS ensure that no part of anyone's body is in line with the pressure outlet on the Valve Body when testing the system without a parachute canister attached.

ALWAYS keep the safety pin in place until you are ready to fly your aircraft. Replace the safety pin as soon as you land.

NEVER fire the valve without a CO2 cartridge in place. Doing so can damage the Cartridge Adapter.

Step	Action	Description	If not nominal	Tool	Fasteners	Check
1	1.1	Make sure the servo arm is in the right position				
	1.2	Remove the arming pin				
	1.3	Thread arming bolt into cartridge adapter.	Arming bolt should fit 1/2" cartridge adapter.			
	1.4	Screw bolt as far as you can by hand. Use allen wrench to screw in bolt until you hear a click from release arm settling in place.				
	1.5	Unscrew a couple turns until you feel no resistance.				
	1.6	Visually verify that the release arm is armed properly. You should see the piston through the sight hole.				
	1.7	Re-install the arming pin into the arming hole. The arming pin should have a long string attached to it.				
	1.8	Completely remove the arming bolt.				
	1.9	Install o-ring into cartridge adapter.				
	1.10	Verify that the CO2 cartridge is an unused cartridge. Preferably have it weighed against a used cartridge.				
	1.11	Thread the CO2 cartridge into the cartridge adapter. Make sure it is firmly in place.	The 33g cartridge should fit the 1/2" cartridge adapter, which is the same as is used for arming bolt. If different cartridge is used, you may have to switch to the 3/8" cartridge adapter.			
	1.12	Attach the temperature sensors on the CO2 cartridge				

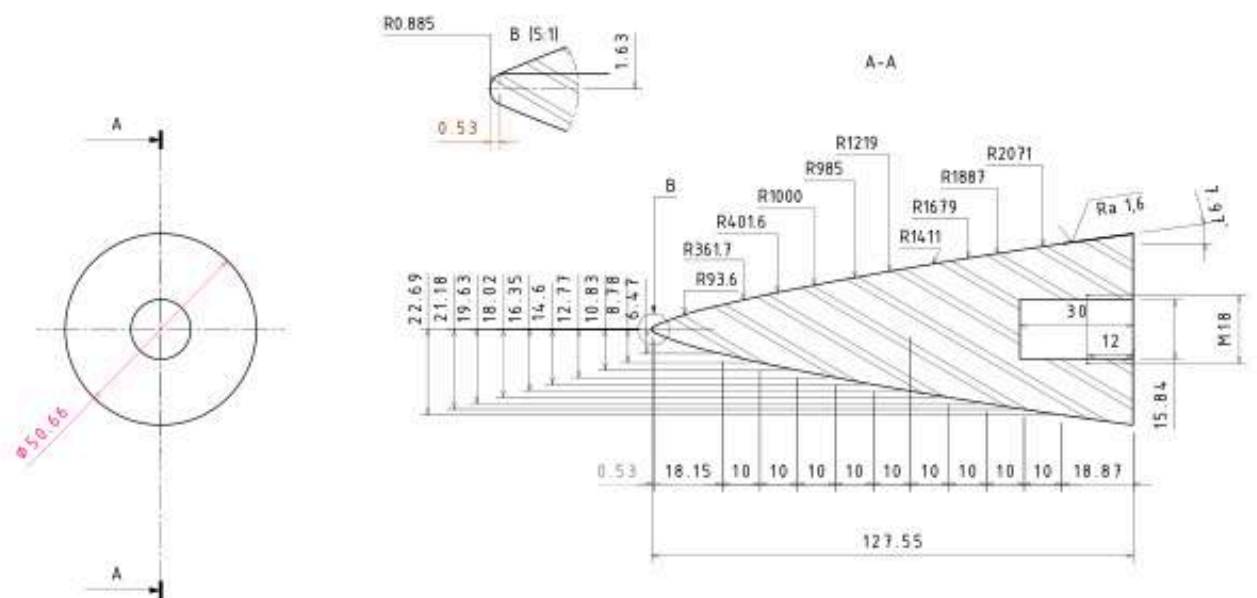
				Inspector:		
				Reader:		
Final assembly inspection - Launchsite						
Location	Action	Description	Method	Responsible	Observer	Check
Launchsite	2.1	Confirm Assembly checklist is complete	Visual inspection of signed and completed master assembly checklist			
	2.2	Clear the 2 exterior camera lenses with cloth	Visual inspection on the 2 cameras			
	2.3	Turn on Eggtimer with magnetic switch	Listen for beep from buzzer on Eggtimer			
	2.4	Turn on Altimax with magnetic switch	Listen for beep from buzzer on Altimax			
	2.5	Turn on SRAD Avionics system with magnetic switch	Check for connection on groundstation			
	2.6	Verify nominal accelerometer and barometer data	Verify that IMU (1,2 and 3) y axis' data are in the range [9.5 - 10.1], x and z axis should be in the interval [-0.5, 0.5] when oriented in upright position. Barometer (1,2 and 3) altitude should be in [-5, 5]			
	2.7	GPS fix for Sensorboard	Check status ground station			
	2.8	GPS fix for Eggtimer	Confirmation on Eggfinder LCD screen			
	2.9	Verify payload online	Verify payload status on groundstation			
	2.10	Verify livestream from cameras	Check stream on ground station			
	2.11	Disarm Payload	Check on ground station that payload is offline and rocket is in idle			
	2.12	Turn off Avionics with magnetic switch	Auditory check (no beeping) and ground station confirmation			
X						
Assembly and Avionics Inspection - Complete						
Signature:						
Date Timestamp:						

						Inspector:		
						Reader:		
Launch rail								
T-[hh:mm:ss]	Location	Action	Description	Verification method	Responsible	Observer	Critical?	Check
		4.01	Mount bolt to launch rail	Ree launch rail to 20 deg. Slide bolt on launch rail				
T-00:25:00		4.02	Mount rocket on launch rail	Slide launch lugs on launch rail			Yes	
		4.03	Verify rocket is tightened					
		4.04	Set launch rail to vertical position	Remove bolt from launch rail base. Verify forward cables are attached. Lift launch rail to +60 deg. Reinsert bolt. Lift launch rail to 84+1 deg. Tighten bolt. Attach rear cable. Tighten until taught, no more.			Yes	
		4.05	Mechanical verification:	Physical checkup and visual examination of: boat tail, motor mount, hawk arming pins, screws, launch lugs, shear pins, fin and fin brackets.			Yes	
		4.06	(optional) Wrap rocket in foil.				No	
		4.07	Turn on Altibase with magnetic switch. Verify on from sound.	Listen for beep from buzzer on Altibase.			Yes	
		4.08	Turn on SRAD Avionics system with magnetic switch. Verify on from Ground station.	Check for connection on groundstation.			Yes	
		4.09	Turn on Eggfinder with magnetic switch. Verify on from Ground station.	Listen for beep from buzzer on Eggfinder.			Yes	
		4.10	Verify SD card mounted (software)	Confirmation from ground station.			Yes	
		4.11	Verify nominal accelerometer and barometer data.	Verify on groundstation that IMU (1,2 and 3) y axis' data are in the range [9.5, 10.5], x and z axis should be in the interval [-0.5, 0.5]. Barometer (1,2 and 3) altitude should be in [-5, 5].			Yes	
		4.12	GPS fix for Eggfinder	Confirmation on Eggfinder LCD screen.			Yes	
		4.13	GPS fix for Sensorboard GPS	Confirmation from ground station.			No	
		4.14	Verify Payload online	Verify payload status on groundstation.			No	
		4.15	Verify connection to encoder	Check on groundstation.			No	
		4.16	Ground station confirms rocket is in idle state.	Check on groundstation.			Yes	
		4.17	Take of hot				Yes	
		4.18	Spray rocket with water.	optional			No	
		4.19	Remove nozzle cap with screwdriver				Yes	
		4.20	All brought equipment packed ready to leave	All brought equipment should be packed and ready to leave the launch pad.			Yes	
		4.21	Ensure all non-essential personnel have evacuated the launch pad	Visual checkup and headcounting.			Yes	
		4.22	Install motor igniters				Yes	
		4.23	Replace nozzle cap				Yes	
		4.24	Verify firing line is not "hot" before connecting to igniters, by measuring the voltage across the wires	Use a multimeter to check if there is a current.			Yes	
		4.25	Arm hawks	Verify safety pins removed. Insert warning rod on string.			Yes	
		4.26	Arm SRAD PBSS	Verify system armed.				
		4.26	Firing line connected with supervision from Range Manager.				Yes	
	Launch rail	4.28	All personnel leave launch pad	Confirm visually and auditory.			Yes	
		4.29	Arm avionics from ground station	Arm rocket from ground station.			Yes	
		4.30	"Go or no go"-confirmation from Range Manager	Check in with euroc pad all is nominal.			Yes	
T-00:00:10		4.31	Countdown initiated				Yes	
T-00:00:00	Launch Command	4.32	Ignite motor				Yes	
		X						

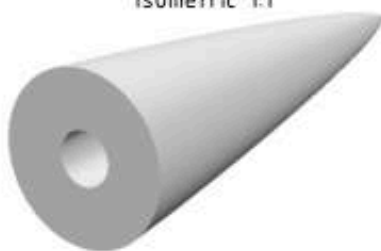
Signature: _____
Date | Timestamp: _____

						Inspector:
						Reader:
Scrub						
Location	Action	Description	Verification method	Responsible	Observer	Check
Ground Station	5.01	Switch from armed to idle state with ground station	State display on ground station	Ola	Steven	FALSE
	5.02	Ask Range Manager for permission to return to launch pad	Auditory verification between launch crew and range manager	Ask	Steven	FALSE
	5.03	Disconnect firing line from igniters		Ask	Steven	FALSE
	5.04	Safety pins inserted back in to the Hawks	Putting safety pin into the corresponding hole for the safety pin on the FWD airframe	Ask	Steven	FALSE
	5.05	Igniters removed		Ask	Steven	FALSE
	5.06	Carefully lower launch rail		Ask	Steven	FALSE
	5.07	Disarm avionics system with magnetic switch	Auditory check (no beeping) and ground station confirmation	Sven	Steven	FALSE
	Launch rail	5.08	Remove rocket from rail	Check that the rocket is off the rail	Sven	Steven
	5.09	Disassemble the rocket and remove the FWD airframe	Scow off the countersunk screws at the FWD airframe	Ask	Steven	FALSE
	5.10	Unload hawks	Unscrew and remove the CO2 canisters from the hawk subsystem	Ask	Steven	FALSE
Assembly Area						
X						
Signature:						
Date Timestamp:						

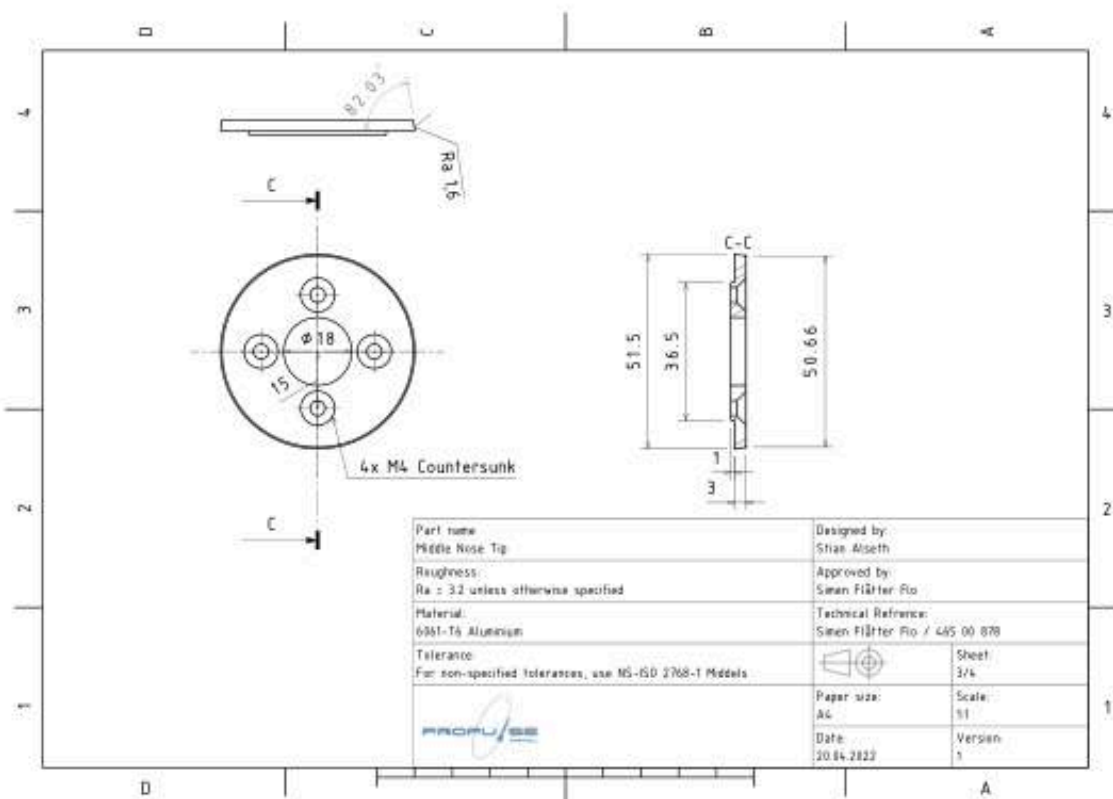
					Inspector:
					Reader:
Post flight Debrief					
Step	Action	Description	Responsible	Check	
	1.1	Fill out flight card	Hannah	FALSE	
	1.2	Take pictures of the rocket	Hannah	FALSE	
	1.3	Upload pictures to teams area	Hannah	FALSE	
	1.4	Gather telemetry and apogee information in a presentable way	Anders	FALSE	
	1.5	Bring rocket to launch range officials	Hegi, Steven, Anders	FALSE	
X					
Signature:					
Date Timestamp:					

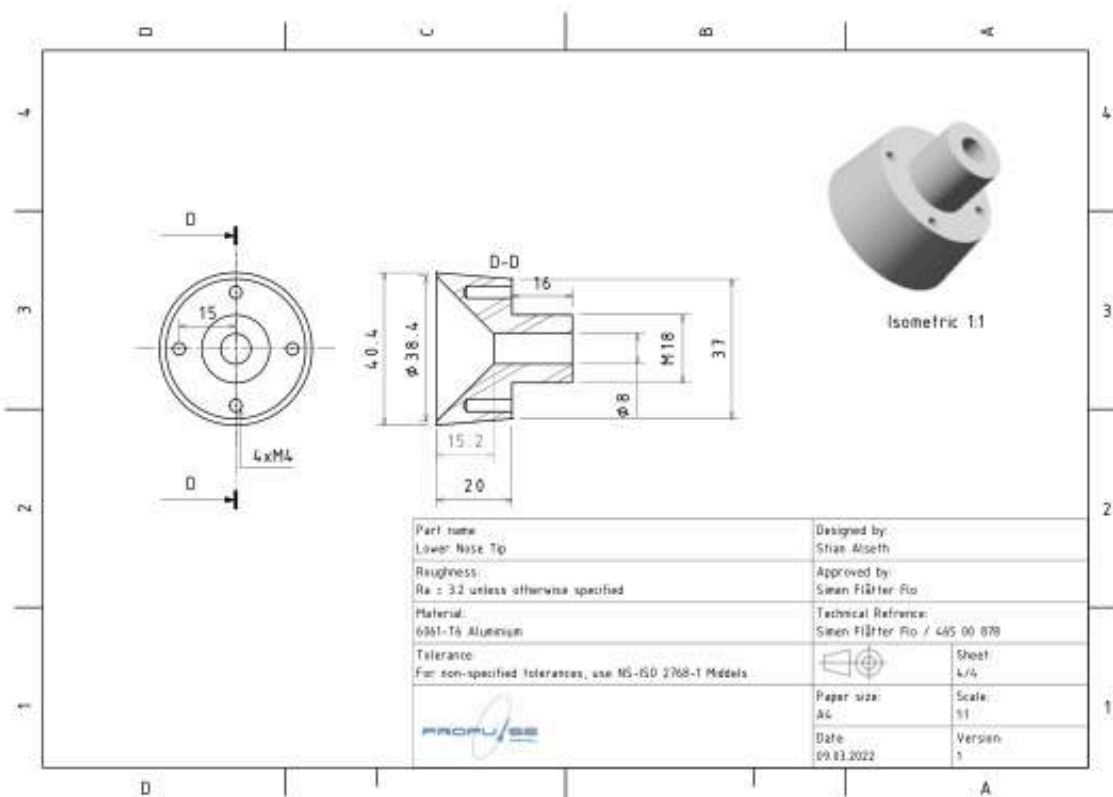


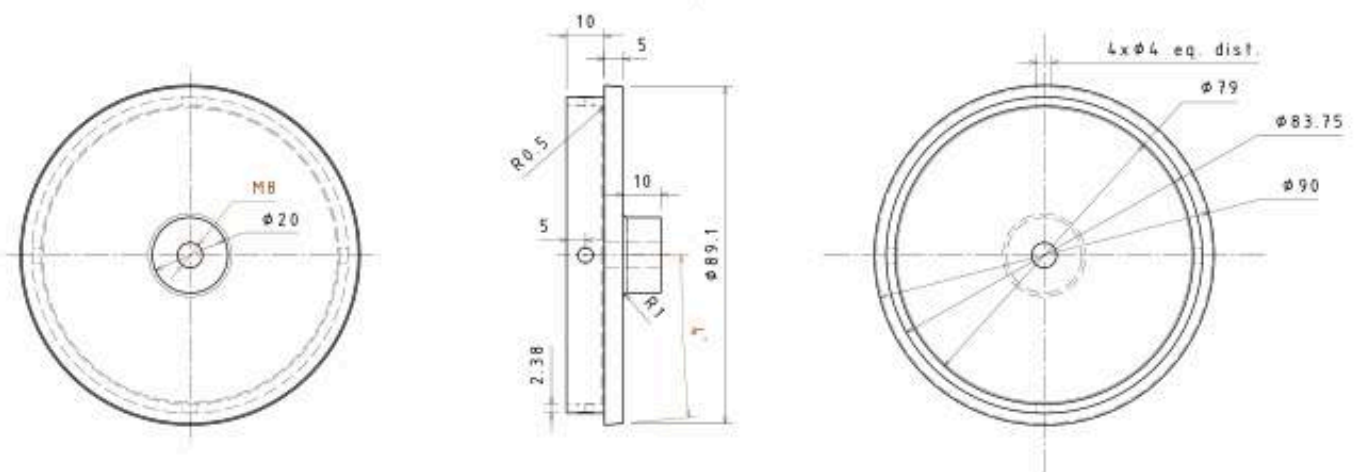
Isometric 1:1



Part name Upper Nose Tip	Designed by Stian Alseth	
Roughness Ra = 3.2 unless otherwise specified	Approved by Simen Flåtter Flo	
Material 6061-T6 Aluminium	Technical Reference: Simen Flåtter Flo / 485 00 878	
Tolerance: For non-specified tolerances, use NS-ISO 2768-1 Mittels		Sheet 2/4
	Paper size: A3	Scale: 1:1
	Date: 09.03.2022	Version: 1



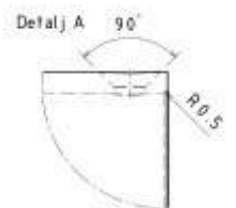
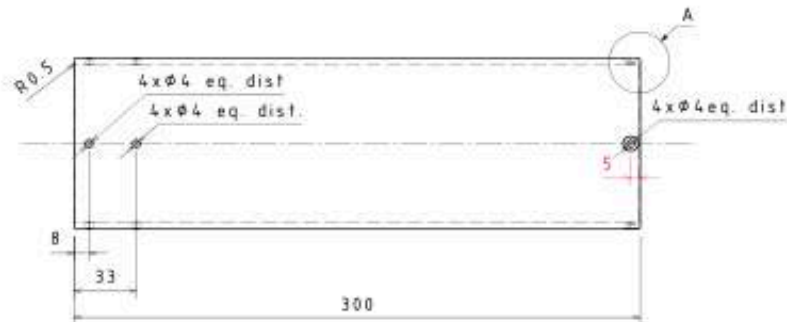
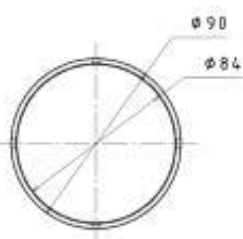




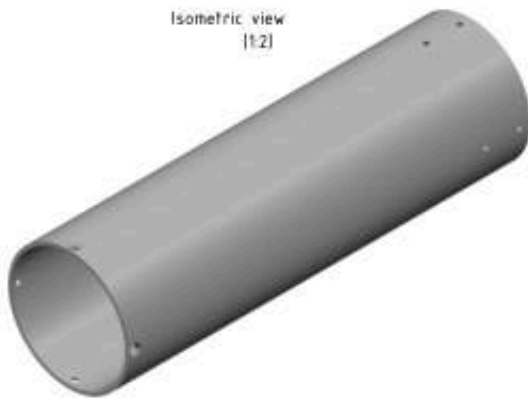
Isometric view



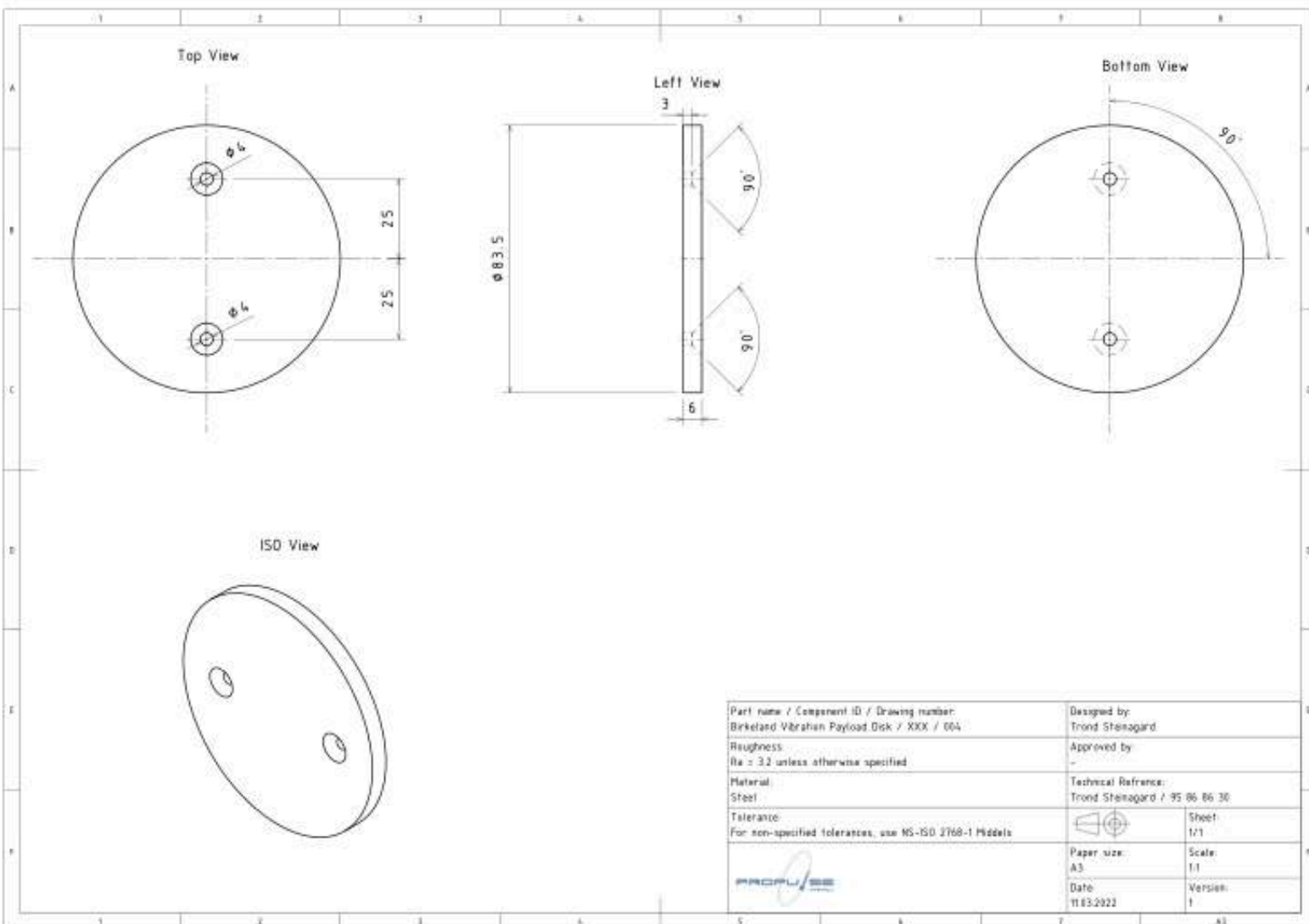
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Roughness: Ra = 3.2 unless otherwise specified	Approved by: Søren Flåtter Flo / 07.04.2022
Material: 6082-T6 Aluminium	Technical Reference: Trond Steinagard / 95 86 86 30
Tolerance: For non-specified tolerances, use NS-ISO 2768-1 Mittels	 Sheet: 2/4
	Paper size: A3
	Date: 11.03.2022
	Scale: 1:1
	Version: 1

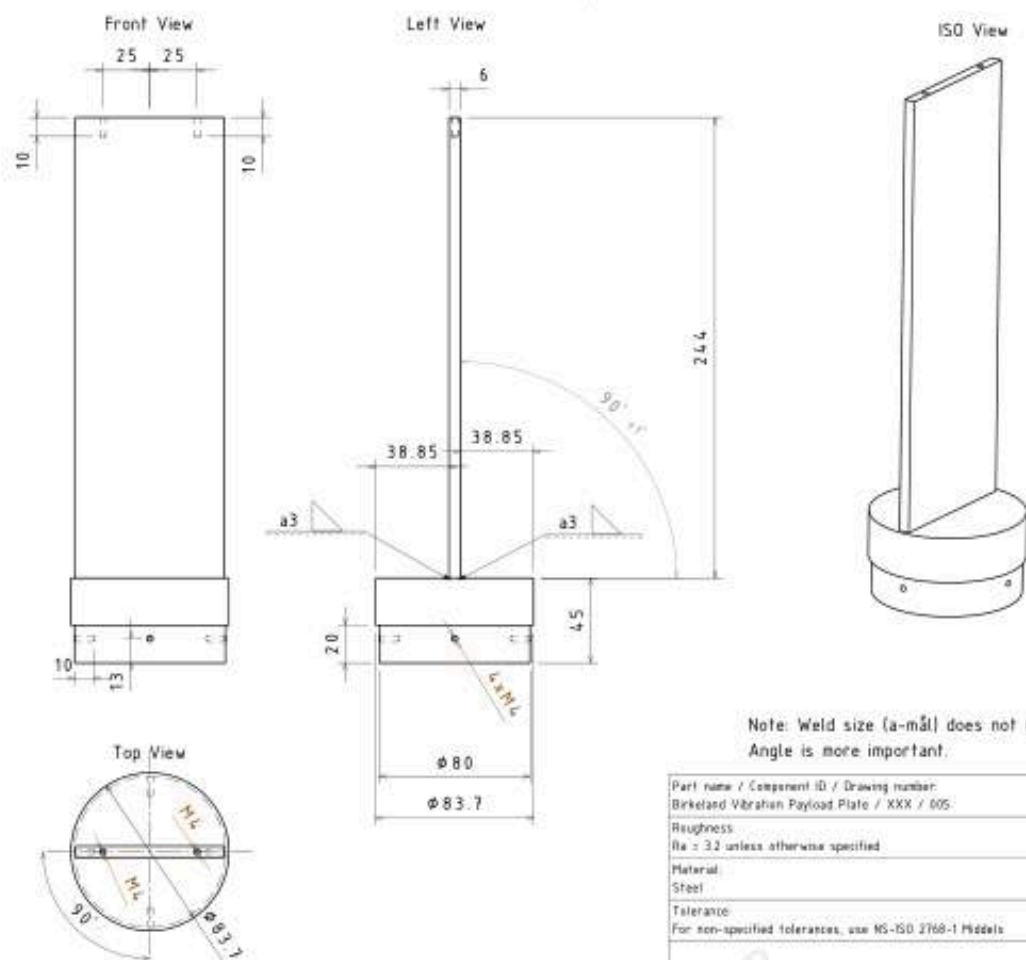


Isometric view
[1:2]



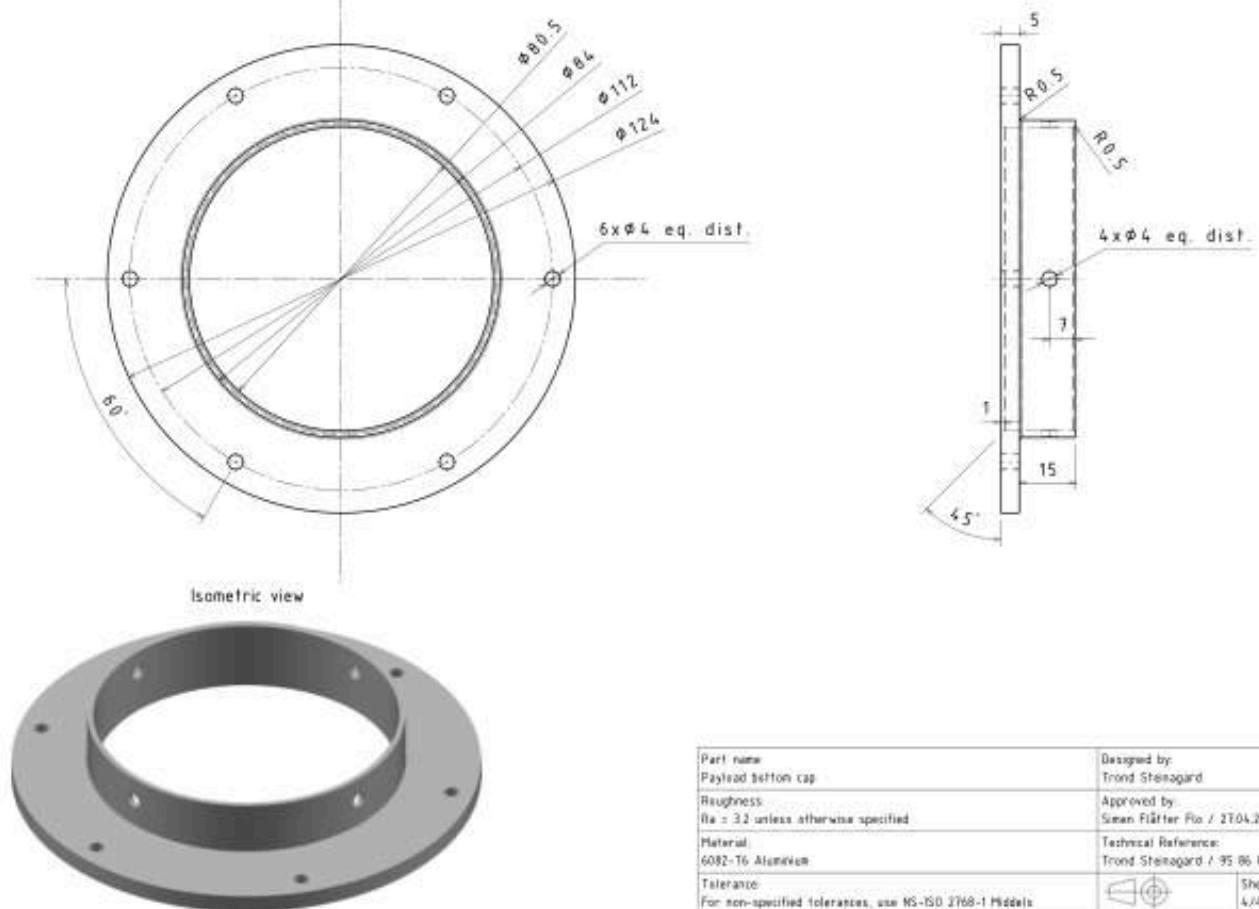
Part name: Payload hub	Designed by: Trond Steinagard	
Roughness: $Ra \leq 3.2$ unless otherwise specified	Approved by: Simon Flåtter Flo / 27.04.2022	
Material: 6082-T6 Aluminium	Technical Reference: Trond Steinagard / 95 86 86 30	
Tolerance: For non-specified tolerances, use NS-ISO 2768-1 Moulds		Sheet: 3/4
	Paper size: A3	Scale: 1:2
	Date: 11.03.2022	Version: 1



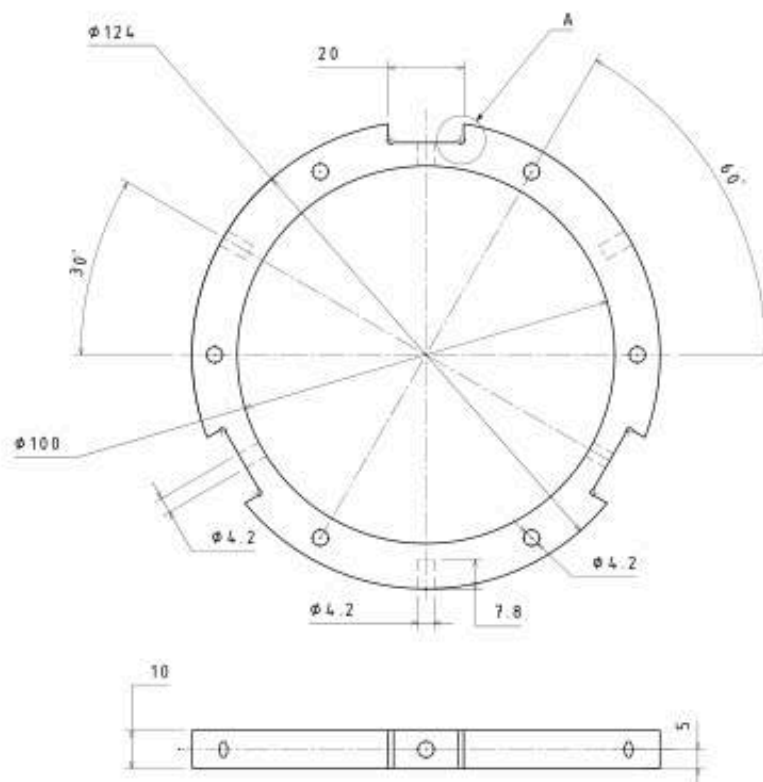


Note: Weld size (a-mil) does not need to be accurate.
Angle is more important.

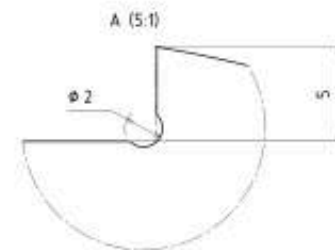
Part name / Component ID / Drawing number: Birkeland Vibration Payload Plate / XXX / 005		Designed by: Trond Steinagard	
Roughness: Ra = 3.2 unless otherwise specified		Approved by: -	
Material: Steel		Technical Reference: Trond Steinagard / 95 86 86 30	
Tolerance: For non-specified tolerances, use NS-ISO 2768-1 Mittels			Sheet: 1/1
		Paper size: A3	Scale: 1:2
		Date: 11.03.2022	Version: 1



Part name: Payload bellon cap	Designed by: Trond Steinagard
Roughness: Ra = 3.2 unless otherwise specified	Approved by: Simon Flåtter Flo / 27.04.2022
Material: 6082-T6 Aluminium	Technical Reference: Trond Steinagard / 95 86 86 30
Tolerance: For non-specified tolerances, use NS-ISO 2768-1 Moulds	Sheet: 4/4 Scale: 1:1
	Paper size: A3 Date: 10.03.2022 Version: 1



Isometric View (1:2)



Part name / Component ID / Drawing number:
Avionics Bulkhead / 1 / 31.

Roughness
Ra = 3.2

Material:
Aluminium 6082-T6

Tolerance:
For non-specified tolerances, use ISO-ISO 2768-1 Mittels



Designed by:
Einar Bergslid

Approved by:
xxx

Technical Reference:
Einar Bergslid, 4766552

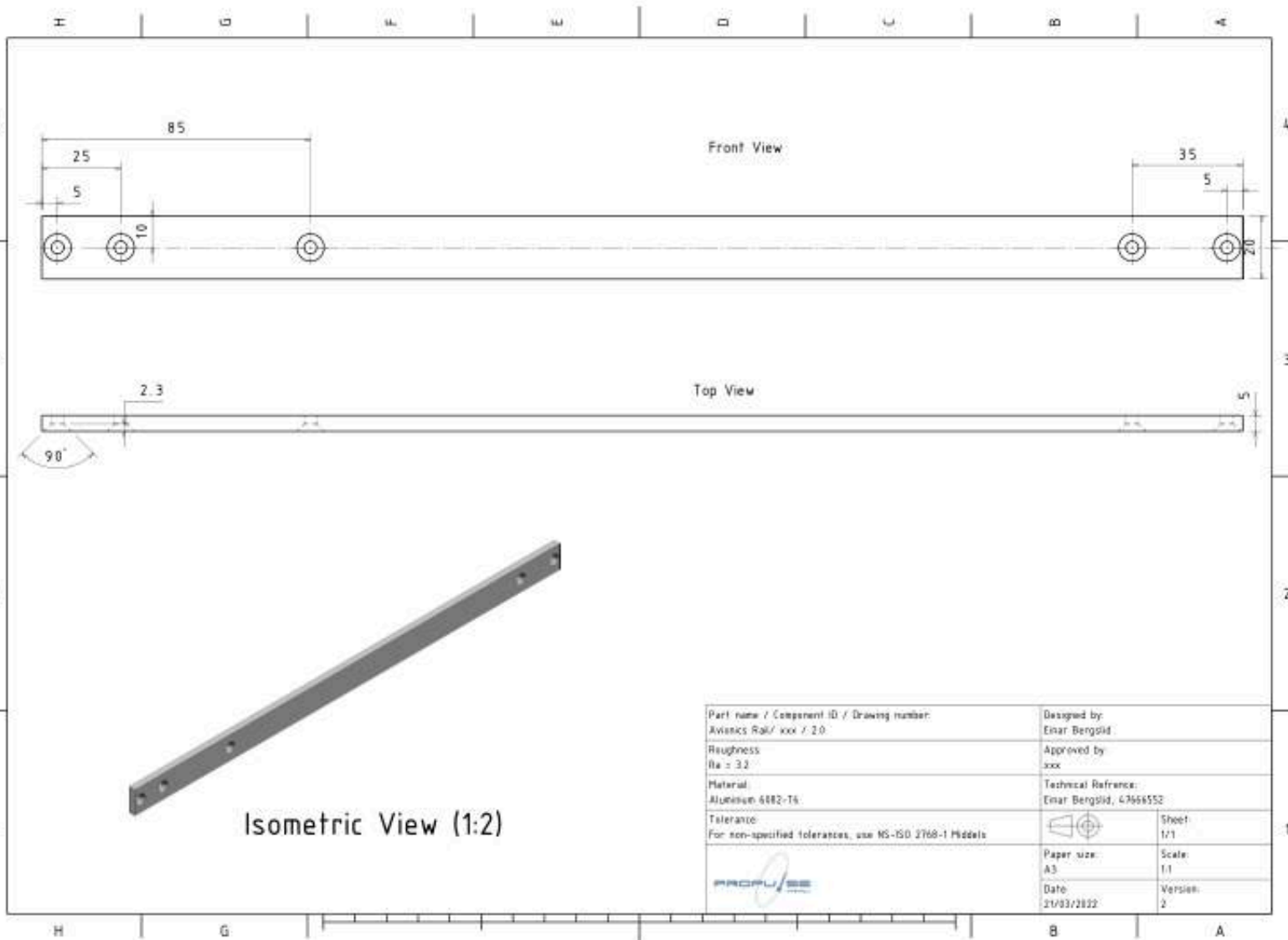
Sheet:
1/1

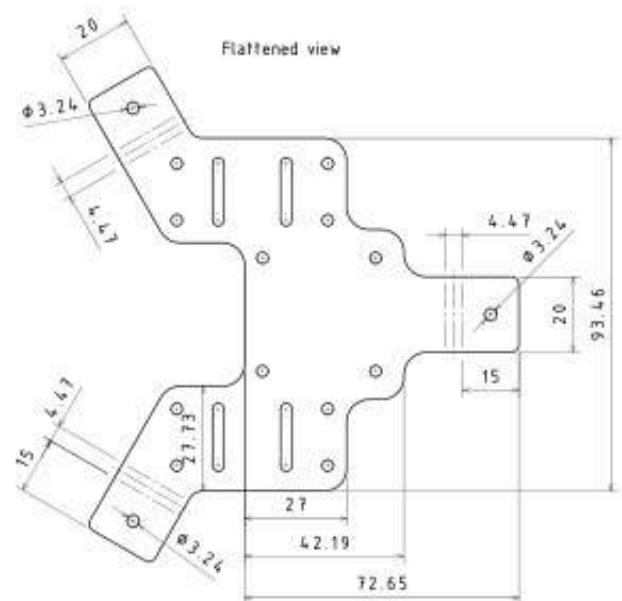
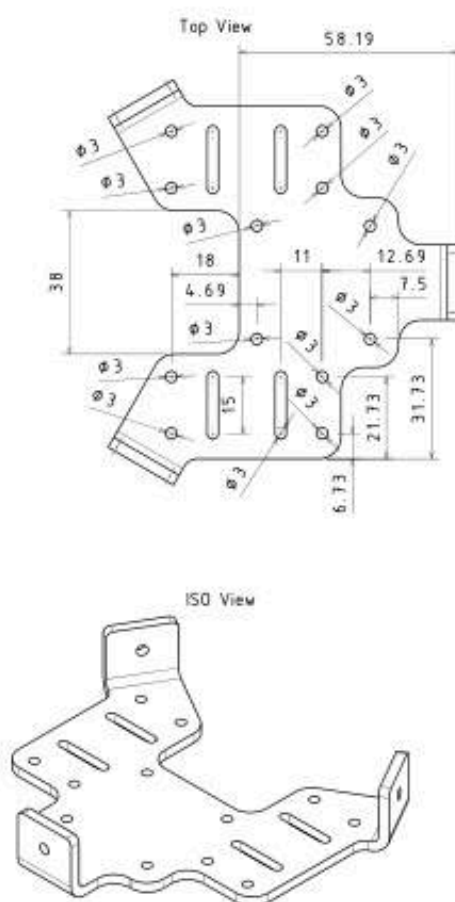
Paper size:
A3

Date:
21/03/2022

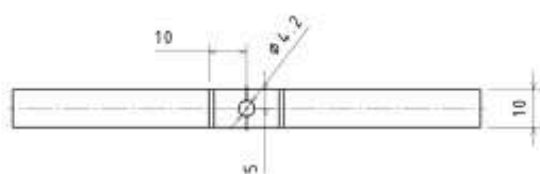
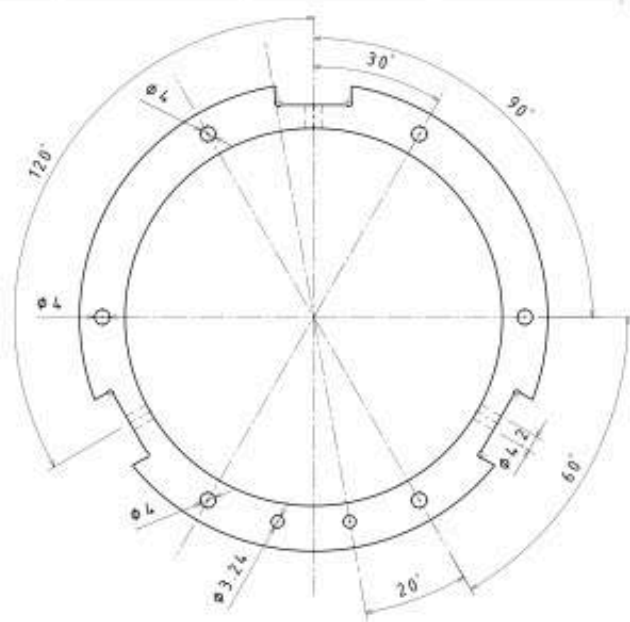
Scale:
1:1

Version:
3

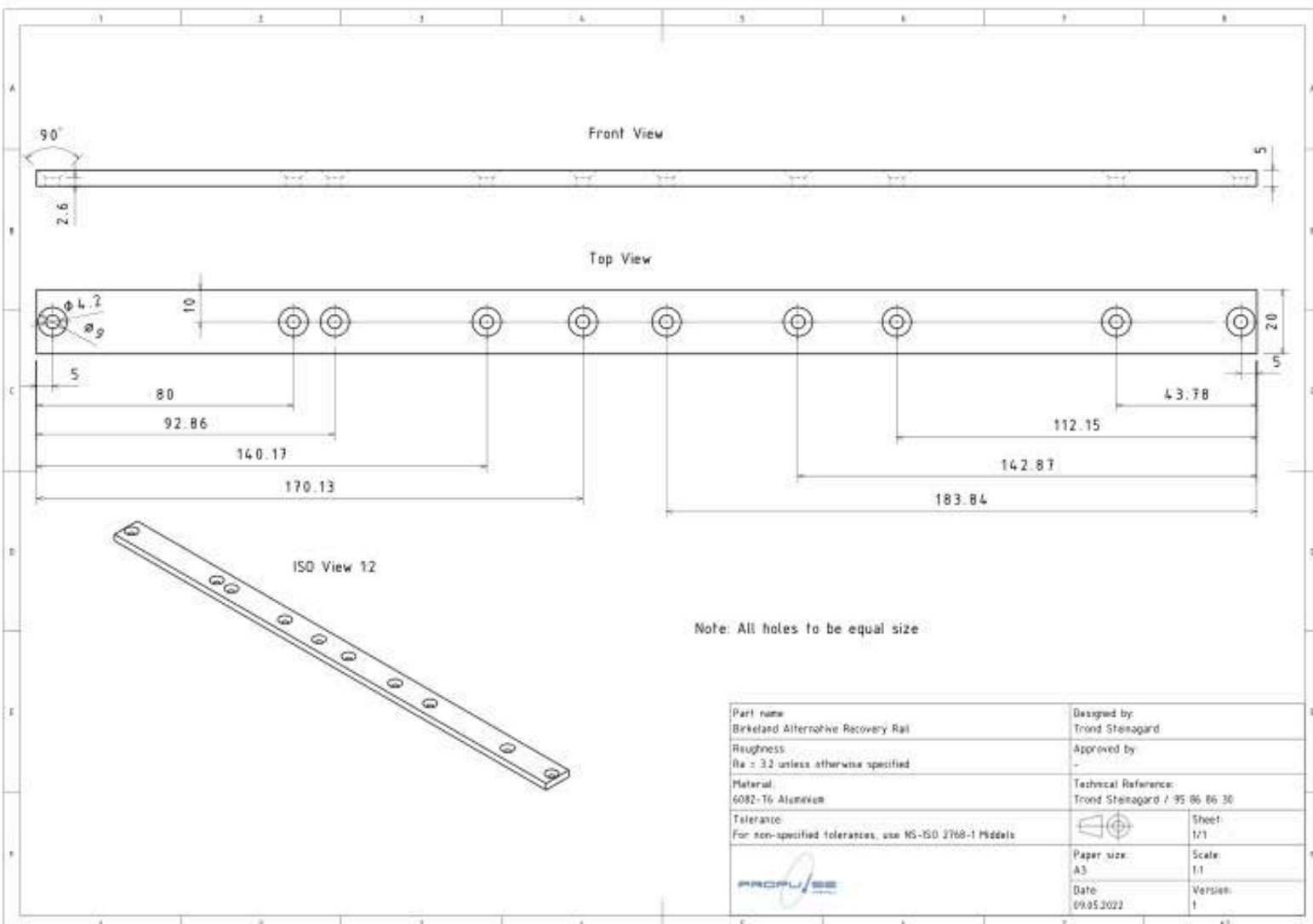




Part name / Component ID / Drawing number: Birkeland Avionics Camera Plate		Designed by: Trond Steinagard	
Roughness: Ra = 3.2 unless otherwise specified		Approved by: -	
Material: Aluminium 6082-T6		Technical Reference: Trond Steinagard 95 96 99 30	
Tolerance: For non-specified tolerances, use NS-ISO 2768-1 Modells			Sheet: 1/1
		Paper size: A3	Scale: 1:1
		Date: 25.03.2022	Version: 1

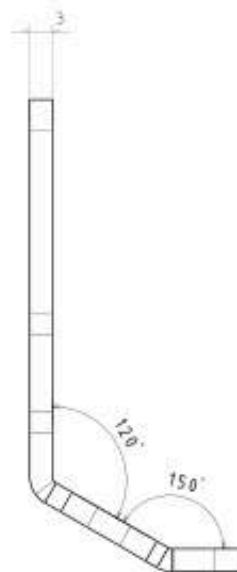
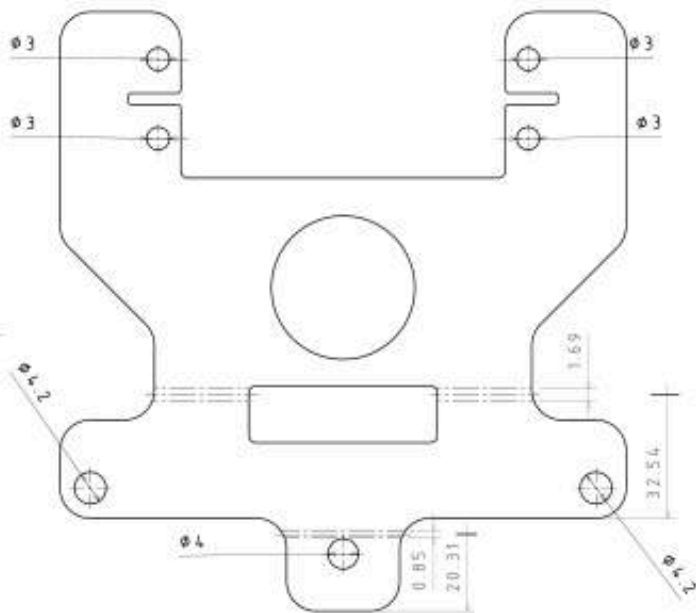


Part name: Module ring	Designed by: Magnus Røssfald
Roughness: Ra = 3.2	Approved by: Trond Steinagard
Material: Aluminium 6082 T6	Technical Reference: Magnus 90233939
Tolerance: NS-ISO 2768-1 middels	 Sheet: 1/1
	Paper size: A3
	Date: 13.05.2022
	Scale: 1:1
	Version: 1

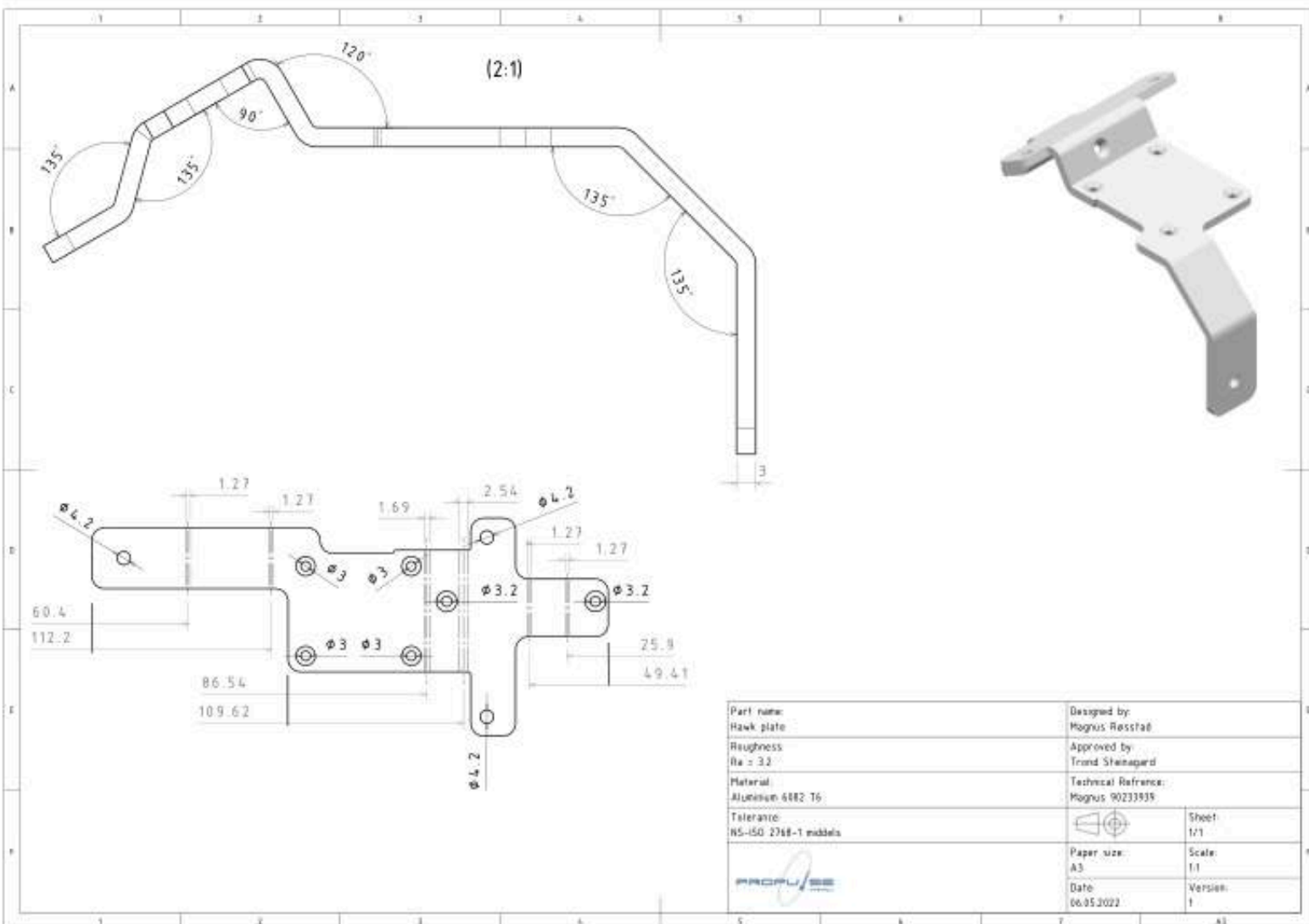


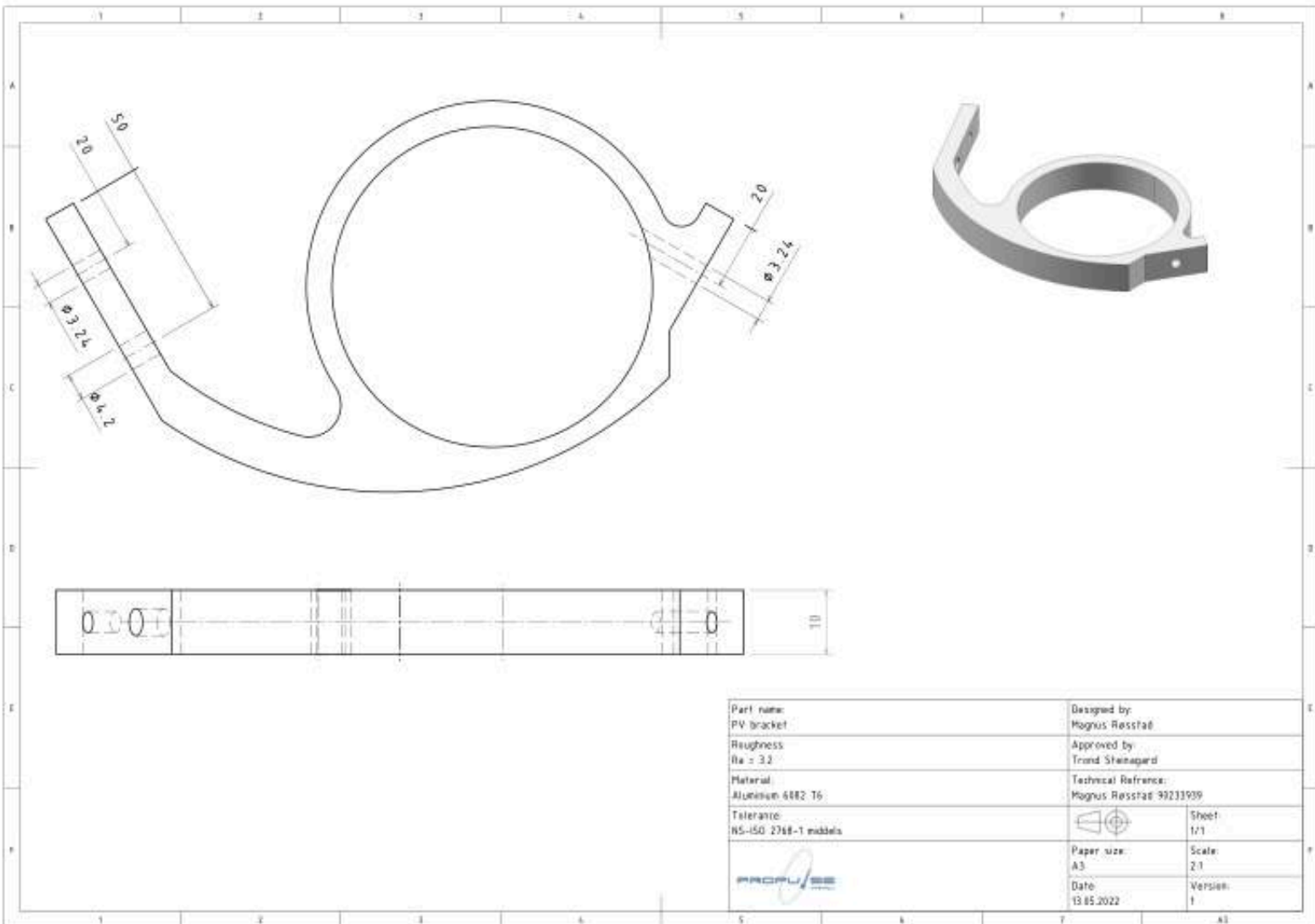


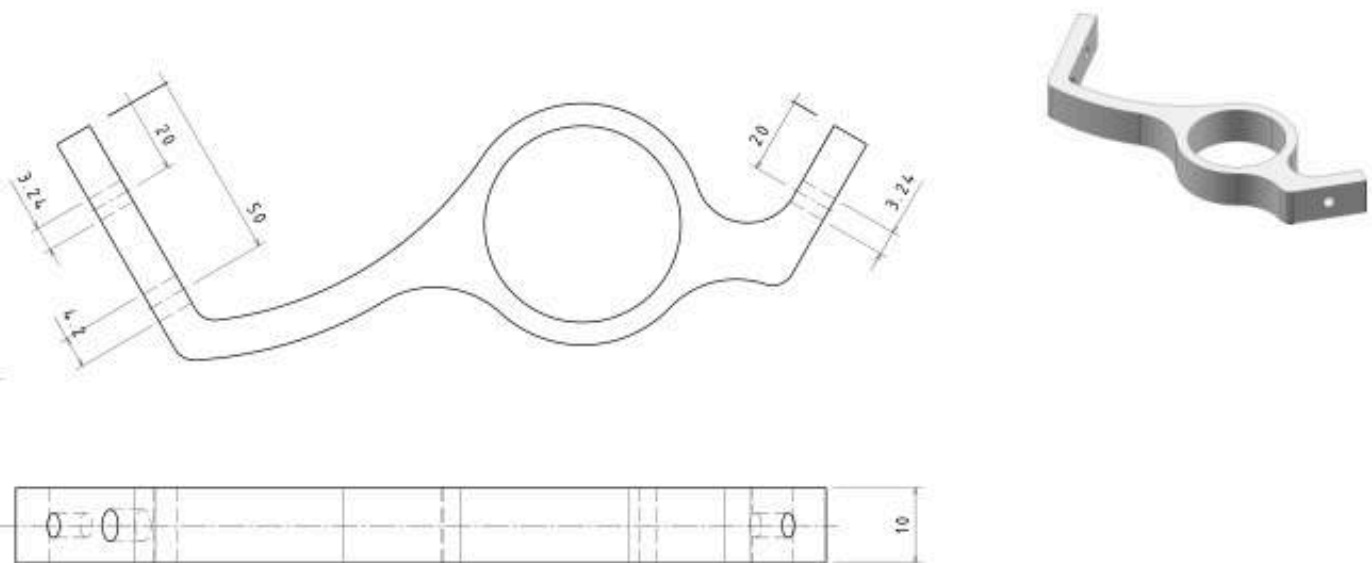
Part name: IS-pin D-sub bracket	Designed by: Magnus Røssfald
Roughness: $Ra = 3.2$	Approved by: Trond Steinagard
Material: Aluminium 6082 T6	Technical Reference: Magnus 90233939
Tolerance: NS-ISO 2768-1 middels	 Sheet: 1/1
	Paper size: A3
	Date: 13.05.2022
	Scale: 3:1
	Version: 1



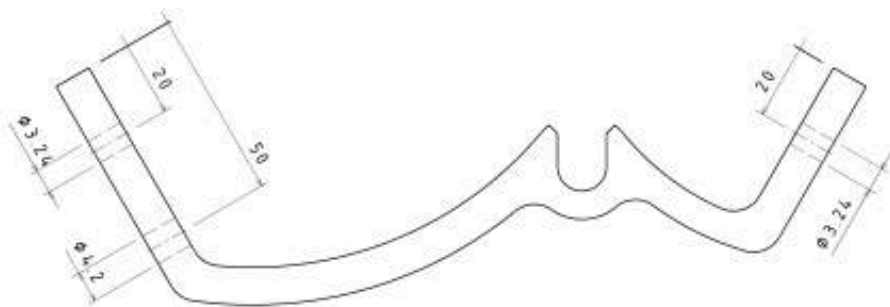
Part name: Servo bracket	Designed by: Magnus Resstadi	
Roughness: Ra = 3.2	Approved by: Trond Steinagard	
Material: Aluminium 6082 T6	Technical Reference: Magnus Resstadi 90233939	
Tolerance: NS-ISO 2768-1 middels		Sheet: 1
	Paper size: A3	Scale: 2:1
	Date: 13.05.2022	Version: 1





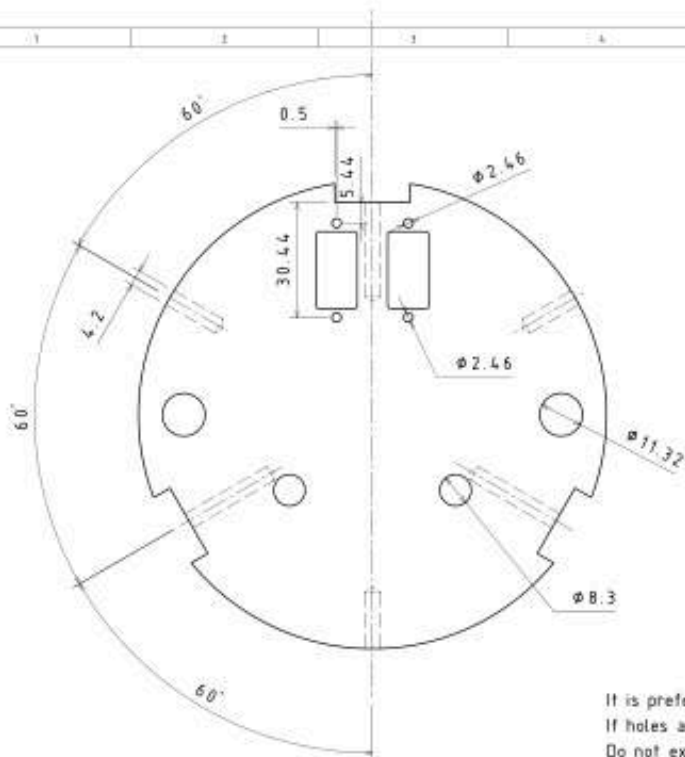


Part name: PV neck bracket	Designed by: Magnus Røssfald
Roughness: $Ra = 3.2$	Approved by: Trond Steinagard
Material: Aluminium 6082 T6	Technical Reference: Magnus 90233939
Tolerance: NS-ISO 2768-1 middels	 Sheet: 1/1
	Paper size: A3 Scale: 2:1 Date: 12.05.2022 Version: 1

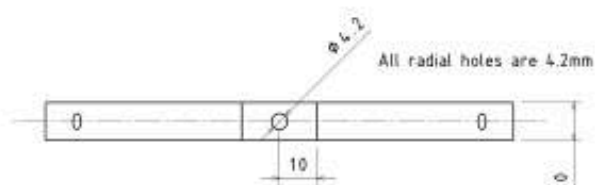


Part name: PV upper neck bracket	Designed by: Magnus Røssfald
Roughness: Ra = 3.2	Approved by: Trond Steinagard
Material: Aluminium 6082 T6	Technical Reference: Magnus 90233939
Tolerance: NS-ISO 2768-1 middels	 Sheet: 1/1 Paper size: A3 Date: 13.05.2022 Version: 1

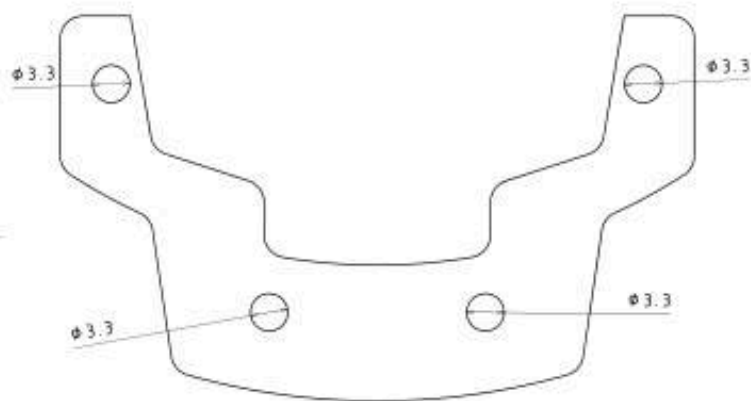




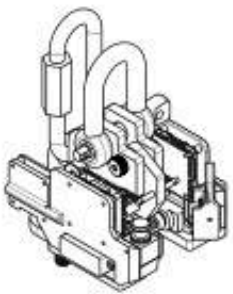
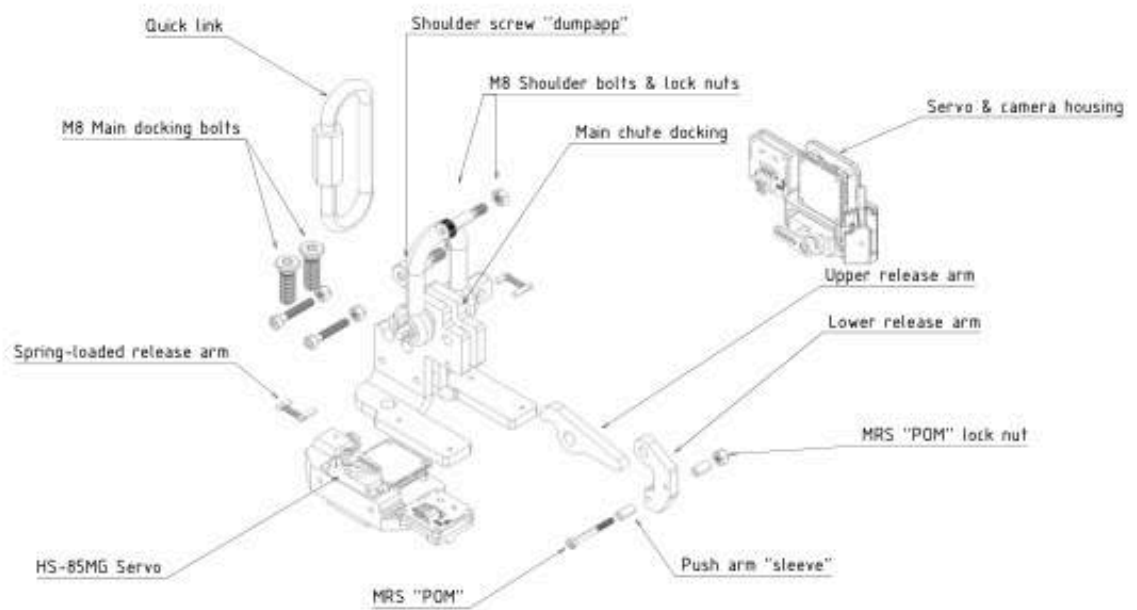
It is preferred if holes are cut with the laser cutter.
If holes are manually drilled, round up to closest available drill bit.
Do not exceed 1mm larger diameter for the drill bit.



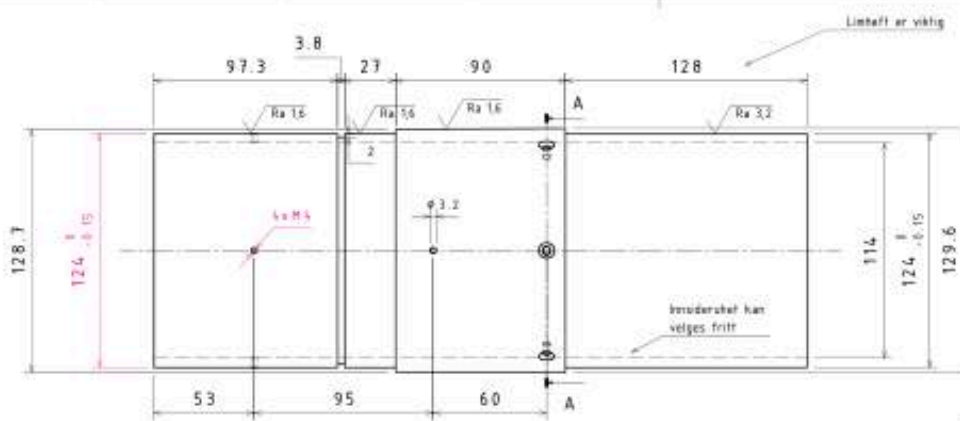
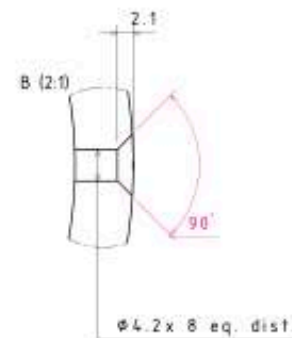
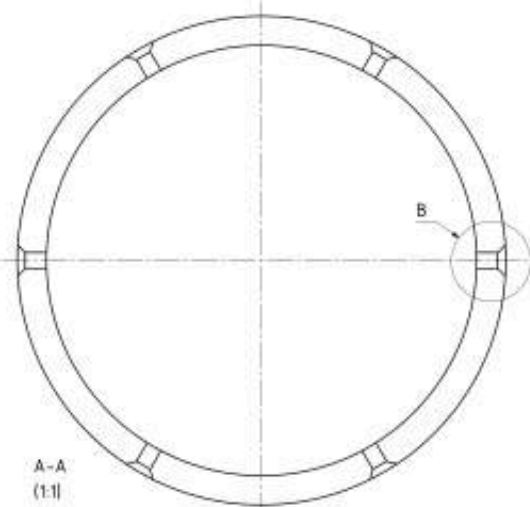
Part name: Recovery plate	Designed by: Magnus Røssfald
Roughness: Ra = 3.2	Approved by: Trond Steinagard
Material: Aluminium 6082 T6	Technical Reference: Magnus 90233939
Tolerance: NS-ISO 2768-1 middels	Sheet: 1/1
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	Scale: 1:1
	Date: 05.05.2022
	Version: 1



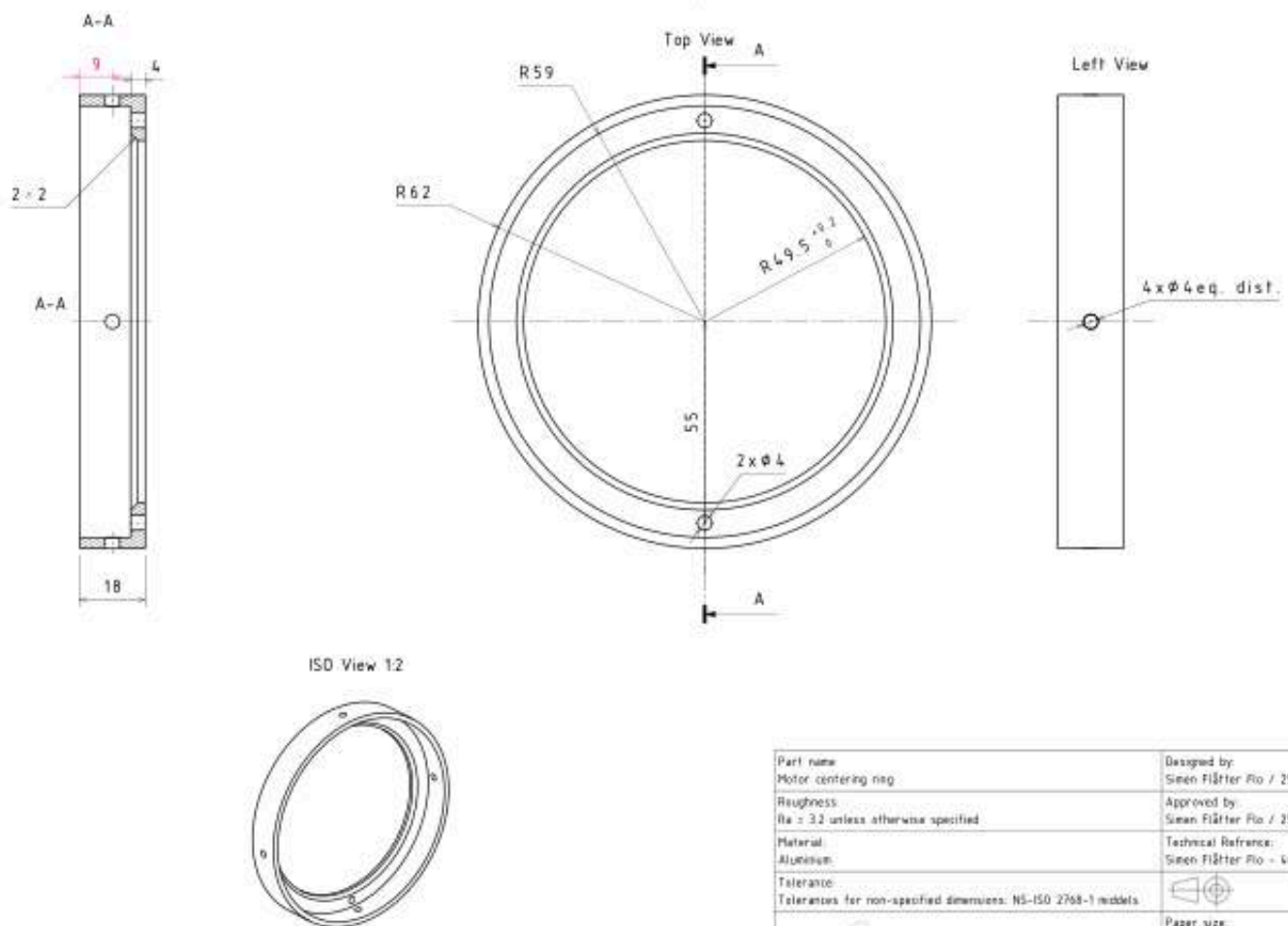
Part name: D-sub bracket	Designed by: Magnus Røssfald
Roughness: $Ra = 3.2$	Approved by: Trond Steinagard
Material: Aluminium 6082 T6	Technical Reference: Magnus 90233939
Tolerance: NS-ISO 2768-M	 Sheet: 1/1
	Paper size: A3 Scale: 3:1 Date: 11.05.2022 Version: 1



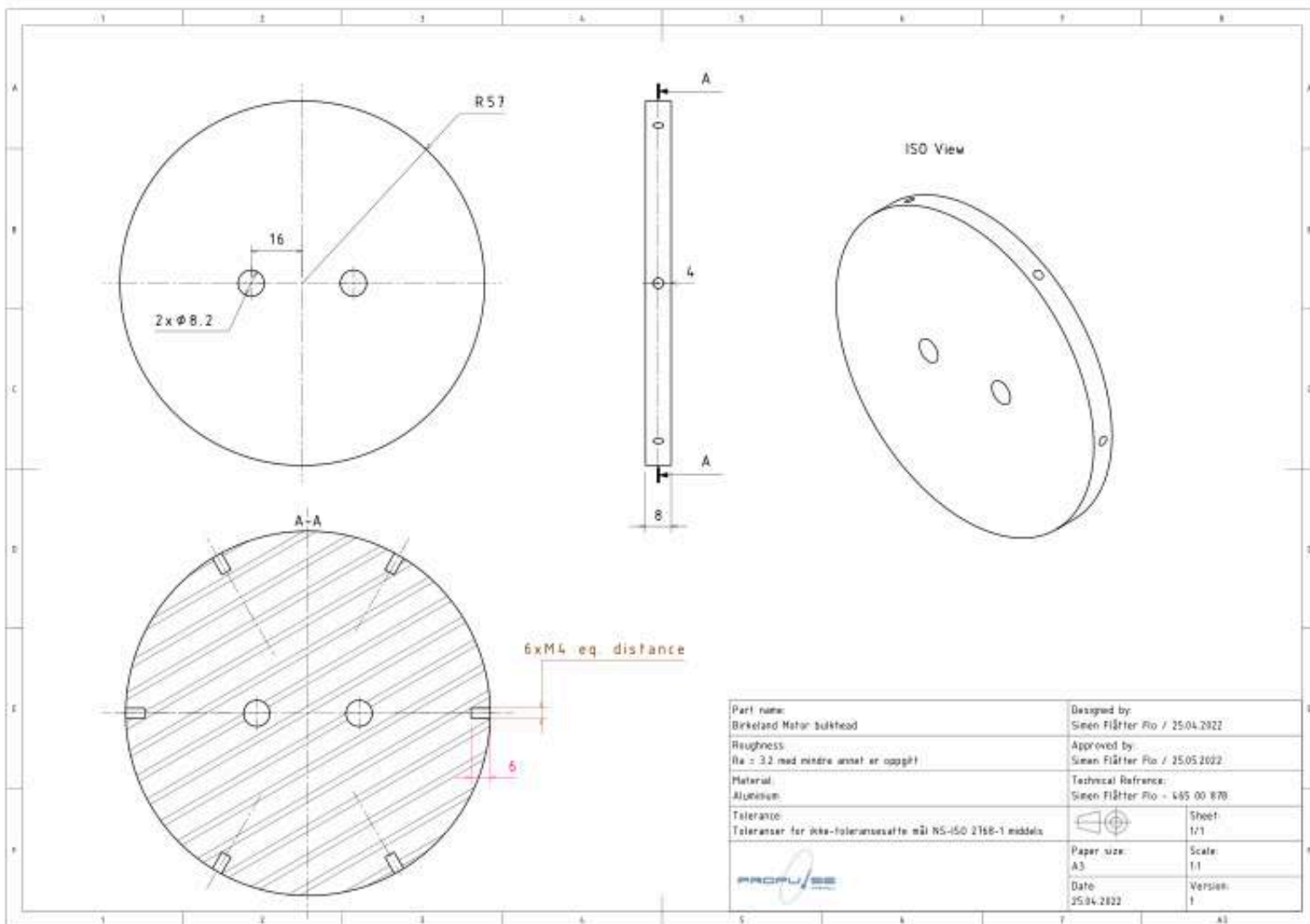
Part name XXX	Designed by Name/date
Roughness: Ra = XX med mindre annet er oppgitt	Approved by Name/date
Material: XXX	Technical Reference: Name/rif
Tolerance: Toleranser for ikke-toleransesatte mål NS-ISO 2768-1 middels	 Sheet X/X Paper size: XX Date XXX Scale: 1/X Version: XXX
	

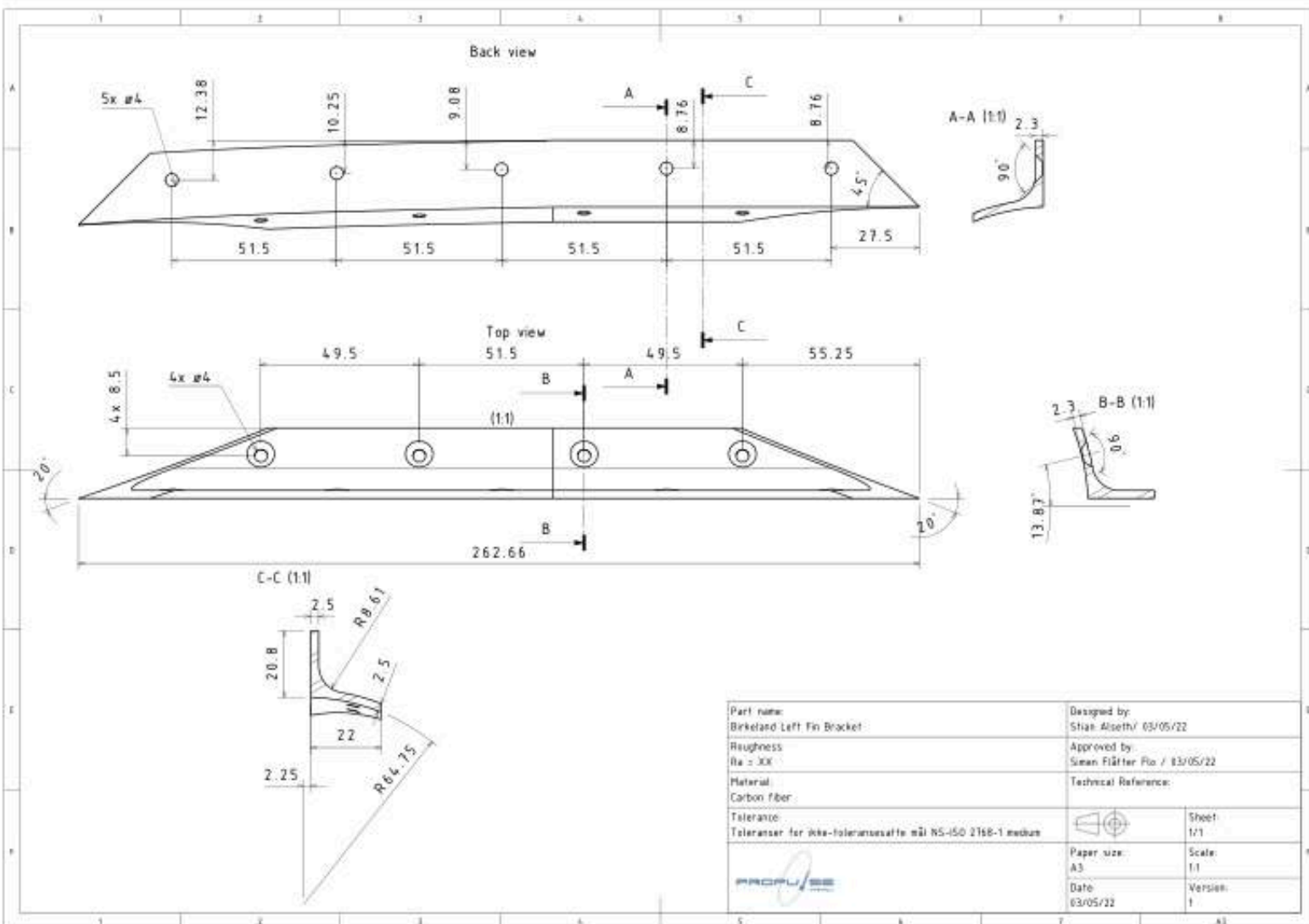
Isometric view
(14)A-A
(1:1)

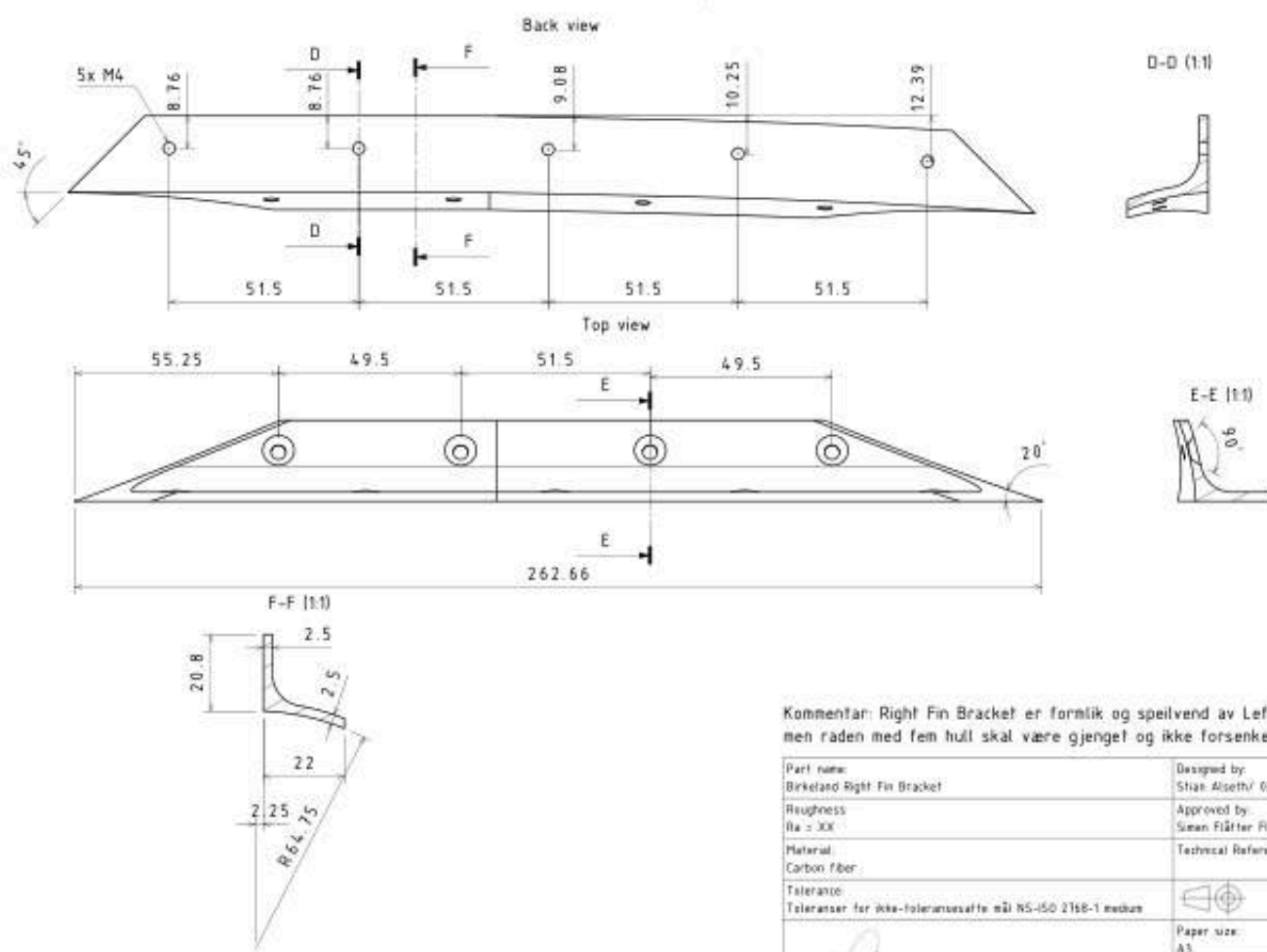
Part name: Birkeland Coupler	Designed by: Søren Flåtter Rø / 14.03.2022
Roughness: Ra = 3.2 med mindre annet er oppgitt	Approved by: Name/date
Material: Aluminium 6082-T6	Technical Reference: Søren Flåtter Rø / 445 00 878
Tolerance: Toleranser for ikke-toleransesatte mål NS-ISO 2158-1 middels	 Sheet: 1/1 Scale: 1:2 Version: 1
	Paper size: A3 Date: 14.03.2022



Part name Motor centering ring	Designed by: Søren Flåtter Flo / 25.04.2022	
Roughness Ra = 3.2 unless otherwise specified	Approved by: Søren Flåtter Flo / 25.04.2022	
Material Aluminium	Technical Reference: Søren Flåtter Flo - 445 00 878	
Tolerance: Tolerances for non-specified dimensions: NS-ISO 2768-1 middels		Sheet 1/1
	Paper size: A3	Scale: 1:1
	Date: 25.04.2022	Version: 1





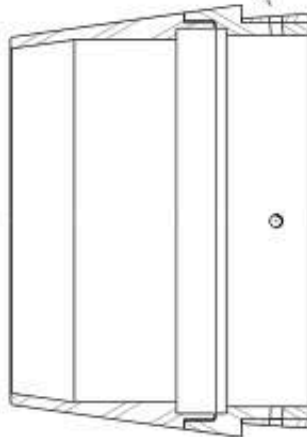


Kommentar: Right Fin Bracket er formlik og speilvend av Left Fin Bracket, men raden med fem hull skal være gjenget og ikke forsenket!

Part name: Birkeland Right Fin Bracket	Designed by: Stian Alseth / 03/05/22
Roughness: Ra = 300	Approved by: Simen Flåtter Flo / 03/05/22
Material: Carbon fiber	Technical Reference:
Tolerance: Toleranser for ikke-toleransesatte mål NS-ISO 2158-1 medium	Sheet: 1/1
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	Scale: 1:1
	Date: 03/05/22
	Version: 1

Hull i Centering Ring og Wedge skal matche

Diameter skal matche



Sectioned view

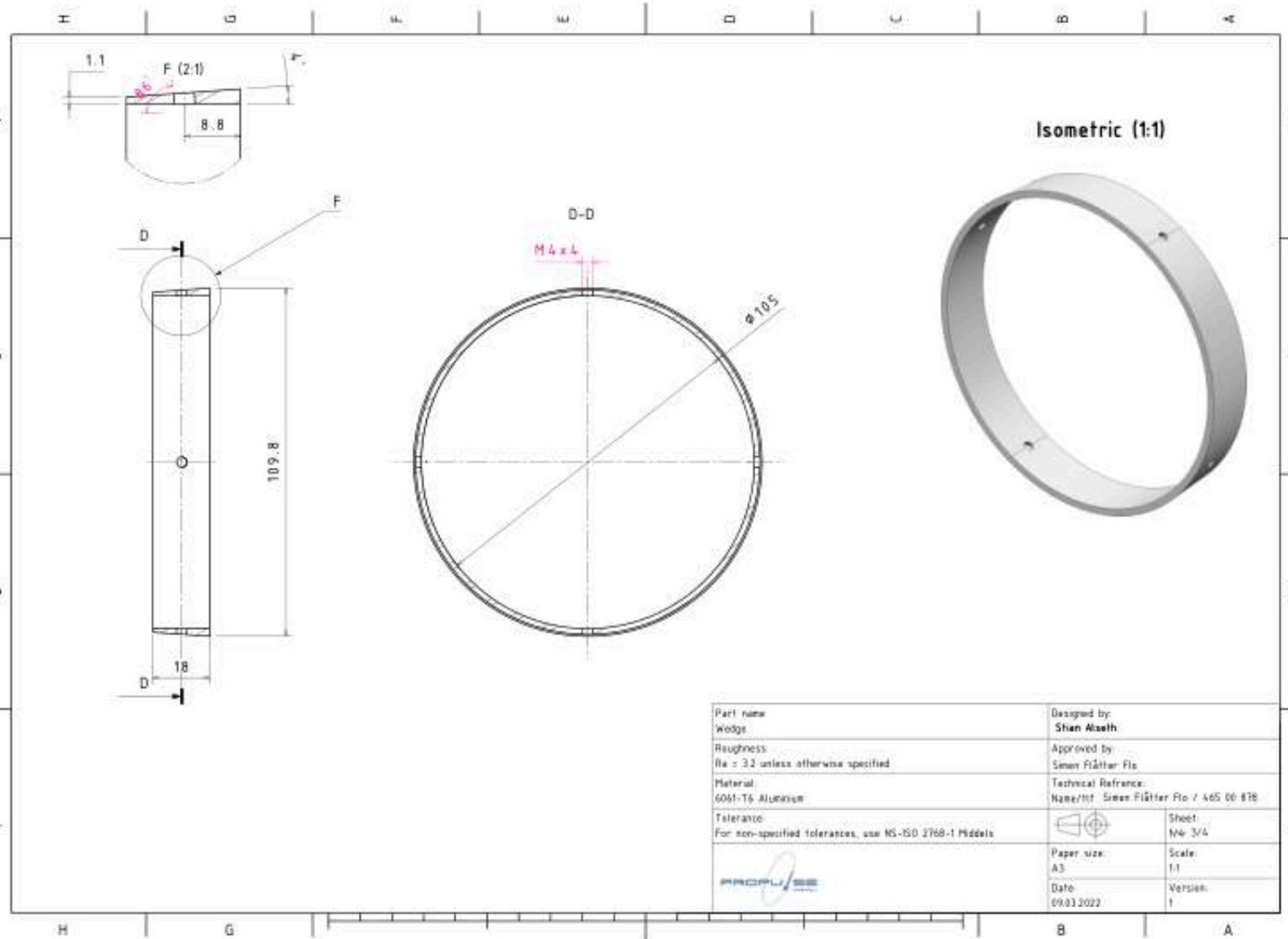


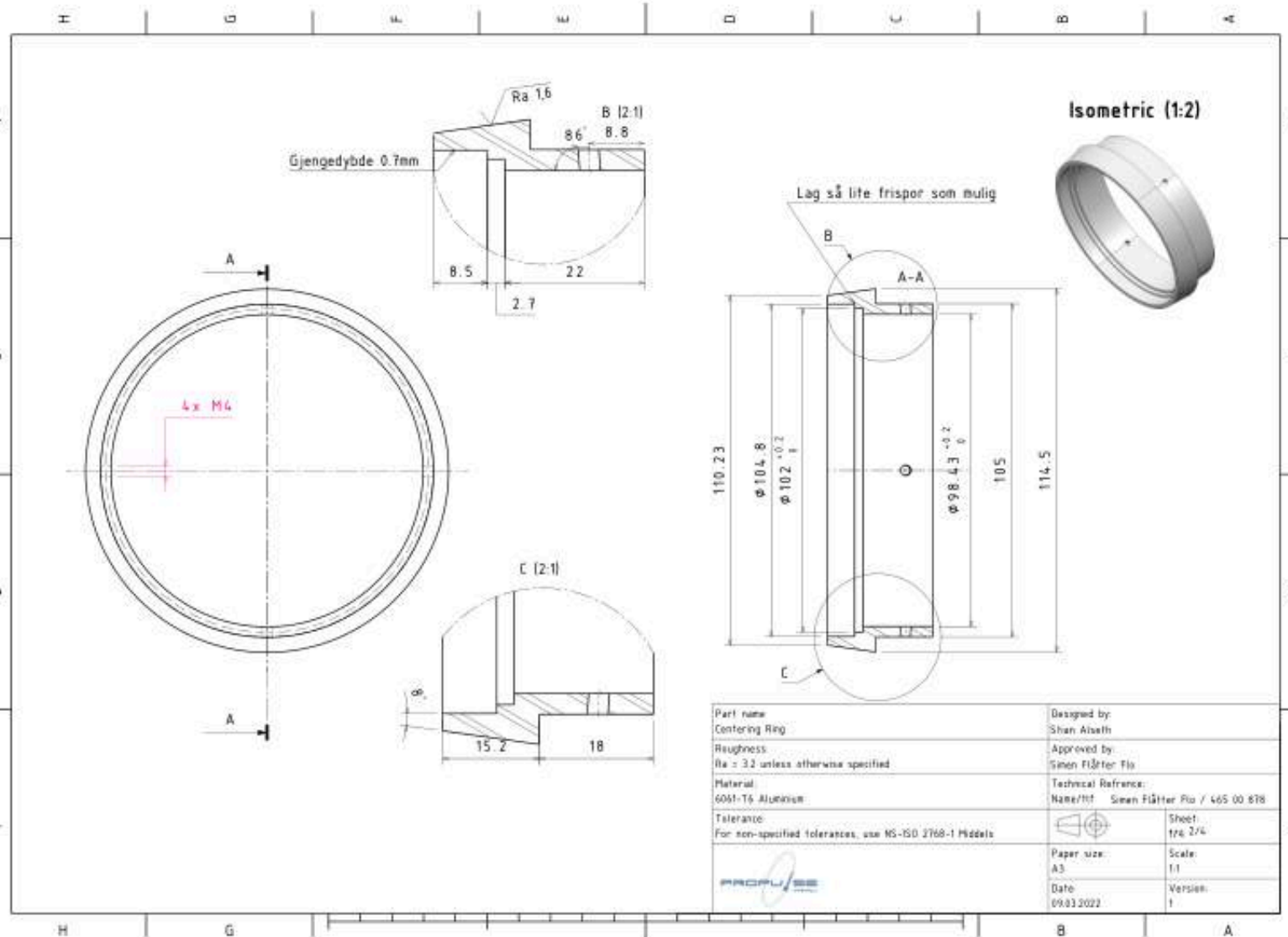
Isometric (1:1)

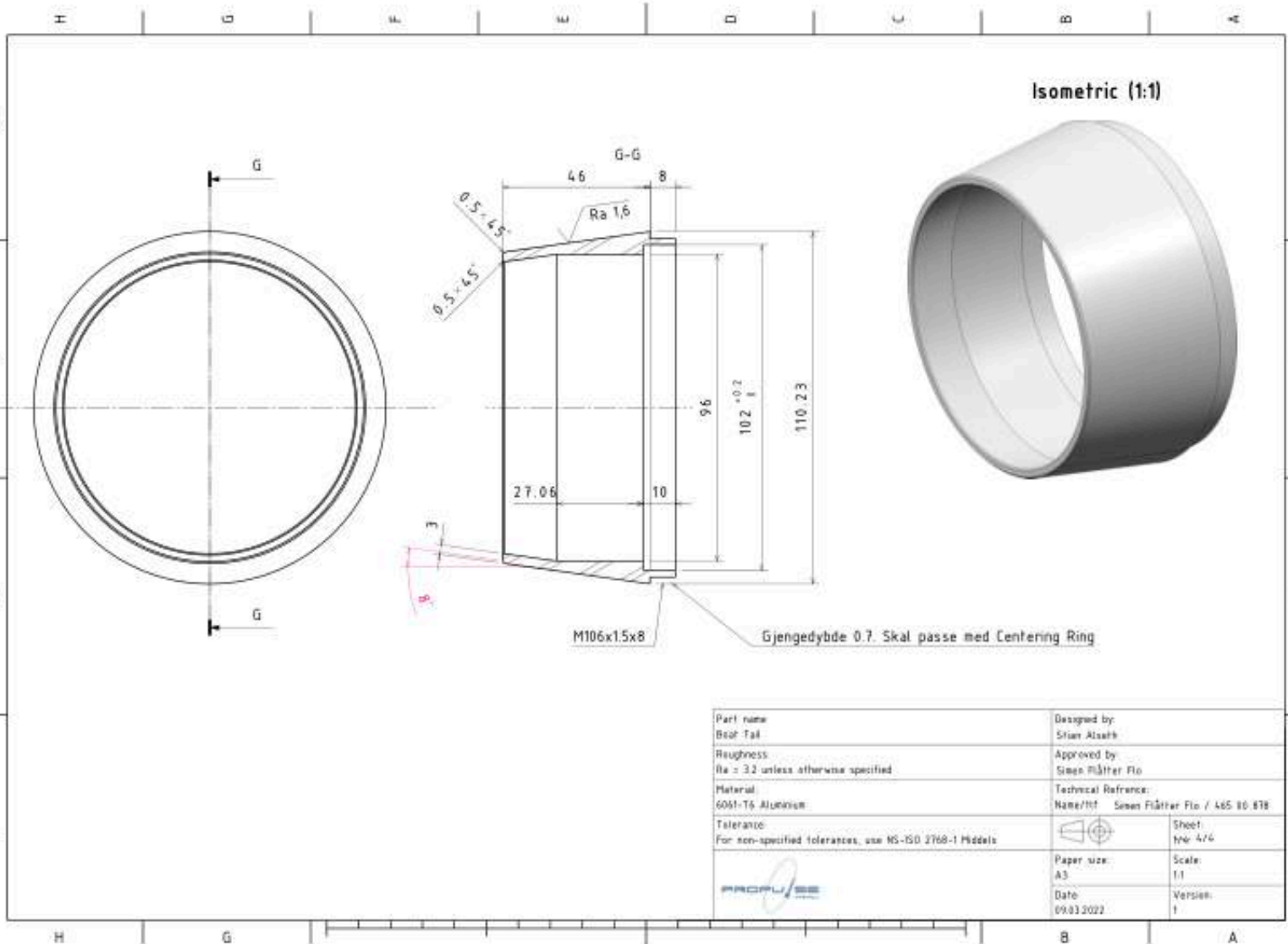
List of parts in assembly

Part name	Sheet	Quantity
Centering Ring	2/4	1
Wedge	3/4	1
Boat Tail	4/4	1

Part name: Boat Tail Assembly	Designed by: Stian Alseth
Roughness: Ra = 3.2 unless otherwise specified	Approved by: Simen Flåtter Flo
Material: 6061-T6 Aluminium	Technical Reference: Simen Flåtter Flo / 485 00 878
Tolerance: For non-specified tolerances, use NS-ISO 2768-1 Moulds	Sheet: 1/4
	Paper size: A3
	Scale: 1:1
	Date: 09.03.2022
	Version: 1



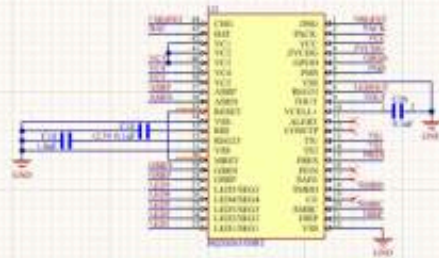




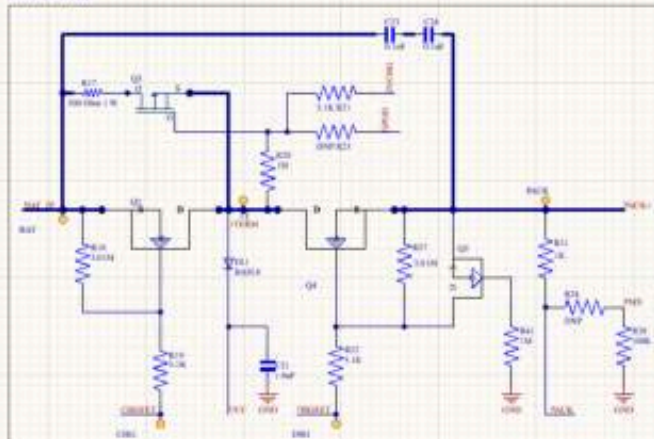
PDB schematics

Main schematics

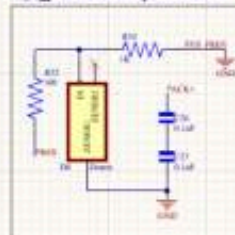
Battery Management System.



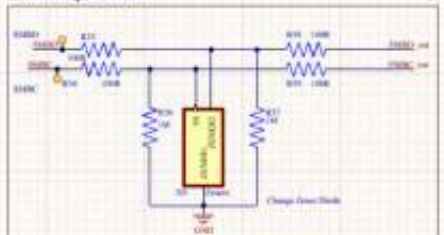
Mosfet circuit



Sys_pres and zener prot. circuit



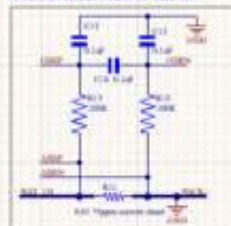
SMBUS prot. circuit



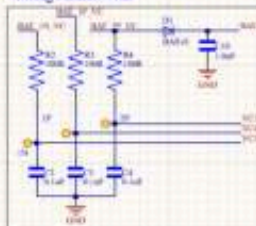
HEADER PINZZZ



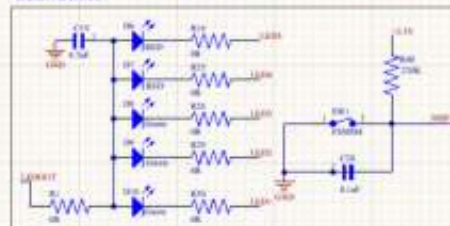
Current shunt resistor circuit



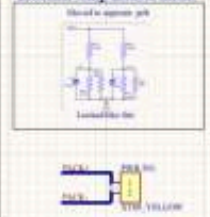
Voltage sense+ bat



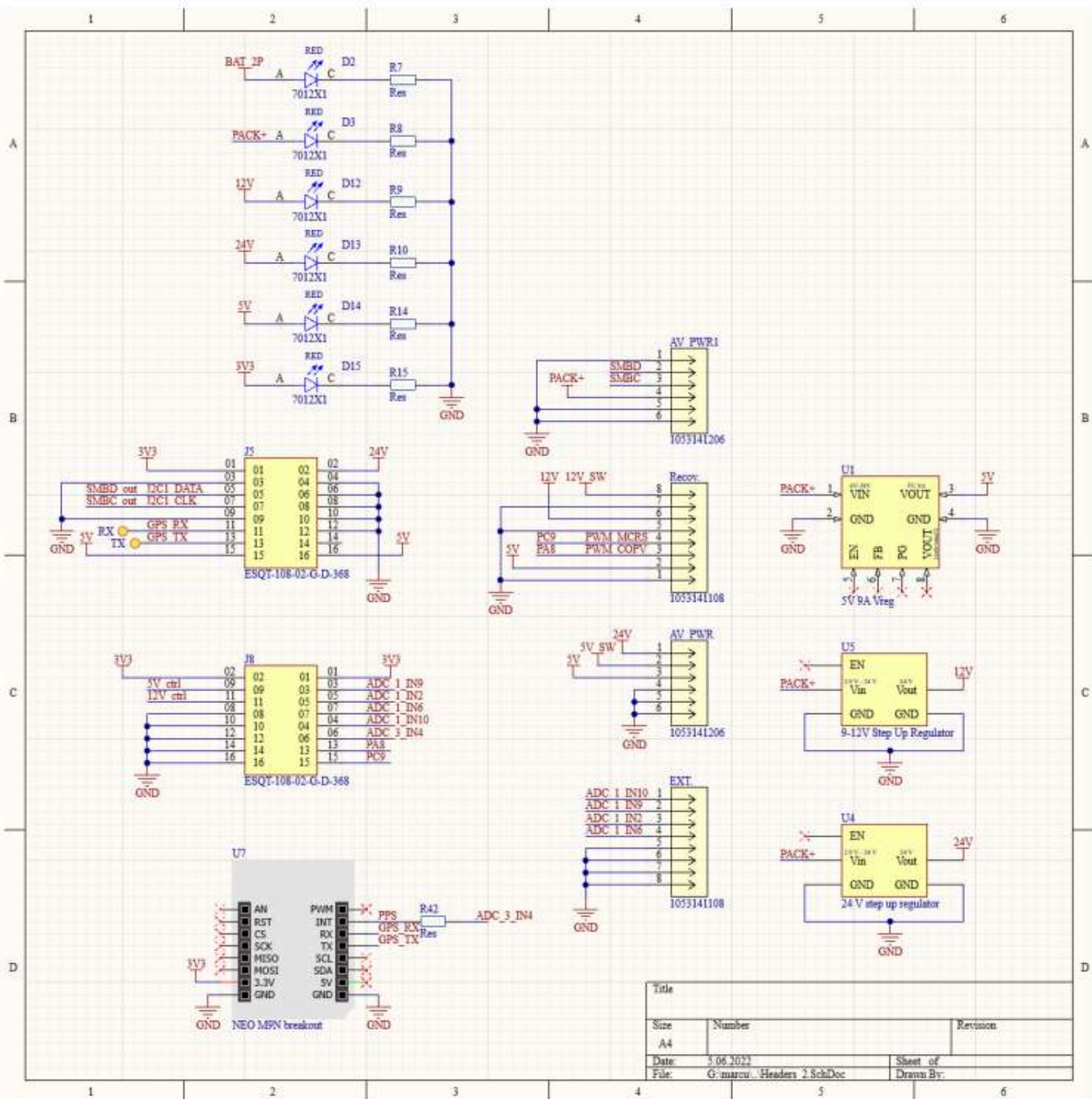
LED ARRAY



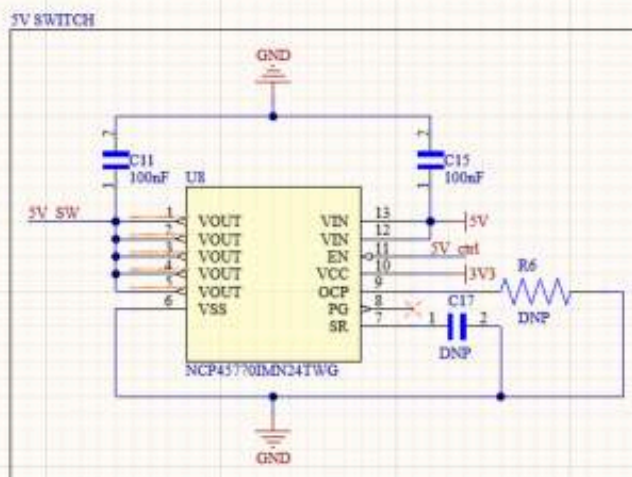
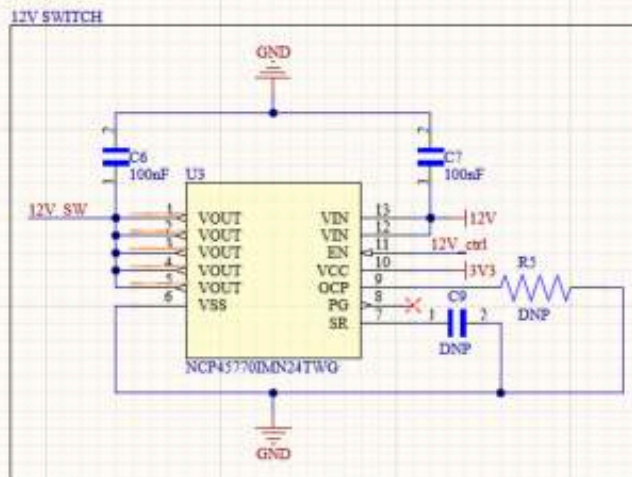
External temp measurement



Rev	Author	Reviewer
1.0	1.0	1.0
1.1	1.1	1.1
1.2	1.2	1.2
1.3	1.3	1.3
1.4	1.4	1.4
1.5	1.5	1.5
1.6	1.6	1.6
1.7	1.7	1.7
1.8	1.8	1.8
1.9	1.9	1.9
2.0	2.0	2.0



Header schematics

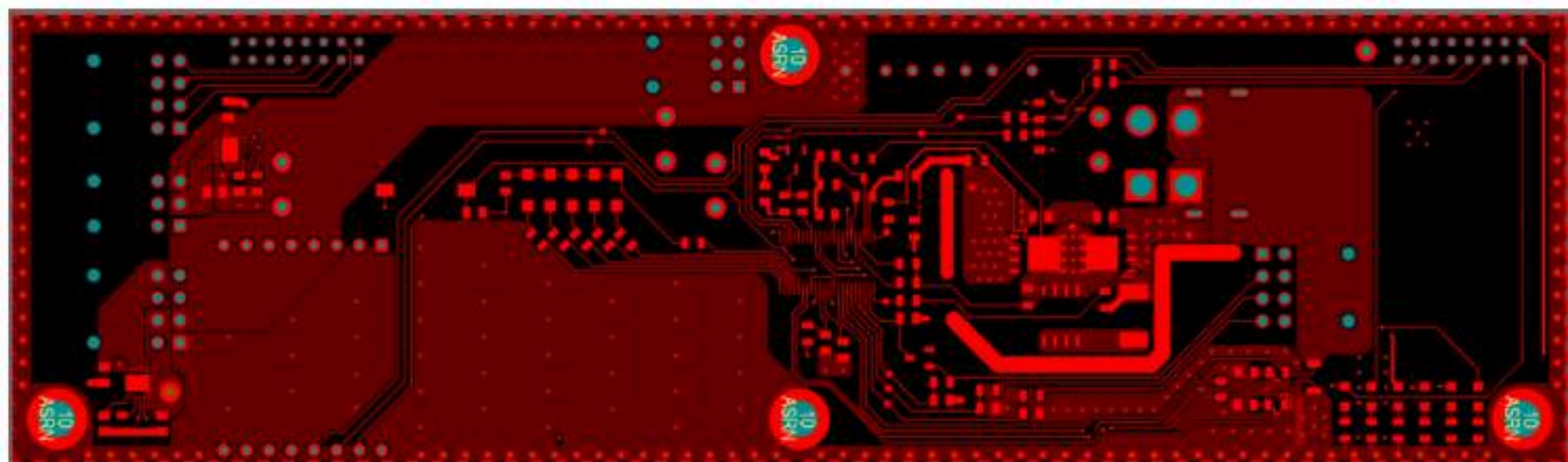


Title		
Size	Number	Revision
A4		
Date:	5/06/2022	Sheet of
File:	G:\marcu\Switches SchDoc	Drawn By:

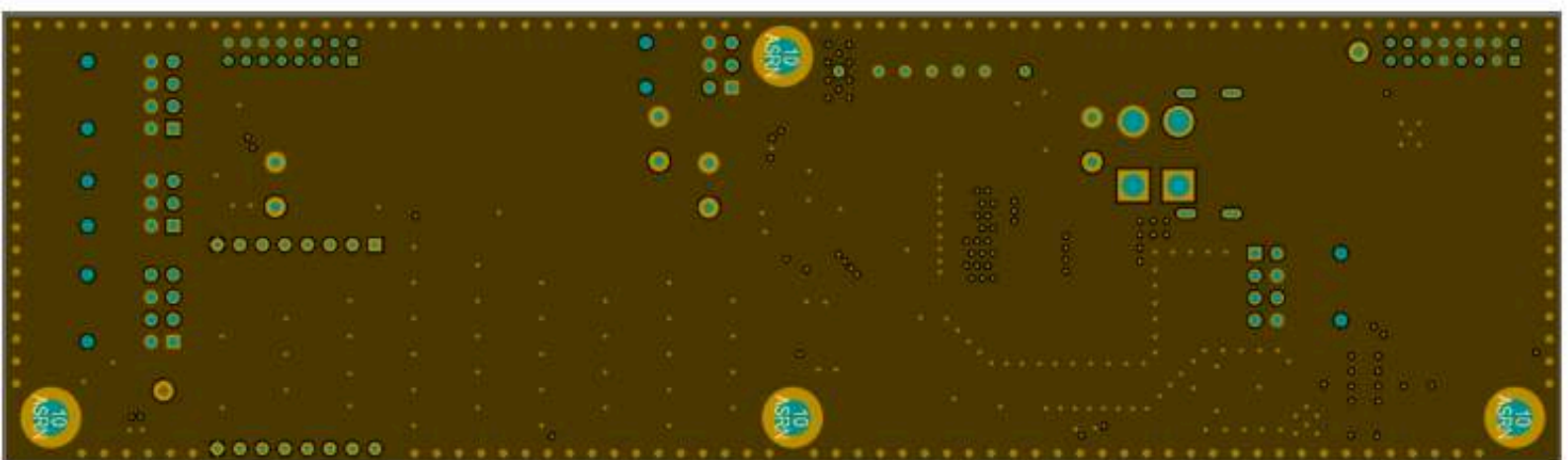
Switch schematics

PDB PCB signal layers

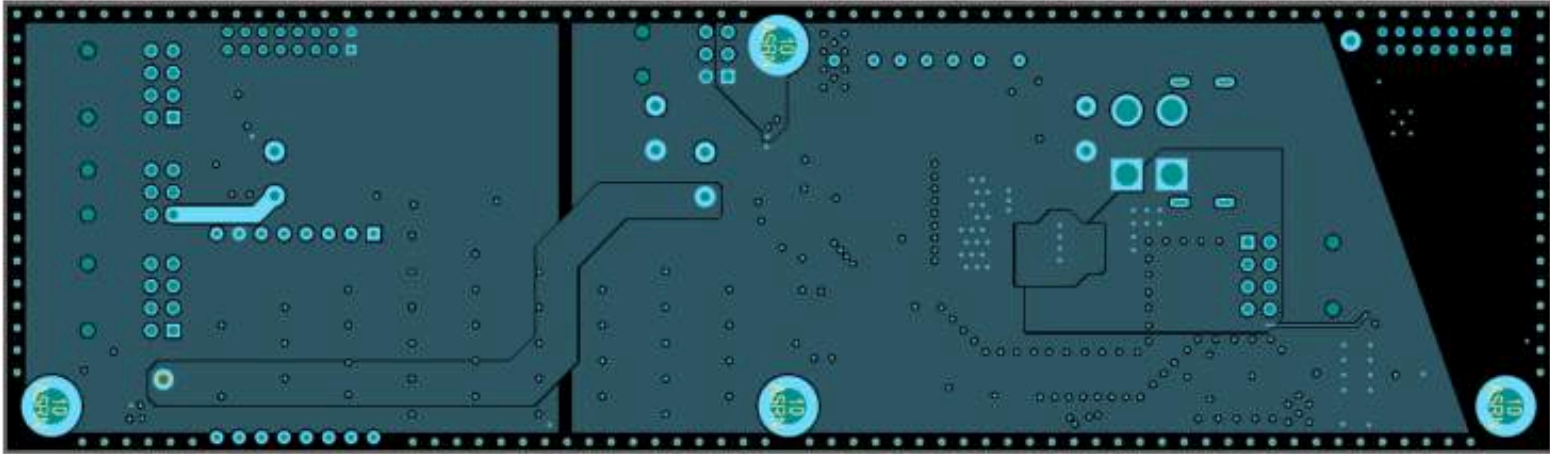
Top layer



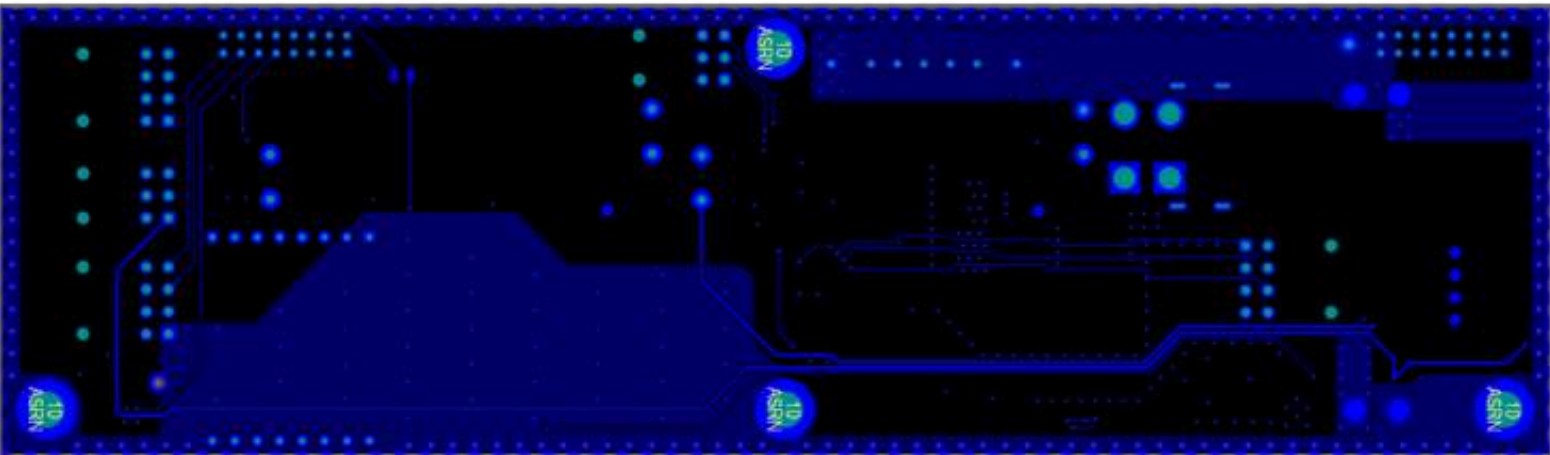
GND layer



PWR layer

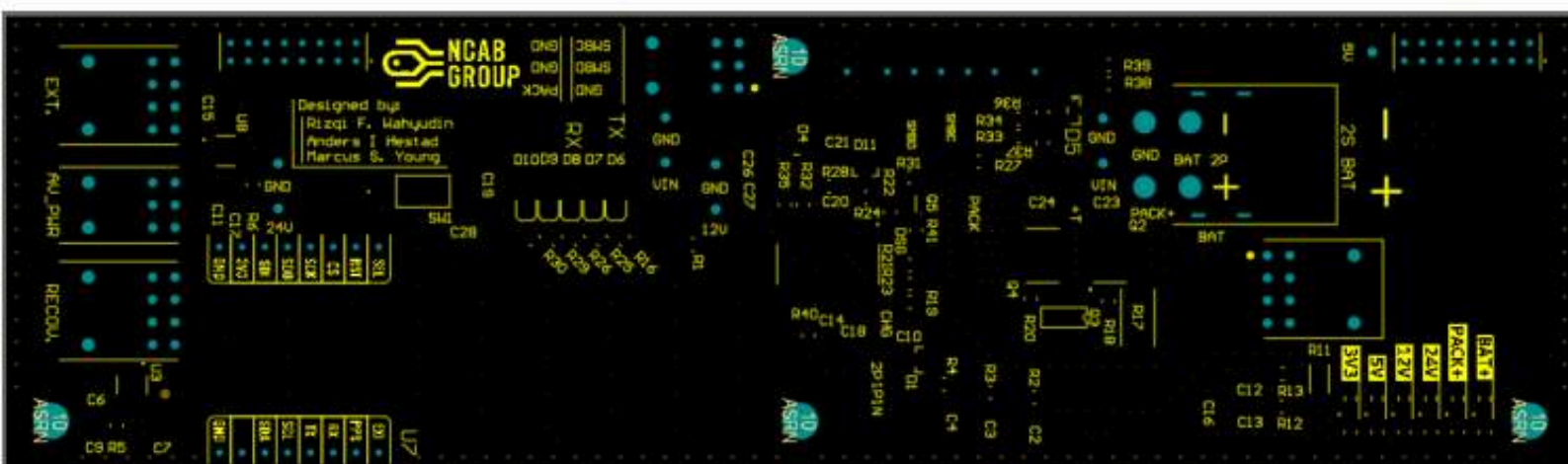


Bottom layer

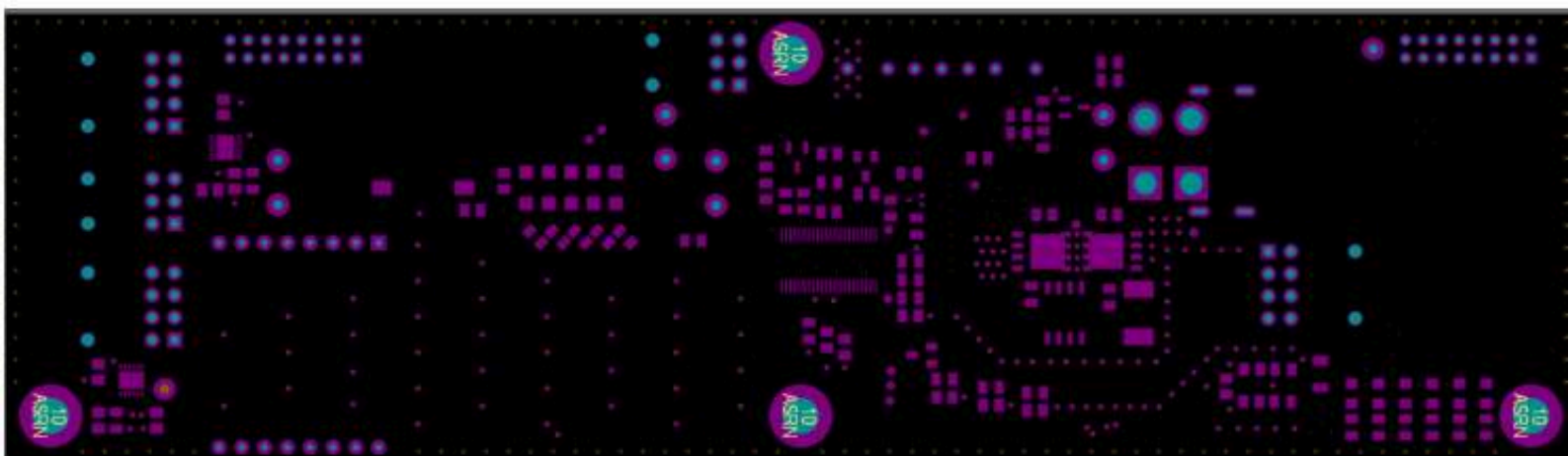


PDB PCB top layers

Top overlay

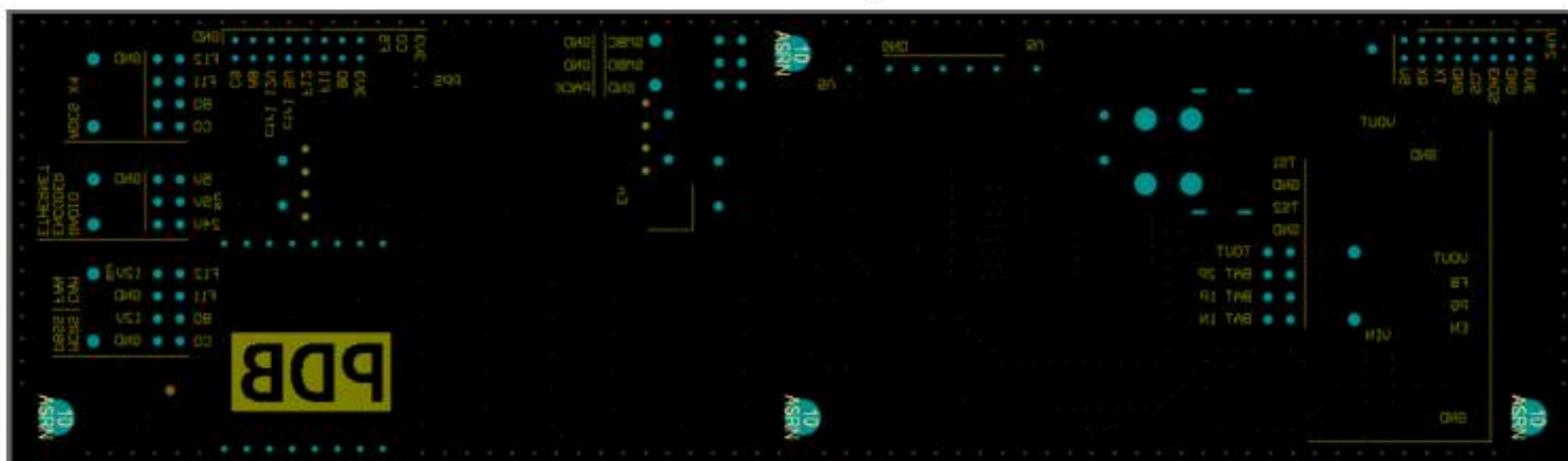


Top solder

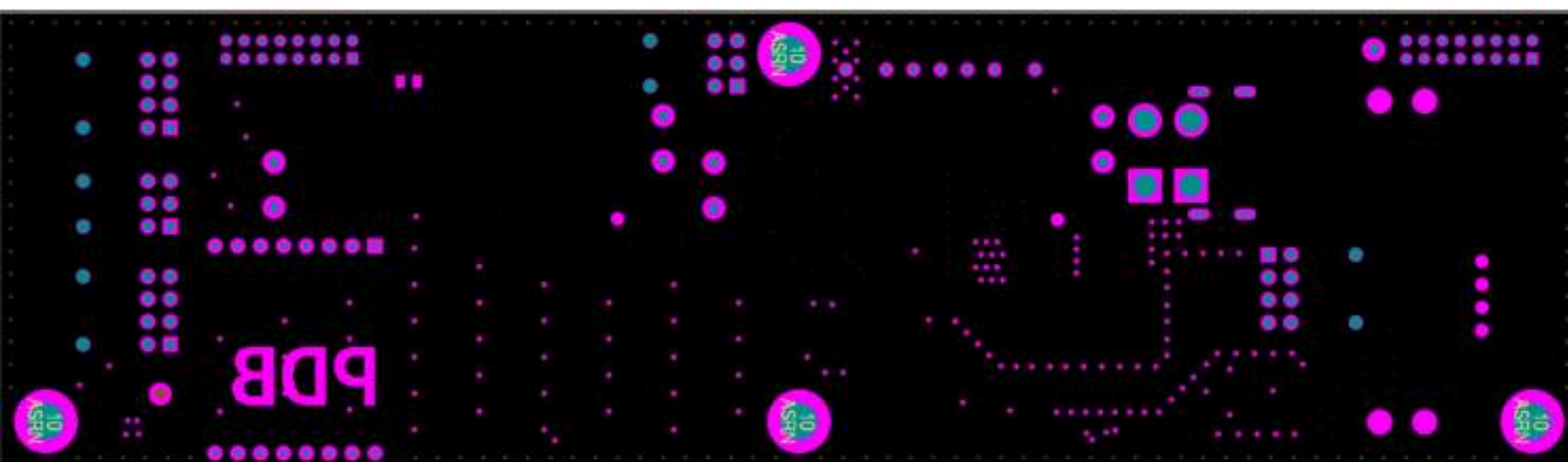


PDB PCB bottom layers

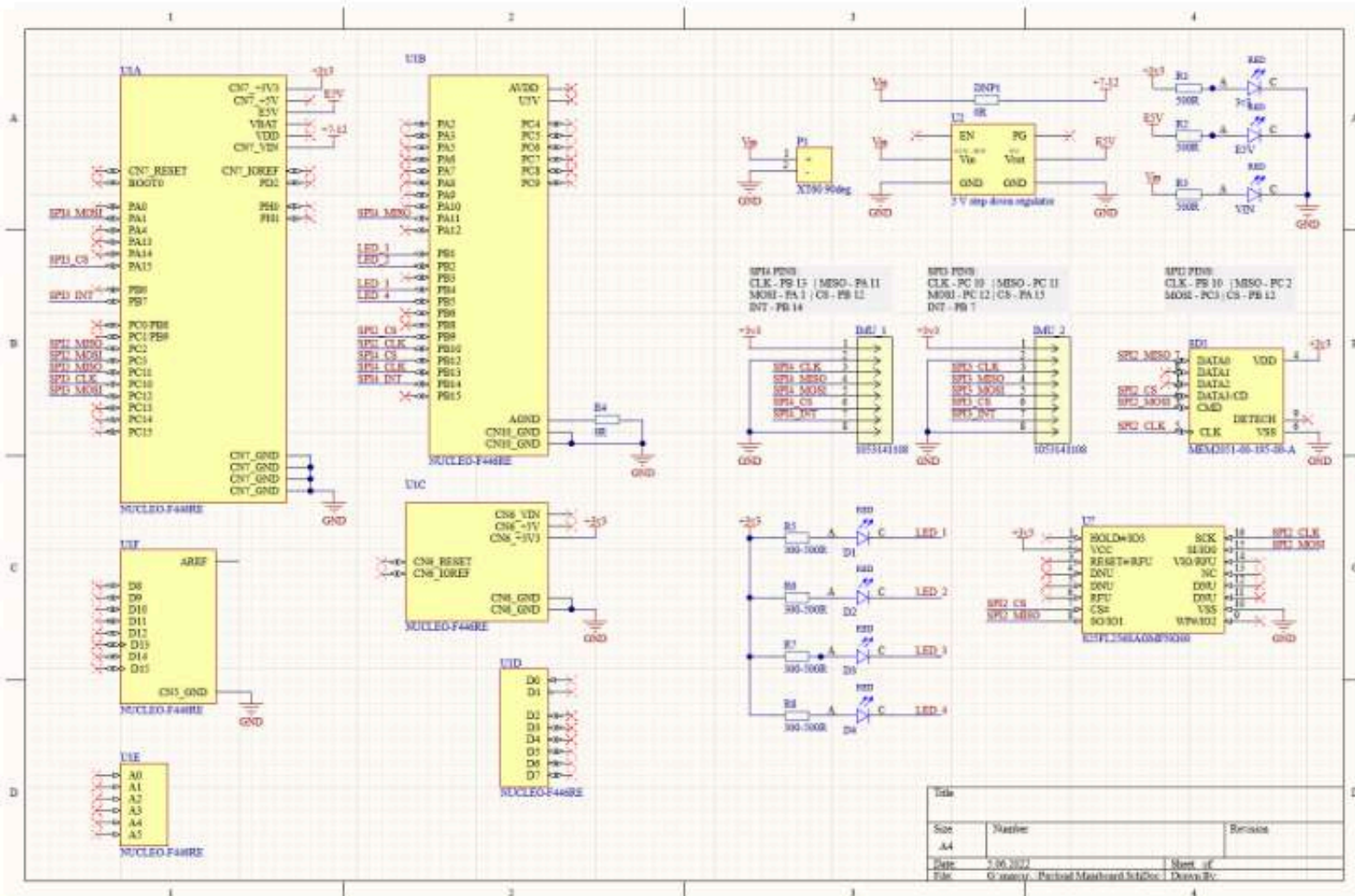
Bottom overlay



Bottom solder



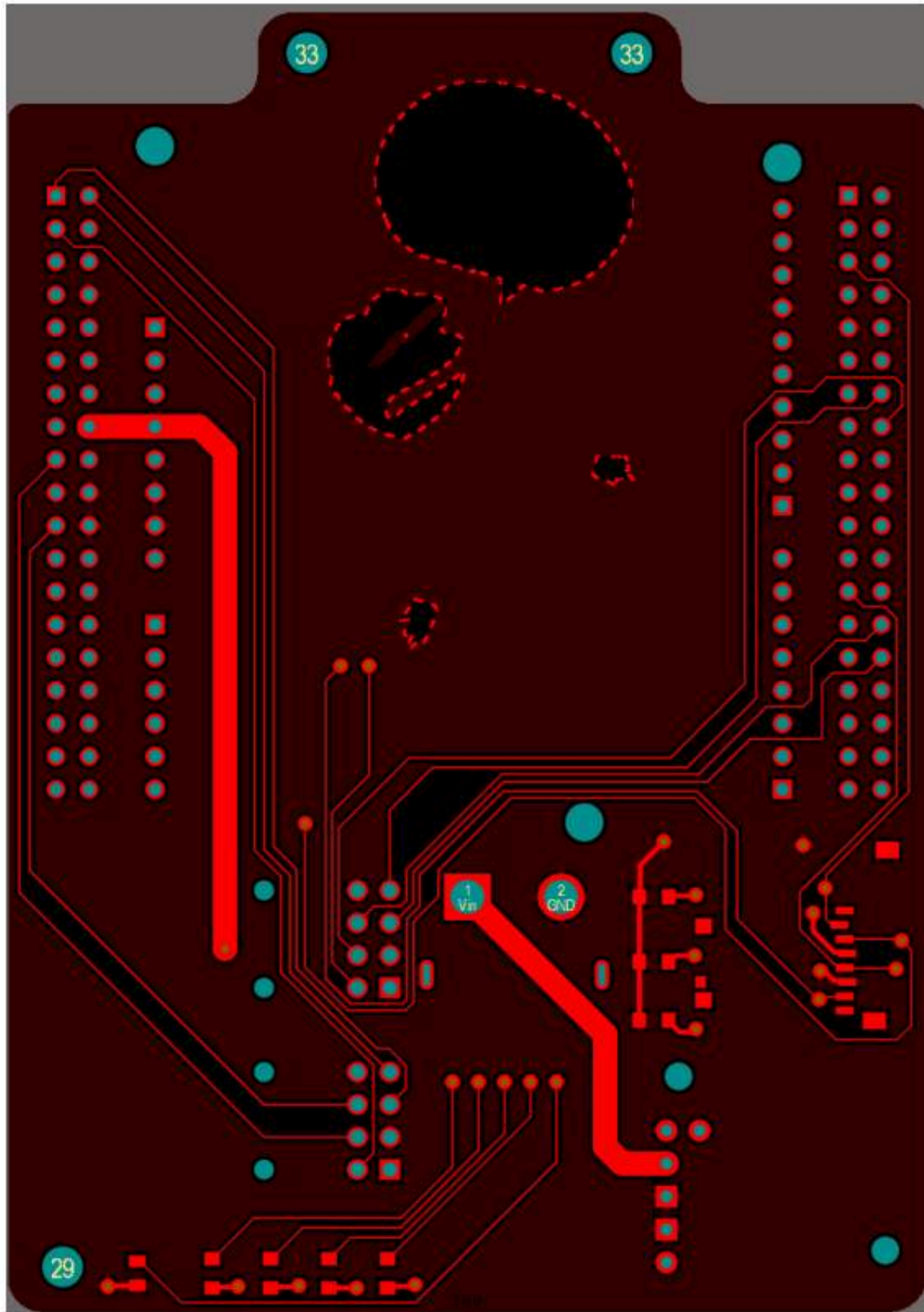
Payload main board schematics



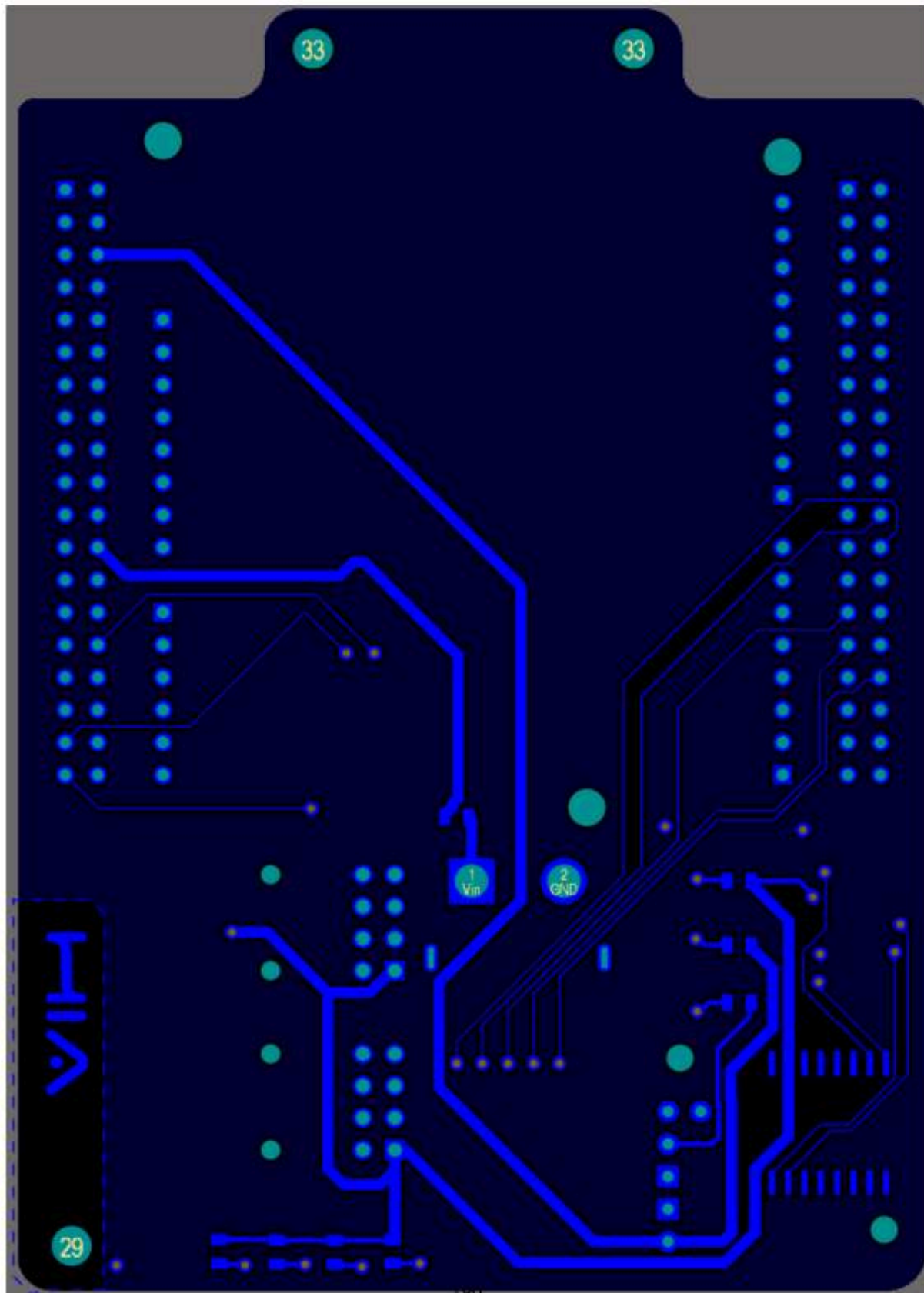
Schematics

Payload main board PCB signal layers

Top layer

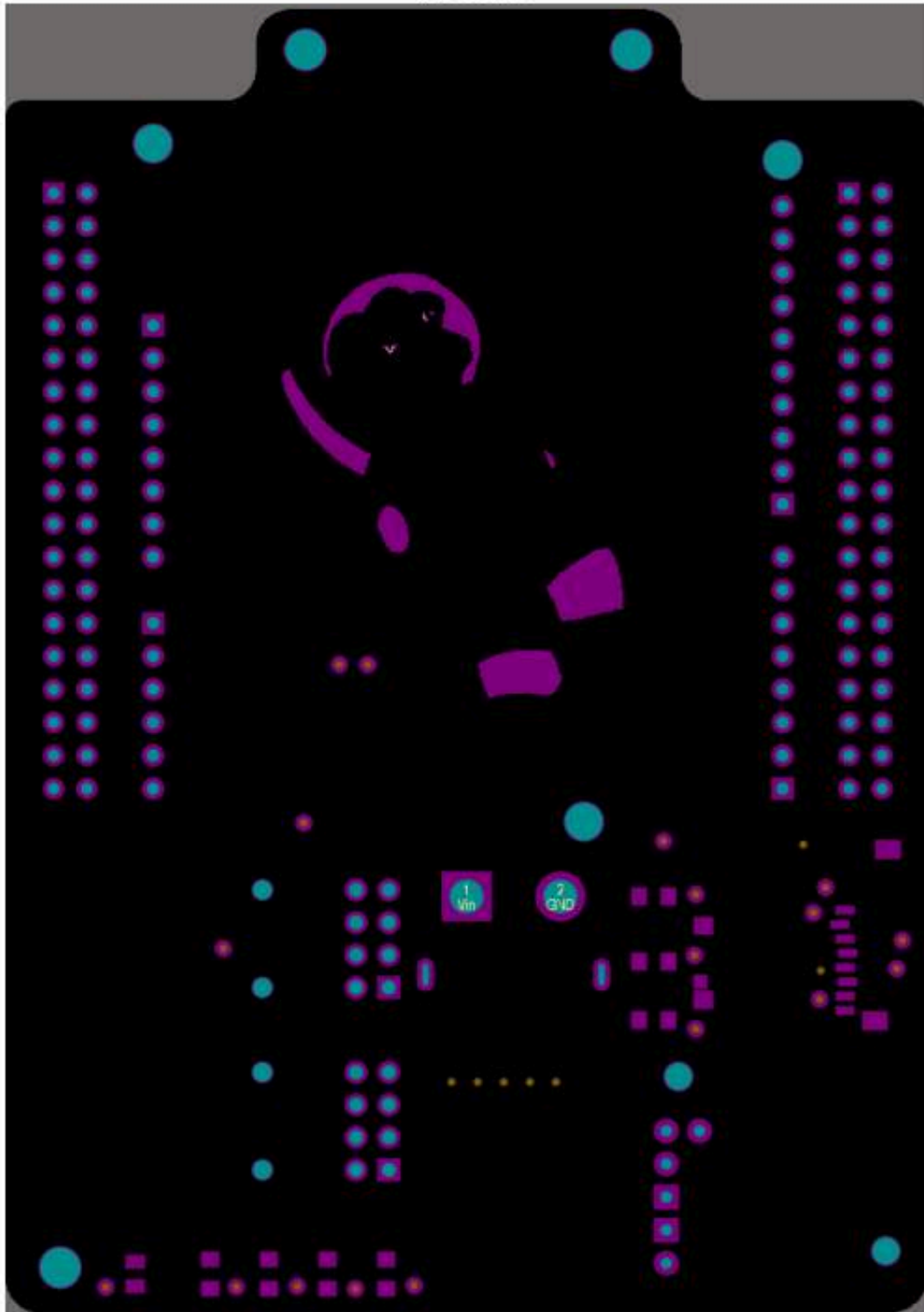


Bottom layer

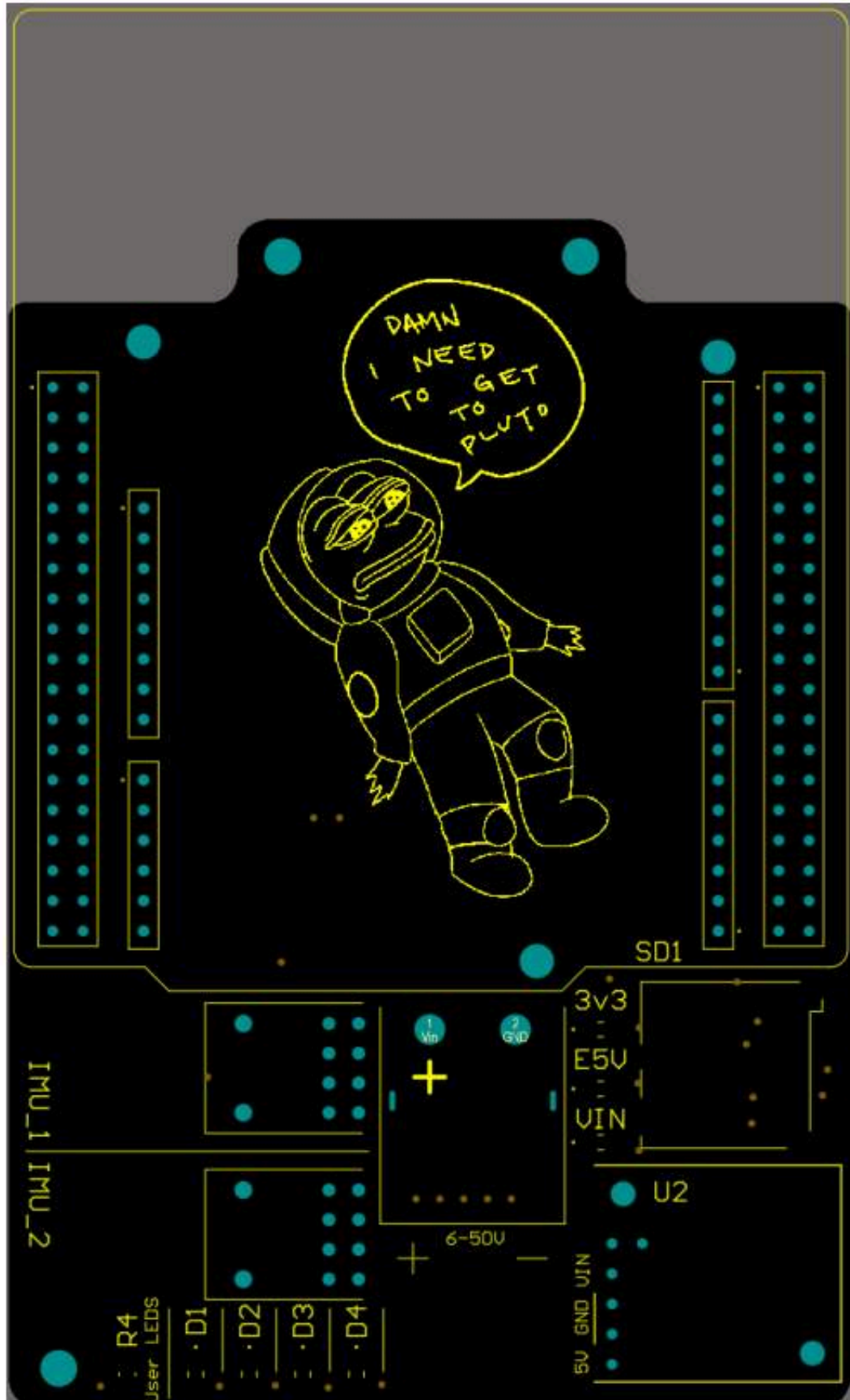


Payload main board PCB top layers

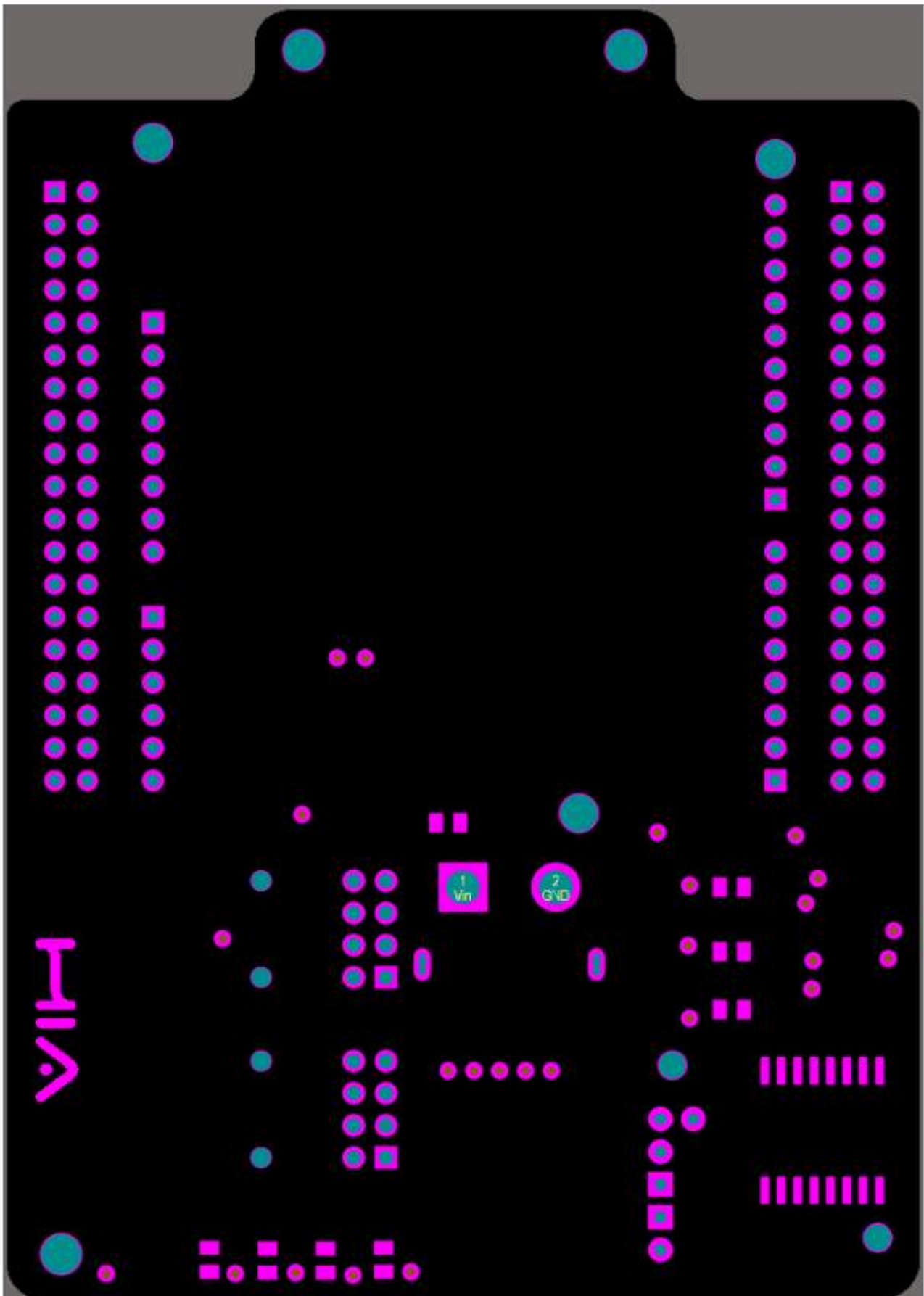
Top solder



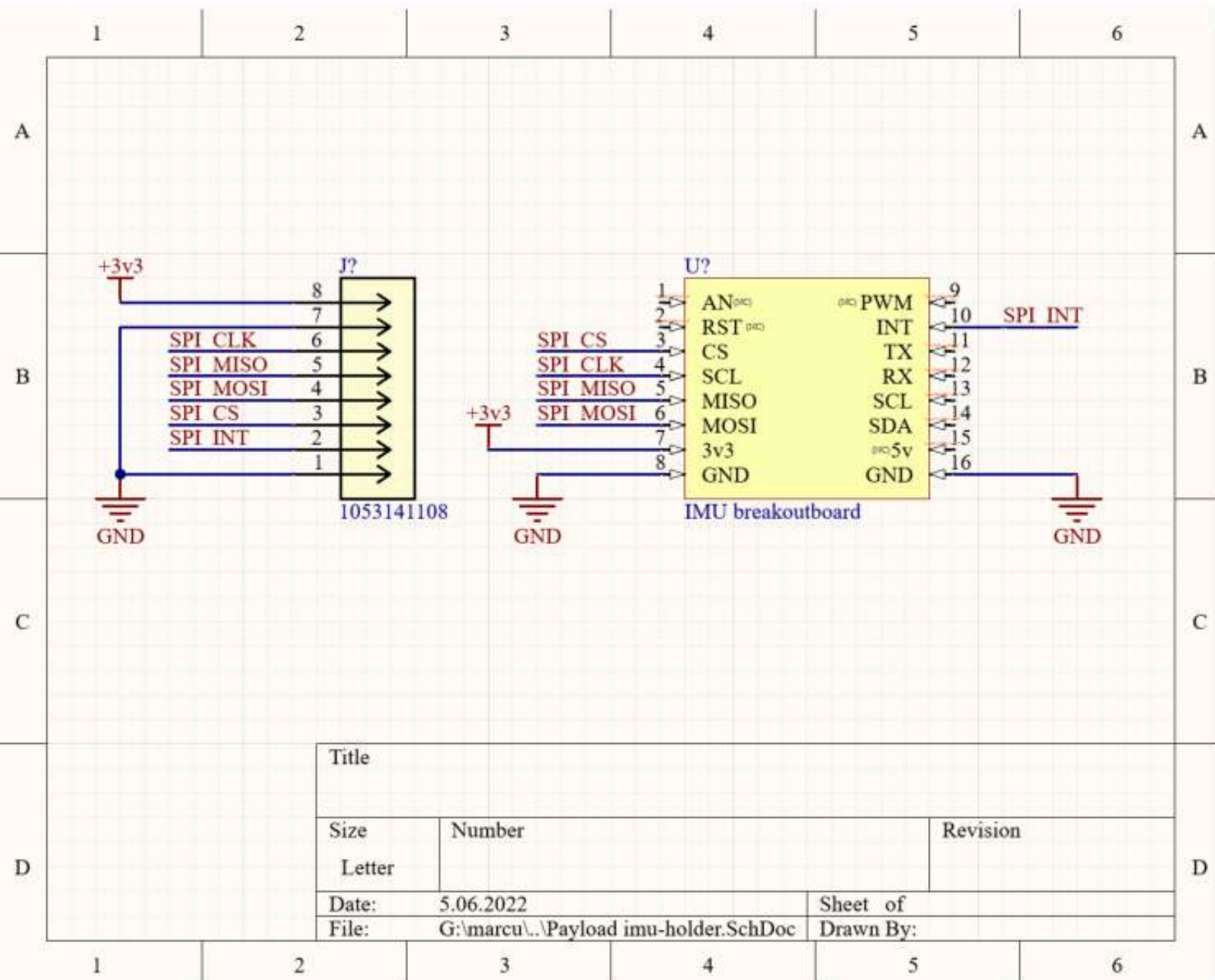
Top overlay



Bottom solder



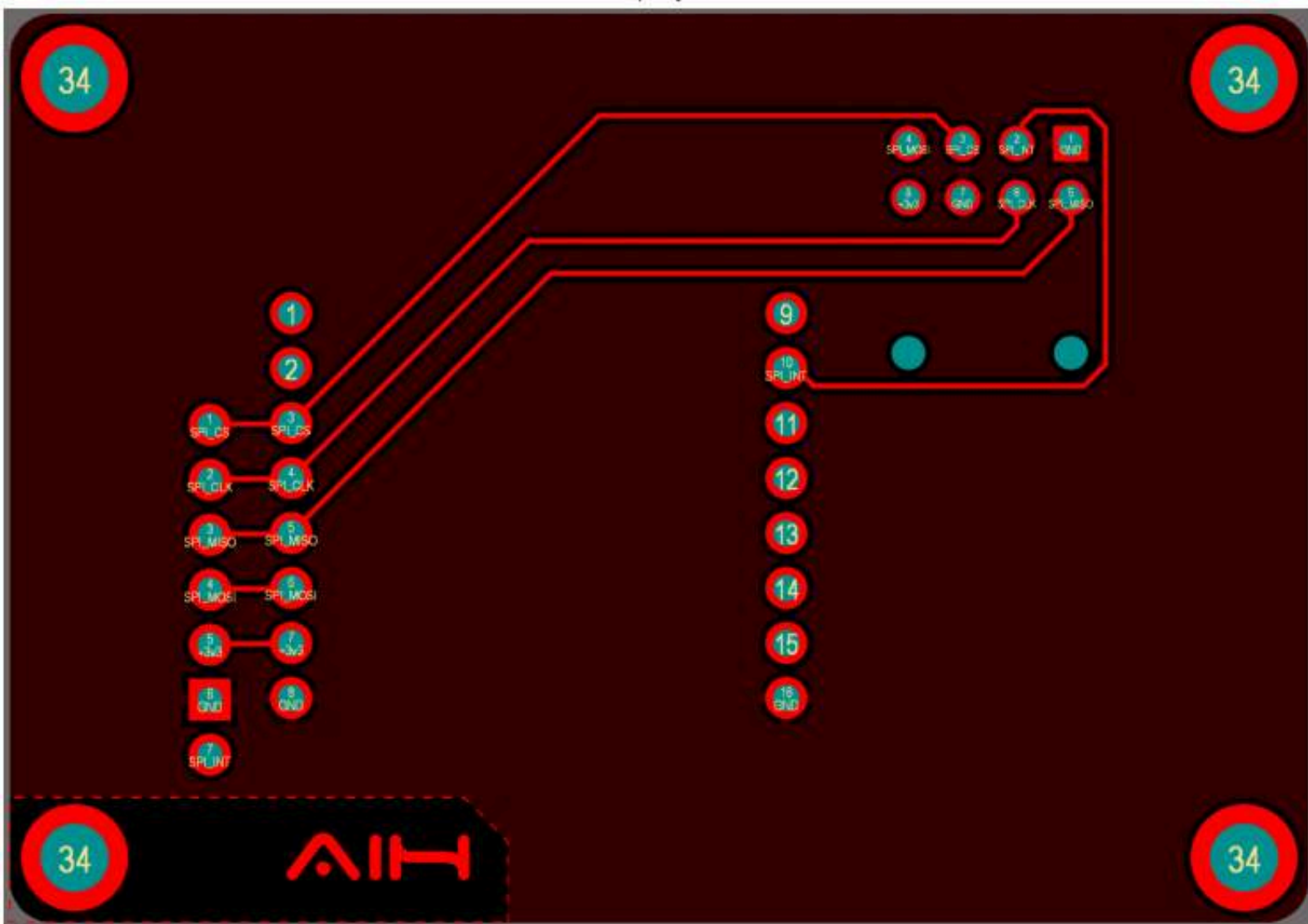
Payload imu holder schematics



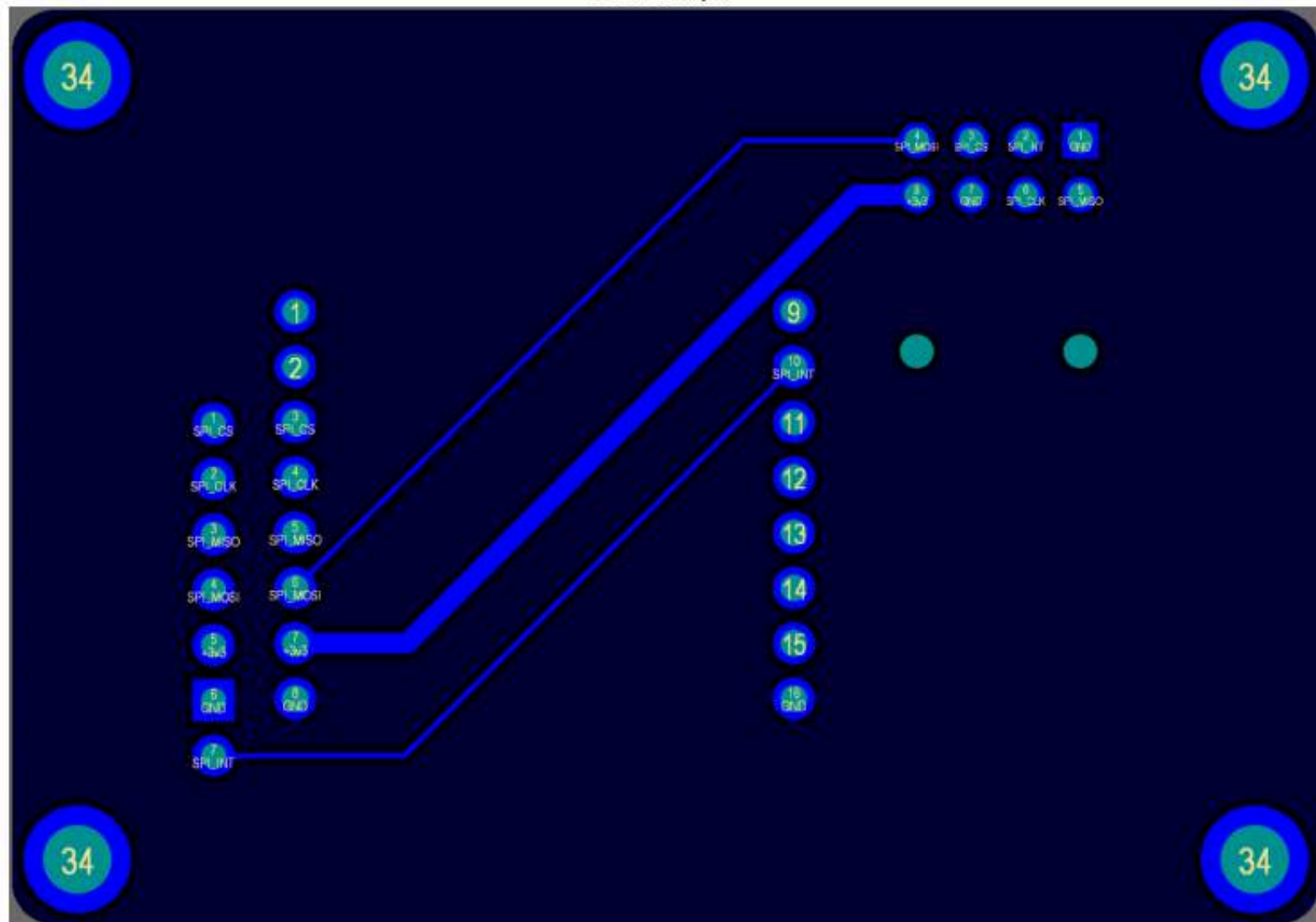
Schematics

Payload imu holder PCB signal layers

Top layer

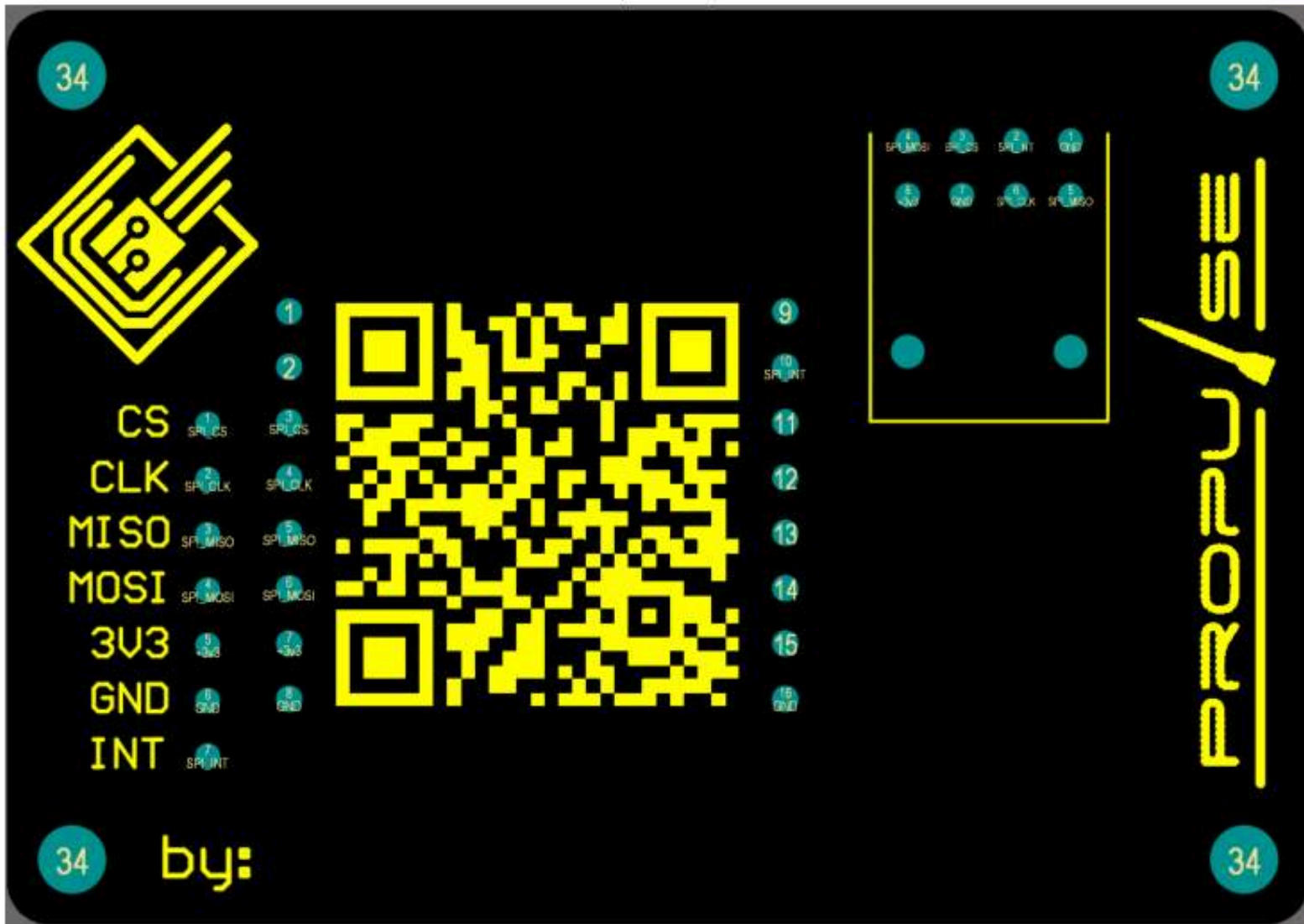


Bottom layer



Payload imu holder PCB top layers

Top overlay

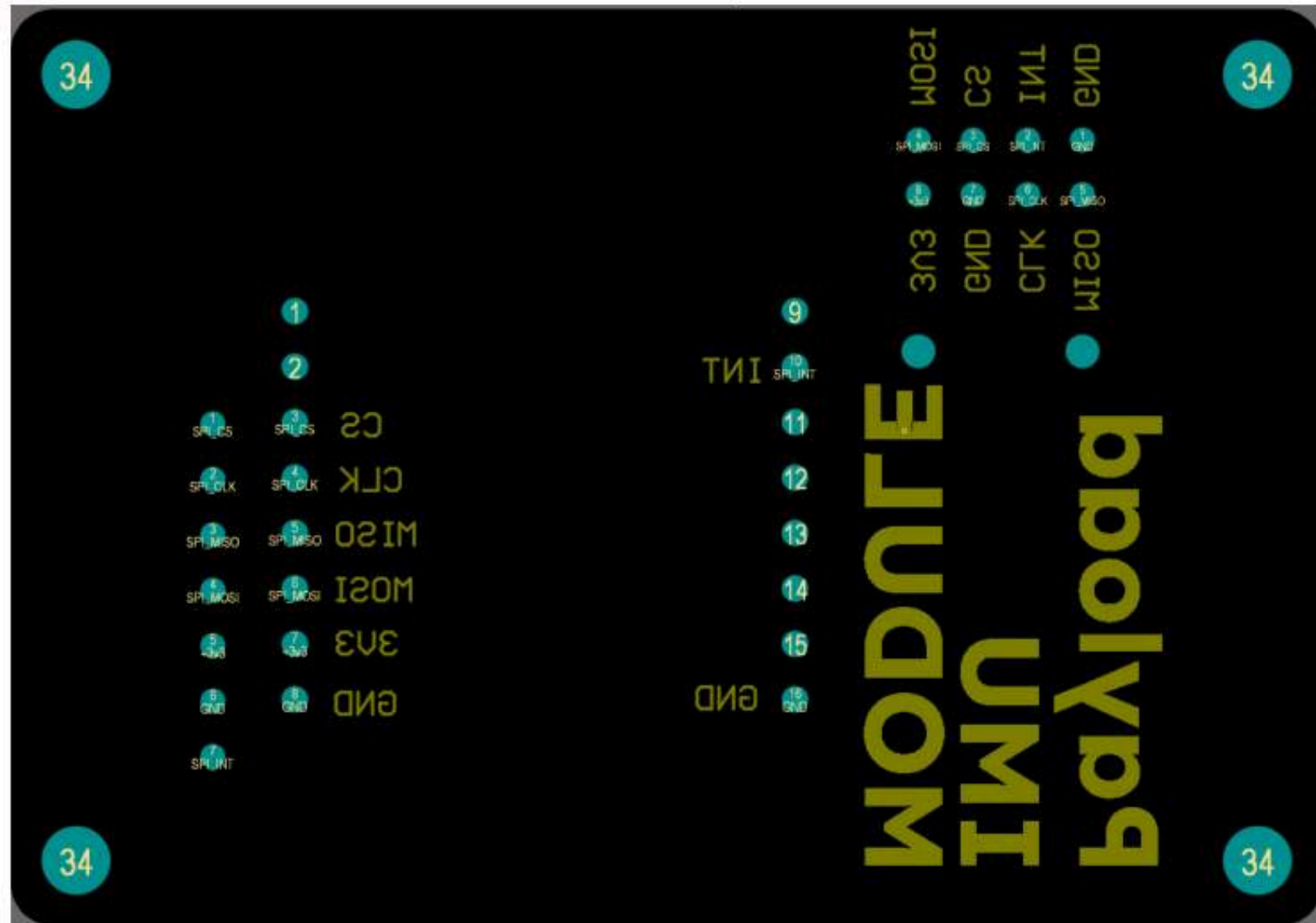


Top solder

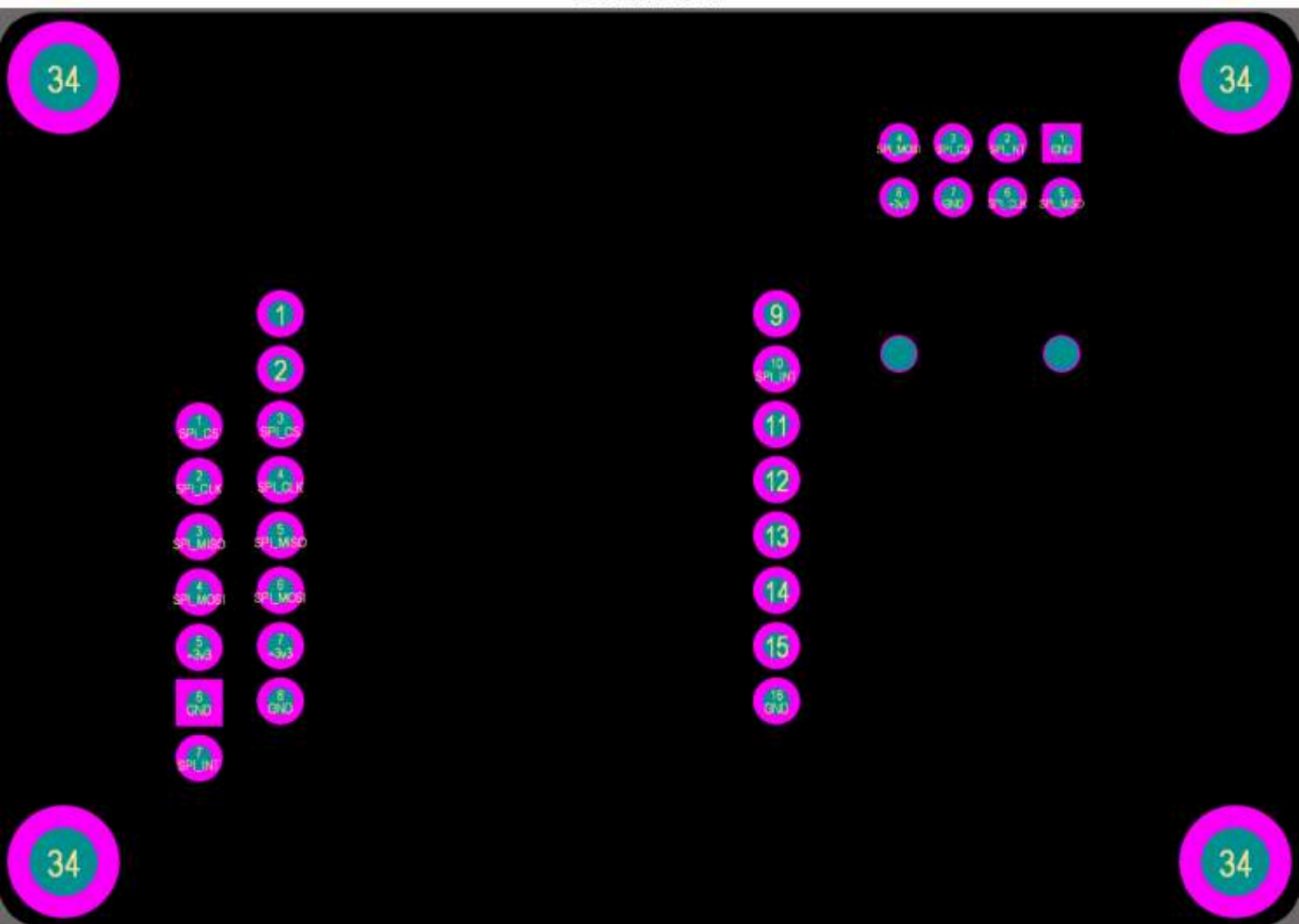


Payload imu holder PCB bottom layers

Bottom overlay

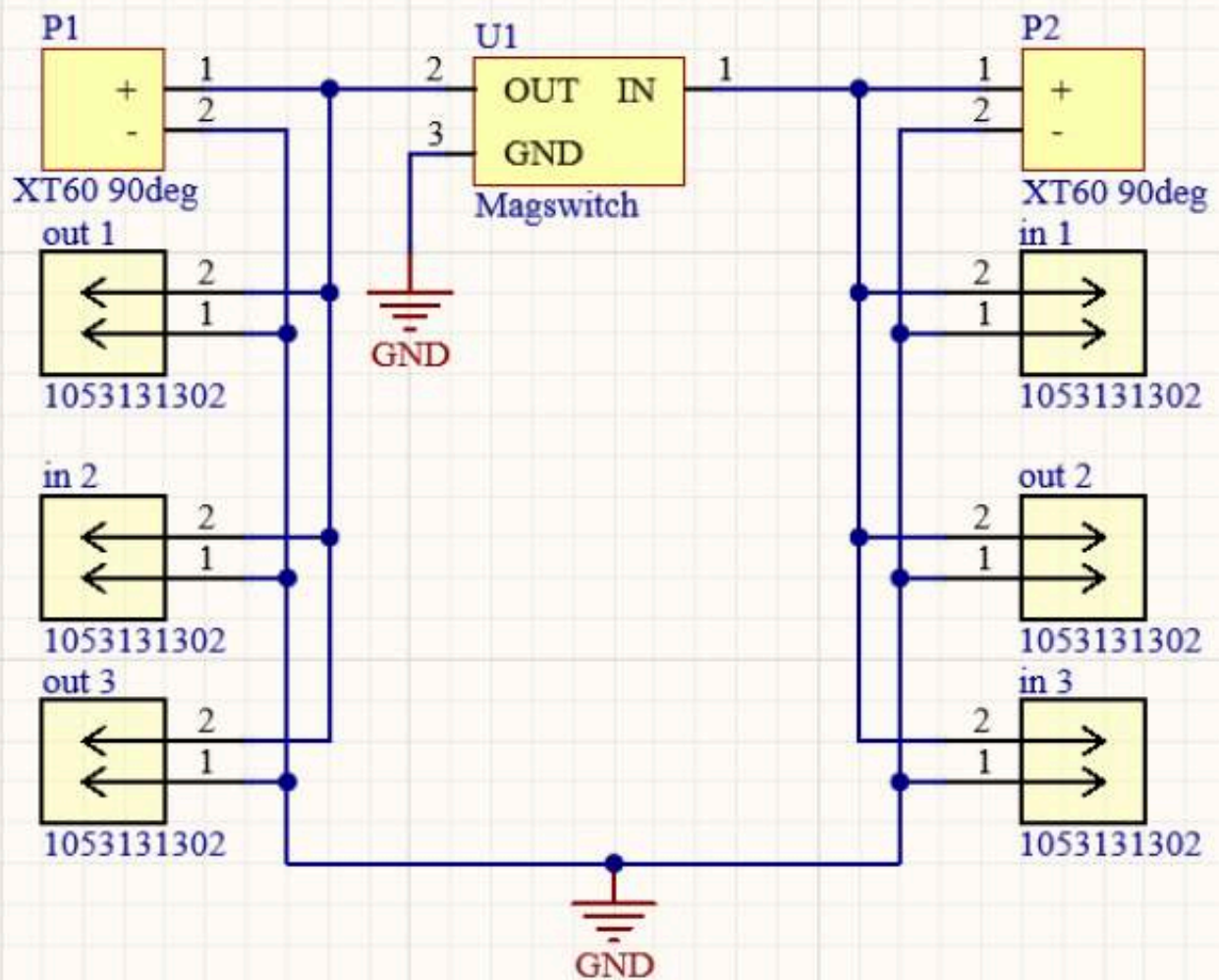


Bottom solder



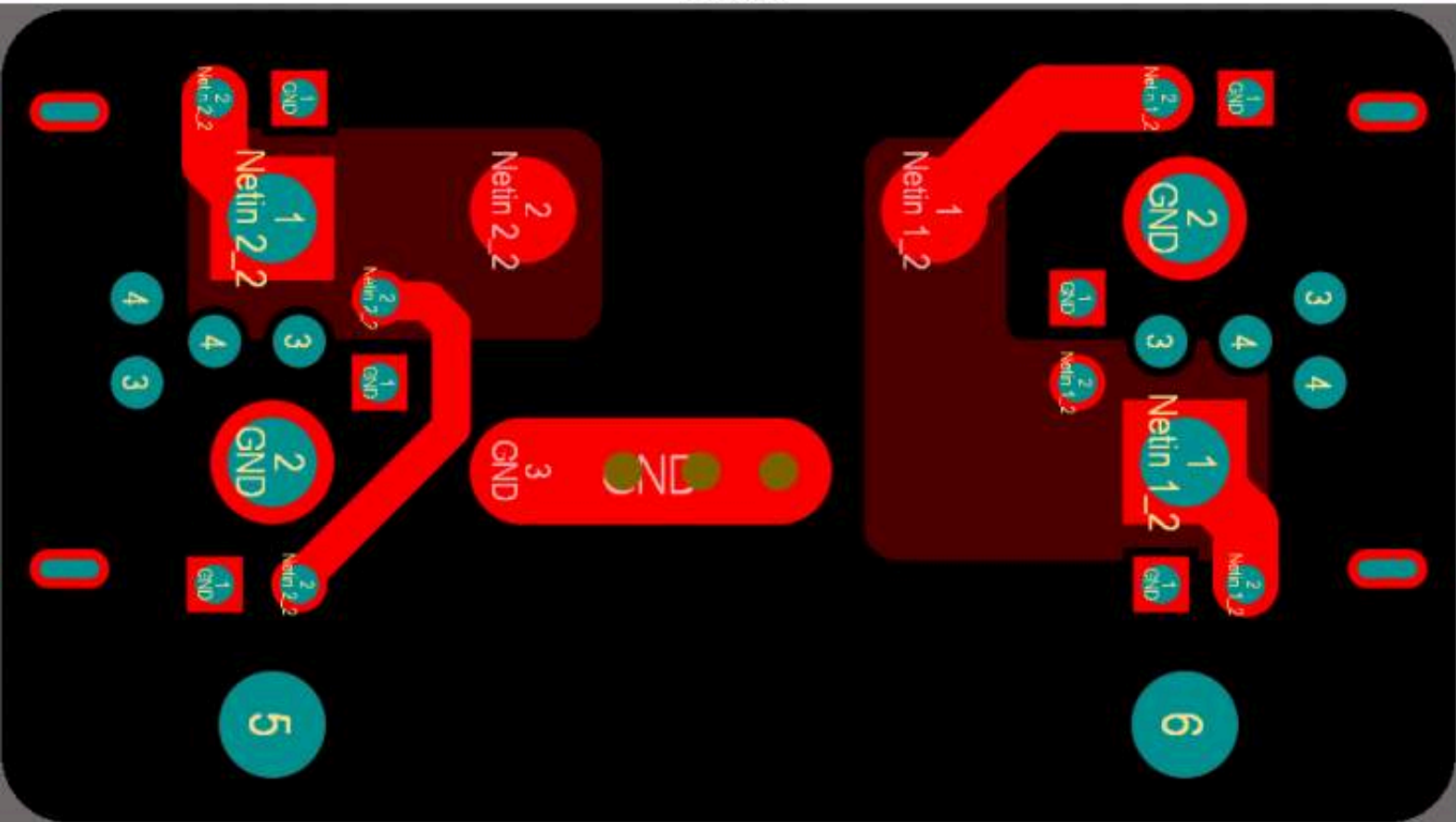
Magswitch schematics

Schematics

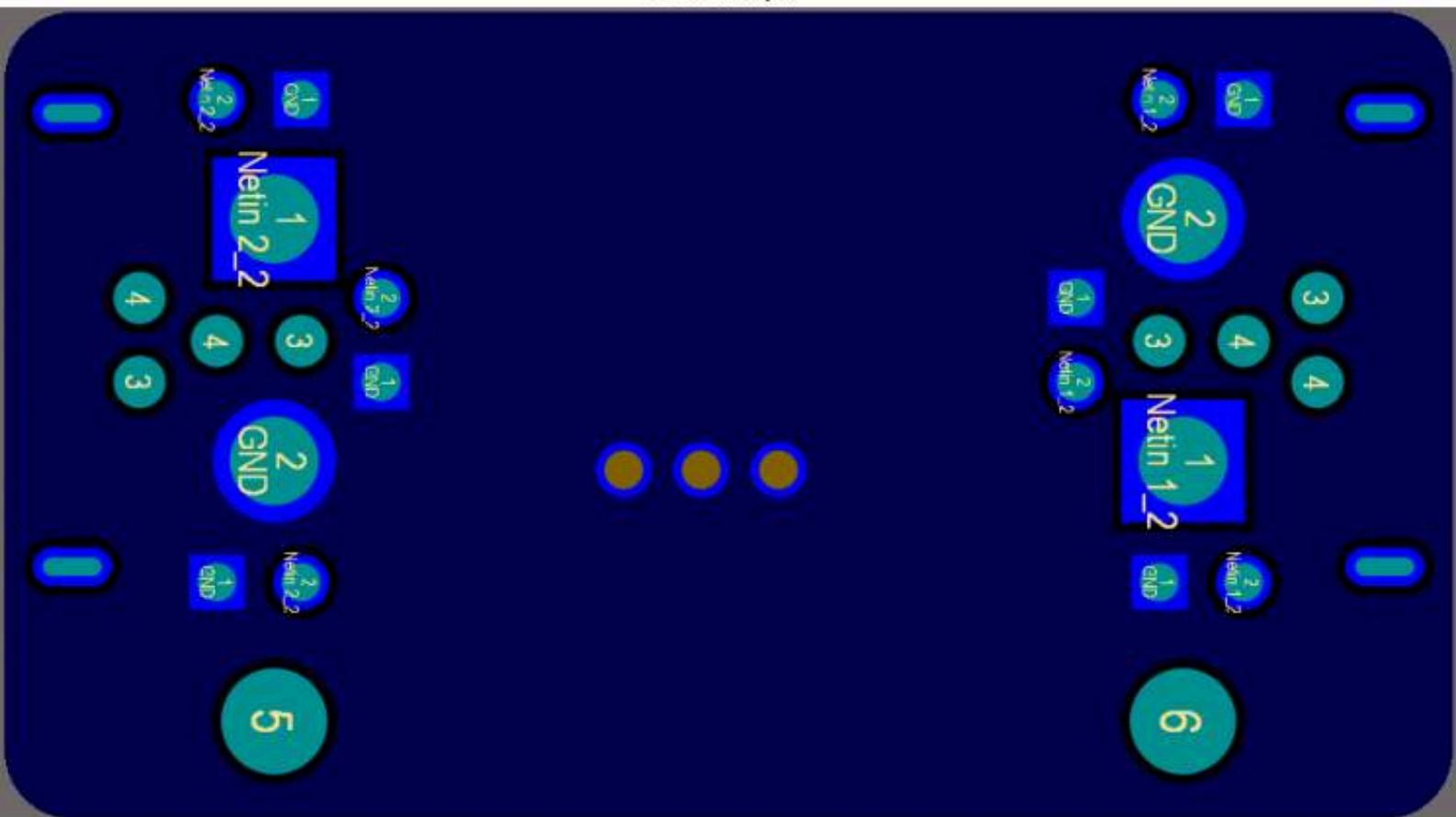


Magswitch PCB signal layers

Top layer

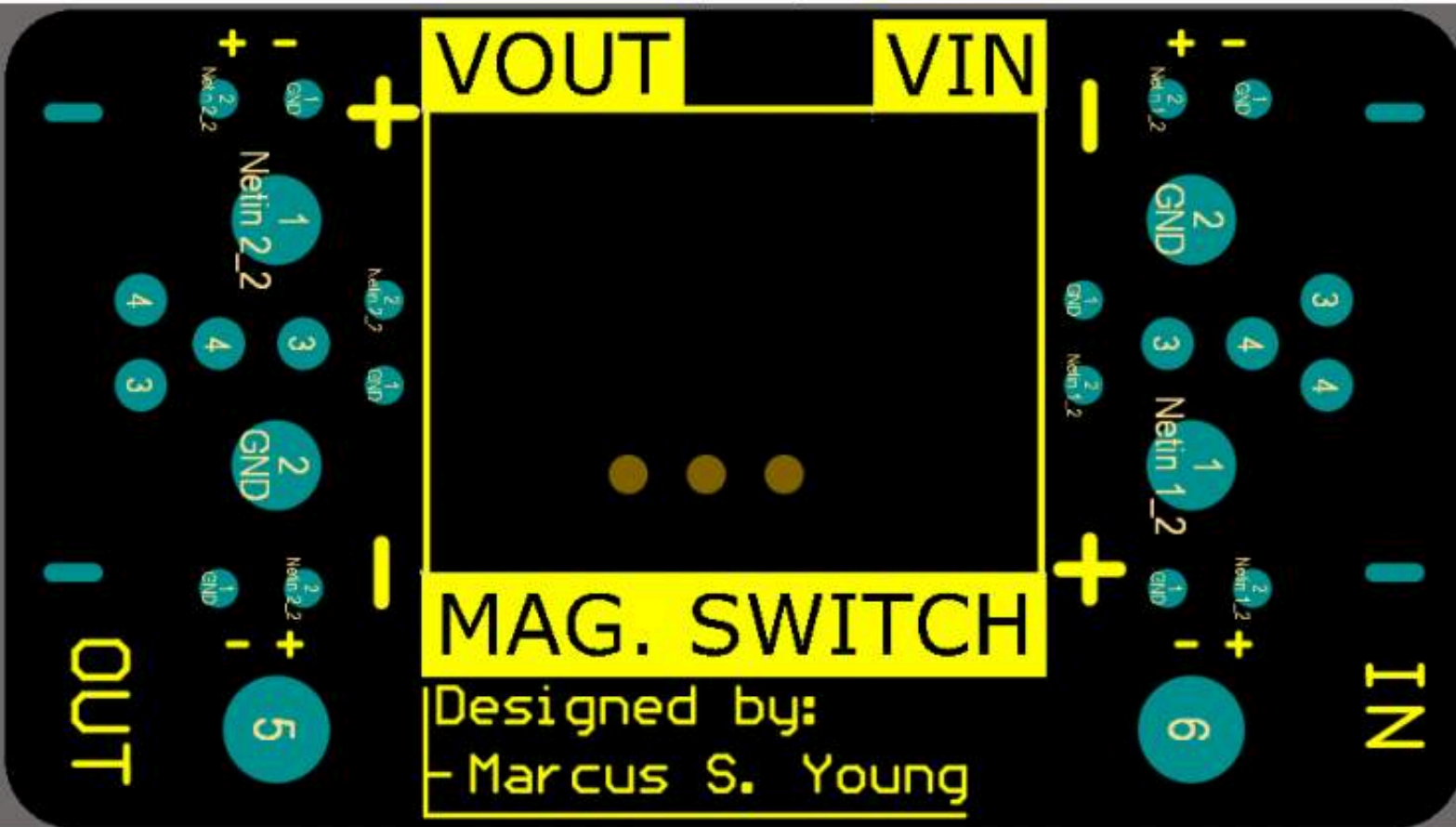


Bottom layer

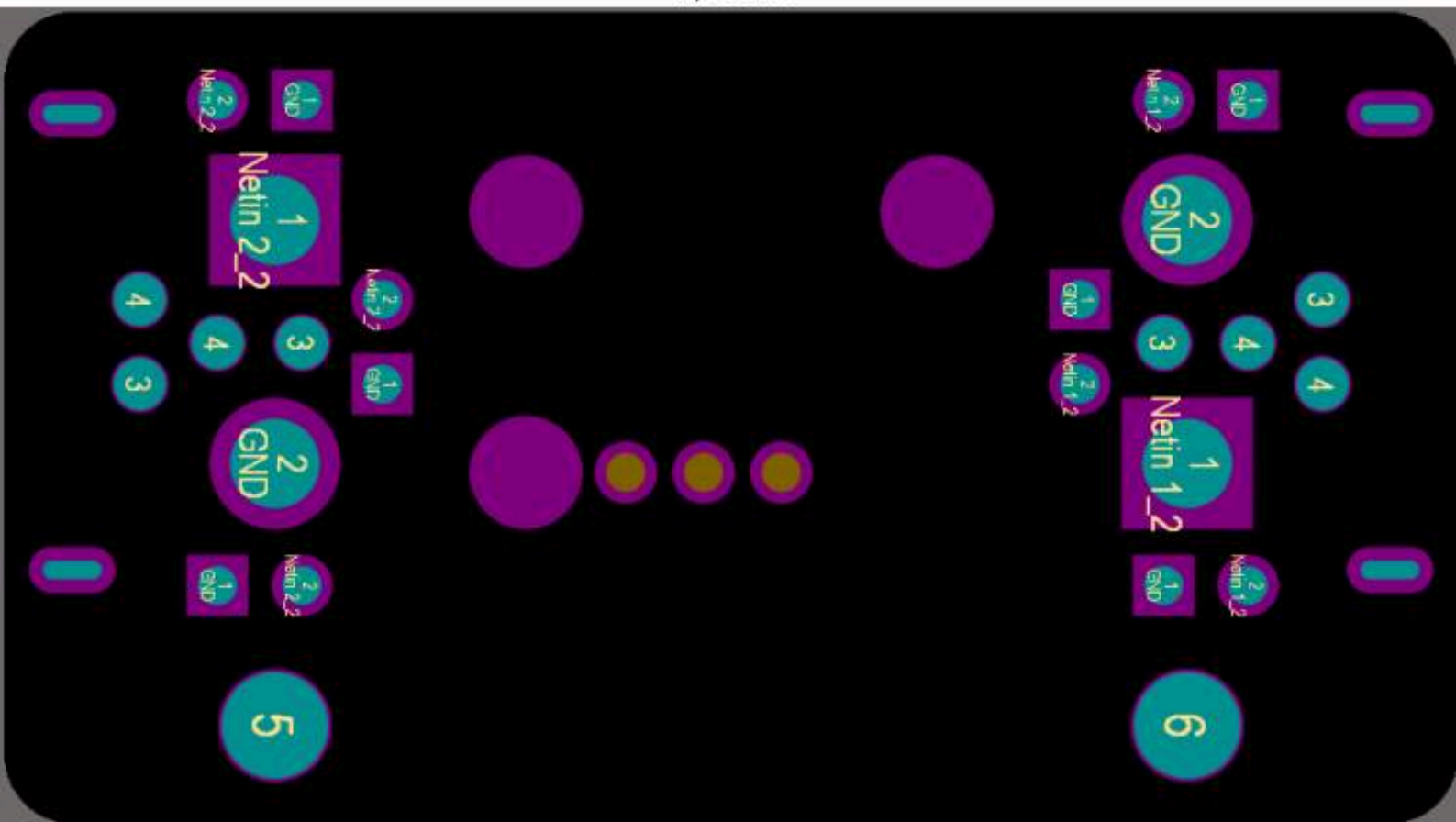


Magswitch PCB top layers

Top overlay

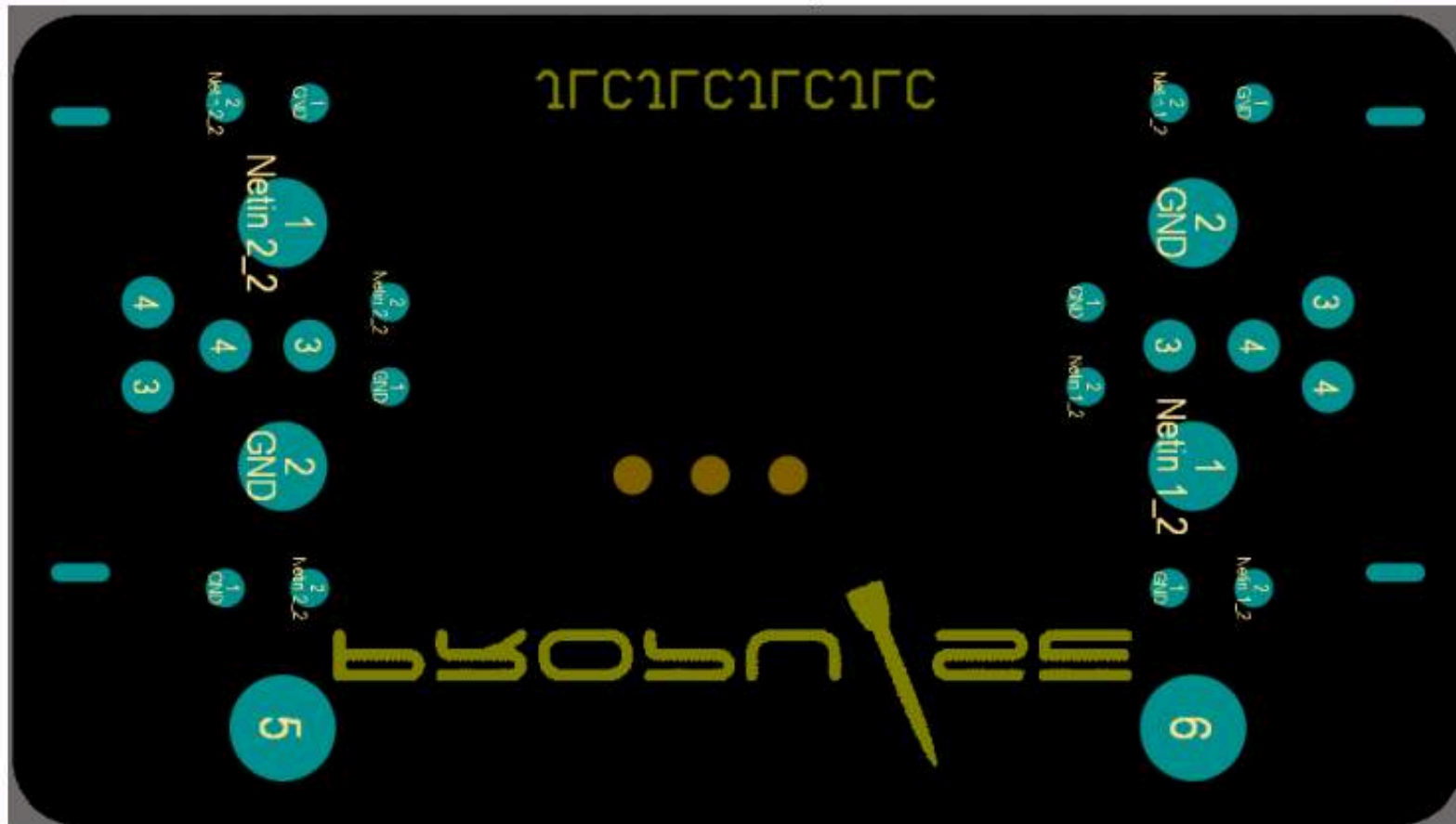


Top solder

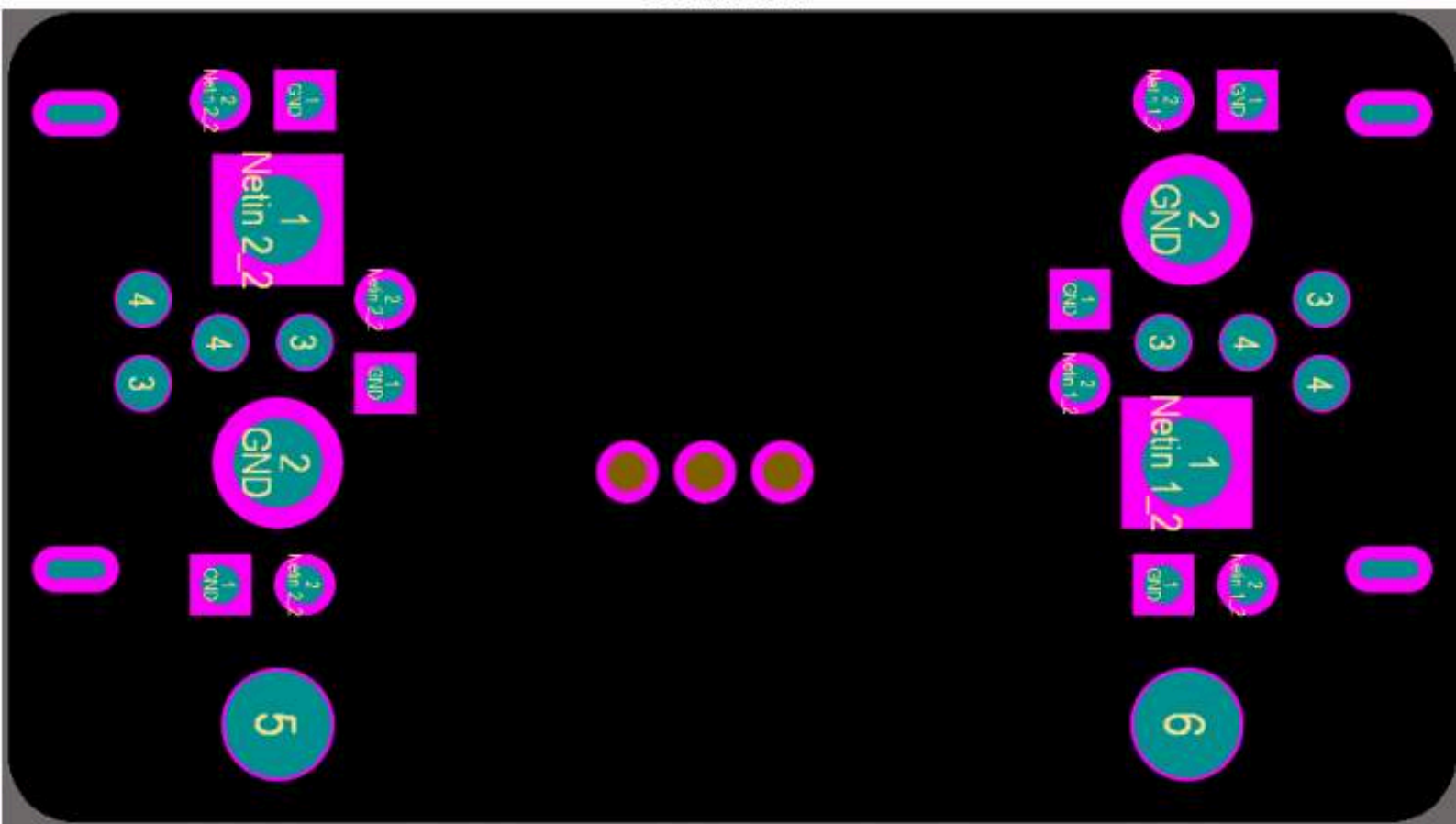


Magswitch PCB bottom layers

Bottom overlay

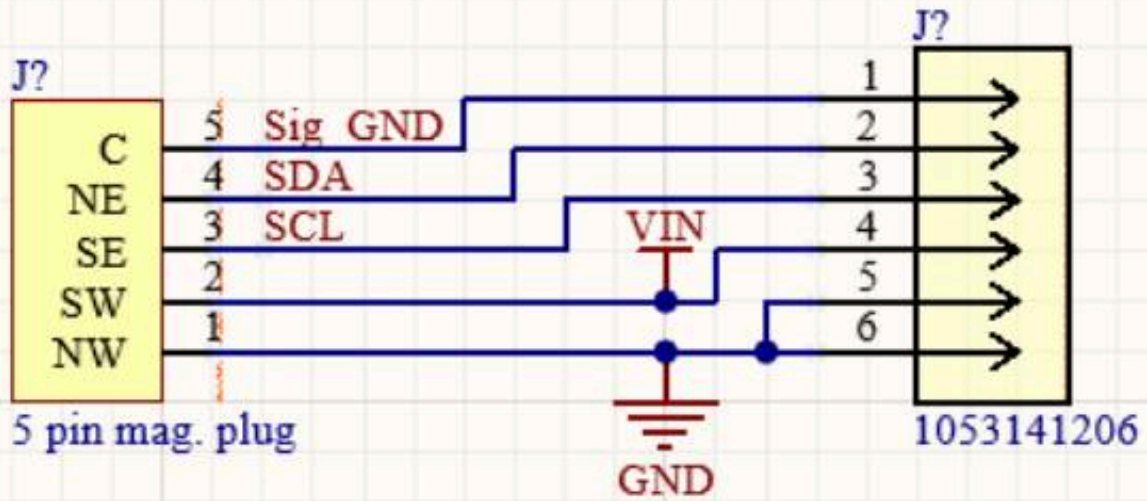


Bottom solder



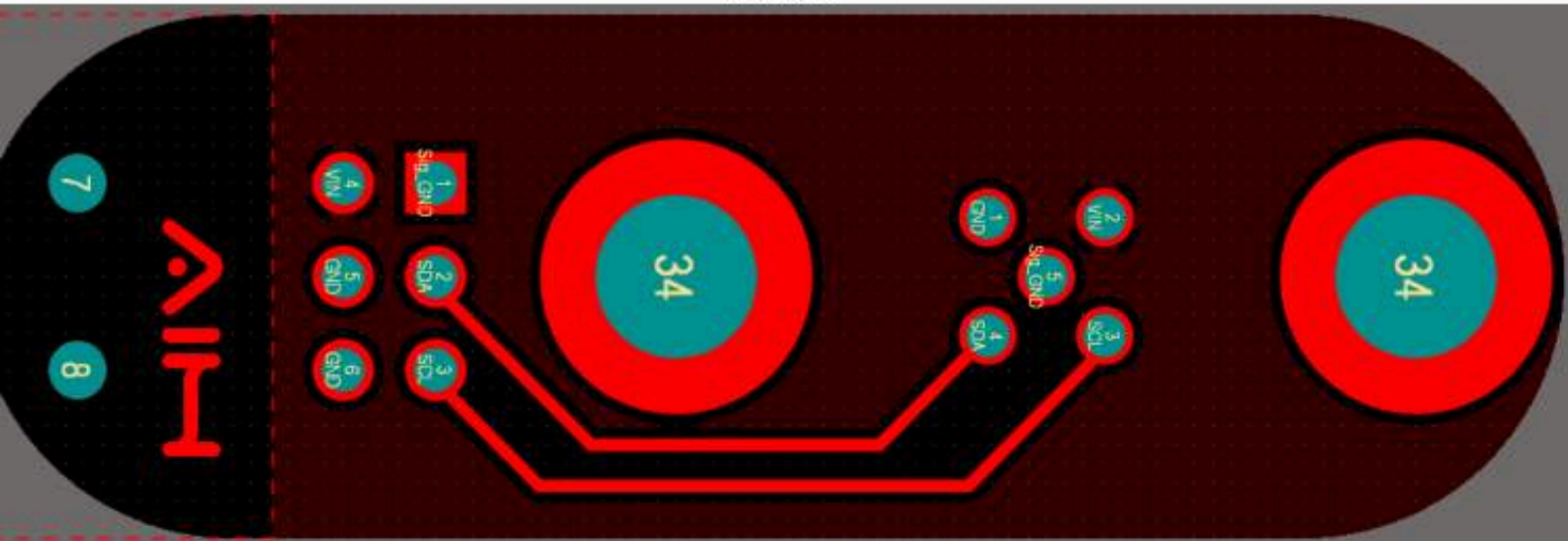
Magnetic plug schematics

Schematics

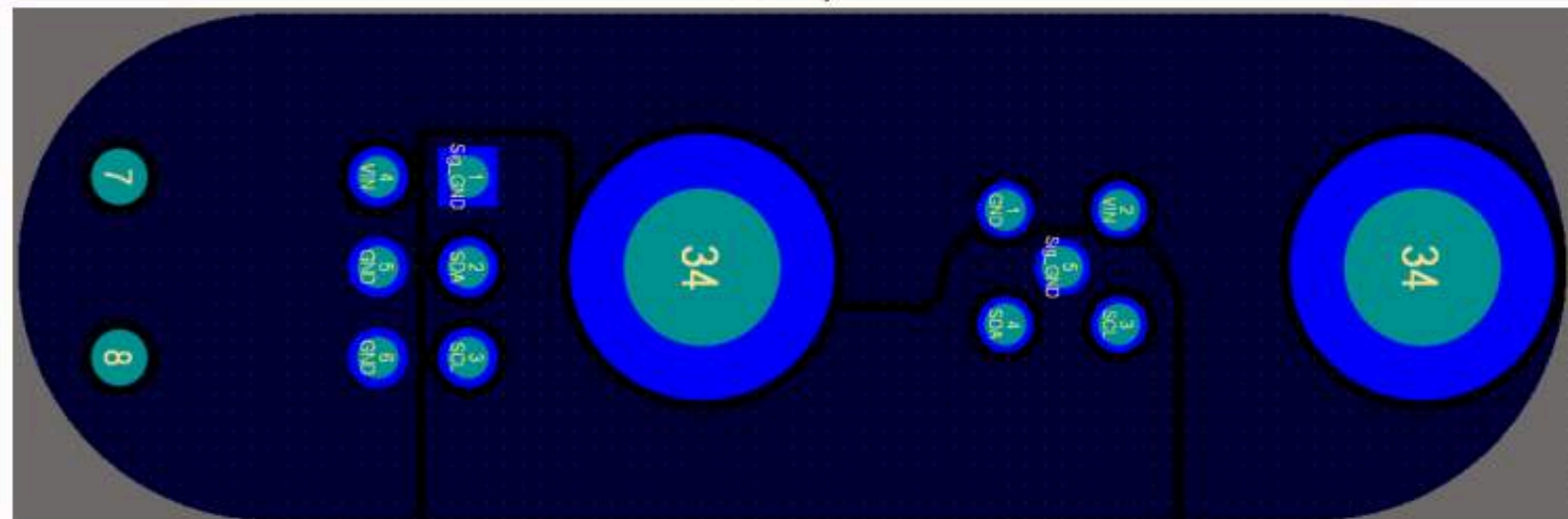


Magnetic plug PCB signal layers

Top layer

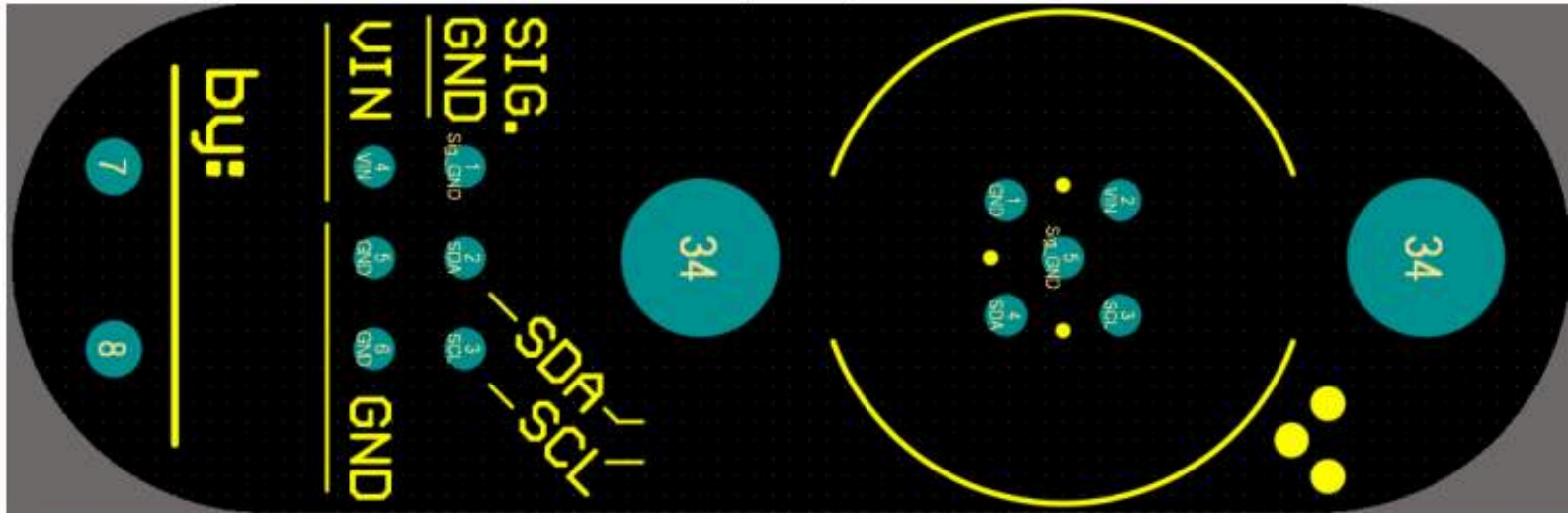


Bottom layer

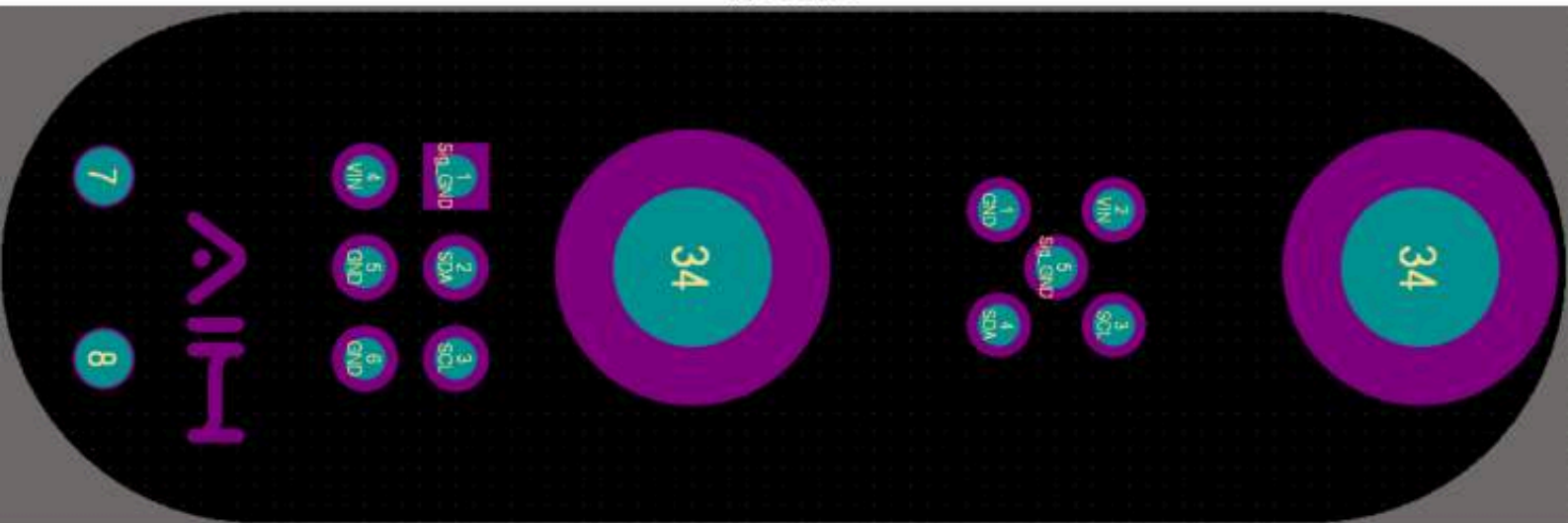


Magnetic plug PCB top layers

Top overlay

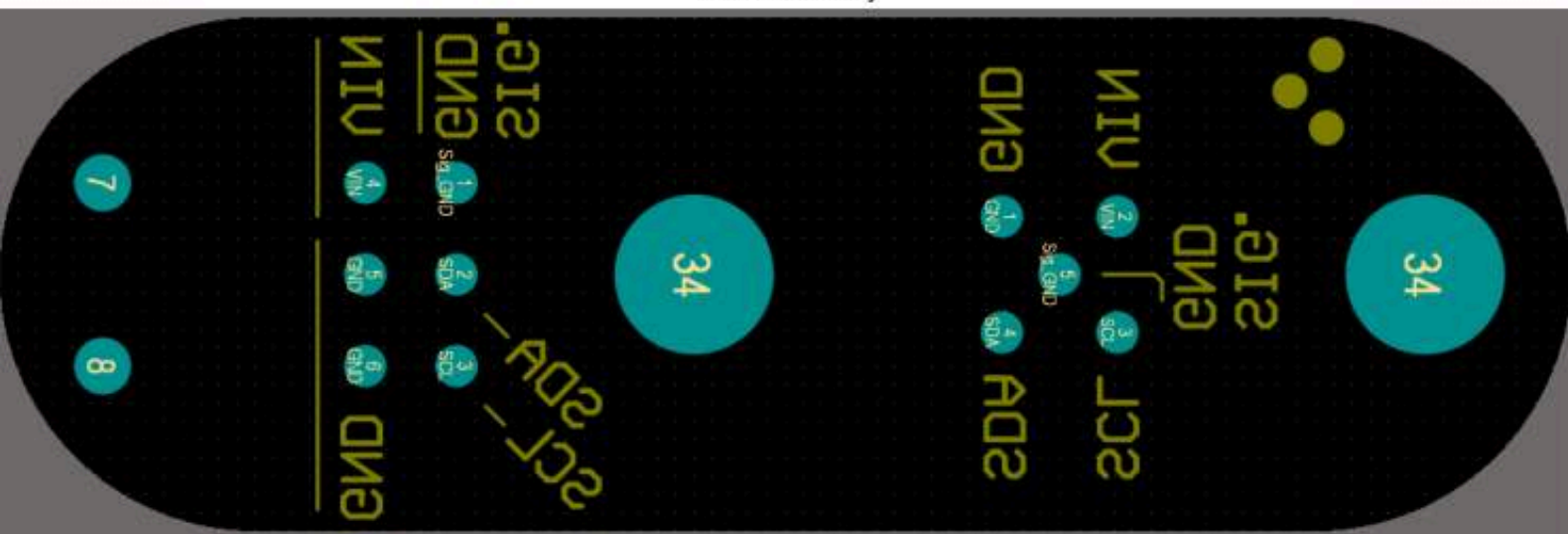


Top solder

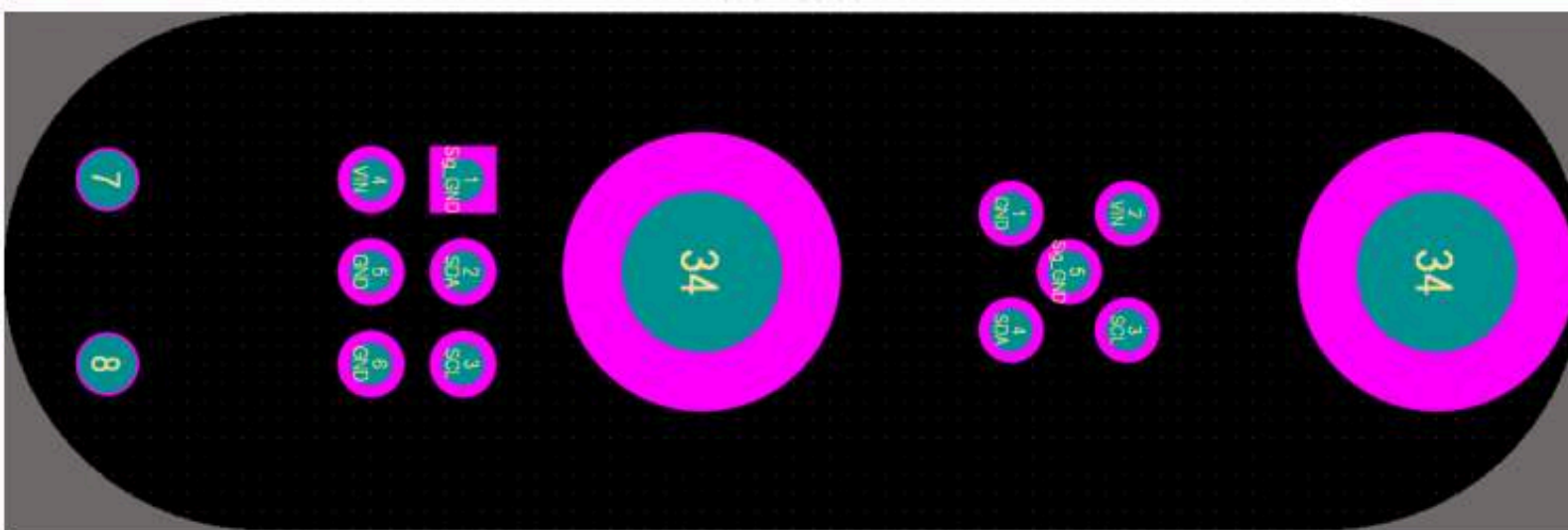


Magnetic plug PCB bottom layers

Bottom overlay

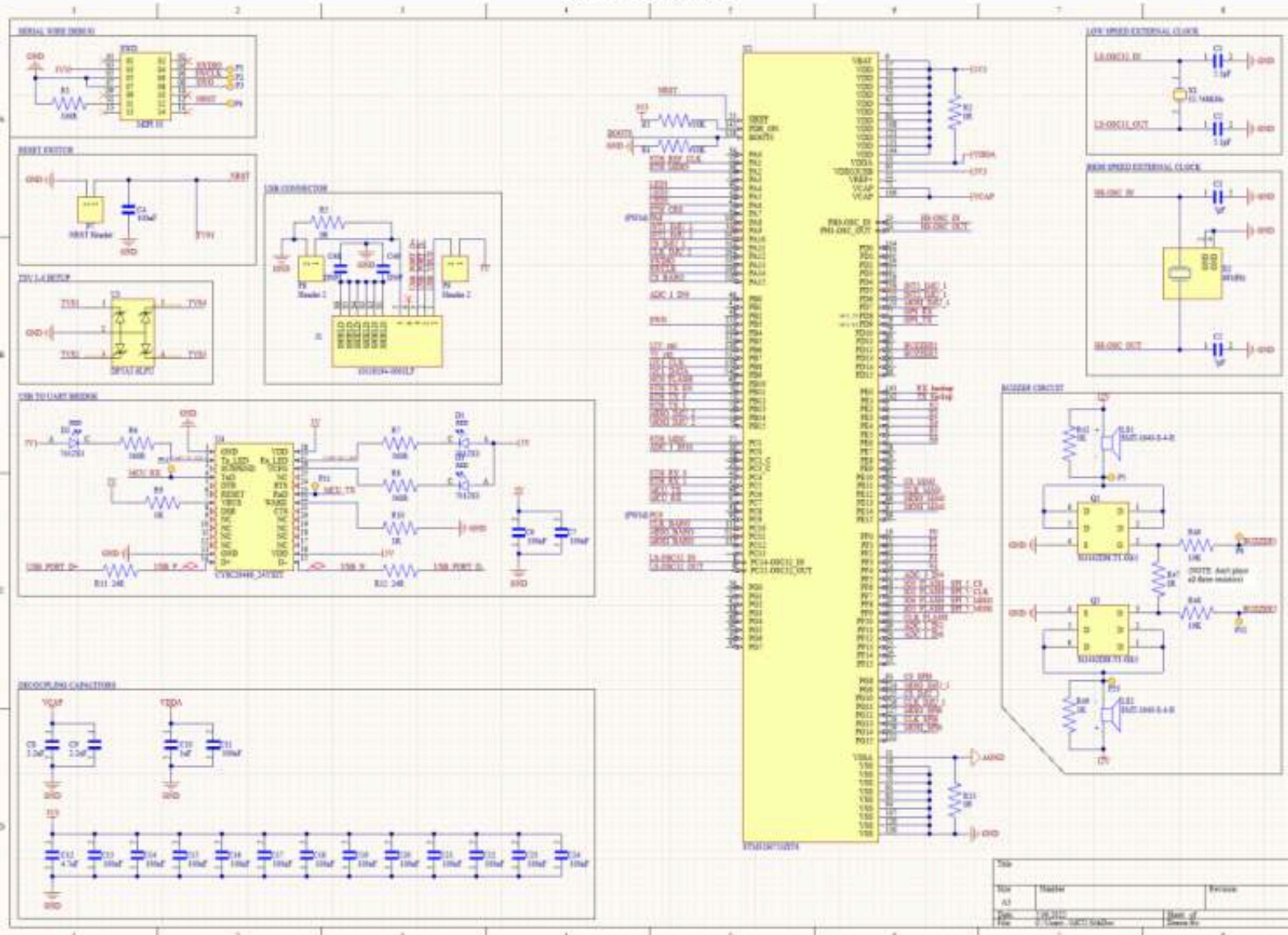


Bottom solder



KB3 schematics

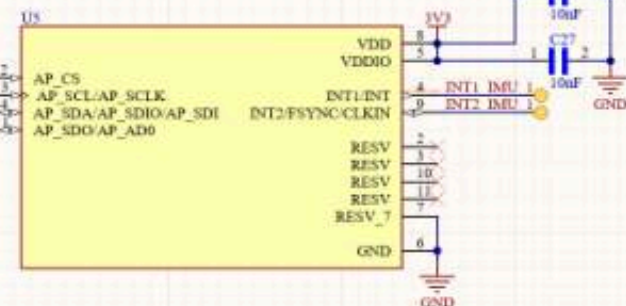
MCU schematics



Sensor schematics

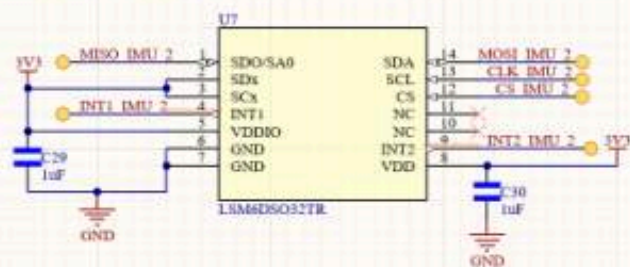
High speed and accurate IMU

SPI 1 - IMU 1
PG 11, 10, 9 || PD 7



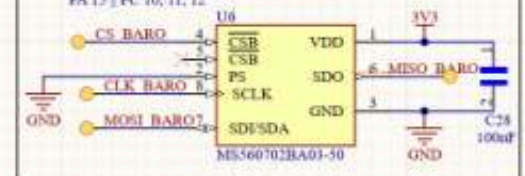
High range IMU

SPI 2 - IMU 2
PA 9, 10, 11, 12 || PB 14, 15



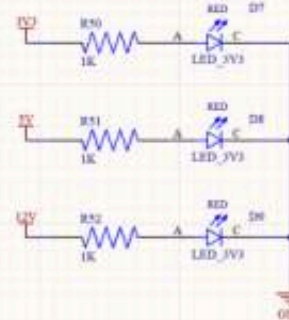
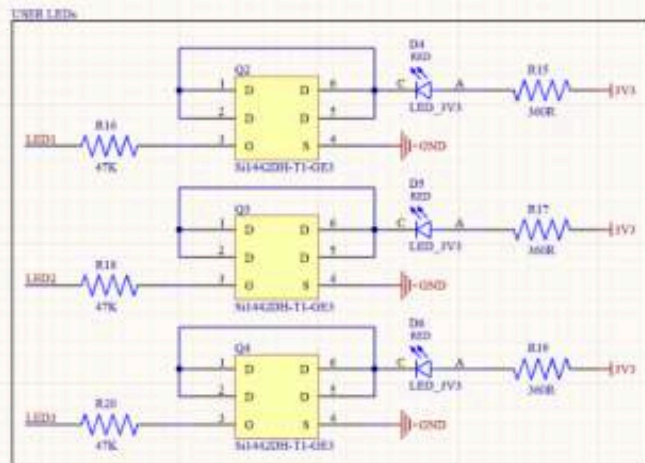
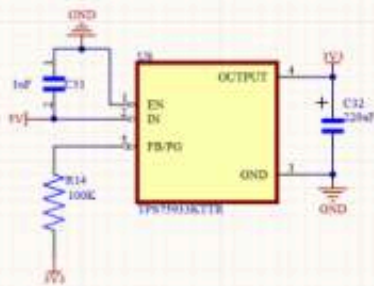
Barometer

SPI 3
PA 15 || PC 10, 11, 12

Title
Sensor schematics

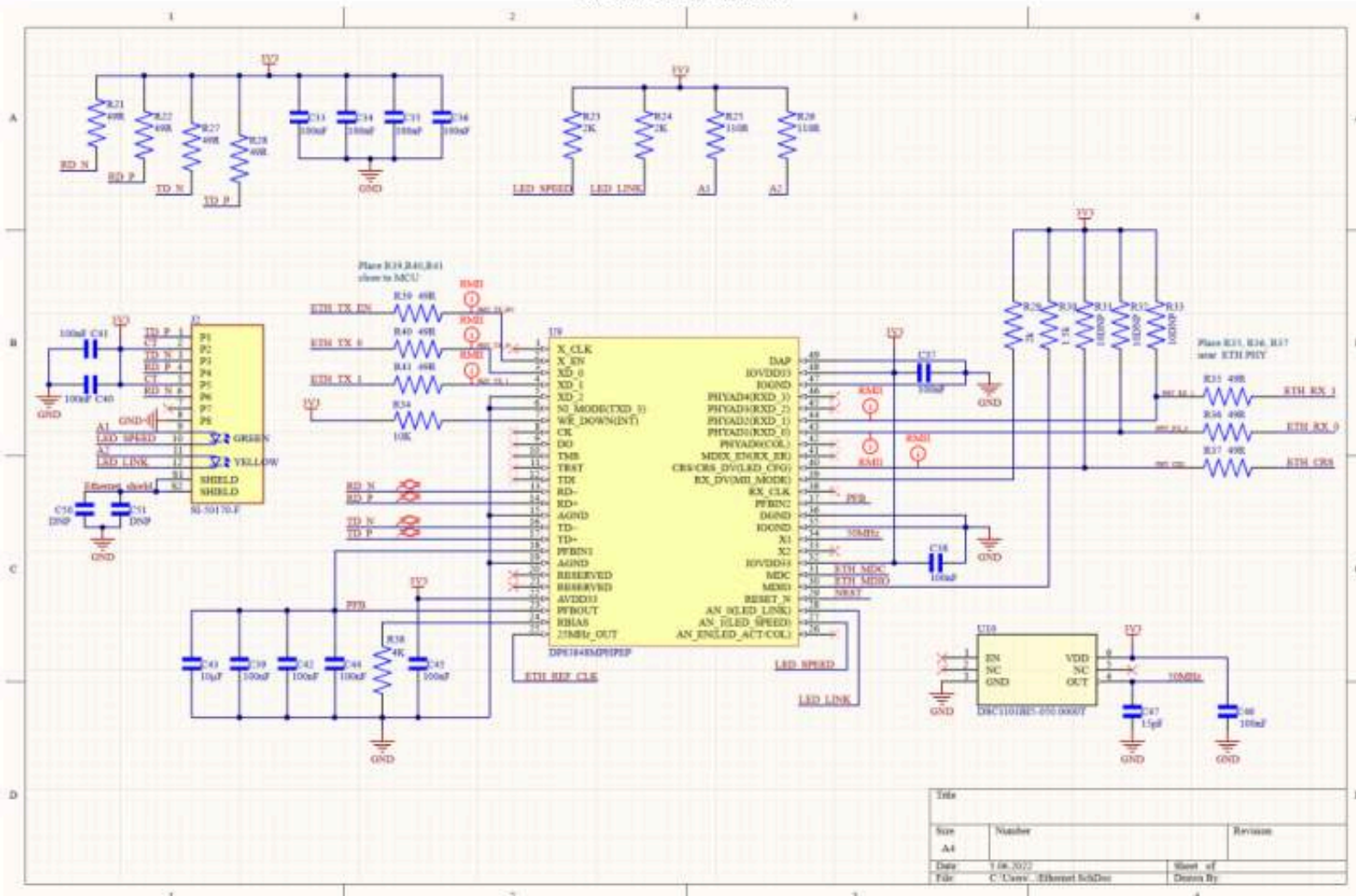
Size	Number	Revision
A4		
Date:	5.06.2022	Sheet of
File:	C:\Users\...Sensors\SchDoc	Drawn By:

Regulator and LED schematics

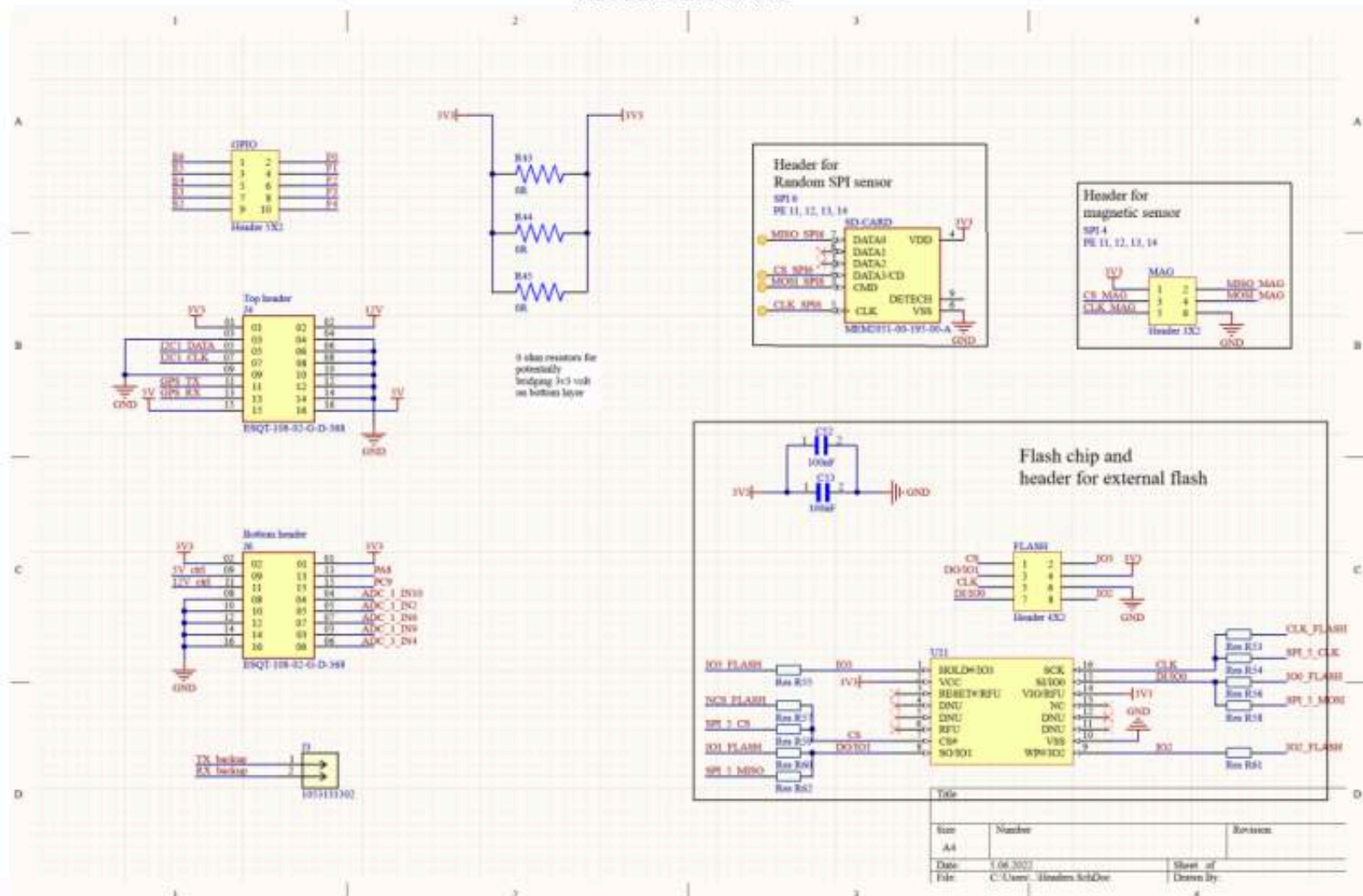


Title		
Size	Number	Revision
A4		
Date:	5.06.2022	Sheet of
File:	C:\Users\Regulator_LEDs\Documents	Drawn By

Ethernet schematics

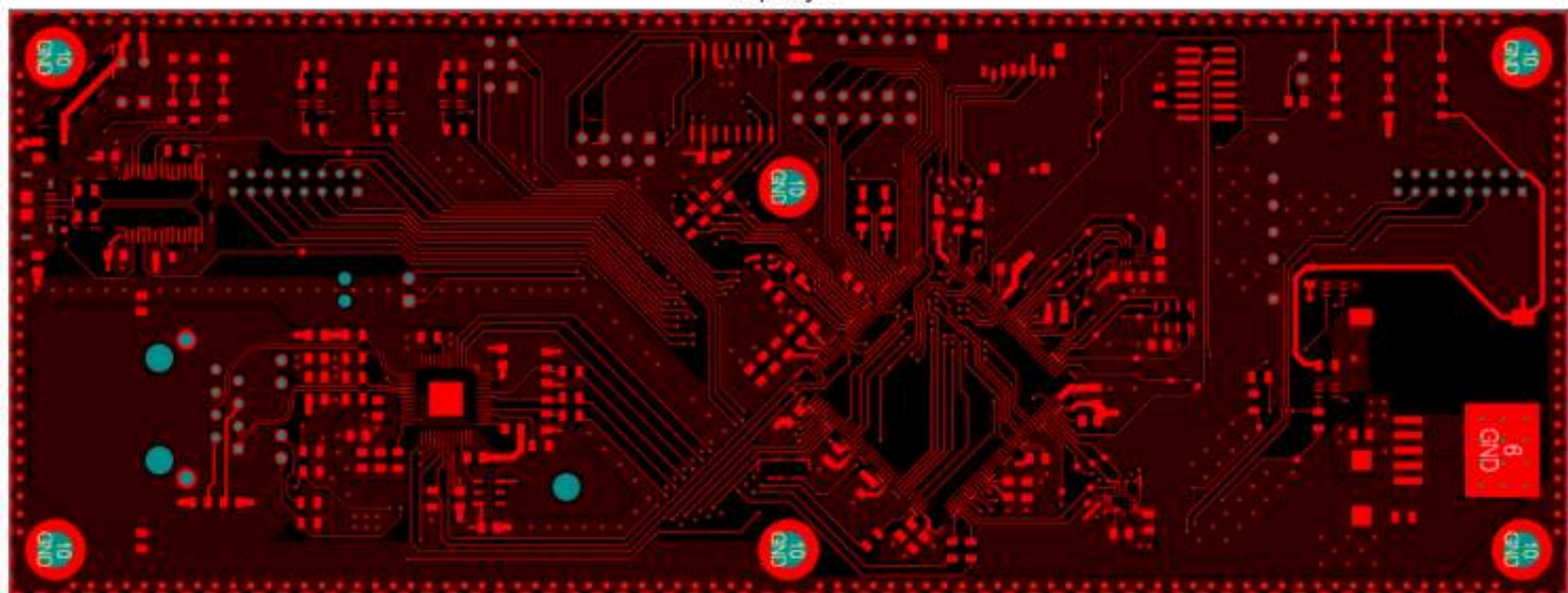


Header schematics

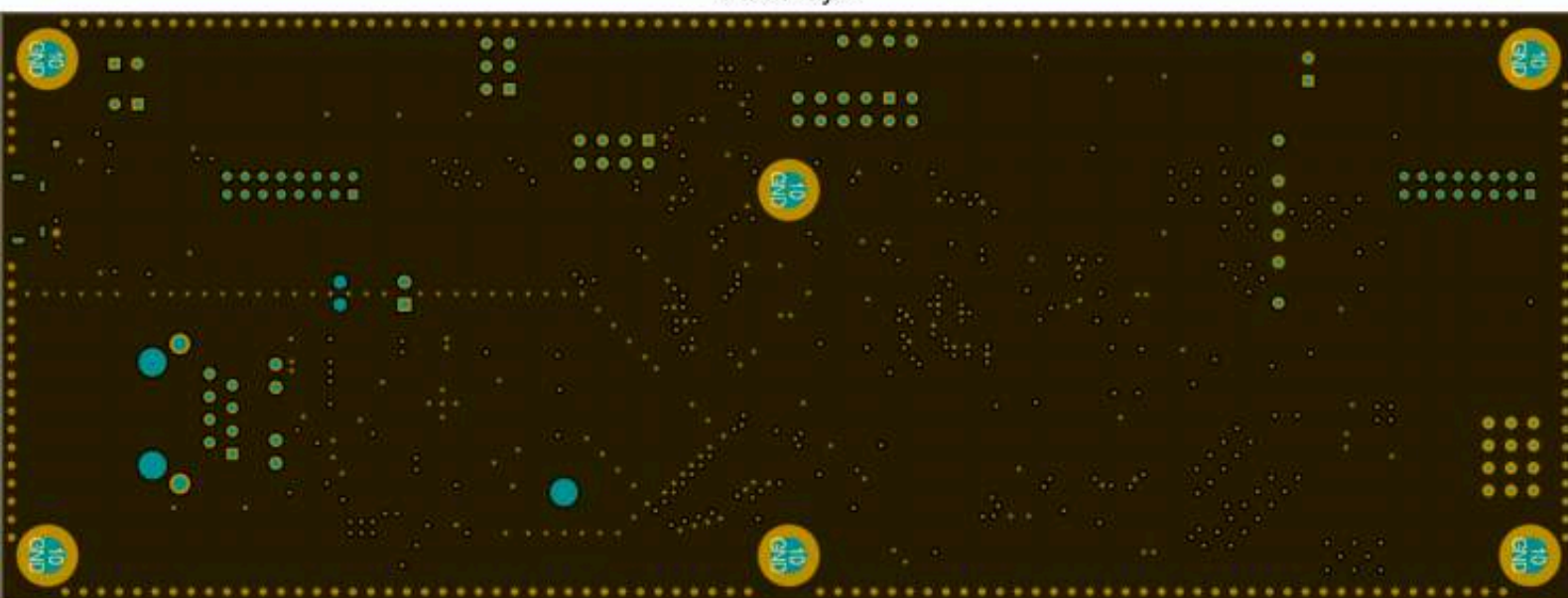


KB3 PCB signal layers

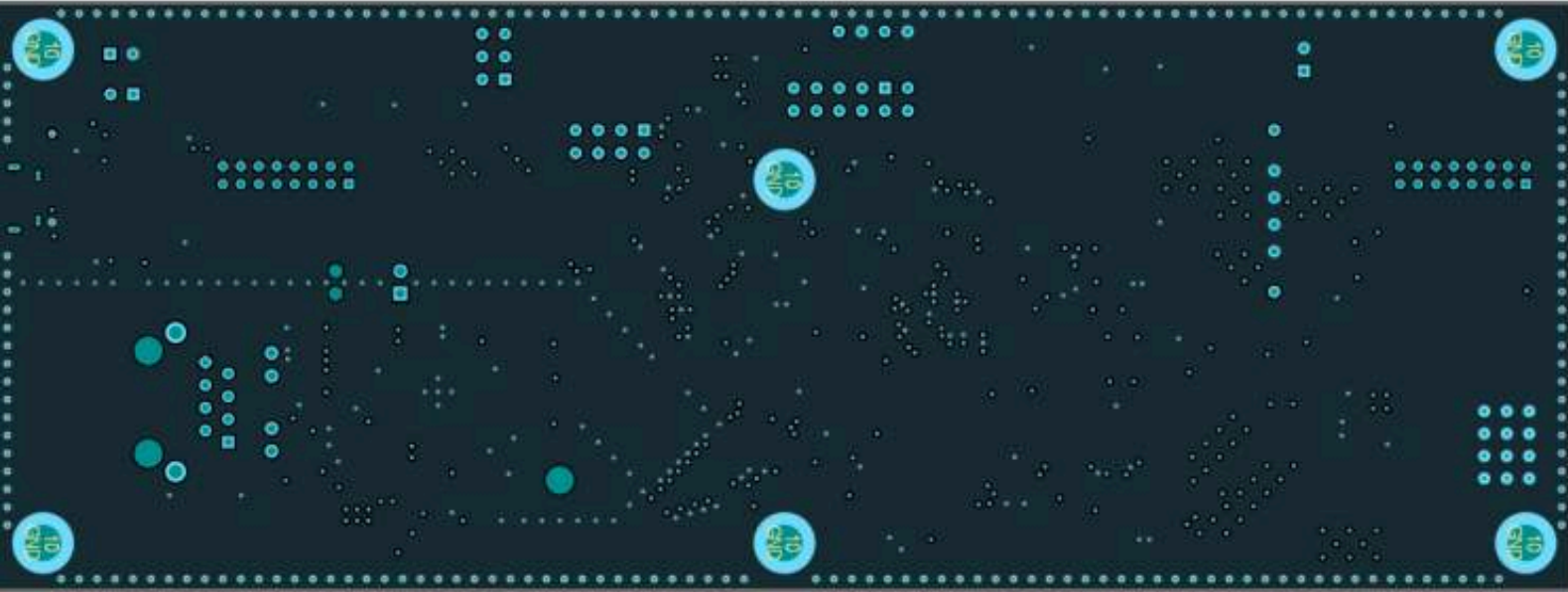
Top layer



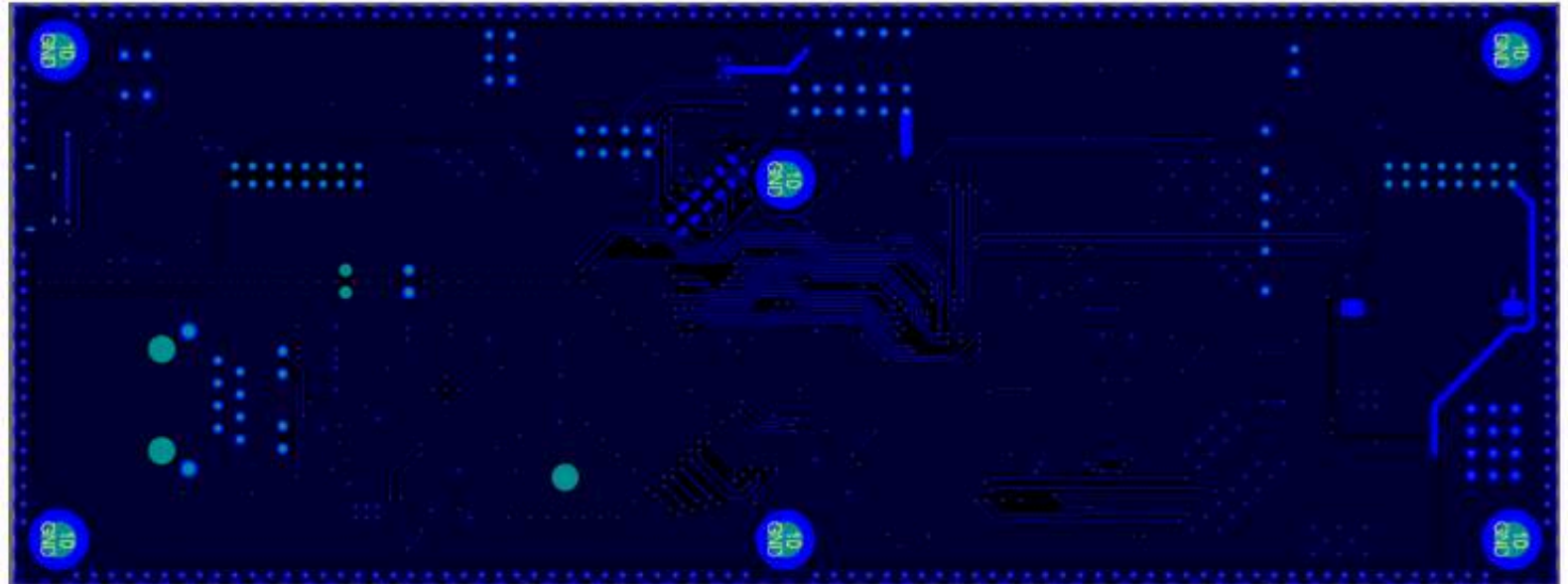
GND1 layer



GND2 layer

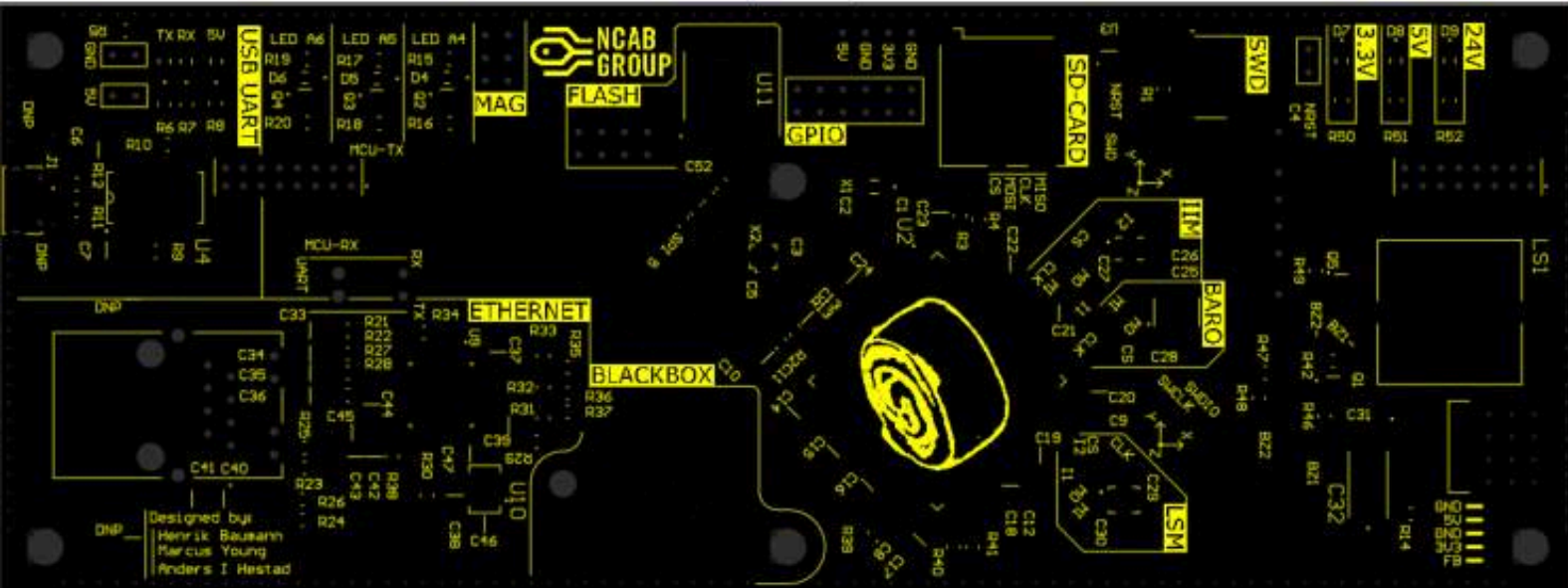


Bottom layer

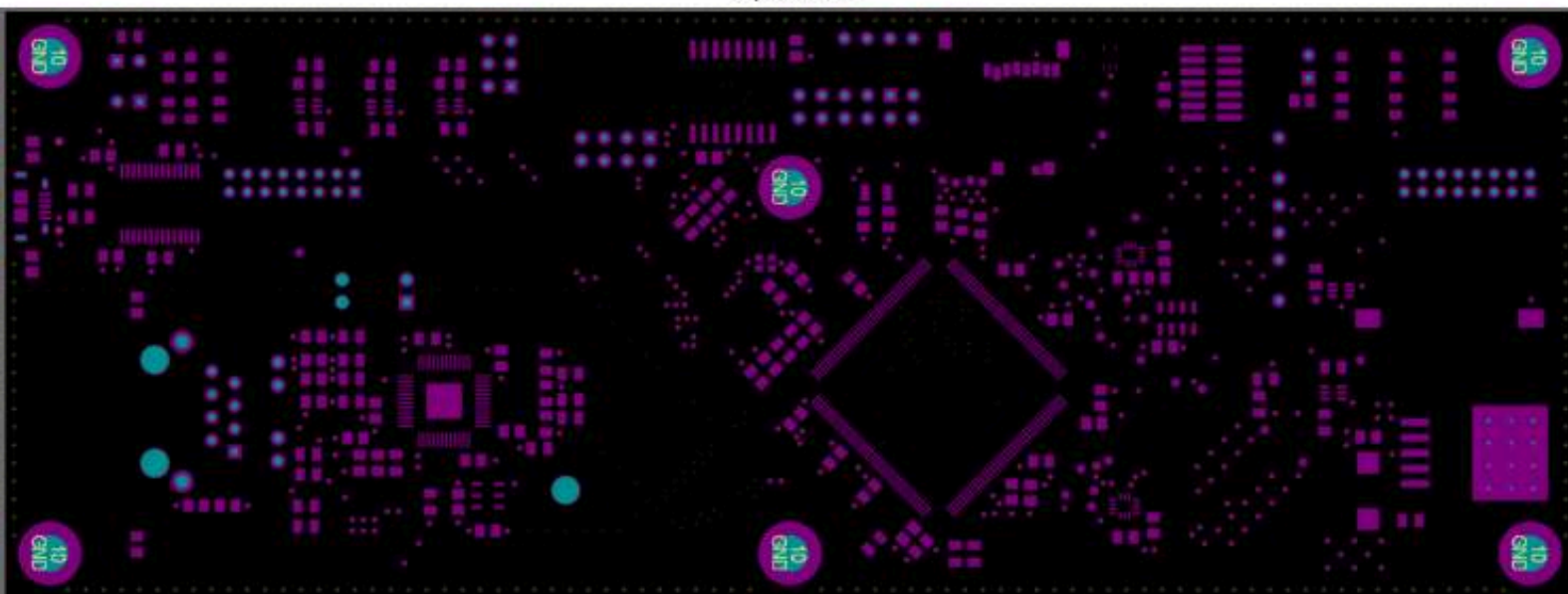


KB3 PCB top layers

Top overlay

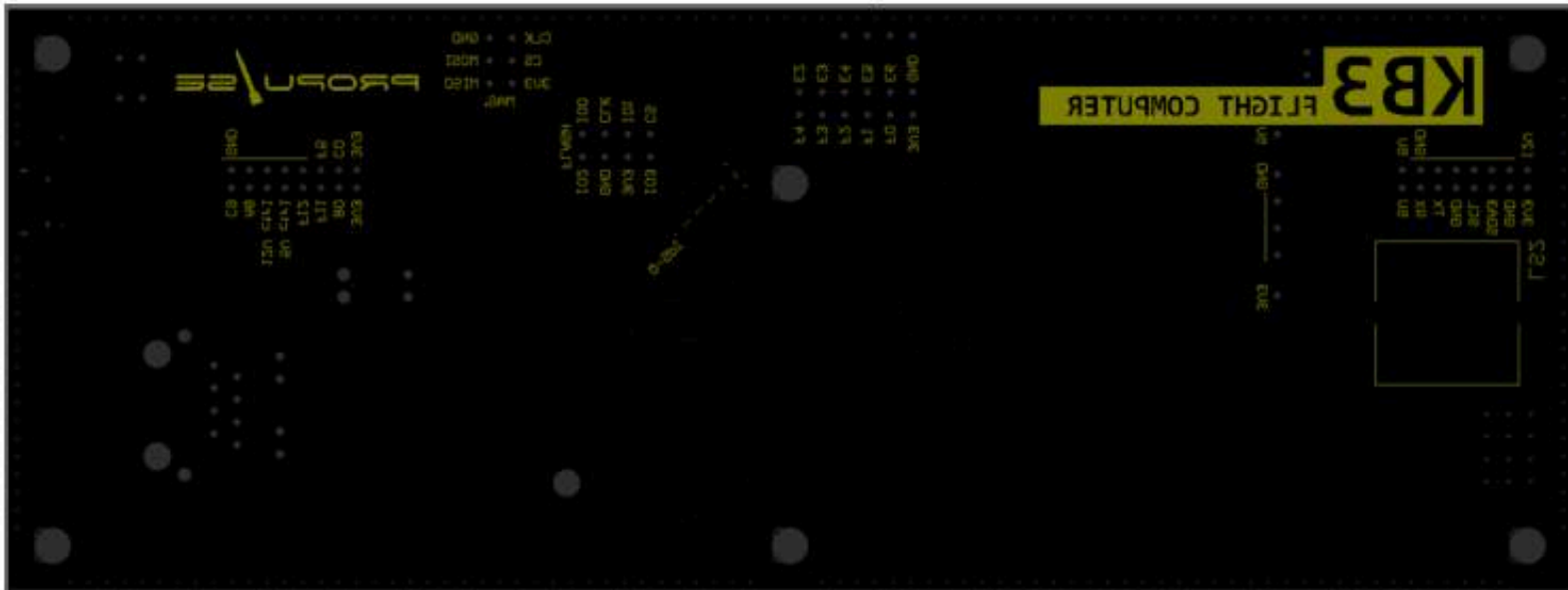


Top solder

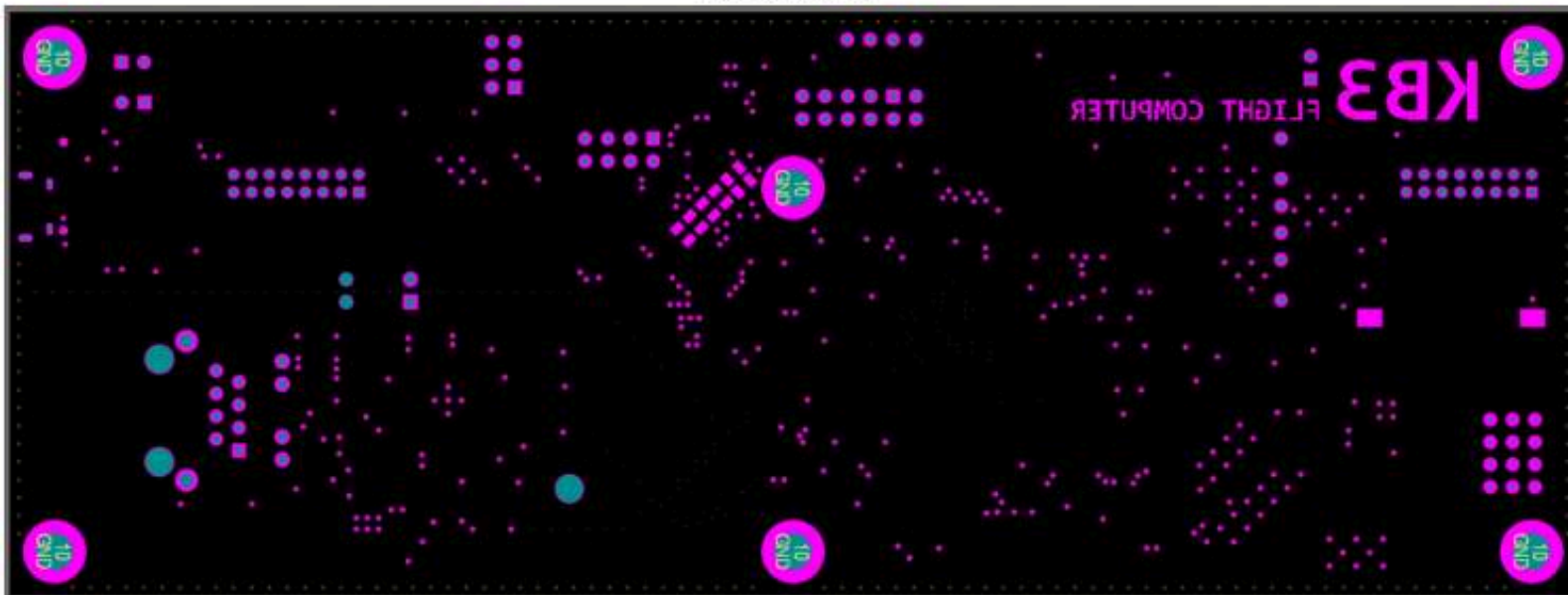


KB3 PCB bottom layers

Bottom overlay

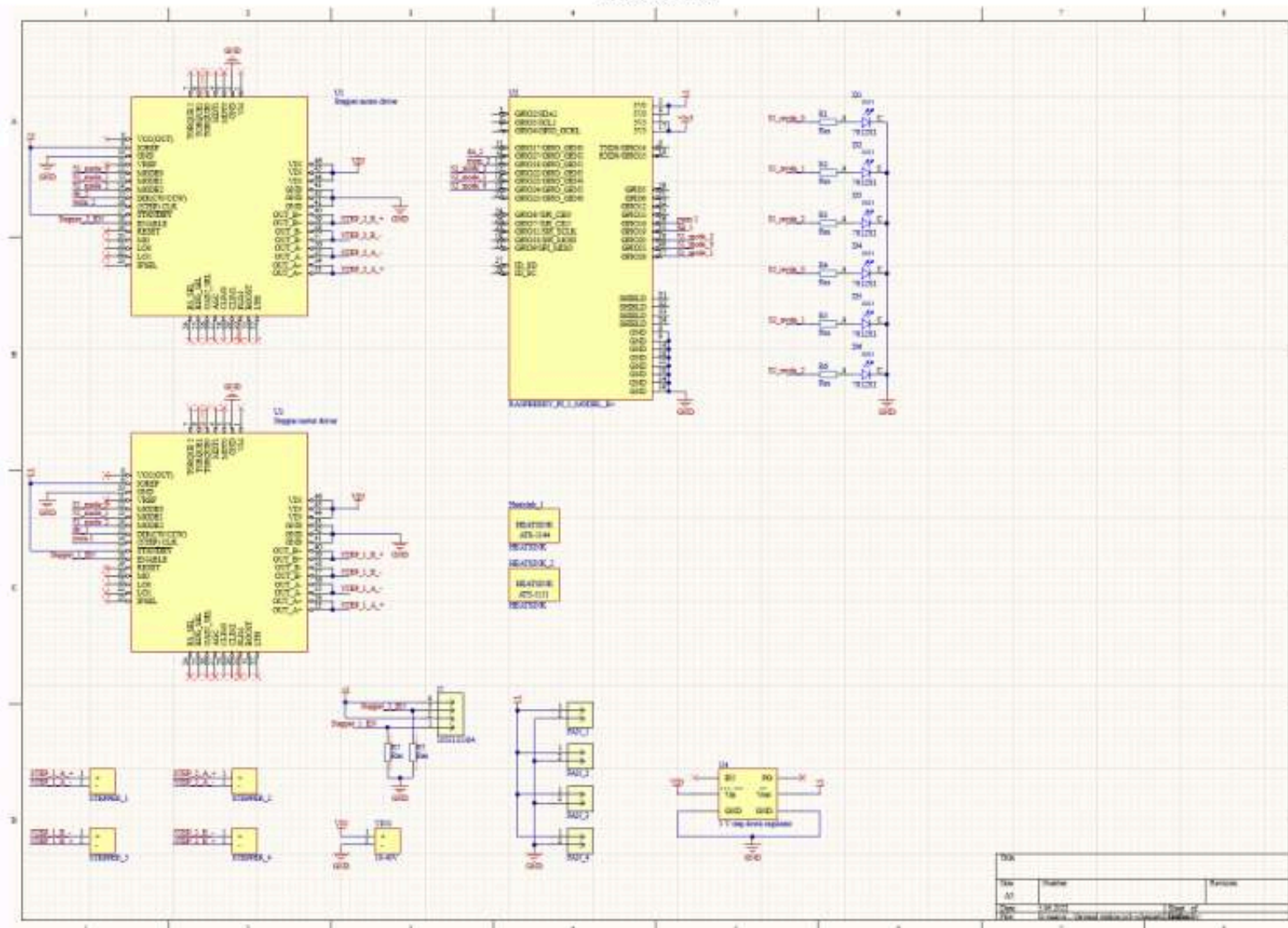


Bottom solder



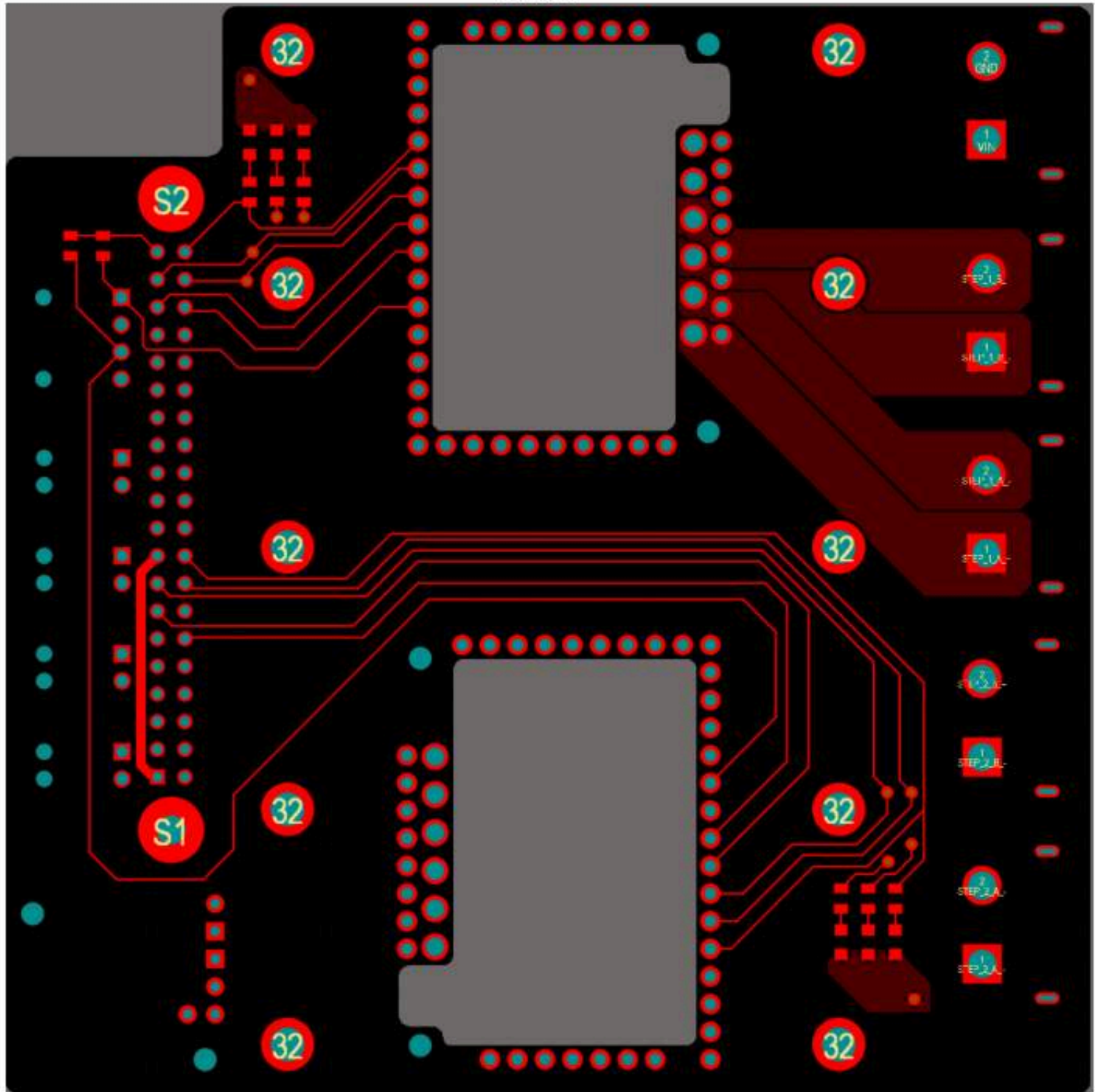
Ground station schematics

Schematics

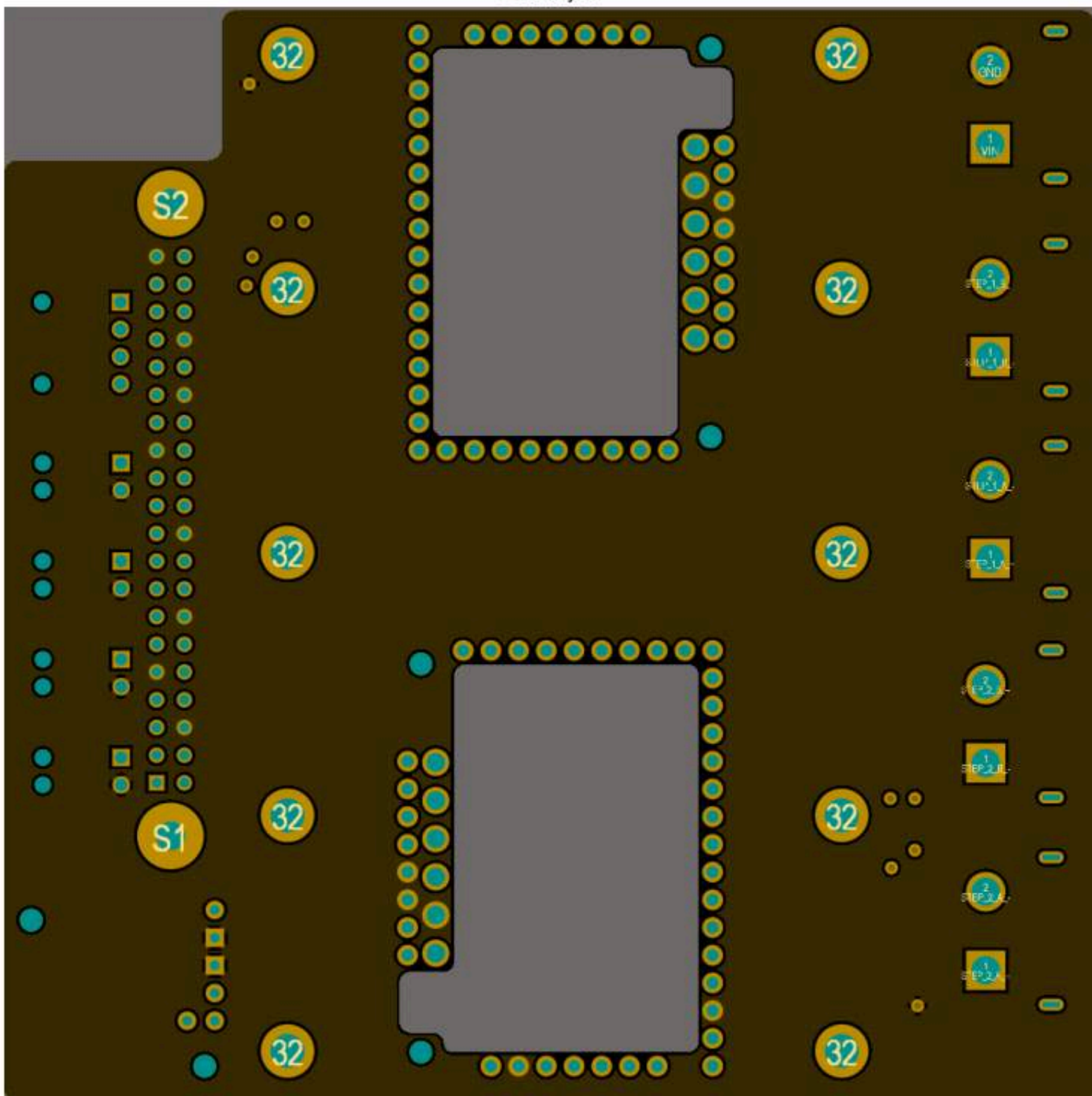


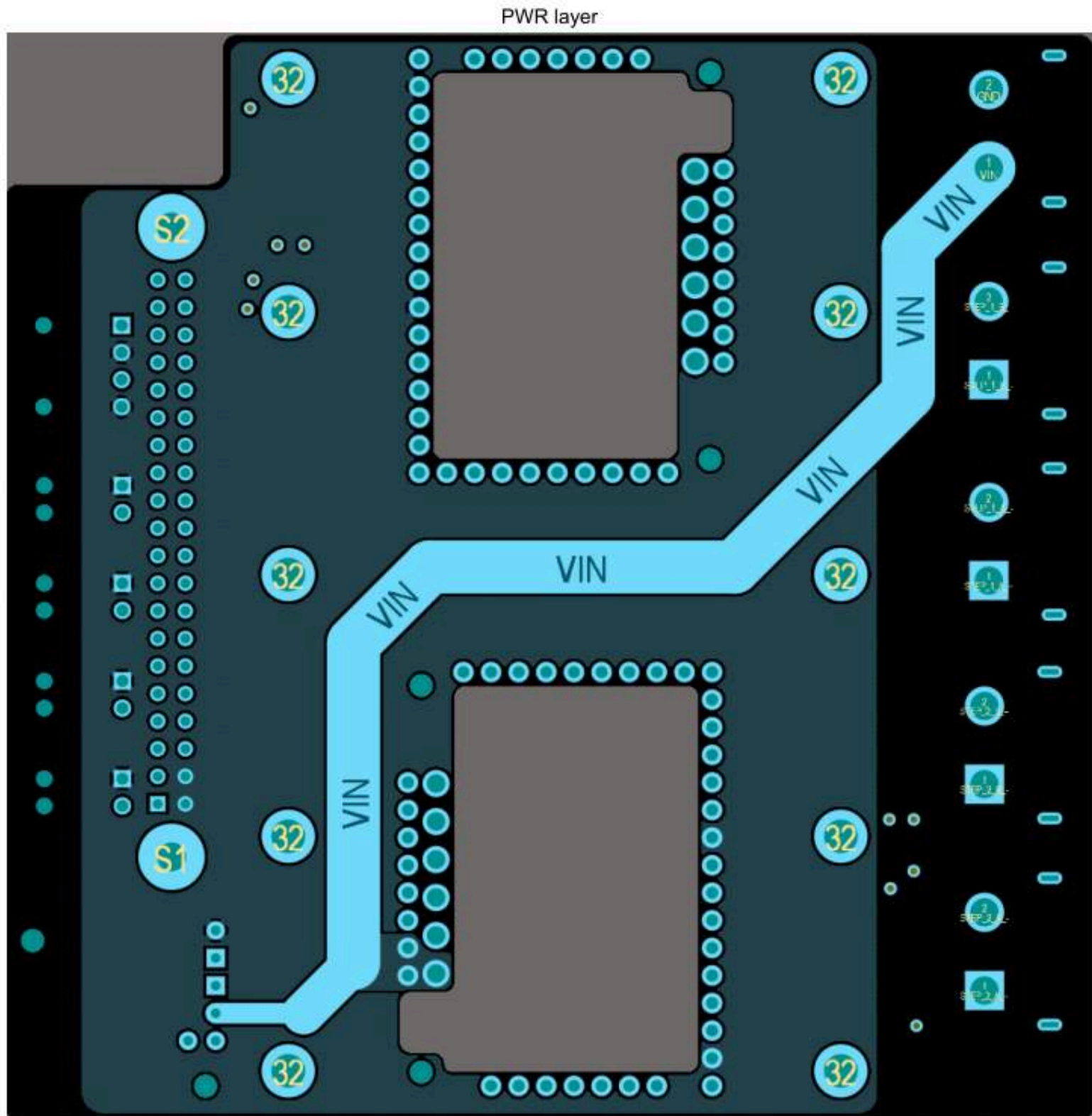
Ground station PCB signal layers

Top layer

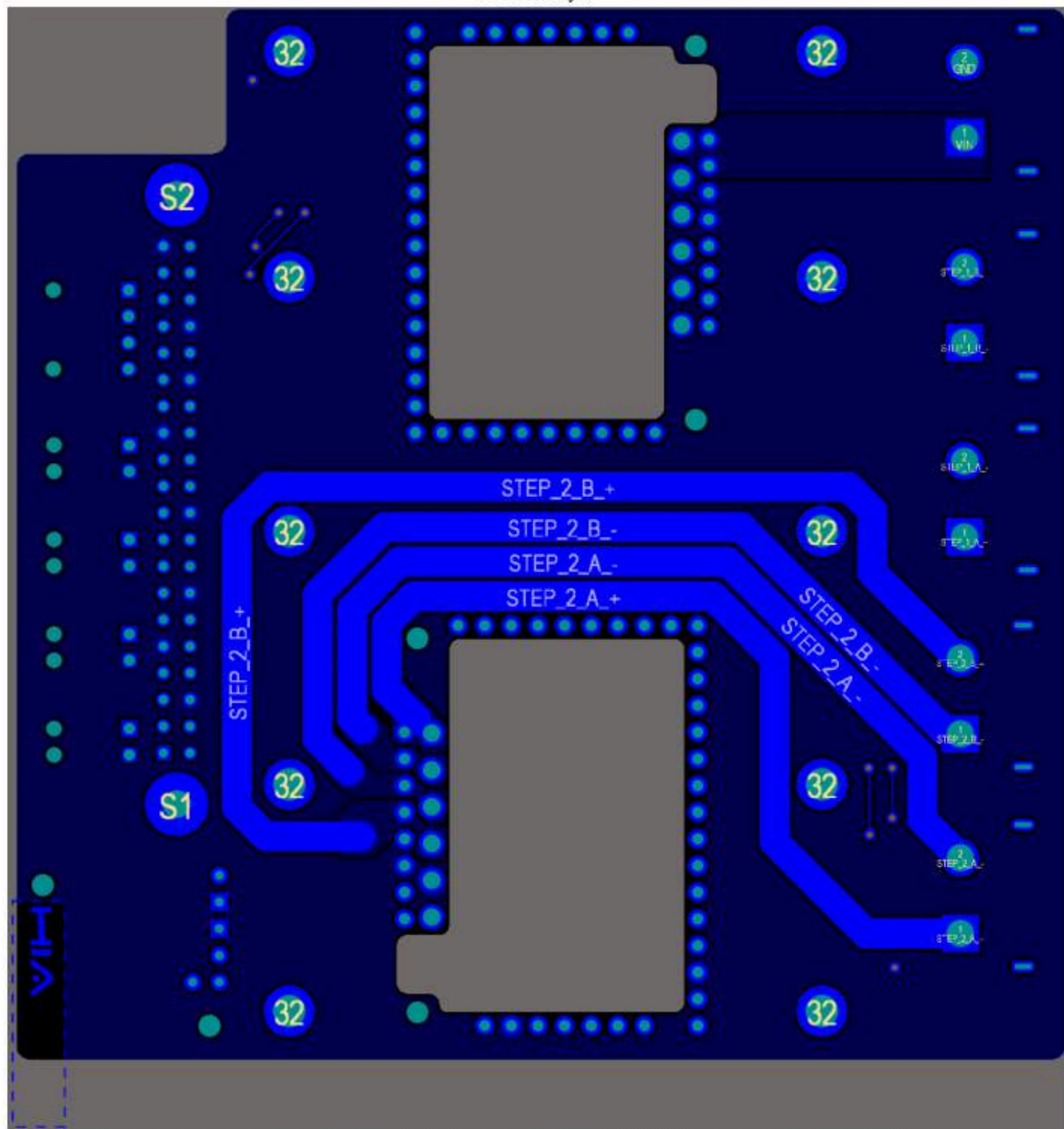


GND layer



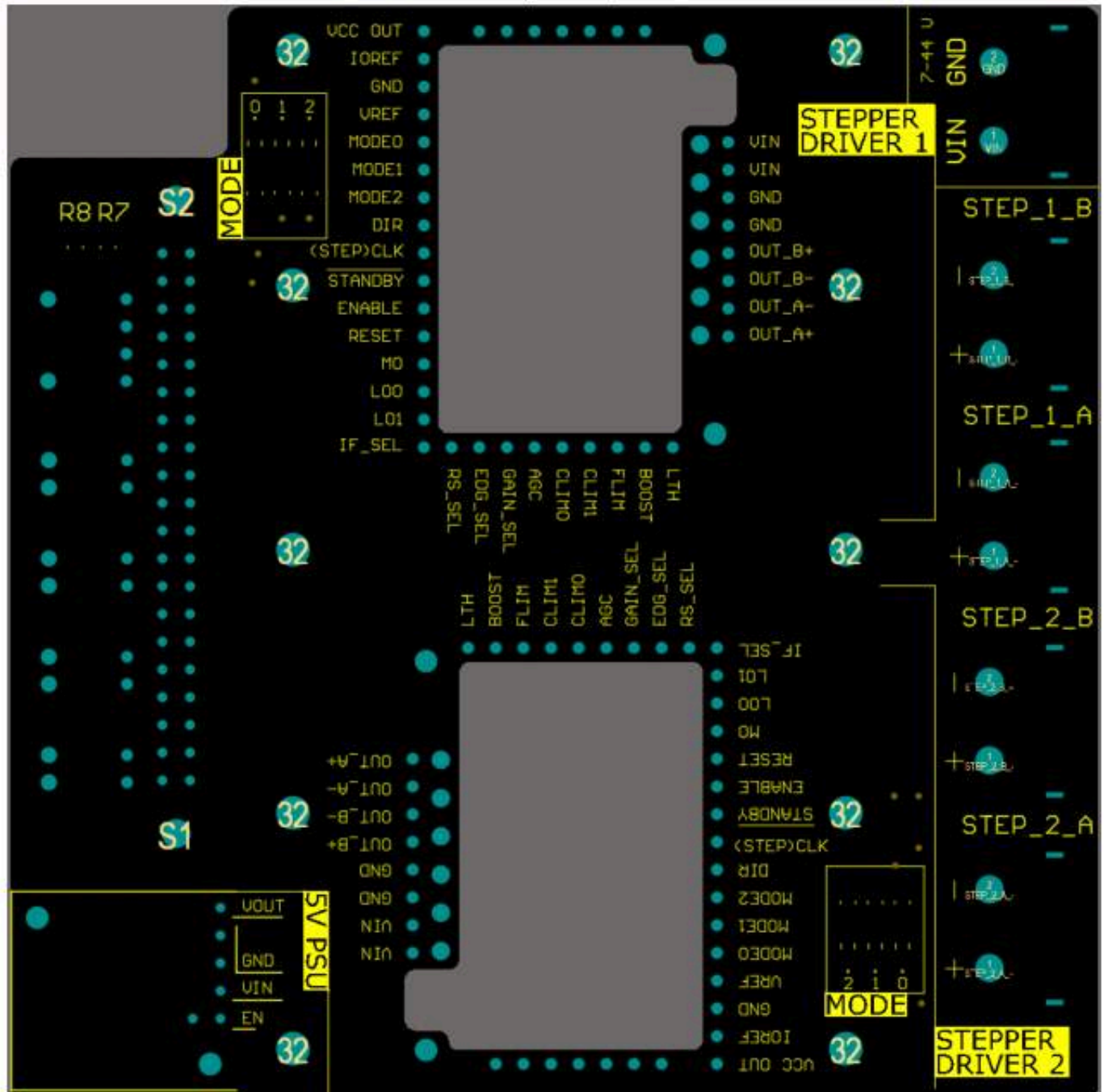


Bottom layer

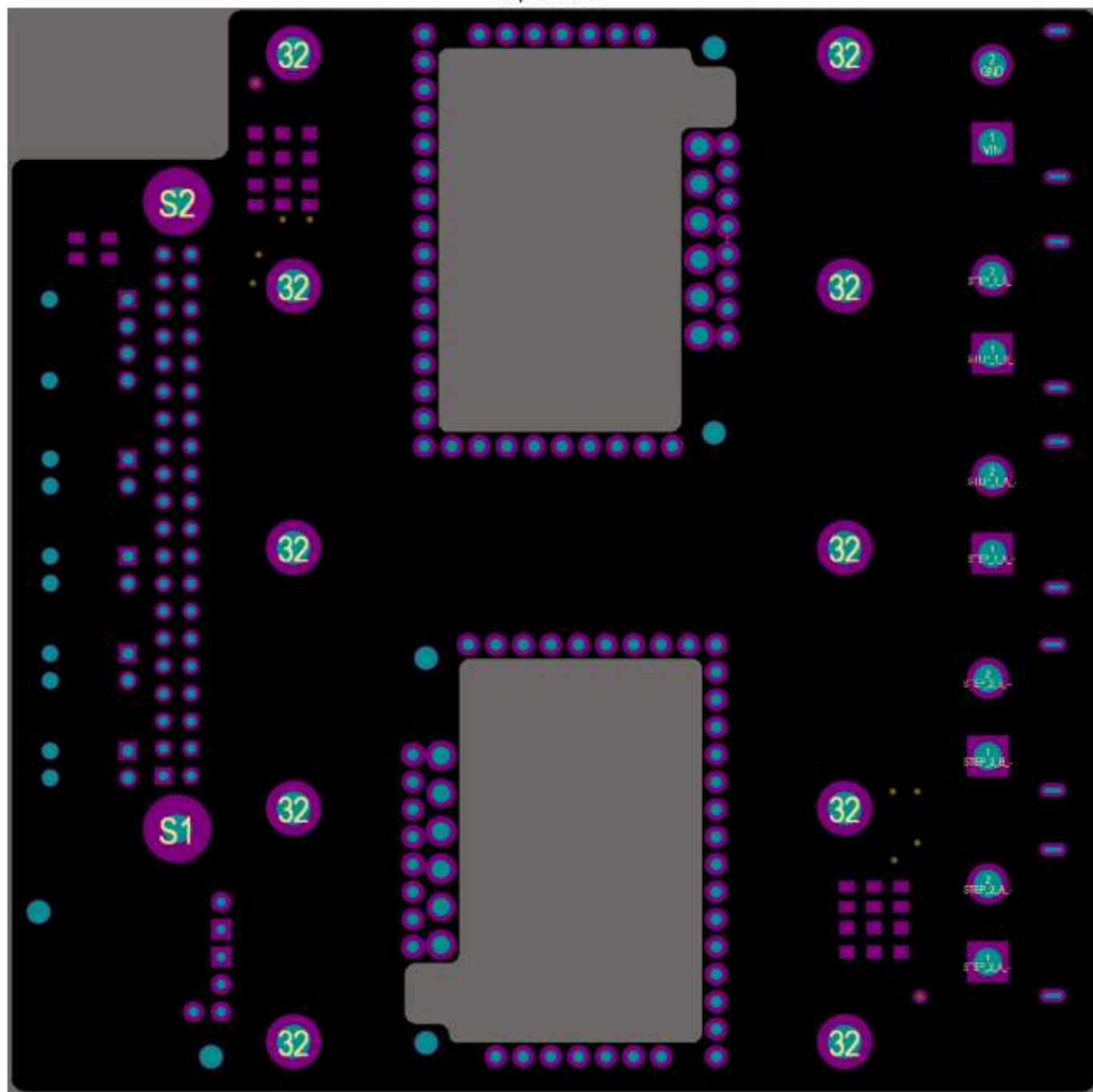


Ground station PCB top layers

Top overlay

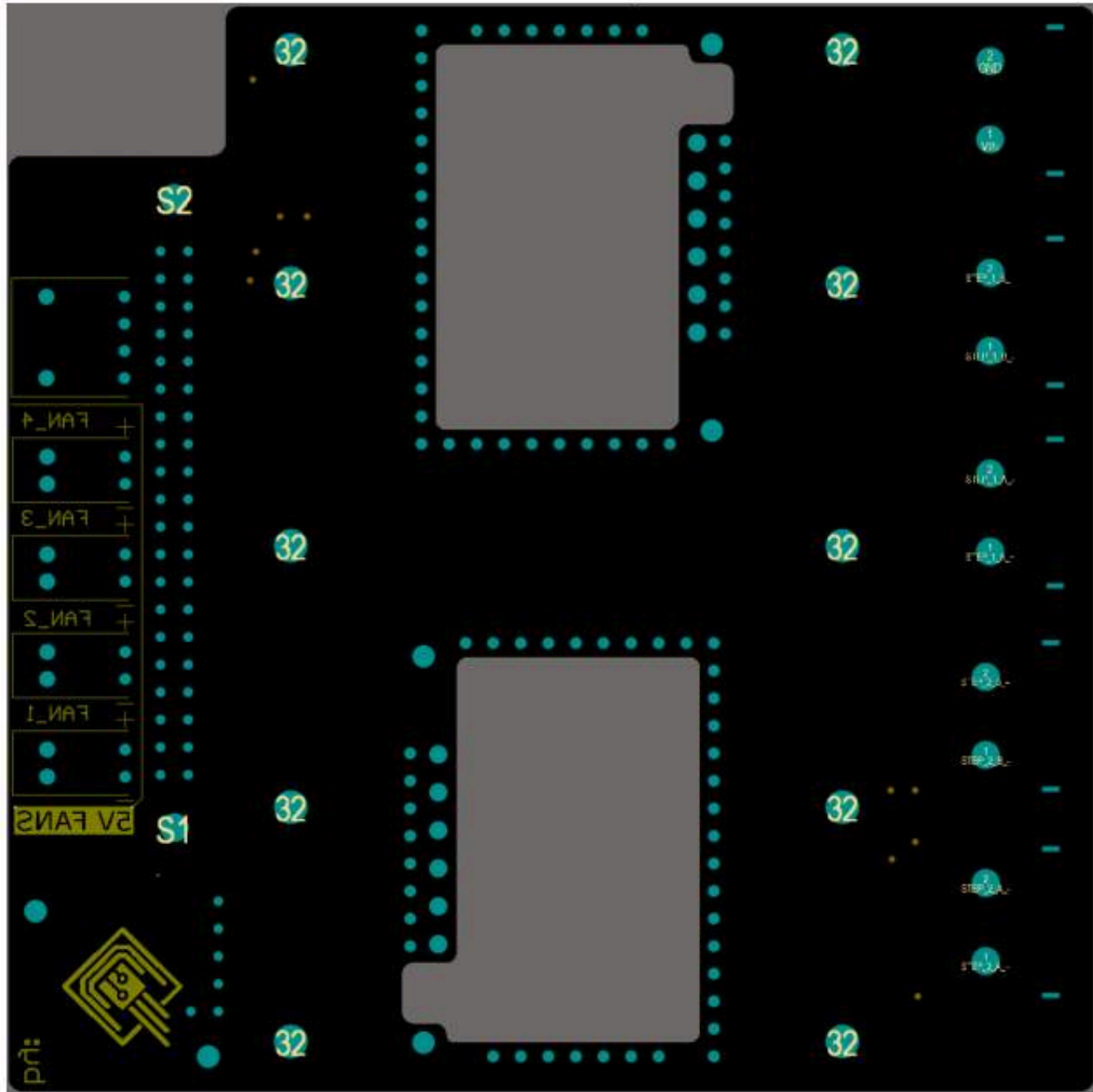


Top solder

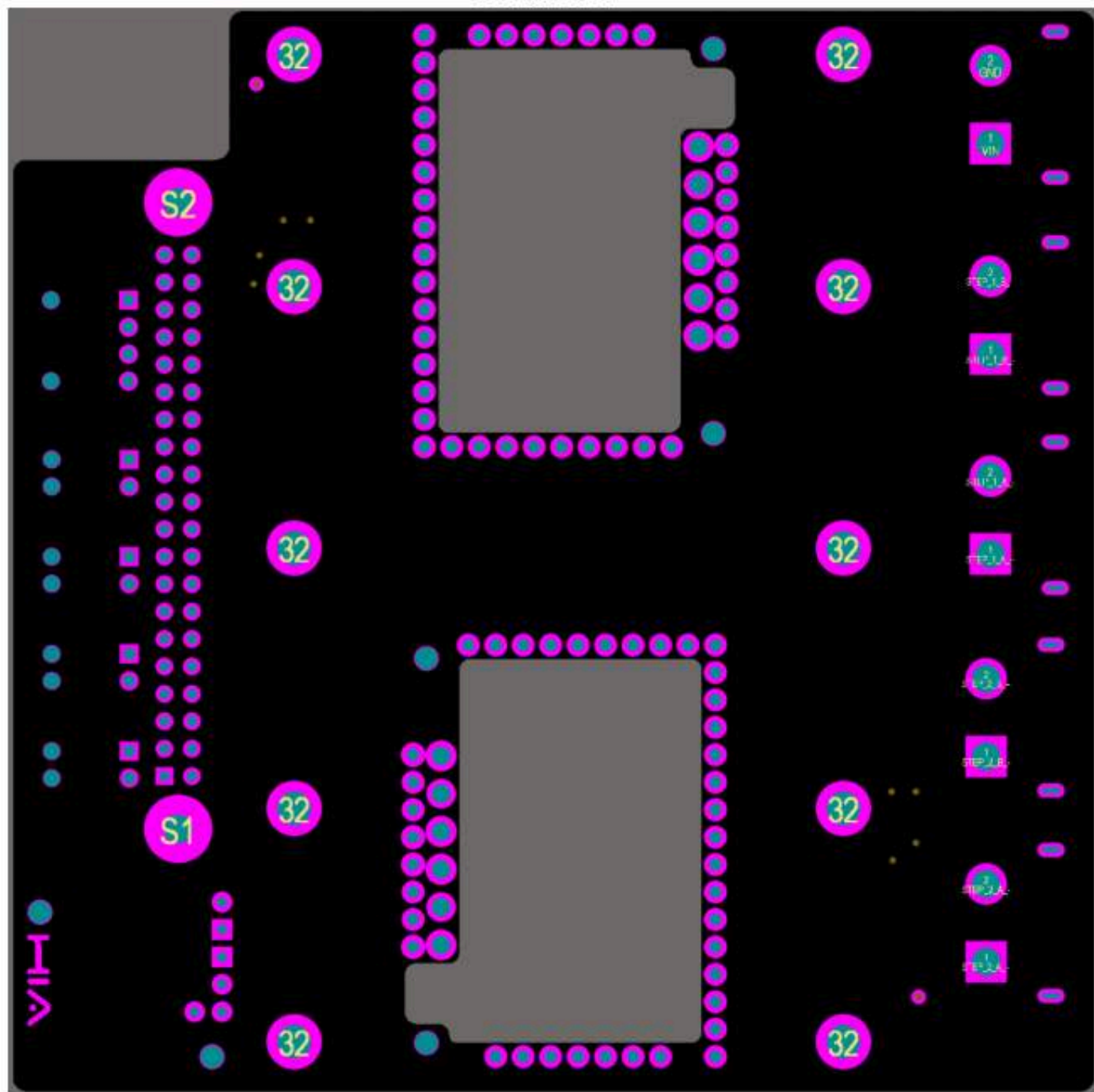


Bat_temp PCB bottom layers

Bottom overlay

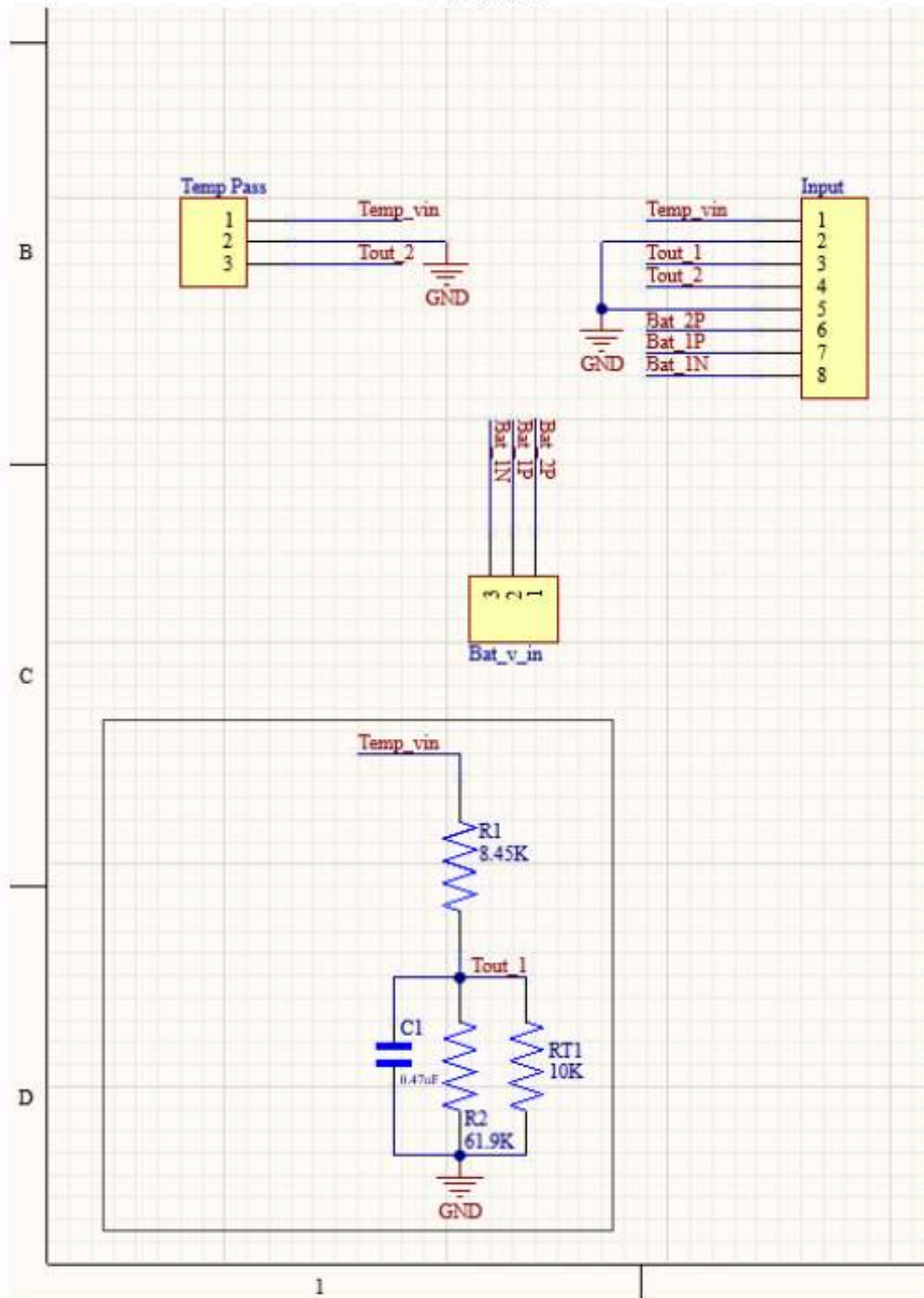


Bottom solder



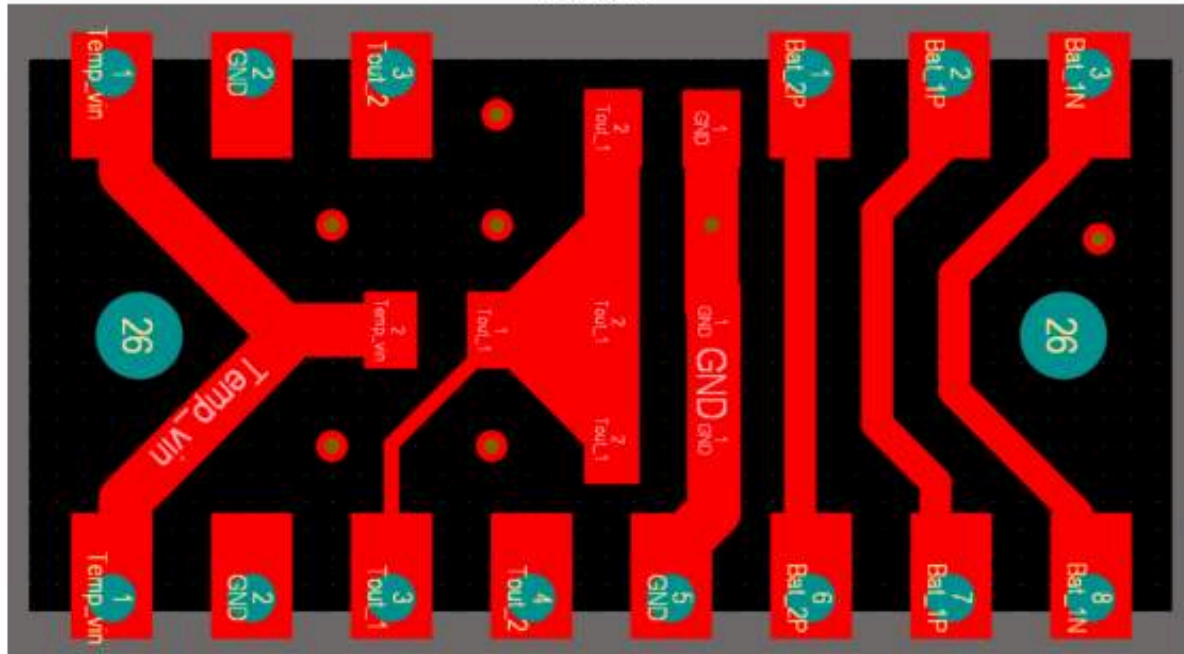
Bat_temp schematics

Schematics

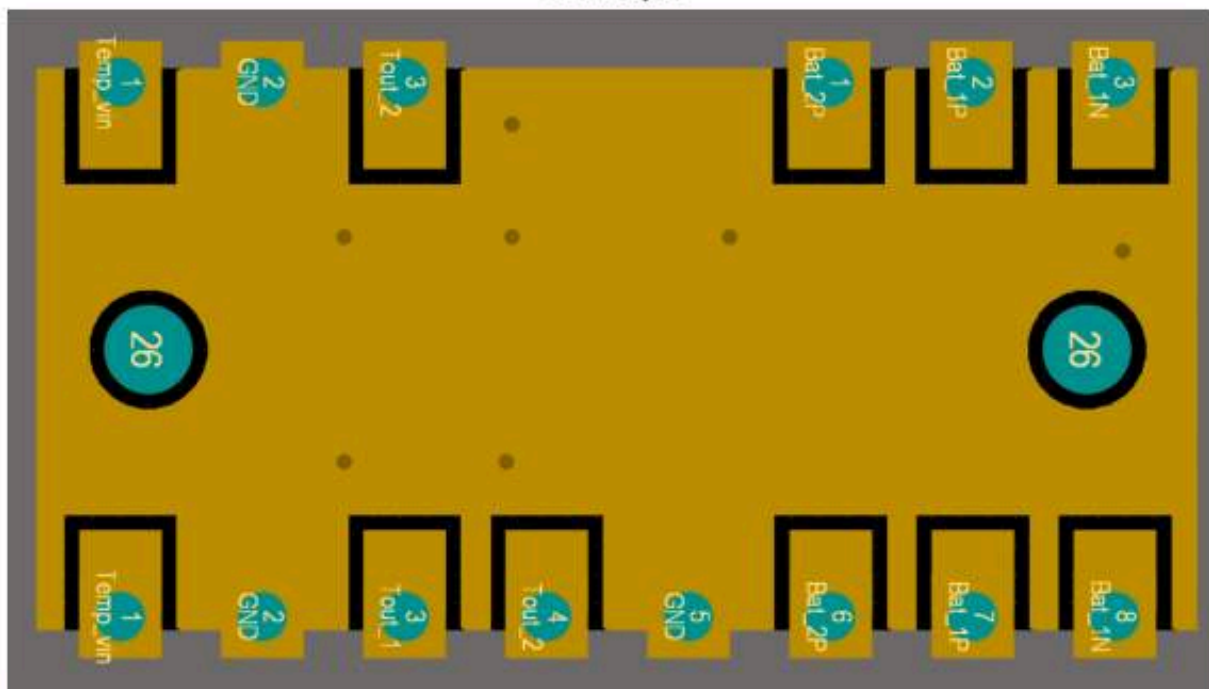


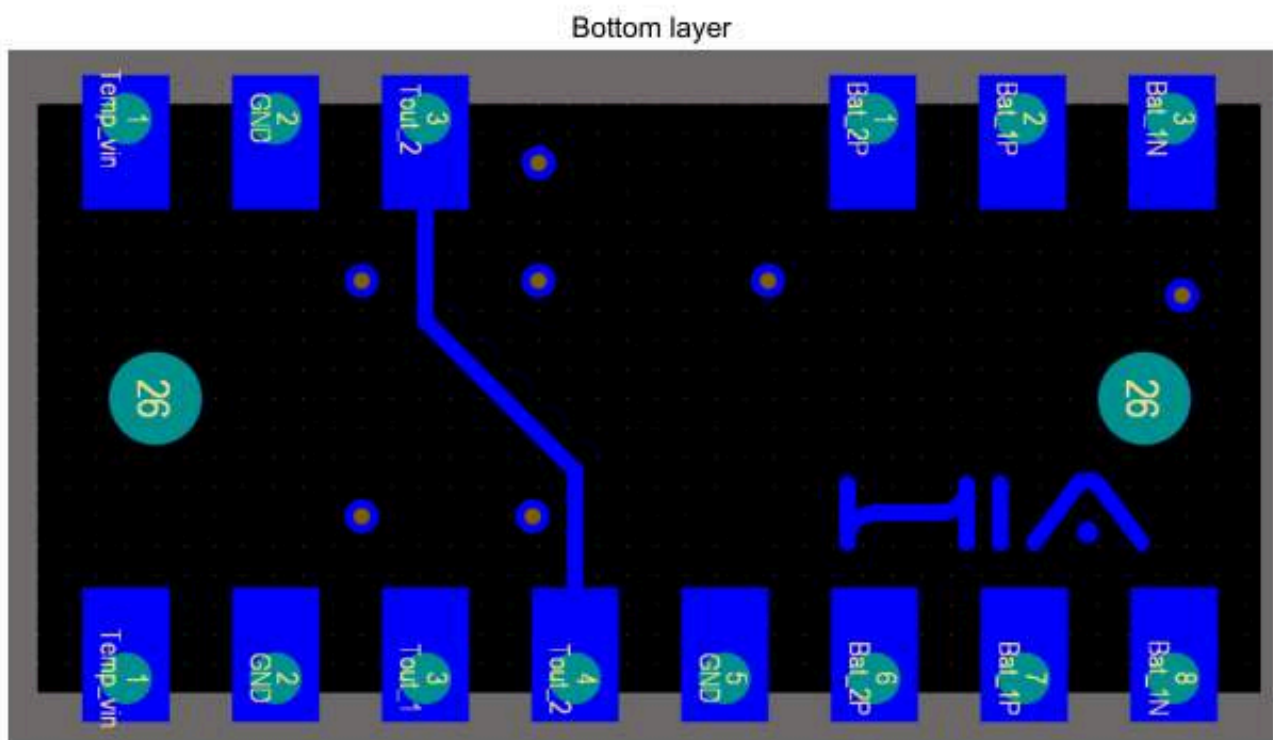
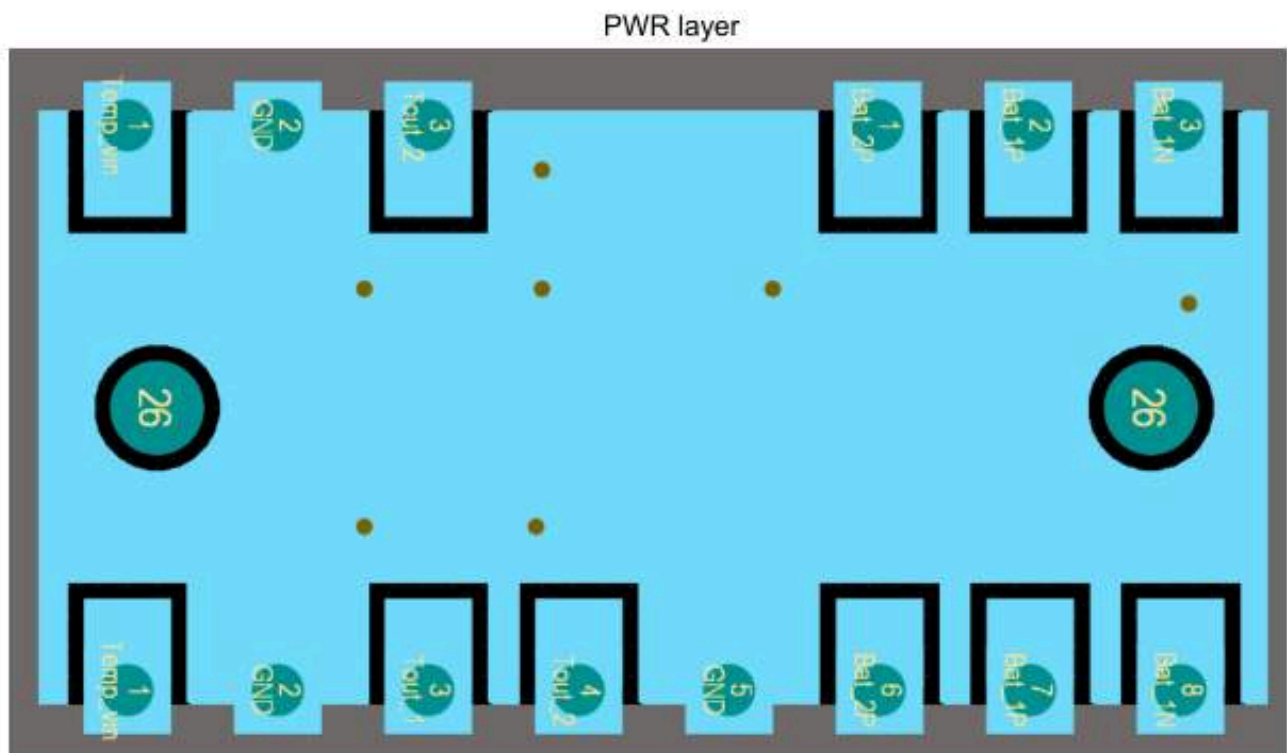
Bat_temp PCB signal layers

Top layer



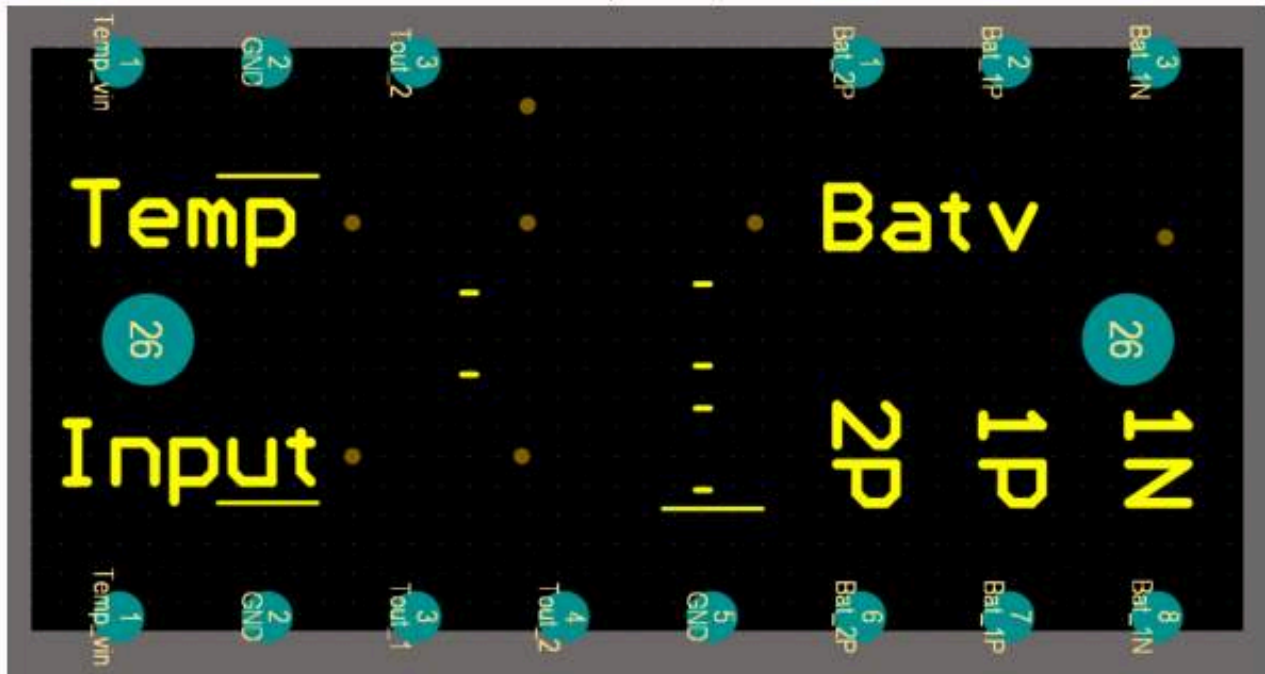
GND layer



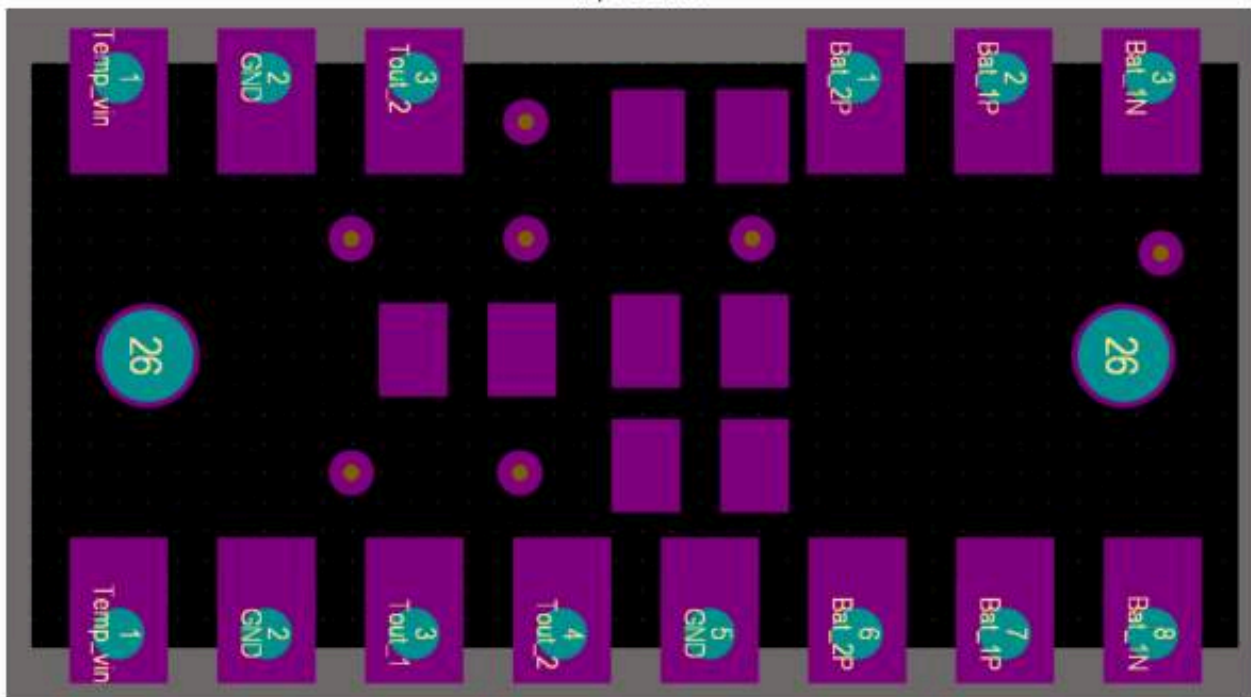


Bat_temp PCB top layers

Top overlay

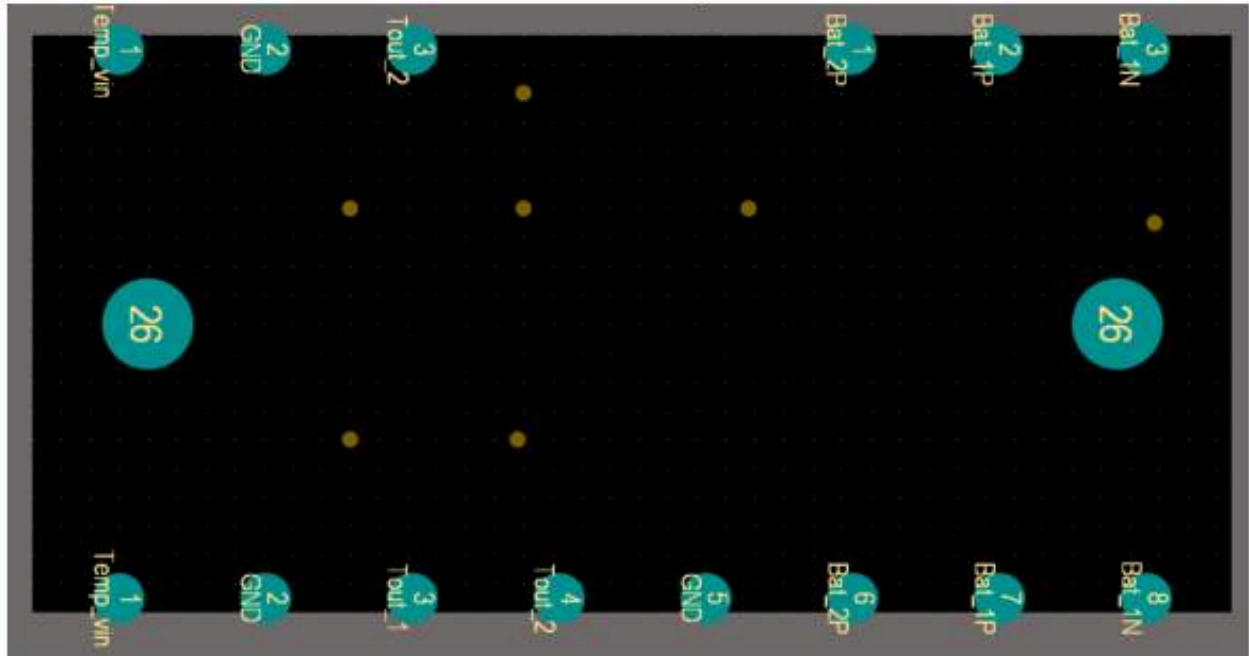


Top solder

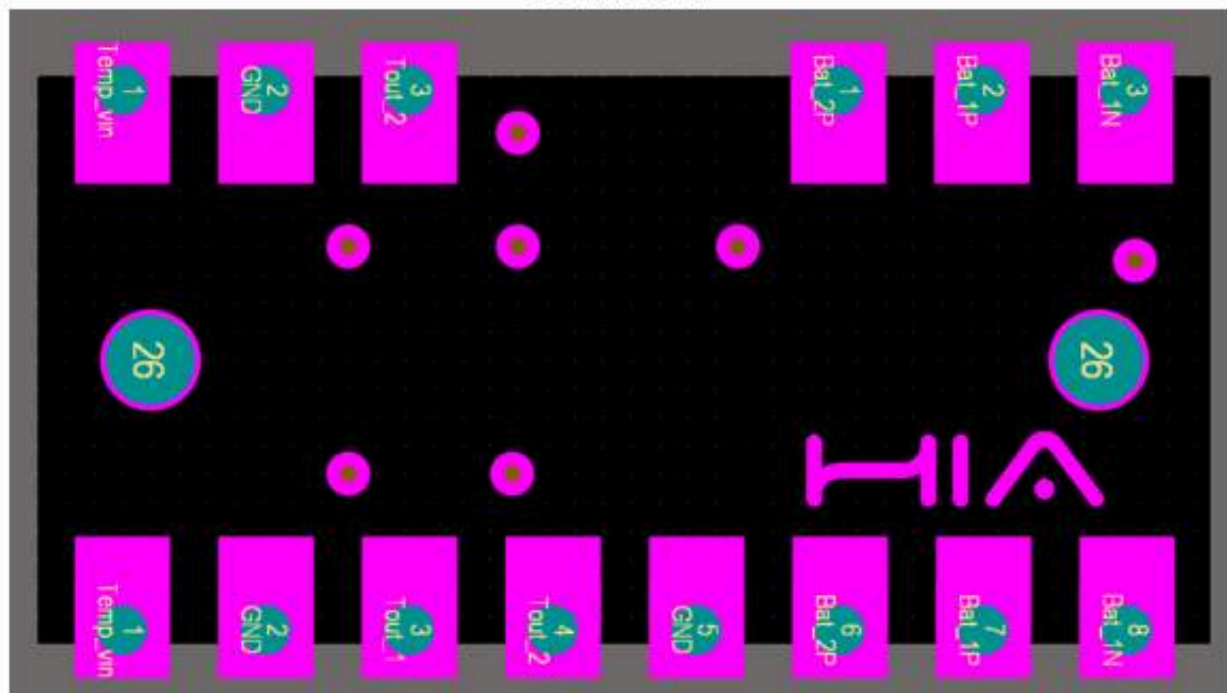


Bat_temp PCB bottom layers

Bottom overlay



Bottom solder



Constraints and Interfaces appendix

Interfaces

Table 1. Project matrix that illustrates the interfaces between systems.

Interfaces							
Output ->							
Input ^	Outer structure	Inner Structure	Recovery	Avionics	Payload	Costs	
	Outer Structure	Coupling, motormount, boat tail attachment, geometry, connections, FEM results (yield strength, Young's modulus), CFD results (dynamic pressure, drag force)	Coupler: Air airframe, Forward airframe, CG/CP, Motormount, boat tail attachment, geometry, FEM results (yield strength, Young's modulus), CFD results (dynamic pressure, drag force)	Motor fore/thrust, geometry, CFD results (dynamic pressure, drag force), CG/CP, stability margin	Weight	Mandrel is already made and most of manufacturing is sponsored	
	Inner Structure	Inner diameter, module Size and amount of holes, Placement of CG	Subsystems fits inner diameter, 124mm Size; Components and chutes fit in the recovery bay	Cable management; Flat cables Centralized avionics bay connection to recovery bay	Removable payload during a readiness review at the competition, Payload fits in payload mount	The lower coupler will be designed with less detail, thus reducing cost. Module-based connections might be more expensive, but will be sponsored or made in-house.	
	Recovery	Inner diameter, mass, placement, parachute deployment, parachute drag	Attaching mechanism Minimum Hawk size & SRAD pressure system	Calculated forces, loads, and G-forces at recovery.	N/A	Parachutes are expensive Moderate to high cost for testing COTS equipment is highly expensive	
	Avionics	Placement	Placement, connection system	Asogee detection; sensors Redundancy; COTS flight computer Cable management	Turning the payload to on/off state	Most equipment is sponsored including ground station/antenna Low actual expense for the system	
	Payload	Placement	Placement, removable attachment system have cables to connect to the avionics bay	N/A	Cables to the avionics bay	Produce as much as possible in-house. Moderate cost for speakers. Low cost for testing	
	Costs	Allocated money for the system	Allocated money for the system	Allocated money for the system	Allocated money for the system	Allocated money for the system	

Constraints and requirements

These requirements are imposed by the team, and are in addition to the requirements stated in *Rules and Requirements* [2] as well as *Design test evaluation and guide* [1]. All requirements prefixed with "S" indicate that the requirement is "Self imposed".

S1. Outer Structure

S1.1 Functional requirements

S1.1.1 Overall Structural Integrity -

The rocket shall be constructed to withstand the operating stresses and retain structural integrity under the conditions encountered during handling, as well as during flight.

S1.1.2 Maintain a stability margin within limits of SA Cup

S1.2 Performance

S1.2.1 Need an aerodynamic design in order to reach targeted apogee.

S1.2 From other systems and the board

S1.3.1 Need a RF transparent area in the nose cone and fore tube where the radio transmitter COTS GPS is situated.

S1.3.2 The parts must be designed in such a way that they can be produced with the equipment available, and within budget.

S1.3.3 Length and diameter must be large enough for all systems to fit inside the rocket.

S1.3.4 Must be validated through tests and/or analyses

S2. Inner structure

S2.1 From other systems and the board

S2.1.1 The parts must be designed in such a way that they can be produced with the equipment available, and within budget.

S2.1.2 The inner structure must be rigid, and withstand forces from multiple directions.

S2.1.3 The structure must house the Cesaroni CTI Pro98 6GXL 21062 O3400-IM P.

S2.1.4 Avionics and recovery have to be in the same part of the rocket after separation as the avionics and recovery needs to be able to communicate and deploy the main parachute after the rocket is split in two.

S2.1.5 Communication lines between avionics and recovery needs enough room and mounting points to be placed and secured properly.

S2.1.6 The radio transmitting subsystems of the avionics system must be placed within a RF-transparent section of the rocket fuselage.

S2.1.7 Secure mounting points on both halves of the rocket for the parachutes.

S2.1.8 The rocket needs to withstand an impact with the ground at up to 7.3 m/s.

S2.1.9 The inner structure must adapt to the shape of the airframe.

S2.1.10 The inner structure must be arranged in a way that accommodates a suitable center of gravity for the rocket.

S2.1.11 Must provide adequate space for wires for avionics.

S2.1.12 Must be designed in a way that makes it efficient and simple to assemble and disassemble during pre-launch procedures.

S2.1.13 Must be validated through tests and/or analyses

S2.1.14 Must be designed for ease of assembly.

S3. Recovery

S3.1 Functional requirements

S3.1.1 The recovery system must be able to withstand the experienced forces from the drogue chute and main chute deployment with a safety factor of 2

S3.2 Performance

S3.2.1 PBSS must be able to separate the rocket

S3.3 From other systems and the board

S3.3.1 Recovery must use electrical components compatible with the COTS flight computer

S3.3.2 The recovery system needs to be able to fit between the coupler and the payload

S3.3.3 Components need to fit within the given inner diameter of 124 mm

S3.3.4 The parts must be designed in such a way that they can be produced with the equipment available, and within budget.

S3.3.5 Must be validated through tests and/or analyses

S3.4 Environmental factors

S3.4.1 Pressure difference between atmosphere and the recovery bay

S4. Avionics

S4.1 Functional requirements

S4.1.1 Must be able to send activation signals to recovery systems at the correct time in flight.

S4.1.2 Must have state estimation for correctly predicting recovery signal timing

S4.1.3 Must be able to handle data input, processing, storage and output

S4.1.4 Must be able to safely log data

S4.1.5 Must have data filtering for sensors (Kalman filter)

S4.1.6 Should be able to send live data from rocket to ground station during flight

S4.2 Performance

S4.2.1 Should be able to set up and verify avionics system status on launch pad within 10 minutes

S4.2.2 Should be able to wire up, assemble and perform initial verification on avionics systems within 2 hours

S4.2.3 Should be able to run diagnostics on the system remotely from ground station

S4.2.4 Should have feedback on system status (Audio, Lights etc.)

S4.2.5 Should be a reusable system

S4.2.6 Should be able to collect accurate flight data during harsh acceleration/pressure changes

S4.3 From other systems and the board

S4.3.1 Must physically fit inside the rocket body

S4.3.2 Must be able to handle rapidly changing temperature and pressure

S4.3.3 Must be able to handle high G-forces and vibrations

S4.3.4 Must have a blackbox like solution for safe data storage

S4.3.5 One of the flight computers must be SRAD so that our members gain engineering experience.

S4.3.6 Must collect data for use in later analysis and development, or for troubleshooting in case of failure.

S4.3.7 Must be designed in such a way that they can be produced with the equipment available, and within budget.

S4.3.8 Should weigh less than 2 kg

S4.3.9 Placement and dimensions of components are restricted by other system components

S4.3.10 Must be able to activate recovery systems

S4.3.11 Must be capable of operating four servo motors total

S4.3.13 Must activate the separation system within 11 seconds of apogee.

S4.4 Environmental factors

S4.4.1 Should have battery life to stay powered on the launch pad for minimum 1 hours

S4.4.2 Should have battery life to stay powered for at least 30 min after launch

S4.4.3 Must survive temperatures ranging from -40°C to 60°C

S4.4.4 Must survive desert conditions (temperatures, humidity, sand)

S4.4.5 Must be able to withstand high percentage of humidity caused by altitude increases

CALCULATIONS AND ANALYSIS

2A.Outer structure:

Airframe composite analyze

Problem statement:

During flight the airframe will have quite an amount of force. For a safe flight we need to figure out if the material used on the airframe; namely Toray T700s carbon fiber and Zentron S2 758 Glass fiber with UF3369 epoxy, can handle the flight, as well as how many holes we safely can allow in the airframe [4].

Figure:



Assumptions and approximations:

The assumptions used for analytic treatment of a composite material is:

Fiber:

- Homogeneous
- Linearly elastic
- Isotropic
- Regularly spaced

- Perfectly aligned

Matrix/Epoxy:

- Homogeneous
- Linearly elastic
- Isotropic

Physical laws:

V_f = volume fraction
 M_f = mass fraction
 E = tensile modulus/young's modulus
 G = shear modulus
 σ_t = Tensile strength
 σ_c = Compressive strength
 Σ = Tensile strain
 ρ = density
 ν = Poisson's ratio
 X_f / X_e = Value fiber / Value epoxy
 X_c / X_g = Value carbon fiber / Value glass fiber
 X_x / X_y = Value longitudinal / Value transverse
 X_{xy} / X_{yz} = Value in plane / Value out of plane
 CP = Specific heat
 K = Thermal conductivity
 CPE = Coefficient Thermal Expansion

From the properties given by the datasheet of the materials and given the assumptions made we can use the following equations to calculate mechanical properties of the carbon and glass fiber reinforced composite [4]:

$$V_{tot} = M f_f \cdot \frac{1}{\rho_f} + M f_e \cdot \frac{1}{\rho_e}$$

$$V f = M f \cdot \frac{\frac{1}{\rho_f}}{V_{tot}}$$

$$E_x = E_f \cdot V f_f + E_e \cdot V f_e$$

$$E_y = \frac{1}{\frac{V f_f}{E_f} + \frac{V f_e}{E_e}}$$

$$\rho = \rho_f \cdot V f_f + \rho_e \cdot V f_e$$

$$G_{G\&C} = \frac{E}{2(\nu + 1)}$$

$$\nu_y = \nu_x \cdot \frac{E_y}{E_x}$$

$$\nu_x = \nu_f \cdot V f_f + \nu_e \cdot V f_e$$

$$G_{xy} = \frac{G_E \cdot ((1 + V f_f) + (1 - V f_f) \cdot \frac{G_E}{G_f})}{(1 - V f_f)((1 + V f_f) \cdot \frac{G_E}{G_f})}$$

$$G_{yz} = \frac{G_E \cdot (V f_f + N(1 - V f_f))}{(N(1 - V f_f)) + (V f_f \cdot \frac{G_E}{G_f})}$$

$$N = Constant = \frac{3 - 4\nu_E + \frac{G_E}{G_f}}{4(1 - \nu_E)}$$

$$\sigma_s = (\sigma_{s(E)} \cdot (1 - V f_f)) + (\sigma_{s(f)} \cdot V f_f)$$

$$\begin{bmatrix} \Sigma_x \\ \Sigma_y \\ \Sigma_z \end{bmatrix} = \begin{bmatrix} S_{xx} & S_{xy} & 0 \\ S_{yx} & S_{yy} & 0 \\ 0 & 0 & S_{ss} \end{bmatrix} \cdot \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \end{bmatrix}$$

$$S_{xx} = \frac{1}{E_x} \quad S_{yx} = -\frac{\nu_x}{E_x}$$

$$S_{yy} = \frac{1}{E_y} \quad S_{xy} = -\frac{\nu_y}{E_y}$$

$$S_{ss} = \frac{1}{G_{xy}}$$

Properties:

Properties of Toray T-700s carbon fiber [6]:

$$Vf_{RC} = 0.58$$

$$\rho_{RC} = 1.8 \text{ [g/cm}^3\text{]}$$

$$\sigma_{RC} = 4900 \text{ [MPa]}$$

$$E_C = 230000 \text{ [MPa]}$$

$$CP_C = 0.7536 \text{ [kJ/kgK]}$$

$$K_C = 9.372 \text{ [W/mK]}$$

$$CTE_C = 3.8 \cdot 10^{-8}$$

$$\nu_C = 0.26$$

$$G_C = 72784.81 \text{ [MPa]}$$

Properties of Zentron S-2 758 Glass Fiber [7]:

$$Vf_{RG} = 0.55$$

$$\rho_{RG} = 2.46 \text{ [g/cm}^3\text{]}$$

$$\sigma_{RG} = 3660 \text{ [MPa]}$$

$$E_G = 86000 \text{ [MPa]}$$

$$CP_G = 0.737 \text{ [kJ/kgK]}$$

$$K_G = 1.1 \text{ [W/mK]}$$

$$CPE_G = 0.00016$$

$$\nu_G = 0.23$$

$$G_C = 27741.94 \text{ [MPa]}$$

Properties of UF3369 epoxy [8]:

$$Vf_{EC} = 0.42$$

$$Vf_{E(G)} = 0.45$$

$$\rho_E = 1.18 \text{ [g/cm}^3\text{]}$$

$$\sigma_{s(E)} = 92.4 \text{ [MPa]}$$

$$\sigma_{k(E)} = 1460 \text{ [MPa]}$$

$$E_E = 3100 \text{ [MPa]}$$

$$\nu_E = 0.2$$

$$G_E = 1291.67 \text{ [MPa]}$$

Calculations:

Calculated Mechanical properties of carbon fiber reinforced composite:

$$\rho = 1.54 \text{ [g/cm}^3\text{]}$$

$$E_x = 134702 \text{ [MPa]}$$

$$E_y = 7246 \text{ [MPa]}$$

$$\nu_x = 0.2348$$

$$\nu_y = 0.01263$$

$$G_{xy} = 4576.52 \text{ [MPa]}$$

$$G_{yz} = 3733.4 \text{ [MPa]}$$

$$\sigma_s = 2880 \text{ [MPa]}$$

$$\Sigma_x = 0.01636$$

$$\Sigma_y = 0.3925$$

$$\Sigma_z = 0.0076$$

Calculated Mechanical properties of glass fiber reinforced composite:

$$\rho = 1.884 \text{ [g/cm}^3\text{]}$$

$$E_x = 48695 \text{ [MPa]}$$

$$E_y = 6598.19 \text{ [MPa]}$$

$$\nu_x = 0.2165$$

$$\nu_Y = 0.02934$$

$$G_{XY} = 3886.00 \text{ [MPa]}$$

$$G_{YZ} = 3274.91 \text{ [MPa]}$$

$$\sigma_s = 2054.58 \text{ [MPa]}$$

$$\Sigma_X = 0.0331$$

$$\Sigma_Y = 0.3023$$

$$\Sigma_Z = 0.0090$$

Reasoning, discussion and verification:

FEA on composite material with calculated material properties will not be accurate. Composite materials are definitely not isotropic or linear elastic, and material properties largely vary on the alignment of fibers. However the purpose of the finite element analysis is to give validation comparing it to the compression test done on a test piece of the airframe and to give an estimate of the mechanical properties. Especially important to keep in mind is that glass and carbon fiber are extremely brittle materials, therefore you can expect variations in mechanical properties on each test piece. For such brittle material, as a minimum at least five test pieces should be tested, the team however only had two test pieces of both the glass and carbon fiber used on the airframe.

A mesh size of 4 mm was chosen on the Finite element model.

Final results:

FEA:

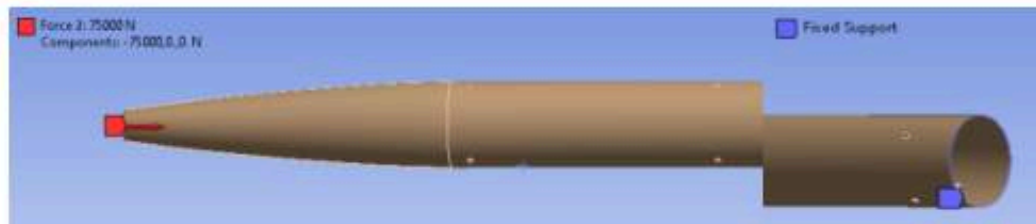
All analyses were done in Ansys, and failure is graded with a safety facto where a score of under 1 means material failure.

Failure tools used:

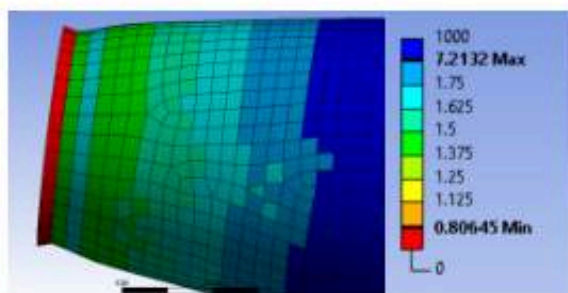
- Max strain
- Max stress
- Tsai-Wu
- Puck
- Von Mises

Compression test on forward airframe:

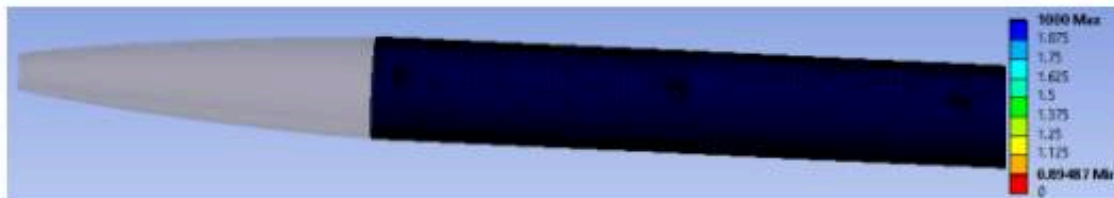
- Fixed support at the edge between forward airframe and coupler, while the load is on the opposite side where the nose tip and nose cone intersect.



- With a Force of 75 kN the glass fiber has a failure at the tip of the nose cone. Failure etc translates to compressive strain failure and the failure is expected in layer 8. The force can be compared to the forcesshitting the nose tip during flight.



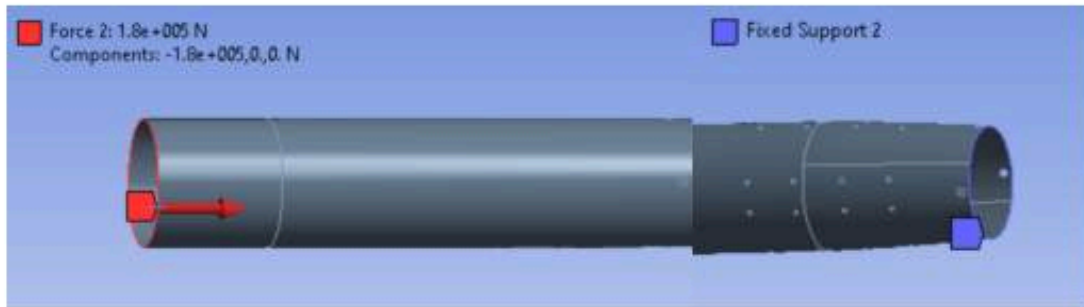
- To compare the analytical test with the compression test done at byåsen it would be beneficial to test max compression until failure at the cylindrical part of the forward airframe as well



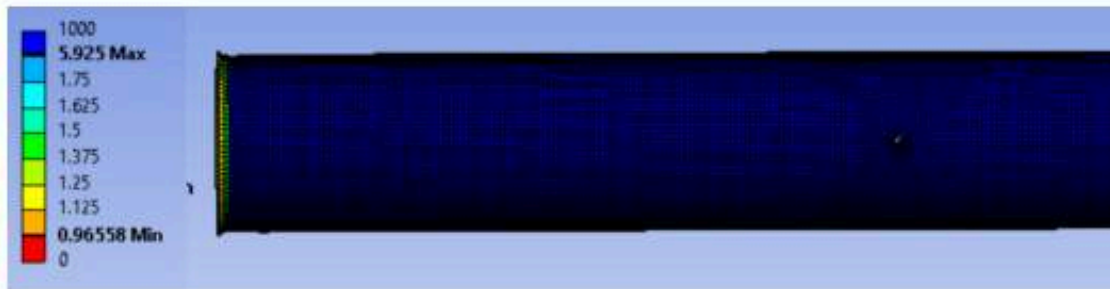
The glass fiber is now experiencing failure at approximately 100 kN of force, and the failure is expected at the holes. E12 is a shear failure, and it is most likely to start from the 2.layer. This result compares with the delamination we experienced at approximately 98 kN at the compression test. Shear failure also corresponds with the delamination we experienced at the compression test, however there the failure startet at the ends of the test piece, not the holes. The ends of the test pieces were however damaged due to machining.

Compression test on Aft airframe

- On the aft airframe the fixed support is placed at the intersection between the aft airframe and boat tail, while the load is placed at the edge between the aft airframe and coupler.

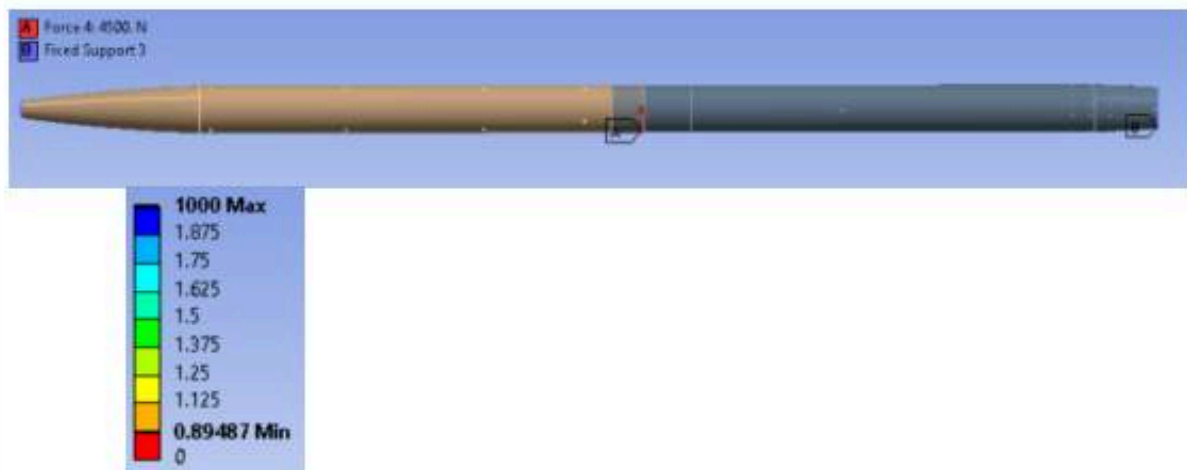


- At a force of 180 kN the woven carbon fiber experiences failure, with max strain being concentrated on the fastening holes for the boat tail and fins. This compares to the compression test done on the carbon fiber test piece which experienced delamination failure at a force of 190 kN. The same occurred at the aft airframe as the forward airframe where at the compression test delamination started at the ends and not at the holes.



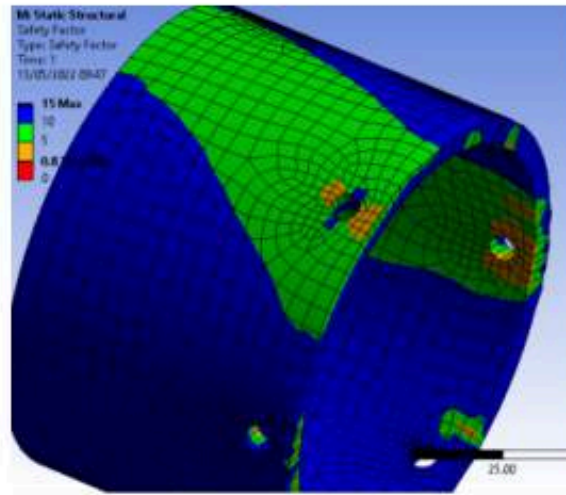
Flexural strength test on airframe

- It is interesting to calculate how much force the airframe can handle perpendicular to the rocket axes. To test this the edge that connects the aft airframe and boat tail and the intersection between the nose tip and nose cone are set as fixed support while the load is acting perpendicular to the rocket's axis on one of the holes in the coupler. The test is similar to a 3-point bending test. Since a different angle of attack will increase the forces working perpendicular to the rockets axis. It is also expected to be some forces working in this direction when Birkeland turns at apogee and starts the descent.



- At 4500 N a failure occurs. With a safety factor of 0.89 the failure is most probable to occur in the forward airframe between the intersection between the coupler and the forward airframe and the shear pin holes. We can also expect failure in the aft airframe, however a smaller area. It can also be observed a higher concentration of stress on the end of the nose cone for the forward airframe and at the boat tail and fin holes for the aft airframe.

- Last but not least the finite element analysis shows that the coupler made out of aluminium 6182 T6 will experience a tensile failure before both the carbon and glass fiber reinforced composite with a safety factor of 0.87.

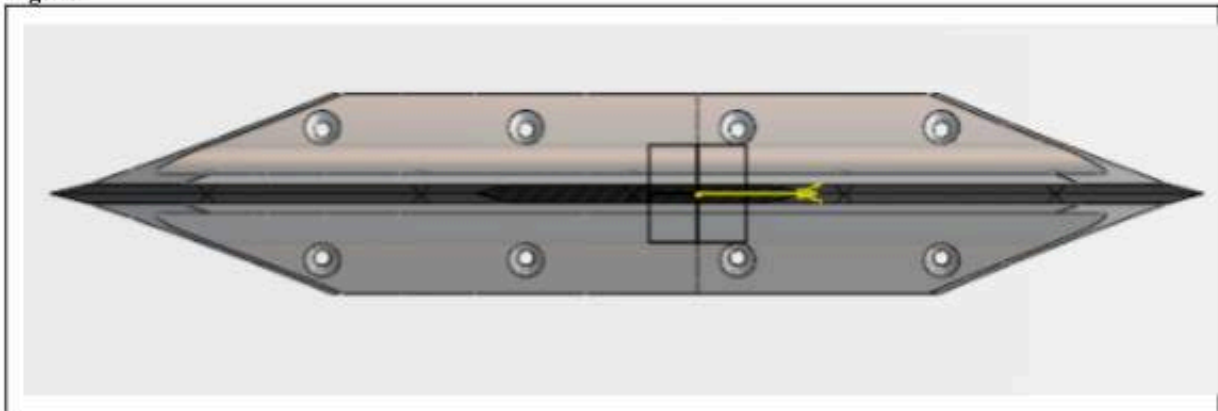


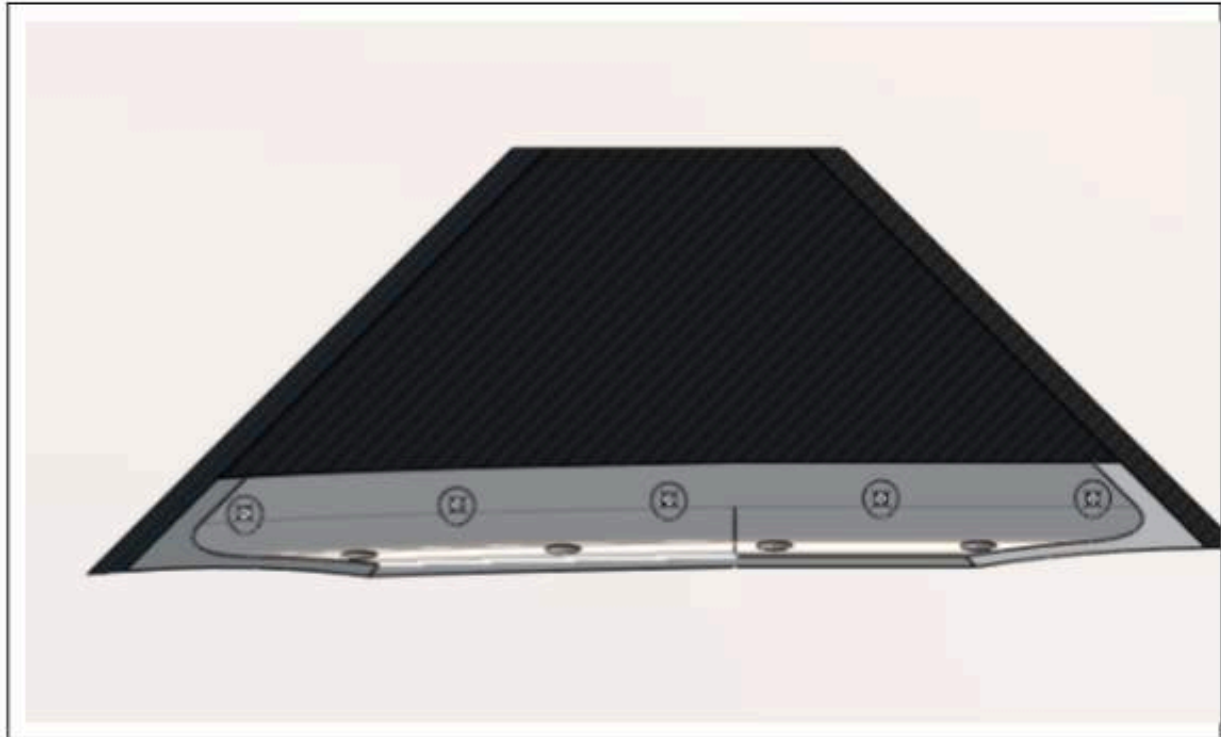
Fin analyze

Problem statement:

Birkeland has four fins made out of carbon fiber reinforced composite, using hexply 5582 fiber. The fins are made using the lay-up method using 21 layers of 0-90 degrees fiber resulting in a final thickness of 4.5mm. Using CFD the most critical forces working on the fins are found. The fins have a major role in ensuring a safe flight, therefore it is important to validate the strength of the fins.

Figure:



**Assumptions and approximations:**

The assumptions used for analytic treatment of a composite material is:

Fiber:

- Homogeneous
- Linearly elastic
- Isotropic
- Regularly spaced
- Perfectly aligned

Matrix/Epoxy:

- Homogeneous
- Linearly elastic
- Isotropic

Because of these assumptions it is assumed that the composite has lower material properties than what the finite element analysis gives.

Assumptions from [4].

Physical laws:

Calculation of strain [4]:

$$\begin{bmatrix} \Sigma_x \\ \Sigma_y \\ \Sigma_z \end{bmatrix} = \begin{bmatrix} S_{xx} & S_{xy} & 0 \\ S_{yx} & S_{yy} & 0 \\ 0 & 0 & S_{ss} \end{bmatrix} \cdot \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \end{bmatrix}$$

$$S_{xx} = \frac{1}{E_x} \quad S_{yx} = -\frac{\nu_x}{E_x}$$

$$S_{yy} = \frac{1}{E_y} \quad S_{xy} = -\frac{\nu_y}{E_y}$$

Calculating transverse poisson's ratio:

$$\nu_y = \nu_x \cdot \frac{E_y}{E_x}$$

$$S_{ss} = \frac{1}{G_{xy}}$$

Properties:

E = tensile modulus/young's modulus

G = shear modulus

σ = Tensile strength

Σ = Tensile strain

ρ = density

ν = Poisson's ratio

X_f / X_E = Value fiber / Value epoxy

X_C / X_G = Value carbon fiber / Value glass fiber

X_x / X_y = Value longitudinal / Value transverse

X_{xy} / X_{yz} = Value in plane / Value out of plane

$$\rho = 1.77 \text{ [g/cm}^3\text{]}$$

$$E_x = 67000 \text{ [MPa]}$$

$$E_y = 66000 \text{ [MPa]}$$

$$E_z = 800 \text{ [MPa]}$$

$$\nu_x = 0.37$$

$$G_{xy} = 3886.00 \text{ [MPa]}$$

$$G_{yz} = 3274.91 \text{ [MPa]}$$

$$\sigma_x = 1014 \text{ [MPa]}$$

$$\sigma_y = 959 \text{ [MPa]}$$

Values from datasheet [9].

Calculations:

$$\nu_Y = 0.36$$

$$\Sigma_X = 0.01185$$

$$\Sigma_Y = 0.01027$$

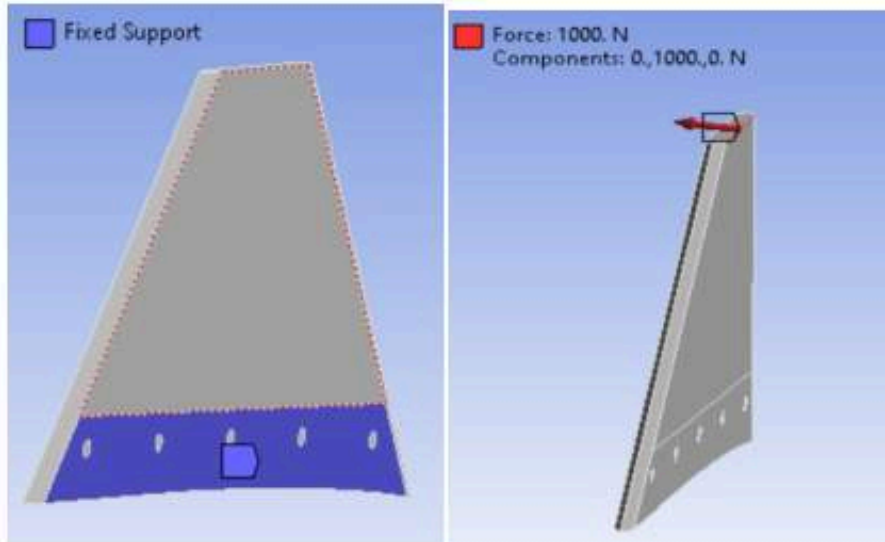
$$\Sigma_Z = 0.443$$

Reasoning, discussion and verification:

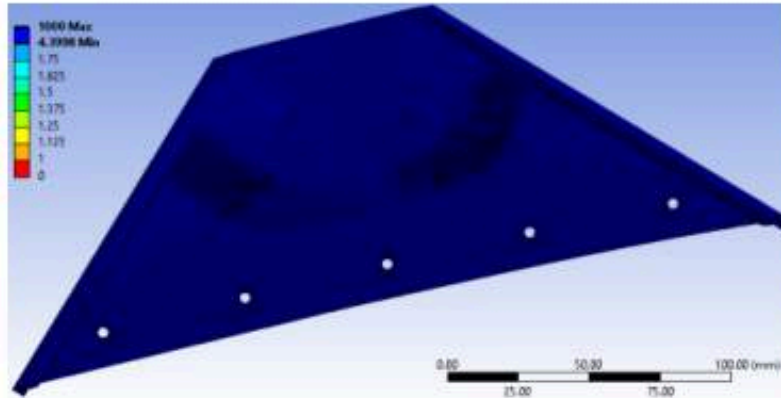
Only the finite element analysis has been completed at this point in time. While the safety factor is high there is expected to be a high difference between properties the finite element analysis calculates and the actual material properties. However early June we are taking the finns to test both shock and vibration. Especially important is to validate at which speed the composite induces fin flutter, which will be tested at the same time as the vibration and shock test. Small test pieces of the carbon fiber reinforced composite will be sent to Kongsberg Aerospace as we also have a deal to do extensive material property testing.

Final results:

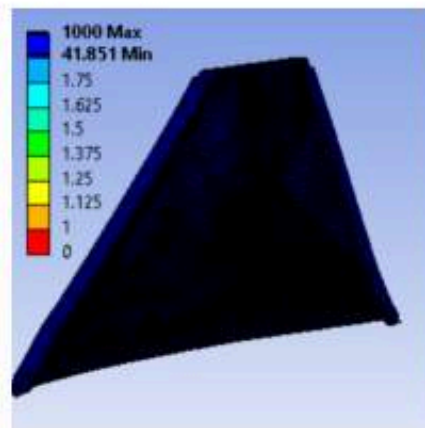
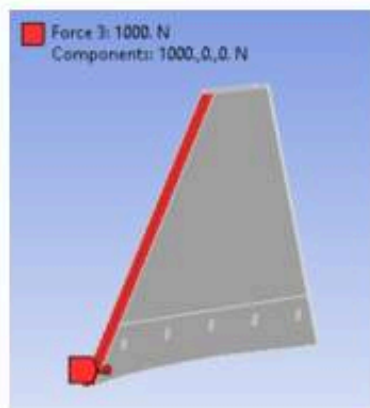
The biggest load working on the fin during flight is a force attacking perpendicular to the rocket's access. To represent this load a fixed support is placed on both sides of the fin with the purpose of imitating brackets. The mesh created around the fin has a dimension of 1.5mm.



- At max Q the perpendicular force is never expected to exceed 1000N, and as shown below the fin is expected to have a safety factor of over 4.



- For forces working directly on the wedge angle the fin is expected to be stronger, however tested to validate.



Coupler

Problem statement:

This analyzes if the coupler can withstand the force applied from the motor to the lip of the coupler. Which is a worst case scenario and not realistic.

Figure:**Assumptions and approximations:**

For this analysis, the force from the motor with 15 G is at 4750 N. Which is applied to the lip of the coupler. And see if the coupler is structurally strong after the force is applied.

Physical laws:

Peak motor force = 4750 N

Properties:

Aluminum 6082-T6
Yield strength: 250 MPa
Young's modulus: 69 GPa

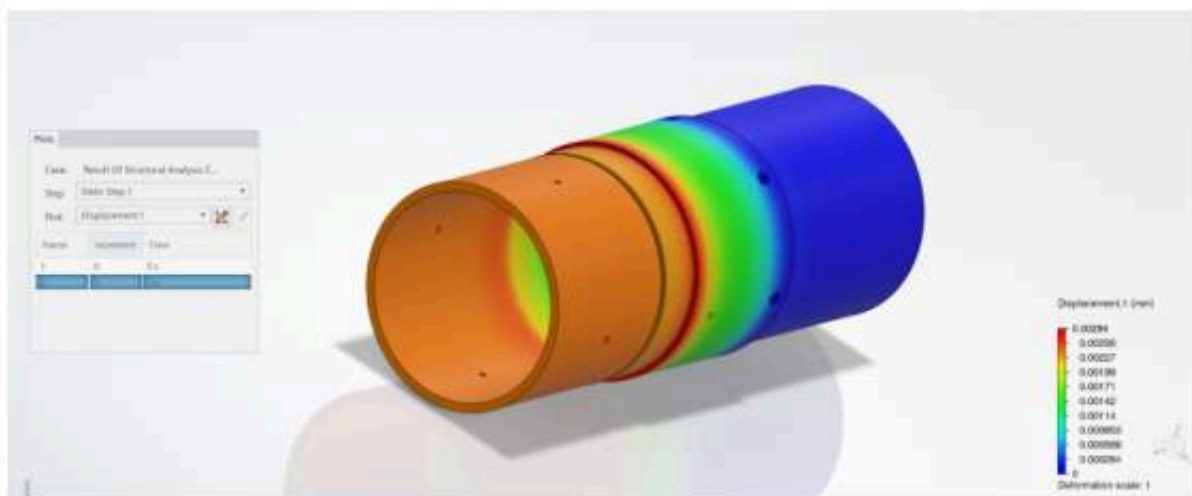
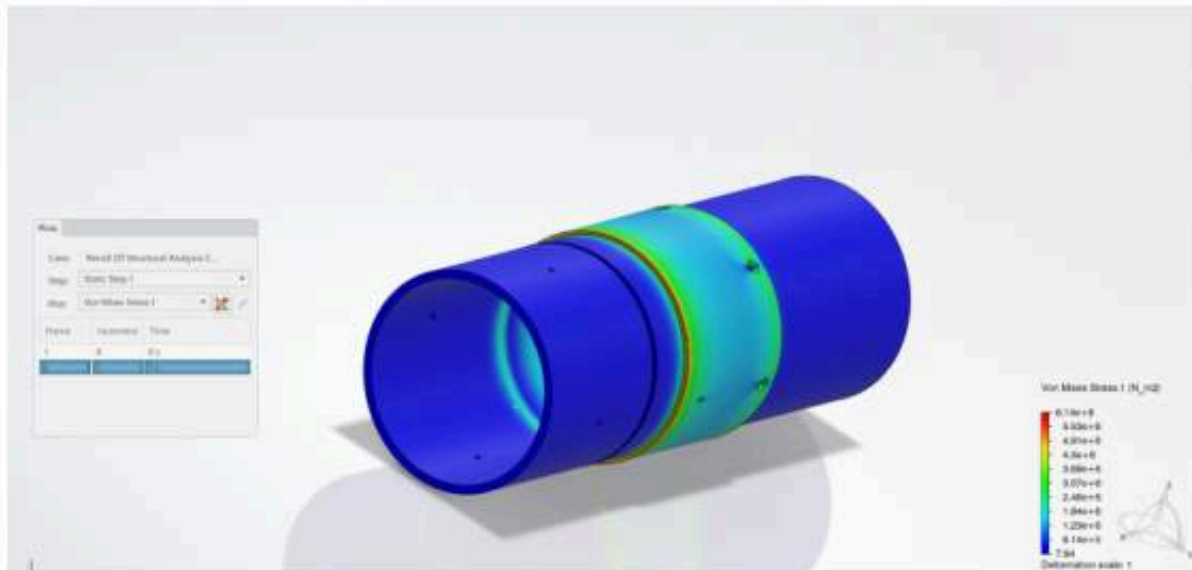
Properties from [10]

Calculations:

Stress analysis of Coupler

Mesh size, Local size
Load type
Load
Restraint
Material
Experienced Load
Safety Factor
Max Displacement

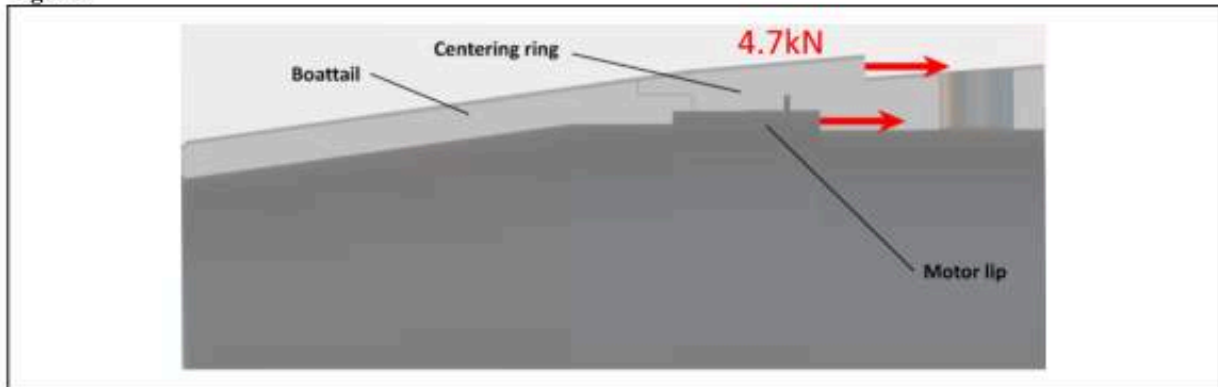
3 mm, 1 mm
Force
4750 N
Clamp
Alu 6082-T6 (Yield strength: 250 MPa)
6.14 MPa
40
<0.001



Boat tail

Problem statement:

The boat tail will be the main way of force transfer from the motor to the airframe. FEA was used to insure the part will be able to sustain the motor force without deforming or breaking.

Figure:**Assumptions and approximations:**

It was assumed that the airframe will not deform significantly. So the interface between boat tail and airframe was assumed fixed normally on the contact surface. The model was made as one solid part rather than three parts fastened with threads and screws. As most of the load should be transferred through the centering ring this was deemed accurate enough.

Physical laws:

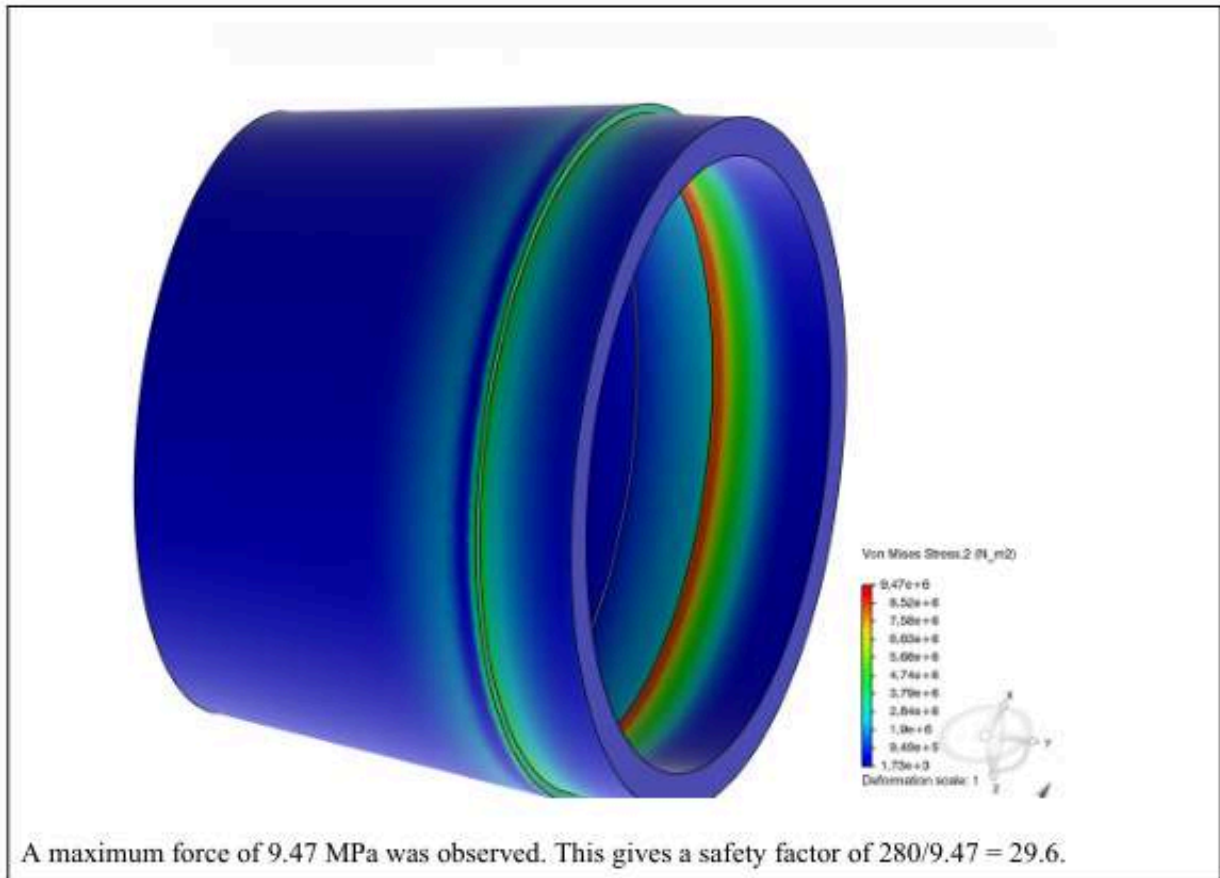
FEA

Properties:

6082-T6 yield strength: 280 MPa
Maximum thrust: 4.7 kN

Calculations:

The Boat Tail was validated with a FEA physics simulation in 3DEXPERIENCE. The model was fixed to the airframe and a force of 5 kN was applied to its interface with the motor lip.

**Reasoning, discussion and verification:**

The assumptions made may make the result less accurate, but as the safety factor is so high it is considered unlikely the boat tail will fail.

Final results:

The boat tail was deemed strong enough for flight. Being much stronger than necessary the thickness could be slightly reduced in some places, but this would make the design more complicated and harder to produce.

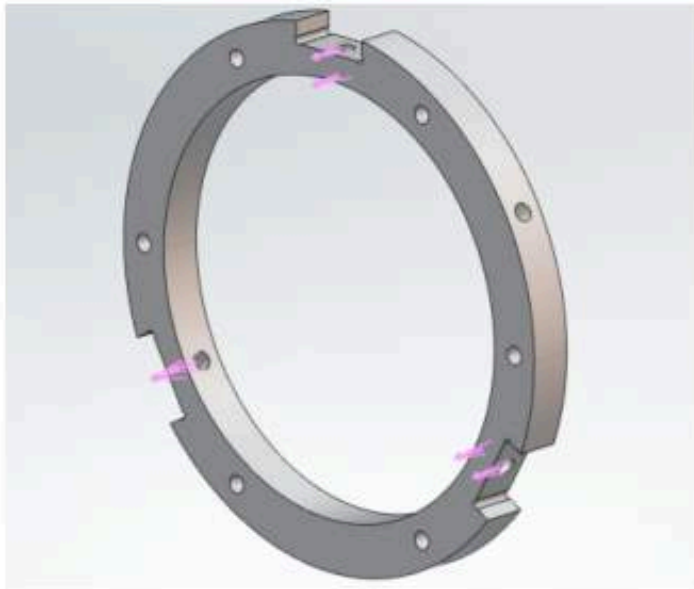
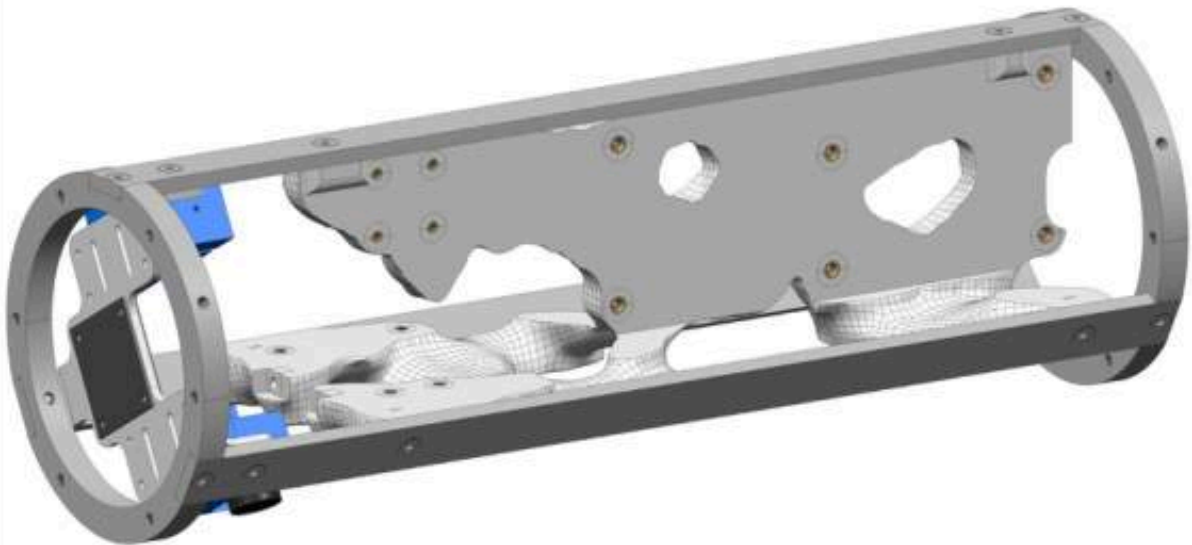
2B. Inner structure:

Avionics Module Ring

Problem statement:

The avionics module rings are the main interfaces between the module and the airframe. In order to validate that the strength of the component is adequate, FEA with the expected forces has been run on the part. A minimum factor of safety of 2 is expected.

Figure:



- Bearing loads are marked with pink arrows.
- Radial holes along the outer diameter are clamped.

Assumptions and approximations:

For this analysis, the weight used to find suitable expected forces is the weight of the avionics module. Including assembled mounting plate, camera mount and rails. Expected G-force during powered flight is 14 G. The module rings do not hold other loads than the mass of the module. Fastener type used is M4 bolts as shown in figure. Approximated forces are applied as bearing loads where rails are attached. Holes that fasten to outer structure are clamped, preventing these surfaces from moving.

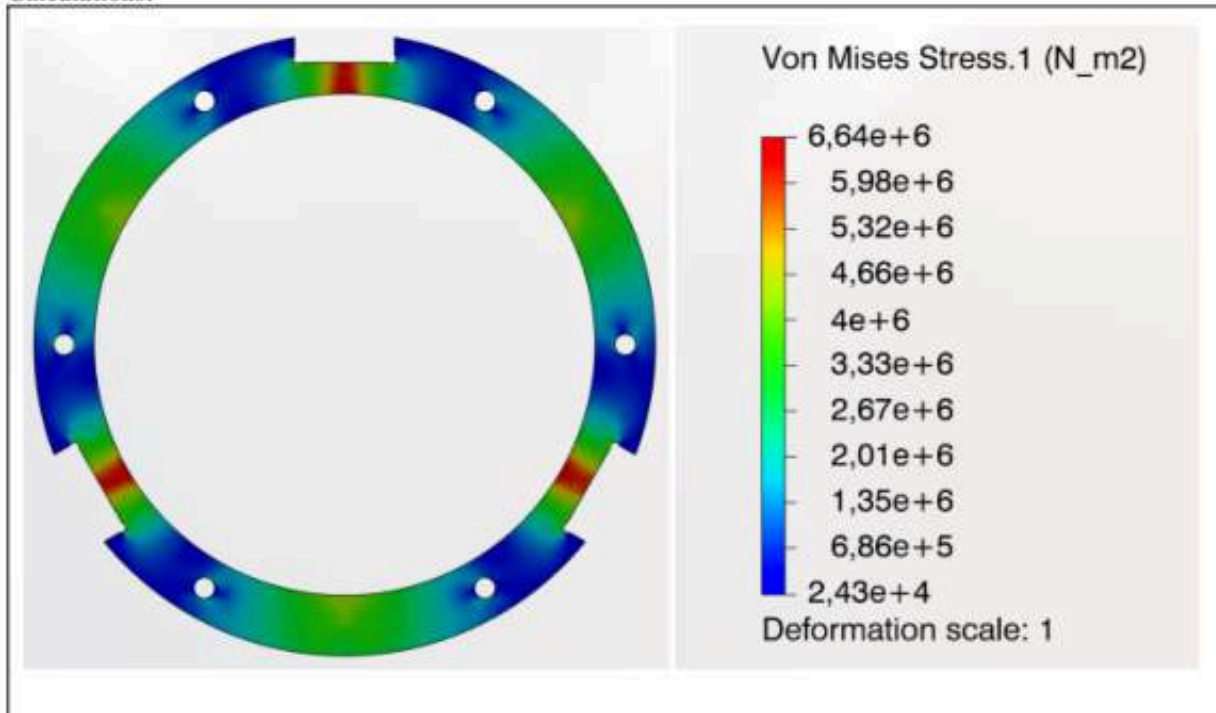
Physical laws:

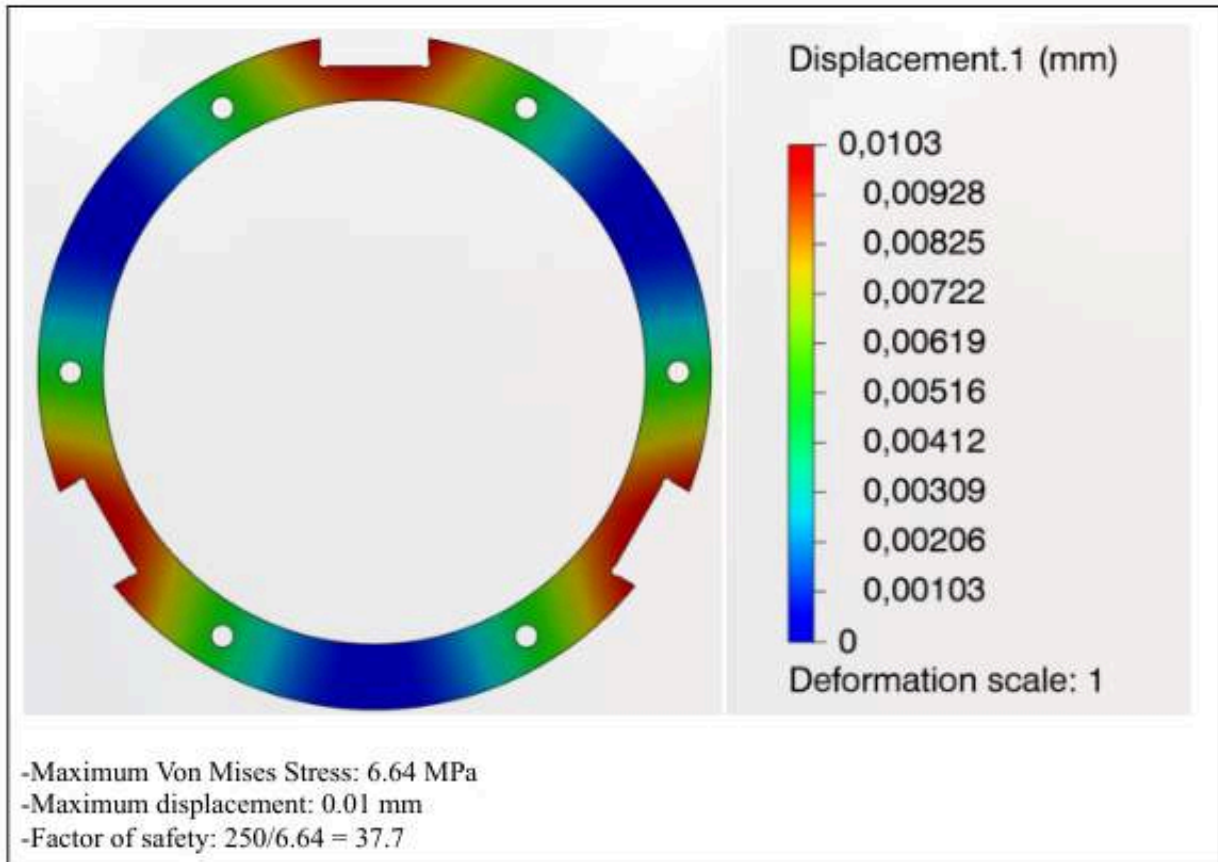
Total mass of module (excluding module rings): 2.08 kg
 Force at 1G: $F = mg = 2.08 \cdot 9.81 = 20.40 \text{ N}$
 Force at 14G: $20.40 \cdot 14 = 285.60 \text{ N}$

The module has two module rings, with three holes attached to the rails which in turn are attached to the mounting plate. Therefore, the force applied to each hole is $285.60/6 = 47.6 \text{ N}$

Properties:

Material: Aluminum 6082-T6
 Yield strength: 250 MPa
 Elastic Modulus: 70 GPa
 Properties from [10]

Calculations:

**Reasoning, discussion and verification:**

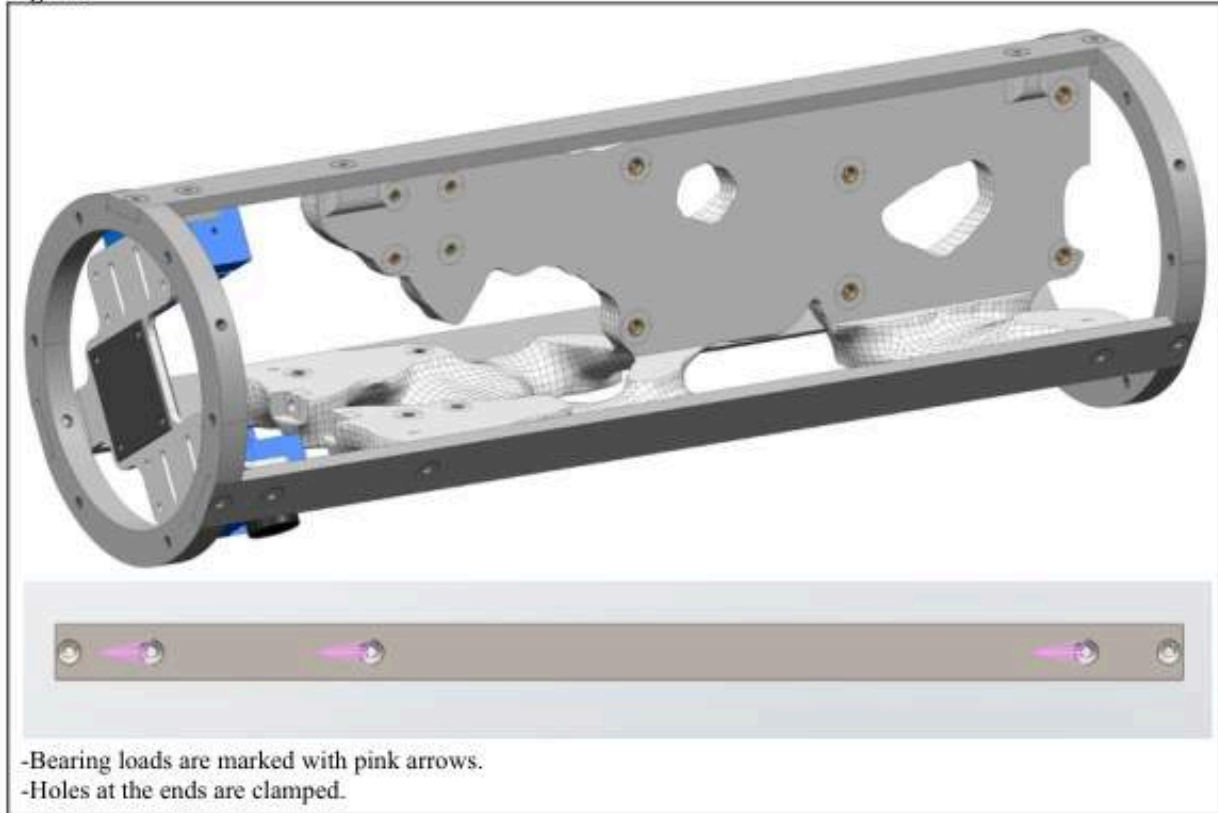
The calculated factor of safety is 37.7 and displacement is negligible in relation to function. FoS of 37.7 well above what is required, but the part will not be altered due to a wanted minimum material thickness where fasteners are to be used. In addition the current design is cheap and easy to manufacture and has been proven effective in assembly.

Final results:

We see that the module ring is able to withstand expected forces with a factor of safety of 37.7, which validates the strength of the part.

Avionics Rail**Problem statement:**

The avionics rails transfer all loads between the mounting plate and the avionics module rings. In order to validate that the strength of the component is adequate, FEA with the expected forces has been run on the part.

Figure:**Assumptions and approximations:**

For this analysis, the weight used to find suitable expected forces is the weight of the mounting plate, including all components and the camera mount fully assembled. Expected G-force during powered flight is 14 G. The rails do not hold other loads than the mass of the assembled mounting plate and camera mount. Fastener type used is M4 bolts in locations shown in figure. Approximated forces are applied as bearing loads. Holes that fasten to module rings are clamped, preventing these surfaces from moving.

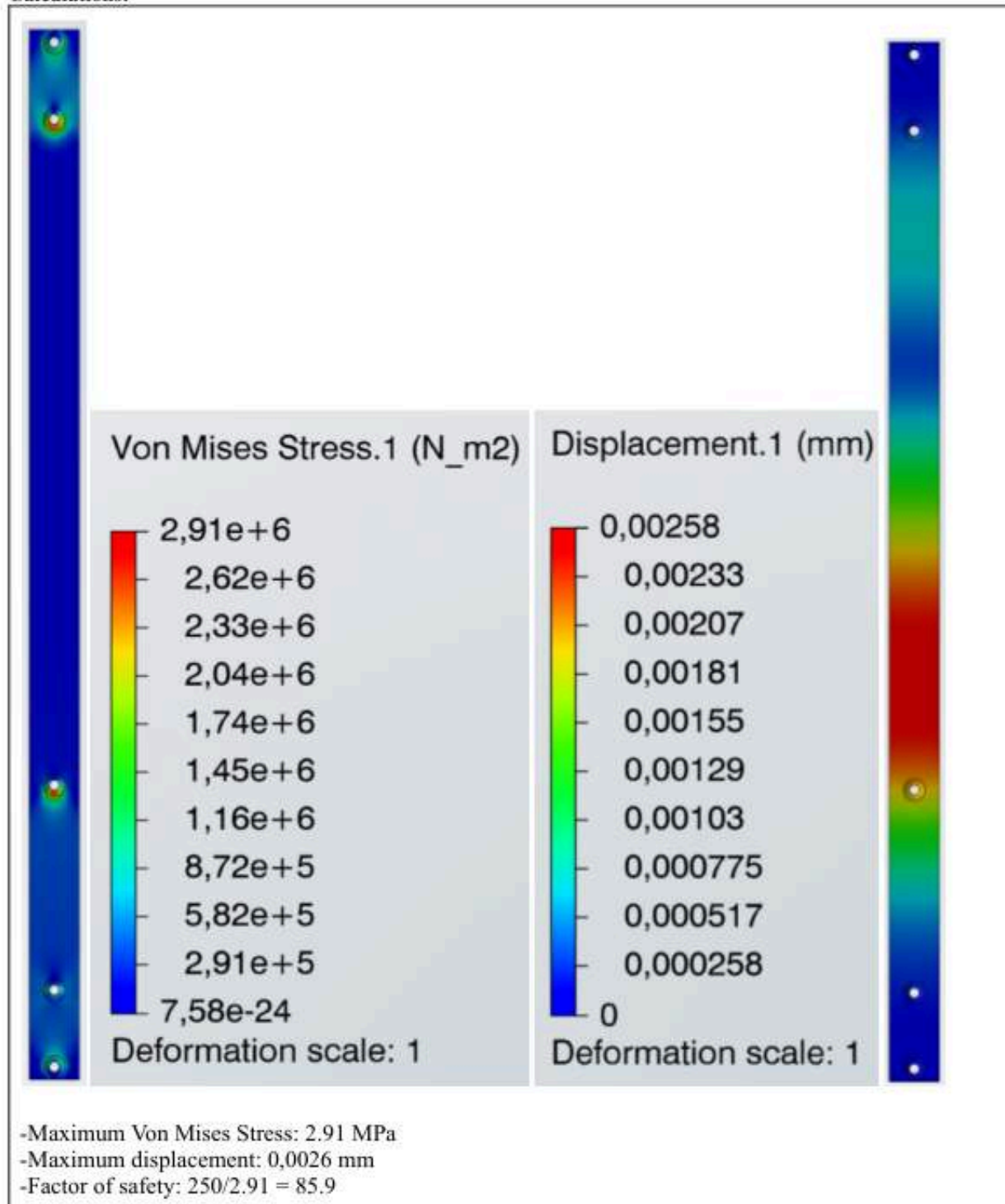
Physical laws:

Total mass of mounting plate with avionics components: 1.63 kg
 Force at 1G: $F = mg = 1.63 * 9.81 = 16.00 \text{ N}$
 Force at 14G: $16.00 * 14 = 224.00 \text{ N}$
 Forces applied from mounting plate are divided into 6 holes (2 per rail): $224.00/6 = 37.4 \text{ N}$

Total mass of the camera mount with cameras and PCBs: 0.12 kg
 Force at 1G: $F = mg = 0.12 * 9.81 = 1.18 \text{ N}$
 Force at 14G: $1.18 * 14 = 16.52 \text{ N}$
 Forces applied from camera mount are divided into 3 holes (1 per rail): $16.52/3 = 5.5 \text{ N}$

Properties:

Material: Aluminum 6082-T6
 Yield strength: 250 MPa
 Elastic Modulus: 70 GPa
 Properties from [10].

Calculations:**Reasoning, discussion and verification:**

The calculated factor of safety is 85.9 and displacement is negligible in relation to function.
FoS of 85.9 well above what is required, but the part will not be altered due to a wanted minimum material

thickness where fasteners are to be used. Material thickness also adds stiffness during pre-launch handling of the inner structure. Thicker rails help increase the eigenfrequency of the finished assembly. In addition the current design is cheap and easy to manufacture and has been proven effective in assembly.

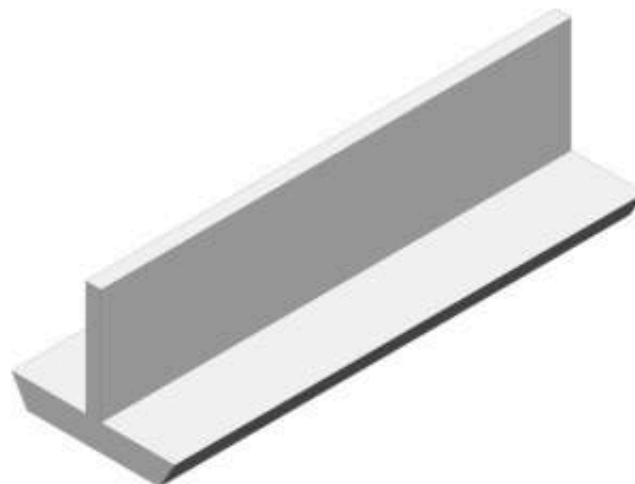
Final results:

We see that the avionics rail is able to withstand expected forces with a factor of safety of 85.9, which validates the strength of the part.

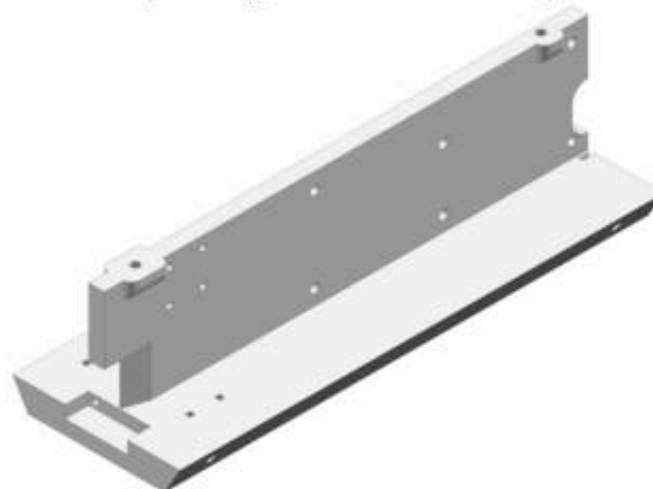
Mounting Plate - Topology Optimization

Problem statement:

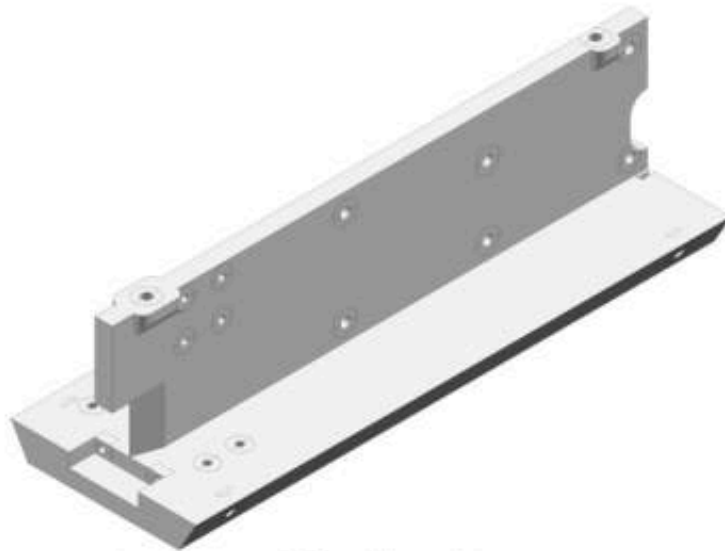
The mounting plate is used to fasten avionic components in an organized matter. To reduce mass and volume, the part has been iterated upon using topology optimization. The part has been run through a series of stress-analyses containing simulated forces where material that is not contributing to structural integrity has been removed. The part is subsequently validated using FEA to ensure required strength in the generated shape.

Figure:

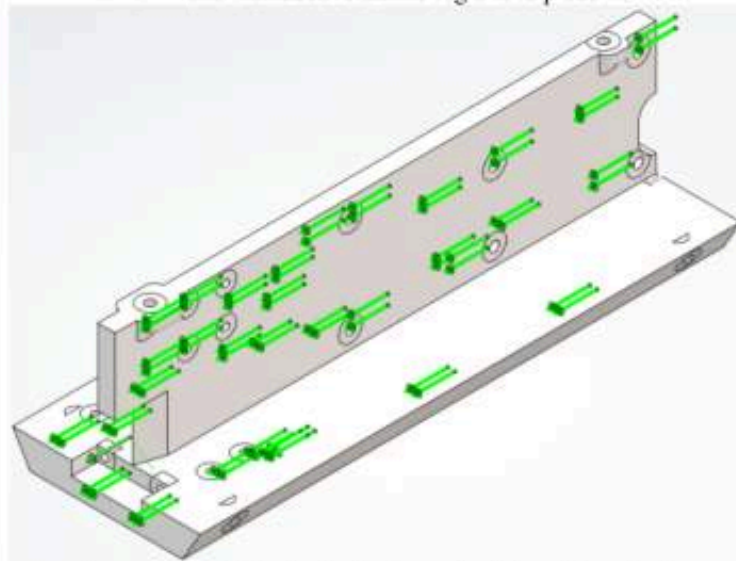
Initial shape creating flat surfaces to mount components



Holes and pockets are added where components are to be fastened



Partitions are added to define regions to preserve



Forces are added to the holes (see calculations for values)

Assumptions and approximations:

For the simulation, The gravitational force of each component is multiplied by 15 G and divided by the number of holes fastening that component. Most loads are applied to all appropriate holes simultaneously and allotted automatically by the software. Some loads are manually divided and applied to each hole to acquire load-paths which lead to better results. This has been discovered through trial and error. Where the mounting plate is attached to the avionics rails, clamps are added to define where loads travel.

Prior to simulation, the optimization strategy is chosen. The chosen strategy for the mounting plate has been to maximize stiffness for a given mass. Optimization constraints are also added to better describe the wanted results. Here several constraints have been attempted, including frequency constraint, overhang control, thickness control

and symmetry control. The latter two have yielded the best results. For the final simulation, thickness control at minimum 20 mm and symmetry across the ZX-plane was added (see figure). The given mass that the simulation aimed for was 50 % of the original weight.

After the shape is generated. A regular FEA is run on the shape with the same clamps and loads as for the optimization.

Physical laws:

The general formula used to find the gravitational force on a part during 1G:

$$F = mg$$

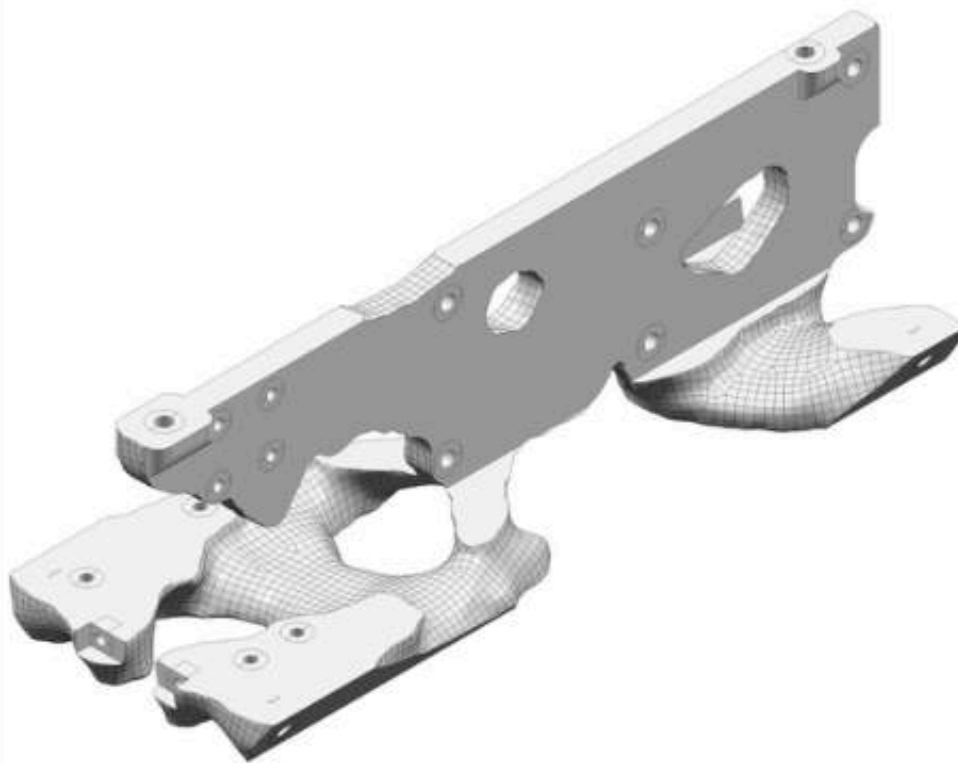
Properties:

Material: PA12/PA2200
Tensile strength: 48 MPa
Tensile modulus: 1650 MPa
Properties from [11]

Calculations:

Calculated forces for all parts mounted to the mounting plate:

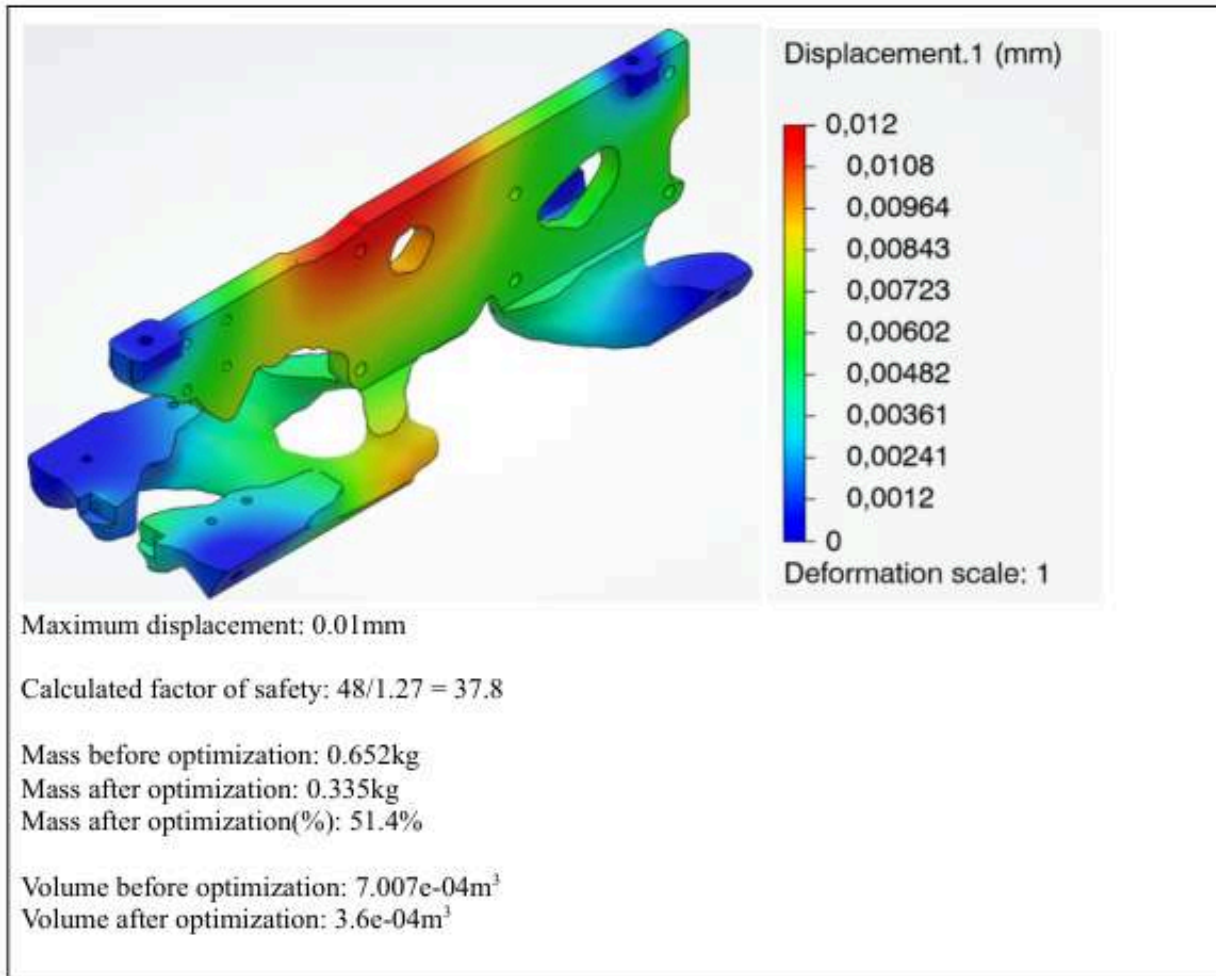
Name of part	Weight [g]	Screwcount	Force on each hole [N]	For Part Total [N]
SRAD PCBs	100	6	2.45	14.72
Ethernet switch	10	4	0.37	1.47
Video encoder	63	2	4.64	9.27
SRAD Battery Pack	409	2	30.09	60.18
Ublox antenna	164	2	12.07	24.13
Featherweight GPS	15	2	1.10	2.21
Altimax G4	13	2	0.96	1.91
Radionor transmitter	85	4	3.13	12.51
Altimax battery casing	95	2	6.99	13.98
Magswitch 1	10	2	0.74	1.47
Magswitch 2	10	2	0.74	1.47
Magswitch 3	10	2	0.74	1.47
Fan	20	2	1.47	2.94
Voltage Regulator	15	2	1.10	2.21



Resulting generated shape after fine tuning the cutting value.



Maximum Von Mises Stress: 1.27 MPa



Reasoning, discussion and verification:

The topology optimization resulted in reducing the mass and the volume of the mounting plate as intended. The resulting part was validated, resulting in a factor of safety of 37.8. The mass goal was not set lower than 50%, as this was attempted with non-usable results (e.g. two parts that were not connected). The removed material gives space for cable management and the shape is rigid enough to not break during handling.

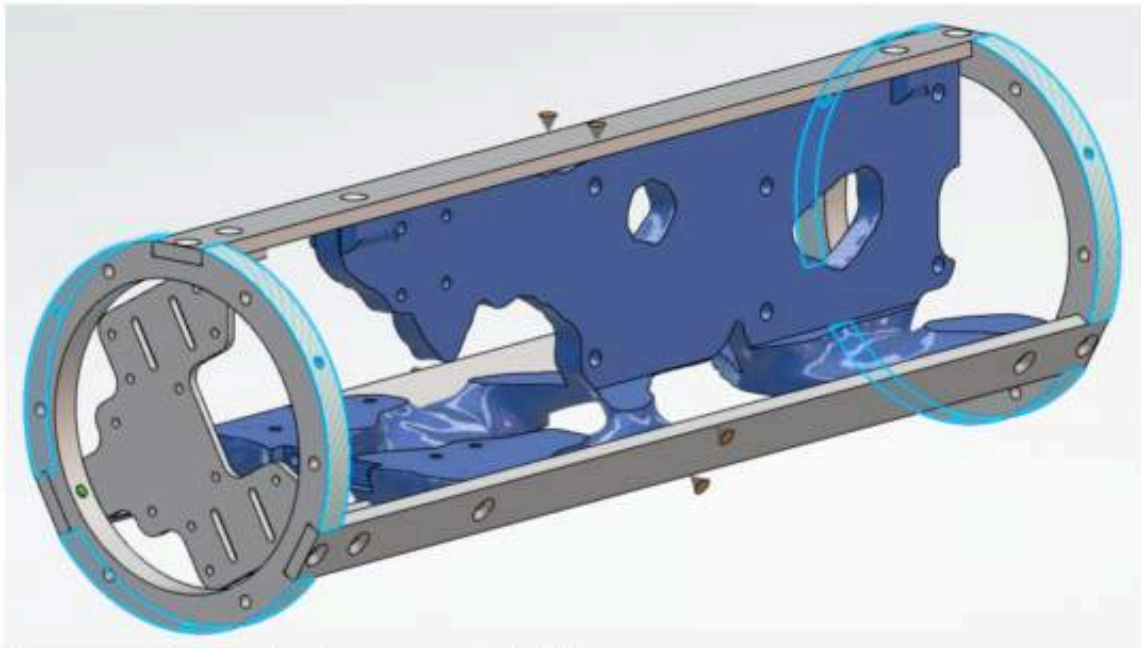
Final results:

The topology optimized part had a mass reduction of 48.6% and was validated to have a factor of safety of 37.8, rendering the part suitable for its purpose.

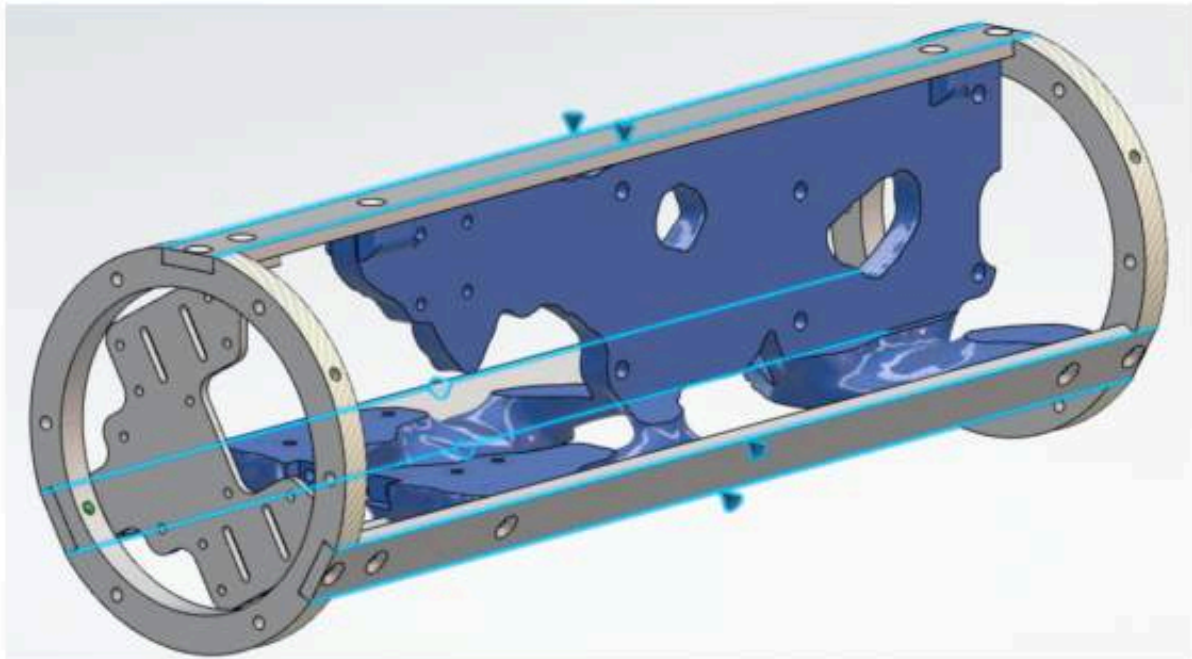
Vibration FEA Avionics Module

Problem statement:

To validate the stiffness of the assembled avionics module, FEA with frequency outputs have been run on the entire module.

Figure:

Blue areas are clamped simulating contact with the airframe.



Edges indicated by blue lines are restricted flow moving outwards, simulating contact with the airframe.
 For the top rail this is directly upwards.
 For the right rail this is 120 degrees to the right.
 For the left rail this is 120 degrees to the left.

Assumptions and approximations:

These simulations are run with the inner structure only, excluding the avionic components. Including these would complicate the setup, and may lead to inaccurate results if not restricted correctly. The program used was 3DEXperience. The resulting output gives the five lowest eigenfrequencies of the module.

Physical laws:

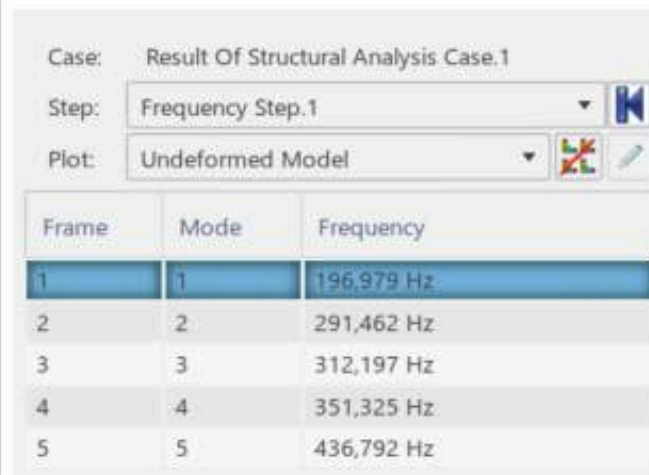
No physical laws have been used during the setup of the simulation. Only restrictions added to the setup affect the results.

Properties:

Material Mounting Plate: Nylon PA12/PA2022
Tensile strength: 48 MPa
Tensile modulus: 1650 MPa
Properties from [11]

Material Rails: Aluminum 6082-T6
Material Module Rings: Aluminum 6082-T6
Material Camera Plate: Aluminum 6082-T6
Yield strength: 250 MPa
Elastic Modulus: 70 GPa
Properties from [10]

Calculations:



Frame	Mode	Frequency
1	1	196,979 Hz
2	2	291,462 Hz
3	3	312,197 Hz
4	4	351,325 Hz
5	5	436,792 Hz

The simulation outputs the depicted eigenfrequencies.
The lowest frequency is 196 Hz, which is a good result.

Reasoning, discussion and verification:

The results in this type of simulation gives only an approximation of real world results. A physical vibration test is planned to be performed.

Final results:

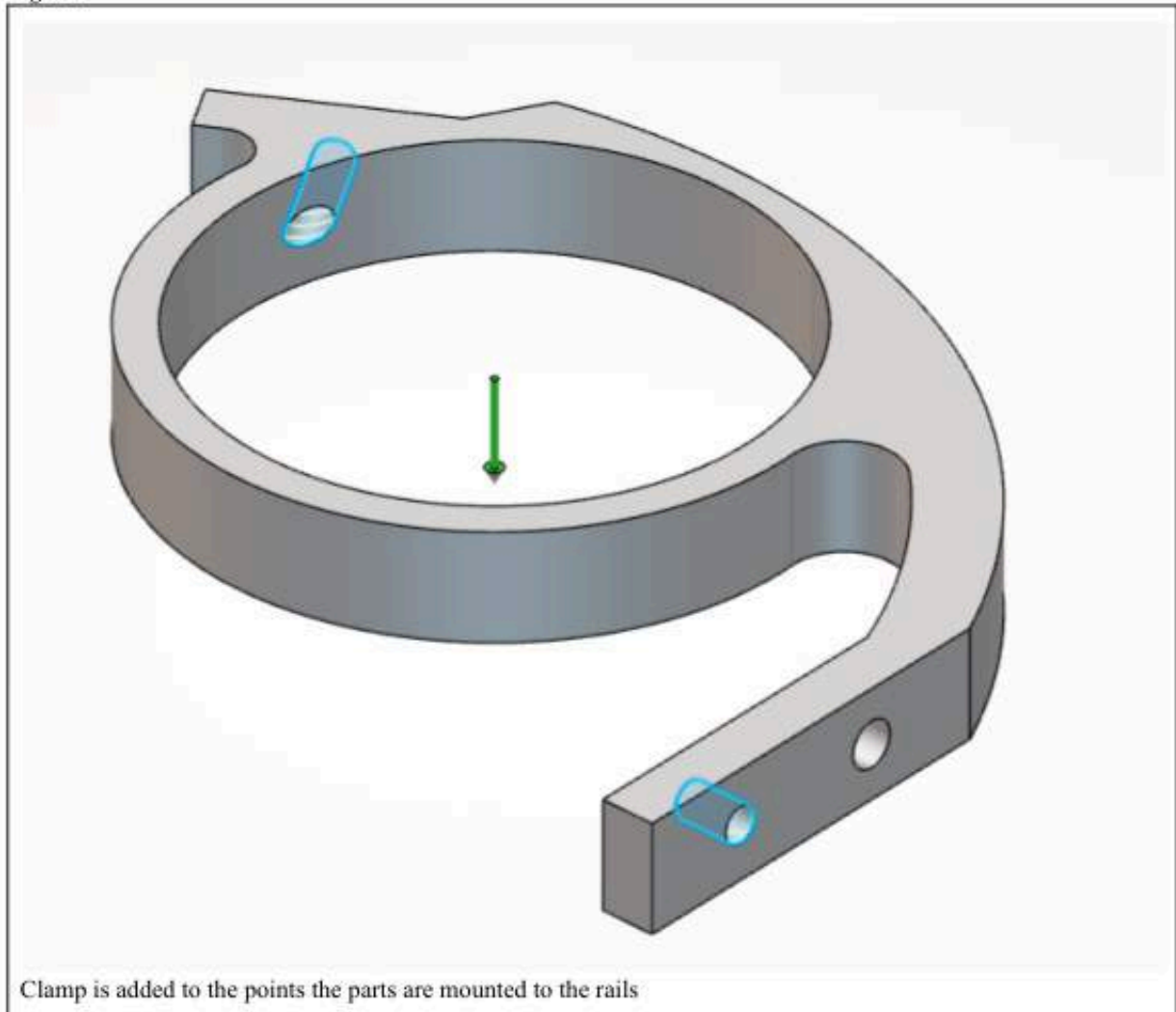
The frequency analyzes show that the lowest eigenfrequency of the module is 196 Hz, reducing the vibrational loads on the structure.

PV Brackets

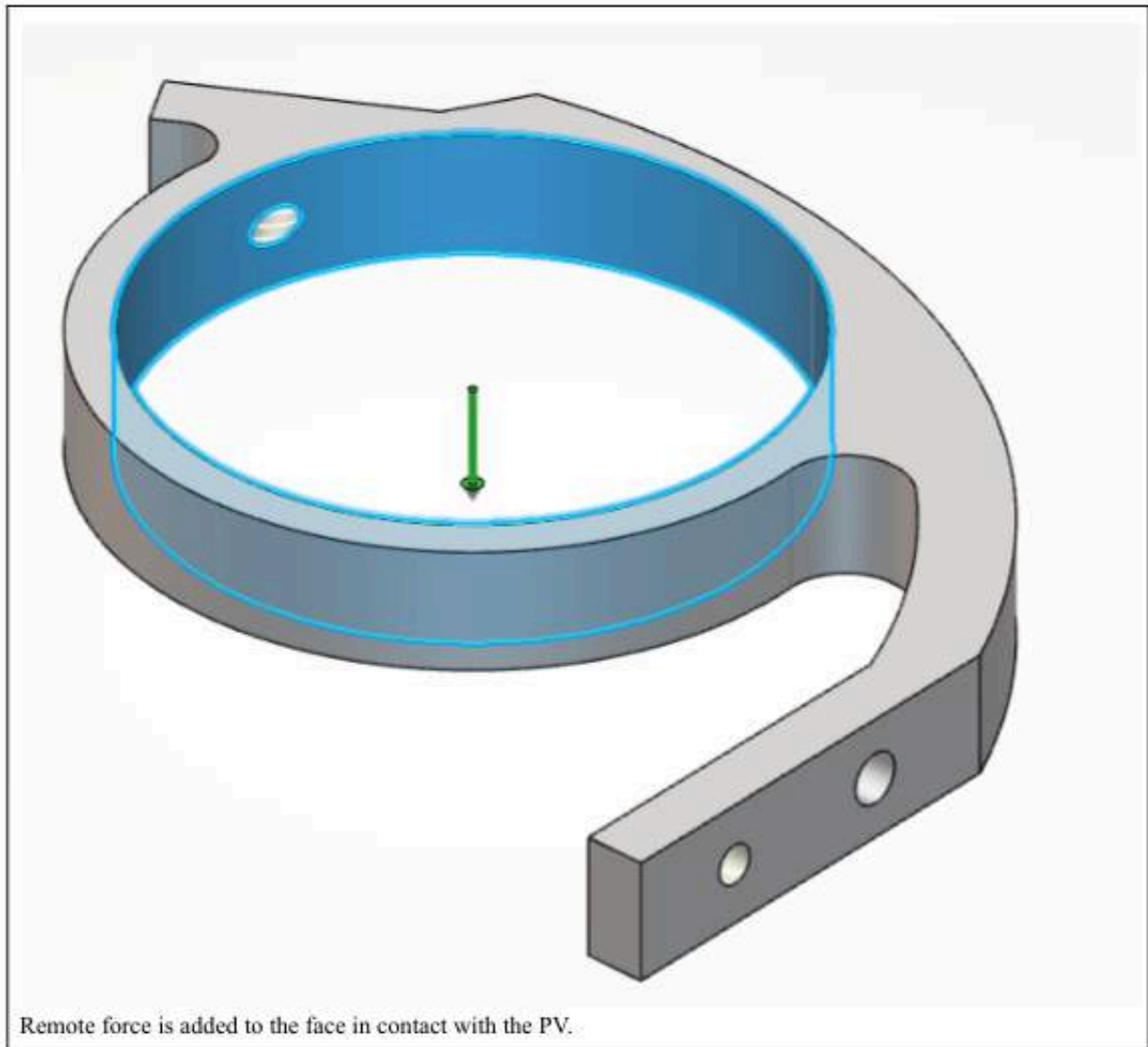
Problem statement:

The PV Brackets are the main interfaces between the PV and the recovery rails. In order to validate that the strength of the component is adequate, FEA with the expected forces has been run on the part. A minimum factor of safety of 2 is expected.

Figure:



Clamp is added to the points the parts are mounted to the rails

**Assumptions and approximations:**

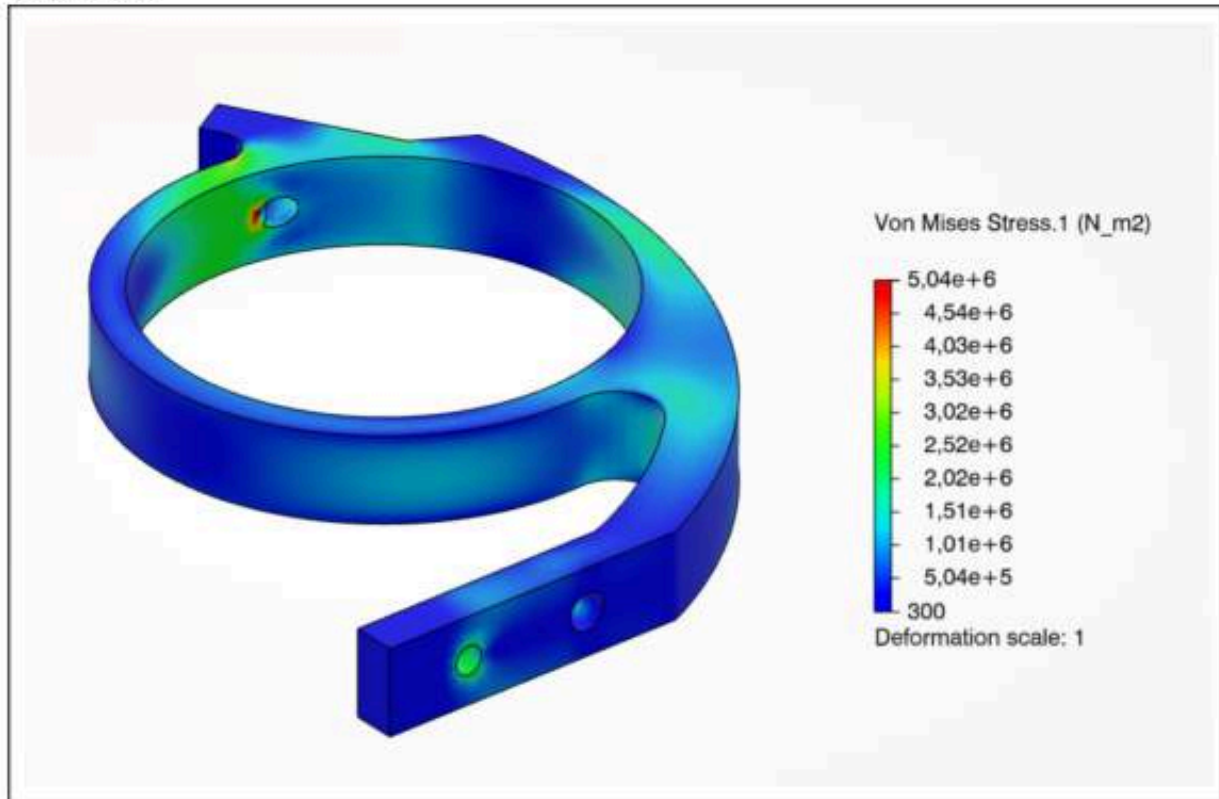
In this simulation the approximated force used is the gravitational force of the PV multiplied by 15G. It is assumed that this force is equally divided between the four brackets holding the PV.

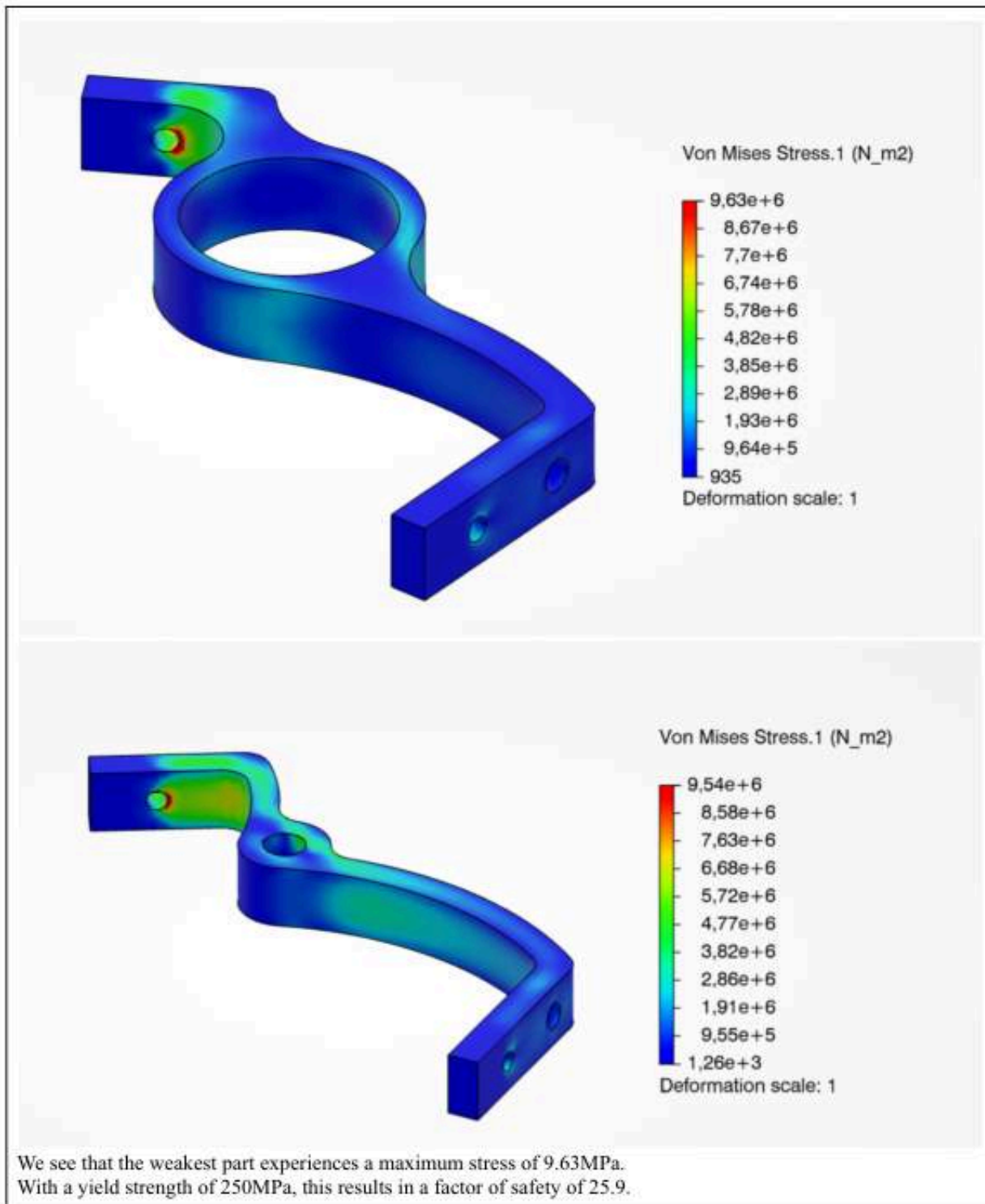
Physical laws:

$F = mg$
Total force from PV during 15G:
 $0.6\text{kg} * 9.81 * 15 = 88.3\text{N}$
This divided in four brackets:
 $88.3/4 = 22.1\text{N}$
This is the force added to each part.

Properties:

All parts are 6082-T6 Aluminum
Yield strength: 250 MPa
Elastic Modulus: 70 GPa
Properties from [10]

Calculations:



Reasoning, discussion and verification:

The calculated factor of safety is 25.9 and displacement is negligible in relation to function. FoS of 25.9 well above what is required, but the part will not be altered due to a cheap and easy to manufacture design which has been proven effective in assembly.

Final results:

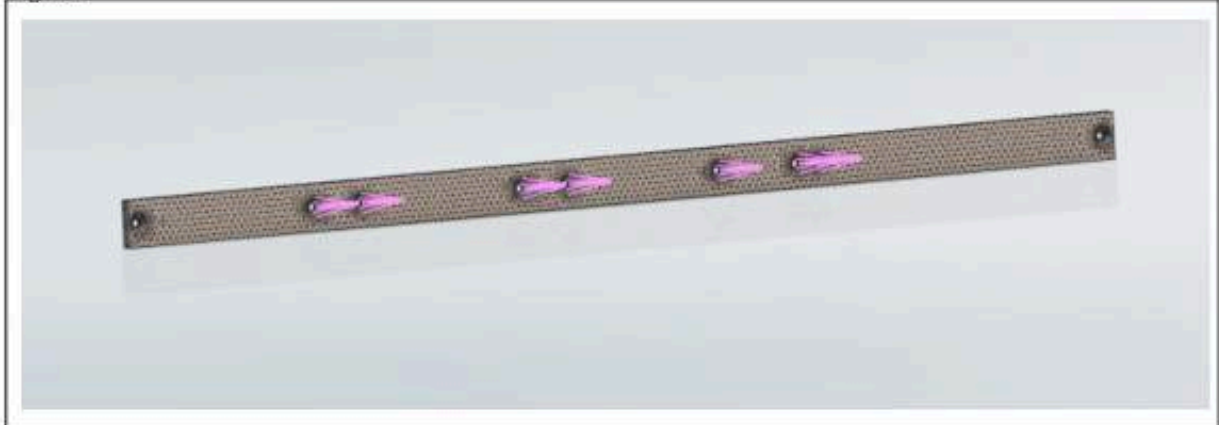
We see that the PV Brackets are able to withstand expected forces with a factor of safety of 25.9, which validates the strength of the parts.

2C. Recovery:

Recovery Rail

Problem statement:

The recovery rails transfer all loads between the bulkheads and components. In order to validate that the strength of the component is adequate, FEA with the expected forces has been run on the part.

Figure:**Assumptions and approximations:**

For this analysis, the weight used to find suitable expected forces is the weight of the recovery module. Including all components. Expected G-force is 15G. The rails do not hold other loads than the mass of the assembled components and brackets.

Physical laws:

Total mass of recovery module (excluding bulkheads): 3 kg
Force at 1G: $F = mg = 3 \cdot 9.81 = 29.43 \text{ N}$
Force at 15G: $29.43 \cdot 15 = 441.45 \text{ N}$

The module has three bulkheads, with 7 holes attached to the rails which in turn are attached to the bulkheads. Therefore, the force applied to each hole is $441.45/14 = 29.43 \text{ N}$

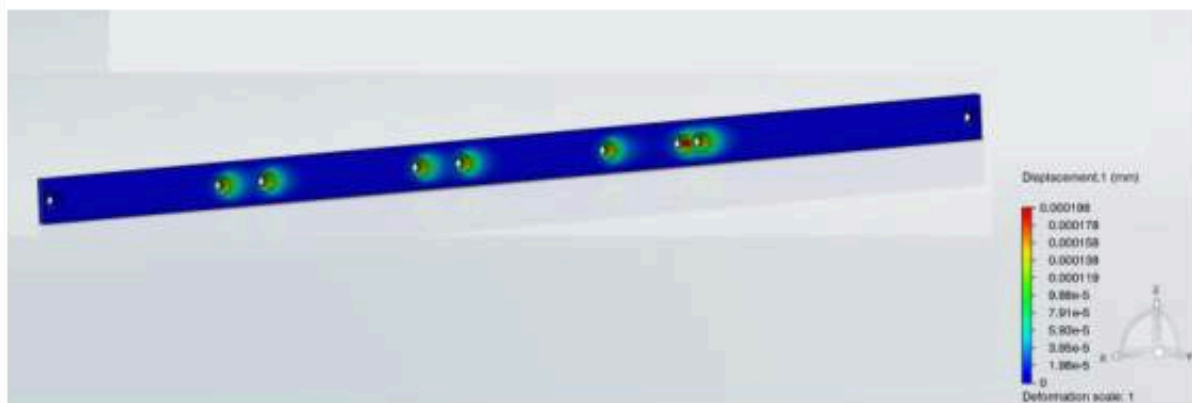
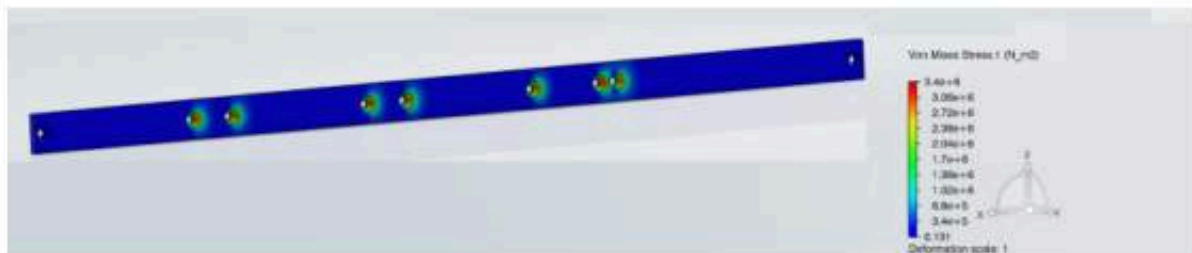
Properties:

Aluminium 6082-T6
Yield strength: 250 MPa
Young's modulus: 69 GPa
Properties from [10]

Calculations:**Stress analysis of Recovery Rail**

Mesh size, Local size
 Load type
 Load
 Restraint
 Material
 Experienced Load
 Safety Factor
 Max Displacement

3 mm, 1 mm
 Bearing Load (180 deg spread)
 30 N
 Clamp
 Alu 6082-T6 (Yield strength: 250 MPa)
 3.4 MPa
 73
 <0.001



Recovery Bulkhead

Problem statement:

The recovery bulkheads are the main interface between the module and the airframe. In order to validate that the strength of the component is adequate, FEA with the expected forces has been run on the part.

Figure:**Assumptions and approximations:**

For this analysis, the weight used to find suitable expected forces is the weight of the recovery module. Including all components, mounting-plate and rails. Expected G-force is 15 G. The bulkheads do not hold other loads than the mass of the module.

Physical laws:

Total mass of recovery module (including bulkheads): 4 kg
Force at 1G: $F = mg = 4 \cdot 9.81 = 39.24 \text{ N}$
Force at 15G: $39.24 \cdot 15 = 588.6 \text{ N}$

The module has two bulkheads, with 3 holes attached to the rails which then holds all the recovery components. Therefore, the force applied to each hole is $588.6/3 = 196.2 \text{ N}$

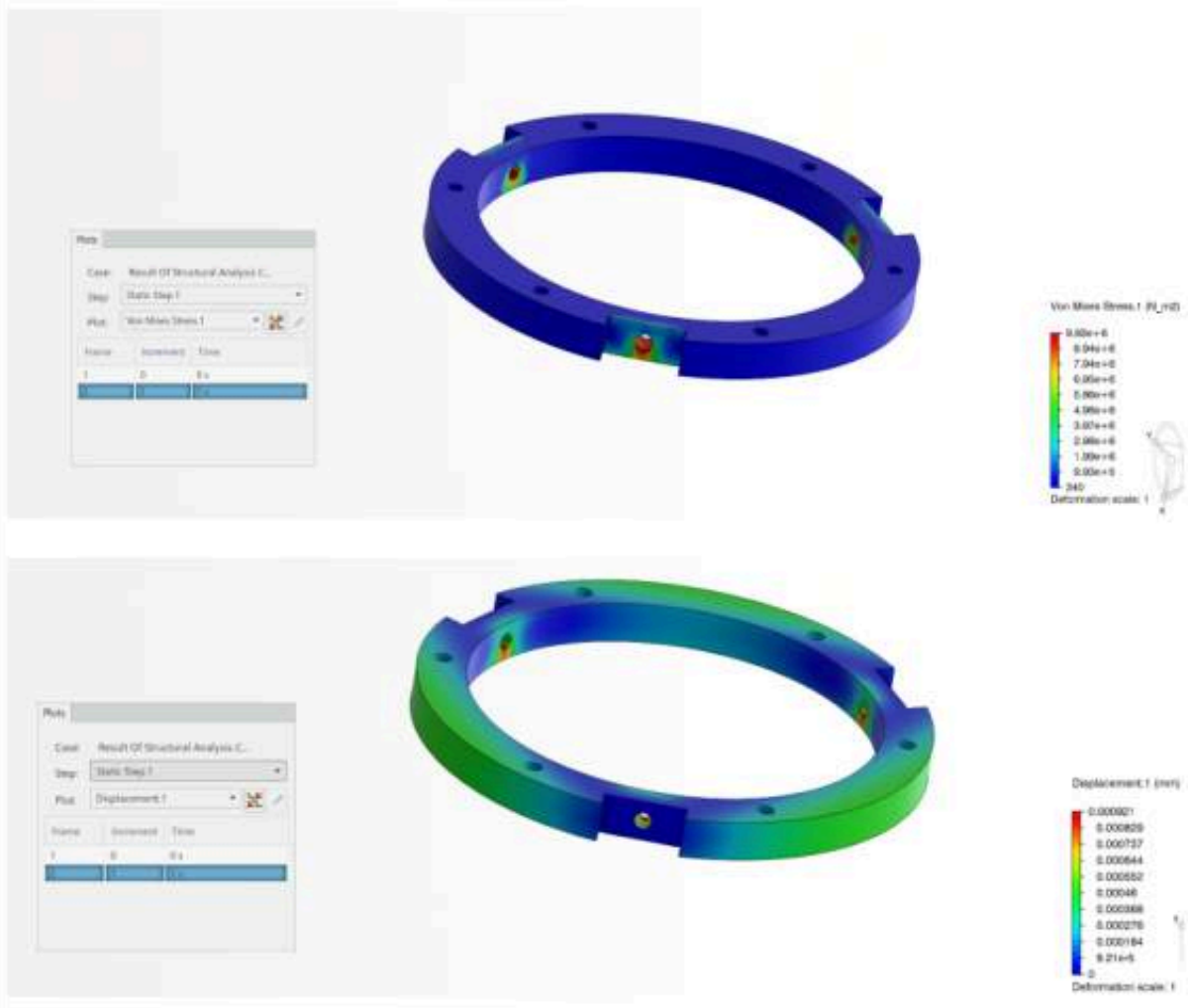
Properties:

Aluminium 6082-T6
Yield strength: 250 MPa
Young's modulus: 69 GPa
Properties from [10]

Calculations:**Stress analysis of Recovery Rail**

Mesh size, Local size
 Load type
 Load
 Restraint
 Material
 Experienced Load
 Safety Factor
 Max Displacement

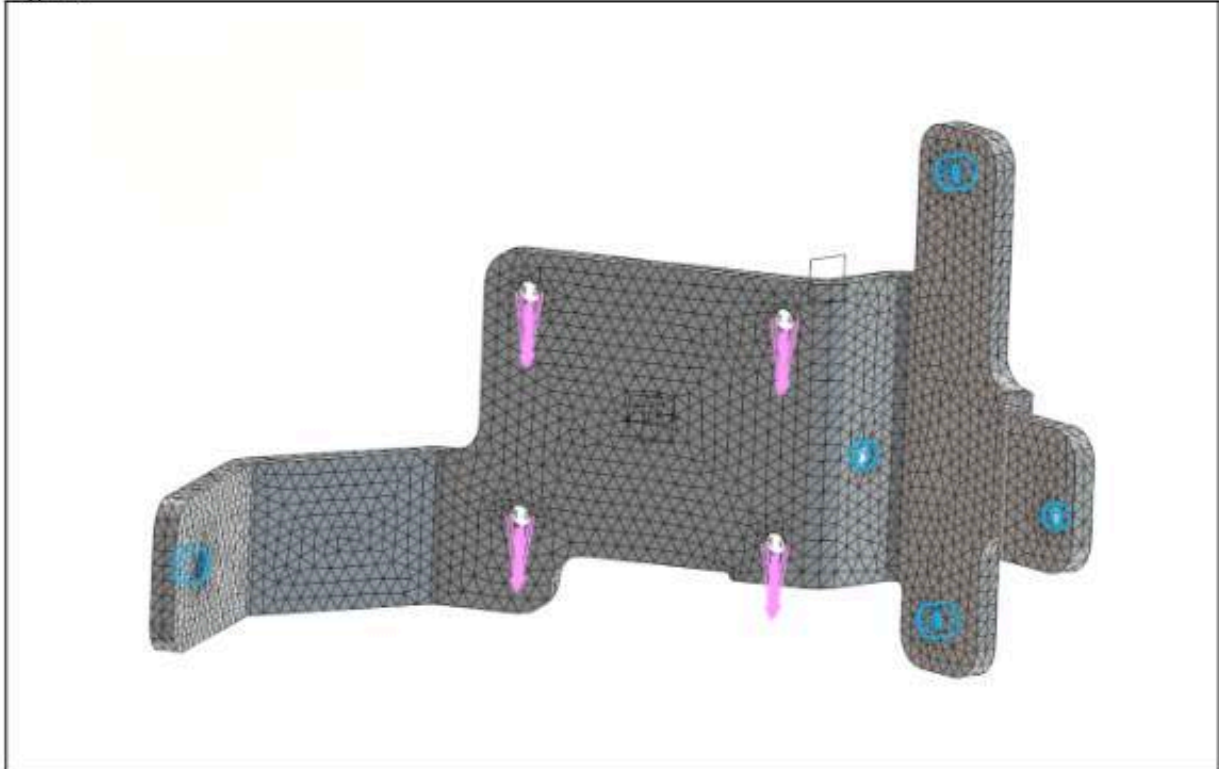
3 mm, 1 mm
 Bearing Load (180 deg spread)
 198 N
 Clamp
 Alu 6082-T6 (Yield strength: 250 MPa)
 9.93 MPa
 25
 <0.001



HAWK Mounting Plate

Problem statement:

The HAWK mounting plate transfers all loads between the components through the plate to the rails. In order to validate that the strength of the component is adequate, FEA with the expected forces has been run on the part.

Figure:**Assumptions and approximations:**

For this analysis, the weight used to find suitable expected forces is the weight of the mounting plate, including all components that's connected to the plate. Expected G-force is 15 G. The HAWK-plate does not hold other loads than the mass of the assembled components.

Physical laws:

Total mass of HAWK-plate including components: 0.45 kg

Force at 1G: $F = mg = 0.45 \cdot 9.81 = 4.415 \text{ N}$

Force at 15G: $4.415 \cdot 15 = 66.22 \text{ N}$

The plate has four mounting holes for components. Therefore, the force applied to each hole is $66.22/4 = 16.55 \text{ N}$

Properties:

Aluminium 6082-T6

Yield strength: 250 MPa

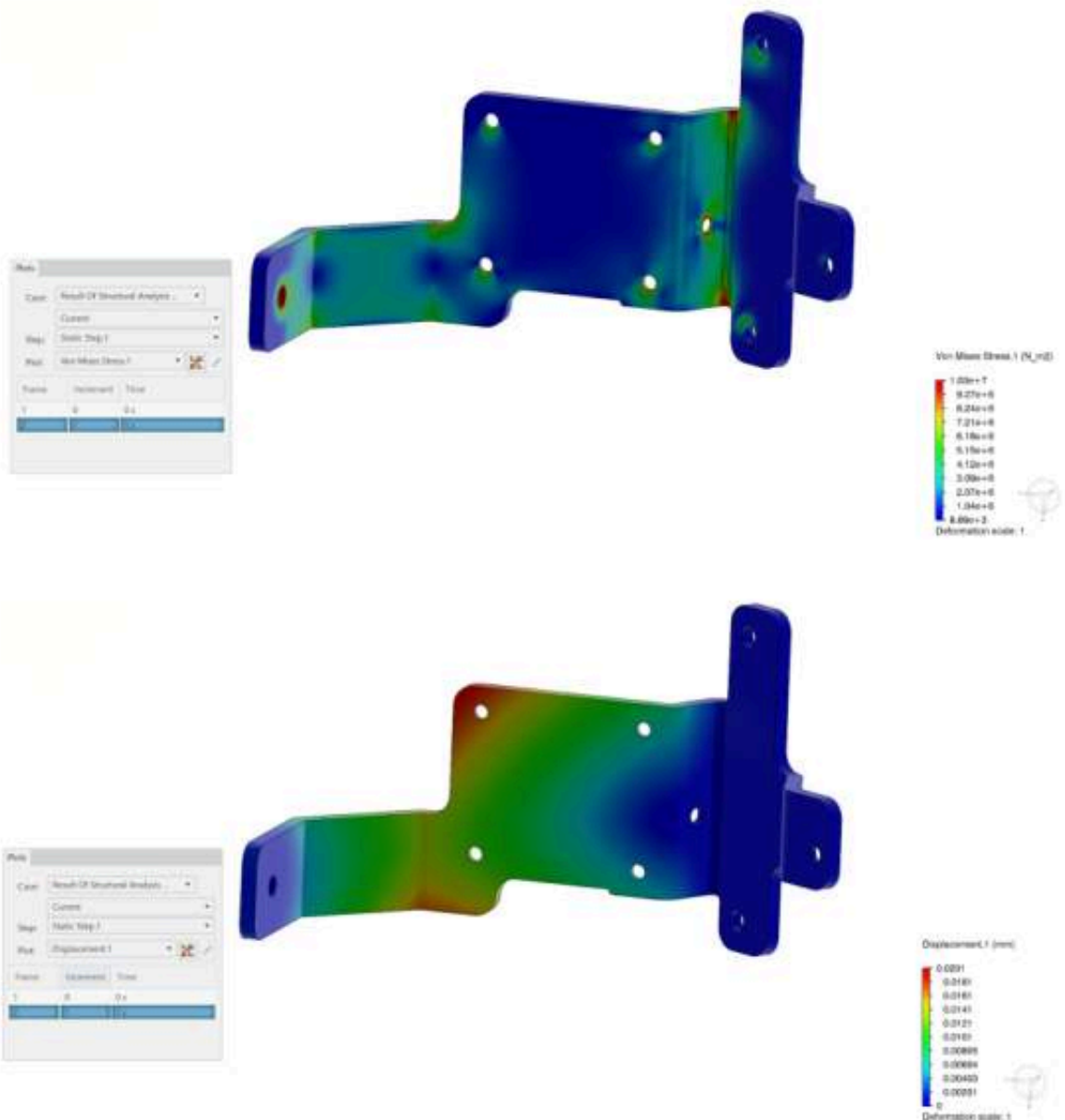
Young's modulus: 69 GPa

Properties from [10]

Calculations:**Stress analysis of HAWK Mounting Plate**

Mesh size, Local size
 Load type
 Load
 Restraint
 Material
 Experienced Load
 Safety Factor
 Max Displacement

2 mm, 1 mm
 Bearing Load (180 deg spread)
 20 N
 Clamp
 Alu 6082-T6 (Yield strength: 250 MPa)
 10 MPa
 25
 <0.01



Forces on MCRS and Recovery Plate

Problem statement:

The forces that act on the components in MCRS and the Recovery Plate are to be found.

Figure:

Figure 1: Main chute docking

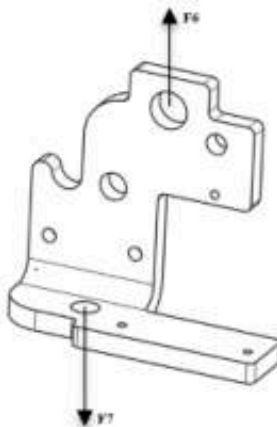


Figure 2: Upper release arm

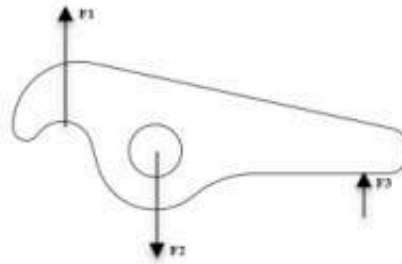


Figure 3: Lower release arm



Free body diagram

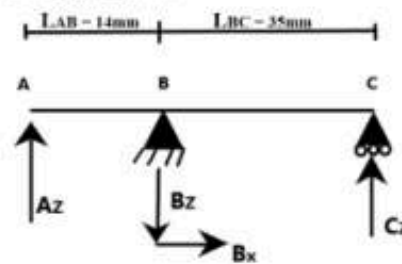
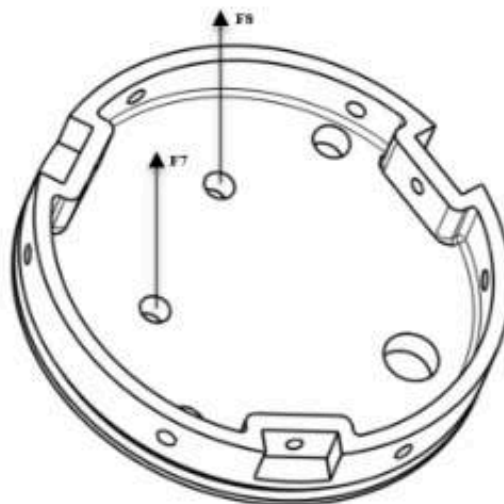


Figure 4: Recovery Plate



Assumptions and approximations:

Assuming that the system is in mechanical equilibrium. Assuming the release forces from the drogue chute and main chute are evenly distributed between the aft and FWD based on their weight.

Physical laws:

Equilibrium equations:

$$\Sigma F_x = 0 \quad \Sigma F_y = 0 \quad \Sigma F_z = 0 \quad \Sigma M = 0$$

where F_i is the force in the i'th force and M is the torque

Force equations from parachute:

$$F_1 = \frac{m_{FWD}}{m_{total}} \cdot F_{dc}$$

$$F_{mc, FWD} = \frac{m_{FWD}}{m_{total}} \cdot F_{mc}$$

- F_1 = Force from drogue chute on FWD
- $F_{mc, FWD}$ = Force from main chute on FWD

Properties:

Given from *parachute trajectory calculations (older version)*:

Parachute	Release force	Final descent rate
Drogue chute(F_{dc})	284.68 N	27.7 m/s
Main chute(F_{mc})	4577.8 N	6.7 m/s

The forces presented here are from older calculations, which give higher forces. This means the calculations here give worse safety factors than it will be.

Object	Weight
m_{AFT}	13.96 kg
m_{FWD}	14.79 kg
m_{total}	28.75 kg

Calculations:

$$F_1 = \frac{14.79 \text{ kg}}{28.75 \text{ kg}} \cdot 284.68 \text{ N} \approx 146.45 \text{ N} \approx 146 \text{ N}$$

$$F_{mc, FWD} = \frac{14.79 \text{ kg}}{28.75 \text{ kg}} \cdot 4577.8 \text{ N} \approx 2354.98 \text{ N} \approx 2355 \text{ N}$$

Forces on upper release arm:

Using $\Sigma M_c = 0$:

$$F_2 = B_z = \frac{F_1 \cdot (L_{AO} + L_{OC})}{L_{OC}} = \frac{146.45 \text{ N} \cdot (14 \text{ mm} + 35 \text{ mm})}{35 \text{ mm}} \approx 205.03 \text{ N}$$

Using $\Sigma F_z = 0$:

$$F_3 = C_z = B_z - F_1 = 205.03 \text{ N} - 146.45 \text{ N} = 58.58 \text{ N}$$

Controlling the calculation using $\Sigma M_B = 0$

$$F_1 \cdot L_{AB} - C_z \cdot L_{BC} = 146.45 \text{ N} \cdot 14 \text{ mm} - 58.58 \text{ N} \cdot 35 \text{ mm} = 0 \text{ N}$$

Forces on lower release arm:

Using $\Sigma F_z = 0$:

$$F_4 = F_5 = C_z \approx 996.2 \text{ N}$$

Forces on the main chute docking:

$$F_6 = F_7 = \frac{F_{mc,FWD}}{2} = \frac{2354.98 \text{ N}}{2} \approx 1177.49 \text{ N}$$

Forces on recovery plate:

$$F_{rec} = F_{mc,FWD} \approx 2354.98 \text{ N}$$

$$F_7 = F_8 = \frac{F_{mc,FWD}}{2} = \frac{2354.98 \text{ N}}{2} = 1177.5 \text{ N}$$

Reasoning, discussion and verification:

The distribution seems reasonable

Final results:

$$\begin{aligned} F_1 &= 146 \text{ N} \\ F_2 &= 205 \text{ N} \\ F_3 &= 58.58 \text{ N} \\ F_4 &= F_5 = 996 \text{ N} \\ F_6 &= 1111 \text{ N} \\ F_7 &= F_8 = 1177.5 \text{ N} \end{aligned}$$

FEA on MCRS components and recovery plate

Problem statement:

The stress and displacement experienced by the following components are to be found:

- Upper release arm
- Lower release arm
- Main chute docking
- Recovery plate
-

Figure:

See *Forces on MCRS and recovery plate*

Assumptions and approximations:

Used Catia 3Dexperience FEA tool and analysis.

Physical laws:

Used Catia 3Dexperience FEA tool and analysis.

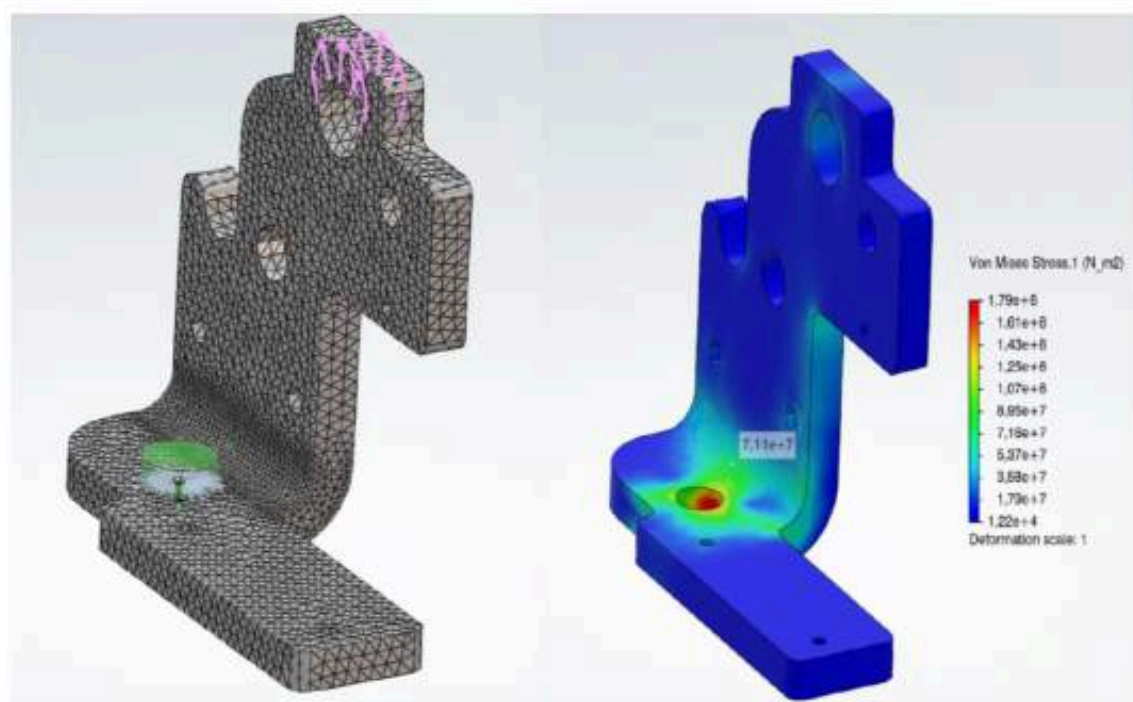
Properties:

Given in *Forces on MCRS and recovery plate*,

$$\begin{aligned} F_1 &= 146 \text{ N} \\ F_2 &= 205 \text{ N} \\ F_3 &= 58.58 \text{ N} \\ F_4 &= F_5 = 996 \text{ N} \\ F_6 &= 1111 \text{ N} \\ F_7 &= F_8 = 1177.5 \text{ N} \end{aligned}$$

Calculations:**Stress analysis of MCRS - Main Chute Docking**

Mesh size	1 mm
Load type	Bearing Load (180 deg spread)
Load	1177.5 N
Restraint	Bolt
Material	S650MC (Yield strength: 650 Mpa)
Experienced Load	71.1 MPa
Safety Factor	9.1

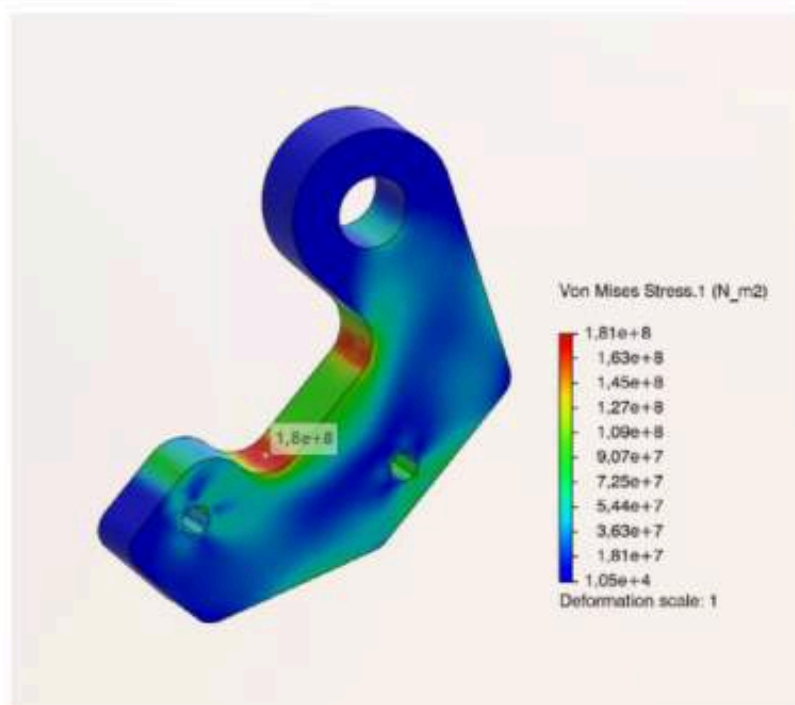


Stress analysis of MCRS – Lower release arm

Mesh size
Load type
Load
Restraint
Material
Experienced Load
Safety Factor

1 mm
Force
966.2 N
Clamp
S650MC (Yield strength: 650 Mpa)
180 MPa
3.6



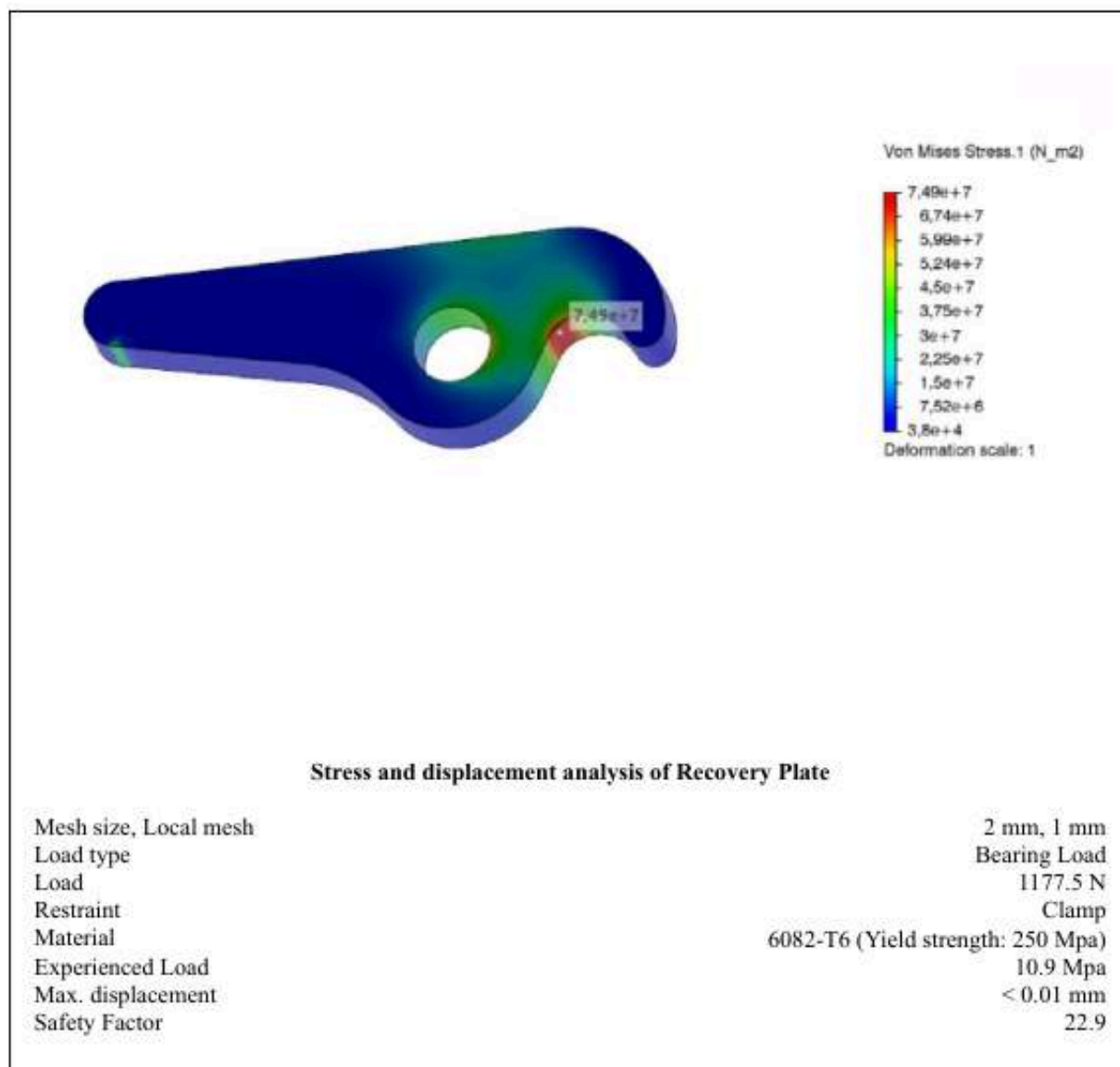


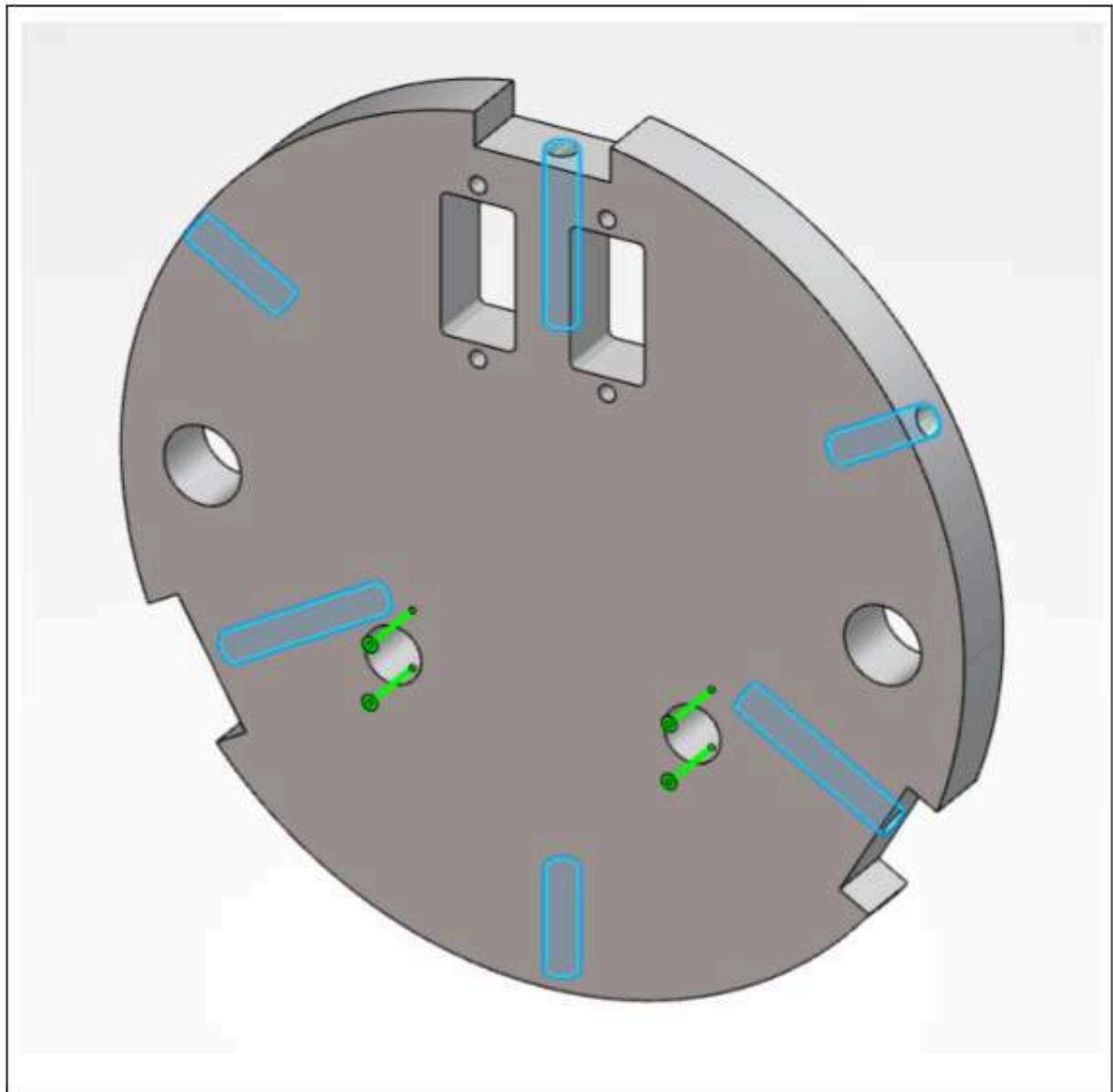
Stress analysis of MCRS – Upper release arm

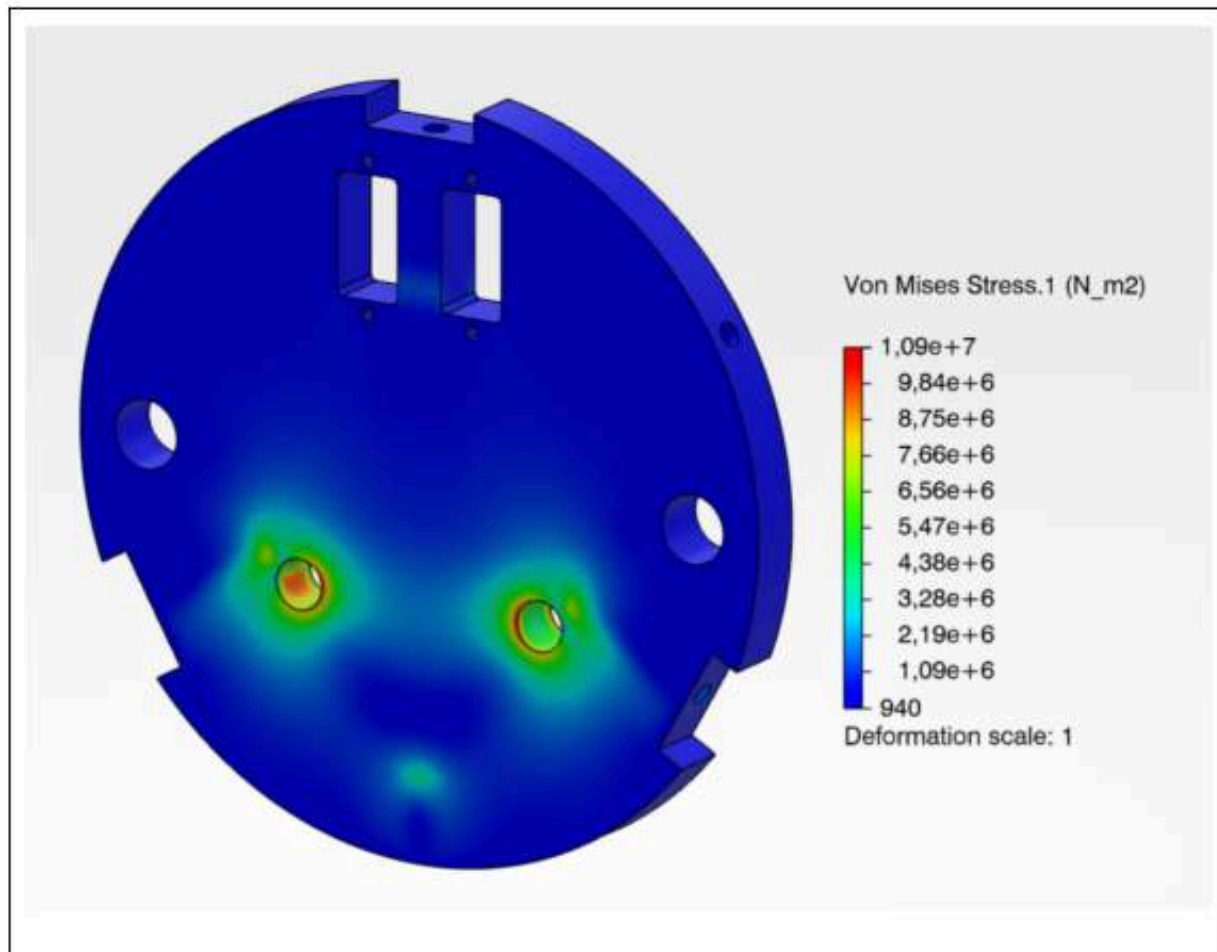
Mesh size
Load type
Load
Restraint
Material
Experienced Load
Safety Factor

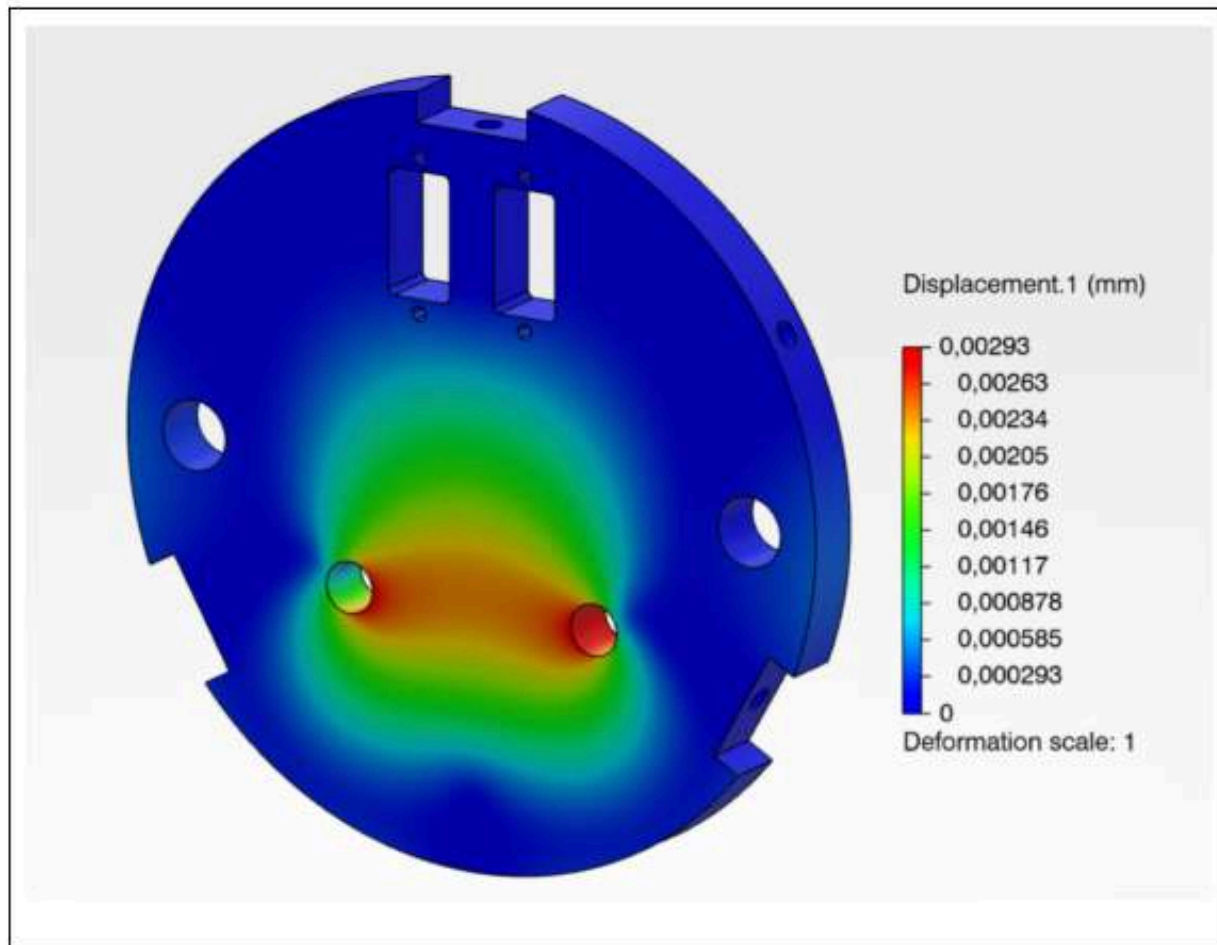
1 mm
Bearing Load
966.2 N
Clamp and fixed displacement
S650MC (Yield strength: 650 Mpa)
74.9 MPa
8.7











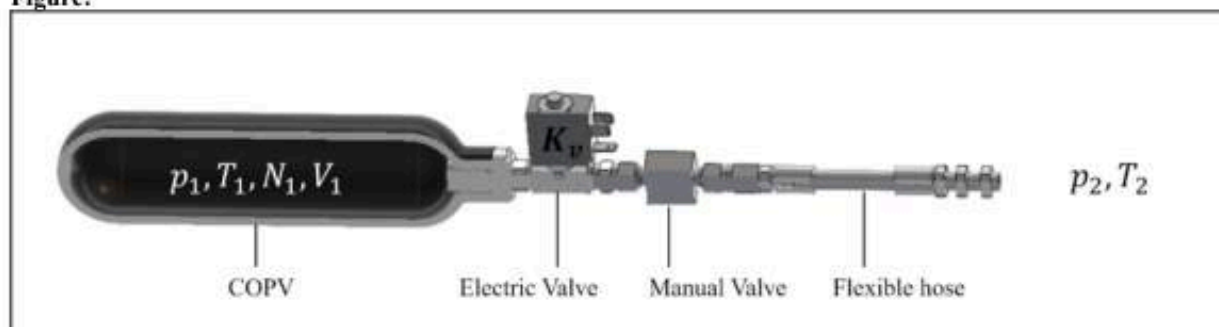
Calculation for the SRAD PBSS pressure test

Problem statement:

For the SRAD Pressure Based Separation System (PBSS), a Composite Overwrapped Pressure Vessel (COPV) is emptied by opening an solenoid valve. The vessel has a volume of 0.36 liter and is pressurized to 117 bar before the valve is opened. The calculation is intended to verify the test result from the V.B *Pressure Test SRAD PBSS* and therefore validate the calculation of the separation pressure.

Comment: The COPV was used in the SRAD PBSS before it was updated. However the test was performed with the COPV and therefore the calculations were also made for this version.

Figure:



Assumptions and approximations:

Three assumptions were made:

1. The ideal gas law applies for the gas in the COPV.
2. Only the electric valve determines the flow rate, as it is the narrowest point in the system.
3. The temperature in the COPV and surrounding are constant.

Physical laws:

Some equations are from [12] and [13].

The flow rate Q of a gas is defined by

$$Q = 257 \cdot K_v \cdot p_1 \frac{1}{\sqrt{\rho_N \cdot T_2}} \quad \text{if } p_1 \geq 2p_2 \quad (1)$$

$$Q = 514 \cdot K_v \cdot \sqrt{\frac{\Delta p \cdot p_2}{\rho_N \cdot T_2}} \quad \text{if } p_1 < 2p_2 \quad (2)$$

with $Q = \text{flow rate} \left[\frac{\text{m}^3}{\text{s}} \right]$

$$K_v = \text{specific flow rate of the valve} \left[\frac{\text{m}^3}{\text{s}} \right]$$

$$\rho_N = \text{density of the gas at sealevel} \left[\frac{\text{kg}}{\text{m}^3} \right]$$

$$p_1, p_2 = \text{pressure} [\text{bar}]$$

$$T_1, T_2 = \text{temperature} [\text{K}]$$

$$\Delta p = |p_1 - p_2|$$

Since the unit of the pressure is in bar, we use the same in the ideal gas law:

$$p \cdot 10^5 \cdot V = N \cdot k_B \cdot T$$

with $V = \text{volume} [\text{m}^3]$

$$N = \text{number of gas particles}$$

$$k_B = \text{Boltzmann constant} \left[\frac{\text{J}}{\text{K}} \right]$$

Properties:

$$\begin{aligned}
p_1^0 &= p_1(t=0) = 117 \text{ bar} \\
p_2 &= 1 \text{ bar} \\
p_N &= 1 \text{ bar} \\
T_1 &= 7^\circ\text{C} = 280 \text{ K} \\
T_2 &= 7^\circ\text{C} = 280 \text{ K} \\
T_N &= 15^\circ\text{C} = 288 \text{ K} \\
\rho_N &= 1.225 \frac{\text{kg}}{\text{m}^3} \\
V_1 &= 0.36 \text{ l} = 3.6 \cdot 10^{-4} \text{ m}^3 \\
K_v &= 0.25 \frac{1}{\text{min}} = 4.167 \cdot 10^{-6} \frac{\text{m}^3}{\text{s}} \\
k_B &= 1.381 \cdot 10^{-23} \frac{\text{J}}{\text{K}}
\end{aligned}$$

Calculations:

In order to appropriately calculate the time for emptying the COPV, the flow rate is considered time dependent and the equations (1) and (2) are transformed to a differential equation.

The flow rate $Q(t)$ corresponds to a negative volume change $-\dot{V}(t)$. This volume change results from the change in the number of gas particles in the COPV over time $\dot{N}_1(t)$. Since the flow rate is given in respect to the standard atmospheric conditions, the ideal gas law is used with pressure p_N and temperature T_N .

$$Q = -\dot{V}(t) = -\frac{\dot{N}_1(t) \cdot k_B \cdot T_N}{10^5 \cdot p_N} \quad (3)$$

The change of the number of particles in the COPV $\dot{N}_1(t)$ leads to the change of the pressure $\dot{p}_1(t)$:

$$\begin{aligned}
\dot{N}_1(t) &= \frac{10^5 \cdot \dot{p}_1(t) \cdot V_1}{k_B \cdot T_1} \\
\Rightarrow Q &= -\frac{T_N}{p_N} \cdot \frac{V_1}{T_1} \cdot \dot{p}_1(t)
\end{aligned}$$

This results in a first order Homogeneous Linear Differential Equation

$$\dot{p}_1(t) = -\underbrace{257 \cdot K_v \cdot \frac{p_N}{T_N} \cdot \frac{T_1}{V_1} \cdot \frac{1}{\sqrt{\rho_N \cdot T_2}}}_{=\alpha} p_1(t)$$

for equation (1) with initial value $p_1(t=0) = p_1^0$. The explicit solution

$$p_1(t) = p_1^0 e^{-\alpha \cdot t}$$

holds until $p_1(t_{\text{valid}}) = 2p_2$. Thus up to the time $t_{\text{valid}} = -\frac{1}{\alpha} \ln\left(\frac{2p_2}{p_1^0}\right)$.

For times greater than t_{valid} , equation (2) will be used. Using equation (3), one get the Separable Differential Equation

$$\dot{p}_1(t) = - \underbrace{514 \cdot K_v \cdot \frac{p_N}{T_N} \cdot \frac{T_1}{V_1} \sqrt{\frac{p_2}{p_N \cdot T_2}}}_{=: \beta} \sqrt{p_1(t) - p_2}.$$

with with boundary condition $p_1(t_{\text{valid}}) = 2p_2$. To get the solution, one has to solve

$$\int_{2p_2}^{p_1(t)} \frac{-1}{\beta \sqrt{y - p_2}} dy = \int_{t_{\text{valid}}}^t 1 ds$$

$$\Leftrightarrow p_1(t) = \left(-\frac{\beta(t - t_{\text{valid}})}{2} + \sqrt{p_2} \right)^2 + p_2$$

This solution applies from t_{valid} until $p_1(t_{\text{end}}) = p_2$ ($t_{\text{end}} = 2\frac{\sqrt{p_2}}{\beta} + t_{\text{valid}}$).

All in all, we thus obtain

$$p_1(t) = \begin{cases} p_1^0 e^{-\alpha \cdot t} & 0 \leq t \leq t_{\text{valid}} \\ \left(-\frac{\beta(t - t_{\text{valid}})}{2} + \sqrt{p_2} \right)^2 + p_2 & t_{\text{valid}} < t \leq t_{\text{end}} \\ p_2 & t > t_{\text{end}} \end{cases} \quad (4)$$

with $t_{\text{valid}} = -\frac{1}{\alpha} \ln\left(\frac{2p_2}{p_1^0}\right)$

$$t_{\text{end}} = 2\frac{\sqrt{p_2}}{\beta} + t_{\text{valid}}$$

For the given values (see Properties) a time of $t_{\text{end}} = 32.463\text{s}$ was calculated. This time is needed to completely empty the COPV.

Reasoning, discussion and verification:

Assuming that the assumptions (see **Assumptions and approximations**) made are correct, the solution should be exact since the differential equations were solved analytically. However, due to the high pressure in the COPV, the ideal gas law might not be completely valid. The energy exchange of the non-isothermal expansion was not considered. Furthermore, the impact of the flexible hose on the flow rate and other components are not considered.

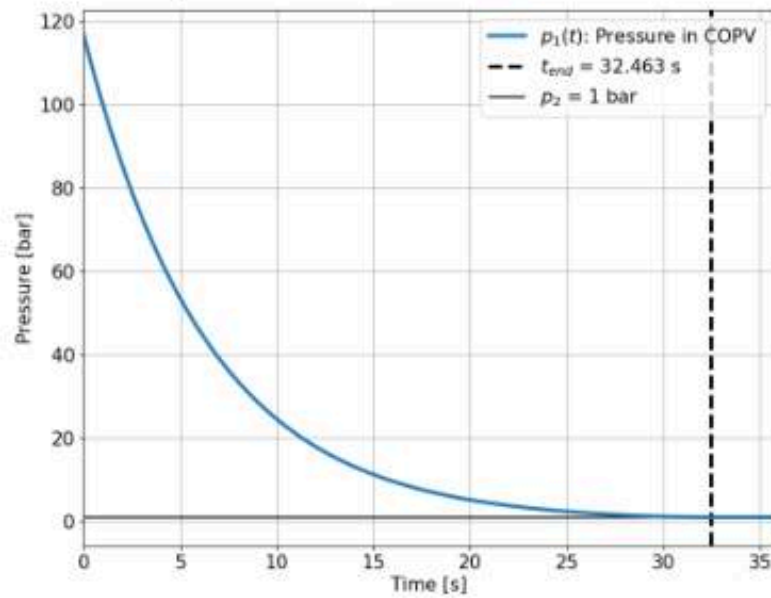
When comparing the calculation with the experiment, the errors in performing and setting up the experiment must be taken into account (see V.B *Pressure Test SRAD PBSS*). For example during the filling of the COPV with the pump, the temperature of the gas probably increased (compared to the atmospheric temperature of $T_2 = 7^\circ\text{C}$), which could also have led to deviations. Likewise, the manual measurement of the time could have led to discrepancies. However, it can be assumed that the calculations are very close to reality, since the calculated time of $t_{\text{end}} = 32.5\text{s}$ does not differ much from the measured time of $t_{\text{exp}} = 30.2\text{s}$. This difference probably originates from the way of measuring. We detected the air flow by the noise that occurs when the air flows out through the valve. This type of measurement has a high uncertainty, since we assume that there is no more outflow when we no longer hear any noise. However, since in the last seconds the pressure difference is so small, probably no more outflow was detected during the experiment.

It is assumed that due to the long outflow time, not enough pressure is built up to ensure separation (this is also confirmed by the V.H *Calculation for the SRAD PBSS separation pressure*). Therefore we replaced the solenoid

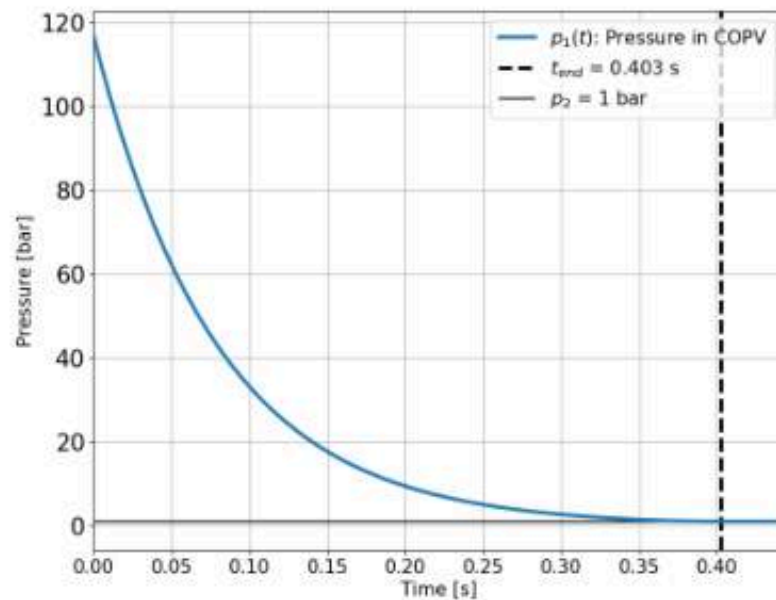
valve with a servo-actuated ball valve ($K_v = 20.16 \text{ l/min}$). For this valve, a time of $t_{\text{end, new}} = 0.40 \text{ s}$ is calculated.

Final results:

Calculations for solenoid valve $K_v = 0.25 \text{ l/min}$



Calculations for servo-actuated ball valve $K_v = 20.16 \text{ l/min}$

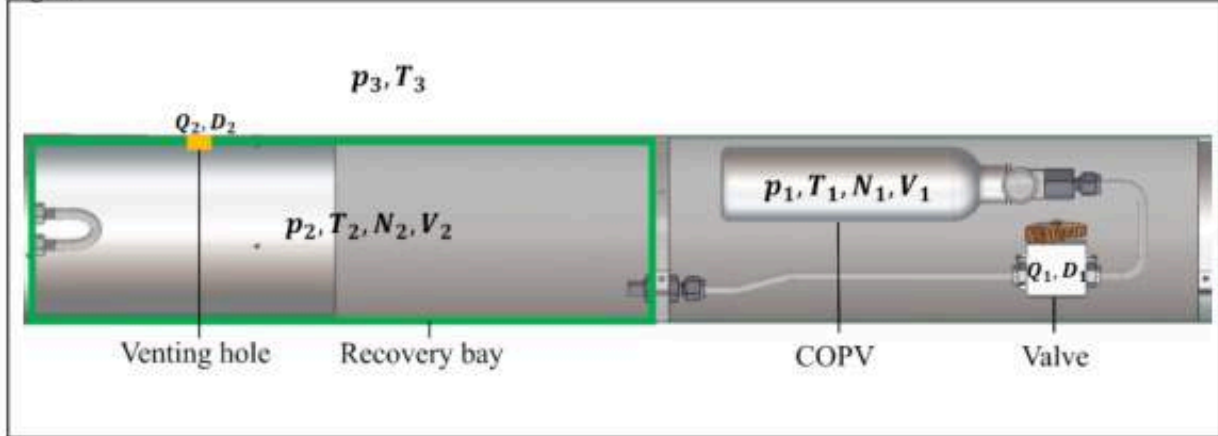


Calculation for the SRAD PBSS separation pressure

Problem statement:

In the SRAD Pressure Based Separation System (PBSS), a Pressure Vessel (PV) is emptied by opening a valve and releasing the air into the parachute bay. The parachute bay must contain, according to the Constraints and Requirements of the SA Cup, a venting hole which allows pressure equalization. This calculation is performed to determine the pressure built up in the parachute bay.

Figure:



Assumptions and approximations:

Five assumptions were made:

1. The ideal gas law applies for the air in the PV and parachute bay.
2. Only the valve determines the flow rate Q_1 of the PV, as it is the narrowest point in the system.
3. The temperatures in the PV, parachute bay and surrounding are constant.
4. The valve opens completely without delay.
5. The air flow out of the parachute bay only happens through the venting hole, otherwise the bay is airtight.

Physical laws:

Some equations are from [12] and [13].

The flow rate Q of a gas is defined by

$$Q = 257 \cdot K_v \cdot p_{in} \frac{1}{\sqrt{\rho_N \cdot T_{out}}} \quad \text{if } p_{in} \geq 2 p_{out} \quad (1)$$

$$Q = 514 \cdot K_v \cdot \sqrt{\frac{\Delta p \cdot p_{out}}{\rho_N \cdot T_{out}}} \quad \text{if } p_{in} < 2 p_{out} \quad (2)$$

$$\begin{aligned}
&\text{with } Q = \text{flow rate} \left[\frac{\text{m}^3}{\text{s}} \right] \\
&K_v = \text{specific flow rate of the valve} \left[\frac{\text{m}^3}{\text{s}} \right] \\
&\rho_N = \text{density of the gas at sea level} \left[\frac{\text{kg}}{\text{m}^3} \right] \\
&p_{\text{in}}, p_{\text{out}} = \text{in- and outside pressure [bar]} \\
&T_{\text{in}}, T_{\text{out}} = \text{in- and outside temperature [K]} \\
&\Delta p = |p_{\text{in}} - p_{\text{out}}|
\end{aligned}$$

Since the unit of the pressure is in bar, we use the same in the ideal gas law:

$$\begin{aligned}
&p \cdot 10^5 \cdot V = N \cdot k_B \cdot T \\
&\text{with } V = \text{volume} [\text{m}^3] \\
&N = \text{number of gas particles} \\
&k_B = \text{Boltzmann constant} \left[\frac{\text{J}}{\text{K}} \right]
\end{aligned}$$

The following formula is used for calculating the specific flow rate K_v of the venting hole:

$$\begin{aligned}
&C_v = 46250.9 \cdot C_d \cdot D^2 \\
&K_v = \frac{0.864}{3600} \cdot C_v \\
&\text{with } C_v = \text{specific flow rate of the valve} \left[\frac{\text{gal}}{\text{min}} \right] \\
&K_v = \text{specific flow rate of the valve} \left[\frac{\text{m}^3}{\text{s}} \right] \\
&C_d = \text{discharge coefficient} \\
&D = \text{orifice diameter [m]}
\end{aligned}$$

Properties:

$$\begin{aligned}
p_1^0 &= p_1(t=0) = 117 \text{ bar} \\
p_2^0 &= p_2(t=0) = 0.259 \text{ bar} \\
p_3 &= 0.259 \text{ bar} \\
p_N &= 1 \text{ bar (normal pressure)} \\
T_1 &= 30^\circ\text{C} = 303 \text{ K} \\
T_2 &= 30^\circ\text{C} = 303 \text{ K} \\
T_3 &= -50^\circ\text{C} = 223 \text{ K} \\
T_N &= 15^\circ\text{C} = 288 \text{ K (normal temperature)}
\end{aligned}$$

$$\begin{aligned}
\rho_N &= 1.225 \frac{\text{kg}}{\text{m}^3} \text{ (normal density)} \\
V_1 &= 2.20 \cdot 10^{-4} \text{ m}^3 \\
V_2 &= 2.97 \cdot 10^{-3} \text{ m}^3 \\
D_1 &= 3.00 \cdot 10^{-3} \text{ m} \\
D_2 &= 3.18 \cdot 10^{-3} \text{ m} \\
C_d &= 0.8 \\
k_B &= 1.381 \cdot 10^{-23} \frac{\text{J}}{\text{K}}
\end{aligned}$$

Calculations:

For calculating the pressure in the Recovery bay, equation (1) is transformed to a differential equation as done in Calculation for the SRAD PBSS pressure test. The solution

$$\begin{aligned}
p_1(t) &= p_1^0 \cdot e^{-\alpha \cdot t} \\
\text{with } \alpha &= 257 \cdot K_{v1} \cdot \frac{p_N}{T_N} \cdot \frac{T_1}{V_1} \cdot \frac{1}{\sqrt{\rho_N \cdot T_2}}
\end{aligned} \tag{3}$$

is used for the pressure in the COPV. The pressure in the recovery bay is calculated with the flow rate

$$\begin{aligned}
Q_{\text{total}} &= Q_1 - Q_2 \\
Q_1 &= 257 \cdot K_{v1} \cdot p_1(t) \cdot \frac{1}{\sqrt{\rho_N \cdot T_2}} \\
Q_2 &= 257 \cdot K_{v2} \cdot p_2(t) \cdot \frac{1}{\sqrt{\rho_N \cdot T_3}} \\
Q_{\text{total}} = \dot{V}_{\text{flow}}(t) &= \frac{\dot{N}_2(t) \cdot k_B \cdot T_N}{10^5 \cdot p_N} = \frac{T_N}{p_N} \cdot \frac{V_2}{T_2} \dot{p}_2(t)
\end{aligned}$$

which results in a first order Linear Differential Equation (inhomogeneous and non-autonomous)

$$\dot{p}_2(t) = \underbrace{257 \cdot K_{v1} \cdot \frac{p_N}{T_N} \cdot \frac{T_2}{V_2} \cdot \frac{1}{\sqrt{\rho_N \cdot T_2}}}_{=: \beta} p_1(t) - \underbrace{257 \cdot K_{v2} \cdot \frac{p_N}{T_N} \cdot \frac{T_2}{V_2} \cdot \frac{1}{\sqrt{\rho_N \cdot T_3}}}_{=: \gamma} p_2(t)$$

with boundary condition $p_2(t=0) = p_2^0$. The homogeneous solution is then

$$p_2^{\text{homo}}(t) = A \cdot e^{-\gamma \cdot t}$$

The partial solution is achieved by the variation of variables:

$$\begin{aligned} p_2^{\text{part}}(t) &= e^{-\gamma \cdot t} \int \frac{\beta p_1(t)}{e^{-\gamma t}} dt \\ &= e^{-\gamma \cdot t} \cdot \beta \cdot p_1^0 \cdot \int e^{(\gamma - \alpha) \cdot t} dt \\ &= \frac{\beta}{\gamma - \alpha} p_1(t) \end{aligned}$$

All in all, we get

$$p_2(t) = A \cdot e^{-\gamma t} + \frac{\beta}{\gamma - \alpha} p_1(t) \quad (4)$$

with $A = p_2^0 - \frac{\beta}{\gamma - \alpha} p_1^0$ (boundary condition). The solution is valid until $p_1(t_{\text{valid}}) = 2 \cdot p_2(t_{\text{valid}})$. With equation (3) and (4), this result in

$$t_{\text{valid}} = \frac{1}{\gamma - \alpha} \ln \left(\frac{2 p_2^0 - 2 \frac{\beta}{\gamma - \alpha} p_1^0}{p_1^0 - 2 \frac{\beta}{\gamma - \alpha} p_1^0} \right).$$

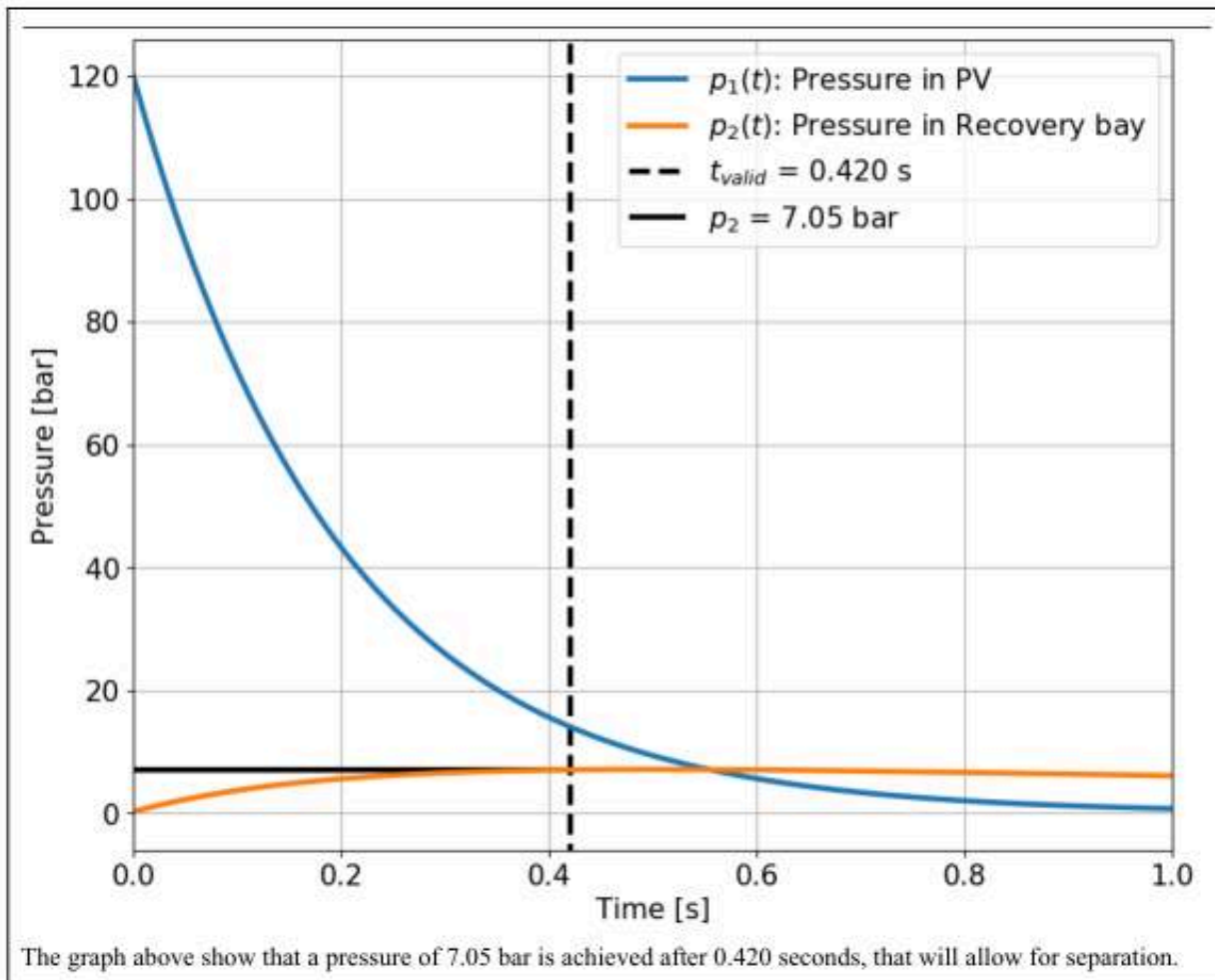
For the given values (see **Properties**) a time of $t_{\text{valid}} = 0.420\text{s}$ is calculated. At this time the pressure in the bay has reached $p_2(t_{\text{valid}}) = 7.05$ bar. After this time, equation (2) would need to be used to determine the flow rate from the COPV. However, this leads to a coupled non-linear differential equation, which cannot be solved analytically. Nevertheless, the pressure of 7.05 bar is already sufficient to separate the rocket (see Calculation for shear pins).

Reasoning, discussion and verification:

Deviations from the calculation to the real conditions could occur because the ideal gas law does not quite apply due to the high pressure. Also the assumption that the temperatures do not change (isothermal process) does not hold. However, the calculation for the pressure test showed that these assumptions (which were also made there) did not lead to large deviations when compared to the experiment.

The time to open the valve could cause errors. It is assumed that this takes up to 0.5 seconds to open completely and thus influences the flow rate Q_1 . This would result in a reduction of the flow rate and therefore also reduce the pressure in the parachute bay. To conclude, the calculated pressure is very likely close to the actual prevailing pressure.

Final results:



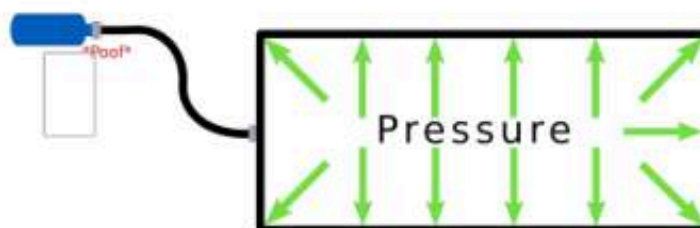
COTS Pressure calculations

Problem statement:

Want to know the pressure inside the packed recovery chamber, as well as the force, from a 33 g CO₂ canisters.

Figure:

Set up:



Assumptions and approximations:

Have assumed the temperature of the CO₂ canister is at the same temperature as the atmosphere at apogee, this will give the worst case.

Have assumed that the CO₂ has the same temperature under free expansion, as the Joule Thompson coefficient is hard to estimate due to the phase change from liquid to vapor. At -50 degrees and 1 atm the Joule Thompson coefficient is positive which means there would be cooling. The assumption of no temperature change is wrong, but partially justified as the CO₂ canister will be either warmer or the same as the atmospheric temperature. Lastly, it is assumed that the recovery chamber is airtight and that there is 1 atm inside the chamber.

-44 degrees celsius is used as the absolute worst case temperature at 9144 m.

Have assumed that CO₂ is not an ideal gas, but instead follows van Der Waals. And have approximated the volume of the gas to only be inside the recovery chamber.

Physical laws:

Van Der Waals equation:

$$\left(p + a \frac{n^2}{V^2}\right) * (V - nb) = nRT,$$

where p is the pressure, n is the mole, V is the volume, T is the temperature in kelvin, a is a correction constant for the attraction force between each particle, b is the correction constant for the volume of each particle and R is the universal gas constant.

Pressure force equation:

$$F = p * A,$$

where p is the pressure, F is the pressure force and A is the area normal to the pressure force.

Properties:

Atmospheric temperature at apogee: 229.15 K

Van der Waals constants [14]:

$$a = 0.364 \text{ Pa} * \text{m}^6 / \text{mol}^2$$

$$b = 0.0427 \text{ m}^3 / \text{kmol}$$

Parachute bay volume (empty):

$$5048 \text{ cm}^3$$

Gas amount:

COTS: 33 grams of CO₂

Component	Compressibility	Volume	Compressed Volume
MCRS	0%	162.4 cm ³	162.4 cm ³
Main chute	30%	1366.5 cm ³	956.6 cm ³
Drogue chute	30%	282.2 cm ³	197.5 cm ³
Shock coords	10%	768.0 cm ³	691.2 cm ³
U-Bolt	0%	7.806 cm ³	7.806 cm ³
5 Swivel links	0%	15.250 cm ³	15.250 cm ³

3 Quick links	0%	83.760 cm ³	83.760 cm ³
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Calculations:

The packed volume is calculated by taking the volume of the recovery chamber and subtracting the volume times the incompressibility of each component. This gives a volume of:

$$V = 2971.2 \text{ cm}^3$$

The Van der Waals equation can be rearranged to express the pressure of the gas:

$$p = \frac{nRT}{V-nb} - \frac{n^2 a}{V^2}$$

The mole amount can be found by dividing by the molecular mass of carbon dioxide.

$$n = m/M$$

Using python, the following results were obtained:

PBSS	Pressure	Force
COTS (33g)	4.63 bar	5589 N

Reasoning, discussion and verification:

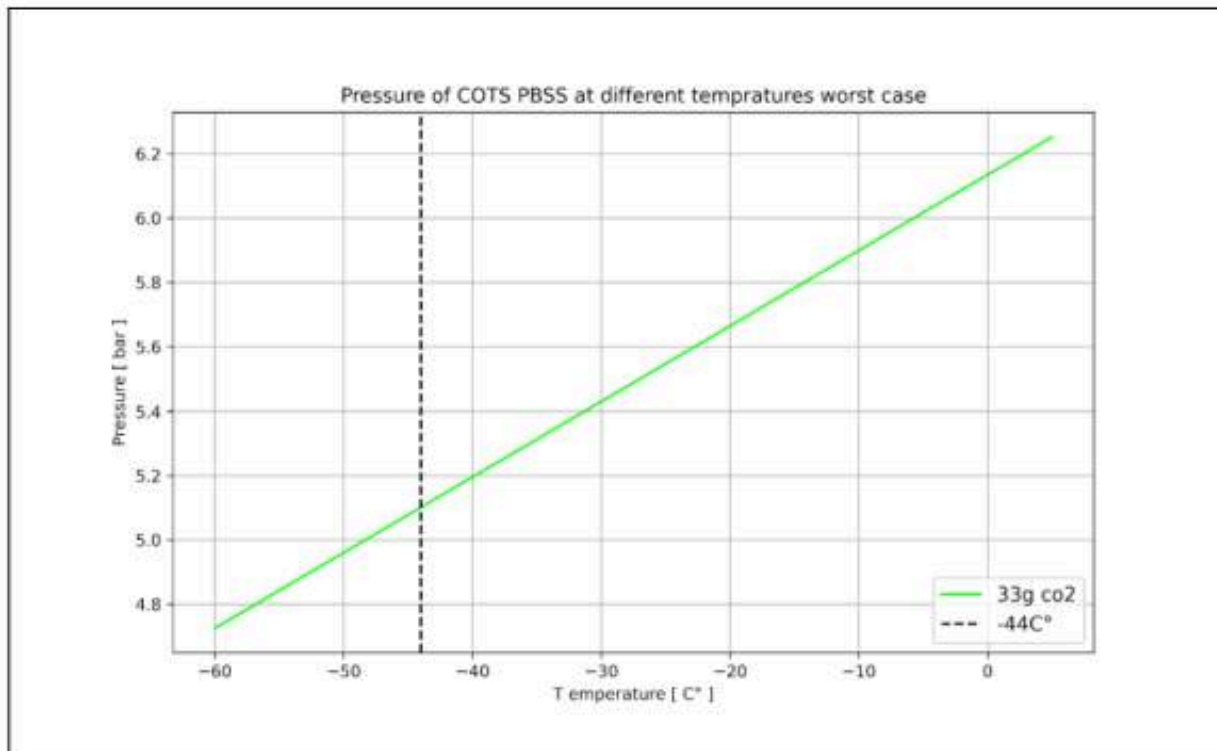
Seeing that the pressure inside the CO2 canister is 59 bar. And, the pressures calculated are way below this, as the gas has expanded, these numbers seem reasonable. The same holds for the COPV.

Final results:

Expected pressure and pressure force for the different cartridges inside the recovery chamber at apogee is as follows:

PBSS	Pressure	Force
COTS (33g)	4.63 bar	5589 N

Since the temperature of the expanded gas is unknown a plot of pressure force versus temperature was made:



Shear screws calculations

Problem statement:

The size and number of nylon 6/6 shear screws needed to prevent unintended and ensure intended separation of the rocket.

The shear strength of nylon shear screws ranges from 66.20 - 72.40 MPa [15]. Pressure forces from the CO₂-canisters are listed in the result table in *pressure calculations*. See Calculation for the *SRAD PBSS separation pressure* and *COTS pressure calculations* for derivation of these quantities.

Figure:

Shear force: F
 Shear strength nylon 6/6 shear screws: T_s
 Diameter screw: d_s
 Cross-sectional area: A

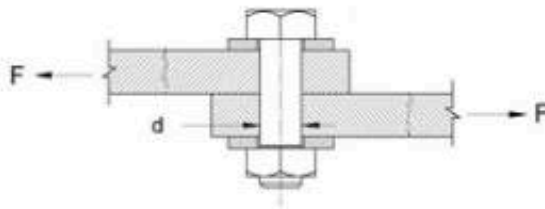


Figure from: https://www.engineersedge.com/material_science/bolt_single_shear_calcs.htm [16]

Assumptions and approximations:

1. The pitch diameter is used to calculate the shear cross-section area.
2. We assume that all screws in the same class are identical with the same pitch diameter. Screws with 6g tolerance with the lower tolerance limit for the pitch diameter will be used in the calculations.

Physical laws:

$$\text{Shear stress: } Ts = \frac{4F}{\pi d_s^2}$$

$$\text{Cross-sectional area circle: } A = \frac{\pi d^2}{4}$$

$$\text{Pressure: } p = \frac{F}{A}$$

Combining the three equations above we get the minimum pressure needed to shear the shear screws:

$$p_{min} = \frac{N \cdot Ts \cdot d_s^2}{d_r^2},$$

where N is the amount of shear screws and d_r is the inner diameter of the rocket.

Properties:

Pitch diameter is found in a table from *EngineersEDGE* [17].

Calculations:

ISO metric thread designation	Pitch diameter [mm]	Area [mm ²]	Minimum pressure one shear screw [bar]*		Number of screws	Minimum pressure all shear strength [bar]	
			Lower value	Upper value		Lower value	Upper value
M4x0.7	3.433	9.256	0.51	0.55	4	2.03	2.22

*Calculating using $Ts=66.2$ and $Ts=72.4$ respectively lower value and upper value

To consider the worst case, the upper value for total shear strength is used to calculate the factor of safety (FoS).

PBSS	Pressure from separation system [bar]	ISO metric thread designation	Number of screws	Safety factor separation
------	---------------------------------------	-------------------------------	------------------	--------------------------

COTS (33g)	4.63 bar	M4x0.7	4	2.08
SRAD (50g)	7.05 bar	M4x0.7	4	3.18

Reasoning, discussion and verification:

Justifying assumptions

1. The approximation of using the pitch diameter is reasonable because the shear cross-section will include both the minor and major diameter of the screw.
2. The difference in pitch diameter is due to tolerances when making the screws. This difference is under 0.1mm. Making this difference neglectable.

The results seem valid at first glance. Still they will be validated via physical testing.

Final results:

For both the pressure systems we get a safety factor above 2 for separation, and therefore the chosen shear screws are sufficient.

PBSS	Pressure from separation system [bar]	ISO metric thread designation	Number of screws	Safety factor separation
COTS (33g)	4.63 bar	M4x0.7	4	2.08
SRAD (50g)	7.05 bar	M4x0.7	4	3.18

Parachute trajectory simulations**Problem statement:**

Want to simulate the velocity and release force of the parachute system over time and get a parachute trajectory.

Figure:

Same as for chute calculations:

**Assumptions and approximations:**

Assumed a ISA [18], which briefly assumes that:

- Air is an ideal gas
- The atmosphere is stable, and therefore no winds
- The temperature with altitude follows a linear curve, with a Lapse rate of 6.49 K/km in the troposphere

Have assumed the chutes fold out instantaneously.

Have assumed constant Latent heat for vaporization.

Have assumed no drag from the rocket body, only the parachutes.

Physical laws:

Drag force equation:

$$F_d = \frac{1}{2} C_d \rho A v^2,$$

where F_d is the drag force, C_d is the drag coefficient, ρ is the density of the fluid, A is the projected area and v is the velocity.

Gravitational acceleration:

$$g(z) = \frac{GM}{r^2},$$

where M is the mass of the Earth, G is the gravitational constant, and r is the distance from the center of the Earth. z is included in the r .

Distance from Earth:

$$r(z) = r_{Earth} + h_{ASL} + z,$$

where r_{Earth} is the average radius of the Earth, h_{ASL} is the height above sea level and z is the altitude.

Temperature at altitude:

$$T(z) = T_0 - \Gamma_{ISA} z,$$

where T_0 is the temperature at ground level, Γ_{ISA} is the ISA lapse rate and z is the altitude.

Clausius clapeyron approximated:

$$e_s(T) = 611.2 \exp\left(\frac{L_v}{R_v} \left(-\frac{1}{273.15} - \frac{1}{T}\right)\right),$$

Where L_v is the latent heat for vaporization, R_v is the gas constant for water vapor and T is temperature in Kelvin.

Pressure at altitude (assumed linear temperature profile):

$$p(z) = p_0 \left(\frac{T(z)}{T_0}\right)^{\frac{g(z)}{R_{air} \Gamma_{ISA}}},$$

where p_0 and T_0 is respectively the pressure and temperature at ground level, T is the temperature at an altitude z , g is the gravitational acceleration at an altitude z , R_{air} is the gas constant for air, Γ_{ISA} is the ISA lapse rate.

Density at altitude (with water pressure): [19]

$$\rho(z) = C \frac{p(z) - 0.378e(z)}{T(z)}$$

where C is a constant $C = \frac{1}{R_{air}}$, p is the pressure at an altitude z , e is the vapor pressure at z based on relative humidity w and temperature $T(z)$. This formula becomes the ideal gas law when $e = 0$.

Lastly the acceleration is set to:

$$\frac{dv}{dt} = g(z) - \frac{F_{d,drag}}{m} - \frac{F_{d,main}}{m},$$

where $\frac{dv}{dt} = a$ is the acceleration of the system, g is the gravitational acceleration at z , m is the mass and F_d is the drag force.

Properties:

Parachute constants [5]:

Parachute	Drag coefficient	Projected Area
Drogue chute	1.5	0.44 m ²
Main chute	2.2	4.53 m ²

Atmospheric constants:

Constant	Value
R_{air}	287.05 J/K*kg
Γ_{ISA}	6.49 K/km
R_v	461.52 J/K*kg

L_v	2.50 MJ/kg
G	$6.67 \cdot 10^{-11} \text{ Nm}^2/\text{kg}^2$
C	$3.48 \cdot 10^{-3} \text{ K} \cdot \text{kg}/\text{J}$
M_{earth}	$5.97 \cdot 10^{24} \text{ kg}$
r_{earth}	6371 km
h_{ASL}	1402 m

Masses:

Object	Weight
m_{AFT}	15.05 kg
m_{FWD}	13.18 kg
m_{total}	28.23 kg

Atmospheric values for worst case (June 20th 2021):

Parameter	Value
T_0	35 C°
(Atmospheric pressure) p_0	862 kPa
w	18%

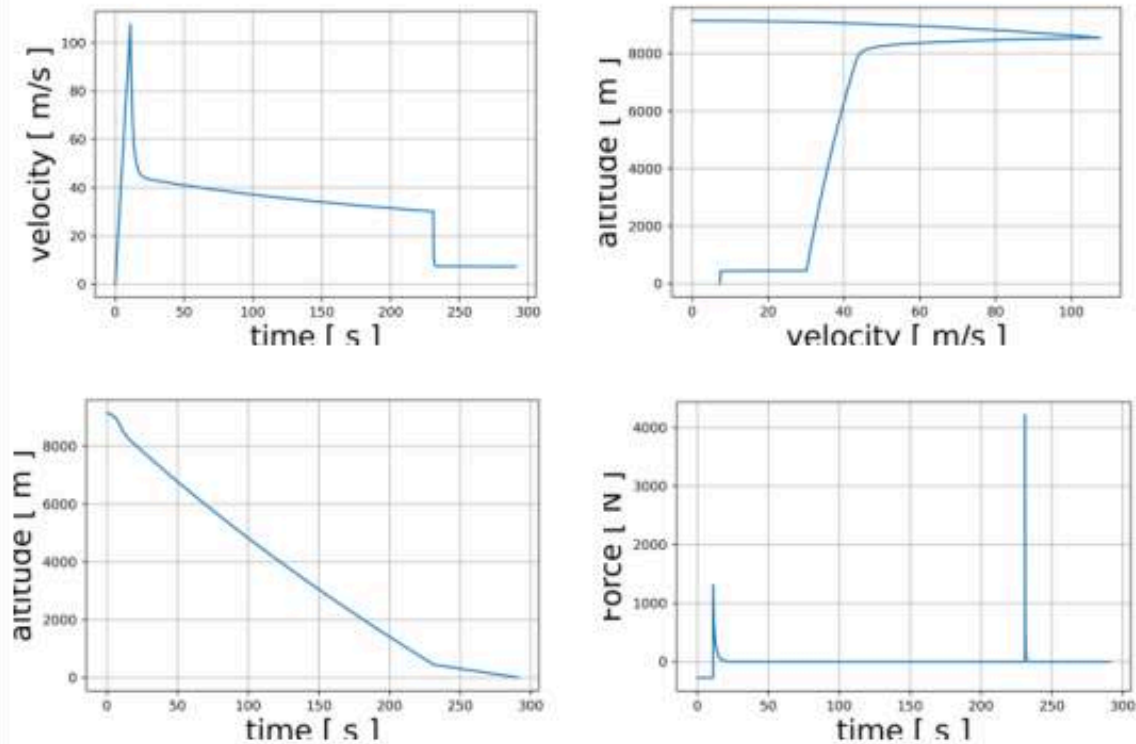
Start height (apogee): 9144 m

Calculations:

Have used python to implement a numerical equation solver with adaptive step size, which checks local error based on the (2,3) ordered pair of the Bogacki-Shampine model [20][21]. This method checks if a certain tolerance is met locally before accepting a new time step. This method takes in $(t_0, t_{\text{end}}, y_0, f, h_0, tol)$ and returns T, Y . Here t_0 is the start time, t_{end} is estimated descent time, y_0 is an array of initial values set to $[0, h_{\text{apogee}}]$, f is a function that returns the derivatives of each parameter in the array $y = [v, z]$. h_0 is estimated step size, but due to the adaptive step size this changes to meet the set tolerance tol . Throughout the calculations $tol = 10^{-6}$. All equations used are based on ISA standards.

The Drogue chute deployment was implemented by setting the $F_d = 0$ before a certain condition is met. For the Drogue chute the condition is set to $t > t_s$ where t_s is the time the drogue chute is deployed. For the Main chute this condition is that $z \leq 450 \text{ m}$.

Using the Bogacki-Shampine method, the atmospheric values above and with a drogue deployment time of $t_s = 11$ gives the following graphs:



And the worst case values:

Parachute	Release force	Final descent rate
Drogue chute	1590.27 N	30.16 m/s
Main chute	4493.09 N	7.34 m/s
Main chute (FWD only)	-	5.36 m/s

*separate simulation with $m = m_{FWD}$

Reasoning, discussion and verification:

The results above are reasonable, since the curves are smooth, and also at each point one can double check with the acceleration equation given above. Winds are being neglected, which might add some noise in the real trajectory, and the force might increase a little, but the general shape will remain. The result was also compared to the result using `scipy.integrate.solve_ivp`, and the values were the same up to the 5th decimal place. Lastly it was compared with OpenRocket, which calculates the exact same descent velocity.

Final results:

The worst case values are as given in the table above:

Parachute	Release force	Final descent rate
Drogue chute	1590.27 N	30.16 m/s
Main chute	4493.09 N	7.34 m/s
Main chute (FWD only)	-	5.36 m/s

*separate simulation with $m = m_{FWD}$

Other:

Battery Calculations

Problem statement:

How much power and current draw will our systems take in idle, nominal, and full operating states? How will this impact battery life?

Assumptions and approximations:

Conditions:

- the battery's minimum voltage of 5V will be used in the power calculations.
- the state of All Systems Operational is assumed to be when Radio, Recovery Servos, Cameras, and MCU are on.
- the state of Nominal Operation is assumed to be when all systems are operational EXCEPT recovery servos.
- the state of Idle Mode is assumed to be when the MCU is on and the Radio is operating at 50%.

Calculations:

We initially assume the current drawn by the battery is 4.7 as seen in Table 10 of [V.N] under Nominal Operation. With a more realistic voltage of 6V supplied by the battery pack, we use the relationship $P = IV$ to calculate power usage at 6V;

$$P(\text{Nominal Operation @6V}) = I(\text{Nominal Operation}) * 6V = 6V * 4.7 A = 28.2 W.$$

To calculate the power usage at All Systems Operational, we use the more realistic estimate of 9W total recovery servo power draw as explained in Table 10 of [V.N]. The total power draw will then be the sum of all the systems' power draws at their respective voltages;

$$\text{Total Power Draw} = \text{Radio} + \text{Recovery Servos} + \text{Cameras (4x)} + \text{MCU MAX} = 25W + 9W + 12 W + 5.28 = 51.28 W.$$

We use this to calculate the current draw at All Systems Operational based on the minimum voltage of 5V of the battery pack, using the relationship $I = P/V$;

$$I(\text{All Systems Operational}) = P(\text{All Systems Operational})/5V = 51.28/5V = 10.26A.$$

We use the same relationship to calculate the current draw at Nominal Operation based on the minimum voltage of 5V,

$$I(\text{Nominal Operation}) = P(\text{Nominal Operation})/5V = 28.2W/5V = 5.64A.$$

And we assume that the radio at 50% capacity translates to its power usage halved, to calculate our Idle Mode power usage, given by the following;

$$P(\text{Idle Mode}) = (0.5)*P(\text{Radio}) + P(\text{MCU MAX}) = 12.5 + 5.28 = 17.78 = 17.8 \text{ (rounded to 1dp)}.$$

With a battery of 72Wh capacity, we use the relationship $\text{Time (in hours)} = \text{Capacity/Power Draw}$ to calculate battery life at Nominal and Idle Mode operation;

$$\text{Time (in hours @ Nominal Operation)} = 72Wh/28.2W = 2.07 \text{ h}$$

$$\text{Time (in hours @ Idle Mode)} = 72Wh/17.8W = 4.04 \text{ h}$$

Reasoning, discussion and verification:

As of now, testing phases done with the current iteration of our circuit boards have shown that the system runs on battery power for long (>4hours) periods of time. Flight time is estimated to be around 15 minutes, but the systems may be turned on for longer than that during the competition. However, with the inclusion of a smart battery charger, the battery life and power usages calculated above should be able to tolerate field conditions.

Final results:

The final results are given as follows;

$$\text{Total Power Draw} = \text{Radio} + \text{Recovery Servos} + \text{Cameras (4x)} + \text{MCU MAX} = 25W + 9W + 12 \text{ W} + 5.28 = 51.28 \text{ W}.$$

$$P(\text{Nominal Operation @6V}) = I(\text{Nominal Operation})*6V = 6V * 4.7 \text{ A} = 28.2 \text{ W}.$$

$$P(\text{Idle Mode}) = (0.5)*P(\text{Radio}) + P(\text{MCU MAX}) = 12.5 + 5.28 = 17.78 = 17.8 \text{ (rounded to 1dp)}.$$

$$I(\text{All Systems Operational}) = P(\text{All Systems Operational})/5V = 51.28/5V = 10.26A.$$

$$I(\text{Nominal Operation}) = P(\text{Nominal Operation})/5V = 28.2W/5V = 5.64A.$$

$$\text{Time (in hours @ Nominal Operation)} = 72Wh/28.2W = 2.07 \text{ h}$$

$$\text{Time (in hours @ Idle Mode)} = 72Wh/17.8W = 4.04 \text{ h}$$

More detailed use of the above results are seen in Tables 9 and 10 of [V.N]

Necessary memory calculations

Problem statement:

How much data is generated during flight, and what memory capacity is needed to save all that data?

Assumptions and approximations:

Time in air = 15min - Don't really need to sample at such high speed for 15 min, but being an estimate we prefer to exaggerate the values rather than doing the opposite.

Loop frequency = 100 Hz - The amount of iterations our program is estimated to be able to do each second at the very best.

Number of datapoints = 50 - This also simply being an estimate of the number of sampled values each iteration.

Size of each datapoint = 32 bits - It is likely that all data points will end up being floats, with the size of 32 bits.

Calculations:

$(15 \times 60 \text{ sec}) \times (100 \text{ Hz}) \times (50) \times (32 \text{ bit}) = 144 \text{ Mb or } 18 \text{ MB}$

Reasoning, discussion and verification:

From a test done at Andeøya, this estimation proved to be quite accurate.

Additionally, an SD chip is likely to be included in the final PCB design, making it possible to save a much larger amount of data points. An SD chip is on the other hand a lot slower, and the flash should be able to save all data at higher loop frequencies. The SD chip should only be needed at lower speeds, at stages when the rocket is not accelerating towards apogee.

Final results:

The result of the above calculations is 144Mb or 18MB. Flash memory usually contains a memory size in the power of 2, hence the closest choice, 32MB/256Mb.

Telemetry bandwidth requirements

Problem statement:

Ensure that the radio link will have enough bandwidth to cover our transmission rate needs.

Assumptions and approximations:

Frame header: 14 octets
 IP header size: 20 octets
 TCP header size: 20 octets
 Target data packet frequency: 100 Hz
 Data values per packet: 60 float values (4 octets per float)
 Minimum packet size: 64 octets
 Video stream bitrate: 5000kbps (CBR)

Calculations:

Packets sent by rocket:

Telemetry:

$(\text{Frame header} + \text{IP header} + \text{TCP header} + \text{data}) * \text{frequency} * 8$
 $(14+20+20+(4*60))*100*8 = 235\,200 \text{ bits/sec} = 235.2 \text{ kbps}$

Video stream:

5000 kbps

Total:

5235.2kbps

Packets sent to rocket:

Ack packets:

$\text{Minimum packet size} * \text{frequency} * 8$
 $51\,200 \text{ bits/sec} = 51.2 \text{ kbps}$

Total both ways:

$5235.2 \text{ kbps} + 51.2 \text{ kbps} = 5286.4$

Reasoning, discussion and verification:

Our datalink's maximum data rate is 8.5 mbps, which is greater than our required rate of 5.2864 mbps.

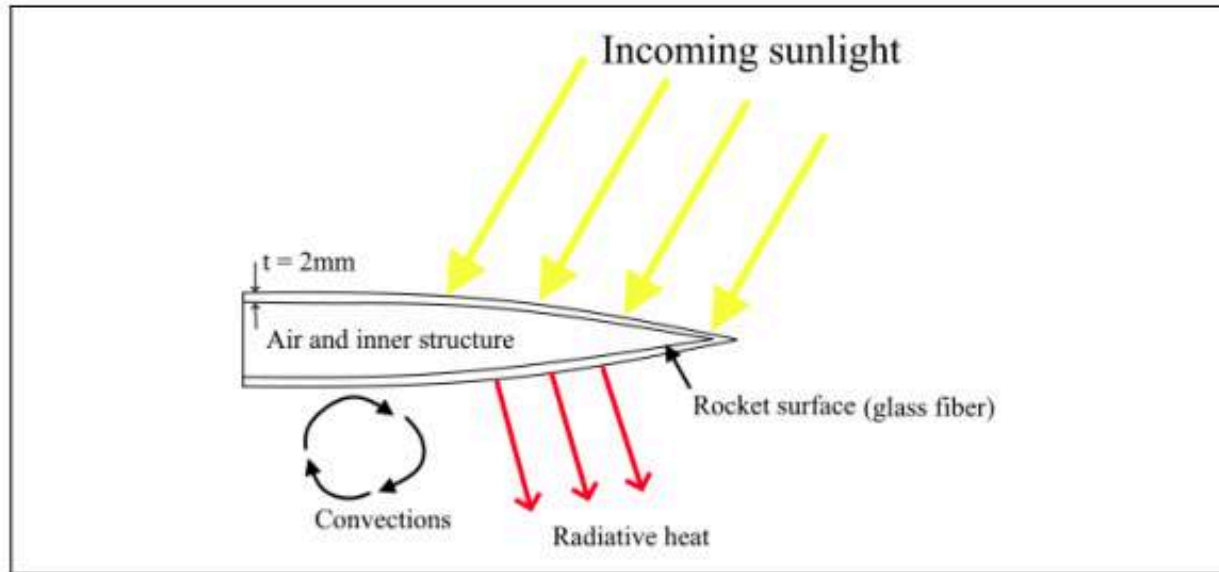
Final results:

The radio (AV.R) is able to cover the transmission rate needs.

*Temperature calculations***Problem statement:**

Want to find the maximum temperature that the rocket reaches in direct sunlight in the desert. If the calculations get above 60 degrees celsius, measures to cool the rocket down will be needed.

Figure:



Assumptions and approximations:

Assumed that:

- convections due to wind.
- air is constantly removed by convection, so the outside air temperature remains constant.
- incoming sunlight is normal to the surface so that all light is absorbed with the highest intensity.
- emissivity and solar absorptivity is constant.
- the air inside the rocket is heated uniformly.
- constant heat capacity.
- 1D heat transfer.
- the avionics power is turned completely into radiative heat.

Physical laws:

Black body heating in an environment:

$$a * j_{net} = \epsilon \sigma (T^4 - T_{env}^4),$$

where a is the absorptivity, j_{net} is the net heat flow, ϵ is the emissivity in the infrared regime (long wavelengths), σ is the Stefan-Boltzman constant and T and T_{env} is the temperature of the airframe and the temperature of the environment respectively.

Heat convection:

$$j_{conv} = h(T - T_{env}),$$

where h is the heat transfer coefficient, A is the surface area and T and T_{env} is as stated above.

Heating of a surface:

$$dQ = jAdt$$

where dQ is heat, j is the heat transfer, A is the surface area and dt is the time interval, which grows infinitesimally small.

Heat capacity (isobaric):

$$c = \left(\frac{dQ}{dT} \right)_p,$$

where c is the heat capacity and $(\frac{dQ}{dT})_p$ is the change in heat for a change in temperature at a constant pressure.

Heat equation 1D:

$$j = -\kappa A \frac{dT}{dz},$$

where j is the heat transfer, κ is the thermal conductivity, A is the surface area and $\frac{dT}{dz}$ is the change in temperature with depth z into the material.

Properties:

The values below have meticulously been chosen to yield the worst case scenarios.

Environmental parameters/properties:

Parameter	Value
T_0	36 °C
T_{env}	36 °C
j_{sun}	640 W/m ² *
c_{air}	1.0035 J/g.K [23]
$j_{avionics}$	44.2 W/m ²

*47% of solar constant = 1367W/m² [22]

** $34/A = 34/0.78 = 43.6 \text{ W/m}^2$

Paint properties [24]:

Name	Absorptivity	Emissivity
White	0.25	0.89

Glass Fibre properties [25]:

Property	Value
Density ρ	2460 kg/m ³
Thermal conductivity κ	1.35 W/m.K
Specific heat c	735 J/kg.K

Constants:

Constant	Value
σ	$5.67 \cdot 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$
h	10 W/m ² [26][27]

Rocket dimensions:

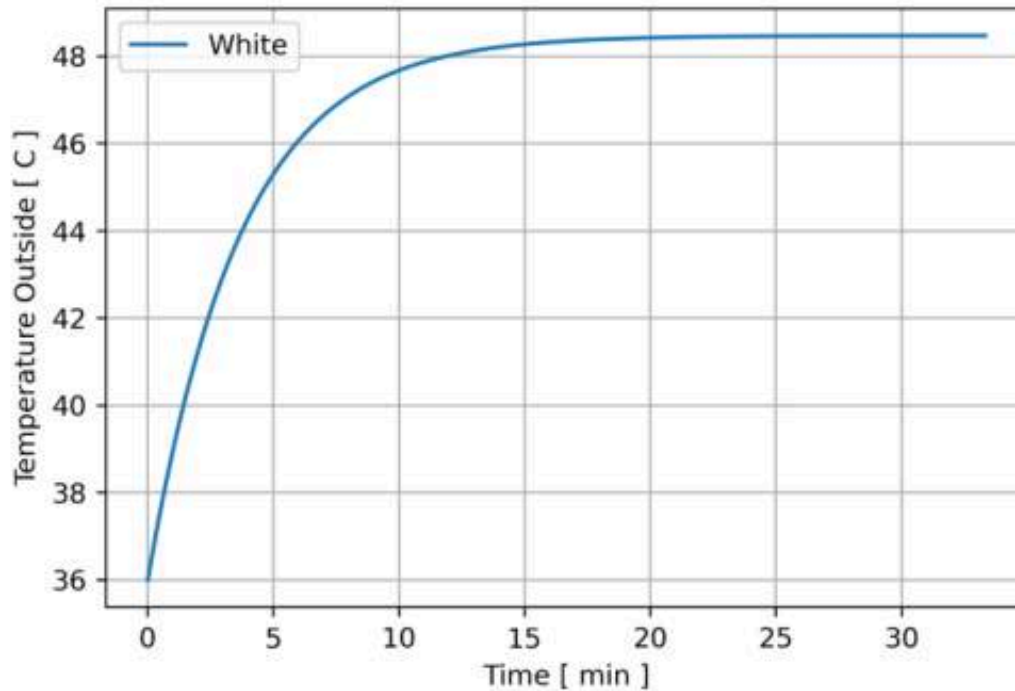
Dimension	Value
A	0.777 m ²
z	0.002 m

Calculations:

Rearranging the equations above yields:

$$\frac{dT}{dt} = \frac{A}{c} (aj_{sun} + j_{avionics} - hT + hT_{env} - \epsilon\sigma T^4 + \epsilon\sigma T_{env}^4).$$

This is a differential equation, which is solved using python with the `scipy.integrate.solve_ivp` method. Using ($rtol = 1e-13$, $atol = 1e-16$) over a long period of time with the properties above the following plot were obtained:



To see how long it takes to heat the air inside from the outside, the heat equation can be written as:

$$\frac{dT_{air}}{dt} = \frac{T_{out} - T_{air}}{zc_{air}} \kappa A,$$

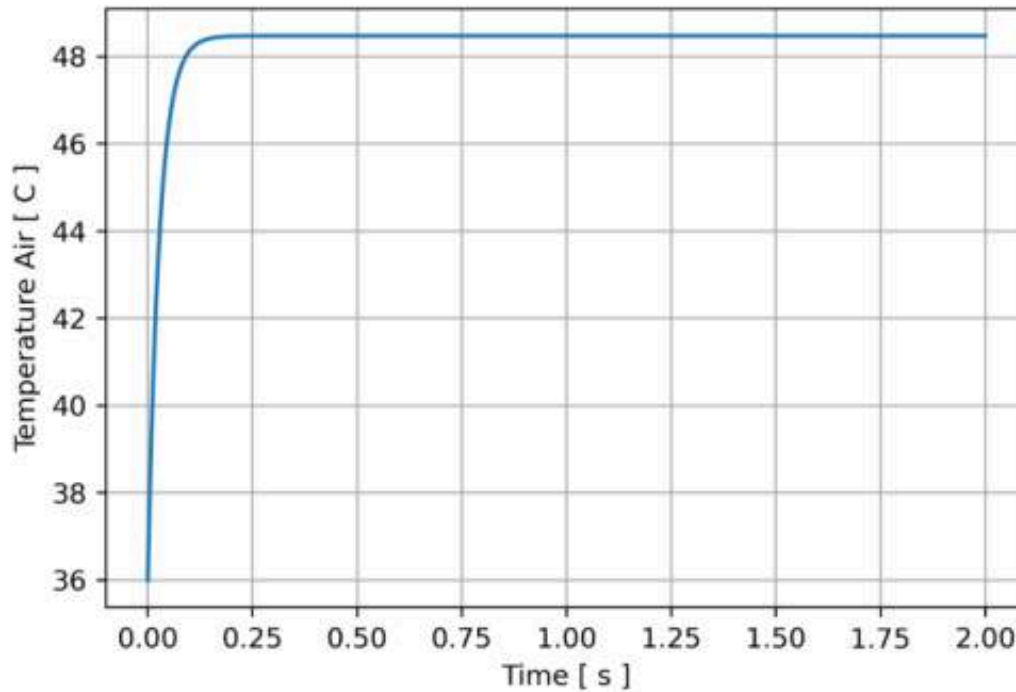
where T_{air} is the temperature inside the rocket and T_{out} is the temperature of the surface area of the fuselage.

This differential equation can be solved, and yields:

$$T_{air} = T_{out} + c * \exp\left(-\frac{\kappa A}{cz} t\right),$$

Here T_{out} is assumed constant. From the initial value $T_{air}(0) = T_{env}$ which implies $c = T_{air}(0) - T_{out}$.

Plotting the solution gives the following plot:



The calculations above yields the following equilibrium temperature:
48.5 °C

Reasoning, discussion and verification:

It seems to take around 15 minutes for the airframe to reach its equilibrium temperature outside. From the second plot it seems to be a tiny delay of 0.10 s between the temperature of the paint and the air inside. These numbers seem intuitive. The temperature is lower than the internal constraint of 60 °C.

Final results:

The airframe coated in white lacquer will reach an equilibrium temperature of 48.5 °C in around 15 minutes. This is the worst case, and the airframe will likely be cooler when at rest.

PAYLOAD

Abstract

This document provides a technical overview of the finished payload product. It provides both an explanation of the payload experiment and an overview of the necessary components, weights, placement, testing and validation.

Introduction

The payload experiment consists of an STM32 NUCLEO-F411RE microcontroller and two IIM42652 IMUs in parallel, so as not to disturb the current in case one of them gets damaged. One of the IMUs will be fastened with moongel in order to dampen vibrations. The experiment measures the vibrations of the rocket and compares the values read by the non-dampened IMU to the dampened one.

Components

Table 1 shows an overview of the required components as well as their respective dimensions and weights.

Component	Dimensions (mm)	Weight per obj (g)	Amount	Total weight (g)
LiPo battery	140 x 45 x 13	175	3	525
NUCLEO-F411RE	82.5 x 70 x 15	33	1	33
IIM42652	22 x 11 x 3	5	2	10
Breakout board	35 x 70	21	2	42
5V regulator	22 x 8	2	1	2
Total weight (g)				589

Table 1: Components overview.

Placement

The payload itself has a 6.0mm metal plate that spans the length of the internal casing. The two IMUs are mounted on a breakout board each that will be as long as possible in order to absorb as much vibration as possible. One of them is mounted on moongel, while the other one is fixed firmly onto the mounting plate as shown in Fig. 1.

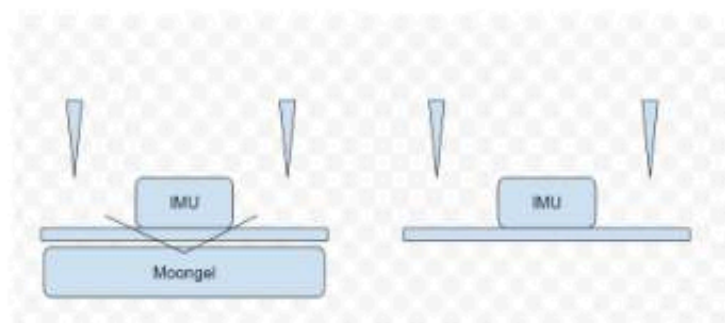


Fig. 1: Setup for the two IMUs.

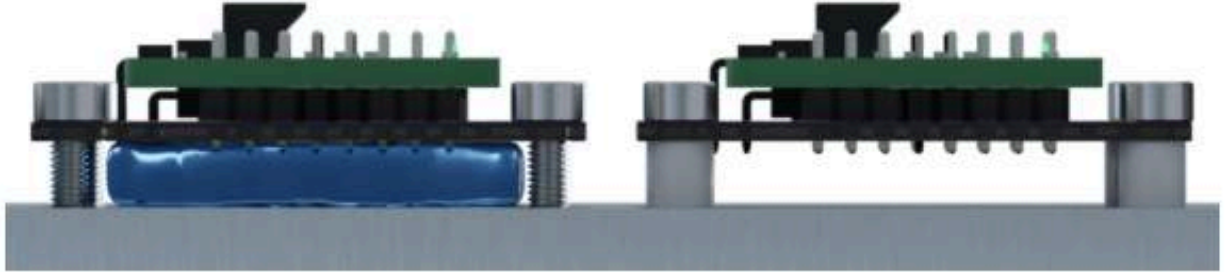


Fig. 2: Realistic rendered demonstration of the IMU setup.

Three LiPo batteries, 140.0mm x 45.0mm x 13.0mm each, are used and located at the bottom of the payload, as shown in Fig. 2. The large green slab above the metal plate is the MCU, the two green ones are the IMUs mounted on breakout boards and the blue cuboids are the batteries.

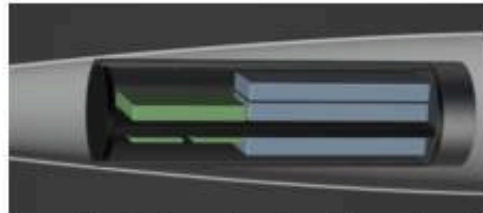


Fig. 3: Approximation of battery location.

Software

The FIFO buffer on the IIM42652 sensor is utilized in combination with the DMA to attain sensor data at its maximum output rate. For the given sensor, this is approximately 32 kHz. However, it is implausible to read at this sampling rate from both sensors simultaneously. In order to maximize our data frequency, the 2048 Byte FIFO buffer on the IMU will be used. Once the buffer is full, an interrupt is routed set the program on pause such that the data may be read and uploaded to memory while the buffer fills up again. This buffer stores all sensor readings while the sensor itself is dormant and the data will be read using DMA (Direct Memory Access) will be utilized to optimize our data rate. Storing this data will involve the use of FreeRTOS, a real time operating system, that will be able to generate and prioritize threads.

Fig. 4 shows what will happen when the NUCLEO-F411RE receives a FIFO_FULL interrupt:

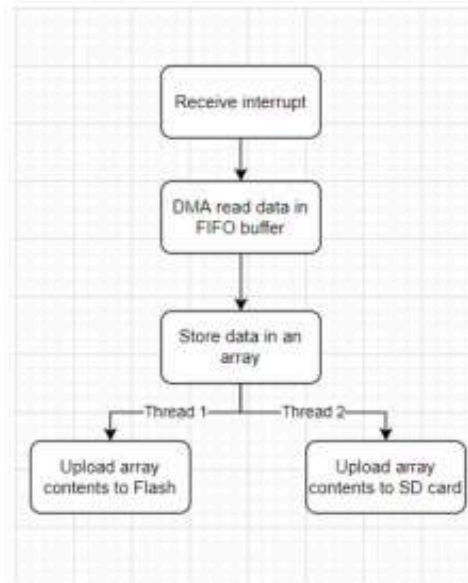


Fig. 4: Diagram shows what the software will do once an interrupt is received.

Information storage

All information is primarily stored in flash memory on the microcontroller as well as an SD card for backup. The SD card poses certain challenges. SD cards act similarly to microcontrollers and will perform internal clean-ups at unpredictable points in time. This will be avoided by formatting the contents of the SD card and the storage data such that the process is executed as infrequently as possible.

Battery capacity

Three LiPo 7.4V 3450 mAh batteries are connected in parallel to drive the whole experiment. This corresponds to a total of 10.35 mAh for the whole system. When used with maximum power consumption settings, the microcontroller, together with the other components, draws a maximum of 15 mA at 5.0 volts. This equates to a total power consumption of 0.075 W and an excessive battery run-time of over 100 hours.

Testing and validation

The easiest way of testing the payload is to shake it and check if the readings make intuitive sense. This test, although very unreliable and susceptible to human error, is the first step of testing and validating. The payload will additionally receive a vibration test with the rest of the rocket, and the readings will be compared to the actual vibrations in order to check reliability.

Outer Structure							
Reference	System	Sub-assembly	Component (Qty)	Function	Material	Production method	Validation method
ON	Outer structure	Nose tip	Nose tip	Reduce aerodynamic forces and retain structural integrity Smooth transition to the Forward Airframe	7075-T6 Aluminum	Assembly	-FEM -CFD -Flight proven
ON.UP	Outer structure	Nose tip	Upper Nose Tip	Reduce aerodynamic forces	7075-T6 Aluminum	CNC machining	
ON.MP	Outer structure	Nose tip	Middle Nose Tip	Transfer drag force to the airframe	7075-T6 Aluminum	CNC machining	
ON.LP	Outer structure	Nose tip	Lower Nose Tip	Fasten the nose tip to the airframe	7075-T6 Aluminum	CNC machining	
OF.FA	Outer structure	Forward half	Forward Airframe	Houses the Inner Structure and reduce its vibration via fastening points; load bearing reduce aerodynamic forces and retain structural integrity	Glass Fiber Zentron S-2 UF3369	Filament winding	-FEM -CFD -Compression test -Wind tunnel test
OL.AA	Outer structure	Lower half	Aft Airframe	Houses the motor, the camera shell, and both the Fins and the boat tail are attached; Load bearing reduce aerodynamic forces and retain structural integrity	Carbon Fiber Toray T-700s UF3369	Filament winding	-FEM -CFD -Compression test -Wind tunnel test
OL.F	Outer structure	Lower half	Fins (4x)	Lower Center of Pressure to increase the stability margin reduce aerodynamic forces and retain structural integrity (fin flutter)	Carbon Fiber	Lay-up	-FEM -CFD -Bending test -Integration test

OL.BT	Outer structure	Lower half	Boat tail	Transferring the force from the motor to the rest of the rocket, through the airframe reduce aerodynamic forces and retain structural integrity	6082-T6 Aluminum	Assembly	-FEM -CFD
OL.BT.C R	Outer Structure	Lower half	Boat tail centering ring	Fasten the boat tail to the airframe. Transfer motor force to the airframe	6082-T6 Aluminum	CNC machining	-FEM
OL.BT.C RW	Outer Structure	Lower half	Boat tail centering ring wedge	Fasten the centering ring to the airframe	6082-T6 Aluminum	CNC machining	-FEM
OL.BT.B T	Outer Structure	Lower half	Boat tail	Fasten to the centering ring	6082-T6 Aluminum	CNC machining	-FEM
OL.CS	Outer structure	Lower half	Camera shell	View of the fins during flight. reduce aerodynamic forces and retain structural integrity	PETG	FDM	-FEM -CFD
OL.CSA M	Outer structure	Lower half	Camera shell Anders Mount	Holds camera 5 and the camera shell in place	PETG	FDM	-FEM -CFD
OL.FB	Outer structure	Lower half	Fin brackets (4x)	Keeping the fins in place	7075-T6 Aluminum	CNC	-FEM
OC	Outer Structure	Coupler	Coupler	-Hardpoint in separation join joint between forward and aft airframe	7075-T6 Aluminum	Turning Drilling	-Fem -Integration test

Inner structure							
Reference	System	Sub-assembly	Component (Qty)	Function	Material	Production method	Validation method
IP	Inner Structure	Payload	Payload	-House the payload experiment		Assembly	-FEA -Integration test
IP.LC	Inner Structure	Payload	Lower Cap	-Keeps payload in place -Interface between Payload and Avionics module	6082-T6 Aluminum	Turning (lathe) Drilling	-FEA -Integration test
IP.T	Inner Structure	Payload	Payload Tube	-Houses the payload	6061-T6 Aluminum	COTS Drilling	-FEA -Integration test
IP.UC	Inner Structure	Payload	Upper Cap	-Keeps payload in place -Interface between tube and threaded rod	6082-T6 Aluminum	Turning (lathe) Drilling	-FEA -Integration test
IP.PP	Inner Structure	Payload	Payload Plate	-Mounting for payload electronics and batteries	S235JRH grade steel	Plasma cutting Drilling	-FEA -Integration test
IP.PT	Inner Structure	Payload	Plate Top	-Defines the top of the Mounting Plate	S235JRH grade steel	Turning Drilling	-FEA -Integration test
IP.TR	Inner Structure	Payload	M8 Threaded Rod	-Support structure -Mounting for nose tip	8.8 Grade Steel	COTS	-Integration test
IA	Inner Structure	Avionics Module	Avionics Module	Housing the avionic component		Assembly	-FEA -Integration test
IA.UMR	Inner Structure	Avionic Module	Upper Module Ring	-Interface between Avionics module, Payload and forward air frame	6082-T6 Aluminum	Laser cutting Drilling	-FEA -Integration test
IA.LMR	Inner Structure	Avionic Module	Lower Module Ring	-Interface between Avionics module Recovery module and forward air frame	6082-T6 Aluminum	Laser cutting Drilling	-FEA -Integration test

IA.R	Inner Structure	Avionic Module	Avionics Rail	-Interface between bulkheads and mounting plate -Ease of assembly	6082-T6 Aluminum	Cutting Drilling	-FEA -Integration test
Reference	System	Sub-assembly	Component (Qty)	Function	Material	Production method	Validation method
IA.MP	Inner Structure	Avionic Module	Mounting Plate	-Common mounting point for avionics components	PA12/PA2200 Nylon	SLS 3D-printing	-FEA -Integration test
IA.CBC	Inner Structure	Avionic Module	COTS battery Casing	-Housing altimax and featherweight battery	PETG	FDM	-Integration test
IA.CBL	Inner Structure	Avionic Module	COTS battery lid	-Enclosing the battery	PETG	FDM	-Integration test
IA.VEC	Inner Structure	Avionic Module	Video encoder casing	-Housing the video encoder	PETG	FDM	-Integration test
IA.VEL	Inner Structure	Avionic Module	Video encoder lid	-Enclosing the video encoder	PETG	FDM	-Integration test
IA.SBC	Inner Structure	Avionic Module	SRAD Battery Pack Casing	-Hosing four 21700 li-ion cells for the SRAD	PETG	FDM	-Integration test
IA.SBL	Inner Structure	Avionic Module	SRAD Battery Pack Lid	-Top lid for the battery pack	PETG	FDM	-integration test
IA.SBB	Inner Structure	Avionic Module	SRAD Battery Pack Bottom	-Fasten on the back of the battery pack giving access for the wiring	PETG	FDM	-Integration test
IA.CP	Inner Structure	Avionic Module	Camera Plate	-Fastening points for cameras -Cooling for camera PCBs	6082-T6 Aluminum	Laser cutting Metal bending	-Integration test
IA.CH	Inner Structure	Avionic Module	Camera House	-Movable housing for the camera allowing alignment of the lens in airframe	PETG	FDM	-Integration test
IA.LB	Inner Structure	Avionic Module	Lining Block	-Lining up the camera house with the hole in the airframe	PETG	FDM	-Integration test

IR	Inner Structure	Recovery module	Recovery Module	-Housing the recovery components		Assembly	-FEA -Integration test
IR.MR	Inner Structure	Recovery Module	Recovery Module Ring	-Interface between Recovery and Avionics	6082-T6 Aluminum	Water-cut	-FEA -Integration test
Reference	System	Sub-assembly	Component (Qty)	Function	Material	Production method	Validation method
IR.RP	Inner Structure	Recovery Module	Recovery Plate	-Interface between rails -Mounting points for MCRS.	6082-T6 Aluminum	Water-cut	-FEA -Integration test
IR.R	Inner Structure	Recovery Module	Recovery Rails (common name for Recovery Rail A, B, C)	-Interface between bulkheads and recovery plate -Ease of assembly	6082-T6 Aluminum	Cutting Drilling	-FEA -Integration test
IR.RA	Inner Structure	Recovery Module	Recovery Rail A	-Interface between bulkheads and recovery plate -Ease of assembly	6082-T6 Aluminum	Cutting Drilling	-FEA -Integration test
IR.RB	Inner Structure	Recovery Module	Recovery Rail B	-Interface between bulkheads and recovery plate -Ease of assembly	6082-T6 Aluminum	Cutting Drilling	-FEA -Integration test
IR.RC	Inner Structure	Recovery Module	Recovery Rail C	-Interface between bulkheads and recovery plate -Ease of assembly	6082-T6 Aluminum	Cutting Drilling	-FEA -Integration test
IR.HP	Inner Structure	Recovery Module	Hawk Plate	-Mounting point for Hawk components -Stiffener between two rails	6082-T6 Aluminum	Bending Water-cut	-FEA -Integration test
IR.PB	Inner Structure	Recovery Module	PV Bracket (2x)	-Mounting point for PV	6082-T6 Aluminum	Water-cut Drilling	-Integration test -FEA
IR.PB.N	Inner Structure	Recovery Module	PV neck bracket	-Mounting point for PV	6082-T6 Aluminum	Water-cut Drilling	-Integration test -FEA

IR.PB.UN	Inner Structure	Recovery Module	PV upper neck bracket	-Mounting point for PV	6082-T6 Aluminum	Water-cut Drilling	-Integration test -FEA
IR.CB	Inner Structure	Recovery Module	Cable bracket	-Cable management	PETG	FDM	-Integration test
IR.UC	Inner Structure	Recovery Module	Umbilical Bracket	-Holds the umbilical cord pcb in place	PETG	FDM	-Integration test
IR.DB	Inner Structure	Recovery Module	D-Sub Bracket	-Cable management -Faster assembly	6082-T6 Aluminum	Water-cut	-Integration test
IR.VB	Inner Structure	Recovery Module	Valve Bracket	-Keeps ball valve in place. -Mounting for servo	6082-T6 Aluminum	Water-cut	-Integration test
IAE.MB	Inner Structure	Aft end	Motor Bulkhead	-Separates recovery bay and motor bay allowing separation using air pressure. -Mounting point for U-bolt	5754-H11 Aluminum	Turning (lathe) Drilling	-Integration test
Reference	System	Sub-assembly	Component (Qty)	Function	Material	Production method	Validation method
IAE.MCR	Inner Structure	Aft end	Motor centering ring	-Keeps motor centered -Ease of assembly	6082-T6 Aluminum	Turning (lathe) Drilling	-FEA

Recovery system							
Reference	System	Sub-assembly	Component (Qty)	Function	Material	Production method	Validation method
RM	Recovery	MCRS	MCRS	-Releasing the main chute at >450m		Assembly	-Drop test -Car test -Wind tunnel test
RM.URA	Recovery	MCRS	Upper release arm	-Keeping the main chute in place	Steel	Laser cutting	-Drop test -Car test -Wind tunnel test -FEM
RM.LRA	Recovery	MCRS	Lower release arm	-Keeping the upper release arm in place	Steel	Laser cutting	-Drop test -Car test -Wind tunnel test -FEM
RM.SA	Recovery	MCRS	Servo arm	-Moving the lower release arm to release the main chute	Aluminum	Laser cutting	-Drop test -Car test -Wind tunnel test -FEM
RM.SM	Recovery	MCRS	Servo motor	-Rotating the servo arm		COTS	
RM.MCD	Recovery	MCRS	Main chute docking (2x)	-Keeping all the components for the MCRS in place - Attachment point for the parachutes - Attaching the MCRS to the Recovery plate (RC.plate legge til navn)	Steel	Laser cutting Metal bending	-Drop test -Car test -Wind tunnel test -FEM
RM.RAS	Recovery	MCRS	Release arm spring (2x)	-Keeping the lower arm in place	Steel	COTS	

Reference	System	Sub-assembly	Component (Qty)	Function	Material	Production method	Validation method
RMLRPA	Recovery	MCRS	Lower release push arm (2x)	-Extending the lower release arm so the servo can make contact with it			
RMS	Recovery	MCRS	Shackle	-Attaches the parachutes to the MCRS		COTS	
RSP	Recovery	SRAD PBSS	SRAD PBSS	-Separates the rocket at apogee		Assembly	-Ground test -Drop test -Integration test
RSP.PV	Recovery	SRAD PBSS	Pressure vessel	Pressure vessel rated for 200 bar of pressure		COTS	-Ground test -Integration test
RSP.PVA	Recovery	SRAD PBSS	Pressure vessel adapter	Adapter from four-way adapter to U-tube		COTS	-Ground test -Integration test
RSP.FWA	Recovery	SRAD PBSS	Four-way adapter	Adapter from pressure vessel to pressure gauge, fill nipple and tube		COTS	-Ground test -Integration test
RSP.FN	Recovery	SRAD PBSS	Fill nipple	Fill nipple used to fill the system	Steel	COTS	-Ground test -Integration test
RSP.PG	Recovery	SRAD PBSS	Pressure gauge	Gauge to check the pressure of the system		COTS	-Ground test -Integration test
RSP.UT	Recovery	SRAD PBSS	U-Tube	Connects the pressure vessel adapter to the manual valve		COTS	-Ground test -Integration test
RSP.BV	Recovery	SRAD PBSS	Ball valve	Actuated valve to separate the rocket at apogee		COTS	-Ground test -Drop test -Integration test
RSP.BT	Recovery	SRAD PBSS	Bent tube	Connects the ball valve to the recovery plate		COTS	-Ground test -Integration test
Reference	System	Sub-ass	Component (Qty)	Function	Material	Production	Validation method

		embly				method	
RSP.BHG	Recovery	SRAD PBSS	Big helical gear	Connected to the ball valve and small helical gear	PA6-CF	FDM	-Integration test -Ground test -Drop test
RSP.SHG	Recovery	SRAD PBSS	Small helical gear	Connected to the servo motor	PA6-CF	FDM	-Integration test -Ground test -Drop test
RH	Recovery	Hawk system	COTS PBSS	Redundant system to separate the rocket at apogee		Assembly	-Ground test
RH.HB	Recovery	Hawk system	Hawk body	Body for the hawk		COTS	-Ground test
RH.HSM	Recovery	Hawk system	Hawk servo motor	Activate the COTS PBSS system		COTS	-Ground test
RH.CS	Recovery	Hawk system	Compression spring	Moves the Piston		COTS	-Ground test
RH.P	Recovery	Hawk system	Piston	Punctures the CO2-canister		COTS	-Ground test
RH.F	Recovery	Hawk system	Fitting	Connects the Hawk to the bent metal pipe	Brass	COTS	-Ground test
RH.BMP	Recovery	Hawk system	Bent metal pipe	Moves the gas from the CO2-canister to the recovery bay		COTS	-Ground test
RH.RA	Recovery	Hawk system	Release arm	Moved to activate the Hawk		COTS	-Ground test
RH.ES	Recovery	Hawk system	Extension spring	Moves the release arm to a not activated position		COTS	-Ground test

Reference	System	Sub-assembly	Component (Qty)	Function	Material	Production method	Validation method
RH.HSP	Recovery	Hawk system	Hawk safety pin	Keep the Hawk safe until it is armed for launch		COTS	-Ground test
RC	Recovery	Chutes	Parachute system	Parachutes to get the rocket down safely		Assembly	
RC.MC	Recovery	Chutes	Main Chute	Decrease descent rate	Kevlar	COTS	-Drop test -Car test
RC.DC	Recovery	Chutes	Drogue Chute	Decrease descent rate and prevent drift	Rip-stop, Nylon shroud lines	COTS	-Drop test -Car test
RC.U	Recovery	Chutes	U-bolt	Connect aft to drogue chute and by this decrease descent of aft. Hold forward frame and aft tube connected after separation	Stainless steel	COTS	-Drop test -Car test
RC.DB	Recovery	Chutes	Deployment bag	Prevent damage on the main chute. Prevent tangling of the threads on the main chute. Hold the main chute compact before it is deployed.	Nylon	COTS	
RC.QL	Recovery	Chutes	Quick link (3x)	Connect cords, chutes and forward/aft tube to each other	Stainless steel	COTS	-Drop test -Car test
RC.SL	Recovery	Chutes	Swivel links (5x)	Prevent entanglement and spin of forward and aft tube	Stainless steel	COTS	-Drop test -Car test
RC.SCD	Recovery	Chutes	Shock cord straight (2x)	Connect chutes to the forward and aft tube.	Kevlar	COTS	-Drop test -Car test
RC.SCY	Recovery	Chutes	Shock cord Y	Replace to straight cords connected to a quick link. Decrease number of parts	Kevlar	COTS	-Drop test -Car test

Avionics Components			
Reference ID.	Component Type	Component	Voltage [V]
AV.R	Onboard radio	CRE2-144-LW	24
AV.FC	SRAD flight computer	KB3 + PDB	
AV.KB3	Flight computer compute board	KB3 (SRAD)	
AV.PDB	Power delivery board	PDB (SRAD)	
AV.ENC	Encoder	AVC-2K	
AV.ETH	Ethernet switch	SwitchBlox Nano	
AV.BB	Blackbox		
AV.FW	GPS tracker	Featherweight (COTS)	
AV.AM	Flight computer	Altimax G4 (COTS)	
AV.GPS	GPS antenna	U-Blox ann-mb	
AV.MAG	Magnetometer	LIS3MDL	
AV.MP	Magnetic plug		
AV.PC1	Protection circuit 1 (MCRS)		
AV.PC2	Protection circuit 2 (SRAD PBSS)		
AV.PC3	Protection circuit 3 (Cam 1 and 2)		
AV.PC4	Protection circuit 4 (Cam 3 and 4)		
AV.MS1	Magnetic switch (SRAD system)		
AV.MS2	Magnetic switch (COTS FC)		
AV.MS3	Magnetic switch (COTS tracker)		
AV.MS4	Magnetic switch (Camera shell)		
AV.CORD	Umbilical cord		
AV.SC	Smart charger	BQ24800	
AV.CAM1	Camera 1	Firefly split 4k	
AV.CAM2	Camera 2	Firefly split 4k	
AV.CAM3	Camera 3	Runcam split 3 LITE	

AV.CAM4	Camera 4	Runcam split 3 LITE	
AV.CAM5	Camera 5	Runcam split 4	
AV.CAM5.REG	Camera shell regulator		
AV.CAM5.BAT	Camera shell battery		
AG.R	Ground radio	CRE2-189	19-55
AG.TRC	Tracking radio mount	(SRAD)	
AG.TRC.VS	Vertical axis stepper motor	QSH6018-65-28-210	5-48
AG.TRC.HS	Horizontal axis stepper motor	23HP30-2804-S	5-48
AG.TRC.VD	Vertical axis stepper driver	TB67S128FTG	7-44
AG.TRC.HD	Horizontal axis stepper driver	TB67S128FTG	7-44
AG.TRC.RP	Radio tracker computer	Raspberry pi 3b+	5
AG.ETH	Ethernet switch		
AG.GSC	Ground station computer	PC (Windows 10/11)	
AG.TRC.PCB	Radio tracking PCB	PCB (SRAD)	

Payload Components		
Reference ID.	Component Type	Component
P.MB	Mainboard	
P.IMU1	IMU 1, dampened	
P.IMU2	IMU 2, undamped	
P.BAT	3S li-po battery	
P.MOUNT	Mounting plate for payload	

Trajectory simulation & CFD

1. Trajectory calculations:

Flight analysis Stetind

In October 2021 we launched our previous project "Stetind" at the European Rocketry Challenge (EUROC). With the recorded data, we calculate important flight parameters (e.g. altitude and drag coefficient) and compare it with the flight simulations of OpenRocket, RasAero II and RocketPy. This analysis should help us to figure out the right settings for the flight simulation, unveil critical parameters and determine the deviations in apogee. Furthermore we use the data to validate the results of the Computational Fluid Dynamics (CFD).

Physical laws:

For calculating the drag coefficient C_d , we use the drag force

$$F_D = \frac{1}{2} \rho A C_d v^2 \quad (1)$$

with the cross sectional area A , the air density ρ and velocity v . We obtain the value of the drag force via the recorded acceleration a (from the accelerometer) using the equation of motion

$$F = F_G + F_T + F_D \quad (2)$$

where $F_G = m g$ is the gravitational force, F_T the thrust of the motor and $F = m a$. For the thrust, we use the data sheet of the provider (Cesaroni 21062O3400).

Simulation programs:

OpenRocket: This simulation program allows to model the rocket exactly. It calculates the aerodynamic properties with the Barrowman equations. However, you only have a limited possibility to adjust the weather and atmospheric conditions.

RasAero II is another flight simulator and works with imperial units. There is only a limited possibility to model the rocket, which leads to deviations for more complex shapes.

RocketPy is a Python library and is easily customizable. It has many options for the atmospheric model (e.g. weather forecast or reanalysis). The disadvantage of this program is that it does not calculate the aerodynamic properties itself. The drag coefficients (Cd-Curves) for Power Off and Power On must be imported by another source (OpenRocket, RasAero II or CFD).

Computational Fluid Dynamics was used to calculate the Cd-Curves as input parameters for the RocketPy simulation.

Evaluation:

For the evaluation a Python script was written, which reads out the data from Stetind's flight and the simulation programs. It calculates the relevant flight parameters and plots the results.

The acceleration from the accelerometer is plotted and compared to the simulation programs in **Figure 1.1**. The acceleration from the flight data is lower compared to the simulation programs. This difference can originate from a deviation in the COTS motor thrust from the provided data sheet. It is remarkable that the RocketPy simulation shows the same peak in the coasting phase as the flight data. This is the first indication that the CFD data is very precise.

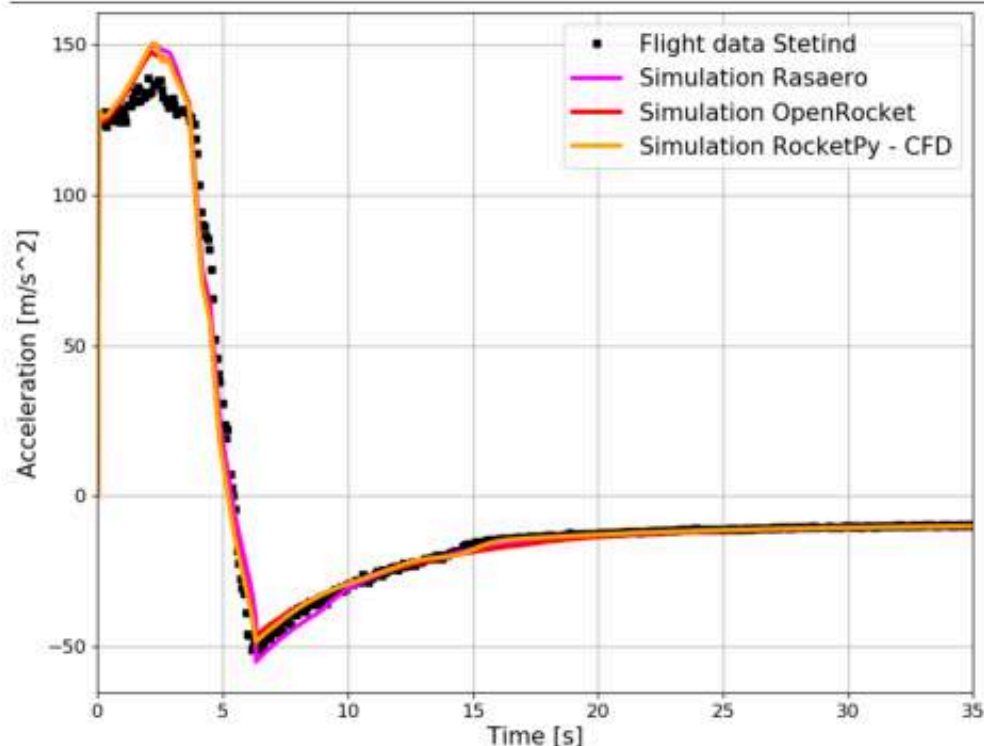


Figure 1.1 Flight analysis Stetind: Acceleration

The acceleration, recorded by the accelerometer, is used for calculating the velocity and altitude. The composite trapezoidal rule is the method used for the integration. The simulations are matching with the flight data, just the RasAero II simulation differs noticeably (see **Figure 1.2** right). This difference can be seen better when recording the drag force.

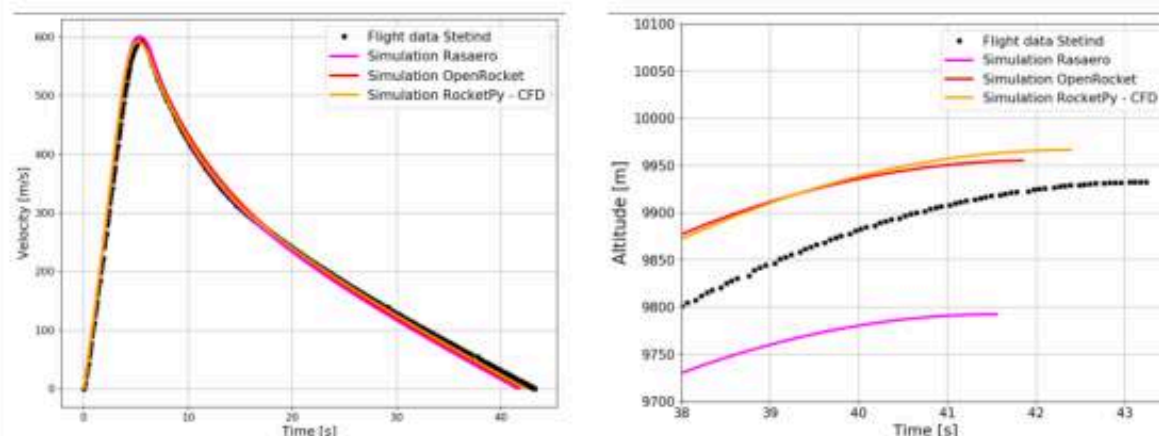


Figure 1.2 Flight analysis Stetind: Velocity and Apogee

For calculating the drag force the equation of motion is used (see **Physical laws**). The values during the coasting period are scraped since the thrust curve is subtracted, but the real thrust differs from the data sheet (see Acceleration). The **Figure 1.3** is obtained for the drag force where the RasAero data has a discontinuous jump at burn-out. This is another indication that RasAero II is not suitable for the trajectory calculation.

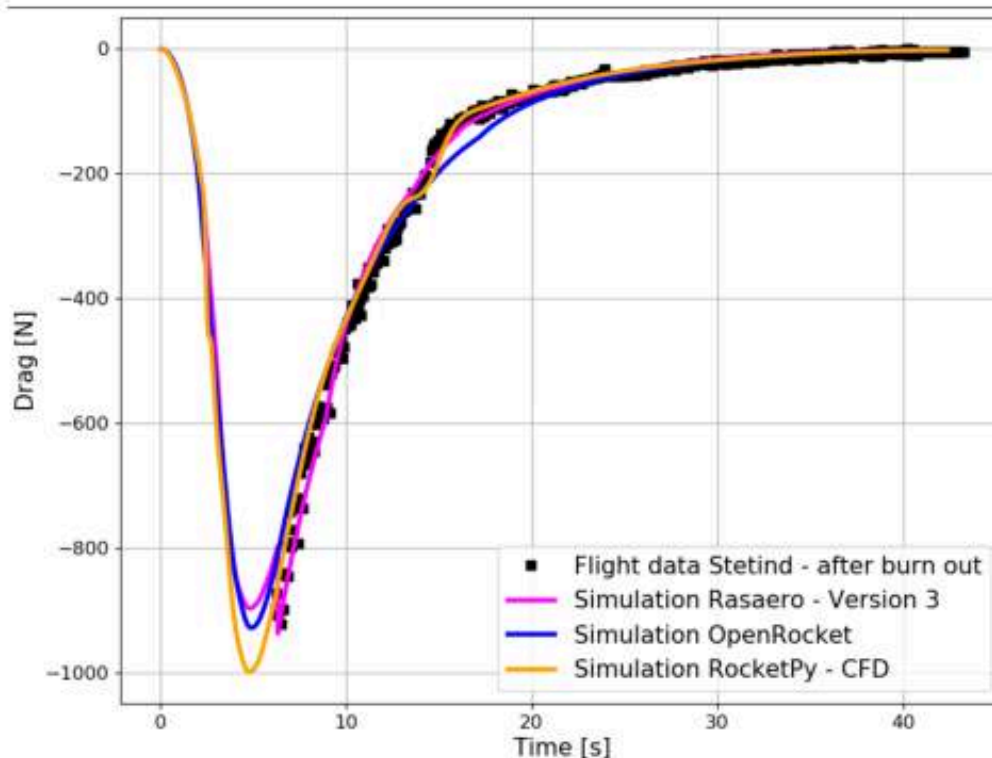


Figure 1.3 Flight analysis Stetind: Drag Force

The drag coefficient can be calculated with equation (1). For the air density the International Standard Atmosphere (ISA) is used. The calculated C_d -Curve is plotted in **Figure 1.4**. The noise of the accelerometer data due to strong vibrations of the rocket amplifies in the C_d data, since these are calculated over the drag force and velocity (square) which both are noisy too. However, it is evident that the curve calculated with CFD (orange) follows the flight data best. It has a slight offset, which most likely originates from neglecting the skin drag. In the CFD a model for the surface roughness is used with two parameters: Surface roughness height and constant. Since the value of the second parameter could not be determined, the default settings of zero roughness were used. OpenRocket and RasAero II both have large discrepancies in the subsonic/transonic regime. OpenRocket underestimates the coefficient in the supersonic region, which counteracts the overestimation in the subsonic regime. RasAero, on the other hand, consistently overestimates the values. The problem is that the tapered end cannot be modeled exactly with this program, which would lower the drag force. This is another reason why RasAero II is not used for flight simulation.

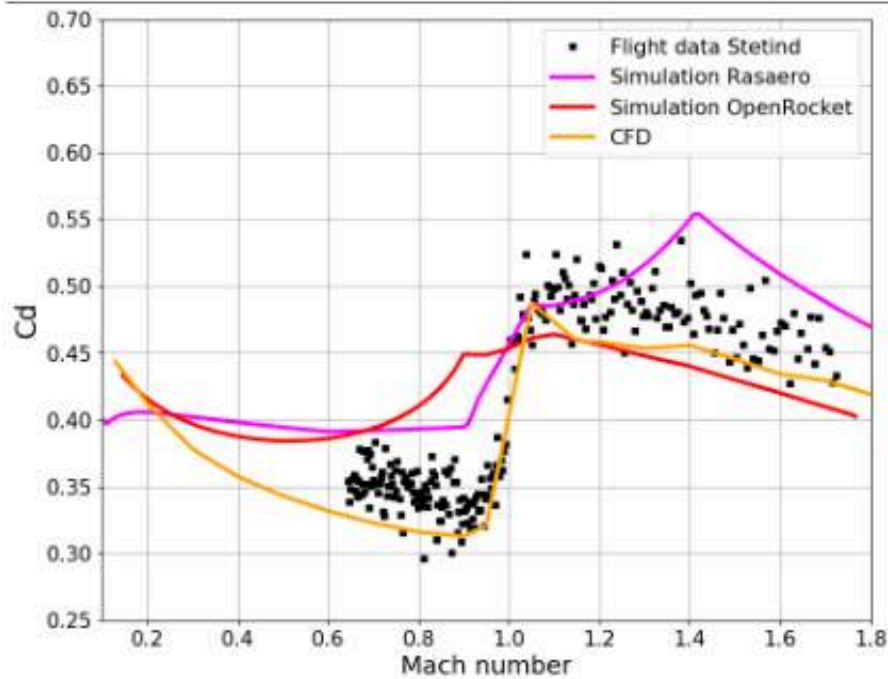


Figure 1.4 Flight analysis Stetind: Cd-Curve

An additional analysis of the flight simulation programs was carried out. It was investigated how stable the simulations are against changes of the initial parameters. It became very clear that RasAero has some critical parameters. The Nozzle Exit Diameter is the most unpredictable. Just by changing this parameter, one can reach space (Karman line). It seems that RasAero II not only uses the thrust data sheet provided by the producer, it seems it uses the Nozzle Exit Diameter to adjust the total impulse.

A lot of iteration were needed to find the right value of this parameter so the apogee from RasAero was near the real apogee.

Flight calculations Birkeland

OpenRocket:

The previous analysis showed that OpenRocket provides the best results by far. Therefore it is mainly used for the flight simulations on Birkeland. The OpenRocket file which is used for the analysis is attached to this report ("Birkeland_ver3-modules.ork"). The overview of the most important simulation settings and main results is given in **Table 1.**

Simulation conditions	Value	Results	Value
Launch elevation [m]	1402	Apogee [m]	9162
Atmospheric model With an initial temperature [°C] and initial pressure [mbar]	ISA 29 865	Max velocity [m/s] (Mach)	507 (1.50)
Avg. windspeed [m/s]	2	Max acceleration [m/s ²]	123
Standard deviation [m/s]	0.1	Off Rail velocity [m/s]	33.7
Rail angle [°]	6	Time to apogee [s]	42
Rail length [m]	5.2	Impact time [s]	347
		Impact velocity [m/s]	7.25

Table 1.1 Simulation conditions and results.

The flight profile is plotted in **Figure 1.5**. We expect a 6 second burn phase, followed by a 36 second coast phase, resulting in a 42 second total ascent duration. This correlates well to the 43 second ascent of our previous rocket, Stetind, which is similar, although lighter, than Birkeland. The predicted apogee is 9162 meters (30 059 ft). The slight overestimation is intentional, as the analysis showed that the real apogee will most likely be lower.

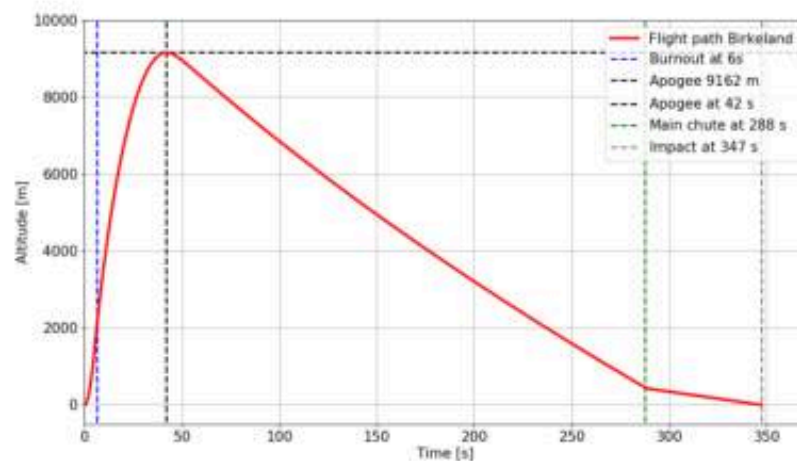


Figure 1.5 Flight simulation Birkeland: Flight trajectory calculated with OpenRocket.

The velocity and acceleration profile are pictured in **Figure 1.6**. The powered flight in the first 6 seconds results in a maximum velocity of 507 m/s. The maximum acceleration $123 \frac{m}{s^2}$ is experienced slightly before the burn-out. At the main chute deployment, the acceleration reaches a peak value of $149 \frac{m}{s^2}$. The values of the main chute deployment force of 4233 N and the impact velocity of $7.25 \frac{m}{s}$ are in accordance with our own calculations (see Appendix V.H. Calculations and Analysis).

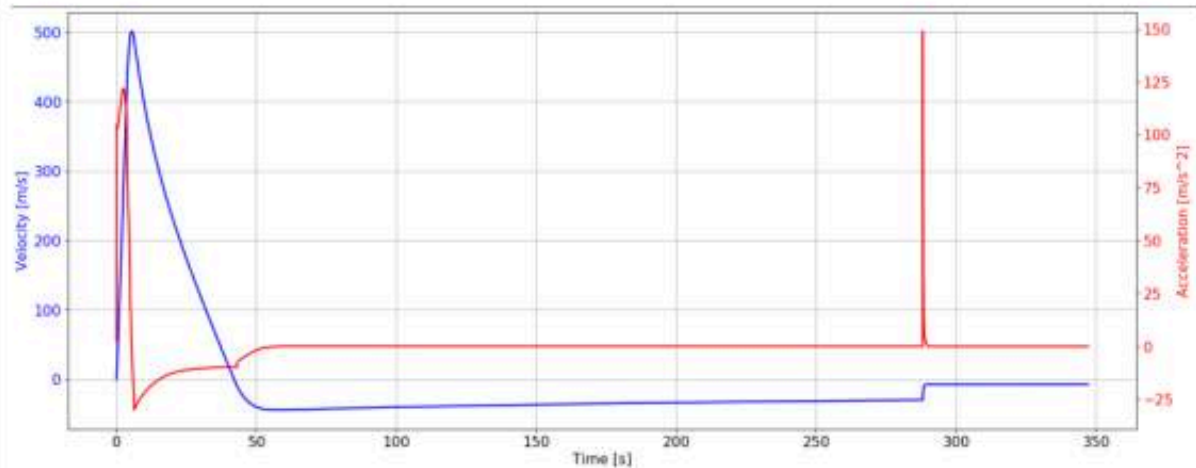


Figure 1.6 Flight simulation Birkeland: Velocity and Acceleration

The stability margin (SM) is shown in **Figure 1.7**. It is the lowest at Rail-Off with 1.78 calibers, but increases to over 2 calibers in 200 milliseconds. Shortly after burn-out, the stability margin reaches its maximum of 5.84 calibers. The rocket is in the supersonic regime, where the speed of the rocket is very high. Therefore, the shear wind would not change the trajectory much despite the high stability.

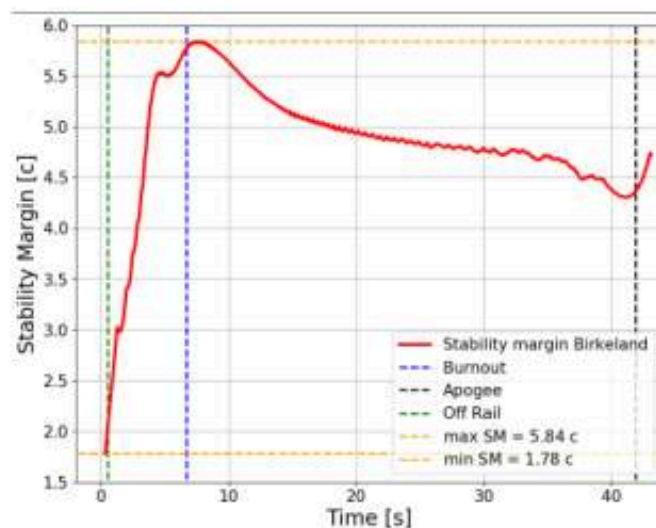


Figure 1.7 Flight simulation Birkeland: Stability margin

Flight calculations Birkeland CFD :

The analysis of Stetind showed that the Cd-Curves from the simulations differ significantly from the real data. The CFD values matched the shape much better. Therefore 35 Cd-values were calculated for different Mach-numbers with the CFD (for further details on which mesh and setup was used see CFD appendix below).

Figure 1.8 compares the Curves from OpenRocket and the CFD. As expected, the shapes of the two curves are quite different. However, the offset in y-direction (Cd-value) is much higher. This can be explained with the neglectance of the skin drag. Since the surface roughness is zero (see Flight analysis Stetind), the drag coefficient is smaller. Furthermore Birkeland has, compared to Stetind, a much higher surface area, which would increase the skin drag in reality. Therefore the difference between the OpenRocket data and CFD is larger than in the analysis. If the simulations with RocketPy shall be performed, one has to counteract this effect. For the RocketPy calculations the CFD values will be added by a constant factor (0.05), so that the difference between the Cd-curves matches with the difference of the curves in the analysis.

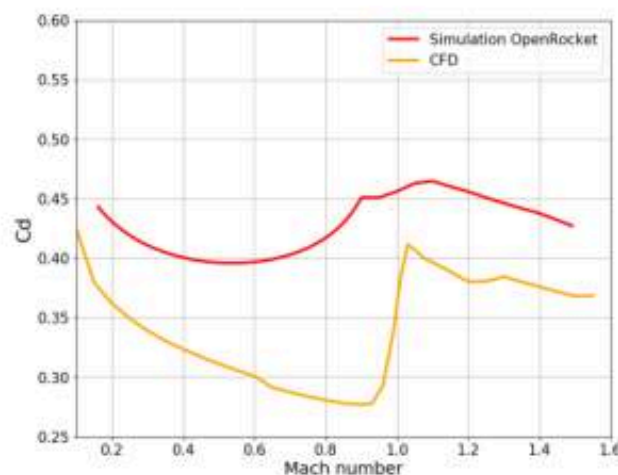


Figure 1.8 Flight simulation Birkeland: Cd-curve; Power-Off

RocketPy:

For RocketPy the adjusted CFD data is used. The advantage of RocketPy is that it can perform a Monte Carlo analysis. Thereby, parameters can be assigned with an uncertainty. RocketPy will pick a randomized value in that interval and simulates the flight with the chosen parameters. A huge number of simulations are performed with changing initial conditions. The apogee is chosen as the investigated result and is therefore saved after each simulation. In the end a normal distribution is obtained with a standard deviation. Thus, besides the apogee, an uncertainty can be specified which results from the uncertainty of the initial parameter.

In **Figure 1.9** the result of a Monte Carlo analysis of Birkeland is plotted. It was assumed that the mass has an uncertainty of 200 grams, the total impulse of the motor differs by ± 50 Ns, the elevation by 5 meters and the Cd-curves by 0.005. A mean apogee of 9205 meters is observed with a standard deviation of 51 meters. Thus the result of OpenRocket is in the uncertainty interval of this analysis.

The flight path of one simulation in the Monte Carlo analysis is pictured in **Figure 1.10**. It reaches an apogee of 9188 meters.

Number of simulations: 6499
Apogee Altitude - Mean Value: 9205.251 m
Apogee Altitude - Standard Deviation: 51.033 m

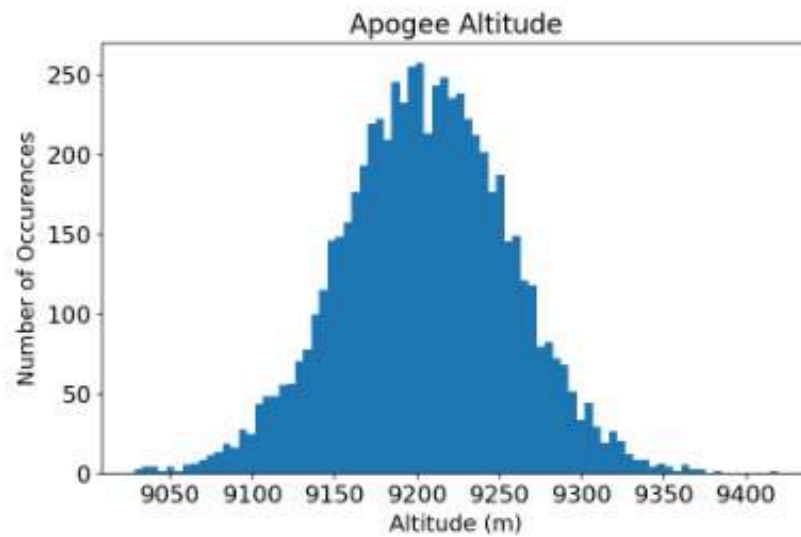


Figure 1.9 Flight simulation Birkeland: Monte Carlo analysis

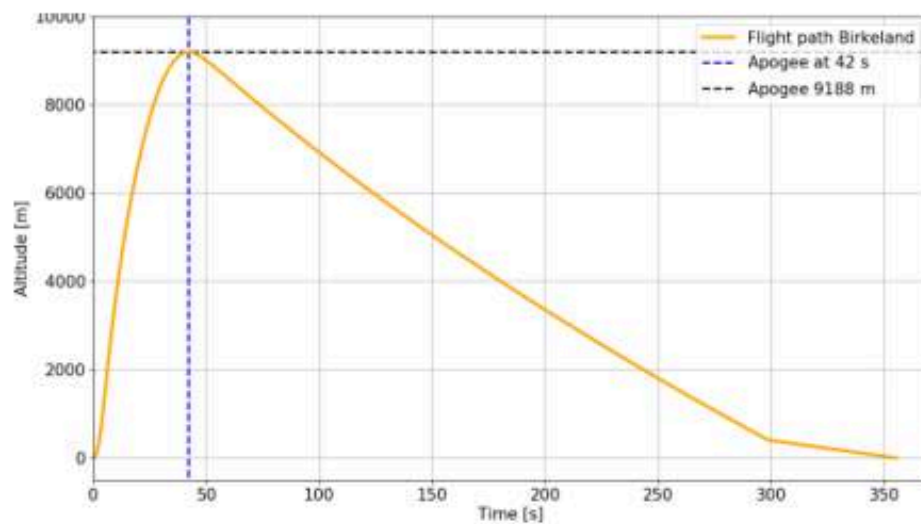


Figure 1.9 Flight simulation Birkeland: RocketPy flightpath

2.Computational Fluid Dynamics:

This is an introduction to the CFD simulations used in this project. A simple presentation of the assumptions and the simulation setup will be presented. Special attention will be paid to the simulations run at the maximum projected velocity, as the result of these simulations have been used to validate the structural integrity of the rocket, but the discussion and validation regarding these largely stay relevant for lower velocity simulations.

Geometry

The outer geometry of the rocket was modeled using CAD, and simplified to make discretization of the fluid domain easier. Holes and perturbations from the rocket body like mounting lugs, stickers, cameras and screws were excluded from the model. The rocket nozzle was also excluded, and replaced with a flat plate as can be seen in Figure 1. It is also worth noting that because of the simplifications made to the model, the rocket body had 2 symmetry planes. This was exploited for simulations run at zero angle-of-attack, where the size of the computational domain was quartered, leading to a drastic reduction in computational demand.

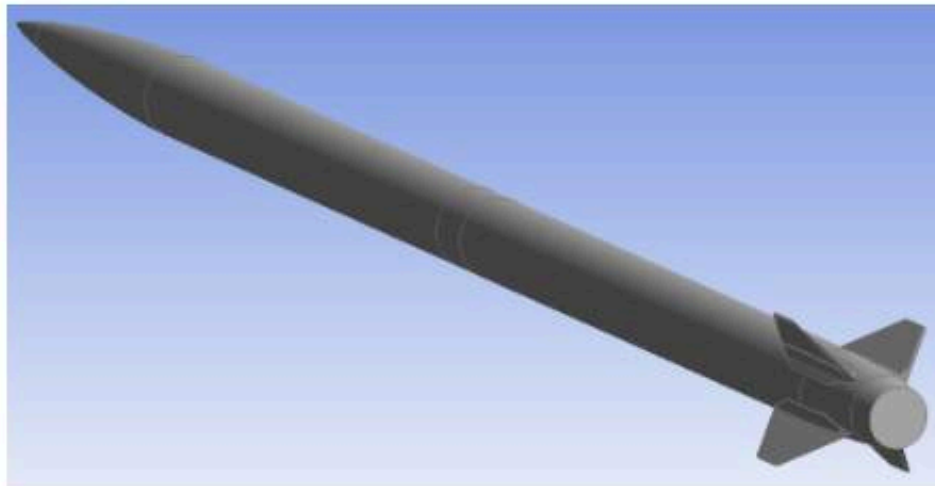


Figure 1: The rocket geometry used for simulations.

Mesh

A number of different meshes were used to discretize the fluid domain for different flow conditions. Most notably, different bodies of influence were also used to refine the mesh for subsonic and supersonic flow according to the behavior of the flow in the different domains. As can be seen in Figure 2 and Figure 3, a wider, conical body of influence was used to refine the areas around the nose to adequately resolve the mach waves expected to propagate in this area.

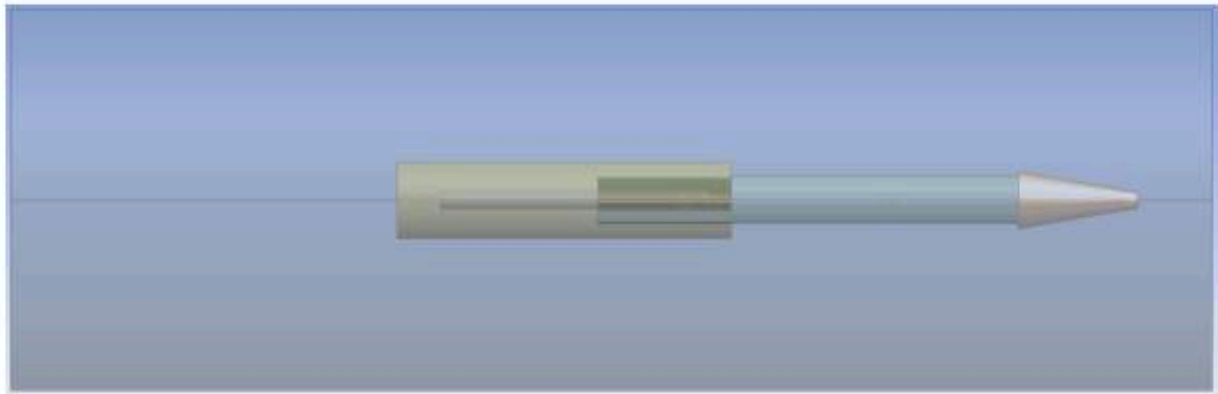


Figure 2: Fluid domain and bodies of influence used for subsonic simulations.

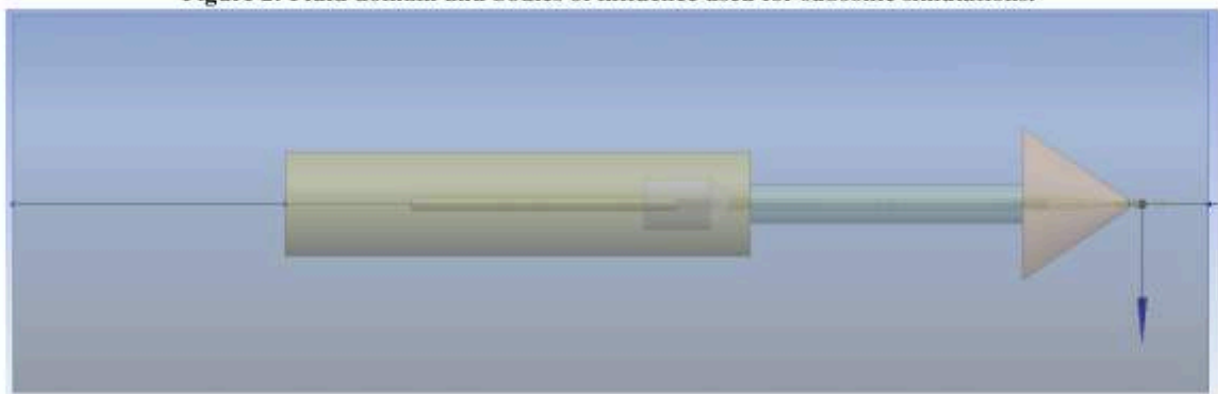


Figure 3: Fluid domain and bodies of influence used for supersonic simulations.

Poly-hexcore mesh was used to discretize the fluid domain as seen in Figure 4. To resolve the boundary layers along the rocket body, inflation layers were added as seen in Figure 5. As seen in Figure 6, the chosen inflation layers were largely capable of keeping the Y_{plus} values in the desired range for wall functions, between 30 and 300, except for at the very rear of the rocket, namely the trailing edges of the fins, and the flat plate at the back.

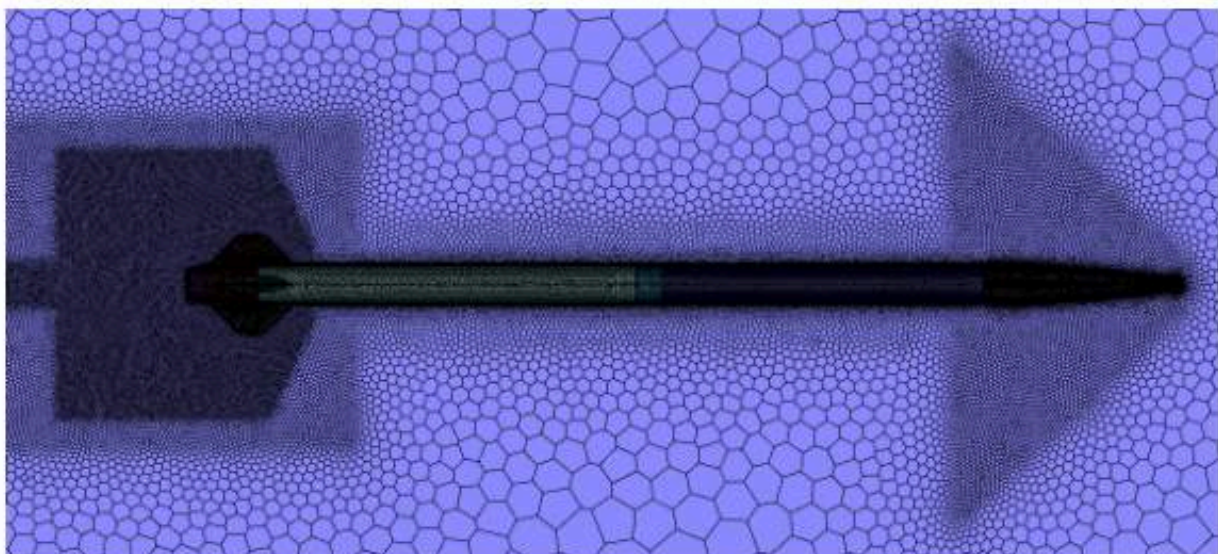


Figure 4: A cross section of the mesh used for supersonic simulations.

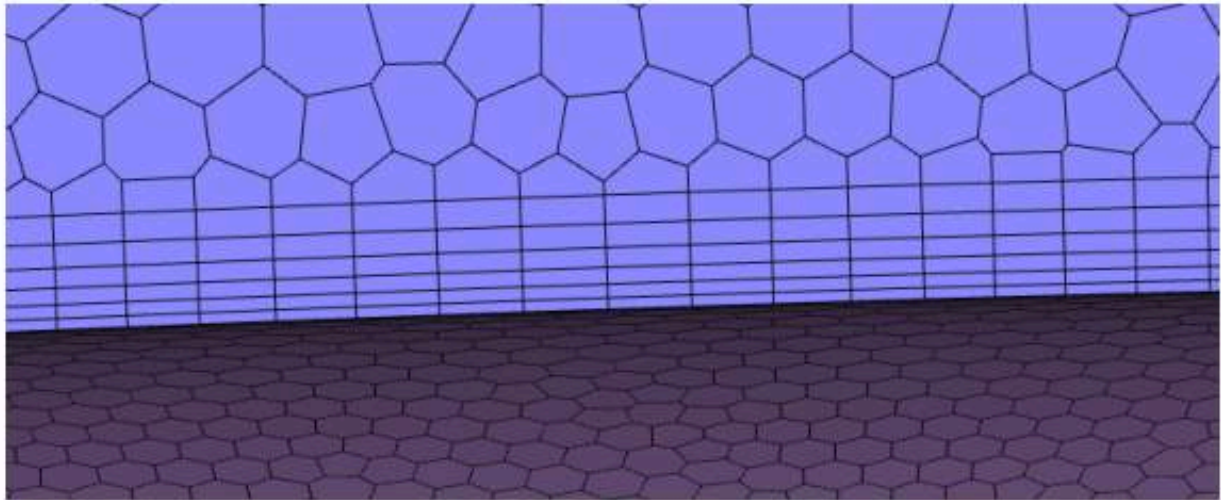


Figure 5: A close-up picture of the inflation layer.

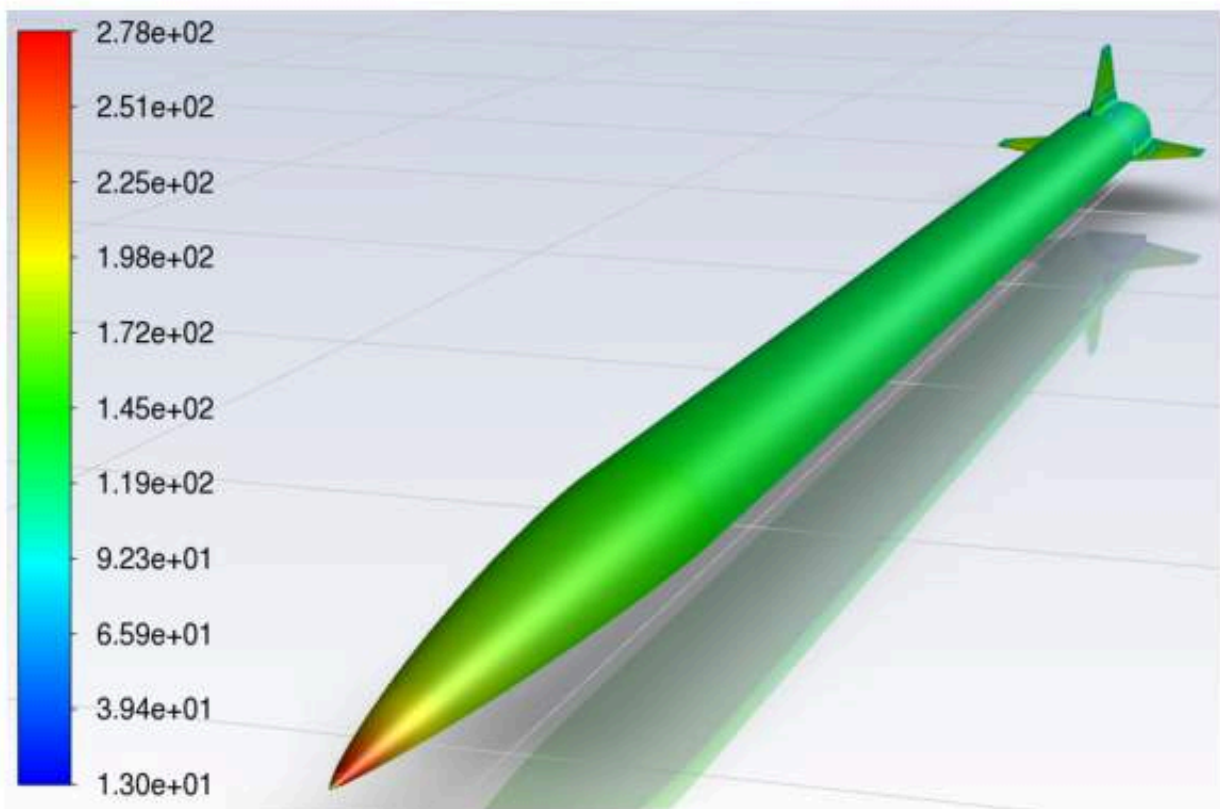


Figure 6: Contour plot of Yplus values on the surface of the rocket.

Table 1. A selection of statistics regarding mesh quality

Mach number	# of Cells	Max. Aspect Ratio	Min. Orthogonal Quality
0.3	371 926	42	0.20
1.5	1 826 295	50	0.20

Some statistics regarding the mesh quality can be seen in Table 1. These meshes are shown because they concern the meshes that were the least, and most refined respectfully. Both the number of cells, maximum aspect ratio and minimum orthogonal quality are kept within the desired range.

Setup

Ansys Fluent 2021 R1 was used to derive numerical solutions on flow analysis of the rocket, where a 3D cylindrical fluid domain was implemented around the rocket. Double precision was used for all calculations, increasing the computational demand, but increasing the precision.

All simulations were run at steady state, with a pressure based solver and absolute velocity formulation. Energy and viscous models were used for all equations. For the viscous model, $k - \omega$ SST with viscous heating and curvature correction was used. The density of the air was modeled using the ideal-gas law, and the viscosity was modeled using the Sutherland law. Because of a lack of empirical data, the roughness height of the surfaces of the rocket was left at a default of zero, i.e. smooth surfaces. The solver is coupled for the pressure-velocity coupling, with second order upwind for both energy, turbulence kinetic energy, density, and momentum.

Results

In addition to the results presented in the main report, the simulations result in some plots which can be used to check the validity of the computations, and further investigate the details of the flow.

As seen in Figure 7, the simulation predicts Mach waves propagating from the nose and fins, as well as expansion fans at the tapering part of the aft. The Mach wave propagating from the leading edge of the fins has a lower angle than the sweep angle of the fin, leading to larger wake-drag.

**Figure 7:** Contour plot of Mach numbers around the rocket at Mach 1.5

In figure 8, the distribution of static pressure can be studied. The highest pressure of 166kPa occurs at the nose tip.

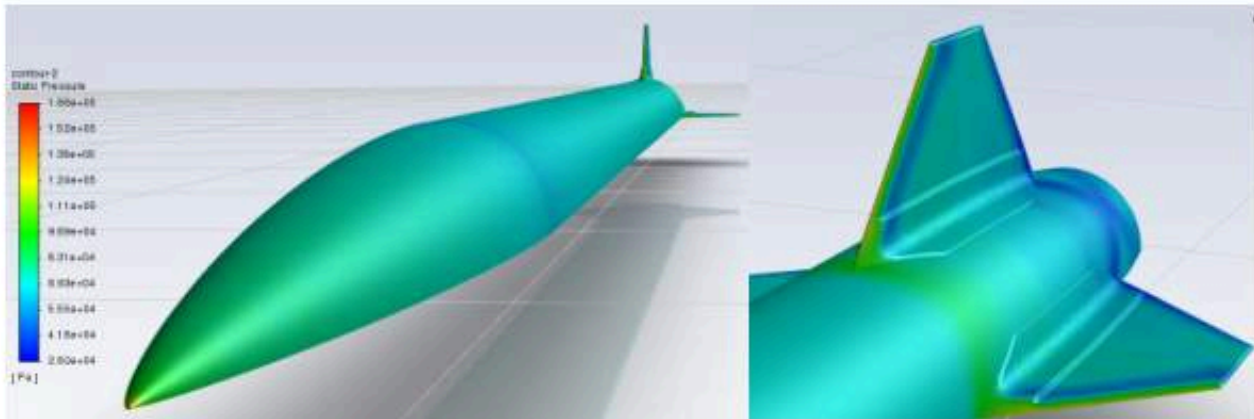


Figure 8: Contour plot of static pressure distribution at Mach 1.5

DETAILED TELEMETRY ARCHITECTURE

Telemetry and ground station system function

Table 1 - Telemetry and ground station functions

Priority	Function	Description
Main	Send arming/disarming signal	Arming or disarming the rocket.
Main	Receive and store telemetry	Store all the telemetry data for later use.
Secondary	Track rocket	Reliably track the rocket with the radio itself.
Secondary	Display telemetry	Display telemetry with OpenMCT at the ground station computer.
Tertiary	Video stream	Video stream from the rocket and display on the ground station.

The purpose of the ground station and telemetry system is to securely receive and store telemetry data from the rocket, as well as remote arming of the rocket to prevent premature separation while there are personnel near the rocket. Telemetry will be displayed live on the ground station, which is beneficial for detecting anomalies such as the rocket going ballistic and faster recovery of the rocket.

This year's design will include a radio tracking system, which will keep the ground based directional antenna pointed towards the rocket at all times. The purpose of this is to ensure a more reliable connection between the ground station and the rocket, as well as providing an additional source of position data to aid with recovering the rocket. This tracking system will function as long as the onboard radio is functional, even if the flight computer fails.

Ground station and telemetry hardware

Table 2 - Radio specifications overview

	Rocket radio	Ground station radio
Component name	CRE2-144-LW	CRE2-189
Connectors	Power & Ethernet	Power & Ethernet
Voltage range	10-32 V DC	19-55 V DC
Power draw	8-25 W	27-250 W
Frequency range	4900 MHz to 5900 MHz	4900 MHz to 5900 MHz
Channel width	14 MHz	14 Mhz
Tx power	2 W	4 W

Antenna gain	Dependent on antenna configuration	24 dBi
Transmission rate	15 Mbps	15 Mbps

The radio system which is used is the CRE2 system from RadioNor. The rocket houses the CRE2-144-LW unit, and the ground station uses the CRE2-189 unit. This system will provide internet protocol based communication between the rocket and the ground station, and can provide a maximum data rate of 15 Mb/s. Because of the high frequency the radio operates at, it drastically loses signal when not in line-of-sight. When it has line of sight it has an operational range of 20 kilometres while still maintaining 7 Mb/s, which was effectively tested during a previous launch to an altitude of 9 kilometers. This data rate will be used for both a videostream and telemetry data, of which a budget is shown in table 3 below.

Table 3 - Radio bandwidth budget

Service	Bandwidth
Total radio bandwidth	7000 kb/s
Video stream	5000 kb/s
Telemetry	286.4 kb/s*
Remaining	1755.6 kb/s

*Assuming telemetry consists of 60 float values being sent at 100 Hz

Ground station and telemetry software

The CRE2 radio system has built-in support for IP routing and the two radios used will be configured to the same network prior to assembly.

For telemetry data the primary protocol will be TCP, while the videostream will use UDP. Using TCP will ensure reliability of data in case of failure, and will provide correct data. TCP will require higher overhead and requires two-way communication, but the radio is designed to handle such use cases. The videostream from the rocket will be transmitted through an ethernet encoder to the radio aboard the rocket, which will be transmitted using RTSP (Real Time Streaming Protocol). The dataflow of the ground station and telemetry system is shown in figure 1.

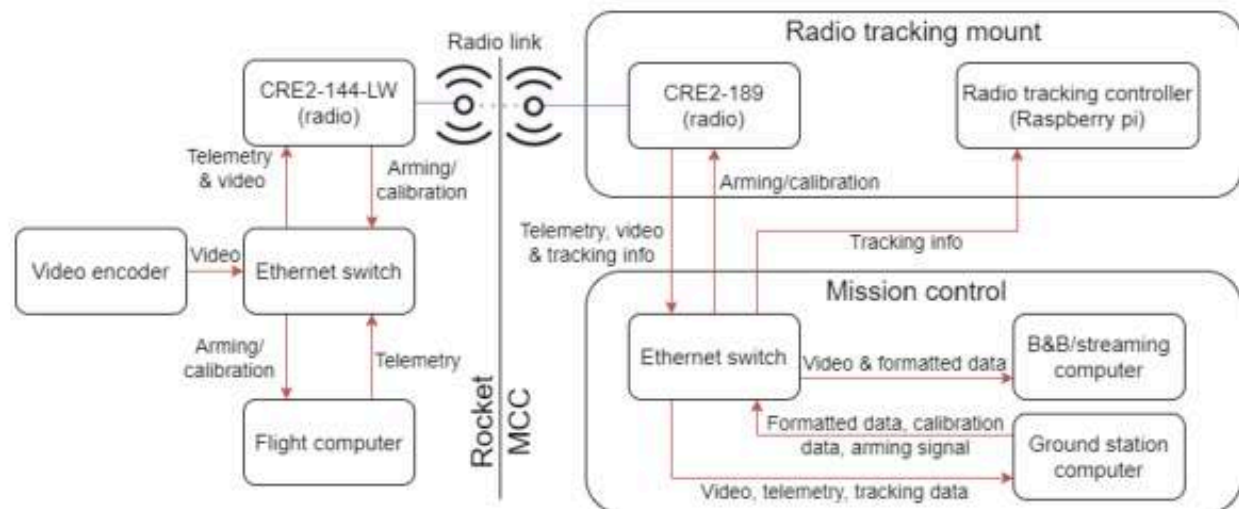


Figure 1 - Schematic of the dataflow for the telemetry

The ground station computer will use a python server for handling and saving incoming telemetry data. This data will be stored as a JSON-format for later uses and will also be forwarded to a realtime javascript server at 5 Hz, which will then update the telemetry display in OpenMCT. The telemetry points will be saved in OpenMCT and available for display. All telemetry points can be viewed separately as shown in figure 2 below. Lastly the arming signal will be sent from a python script on the ground station computer, which will be received by the flight computer. This will in turn change the state of the finite state machine from idle to armed.

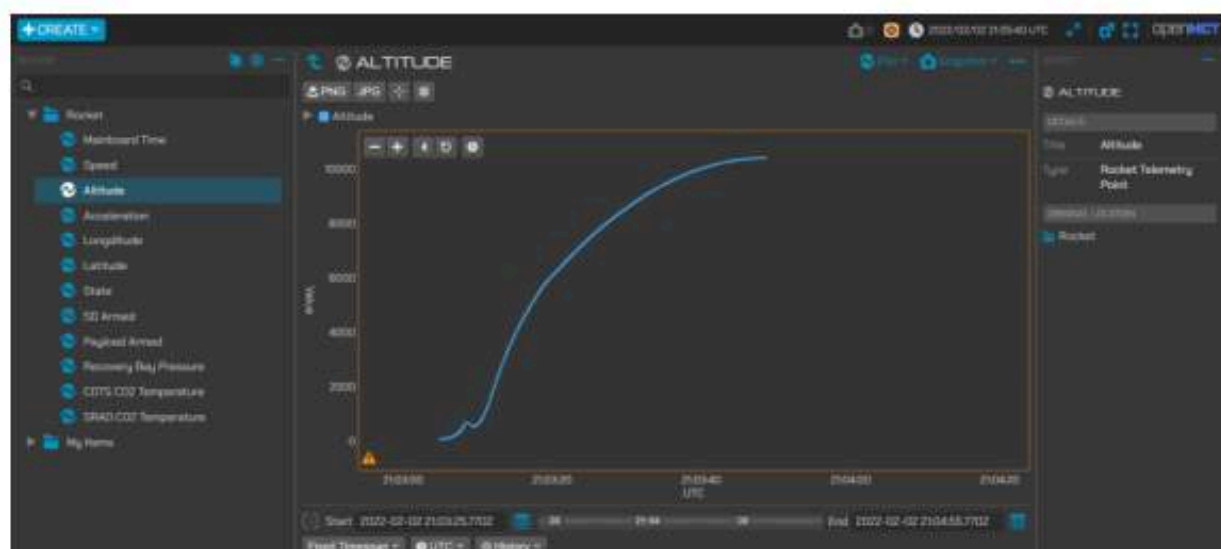


Figure 2 - Screenshot, example telemetry display in OpenMCT

OpenMCT is a great piece of software, mainly because of the ease of use and ability to modify the UI. With this functionality we are able to make OpenMCT suit our goals. It also allows us to show all telemetry in either graphs, tables or numbers.

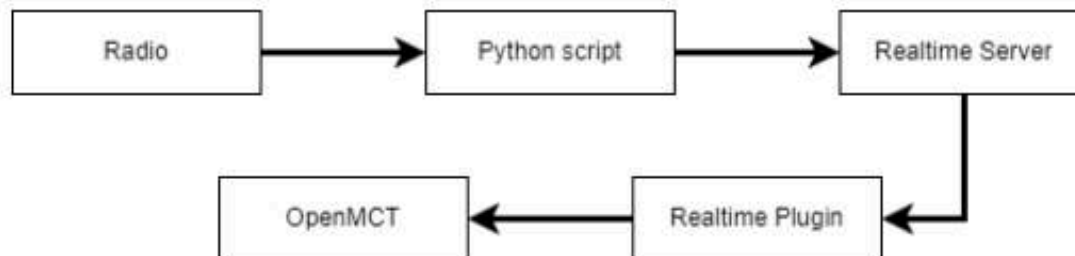


Figure 3 - Schematic of the dataflow for the ground software

The software is mainly made in python for the backend and handling of telemetry of the rocket, and the frontend is made out of javascript. The realtime server is also made in javascript for compatibility with the realtime plugin for OpenMCT.

Radio tracker system function

The radio tracker system functions as a measure to avoid signal loss during the flight and to keep a reliable connection with the rocket. Although the CRE2-189 is a phased-array radio, it still has a maximum operating angle at about 120 degrees. Therefore it is vital that we are able to keep it pointed at the rocket with the radio tracker system.

Function	Requirement	Description
Vertical axis rotation	30 degrees per second	Able to track the rocket according to model and radio signal vector
Horizontal axis rotation	10 degrees per second	Able to track the rocket according to model and radio signal vector
Tracking accuracy	± 0.36 degrees	Tracking accuracy according to model and radio signal vector

Table 4 - Radio tracker requirements

The tracking software is based on a finite state machine, which will be similar to the rocket's. The finite state machine will be controlled from a raspberry pi and will be mounted to the system. A model for the rocket's flight trajectory will be used to track the rocket during the ascent and descent. If the tracker software and/or hardware malfunctions, we will be able to manually control it.

The radio tracking is based on the radio signal vector, and as such is independent of the rest of the flight data. Should the flight computer be faulty, or even the data received corrupted, the system will still function based on the signal direction alone. To calibrate the absolute direction of the rocket in relation to earth's magnetic field it will use the GPS position of the rocket at the launch pad and the GPS position of the radio transceiver, from there on we will record how many degrees the mount has turned. This heading combined with the distance to the rocket, which is also given by the radio, we'll be able to calculate the rocket's current coordinates at all points in the flight.

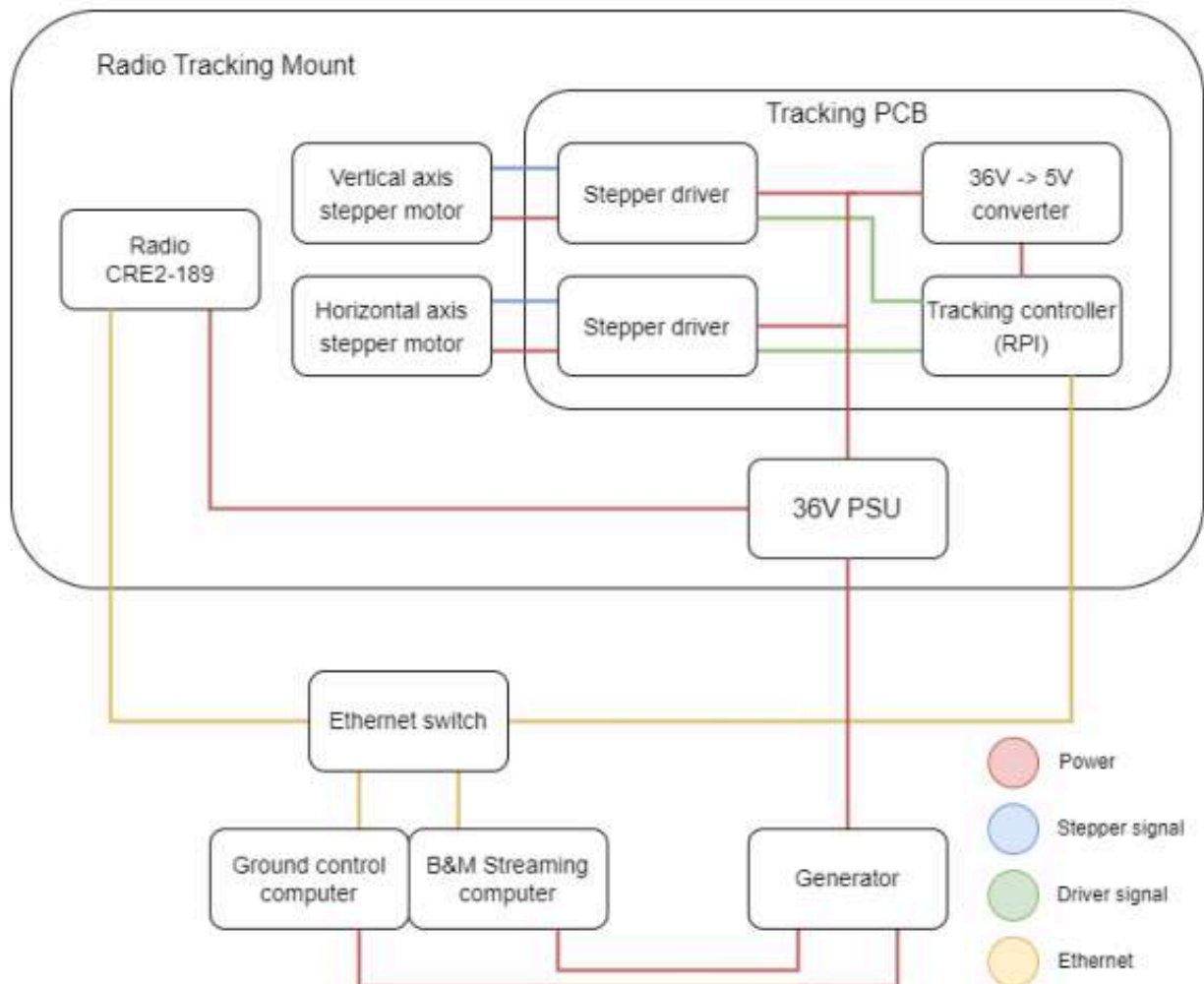
Electrical and mechanical system setup

Figure 4 - Example electrical system setup

The electrical system is connected together by the radio tracker system PCB. This PCB connects the AG.TRC.RP, the drivers, the motors and the power supply together. Since the driver can become very hot and the temperature in the environment it will be used is very hot, we have implemented heat sinks to radiate heat away from the driver. The heat sinks are seen in figure 5 below.

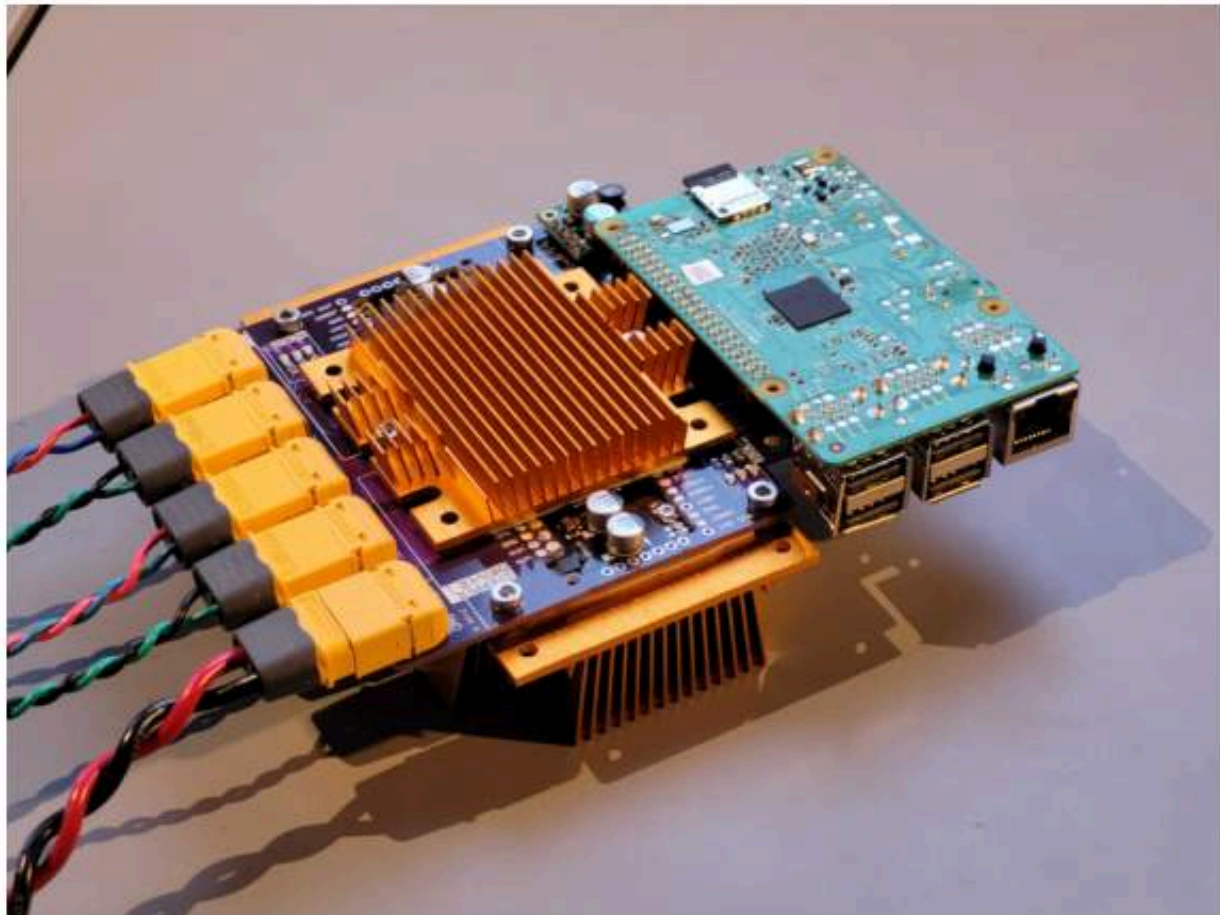


Figure 5 - Ground station tracker controller

The stepper motor used for the vertical motion is the AG.TRC.VS and the stepper motor used for the horizontal motion is the AG.TRC.HS. The drivers used for this are the AG.TRC.VD/AG.TRC.HD drivers. The specifications are given in appendix 10.

The following table describes the power draw of the radio tracking mount.

Total System Draw (Estimate)		
Item	Max amp draw	Max watt usage
AG.R	7.0 A	250 W
AG.TRC.VS	3.0 A	108 W
AG.TRC.HS	3.0 A	108 W
AG.TRC.VD / AG.TRC.HD	0.86 mA	4.3 mW
AG.TRC.RP	1.0 A	5.0 W

Table 5 - Ground station tracker power draw

The tracker mount is manufactured in aluminum to make it light and moveable, so it fulfills DTEG 11.3. The gearing is one to five to increase the force when moving the radio. It is possible to turn the mount 360 degrees horizontally, but we have limited it to 90 degrees to the right or the left. It is also limited to 90 degrees vertically. A sketch of the ground station tracker mount is shown in figure 6 below.

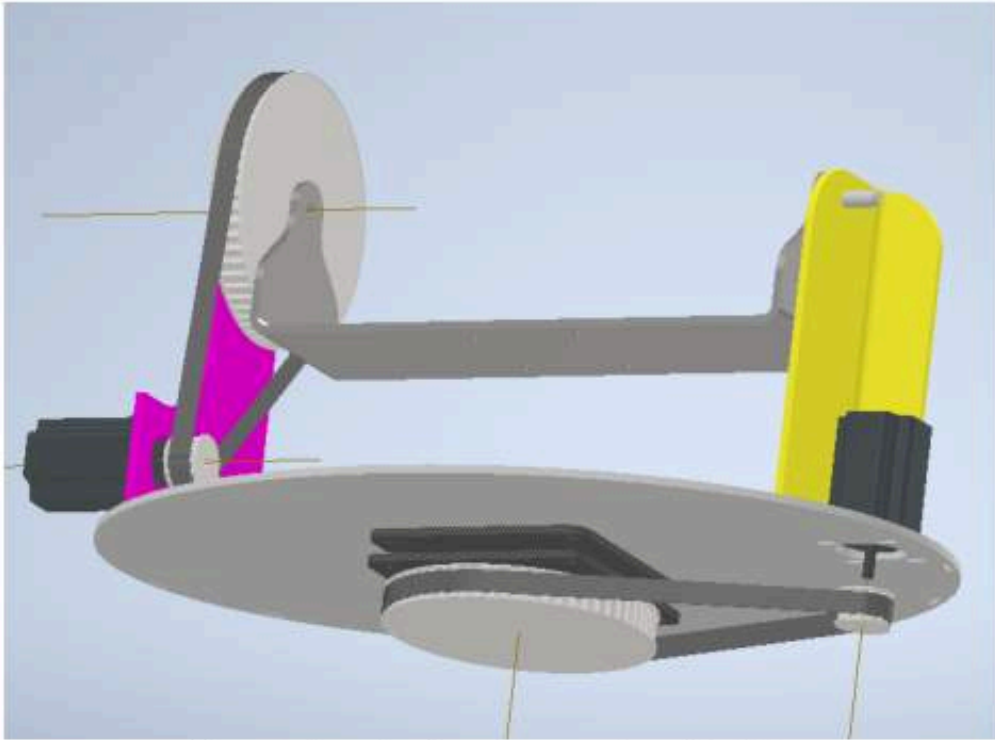


Figure 6 - Ground station tracker mount shown from below

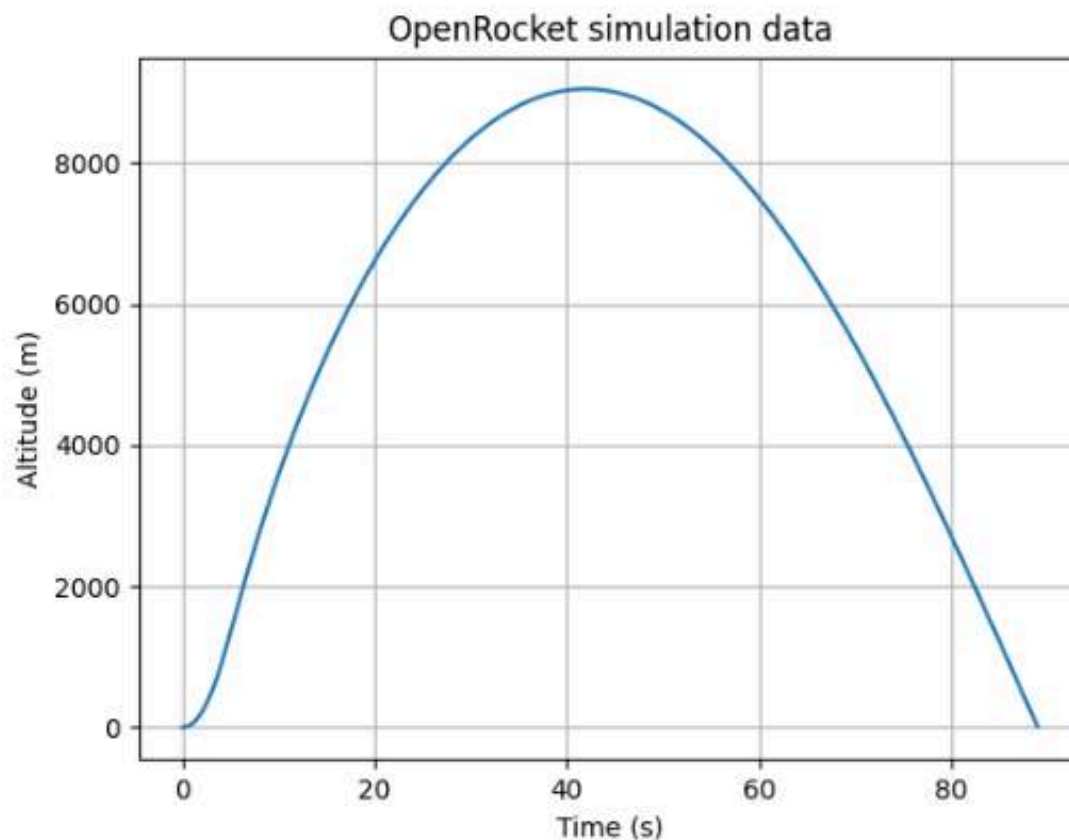
Tracking model

Figure 7 - OpenRocket model of Birkeland used for tracking

For the tracking model we are using data from OpenRocket, which is shown in figure 7 above. This data will give us the position of the rocket during the ascent and coasting, which should be good enough for the phased array radio's internal tracking. To increase the accuracy of this model we are also using the radio's heading update each second to adjust the angle and go to the timestamp which has the closest angle to the updated one. This will be beneficial for when the model does not represent the flight trajectory of the rocket during ascent and coasting.

The vertical velocity for the tracker is set to 30 degrees per second, which should suffice according to the models. A representation of this is shown in figure 8 below. Here it is assumed that the bare minimum distance from the launch site is about 450 meters as stated in DTEG 11.5.

It should be noted that this requirement most likely will not suffice if the tracker goes ballistic as seen in figure 9 below, however we will still maintain radio connection because of the phased array.

As we enter into the drogue phase, we are completely switching from model tracking to radio vector tracking, since the velocity of the rocket is low enough to be properly tracked.

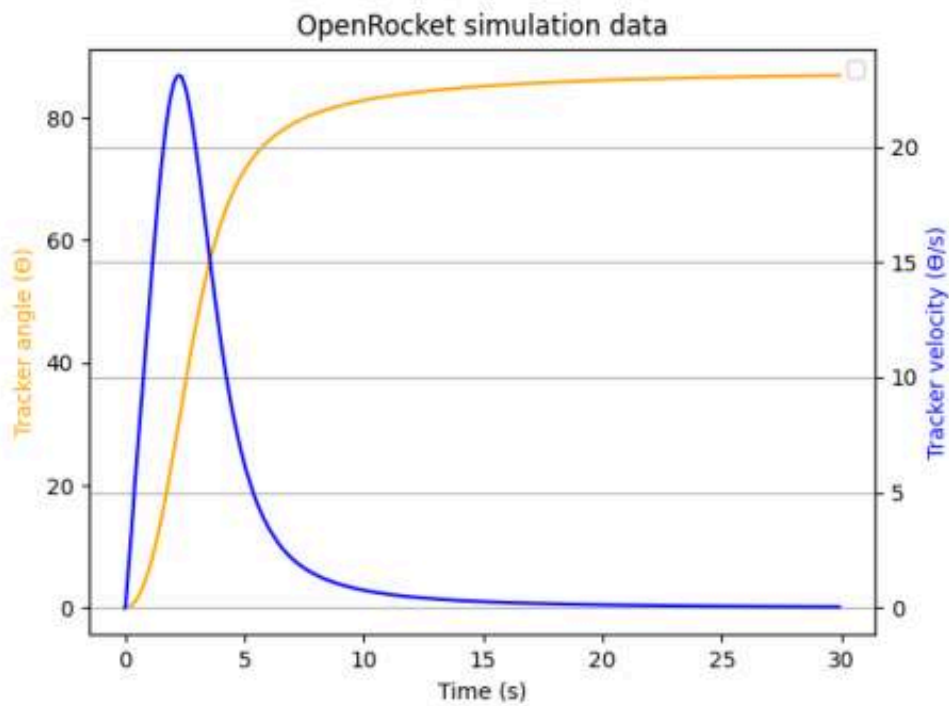


Figure 8 - Tracker angle and velocity according to model when tracker is 450 m away from launch

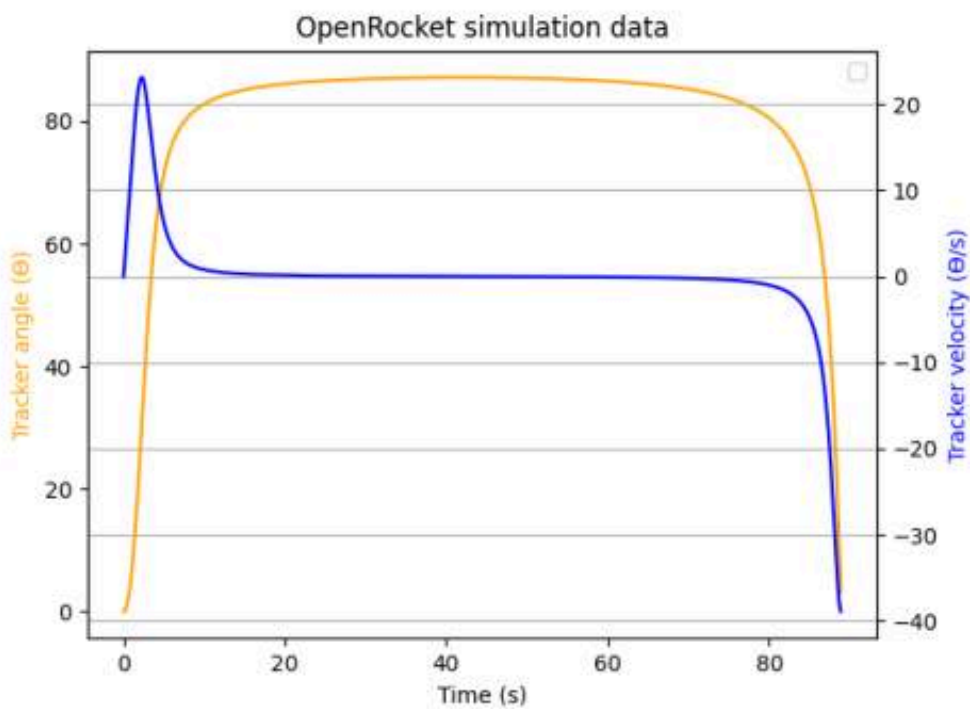


Figure 9 - Tracker angle and velocity assuming the rocket is going ballistic

DETAILED SOFTWARE ARCHITECTURE

Software architecture overview and RTOS task specifications

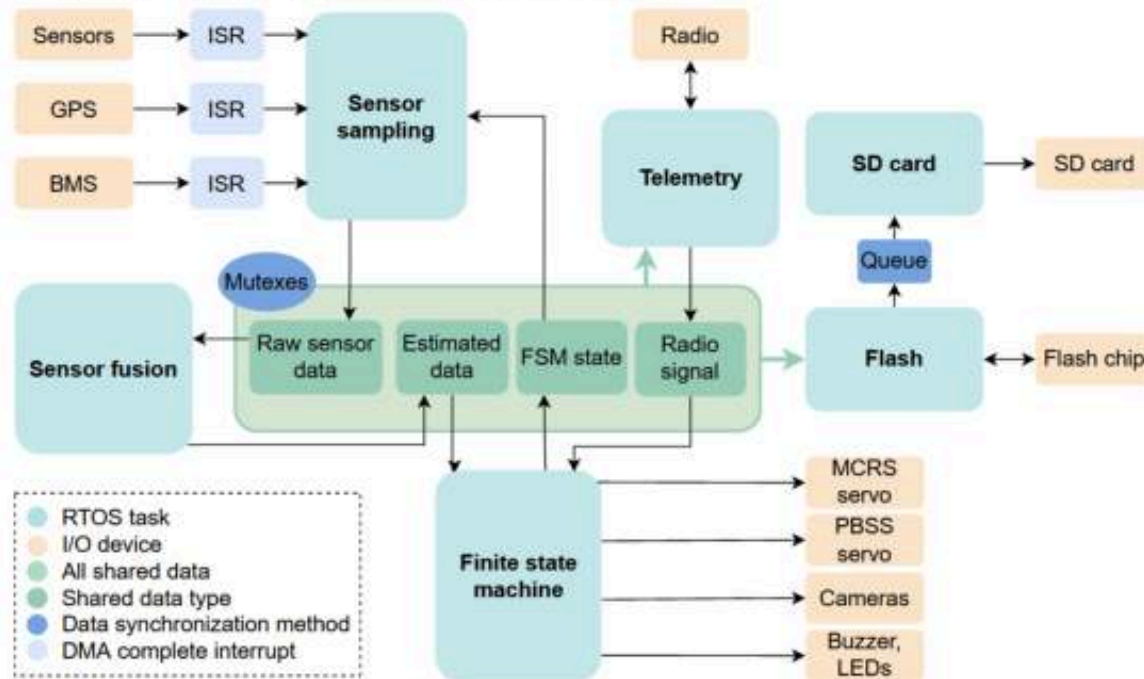


Figure 1- Overview of the software architecture.

The SRAD software uses a Real-Time Operating System (RTOS), as we have a real-time system that can be structured into largely independent tasks. Specifically, FreeRTOS is used with the CMSIS-RTOS API. The selected tasks are specified in Figure 1 and Table 1.

Table 1 - RTOS tasks overview

Task	Description
Sensor sampling	Reading data from buffers from all the sensors, the GPS, and the BMS system, with different sampling rates depending on the state. The buffers are filled by the ISRs, and the data is stored in global variables protected by different mutexes.
Finite State Machine	Updates the FSM based on estimated altitude and acceleration from Sensor fusion, and messages from the Ground station. Updates FSM state. Controls peripherals that are specific to a state, like activating the recovery servos and controlling the buzzer.
Sensor fusion	Processing sensor data to provide more accurate results.
Flash	Store global variables on the flash chip at the same rate as new data is updated.
Telemetry	Transmitting data and event messages to the ground station over Ethernet, with the same rate as new data is updated.
SD card	Store all data saved in the flash chip to the SD card after reaching apogee.

The data used by all the tasks will be stored as shared variables protected by mutexes, as is shown in Table 2. We could have utilized queues to send data from, for example, the Sensor fusion task to the FSM task. However, the estimated data also needs to be available to the Telemetry and Flash tasks, and this is the case for most of the data. As the variables are only updated by one task, we found that this solution worked well for our needs, as long as they're protected by mutexes.

Table 2 - Overview of shared data types / critical sections protected by mutexes

Data type	Task to update data	Task to use data
Barometer	Sensor sampling	Sensor fusion, Telemetry, Flash
IMU	Sensor sampling	Sensor fusion, Telemetry, Flash
Magnetometer	Sensor sampling	Sensor fusion, Telemetry, Flash
GPS	Sensor sampling	Sensor fusion, Telemetry, Flash
Battery (BMS)	Sensor sampling	Telemetry, Flash
Analog barometer	Sensor sampling	Telemetry, Flash
Analog temperature	Sensor sampling	Telemetry, Flash
FSM state	FSM	Telemetry, Flash
Kalman filter estimates	Sensor fusion	FSM, Telemetry, Flash
Radio signal (arm/disarm)	Telemetry	FSM

Finite State Machine (FSM)

Each of the states in the finite state machine is defined as a class that all include the following functions; `onEnter()`, `onUpdate()`, and `transitionValid()`. With these functions one can easily structure the code so that it is effective and readable. In order to transition between classes, an integer value ranging from 0 to 6 is defined, starting at the Idle state which is defined as 0. The transitions between classes are decided based on the triggers in Table 3. These triggers will be checked in `transitionValid()`. The functionality of the states, that are presented in the last column in Table 3, are defined in `onEnter()` and `onUpdate()`. Which of these depends on whether the function is to happen once, such as the rocket separation in the Drouge state, or if it is continuous within the state, such as apogee detection in the Coast state. This is presented more clearly in Figure 2, in which the functions of the states are separated by entry/ and do/ depending on when they are to happen.

FSM Apogee detection algorithm

The apogee detection, the most critical transition, consists of a step where the difference between the previous maximum average altitude and the current average altitude is calculated. If this difference is larger than a set margin, the apogee is detected and the drogue can be deployed.

Table 3 - FSM states and triggers

State nr.	State	Trigger	Rocket state and functionality
0	Idle	Powered on/ Dearming signal from GS	Initial state when the rocket is first powered. Microcontrollers and radio the transmitter turn on. If dearmed, power to the cameras is turned off, live stream stops and sampling rate is slowed down.
1	Armed	Arming signal from GS	Still on the launchpad. Cameras are powered up, live stream begins and logging of data starts with a fast sampling rate.
2	Powered	Acceleration > 3g	While the rocket engine is burning. Sets start time for the mach delay.
3	Coast	Acceleration < 0	Motor no longer burning. Apogee detection begins.
4	Drogue	Apogee detected	After apogee. On entering this state, the servos are activated and the rocket will separate and the drogue chute will deploy. Slows down the sensor sampling rate, and starts storing data on the SD card.
5	MainChute	Altitude < 1500ft/450m	Below 1500ft/450m. Main parachute released upon entering this state.
6	Retrieval	Altitude constant	When the rocket has landed. Increase the sound of the buzzer. Cameras will after some time turn off to save power.

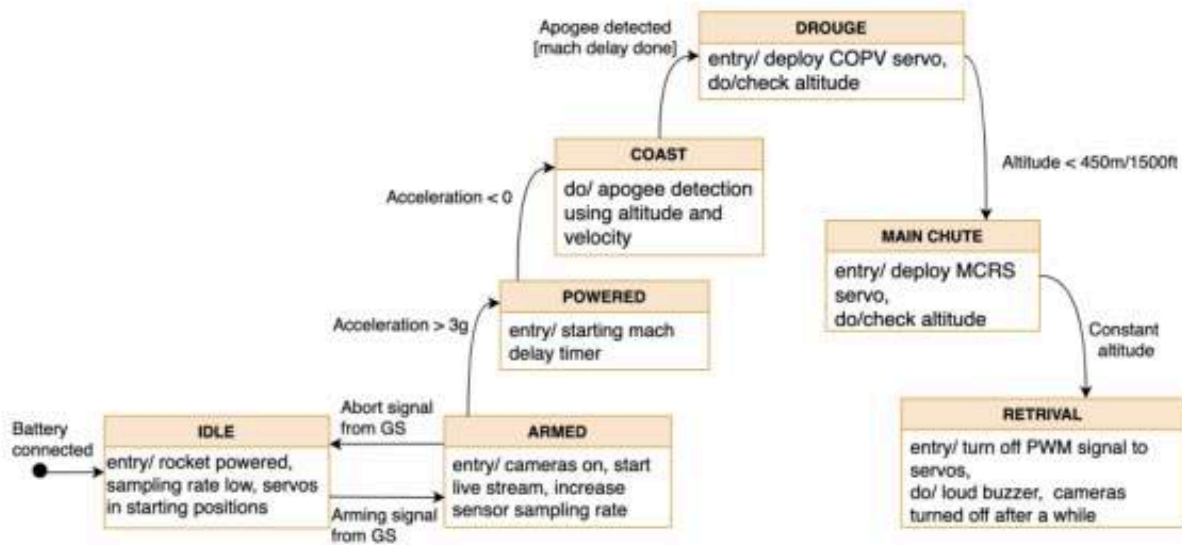


Figure 2 - Overview of FSM states and transitions during normal flight.

Sensor reading

We are using SPI with DMA and interrupts for the barometer, magnetometer and both the IMUs, each connected to their own SPI buses. This is to make the data transfer go as fast as possible, as the polling rate isn't dependent on the main program, and the CPU doesn't need to transfer data to memory. This way, the DMA can fill a buffer while the main program is running, only sending an interrupt when the buffer is full. The Interrupt Service Routine (ISR) then sends this data to the Sensor sampling task to be stored in shared variables. Then the DMA refills the buffer, while

the other tasks read from these variables. More information about how the Sensor sampling task works is found in Table 2.

Handling a restart during flight

As mentioned in the Drop Test report in Appendix V.B, during tests the avionics system has happened to restart when activating the PBSS, meaning there is a non-zero chance this happens during the actual flight at SA Cup. Without handling a possible restart, the FSM can get stuck in Idle state without any way of moving forward or activating the main chute. Even though this is a hardware issue which has been addressed since the test where it failed, the software is designed in order to perform its main function of releasing both the parachutes in case this happens again.

In order for the program to know whether it should start in Idle as normal, or jump to the previously stored FSM state, we have an additional arming signal called *enable_restart*. When the rocket is in Idle state and ready to launch, both *enable_restart* and the normal *arming_signal* will be set to 1 by the ground station. Both are initialized to 0 by default, and can also be changed back to 0 by the ground station if needed. The *enable_restart* variable is then stored in the external flash chip every loop, along with the FSM state, where they can be accessed after a potential restart. Both of these are read first thing when starting the program, as shown in Figure 3. The next FSM state after Idle is then based on whether *enable_restart* was 0 or 1 in the previous run of the program. A 0 means the FSM continues in Idle as normal, waiting for the arming signal to continue, while a 1 enables a jump to the previous FSM state.

The reason we use a separate variable to enable this restart mechanism is because it is a backup solution that is technically separate from the FSM, as it makes jumping between Idle and *any* state possible. We still want the FSM to work as normal if *enable_restart* is 0, as the transitions in the FSM have been validated on multiple test launches.

The risk of doing this is if the FSM state read from flash is faulty, which would result in unwanted behavior. For this reason, multiple iterations are read and checked before actually jumping to the given state, see the transition in Figure 3. This includes ensuring that it's a number between 0/Idle and 6/Retrieval, and if it isn't the same for every iteration read, it needs to be a logical change, ex. from 1 to 2 to 3, not 1 to 3. Furthermore, initializing *enable_restart* to 0 ensures that the restart mechanism isn't accidentally enabled when turning on the avionics for tests or checkups during assembly, where it's crucial that the FSM never goes beyond Idle, as it makes recovery activation possible.

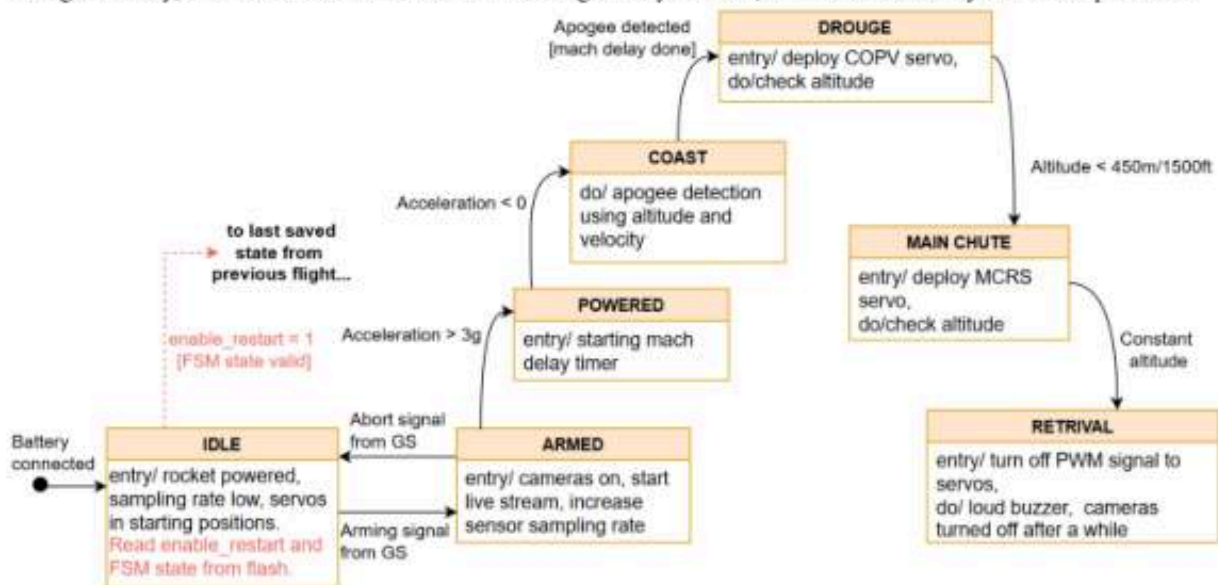


Figure 3 - updated FSM with enabled restart.

DETAILED ELECTRICAL ARCHITECTURE

I. SRAD Flight Computer Details

The SRAD flight computer consists of two stacked four layer PCBs, they are the KB3 (AV.KB3), and PDB (AV.PDB). They can be seen in Fig.1 below.



Fig. 1: Picture of the PDB (top) and the KB3 (bottom) boards.

The KB3 board houses the microcontroller which controls all of the SRAD system as well as most sensors, ethernet communication circuitry. The PDB houses the Battery Management System (BMS), as well as the GNSS-receiver and connections to external peripherals in the SRAD system. Details on the functionality onboard this flight computer is further described in this document.

A. Microcontroller details

The microcontroller used on the flight computer is an STM32H753ZIT6. This is part of the STM32 series H7 chips, which is one of the most powerful ARM microcontrollers available on the consumer market. Noteworthy specifications for the microcontroller used are listed below in table 1.

Table 1 - SRAD Flight Computer Microcontroller Specifications

Feature	Specification
Architecture	Arm® Cortex®-M7 32-bit RISC
Clock speed	480 MHz
Flash memory	2 Mbytes
RAM	1 Mbyte
Used connectivity features	5x SPI buses, Dual Quad SPI, Ethernet, I2C, 3x UART

B. Sensor details*1. Barometer - MS5607-02BA03*

The barometer operates with a supply voltage of 1.8 to 3.6 V, and supports both I2C and SPI for communication. This model employs a 24-bit ADC to achieve a resolution of 0.13/0.084/0.054/0.036/0.024 given an OSR of 256/512/1024/2048/4096. Below in table 2 is a description of the most important electrical specifications.

Table 2: Specifications for the MS5607-02BA03 Barometer.

Specification	Operating range	Absolute min / max	Note	Unit
Supply voltage	3.3	-0.4 / 4	–	V
Peak supply current	N/A	(N/A) / 1.4	During conversion	mA
Pressure	300 - 1100	(N/A) / 6000	Full accuracy	mbar
Extended pressure	10 - 1200	(N/A) / 6000	Linear range of ADC	mbar
Communication protocol	N/A	N/A	–	SPI

2. IMU - IIM42652

The deciding features of this IMU was its low noise density as well as its high data output rate. The IMU can measure up to 16g acceleration, which will be slightly lower than the expected maximum acceleration force the rocket will experience. Below in table 3 is a description of the most important electrical specifications.

Table 3: Specifications for the IIM42652 IMU.

Specification	Operating range	Absolute min / max	Note	Unit
Supply voltage	3.3	-0.5 / 4	–	V
Current consumption	0.88 - 0.95	N/A	Low-Noise mode	mA
Linear acceleration	+/-16	N/A	–	g (gravitational acceleration)
Angular rate	+/-2000	N/A	–	dps
Rate noise density	3.8 - 5.2	N/A	@ 10 Hz	mdps/ $\sqrt{\text{Hz}}$
Acceleration noise density	70 - 100	N/A	@ 10 Hz	$\mu\text{g}/\sqrt{\text{Hz}}$
Communication protocol	N/A	N/A	–	SPI

3. IMU - LSM-6DSO32

This IMU is capable of measuring up to 32g acceleration. This is an important feature as the rocket will be able to measure acceleration forces above 16g, which would cover our expected maximum acceleration force under flight. Below in table 4 is a description of the most important electrical specifications.

Table 4: Specifications for the LSM-6DSO32 IMU.

Specification	Operating range	Absolute min / max	Note	Unit
Supply voltage	3.3	-0.3 / 4.8	–	V
Current consumption	0.55	N/A	High-performance mode	mA
Linear acceleration	+/-32	N/A	–	g
Angular rate	+/-2000	N/A	–	dps
Rate noise density	3.8	N/A	High-performance mode	mdps/ $\sqrt{\text{Hz}}$
Acceleration noise density	220	N/A	High-performance mode	$\mu\text{g}/\sqrt{\text{Hz}}$
Communication protocol	N/A	N/A	–	SPI

4 Magnetometer - LIS3MDL

This magnetometer is an all-around solid choice to use as a compass, given its characteristics. Below in table 5 is a description of the most important electrical specifications.

Table 5: Specifications for the *LIS3MDL Magnetometer*.

Specification	Operating range	Absolute min / max	Note	Unit
Supply voltage	3.3	-0.3 / 4.8	–	V
Current consumption	270	N/A	Ultra-high resolution mode	μA
Linear acceleration	+/-32	N/A	–	g
Angular rate	+/-2000	N/A	–	dps
Rate noise density	3.8	N/A	High-performance mode	mdps/ $\sqrt{\text{Hz}}$
Acceleration noise density	220	N/A	High-performance mode	$\mu\text{g}/\sqrt{\text{Hz}}$
Communication protocol	N/A	N/A	–	SPI

5. GPS - U-Blox Neo M9N

This GPS was chosen because it is able to handle relatively high speeds and acceleration compared to other brands. This will be crucial for flight analysis, both in real-time and post-flight when attempting to recover the rocket. Below in table 6 is a description of the most important electrical specifications.

Table 6: Specifications for the U-Blox Neo M9N GPS.

Specification	Operating range	Absolute min / max	Note	Unit
Supply voltage	3.3	-0.5 / 3.6	–	V
Voltage ramp on VCC	N/A	20 / 8000	–	$\mu\text{s}/\text{V}$
VCC_RF voltage	VCC - 0.1	N/A	–	V
VCC_RF output current	N/A	(N/A) / 50	–	mA
Communication protocol	N/A	N/A	–	UART

C. BMS System

The Avionics stack is powered through a dedicated Power Delivery Board (PDB), mounted onto the main KB3 (Kristian Birkeland Brain Board). The PDB essentially acts as a large power routing and protection system. It also houses connectors to peripherals, our COTS GPS module, and voltage regulators. It is mainly based on the BQ20z655-R1 Battery Gauging Chip, programmed to perform Battery Management Operations under flight.

The BQ20z655-R1 was chosen for its ability to accurately monitor individual battery cell voltages for 2-4 Lithium-based battery cells in series. Its tasks are outlined in the following paragraphs.

1. Measurement

Current draw and battery cell voltages are measured by the BQ20z655-R1's Impedance Track™ algorithm, which integrates current over time through a low resistance shunt. These values will be reported through the STM32 microcontroller to Ground Station. The battery voltage and current values will also be used to broadcast to the Smart Charger IC (BQ24800), which will then provide the right amount of current.

2. Power Supply and Delivery

The BQ20z655-R1 circuit is equipped with MOSFETs to control positive- to negative- terminal connections for charge (CHG) and discharge (DSG). The battery pack will be connected to the PDB Board through an XT60 plug and Molex Nanofit connectors located at the top of the PDB board as seen in Fig. 1.

The power delivery is done mainly through the board itself. Taking advantage of the board's 4-layers, the bottom two layers are used to distribute power throughout the board. The second bottom layer is the board's power layer, and is dedicated to providing wide copper traces to create high current paths. This is shown in Fig. 2;

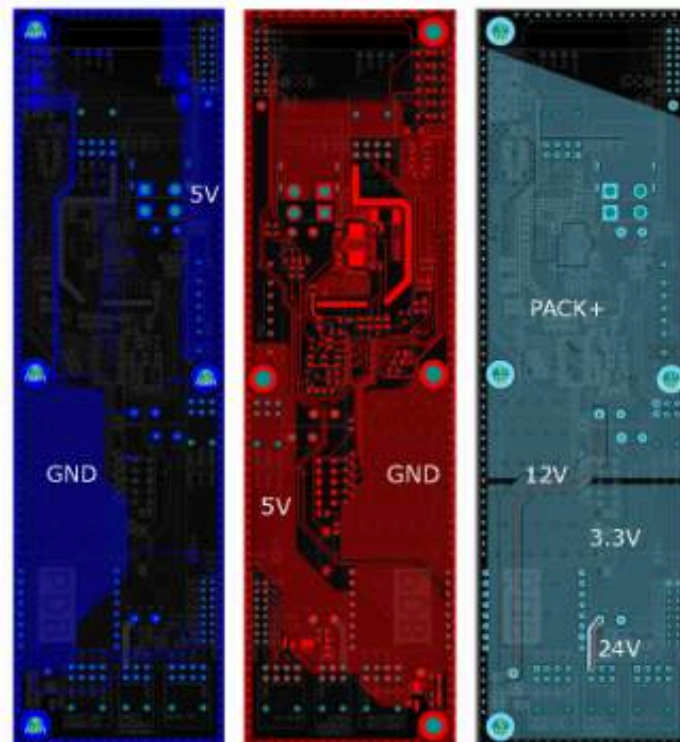


Fig. 2: Picture showing the bottom, top, and power layers from left to right. PACK+ is the designator for the most positive copper trace in the PDB board, connected to the positive end of the battery plug.

The bottom layer is used to route power from our voltage regulators to output pins, sending power to our cameras, radio, and ethernet. A table showing the dependencies of the regulators are listed below,

Table 7: Description of Voltage Regulators used and their dependencies.

Voltage	Regulator Type	Component Name	Dependencies
2.5 V	Linear/LDO	BQ20Z655-R1 (built-in)	DISP pin on the BQ20Z655-R1
3.3 V	Linear/LDO	TPS75933KTTR	Logic-level components such as MCU, sensors and switches
5 V	Buck	5V, 3.2A Step-Down Voltage Regulator D36V28F5	Video encoder, Ethernet switch
24V	Boost	Pololu 24V Step-Up Voltage Regulator U3V50F24	Radio
12V	Boost	Pololu 12-V Step-Up Voltage Regulator U3V50AHV	Cameras, Avionics bay fan

3. Protection features

The BQ20Z655-R1 contains electrical protection features that covers Overvoltage, Undervoltage, Overtemperature, and Overcurrent. These values are programmed into the board during testing. By default, the chip is made to physically tolerate voltages between 6V-25V, and a maximum of 7A current.

4. Redundancy

A bypass is included in the design where the pack is able to be charged. Prior testing confirmed this would enable power to be distributed the same way as using the intended battery plug going into the BMS, without the possibility of battery gauging or protection against undesirable situations. This is added to prevent the possibility of power distribution failure to the Avionics stack due to defects in the Battery Management System.

D. Battery

The battery pack used in the avionics stack will be 4 x 21700 cells in a 2S2P configuration. With this combination, the following power characteristics are obtained;

Table 8: Characteristics for the 21700 cells used.

	2S2P setup
Total capacity	72 Wh
Min-Nominal-Max voltage	5v - 7.2v - 8.4v
Max continuous output current*	14.55 A

The voltages also fall within operating range of the BMS as referred to in subsection C.3 above. The battery's maximum continuous output current is rated at 14.55, but this does not mean the system will actually reach this current. Table 9 describes the power draw of the system as a whole to compare with our battery's power characteristics.

Table 9 - SRAD System power draw

Total System Draw (Estimate)			
Item	Voltage	Max Amp Draw	Max Watt Usage
Radio	12 V	2.1 A	25 W
Recovery Servos*	5 V	6 A	30 W
Cameras (4x)	12 V	1 A	12 W
MCU MAX	3.3 V	1.6 A	5.28 W
TOTAL BAT DRAW	7.4 V	6.75 A	50 W

*The max amp draw value listed here assumes that the SRAD PBSS servo draws 5A of current, with the MCRS servo drawing 1A. In practice, the PBSS has never drawn more than 0.8A. The real estimate will then be much closer to about 1.8A, which uses about 9W of power instead of the 30W listed above.

Table 10 - SRAD Power usage

Total Power Usage From Batteries	
Watts MAX (@ All Systems Operational)*	54,28 W
Amps MAX (2S2P battery, @5V)	10,86 A
Watts MAX (@ Nominal Operation)**	37 W
Amps MAX Nominal** (2S2P bat, @5V))	7,4 A
Watts (Idle Mode)***	17.8 W
Battery life (2S2P battery, @ Nominal Operation)	1.94 hours
Battery life (2S2P battery, @ Idle Mode)	4.04 hours
Battery life Predicted****	2 hours 45min (Idle Mode), 45 min @MAX nominal

*The values in table 9 above were used to calculate this value. It assumes that all systems listed in table 9 are operational.

**This is the maximum power draw without the recovery servos operational. It will only draw power with the recovery servos for short periods of time, which is about 2-4 seconds.

***This is a power draw estimate with only MCUs running, and Radio at 50% power, a very rough estimate of power draw.

****Based on a 'realistic' estimate, where the system will be partially at (Idle Mode) for 2 hours and 45 minutes; power usage at Nominal Operation is used to calculate the rest of the power left.

E. PCB Layer stackup

The following figure shows the layout stackups for the KB3 and PDB PCBs.

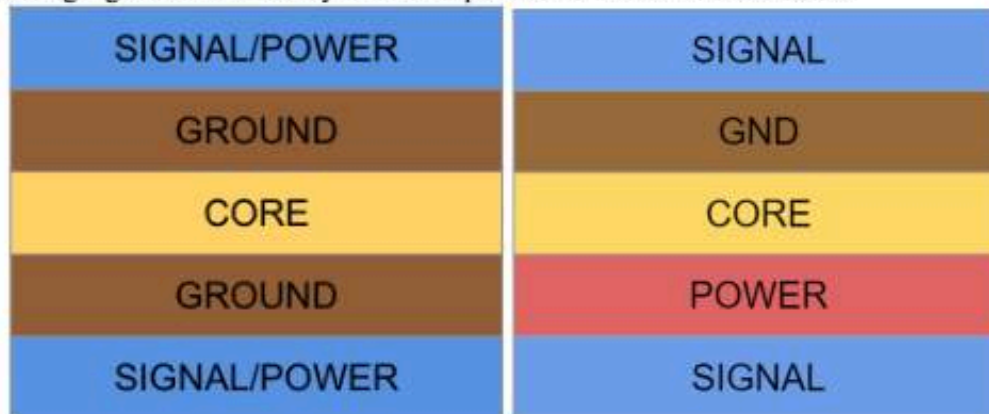


Fig. 3: Layout stackups for the KB3 (left) and PDB (right).

This is a four-layer PCB, containing two combined signal and power planes for each of the sides of the mainboard. On the KB3, surrounding the central core, two ground planes are included. Placing the ground plane close to the power plane will create a high impedance bypass filter isolating the two signal/power planes from one another. A ground plane also being close to the signal layer establishes a controlled impedance for the transmission lines, preventing a high inductance path for return current flow. Placing the ground planes in this manner, no matter where the trace is run it is always a ground path directly underneath it, further managing current loops. As mentioned in subsection C.2, the PDB board has one dedicated power layer to ensure that the top layer receives minimal inductive side-effects from high-current. In addition, the ground layer is placed between the Top Signal layer and the Power layer to further reduce the effects of EMI. Vias are used to further increase the quality of connections to ground, reducing inductive effect and EMI at the cost of only a marginal increase to capacitance.

F. PCB impedance control

KB3 introduces controlled impedance matching on more or less all high speed signals. Different types of impedance matching on different data lines is listed in the table below.

Table 11: Impedance table for PCB impedance control.

Data line	Impedance	Type
Ethernet	100 Ω	Differential
USB	90 Ω	Differential
Other high speed signals (UART, SPI...)	50 Ω	Single ended

Impedance matching in transmission lines is done in an attempt to set a consistent impedance throughout the interconnects. In the case of a perfect matching there is no reflection along the lines, causing an maximum power transfer downstream from the transmitter to the receiver. The values for the impedance matching in our case is set to common values, (not calculated) and is therefore not guaranteed to be set to a perfect matching, however, it is expected to have a better driver, line, and receiver matching, than not matching at all. High reflection on the transmission lines could cause an undesired transient response, corrupting the transmission lines. This is illustrated in the figure below.

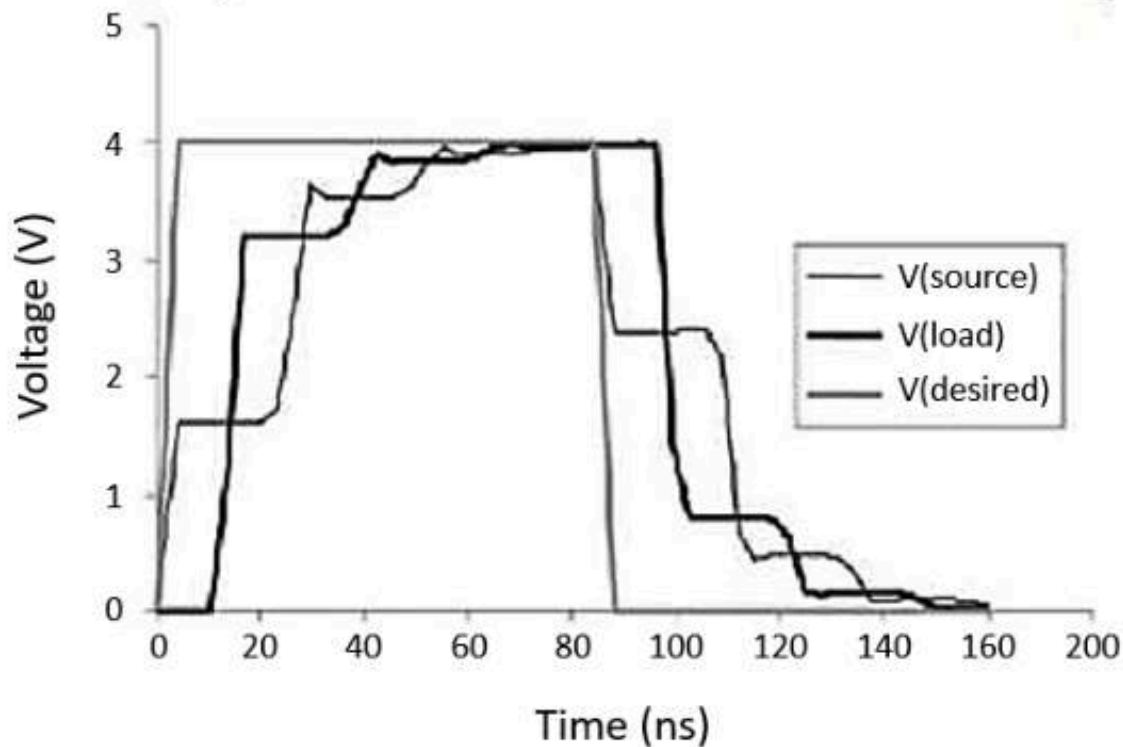


Fig. 4: Voltage-Time graph for impedances in

II. Umbilical Cord

The umbilical cord consists of a magnetic plug and a Smart Charger IC. Below we find a figure of the magnetic plug:

Fig. 5 of connections, and of the plug itself

The plug will provide power to the rocket while it is idle on the launchpad, this is to avoid draining the batteries inside the rocket while its not in flight. During liftoff the magnetic plug will easily be disconnected by the force of launching as it is held in place by relatively weak magnets.

To provide power to the system a Smart Charger IC from Texas Instruments, BQ24800, is used. The Smart Charger IC is implemented as COTS, using a ready-made evaluation module (EVM) to deliver a constant amount of voltage,

which will be actively adjusted according to the voltage across the batteries inside the rocket. The charger is planned to be powered from a mains supply or a large industrial battery (eg. a car battery). The module is rated to provide current up to 8.1 A, which compared with the Avionics' idle current consumption of 7.4 A ensures sufficient power delivery with acceptable leeway for any spikes.

III. Circuit protection

On all servo motors intended for the SRAD recovery system and on all cameras, an electronic fuse will be integrated to protect against electrical faults. This is to ensure any error during assembly won't result in any permanent damage to either the servos/cameras or the rest of the connected SRAD systems. It will also protect the system in case a critical fault occurs during flight.

The electronic fuse (eFuse) used is a TCKE712BNL,RF. This eFuse/PMIC is located on a small PCB which will be placed either on top of or nearby the servo motor or cameras it is intended to protect. To reduce required wiring the PCBs also function as a passthrough for power such that multiple cameras/servo motors can be essentially daisy chained through these PCBs.

Illustration of eFuse here

To set thresholds for what parameters the eFuses operate in, passive components on the PCBs are selected with specific values. Because the servo motors and cameras run on different voltages and draw different amounts of current we have set up three variants of eFuses, the protection ranges chosen can be seen in the table 12 below.

Table 12: Protection Limits for Circuit Protection boards

PCB variant	5 V MCRS servo protection	5 V, SRAD PBSS protection	12 V, camera protection
Over voltage limit	6 V	6 V	13 V
Starting operating voltage	4.5 V	4.5 V	11 V
Under voltage limit	3.89 V	3.89 V	9.5 V
Overcurrent limit	1 A	5 A	1 A
Voltage slew rise time	10 ms	10 ms	10 ms

IV. Cameras

Onboard the rocket there will be five cameras in total, one of which will be streamed live to the ground station. Details for each of the five cameras can be found in table 13 below, and a visualization of their positions in figure 6 below.

Table 13: Specifications for cameras used by the Avionics Module

Camera nr.	Camera model	Comp. ID.	Resolution	Framerate	Field of view	Live streamed
1	Firefly split 4k	AV.	3840 x 2160	30 FPS	210 or degrees	yes
2	Firefly split 4k	AV.	3840 x 2160	30 FPS	210 or degrees	no
3	Runcam split 3 lite	AV.	1920 x 1080	60 FPS	160 degrees	no
4	Runcam split 3 lite	AV.	1920 x 1080	60 FPS	160 degrees	no
5	Runcam split 4	AV.	3840 x 2160	30 FPS	170 degrees	no

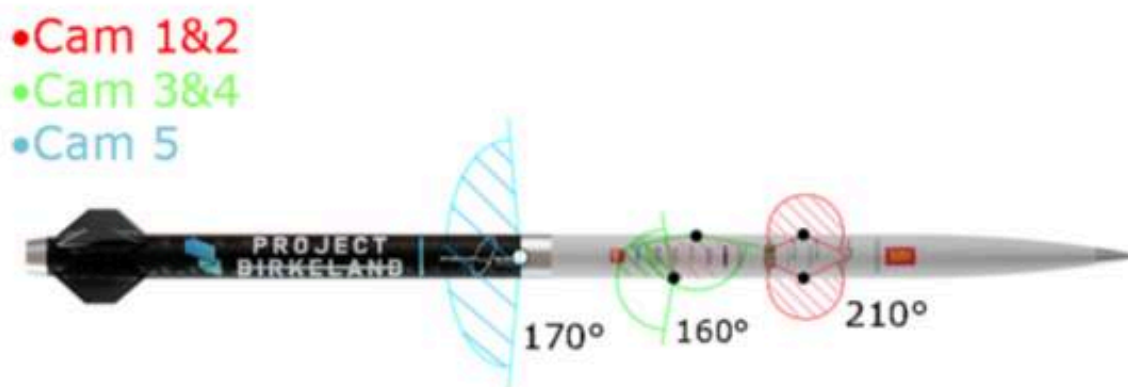


Figure 6: Camera placements in the rocket

1. Camera 1 and 2

These two cameras will be recording out towards the horizon with the lens of the camera barely sticking out of the airframe. They will both use a very high field of view lens which allows us to see everything around the rocket with just two cameras and with minimal protrusions out of the airframe. These cameras will therefore be able to provide us information about everything that happens to the outside of the rocket, with a main point of interest being parachute release. Camera 1 will be live streamed to the ground station at 1080p 30fps, more details on this can be found in ground station and telemetry appendix [V.L].

2. Camera 3 and 4

These two cameras will both be placed in the recovery bay on the recovery plate (IR.RP). Camera 3 will be pointed towards the MCRS mechanism to record its motion during flight. The goal of this camera is to capture the behaviour of the MCRS system during the entire flight, but certain events such as launch, rocket separation and main parachute release are especially interesting for post flight analysis. Camera 4 will be pointed out of the airframe and will attempt to record the release of the main parachute, though it will have limited field of view due to it being inside the body tube, and the parachute bag potentially being in the way, none the less it will likely be able to capture interesting data.

Because these two cameras are placed inside the rocket, a small LED light bar will be located just above camera 3. This is to provide light for recording, as not much light will be let through the airframe itself.

3. Camera 5

Camera 5 will be placed somewhat outside of the airframe in the camera shell (OL.CS), pointed towards the fins. The goal of this camera is to record the fins behavior during flight. While camera 1 and 2 will record the fins as well, they will be very small in the image due to the inherent distortions which a high FoV lens produces. This camera, which has much less distortions, also has the fins closer to the center of the image which will provide us with a much better view.

Because this camera is placed below the separation point of the rocket it is completely independent from the rest of the avionics system. A block diagram of this system can be seen below in figure 7.

Block diagram of camera shell

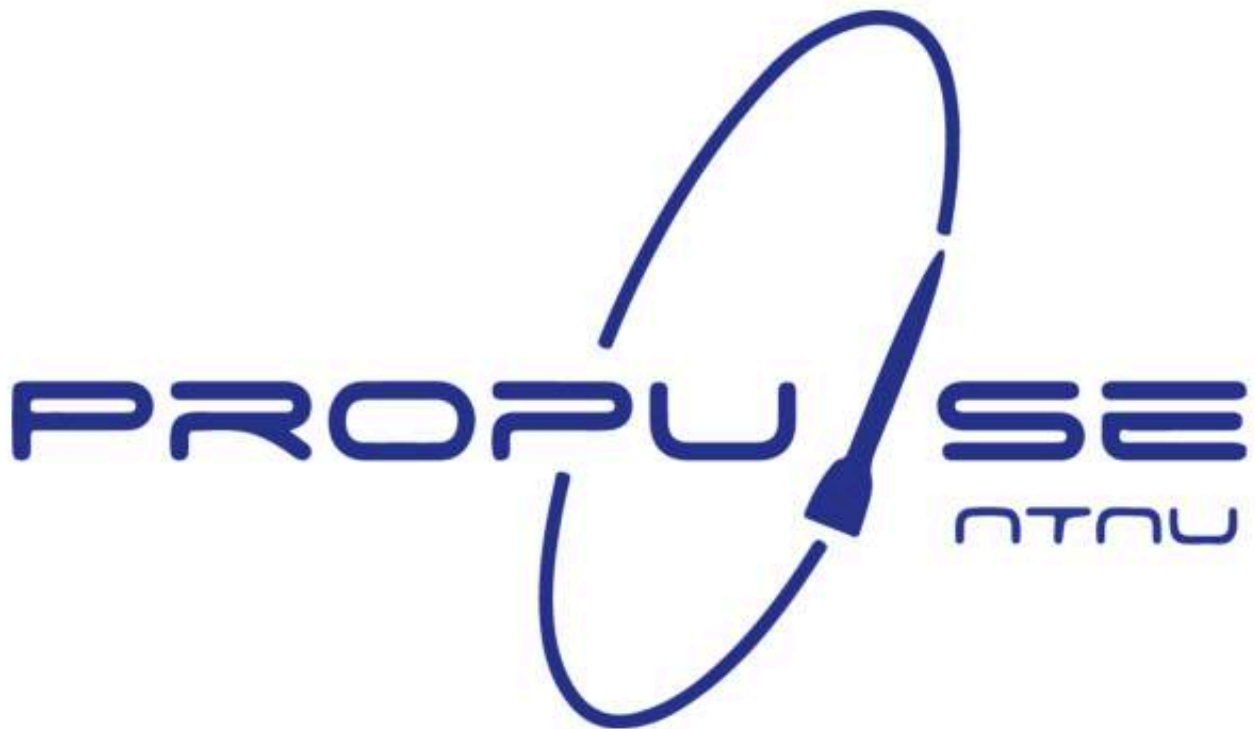
Details for this independent camera system can be found in table x below.

Table 14: List of Camera shell electronics

Item	Comp. ID.	Product name/note
Battery	AV.CAM5.BAT	2S1P Li-ion pack. Protected 18650 cells
Magnetic switch	AV.MS4	Featherweight magnetic switch
Voltage regulator	AV.CAM5.REG	Pololu 12 V regulator
Camera	AV.CAM5	Runcam split 4

Navigation System Design Document

Written by Even Drugli



Project Birkeland 2022

Intro

This document describes and discusses the navigation system used on Birkeland.

Overall goal of the navigation system is to *provide accurate real-time information about the vehicle's position, speed and attitude (rotation).*

The task can mainly be divided into the following:

- Access sensor data
- Filter and fuse data to estimate flight states.
- Identify erroneous sensor data and recover and/or isolate the fault if possible.

Several architectures were considered for the navigational system. The current system consists in short of:

- Full 6 DOF real-time vehicle estimation
- Multiplicative Extended Kalman Filter with 27 state variables.
- GNSS System with online error correction
- Sensor & system fault detection & recovery
- Context-based modeling, which excludes unreliable sensors for given parts of flight.

The main system function of the navigation system is to provide reliable navigational aid to the finite state machine (FSM). The navigational aid is mainly height, velocity and acceleration data.

The navigation system is done as a Master thesis by Even Drugli in spring 2022. The thesis will conclude with the launch at SA Cup.

System goals

The goals of the system is to:

- Provide accurate navigation data
- Be as robust as possible, both with regards to real-time navigation and debugging.
- Be fairly development friendly and expandable for coming years.
- Be a solution that supports higher and longer flights than 10km height.

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Abbreviations

GNSS	Global Navigation Satellite System. For many just 'GPS'.
IMU	Inertial Measurement System. Accelerometer and attitude rate sensor (ARS, often called 'gyro').
Magnetometer	3 DOF compass
DOF	Degree of Freedom. Number of independent motions/measurements that are allowed to a body/system.
KF	Kalman Filter
MEKF	Multiplicative Extended Kalman Filter
ECEF	Earth-centered, Earth Referenced
NED	North - East - Down

System fundamentals

Reference frames

For reference frames, ECEF, NED and BODY are used.

ECEF: Global reference frame, which rotates with Earth. Thus, a given landmark on Earth will always have the same ECEF-coordinate.

NED: North East Down. A local reference frame given geographical references with a self-defined origo. Will be used for initially defining the launch site.

BODY: Fixed to the vehicle. Origo is defined as the nose tip, mainly due to a shifting Center of Pressure and Center of Mass. It is also the same reference frame as the Mechanical group.

Rotation

Rotation/attitude of the vehicle is expressed in Quaternions. This was chosen given its computational efficiency and no singularities. Quaternions make the Kalman Filter architecture vastly more complicated, as will be described below.

For visualization and debug purposes, Euler angles is used since it's easier to grasp for humans.

Sensor package:

The following sensor package is onboard Birkeland:

Low-G IMU	IIM-42652	Datasheet
High-G IMU	LSM6DSO32	Datasheet
GPS	NEO-M9N	Standard Datasheet / Comms. Datasheet
Barometer	MS5607	Datasheet
Magnetometer	LIS3MDL	Datasheet

Table 2 - Birkeland sensor suite

Multiplicative Extended Kalman Filter

A Kalman filter (KF) was chosen as the main estimation algorithm for the system. Further, given the non-linearities involved, an extended KF (EKF) was chosen. Due to the use of unit quaternions as attitude parameterization, a standard EKF cannot be used. KF operates on vectors, and doing vector addition for quaternions does not preserve the properties needed for a rotation representation. There are methods to do this³, but a more preferred way is to use a multiplicative extended Kalman filter (MEKF).

With MEKF an error-state kalman filter is utilized. This filter carries two state vectors, one unfiltered accumulated state estimate calculated directly from the IMU, and one error state estimate. See figure 1. Since the IMU-accumulated state estimate will deviate over time, the kalman filter takes input from all other sensors, estimates the error in the IMU-state and continuously corrects and reset the accumulated IMU-states.

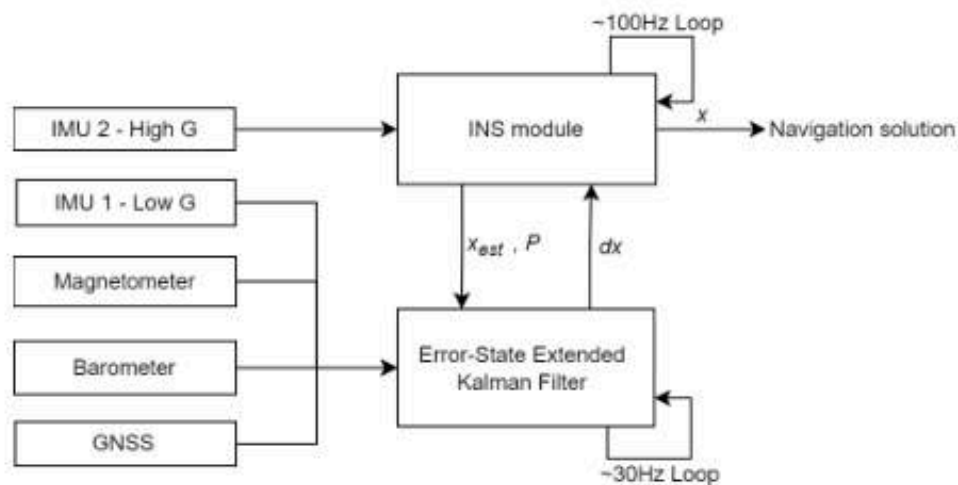


Figure 1: Multiplicative Extended Kalman Filter architecture

MEKF allows much higher frequency updates of flight states since the IMU can run as an Inertial Navigation System even when no other sensor data and state corrections are available. This, combined with RTOS, gives us the possibility to achieve the sample frequencies seen in table X.

	Frequency
IMU Supersampling	32kHz
IMU dead-reckoning navigation solution	100 Hz
Sensor-fused, filter corrected navigation solution	30 Hz

Table 2 - sample frequencies for filter

KF States

The Kalman Filter states used are shown in figure .

Flight states to estimate					
1	Position X	11	Bias Acc1 Y	21	Bias Gyro2 Z
2	Position Y	12	Bias Acc1 Z	22	Bias hard magnetometer
3	Position Z	13	Bias Gyro1 X	23	Bias soft magnetometer
4	Velocity X	14	Bias Gyro1 Y	24	Altitude/pressure
5	Velocity Y	15	Bias Gyro1 Z	25	Gravitational acceleration
6	Velocity Z	16	Bias Acc2 X		

7	Ang. pos. X	17	Bias Acc2 Y		
8	Ang. pos. Y	18	Bias Acc2 Z		
9	Ang. pos. Z	19	Bias Gyro2 X		
10	Bias Acc1 X	20	Bias Gyro2 Y		

Table 3 - KF states to estimate

States explained:

1-3 and 7-9 gives 6 DOF position for the rocket

7-9 is linear velocity

10-21 is standard bias for all IMU measurements. Bias is an 'constant' offset error in the measurements, that have a constant part calibrated out and a dynamic part, which should be estimated.

22-23 is the bias for the magnetometer. .

24 is pressure, which is used to estimate height.

25 is to account for changing gravitational acceleration

System model

A rocket simulator model for the system has been developed both by the author in a separate project and by Penumbra. Birkeland is also fairly similar to the previous flight-proven Stetind, where we have good flight data. The biggest unknown in the model is expected to be rotation due to possibly slightly erroneous fin attachment or -angle. This is accounted for in the tuning. The thrust curve from the motor is also somewhat unknown and must be accounted for. The expected drag force on the vehicle is another variable, but it is relatively known from Stetind flight data & matching simulations.

Context-Adaptive Modeling

Barometers are really powerful sensors for sounding rocketry for sub-Karman altitudes. However, for supersonic flight, which Birkeland will experience, the shockwaves created will drastically affect the pressure around the vehicle and cause the barometer to give wrong pressure estimates. This was experienced on Propulse NTNU's last flight with Stetind, the predecessor to Birkeland, where it was observed a 200 meter altitude drop during max-Q. We therefore want to adjust the sensor influence in the KF based on context. In literature, this method has several names, but is often referred to as *context-adaptive modeling*⁵ or *variable-gain kalman filter*⁶.

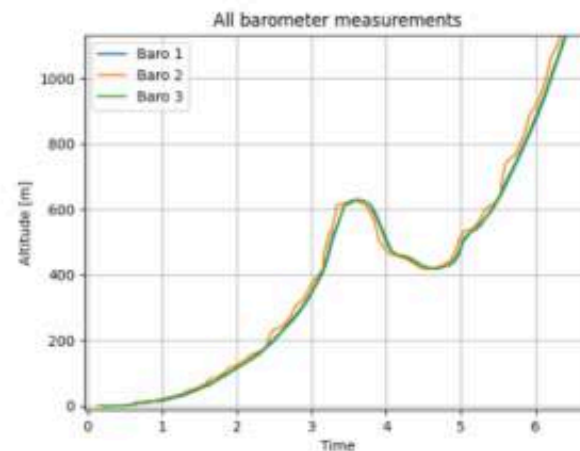


Figure: Barometer data from Stetind flight.

By adjusting the trust in the sensor measurements for parts of the flight where the measurements are considered bad, other parts of the flight can achieve higher accuracy with correct sensor gain. One paper on other applications using context-adaptive KF is (Teruyama et al., 2013).

To ignore these measurements the Kalman Gain must know that these sensors are unreliable. This is accomplished by increasing the corresponding values for the given sensor in the measurement noise covariance matrix R . This tells KF that the sensor will have much higher noise variance than normally. Thus KF will rather use other sensors or thrust the system model.

Rocket velocity	Noise gain k , Baro measurement
$v < \sim 275\text{m/s}^*$ (Mach 0.8)	$kI = 1$
$v > \sim 275\text{m/s}^*$ (Mach 0.8)	$1 \ll kI^{**}$

*exact threshold is not determined, but over mach 0.8 is the transonic phase.

More sophisticated noise gain functions have been discussed, but deemed not necessary.

Sensor & system fault detection & recovery

A number of fault checks is done in real-time to detect abnormalities within the sensor measurements or the filter system.

Sensor validity-checks:

Direct validity-checking is used to check if sensor values are clearly outside the expected range. Some of these are caught by the Innovation Filtering (described below) too, but direct error-checking is simpler and can be used without a valid Kalman Filter (i.e. during smaller tests). Such, it can be seen as real-time unit testing.

Thoughts have been to include flight states (from FSM) as a parameter for these checks, but this is currently not planned due to the added complexity, i.e. state transition edge cases and in-flight restart.

Any failing checks will raise an appropriate system alert.

Currently the checks done are:

System/variable to check	Only valid if within	
	Lower limit	Upper limit
At startup & in-flight:		
Barometer	-50 meters	15 000 meters
GPS fix (position found)	1	1
GPS location	NA	15 km away test/launchsite
Low-g IMU	-16g	16g
High-g IMU	-32g	32g
On startup: (If no in-flight restart capability)		
IMU Mounting axes	Check correct axes/pcb-mounting.	
Barometer	Expected ground-level - 50m	Expected ground-level + 50m
Magnetometer	Check the correct axes.	

Innovation Filtering

A number of solutions are implemented inline with the EKF to detect abnormalities. Three of these are Measurement Innovation, Innovation filtering and Innovation Sequence Monitoring.

The *Measurement Innovation* is the difference between the true sensor readings and what the state estimator estimates. By comparing this value to the covariance of innovations, we get the normalized innovations. We can then detect if a sensor reading is far outside the expected value window. The thresholds for this must be determined by testing since the values are not exactly zero-mean, but around 3 is assumed a good start. This is called innovation filtering, and will be implemented on the system.

When rejecting a measurement in a 'normal' EKF, the corresponding rows of H and rows and columns of R must be excluded from the Kalman gain calculation, error covariance update, as well as the state-vector update.

Innovation Sequence Monitoring:

By comparing the average measurement innovation over a period against the expected standard deviation, slowly-building discrepancies between the measurements and the state estimates can be detected. A threshold can be set theoretically, but should be set by testing.

If discrepancies are detected, it may be recoverable by doing the same steps as for Innovation Filtering, but in the worst case, the filter has deviated too much and must be rejected entirely.

Mach-delay

A 'Mach-delay' has been implemented. This is a timer who makes sure that the recovery cannot be activated before a defined amount of seconds. This is a For Stetind it was until 18 seconds after launch, as apogee was expected around T+40 sec. This was mainly as a precaution, since the Kalman Filter relied heavily on the barometer data. Analysis afterwards shows this was the a (at-least near) mission critical implementation.

The downsides for implementing such a timer is low. The only bad scenario seen is if a mission fatal RUD (i.e. motor disintegration) happens before timeout, and the rest of the structure can be saved by activating the recovery system. This scenario is very likely to damage other critical systems or throw the Kalman Filter estimations around. Thought has been going into being able to override the timer if i.e. both GPS, accelerometer and barometer agree that the altitude is decreasing. This might be implemented, but is not prioritized due to complexity (i.e. how to measure downwards acceleration after a RUD tips the vehicle rapidly?).

In-flight restart

Due to past experience with Stetind and the added complexity of RTOS this year, the possibility and consequences of restarting the navigation system in-flight must be considered. Restart can happen both on task-level (soft restart) and on system-level (hard restart).

Restarting mid-flight is a quite complex task for the filter. For a full filter restart, the right initial values must be found. These can either be gotten from the saved flight data or using the sensors that measure absolute value. That is the GNSS, barometer and magnetometer.

System after apogee

After apogee and rocket separation, the nose including the avionics system will point downwards. This could create somewhat erroneous sensor fusion, especially regarding IMUs and the system model. Measures will be taken to cope with it.

Testing and validation

To be sure the system works as intended, testing and validation is essential. This is done using Stetind's, flight data, simulations and other rocket launches. The data from the Stetind flight is used to understand the expected flight dynamics, as Birkeland will have a similar flight profile. Since the sensor suite and microcontroller has changed from Stetind, a smaller scale rocket launch to 1600 meters has been done at Andøya Space Center to gather data for simulation with relevant sensors. More validation will be done with several small rocket launches to 400 meters with the same sensor suite. Combined, this is seen as enough to fly the system on Birkeland.

Acknowledgments

The team thanks our mentors for feedback and guidance throughout the project.

External mentors: Mariusz Eivind Grøtte at the Department of Engineering Cybernetics, NTNU, Arve Tokheim at 4Test Instruments, Vegard Melvær at Byåsen High School, Rune Hummen at Swagelok and Jarle Øye at Nammo. Alumni mentors: Hannah Laugaland, Rannveig Marie Færgestad, Sheikha Al-Nasser, Andreas Fanebust, Erik Fjeldstrøm Trydal, Svein Jostein Husa, Kristian Hope.

References

- [1] AGY. "advanced materials", zentron 758 glass fiber datasheet, page 16, Cited May 13th 2022.
- [2] AZOMATERIALS. Properties: S-glass fibre.
- [3] BURKERT. Fluid calculator (kv value), Cited May 13th 2022.
- [4] CUP, S. A. Intercollegiate rocket engineering competition design, test, evaluation guide.
- [5] CUP, S. A. Intercollegiate rocket engineering competition rules requirements document.
- [6] DRUGLI, E. *Flight state estimation using Multiplicative Extended Kalman Filter*, Master Thesis. NTNU (Unpublished), July 2022.
- [7] ENGINESEDGE. Bolt or pin in single shear equation and calculator.
- [8] ENGINESEDGE. External metric thread table chart and fastener sizes m1.6 - m18.
- [9] ENGINESEDGE. Shear pin/screw calculations.
- [10] EOS. Polyamide 12 for 3d printing, Cited May 13th 2022.
- [11] FRUITYCHUTES. Fruitychute website, Cited March 3rd 2021.
- [12] GROVES, P. *Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems, Second Edition*, 2 ed. Artech, 03 2013.
- [13] HARTMANN, E. A. *Observations: Atmosphere and Surface*, 1 ed. Cambridge University Press, 2013.
- [14] HEXCEL. Hexply 8552 carbon prepreg datasheet, Cited May 13th 2022.
- [15] JOHNSON, D. Table of absorptivity and emissivity of common materials and coatings, Cited April 15th 2021.
- [16] MARKLEY, F. L. *Multiplicative Versus Additive Filtering for Spacecraft Attitude Determination*. NASA's Goddard Space Flight Center, 2013.
- [17] MATWEB.COM. Aluminum 6082-t6, Cited May 13th 2022.
- [18] NEUTRIUM. Cv versus orifice size, Cited May 13th 2022.
- [19] SHEET, T. D. Uf3369 tcr resin system, Cited May 13th 2022.
- [20] SHITZER, A. Convective heat transfer coefficients vs. wind speed, Cited April 15th 2021.
- [21] SOLA, J. *Quaternion kinematics for the error-state Kalman filter*. arXiv preprint, 2017.
- [22] STRUCTURES, AND NETHERLANDS, M. D. E. N. T. *ESA PSS-03-203 Issue one "Structural materials handbook"*, 1 ed. ESA publication division, 1994.
- [23] TOOLBOX, E. Air - specific heat at constant pressure and varying temperature.
- [24] TOOLBOX, E. Convective heat transfer.
- [25] TORAYCA. Torayca "t700s datasheet", Cited May 13th 2022.
- [26] WIKIPEDIA. Van der waals constants (data page), Cited April 10rd 2021.
- [27] WIKIPEDIA. Adaptive step size, Cited April 12th 2021.
- [28] WIKIPEDIA. Bogacki–shampine method, Cited April 12th 2021.
- [29] WIKIPEDIA. International standard atmosphere, Cited April 29th 2021.
- [30] WIKIPEDIA. Nose cone design, Cited May 13th 2022.
- [31] WILLIAMS, N. R. The calculation of air density in various units. 319–320.

