Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

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TVAC testing, redesign, and assembly of a 6U CubeSat payload

Master's thesis in Mechanical Engineering
Supervisor: Bjørg Margrethe Granly
Co-supervisor: Marie Bøe Henriksen
June 2023

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Abstract

The HYPSO-2 satellite will be the second satellite launched as a part of the HYPerspectral Smallsat for Ocean Observation (HYPSO) mission at the Norwegian University of Science and Technology (NTNU). HYPSO-2 aims to improve the Hyperspectral Imager (HSI) payload to observe algal blooms in the ocean at a greater quality than HYPSO-1. The first goal of this project was to perform environmental tests on the Engineering Qualification Model (EQM) of the payload to ensure the payload could handle the conditions of space and launch. The second goal was to construct the Flight Model (FM) of the payload that is to be launched into orbit in the fall of 2024. The EQM was tested for shock and vibrations at Forsvarets forskningsinstitutt (FFI) Kjeller and tested in a thermal vacuum chamber at NTNU, where the latter is the focus of this thesis. A small spectral shift was found in the HSI after Thermal Vacuum Chamber (TVAC) testing. The spectral shift was not viewed as a major issue, and a similar shift was present for HYPSO-1. No harmful outgassing occurred, which was a concern prior to testing. The HSI payload FM was constructed without any major issues. Calibration and quality measurements indicate an improvement in the focus of spectrograms from HYPSO-1. The onboard processing unit, PicoBoB, has not yet been assembled due to a delay in components. This will be constructed during the summer of 2023 before the payload is sent to NanoAvionics in Lithuania, which is responsible for providing the satellite bus and integrating the payload into the bus.

Sammendrag

HYPSO-2 vil bli den andre satellitten som sendes opp som en del av HYPerspectral Smallsat for Ocean Observation (HYPSO) prosjektet ved Norges teknisk-naturvitenskapelige universitet (NTNU). HYPSO-2 skal forsøke å forbedre Hyperspectral Imager (HSI)-nyttelasten for å observere algeoppblomstringer i havet i en høyere kvalitet enn HYPSO-1. Det første målet med dette prosjektet var å utføre miljøtester på testmodellen av nyttelasten for å sikre at den kunne håndtere forholdene i rommet og kreftene under oppskyting. Det andre målet var å bygge Flight Model (FM) av nyttelasten som skal skytes opp i bane høsten 2024. Testmodellen ble testet for støt og vibrasjoner ved Forsvarets forskningsinstitutt (FFI) Kjeller, og testet i et termisk vakuumkammer ved NTNU. Testene i det termiske vakuumkammeret vil være ha hovedfokus i denne masteroppgaven. En liten spektral forskyvning ble funnet i HSIen etter Thermal Vacuum Chamber (TVAC)-testing. Dette ble ikke ansett som et stort problem, da en lignende forskyvning var tilstede for HYPSO-1. Ingen skadelig utgassing fant sted, noe som ble fryktet at kunne oppstå før testing. FM for HSI-nyttelasten ble konstruert uten store problemer. Kalibrering og kvalitetsmålinger indikerer en forbedring i fokus på spektrogrammene fra HYPSO-1. Prosesseringsenheten, PicoBoB, har ennå ikke blitt satt sammen på grunn av en forsinkelse i levering av komponenter. Denne vil bli konstruert før nyttelasten sendes til NanoAvionics i Litauen, som er ansvarlig for å levere satellittbussen og montere nyttelasten i bussen.

Preface

This thesis is a part of the HYPerspectral Smallsat for Ocean Observation (HYPSO) project and is a continuation of the work performed during the specialization project, Heggelund and Håland [1]. During the specialization project, a new model for the HSI payload was developed and manufactured. This model is an iteration of the design for the HYPSO-1 satellite. During the master's thesis, the model has been further developed and tested. A Flight Model (FM) of the payload has been manufactured and assembled. The FM will be sent to the satellite bus provider and eventually launched into orbit. Sections in chapter 2 and chapter 3 are based on the specialization project.

Despite my lack of previous experience in mechanical development for space applications, I was able to use insights gained from courses in mechanics, machine parts, and product development in my work on the payload. However, most of the knowledge needed for the design of the satellite payload has been acquired through communication with HYPSO team members and by reading reports and papers on the subject.

Over the course of the semester, extensive work has been performed to prepare a flight-ready model of the payload before my departure from the project. Some of this work, although necessary, fell outside the scope of this master's thesis. The Appendixes B, C, F, H, I, and the reference HYPSO-team [2] present parts of this work.

I would like to thank my supervisor Bjørg Margrethe Granly for guidance in writing, my co-supervisor Marie Bøe Henriksen for information regarding the optics of the payload, and for providing analysis on test results and calibrations. Further, I would like to thank Roger Birkeland and Amund Gjersvik for advising and supporting with software and electrical competence. Finally, thanks to my collaborator on the specialization project and co-member of the HYPSO mechanical team, Simen Eger Heggelund.

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Acronyms

AMOS	Autonomous Marine Operations and Systems.
ASVs	Autonomous Surface Vehicles.
AUVs	Autonomous Underwater Vehicles.
CAD	Computer-Aided Design.
COTS	Commercial Off-the-Shelf.
CP	Characterisation Point.
CVCM	Collected Volatile Condensable Material.
DUT	Devive Under Testing.
EDM	Electrical Discharge Machining.
EQM	Engineering Qualification Model.
ESA	European Space Agency.
ESCC	European Space Components Coordination.
ESD	Electro-Static Discharge.
FAA	Federal Aviation Administration.
FFI	Forsvarets forskningsinstitutt.
FM	Flight Model.
HABs	Harmful Algae Blooms.
HSI	Hyperspectral Imager.
HYPSO	HYPerspectral Smallsat for Ocean Observation.
IDE	integrated development environment.
IR	Infrared Radiation.
LEO	Low Earth Orbit.
NASA	National Aeronautics and Space Administration.
NTNU	Norwegian University of Science and Technology.
QM	Qualifying Model.
QTH	Quartz Tungsten Halogen.
RGB	Red, Green and Blue.
SDR	Software-Defined Radio.
TML	Total Mass Loss.
TVAC	Thermal Vacuum Chamber.
UAVs	Unmanned Aerial Vehicles.
UV	ultra violet.

1 Introduction

The HYPerspectral Smallsat for Ocean Observation (HYPSO) mission is a part of the larger Autonomous Marine Operations and Systems (AMOS) project. HYPSO uses satellite technology to contribute to ocean research [3][4]. The first HYPSO satellite was launched in 2021. The satellite had some minor issues but was an overall success and the first operating satellite to be successfully launched by the Norwegian University of Science and Technology (NTNU). HYPSO-1 is still in operation and will hopefully continue to work for the next three years. HYPSO-2 is the second generation of this satellite and aims to improve the issues of its predecessor. It is planned to launch near the end of 2024. This chapter will introduce the motivation behind this thesis and present the objectives for the work performed.

1.1 Background

The increase of Harmful Algae Blooms (HABs) in the last century has become a prominent global concern [5]. The issue is of particular significance in countries like Norway where fish is a major part of their export. HABs has caused major losses to Norwegian fish farms in the past [6]. Thus, constant ocean monitoring for early detection of such events can aid in minimizing their impacts and provide useful information to enhance the understanding of algae blooms.

As a part of the AMOS project, several autonomous vehicles are employed to observe the ocean. Among these are Autonomous Underwater Vehicles (AUVs), Autonomous Surface Vehicles (ASVs), and Unmanned Aerial Vehicles (UAVs). Figure 1 shows the observation pyramid of the project, which observes targets with different spatial, temporal, and spectral resolutions [7]. The HYPSO mission provides the top of this pyramid and the possibility for continuous monitoring without the need for deployment.

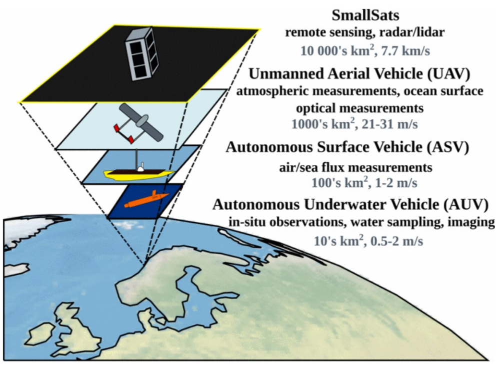


Figure 1: Observation pyramid. From [7].

The main component of the satellite is the Hyperspectral Imager (HSI), which enables the satellite to take hyperspectral images of the surface of the earth. A normal Red, Green and Blue (RGB) camera can only capture the intensity of three wavelengths on the electromagnetic spectrum. The HSI can capture information from hundreds of narrow bands on the visible spectrum. This enables vastly more data to be extracted from one image and can provide us with information that normal images can not.

The HSI is mounted on a platform alongside an RGB camera used for georeferencing. The captures are processed on the central processing unit called the PicoBoB. The HSI, RGB, PicoBoB, and a Software-Defined Radio (SDR) radio makes up the payload developed at NTNU. The satellite bus is provided by NanoAvionics, housed in Lithuania, which also aids in the development of the payload.

The HYPSO-2 satellite aims to fix the issues found on the previous satellite and to continue providing useful data for ocean research.

1.2 Scope of the master thesis

During the specialization project leading up to this thesis, a new design was made of the HSI payload for HYPSO-2. An Engineering Qualification Model (EQM) of the payload was developed according to European Space Components Coordination (ESCC) by The European Space Agency (ESA)[8], and Cubesat standards developed by California Polytechnic State University [9]. The design is strongly based on the Flight Model (FM) for HYPSO 1, incorporating a new RGB camera and a new circuit board called ALICE, for the PicoBoB.

Over the course of this thesis, environmental tests were conducted on the EQM to ensure the payload can handle the harsh space environment and conditions during launch. Several tests were conducted, however, the main focus of the thesis will be on the Thermal Vacuum Chamber (TVAC) test. Throughout this test, the payload was subjected to a high vacuum over varying temperatures, replicating the climate of space.

Following the environmental tests, the FM was designed, manufactured, and assembled. The FM is the model intended for launch, and it is therefore important to take caution during assembly and correct issues found during environmental testing.

All of the work is conducted in cooperation with Simen Eger Heggelund, the other member of the HYPSO mechanical team, who's master thesis will focus on the shock and vibration testing of the satellite [10].

1.3 Thesis structure

The master thesis is composed of seven sections:

Section 2 provides an overview of the space environment where the satellite will operate, along with a presentation of the HYPSO-2 payload and a brief description of the environmental tests required.

Section 3 outlines the methodologies and tools employed in thesis.

Section 4 presents the TVAC test as well as changes made to the payload design.

Section 5 documents the manufacturing, assembly, and calibration of the FM.

Section 6 discusses the project outcomes, confront the challenges faced, and debates the results from environmental tests.

Section 7 provides a conclusion to the thesis and describes the future of the HYPSO project.

Appendix A contains the datasheet for the epoxy used on screws.

Appendix B contains the shock and vibrations test report.

Appendix C contains the assembly report for the EQM.

Appendix D contains a list of the HYPSO-2 Payload parts.

Appendix E contains the risk analysis done by identifying and analyzing risks that may arise during the project.

Appendix F contains the vacuum test report of the RGB.

Appendix G contains the report for making temperature profiles in the Nanovac vacuum chamber.

Appendix H contains the TVAC test report.

Appendix I contains the assembly and calibration report for the FM.

2 Theory

A cube satellite is a small satellite made up of $10\times10\times10$ cm cubic units. HYPSO-2 is a 6U cube satellite, meaning it is made up of 6 cubic units.

When designing components for a cube satellite it is important to understand the factors that will affect the components during orbit and launch. This chapter provides a theoretical background on these factors and a description of the HYPSO-2 payload. The chapter also describes the theory regarding the tests conducted on the satellite. Parts of Section 2.1, Section 2.7, Section 2.8, Section 2.9, and Section 2.10 have been repurposed from the specialization project leading up to this thesis [1].

2.1 Space Environment

The following challenges are listed by the Federal Aviation Administration (FAA) as difficulties when designing a spacecraft aimed to operate in space[11]:

- *The gravitational environment causes some fluid containment problems but also provides opportunities for manufacturing.*
- *Earth's atmosphere affects a spacecraft, even in orbit.*
- *The vacuum in space above the atmosphere gives spacecraft another challenge.*
- *Natural and man-made objects in space pose collision hazards.*
- *Radiation and charged particles from the Sun and the rest of the universe can severely damage unprotected spacecraft.*

The following sections will discuss the challenges most relevant to the HYPSO satellite.

2.1.1 Launch to Orbit

The vibration and acoustic environment to which the payload will be subjected are impacted by the operation of the launch vehicle's main engines and the aerodynamic buffeting experienced as it rises through the Earth's lower atmosphere. Because of the aerodynamic excitation, the vibration is at its highest intensity at lift-off and during transonic flight. Shock and vibration tests will be performed to decide if the HYPSO payload can handle the anticipated shock and vibration loads experienced from a Falcon 9 launch and during flight. This test is discussed further in Section 2.11.1

2.1.2 Gravity

Gravity is one of the four fundamental interactions of nature and is a natural phenomenon by which physical masses are attracted to each other. HYPSO-1 orbits around 500km above the Earth's surface, and by using:

$$g = \frac{GM}{R^2} \tag{1}$$

and the fact that:

M (Earth's mass) is $85.972 \cdot 10^{24} kg$,
G (Universal gravitational constant) is $6.674 \cdot 10^{-11} m^3 kg^{-1} s^{-2}$,
R (The distance from the center of Earth to the satellite) is $6871 km$,

results in a gravitational field strength(g) of $88.44 m/s^2$. This is approximately 86% of standard gravity. However, the satellite is essentially in a state of continuous free fall, creating a condition of weightlessness. Therefore, it is important to securely fasten screws and components to avoid the possibility of parts becoming loose and possibly damaging vital instruments.

2.1.3 Radiation

In Low Earth Orbit (LEO), the primary contributor to radiative heat is solar radiation. Another notable source of radiation is Earth's albedo, meaning solar radiation reflected off the Earth's atmosphere or surface. The most intense radiation occurs within the Van Allen radiation belts. The inner belt extends up to 10,000 km above ground level and is primarily concentrated around 300 km and 1,000 km above the Earth. Primarily, the belt consists of protons with energies around 100 MeV [12].

Radiation poses several potential risks to the HYPSO satellite. For instance, heating on the satellite's surfaces can lead to surface material degradation or damage to the electronic components housed within the satellite bus. Therefore, the selection of appropriate coatings for the materials is important.

2.1.4 Outgassing

Outgassing occurs when gas molecules get released from the surface of materials such as polymers and even metals due to low pressure. A significant concern for HYPSO is the potential condensation on the lenses due to outgassing.

The Total Mass Loss (TML) and Collected Volatile Condensable Material (CVCM) are the two primary measurements used to estimate outgassing. National Aeronautics and Space Administration (NASA) has defined a set of requirements for spacecraft materials, stating that the maximum values for TML and CVCM should be 1.00% and 0.10%, respectively [13]. When using Commercial Off-the-Shelf (COTS) parts, it is important to ensure all components comply with the standards of NASA. These requirements were also taken into account when selecting materials and coatings for the payload.

During the development of HYPSO-1, the team encountered issues related to outgassing in the HSI objectives. This problem arose because the COTS lenses from Edmund Optics had grease on their internal seals to easier adjust the focus of the lenses. The grease caused major outgassing during vacuum chamber testing. A combination of microscope images taken of one of these lenses after vacuum testing is presented in Figure 2. Thorough cleaning of all internal parts of the objectives solved this issue [14].

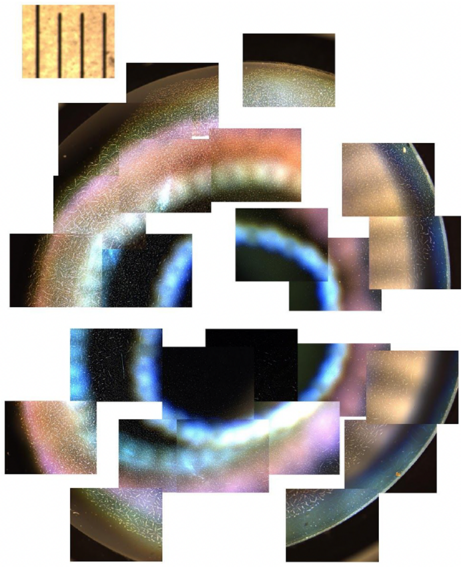


Figure 2: Damage to HSI lens caused by outgassing. Image compiled by the HYPSO-team using multiple photos taken through a microscope.

2.1.5 Atomic Oxygen

Atomic oxygen (O_1) and helium (He) are the predominant elements in the LEO atmosphere, as depicted in Figure 3. Data from NASA indicates that atomic oxygen accounts for approximately 96% of the LEO atmosphere [15]. Atomic oxygen is produced when oxygen molecules split due to intense ultraviolet radiation from the sun [16].

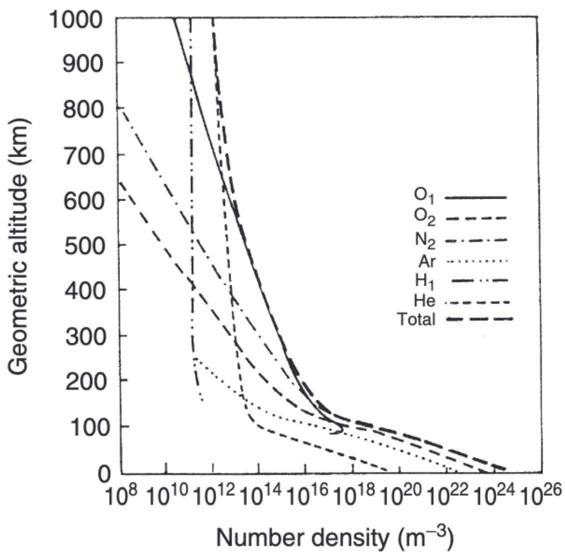


Figure 3: The figure shows that most of the atmospheric species at 500 km altitude is atomic oxygen(O_1). From [17].

Based on findings from NASA's third space shuttle mission, STS-3, it was noted that atomic oxygen atoms at an altitude of 272 km moved at a relative speed of about 8 km/s compared to the spacecraft [17][18]. This interaction between atomic oxygen atoms and satellite surfaces can lead to erosion, resulting in material loss and oxidation of exposed materials. Such effects can reduce the performance of the satellite, decrease its lifespan, and increase failure risk. Consequently, all the aluminum parts on the HSI payload will be anodized to protect against the slow erosion caused by atomic oxygen.

2.1.6 Cold Welding

In space, cold welding is a phenomenon where two metal surfaces permanently bond together when they come into contact within a vacuum environment. This is due to the absence of an atmospheric protective layer that typically forms on a metal surface through a reaction with atmospheric oxygen on Earth, preventing metal pieces from joining. However, this oxide layer can be eroded in space. If there's a significant force or a substantial impact, two metal pieces can merge, allowing electrons to flow from one metal piece to another. To minimize contact adhesion, materials can be coated. A method known as anodizing, which offers a solution to this issue, is discussed in greater detail in Section 2.8.

2.1.7 Tin whiskers

Tin whiskers present a significant reliability concern to electronics in satellite technology. Tin whiskers are thin, hair-like formations of metal that can sometimes grow from surfaces where tin is used. Although, other metals such as zinc and cadmium can cause the same phenomena.

Tin whiskers typically grow from solder, tin coatings, or other surfaces containing tin. They can grow several millimeters and have in rare cases been observed in lengths over 10mm [19]. The problem arises when these whiskers grow long enough to bridge the gap between two electronic components, causing an electrical short. This can lead to malfunction or even failure of a component.

Despite ongoing research, the growth of tin whiskers is not fully understood and remains a major concern in high-reliability electronics applications. Factors believed to contribute to tin whiskers are residual stress, bending, stretching, scratches, and thermal expansion.

Using a lead-based solder reduces the risk of tin whiskers profoundly. Most industries try to avoid lead due to environmental and health concerns. The aerospace industry has yet to find a reliable replacement for lead-based solder in electronics.

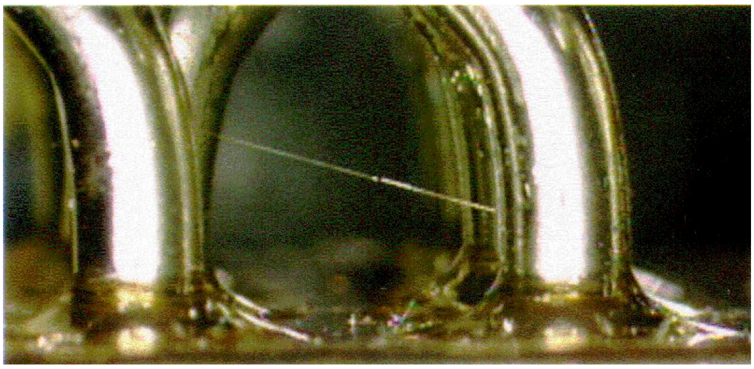


Figure 4: Tin whisker between pure tin-plated hook terminals of an electromagnetic relay [19].

2.1.8 Requirements and Standards

ESA has established standards and guidelines, known as ESCC, to guarantee the safety and reliability of spacecraft and other systems destined for space missions[8]. These standards address various areas such as materials, production, design, engineering, and testing. Furthermore, ESA updates these criteria from time to time to keep up with technological advancements and ensure the highest level of safety and reliability for satellite systems.

California Polytechnic State University has developed a standard for the design of small satellites, with the objective of reducing costs, shortening development time, and broadening space accessibility. This CubeSat Standard is widely adopted by universities, private companies, and governmental agencies worldwide in the development of small satellites [9]. Details on the 6U CubeSat Standard can be found in The CubeSat Program, California Polytechnic State University [9].

2.2 Hyperspectral Imager (HSI)

The primary function of the HSI Payload Subsystem is to capture hyperspectral images to collect data about Earth's surface. This is done by the HSI camera, which records light reflected off Earth's surface across various wavelengths. This data enables researchers to identify and analyze particular features on the Earth, including environmental changes, algae blooms, and more. The optical design is demonstrated in Figure 5.

Light enters through the front lens (L0) with a specific diameter, D, and is then focused through a slit (S). Before the light hits the grating (G), it is collimated(light rays are made parallel) by the collimating lens (L1). Next, the grating (G) diffracts the light into various wavelengths, and the detection lens (L2) focuses the light once more before it reaches the camera sensor[20]. The image data collected by the HSI is referred to as a data cube.

The final optical design on HYPSO-1 is based on Fred Sigernes design HSI V6 [20]. Before settling on the final design, several iterations of the HSI design were explored. As the design evolved, the number of components was reduced to minimize the risk of machining errors and lower the complexity of the instrument.

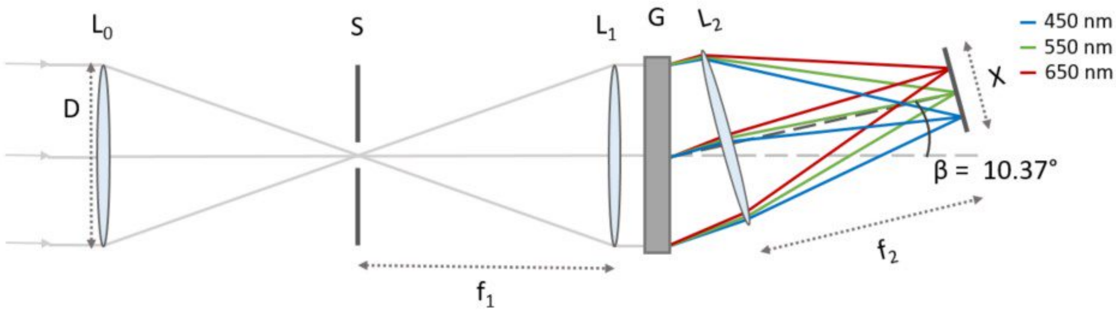


Figure 5: Optical diagram of the HSI. Figure by HYPSO-team.

The camera sensor of the HSI captures different wavelengths and a single spatial dimension. The hyperspectral data cube, a three-dimensional data set processed by the onboard computer when the satellite passes over a surface, has two spatial and one spectral dimension. As discussed in Section 1, the main mission of HYPSO is to detect harmful algal blooms along the Norwegian coast. A case study by Klemas on remote sensing of algal blooms describes how water infested with algae can be identified using data gathered by an HSI [21].

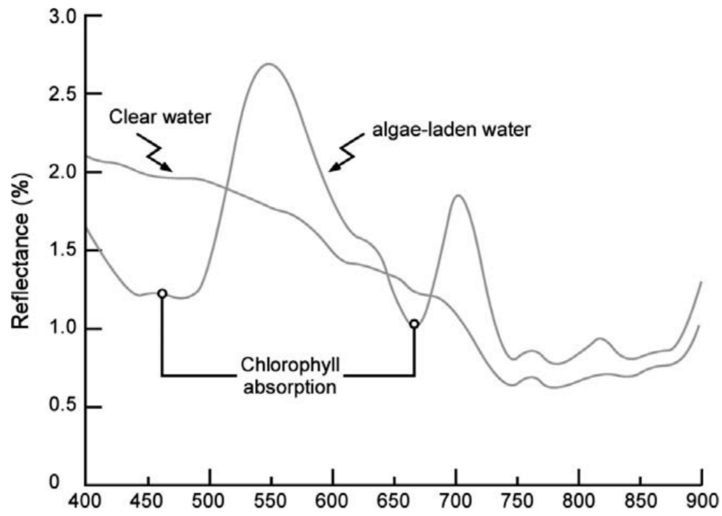


Figure 6: Reflection in clear, algal-filled water. Blue wavelengths are strongly absorbed by chlorophyll. From [21].

2.3 Definition of HYPSO-2 payload

The payload on the HYPSO satellite, which the mechanical team is responsible for, consists mainly of two assemblies:

- Onboard Processing Unit and Break Out Board (PicoBoB)
- The HSI payload with the RGB camera

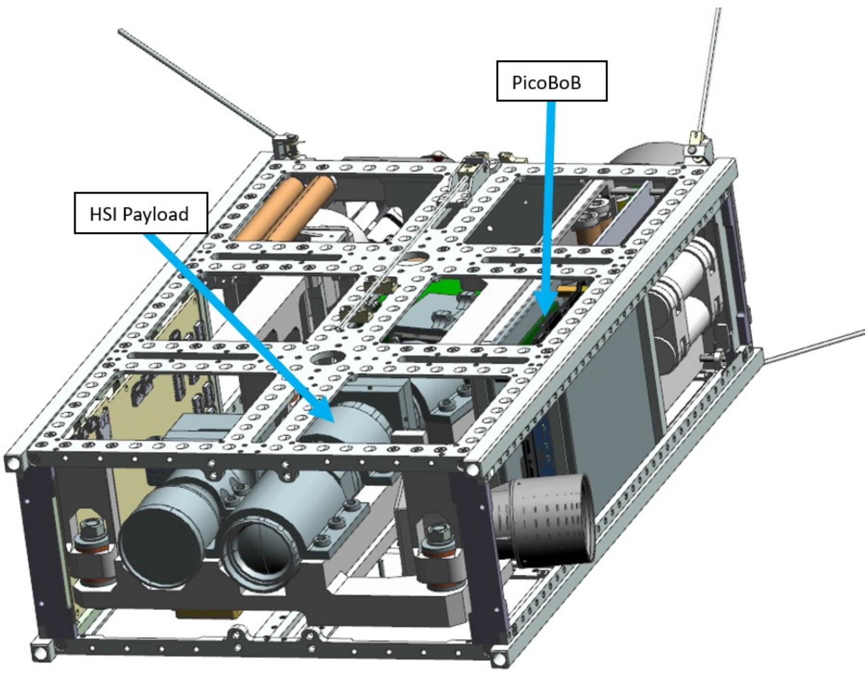


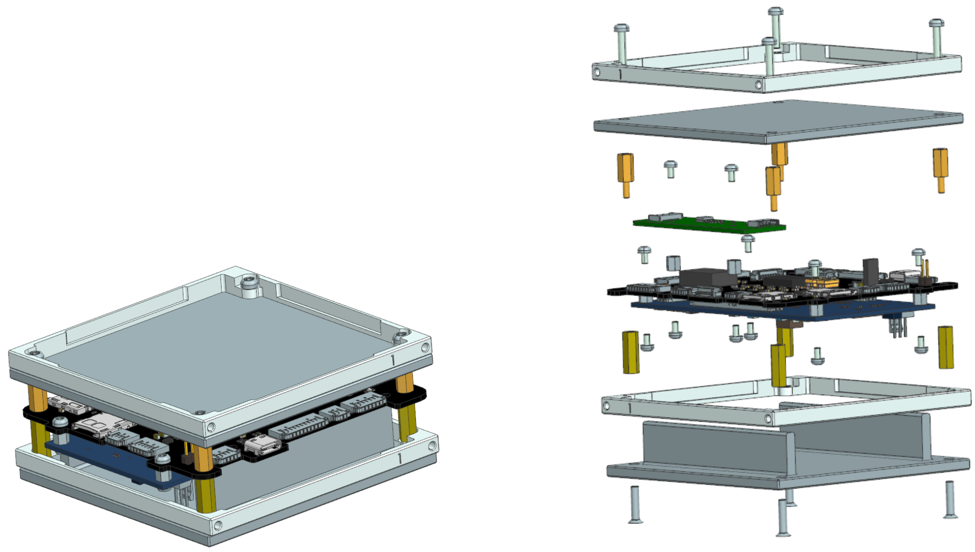
Figure 7: HYPSO-2 Satellite FM. Solar panels removed.

An interface based on dampers was designed to structurally and thermally insulate the payload from the spacecraft, reducing heat transfer and vibrations. The placement of the HSI payload and the PicoBoB in the HYPSO-2 satellite is shown in Figure 7.

2.4 PicoBoB

The PicoBob is the central processing unit of the payload. It enables the capturing and storing of images and spectrograms from the HSI and RGB camera. The PicoBob consists of a COTS Picozed 7030 SOM board and the BoB Circuit board made at NTNU. For HYPSO-2, the circuit board Alice will be added to the PicoBob stack. The purpose of the Alice board is to provide a high-speed connection between the PicoBoB and the payload controller. The payload controller is a component provided by NanoAvionics.

As illustrated in Figure 8, the PicoBoB assembly has two shield plates on both sides. These are included to shield against electromagnetic fields.



(a) PicoBoB assembly

(b) PicoBoB - exploded view

Figure 8: CAD models of the PicoBoB.

2.5 HSI Payload

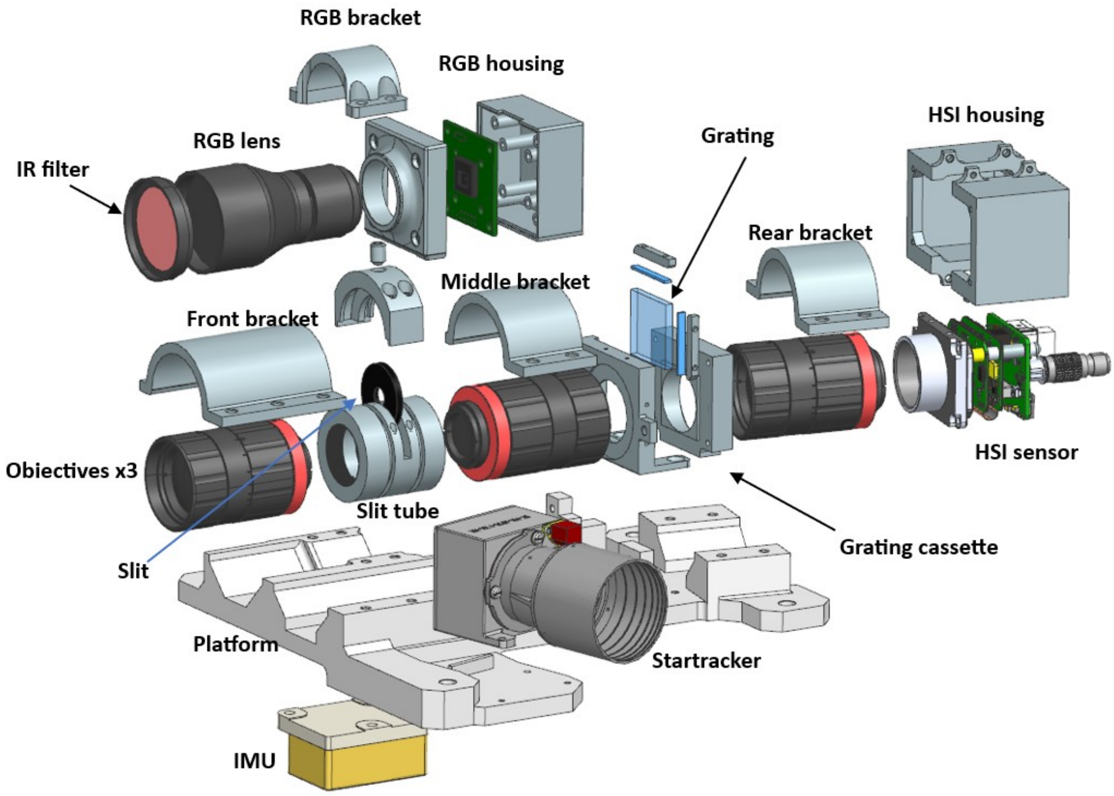


Figure 9: Exploded view of the HYPSO-2 HSI Payload FM with the RGB camera.

The payload of the satellite consists of an HSI and an RGB camera placed on a platform and fastened with brackets. The RGB camera is among other things used for georeferencing. The RGB and HSI are controlled by the onboard processing unit, PicoBoB. The design of the platform and brackets differs between the EQM and the FM. The EQM and FM should preferably have the same design, however, last-minute changes from the satellite bus provider led to alterations. An exploded view of the HYPSO-2 HSI Payload with the RGB camera is shown in Figure 9. A list of all components included in the payload assembly is listed in Section D.

- **Platform:** All of the optics are placed on the payload platform. The platform, therefore, decides the orientation of the optics with regard to each other and the satellite bus.
- **Objectives:** COTS parts provided by Edmund Optics. All of the objectives are of the type 50mm C VIS-NIR Series Fixed Focal Length Lens. The two front objectives have a custom aperture inserted, while the rear objective has no aperture.
- **Brackets:** To ensure the proper alignment and stability of the optical train, it must be securely attached to the surfaces of the grooves in the platform. Therefore, brackets are used to provide the necessary force on the objectives. All the objectives are secured with one bracket each. Kapton tape will be used as gaskets to create a tight seal between the bracket and the objective.

- **Slit tube:** The slit tube houses the slit, which among other things controls the spatial and spectral resolution of the spectrogram. It is important that the slit is oriented vertically and that it does not shift after launch. A bracket design was made by a group of bachelor students to easier adjust the slit, compared to the design from HYPSO-1 [22]. Vibration testing is needed to verify that the slit does not shift in the new slit tube.

- **Grating Cassette:** The grating cassette consists of the grating cassette front, grating cassette back, the grating, grating clamps, and gaskets. The grating disperses light and separates it into its different wavelengths.

- **HSI and RGB housing:** The sensor housing for the HSI and RGB sensors aims to protect them from radiation and enhance their mechanical stability. By reducing external radiation, the sensor housing ensures that the sensors remain accurate and reliable. Additionally, the housing increases the mechanical integrity and enhances the overall durability and longevity of the sensors.

- **HSI Detector:** The HSI detector is a UI-5261SE Rev.4.2 COTS detector provided by IDS.

- **RGB lens:** The lens of the RGB assembly is a 35mm f/4.0, HPi Series Fixed Focal Length Lens lens from Edmund Optics. A different lens was used for HYPSO-1.

- **IR filter:** An IR filter is attached to the front of the RGB lens. This is needed to hinder Infrared Radiation (IR) and ultra violet (UV) radiation that would normally be filtered out by the atmosphere from hitting the RGB detector. The FM for HYPSO-1 lacked an IR filter, rendering the RGB camera practically useless.

- **RGB detector:** The RGB detector is a UI-1492LE COTS part provided by IDS. A different detector was used for HYPSO-1.

- **Startracker:** The Startracker is an important instrument to detect the position of the satellite. The startracker is provided and mounted by the satellite bus provider, NanoAvionics.

- **IMU:** The IMU is an onboard flight computer. It is provided and mounted by NanoAvionics. A shield will be added to protect the IMU. This is not shown in Figure 9, since the model has not yet been provided by NanoAvionics.

2.6 Slew Maneuver

The slew maneuver is performed when the satellite is doing captures with the HSI in orbit. In the context of HYPSO, it refers to rotating the satellite at a constant angular rate during a short period to compensate for the forward motion of the satellite in relation to the Earth. This is performed to scan a specific area of the Earth with the HSI. The slew maneuver makes the HSI gather more detailed information over a smaller area of interest, compared to a scan without the maneuver. The operation is illustrated in Section 2.6.

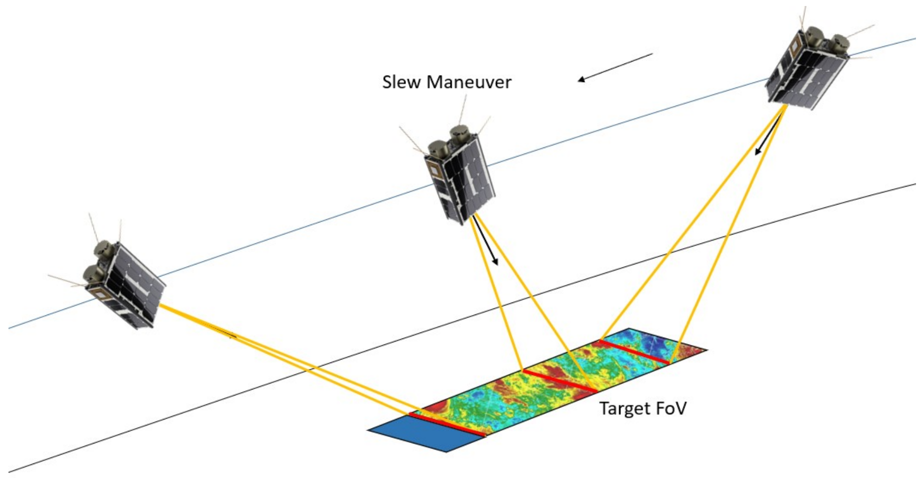


Figure 10: Illustration of a slew maneuver. Figure made by the HYPSO team.

2.7 Materials

The HYPSO team prepared a material analysis report detailing the properties of the materials used in the payload [23]. The report provides insights into the materials' yield strength, durability, and ability to withstand various environmental conditions.

As specified in Requirement 3.2.11 in the 6U CubeSat Design Specification:
"Typically, Aluminum 7075, 6061, 6082, 5005, and/or 5052 are used for both the main CubeSat structure and the rails. If materials other than aluminum are used, the CubeSat Developer should contact the Mission Integrator or dispenser manufacturer"[9].

AA7075 was initially evaluated to be used in the payload. However, due to its higher cost and the fact that aluminum 6000-series are easier to work with during machining, the 6000-series was considered instead. The aluminum 5000-series was not evaluated due to its poor machinability.

Both the AA6082 and AA6061 aluminum share similar yield strength and density. Although, AA6082 has a higher stiffness and thermal conductivity compared to AA6061 [24]. Due to these factors and availability from suppliers, AA6082-T6 was selected [23].

Heat treatment is commonly employed to enhance the strength and hardness of aluminum. The T6 heat treatment process involves heating the aluminum to 500-600°C and then rapidly cooling it with water. This process is known as quenching. After this, the aluminum is artificially aged by heating it for 2-10 hours [25]. The resulting aluminum alloy is often used in applications that require high strength and durability, such as the aerospace industry.

2.8 Anodizing

Light reflecting on the satellite can affect the spectrograms by increasing light pollution, leading to noise in the captures. To reduce this, the entire payload will be anodized black. Only the grating cassette and slit tube were anodized on HYPSO-1.

Anodizing aluminum is an electrochemical process that enhances the thickness of the metal's natural oxide layer. The process involves submerging the aluminum in an acid bath and introducing an electrical current. This layer can be colored by using dyes or other chemicals during the anodizing process. Anodizing Aluminum 6082-T6, which is used in the HSI payload, provides the alloy with a protective layer, increasing its resistance to cold welding [26], corrosion, oxidation, and wear. This is particularly important in space, where the environment is harsh and subject to extreme temperatures. The anodized layer is also resistant to UV radiation, which is crucial for space operations [27]. Anodizing aluminum has several advantages compared to other methods. It is relatively inexpensive and provides a durable protective coating. However, not all aluminum alloys are suitable for anodizing, as it may damage certain alloys. Fortunately, Aluminum 6082-T6 is well-suited for anodizing.

Black anodized aluminum surfaces have a solar absorptance to emissivity ratio near 1.0, allowing for passive thermal control of the equipment [27]. The anodization specification for HYPSO-1 is MIL-A-8625 Type II, Class 2 Black.

It is important to note that the anodization process can add up to $20\mu m$ to the thickness of parts and slightly roughen surfaces. Nevertheless, experiences from HYPSO-1 indicate that the anodization process does not seem to cause any problems. Even for critical parts requiring a high precision tolerance such as the slit tube and platform [20].

2.9 Torque and Epoxy

It is very important to make sure fasteners, such as bolts and objective mounts, remain tight vibrations from launch and do not loosen. As discussed in Section 2.1.2, the satellite will operate in a weightless environment where loose fasteners could potentially lead to damage. To prevent this, 3M Scotch-Weld Epoxy Adhesive 2216 will be utilized to secure the fasteners. According to the datasheet provided by the manufacturer in Appendix A, the epoxy has a TML value of 0.77% and CVCM value of 0.04%. This falls within the requirements for outgassing provided by NASA [28].

NanoAvionics has provided torque values to be used on the payload. These are presented in Table 1 [29].

Screw	**Torque (Nm)**
M2	0.315 (0.4 Max)
M2.5	0.650 (0.9 Max)
M3	1.140 (1.6 Max)
M4	2.600 (2.7 Max)
M6	8.8 (9.5 Max)

Table 1: Torque Values.

It is vital to use compressed air, preferably pressurized nitrogen, to clear and dry each threaded hole to prevent unwanted debris in the threads during assembly.

2.10 Tolerances

During the design and development stages of the HSI assembly for HYPSO-1, various machining methods were employed to achieve a high level of precision. With the lack of specific requirements regarding the spacing of components, a small tolerance grade was implemented. This led to the parts being subjected to a general tolerance of IT10 [20]. Furthermore, stricter tolerances were employed on features critical for the optics, such as the 10.37-degree feature on the HSI depicted in Figure 5. The IT 10 tolerances can be found in Table 2.

Nominal dimensions (mm)		**Limits IT10 (μm)**
Over	Up to	
-	3	40
3	6	48
6	10	58
10	18	70
18	30	84
30	50	100
50	80	120
80	120	140
120	180	160
180	250	185
250	315	210

Table 2: IT 10 Tolerance Table [30].

2.11 Environmental tests

Environmental tests are conducted to ensure the satellite can handle the conditions of launch and orbit. The ESCC has constructed a standard that describes environmental tests that should be performed prior to launch [31]. However, not all of these tests are relevant to CubeSats. The launch provider, which in the case of HYPSO-2 is the Falcon 9 space shuttle from SpaceX, poses the required tests prior to launch. The satellite bus provider, NanoAvionics, is responsible for performing the required tests to ensure that the satellite qualifies for launch. Some tests will, however, be performed on the payload by the HYPSO team, prior to the payload being mounted in the satellite bus. The next subchapters describe the environmental tests that are to be performed by the HYPSO team.

2.11.1 Shock and Vibration testing

During launch, the satellite will be impacted by forces caused by the engines of the rocket, the rocket piercing the atmosphere, and several other factors. These forces have been measured during previous launches and are provided in the Falcon Users guide [32]. Based on this data, the payload will be tested for shock forces, random vibrations, and sine sweeps. The shock and vibration test facility at Forsvarets forskningsinstitutt (FFI) Kjeller was used for this test.

The payload was tested directly on the vibration table and while mounted in the satellite bus mass model. The satellite bus mass model is a mechanical replica of the satellite bus provided by NanoAvionics. Accelerometers were used when testing to detect forces and resonance on specific components of the payload.

2.11.2 Thermal Vacuum testing

In orbit, the satellite will experience significant changes in temperature due to direct radiation from the sun and the lack of temperature-stabilizing convection from the air. To verify that the satellite can withstand such an environment, a TVAC test in a thermal vacuum chamber is necessary.

During launch, the satellite will be exposed to a rapid decrease in pressure. This will lead to outgassing, refer to Section 2.1.4 for further information. High outgassing can cause damage to the instruments of the satellite. TVAC testing, therefore, provide useful data on the levels of outgassing from the satellite.

The test requirements were set based on requirements from the ESCC were the same as for HYPSO-1. The payload was tested in the non-operational temperature range of -30°C to 60°C and in the operational range of -20°C to 50°C. For further information on this, see Appendix H and team [33]. A TVAC test with more detailed requirements will be performed by NanoAvionics when they mount the payload in the satellite bus.

The test was performed with the newly installed Nanovac AB horizontal load test chamber at NTNU, see Figure 11. This chamber can provide a pressure below $1 \cdot 10^{-7}$ mbar and cycle between temperatures of -50°C to 90°C. The TVAC-test for HYPSO-1 was performed at Kongsberg in a similar chamber. The TVAC-test procedure and results are explained in greater detail in section Section 4.2.

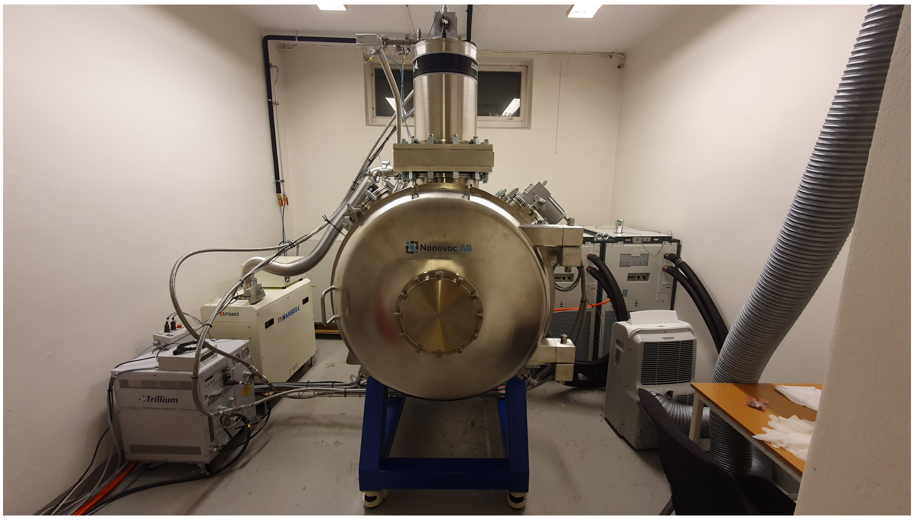


Figure 11: Nanovac thermal vacuum chamber at NTNU.

3 Methods

This chapter explains the methods, tools, and processes used when conducting work on the master's thesis. Parts of this chapter have been repurposed from the specialization project report [1].

3.1 Development Process

Figure 12 shows the requirement process implemented in the HYPSO project. Mission needs, objectives, and requirements are derived from the system requirements. Prototyping and analysis are conducted and verified based on the verification requirements. The resulting components and systems are then assembled into the final product.

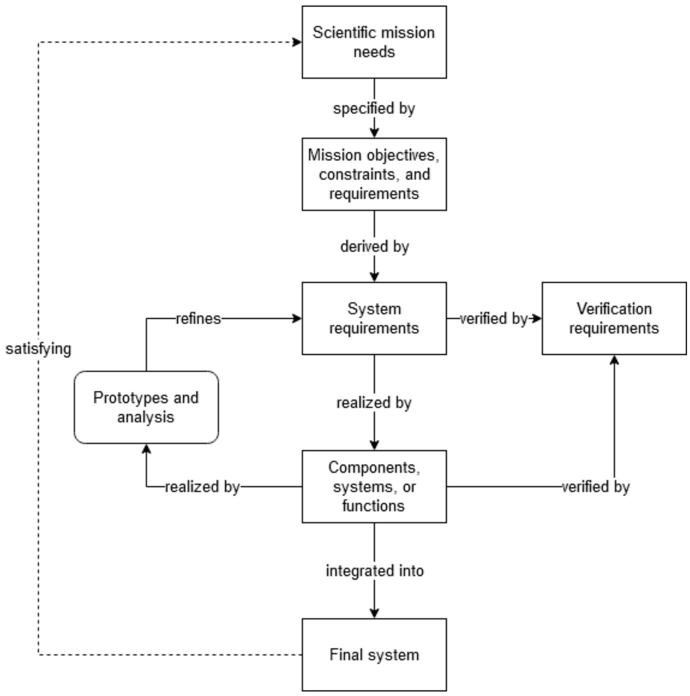


Figure 12: Requirements process. Credit Evelyn Honoré-Livermore[34].

The use of Agile principles in the HYPSO project aid the team with the flexibility to rapidly adjust to alterations in design and requirements. This ensures that the final payload aligns with the requirements of the satellite bus provider, NanoAvionics. Even when certain standards present a specific requirement, NanoAvionics, as the Mission Integrator, may overrule them.

Consistent communication among the mechanical team members and other HYPSO team members has been important. Participating in weekly meetings and shorter status report meetings has been encouraged to keep everyone updated on the progress of the project. It also aids in identifying any potential issues. In Agile product development, a team typically works on prioritized tasks to deliver a functional product or result at the end of the period. This period is called a sprint. Sprints are typically time-boxed, meaning they have a fixed duration, usually a few weeks. This helps the team focus on the most critical tasks and ensures progress. During this project, the weekly meetings functioned as sprint meetings where past and future goals were discussed. A study conducted by Lieberum et al. suggested that participants performed more effectively within time-bound progression compared to flexible progression for a given duration. Projects following flexible progression tended to consume more time during the early phase, which negatively impacted the rest of the project[35].

Agile development promotes collaborative and cross-functional teamwork, a practice that is beneficial for this project, especially considering certain resource constraints. By bringing together team members with diverse skills and expertise, the mechanical team can efficiently utilize the resources at their disposal and tackle challenges from several perspectives.

3.2 Risk analysis

A risk analysis aims to identify potential project risks and develop strategies to minimize and manage those risks. It is important to note that risk analysis is an ongoing process that evolves throughout the project, as new information becomes available and risks change. Thus, it is crucial to regularly review and update the risk analysis to accurately reflect the project's risks. In the case of this project, the risk analysis from the specialization project leading up to this master thesis was reused and altered throughout the semester. A large portion of the risk analysis could be reused due to the similarity of tasks. Sections regarding vibration testing and vacuum chamber testing were added. The latest version of the risk analysis for this project is attached in Appendix E.

3.2.1 Quality Assurance

Quality assurance in this project includes verifying that the machined components align with the specified tolerances. Detailed drawings specifying crucial dimensions were provided to outline the tolerance level required by the machinist. The applicable tolerance is explained further in Section 2.10.

Visits to the workshop were conducted during the manufacturing of parts, primarily to monitor progress and address any issues or concerns raised by the operator. Upon receiving and assembling the components, a digital caliper was used to check the dimensions. A visual inspection was also conducted. These steps form a part of the quality assurance process, ensuring that the manufactured components line up with standards and required measurements.

3.3 Handling, Disassembly, Cleaning, and Assembly

When handling the parts, it is essential to take certain precautions to prevent contamination and reduce the risk of damaging the components due to inappropriate handling. Using gloves and having clean desks should be practiced.

It is also necessary to manage electronic components in a way that eliminates the risk of Electro-Static Discharge (ESD). This is explained further in section Section 3.4.

When disassembled, all parts are rapidly bagged unless they are to be used immediately. Parts are cleaned using non-linting papers and ethanol. For parts that are extra dirty or hard to clean manually, for example greased HSI objective parts, an ultrasonic cleaner is used. An ultrasonic cleaner uses high-frequency sound waves to generate rapidly expanding and collapsing bubbles which in combination with a solvent, cleans parts with high efficiency. The ultrasonic cleaner used at the smallsat lab is shown in Figure 13.

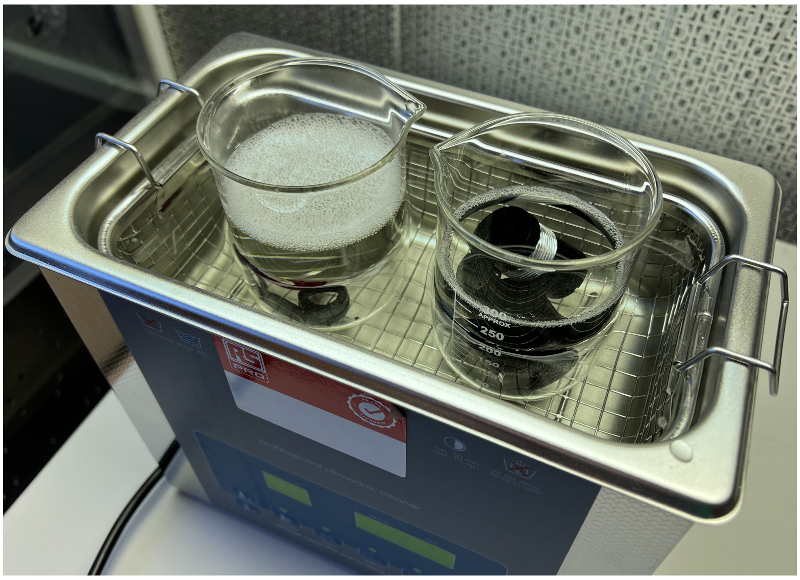


Figure 13: Ultrasonic cleaner at NTNU smallsat lab.

When assembling parts, a torque wrench set to the proper torque is used. This is described further in Section 2.9. The complete procedure for disassembling, cleaning, and reassembling the parts is outlined in "*HSI Objective Disassembly and Cleaning: Flight Model, HYPSO- RP-039*"[14].

3.4 ESD Protection

Some of the components for the HYPSO-2 payload are sensitive electronics. Electrostatic discharge from contact with humans or other charged objects poses a risk of damaging these components. The smallsat lab, where most of the work is conducted, is therefore ESD protected.

Figure 14: Entrance to the smallsat lab

The floor of the lab is connected to ground. Special shoes are worn to ensure conductivity between the body and the floor. ESD-coats are worn to protect against electrostatic fields that can be generated by the user's clothing. Wristbands that are connected to ground through a cable are also worn.

The procedure before entering the lab is to test that the wristband and shoes provide sufficient conductivity.

When handling a sensitive component, the work is conducted on an anti-static mat. The wristband is connected to ground either through the mat or directly via an ESD grounding plug. This procedure is shown in Figure 15. After the component is handled, it is bagged in an anti-static bag and securely stored.

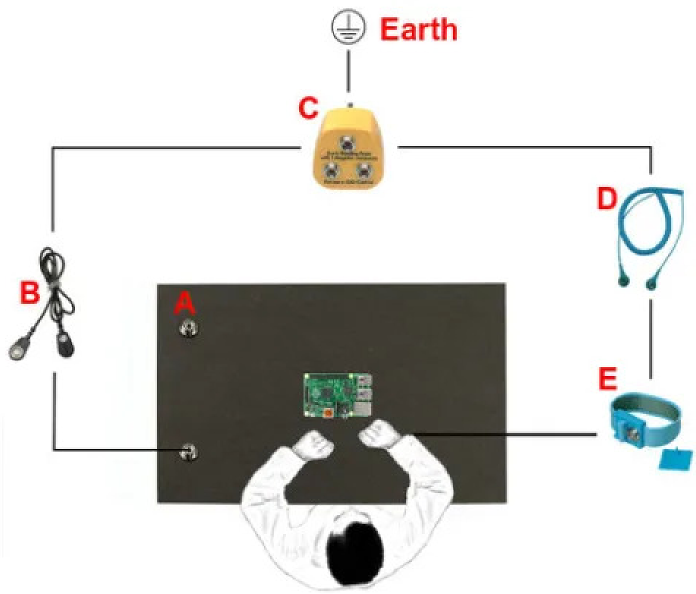


Figure 15: ESD-procedure A: antistatic mat B: ground cable C: grounding plug D: ESD loop E: ESD wristband. From [36].

3.5 Software

This subsection describes the different software utilized during the master thesis.

3.5.1 Siemens NX

Siemens NX was the main Computer-Aided Design (CAD) software used in this project. Developed by Siemens PLM Software, Siemens NX is an advanced CAD tool widely used for 3D modeling, assembly, and analysis. It is commonly used for design, engineering, and manufacturing purposes across diverse sectors such as automotive, aerospace, and industrial automation [37].

3.5.2 Other Software Used

- The mechanical team employed Microsoft Teams as one of the communication platforms. This platform facilitated effective communication and collaboration among team members through features like video conferencing, screen sharing, file sharing, and instant messaging. Most of the communication with NanoAvionics was done in Microsoft Teams, in addition to emails.

- Sharepoint is a collaboration platform that was used for sharing, storing, and managing various documents within the HYPSO team. All pictures taken during the project are stored here as well as backups of the CAD files and internal documents from all departments of the HYPSO team.
- Slack, another collaboration platform, was used by the mechanical team for instant messaging, file sharing, and integration with other tools and services. Slack offers a high degree of customization, such as the creation of separate channels for different topics or teams related to the project. It was used by the mechanical team to communicate, coordinate activities, and share project-related documents and information.
- Visual studio code was used as an integrated development environment (IDE) to write scripts in Python.
- uEye Cockpit was used to capture images with the RGB camera and the HSI sensor. uEye Cockpit allowed for rapid testing when focusing the objectives and constructing the HSI.

3.6 Communication

Effective communication with NanoAvionics, suppliers, FFI, Nanovac, and the mechanical workshop is vital for successful results. To communicate effectively, it is crucial to establish clear lines of communication.

The communication with NanoAvionics was done by Microsoft Teams and email. FFI was contacted through email. The communication with Trondheim Eloksering regarding anodization was done through telephone and email. Edmund Optics was contacted through email. The communication with the mechanical workshop was performed by visiting the shop in person and via email. Most communication with HYPSO members was done through Slack, email, and in person at the smallsat lab.

4 Tests and development

This chapter describes the environmental tests performed on the payload EQM. The TVAC test is described in detail since it is the focus of the thesis. Changes to the payload, resulting in differences between the EQM and FM are presented at the end of the chapter. How these changes affect the results of the environmental tests will be described in Section 6. Figure 16 displays the X, Y, and Z axis of the payload. These axes will be used to describe alterations to the payload.

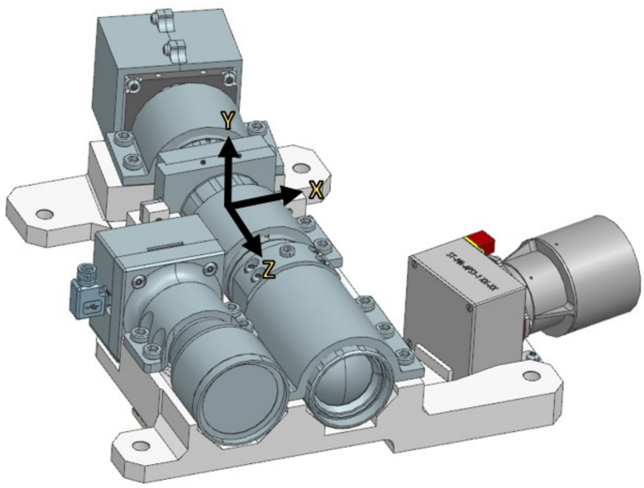


Figure 16: HSI payload FM with X, Y, and Z axis displayed.

4.1 Shock and Vibration testing

As mentioned in 2.11.1, shock and vibration testing is one of the environmental tests required prior to launch. The shock and vibration tests were conducted at the vibration lab at FFI in Kjeller. The payload was tested on a shaker table, both on a custom mounting plate and in the mass model. The mass model is a replicate of the satellite bus provided by NanoAvionics.

No major issues were found from the results of these tests. The results and procedure of the tests conducted at FFI can be found in Section B and will be discussed in greater detail in the master thesis of Simen Eger Heggelund [10].

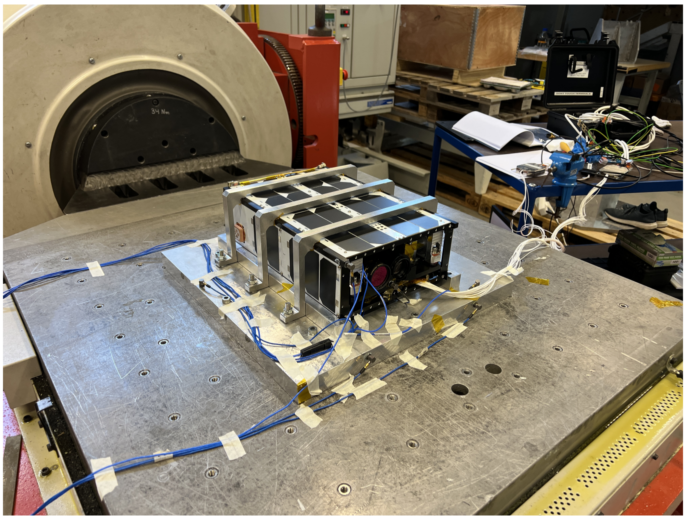


Figure 17: test setup of the HSI payload mounted in the satellite bus mass model.

4.2 Thermal Vacuum testing

As stated in Section 2.11.2, the TVAC-test is an important pre-launch test mandated to ensure the payload is capable of enduring the variable temperatures present in the thermosphere, as well as the thermal and pressure conditions encountered during launch. Furthermore, the test will evaluate the potential occurrence of any outgassing harmful to the instruments.

For the payload to pass the TVAC test, it must be subjected to the non-operational temperatures of -30°C to 60°C and capture RGB images and HSI spectrograms in the operational range of 20°C to 50°C. Based on previous tests the payload was expected to handle these temperatures well, and captures were therefore taken at the non-operational ranges as well.

The central focus of the test lies in evaluating the outgassing and performance of newly introduced payload components. Specifically, the evaluation will focus on the RGB lens and sensor, as well as the Alice breadboard of the PicoBoB stack. It is expected that components that are not altered from HYPSO-1 will successfully pass the TVAC-test, given that the payload from HYPSO-1 successfully cleared the TVAC assessment. Additionally, the investigation of spectrogram alterations that may occur when subjecting the HSI to varying temperature conditions is of interest.

The FM and EQM of HYPSO-1 had thermal straps between components to distribute heat. The EQM of HYPSO-2 does not have these straps. By comparing test results from HYPSO-1 and HYPSO-2 it will be decided if the thermal straps are necessary.

All of the TVAC testing is performed on the EQM model of HYPSO-2. It will be discussed in Section 4.2.3 how the changes between the EQM and FM affect the interpretation of the test results.

4.2.1 Bakeout

It is desirable to keep the outgassing at a minimum when testing in the TVAC chamber. High levels of outgassing can permanently reduce the efficiency of the chamber. All components are therefore thoroughly cleaned prior to testing. The cleaning is done with either ethanol or with an ultrasonic cleaner, see Section 3.3 for further information. After cleaning, a bakeout is performed. During a bakeout, the components are placed in a vacuum chamber where high amounts of outgassing can be allowed, see Figure 18. This vacuum chamber can provide a pressure below $1 \cdot 10^{-5}$ mbar. Heating pads are used to increase the temperature which leads to higher levels of outgassing. The heating pads were kept at a temperature of 50°C during the bakeout of the HSI payload and at 80°C for the PicoBoB. For further information on this, see [38]. A bakeout test will usually indicate if the component's levels of outgassing are too high.

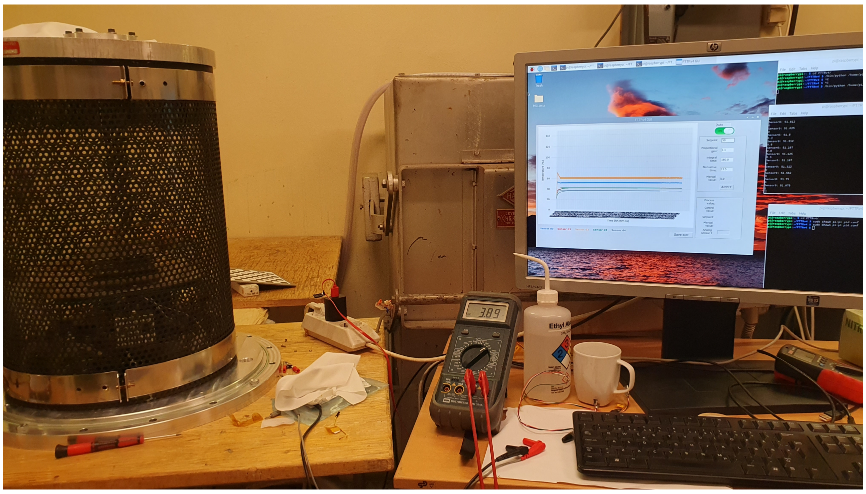


Figure 18: The image shows the test setup when performing a bakeout. Vacuum chamber on the left side of the image and telemetry readings from a Raspberry Pi on the PC screen.

To assess the outgassing of components, weighing components prior to and after the bakeout is performed. As stated in Section 2.1.4, each component can not have a higher TML than 1.00%.

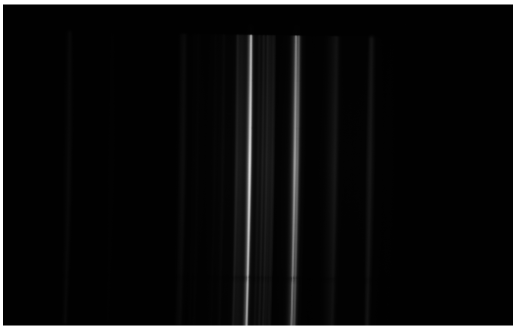
A separate bakeout of the RGB assembly was performed prior to the bakeout of the whole payload. This was performed to assess if the RGB-lens needed to be cleaned internally, as was the case with the HSI objectives, see Figure 2. The bakeout was also a test to assess the functionality of the RGB in a vacuum. Appendix F contains the report from the first vacuum test of the RGB, as well as a more thorough description of the bakeout procedure.

Measuring any change in the weight of the components was not possible. The weight used could measure at a sensitivity of 0.5 grams. The RGB-camera has a weight of 179 grams, therefore, the TML was under 1.00%. After the bakeout, the chamber's interior walls were cleaned, and the cleaning cloth's discoloration suggested that some outgassing had occurred. Additionally, the pressure increased when the heating pads were activated, eventually decreasing over time, which further indicated outgassing. The increase in pressure with temperature is expected and not viewed as an issue. Following the bakeout, the HSI and RGB objectives were examined under a microscope. No damage was observed. Figure 19 and Figure 20 present captures taken with the RGB and HSI before and after the bakeout, with no noticeable difference in performance.

(a) **Pre**

(b) **Post**

Figure 19: RGB captures before and after the bakeout. Exposure time 15ms.



(a) **Pre**

(b) **Post**

Figure 20: HSI captures before and after the bakeout. Exposure time 300ms.

4.2.2 Setup

The TVAC-test was conducted at the newly installed Nanovac AB thermal vacuum chamber at NTNU. The chamber can provide a high vacuum with a pressure below $1 \cdot 10^{-7}$ mbar. A dry vacuum pump provides the initial reduction in pressure. To achieve a higher vacuum, a cryogenic pump is initiated at a pressure of around $1 \cdot 10^{-5}$ mbar. The cryogenic pump works by removing gases and vapors at extremely low temperatures. The interior of a cryogenic pump has a sponge-like texture causing a large surface area where adsorption of molecules can occur. For the pump to function properly, it needs to keep a temperature of around 10K (-263°C). To achieve this, liquid helium is used to cool the pump. A helium compressor is therefore present by the chamber.

The Devive Under Testing (DUT) that is to be tested in the chamber is mounted on the 600×600mm table plate in the chamber. The table plate is surrounded by the shroud. Both the table and the shroud are temperature controlled and can vary between -50°C to 90°C depending on the user input. More extreme temperatures could be achieved by using another type of coolant for the chamber.

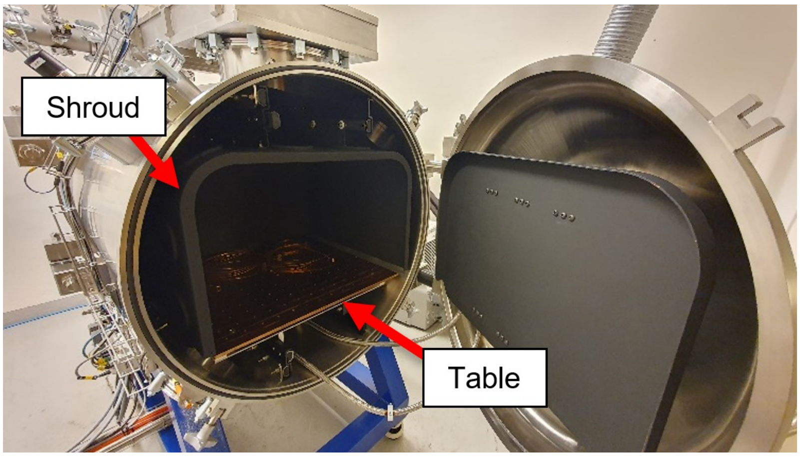
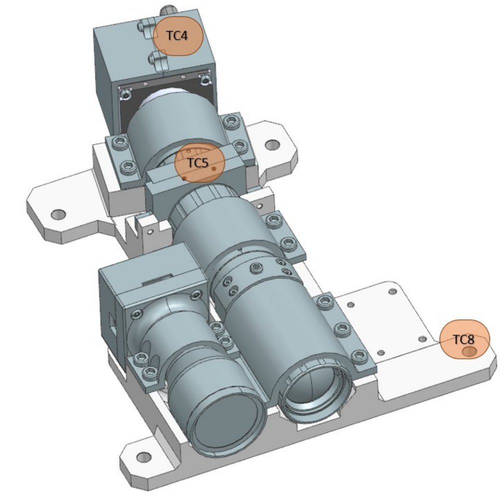


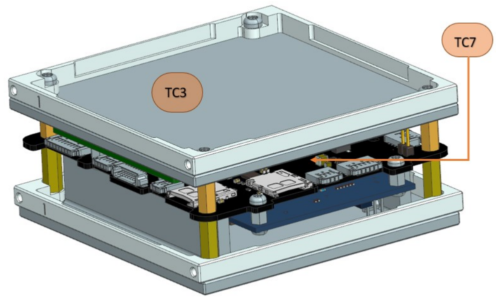
Figure 21: Image showing the shroud and table of the vacuum chamber.

To ensure precise temperature control within the chamber, thermocouples were employed. The chamber houses a total of eight thermocouples, two of which are permanently fixed to the shroud and table. The remaining thermocouples can be positioned at desired locations to measure temperatures accordingly. The Nanovac AB software facilitates the assignment of thermocouples to either the DUT, shroud, or table. The temperature readings obtained from the thermocouples play a crucial role in regulating the temperatures of the chamber. These readings are utilized to maintain the desired temperature, as determined within the software settings. It is important to establish proper contact between the thermocouples and the surfaces they are placed on. Inadequate contact can lead to the temperature overshooting within the chamber, as it takes longer for the thermocouples to obtain the intended temperature.

The arrangement of the thermocouples is depicted in Figure 22. Initially, there were plans to include more sensor placements on the DUT. However, during chamber testing, it was determined that an extra thermocouple on the table was necessary to effectively regulate the temperature of the chamber. Consequently, fewer sensors were allocated to the Payload. For the PicoBoB, one thermocouple was positioned on the top shielding plate, while another was placed on the 5V regulator. Due to suboptimal connections with the 5V regulator, this sensor was not utilized in the temperature regulation of the DUT. As illustrated in Figure 22 and Figure 23, the measurements for the sensors placed on the EQM of HYPSO-2 can be directly compared to sensors 1,3,5, and 6 from the TVAC test results for HYPSO-1.

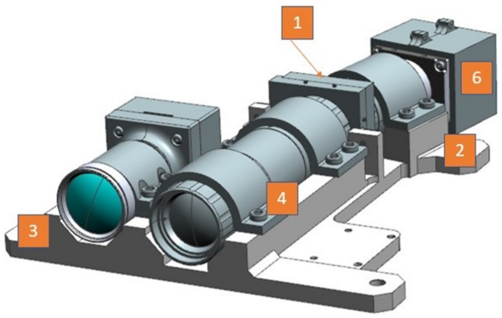


(a) Sensor placements on the HSI payload

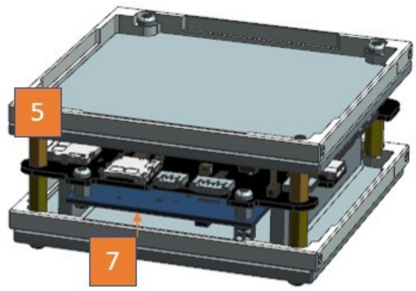


(b) Sensor placements on the PicoBoB

Figure 22: Sensor placements for the TVAC test of the EQM of HYPSO-2.



(a) Sensor placements on the HSI payload



(b) Sensor placements on the PicoBoB

Figure 23: Sensor placements for the TVAC test of the QM of HYPSO-1. From [33].

A temperature profile was developed using Nanovac AB software, outlining the specific temperatures the chamber should maintain over a designated time period. The profile is based on the profile from HYPSO-1, which accounts for both the non-operational and operational extremes associated with the HSI payload [33]. Detailed information on how to create a profile and the parameters involved can be found in Appendix G.

Whenever the chamber achieved its target temperature, a Python script was run to capture images with the RGB and HSI, and to save information about the temperature of the HSI sensor and upload time of the PicoBoB. This is referred to as a Characterisation Point (CP) and serves to verify the proper functioning of the payload and provide data for post-test analysis. Figure 24 illustrates the temperature profile, including the CPs.

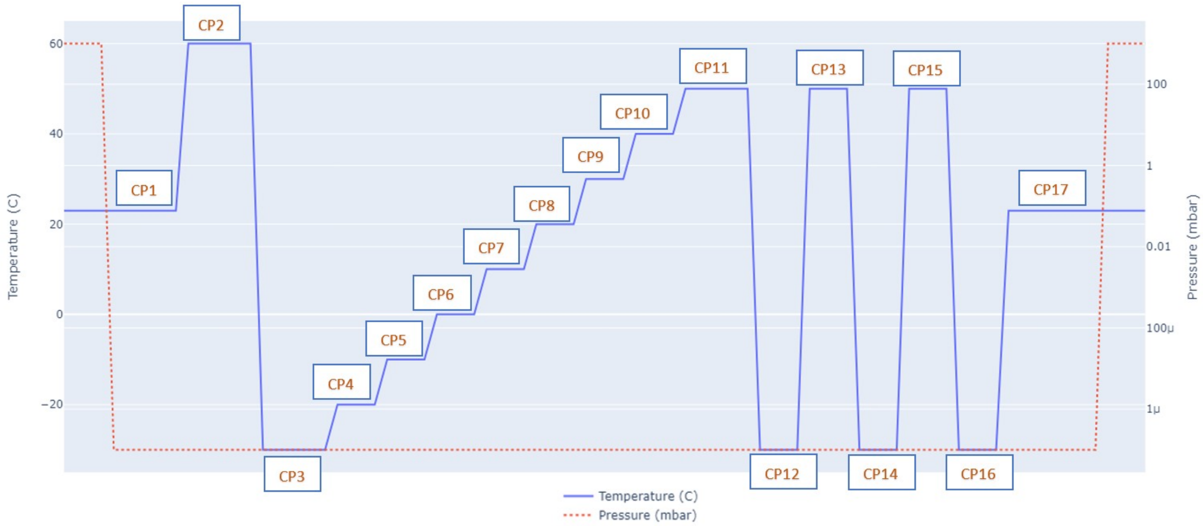
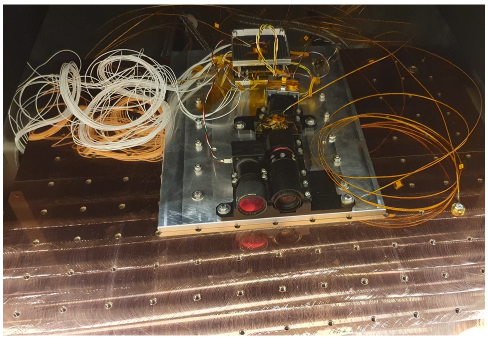
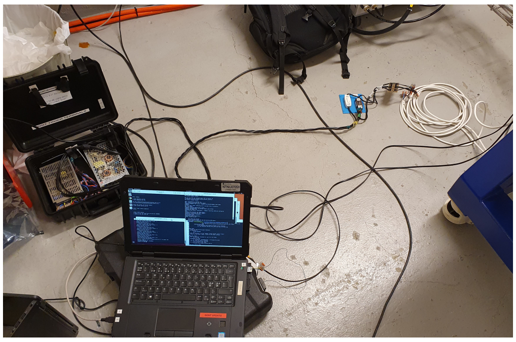


Figure 24: Graph illustrating the planned temperature profile for the TVAC test.

For the electrical setup of the payload, the HSI and RGB were connected directly to the PicoBoB. From the PicoBoB there are two umbilical cord cables connected to the power supply and field laptop through an air-tight adapter in the chamber. It is important that the power supply and field laptop are connected to a common ground. The field laptop was used to capture images with the payload. The power supply provides energy to the payload and offers the capability to independently switch off power to the HSI and RGB.



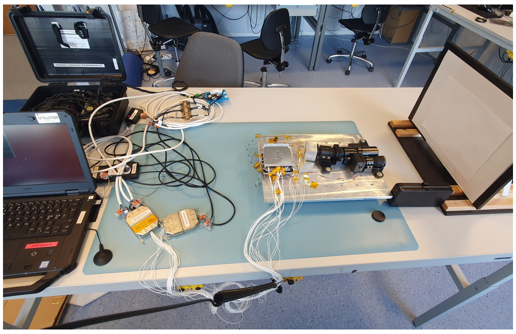
(a) Payload in the chamber with thermocouples



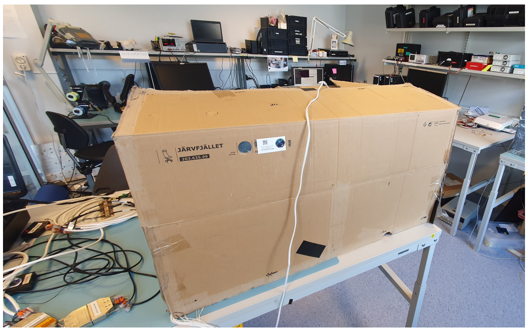
(b) Field laptop and power supply

Figure 25: Mechanical and electrical setup.

Validation images were taken using a Python test script prior to and after each of the TVAC tests. For the test without a window, the validation was performed by pointing the HSI and RGB toward a sheet of white paper. A box was placed over the setup to block out unwanted light and a fluorescent lamp was mounted on the inside of the box. Figure 26 displays this setup.



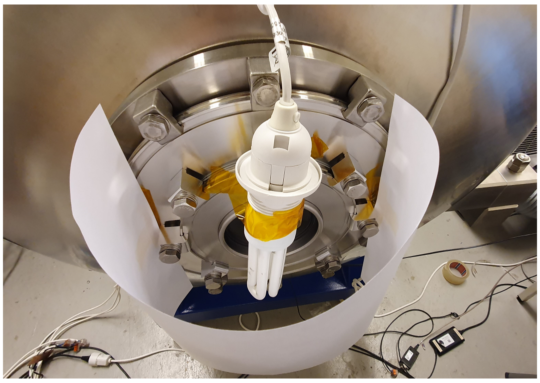
(a) Validation test setup without the box



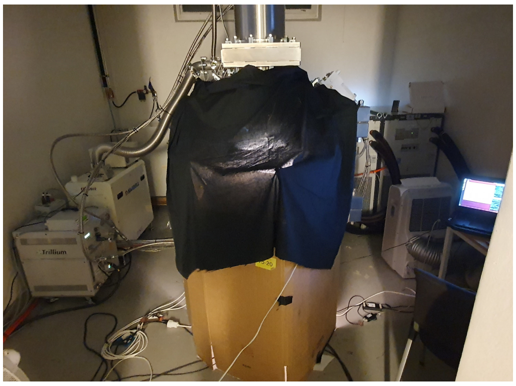
(b) Validation test setup with the box

Figure 26: Validation test setup for the TVAC test with no window.

The validation of the TVAC test involving the window was carried out while the payload was installed in the chamber, prior to activating the vacuum. A fluorescent lamp was positioned right in front of the window, while a combination of a cardboard box, paper, and a black cloth was employed to obstruct external light. The same setup was used when taking captures at CPs during the test itself. Figure 27 illustrates this setup.



(a) Fluorescent lamp placed in front of the window



(b) Cardboard box and cloth employed to block outside light

Figure 27: Validation test setup for the TVAC test with a window.

After validation, the vacuum was turned on. The temperature profile was initiated when the chamber reached high vacuum. After the test was performed and all data had been collected, a new validation was performed. The EQM was then bagged to prevent it from getting contaminated or dirty.

4.2.3 Results

Measured temperature profiles

The Nanovac AB software generates a CSV file containing the measured temperature and pressure data when a temperature cycle is executed. Figure 28 and Figure 29 display the measured temperature profiles from the two TVAC tests, along with a pressure reading. Refer to Figure 22 for sensor placements on the payload.

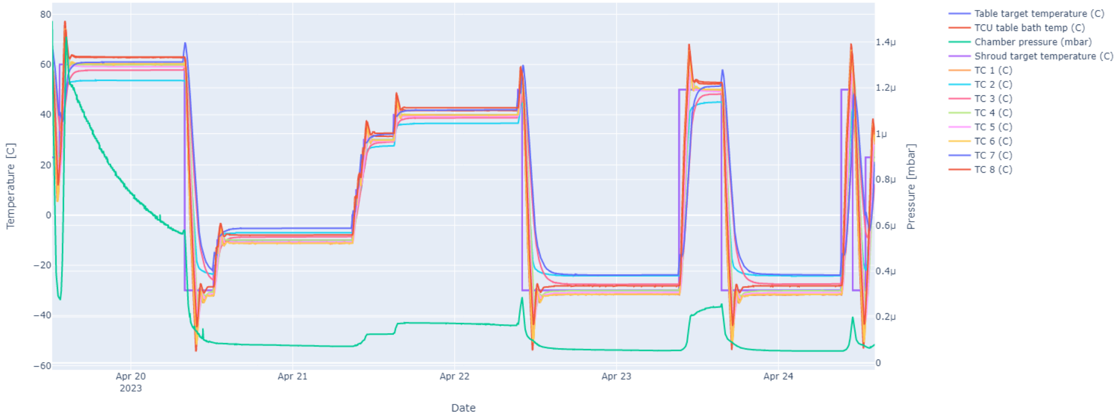


Figure 28: Measured temperature profiles for the TVAC window test.

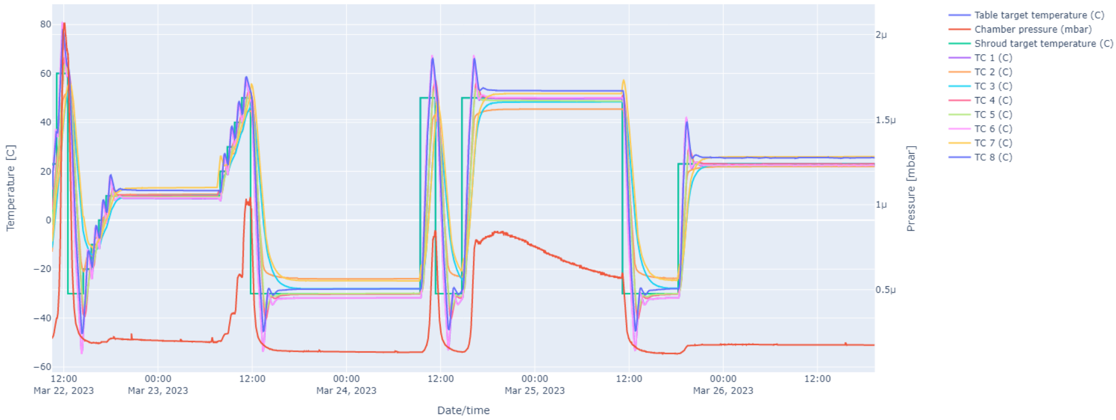


Figure 29: Measured temperature profiles for the TVAC no-window test.

It can be observed that the temperature of some components rises when a CP is performed. The most significant increase is seen in the sensor on the 5V regulator of the PicoBoB. The sensor on the HSI housing also experiences a temperature increase, although not as significant.

When executing the Python script, telemetry readings are provided, which include the temperature of the HSI sensor before and after capturing spectrograms. Based on these readings, it is expected that the HSI housing undergoes a temperature increase. The telemetry readings can be found in the EQM TVAC report of HYSPO-2 in Appendix D. Figure 30 illustrates the temperature elevation of the PicoBoB and HSI at CP2.

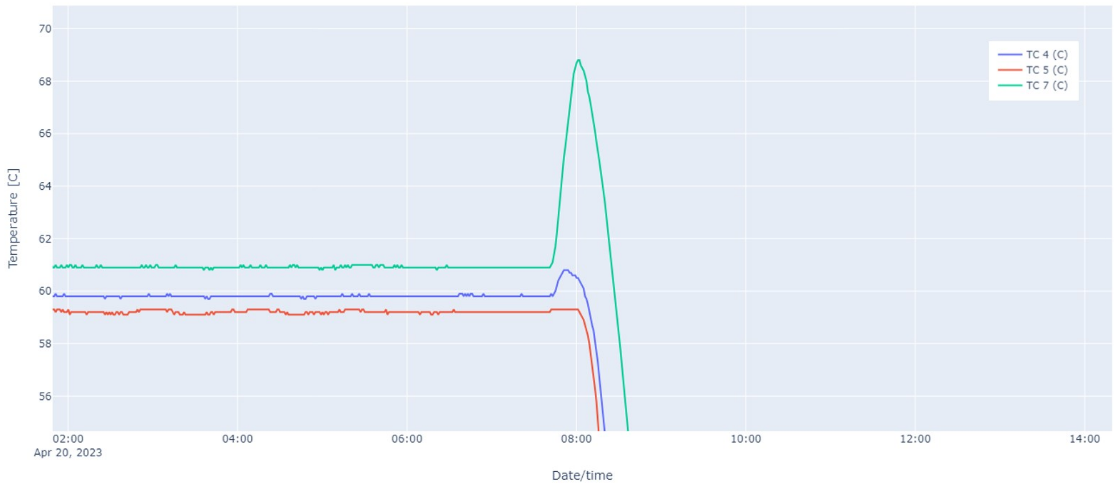


Figure 30: Closeup of temperature measurements at CP2 for the window test. TC4: HSI housing, TC5: Grating cassette, TC7: 5V regulator PicoBoB.

When comparing the pressure readings with temperature fluctuations, it appears that some outgassing is taking place. The pressure rises when the temperature is high. The temperature increase is more noticeable in the first TVAC test, suggesting that most of the outgassing might have occurred during this test, which is expected. It is possible that some substances did not outgas during the bakeout due to the weaker vacuum provided by the chamber used for the bakeout.

Another indication of outgassing can be observed at CP2 of the TVAC window test. In this case, the pressure significantly increases at the beginning and then gradually decreases while the temperature remains stable. Figure 31 and Figure 32 display the pressure and temperature of the chamber for both of the TVAC tests.

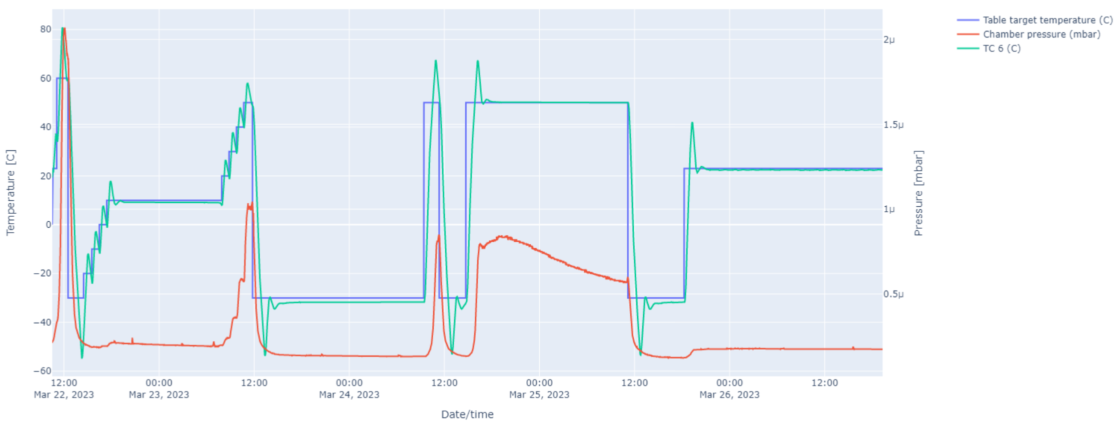


Figure 31: Readings from the TVAC no-window test. Table target temperature represents the planned temperature profile, TC6 is the temperature of the chamber.

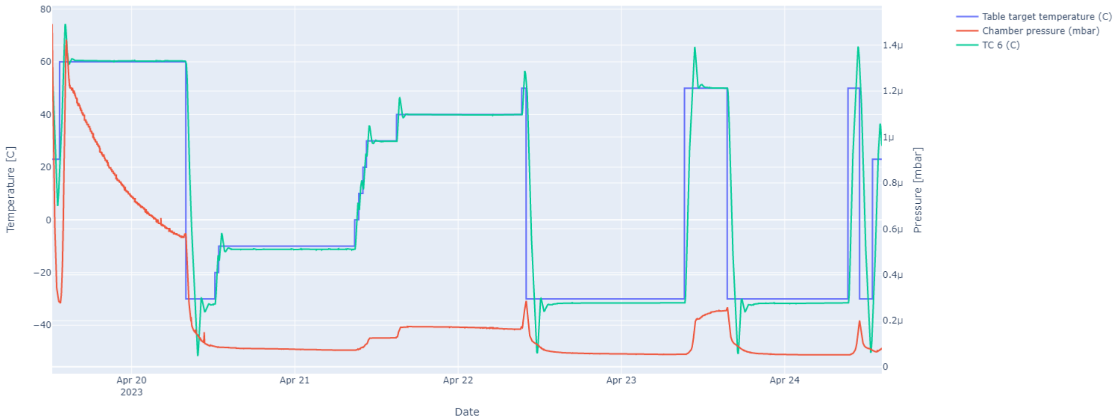


Figure 32: Readings from the TVAC window test. Table target temperature represents the planned temperature profile, TC6 is the temperature of the chamber.

CP results - HSI spectrograms - no window

During the TVAC test without a window, no light source was present inside the chamber, resulting in dark spectrograms for all captures. These captures can be utilized to identify noise at varying temperatures. For each CP performed, five spectrograms were obtained. Figure 33 displays histograms that illustrate the distribution of pixel intensity in the spectrograms. Each histogram contains data from all spectrograms within a specific CP. The x-axis represents the intensity measured in counts, with higher counts signifying brighter pixels. The y-axis, on a logarithmic scale, shows the number of pixels with a particular count. The plots reveal that values at -30°C (cold case), tend to be centered around 20-30 counts, while higher counts appear at increased temperatures.

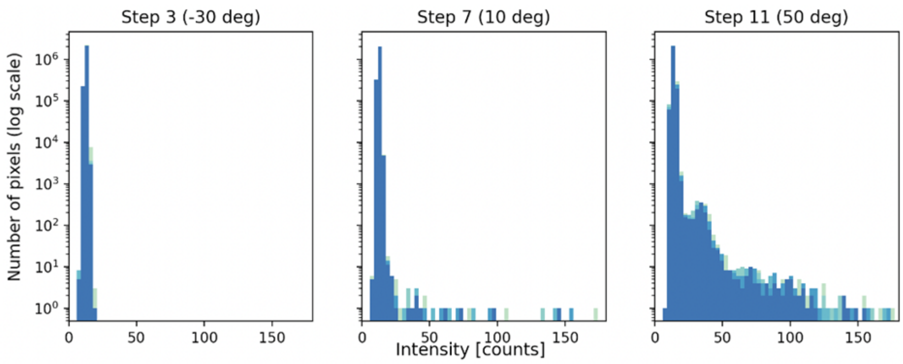


Figure 33: Histograms generated from captures taken at CP3 (-30°C), CP7 (10°C) and CP11 (50°C). From TVAC report in Appendix H.

As the captures are obtained in a dark room, an ideal capture without noise should exhibit the lowest possible values. It can therefore be concluded that higher temperatures result in increased noise. This is further confirmed when comparing all cold cases and warm cases, as depicted in Figure 34. It should be noted that an increase in noise with temperature is common for camera sensors.

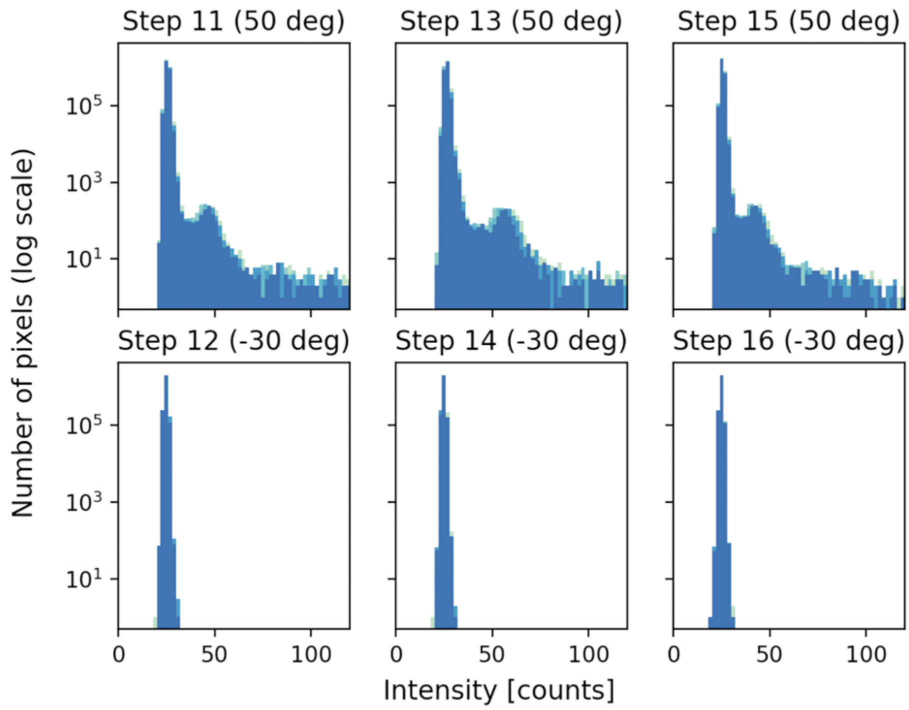


Figure 34: Histograms generated from captures taken at CP11, CP13 and CP15 (50°C), and for CP12, CP14 and CP16 (-30°C). From TVAC report in Appendix H.

CP results - HSI spectrograms - window

During the TVAC test with a fluorescent lamp shining through the window of the chamber, it was challenging to introduce sufficient light into the chamber. Despite positioning the fluorescent lamp directly in front of the window and setting the HSI exposure time to its maximum (1000ms), the spectrograms remained relatively dark. Figure 35 is an example of a spectrogram captured during the test. Fortunately, these spectrograms contained enough data for the HYPSO team to conduct their analysis.

Figure 35: Capture 1 from CP3 of the TVAC window test. The image looks dark, however, it contains sufficient data for analysis.

When comparing the spectrum of the initial and final captures (CP1 and CP17), a spectral shift of approximately 3 pixels or 1 nm is noticeable. The shift could be attributed to the expansion and contraction of materials at different temperatures or a temperature difference when performing captures for CP1 and CP17. The spectrograms for CP1 and CP17 are illustrated in Figure 36, with the plot representing an average of the five captures taken at each CP.

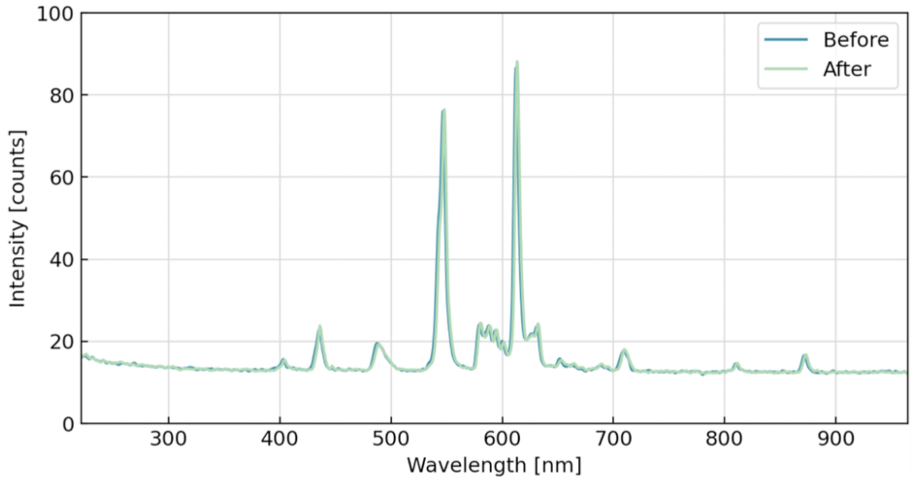


Figure 36: Spectral response of the HSI before (CP1) and after (CP17) the TVAC test. From TVAC report in Appendix H.

The high and narrow peaks of the plot indicate a good focus of the HSI. When plotting the spectrum for all temperatures it becomes evident that the best focus is achieved around 30-40 degrees, as shown in Figure 37. The focus appears to diminish at temperatures above and below this range, which is expected since temperature variations can affect the distance between components.

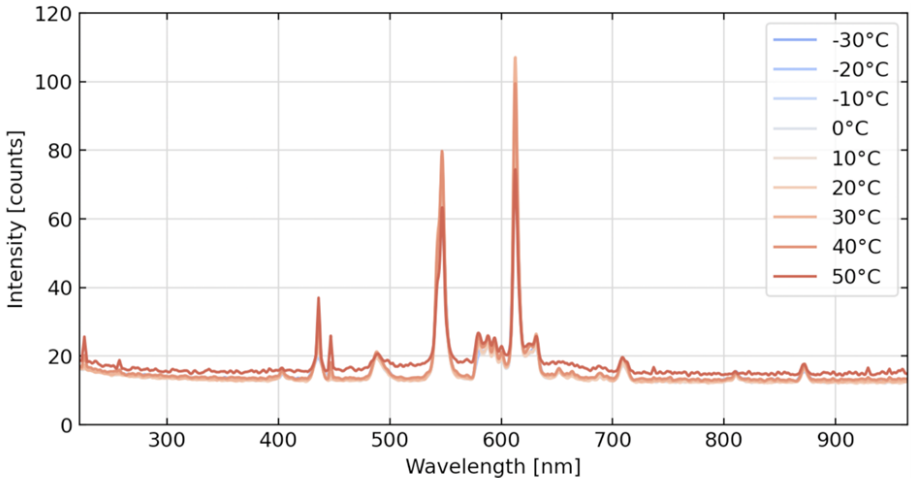


Figure 37: Spectral response categorized in temperatures. From TVAC report in Appendix H.

When comparing all hot and cold cases (-30 °C and 50 °C), it is clear that hot cases exhibit greater variation and increased noise. The noise is signified by the irregular base of the lines in the plot. See Figure 38.

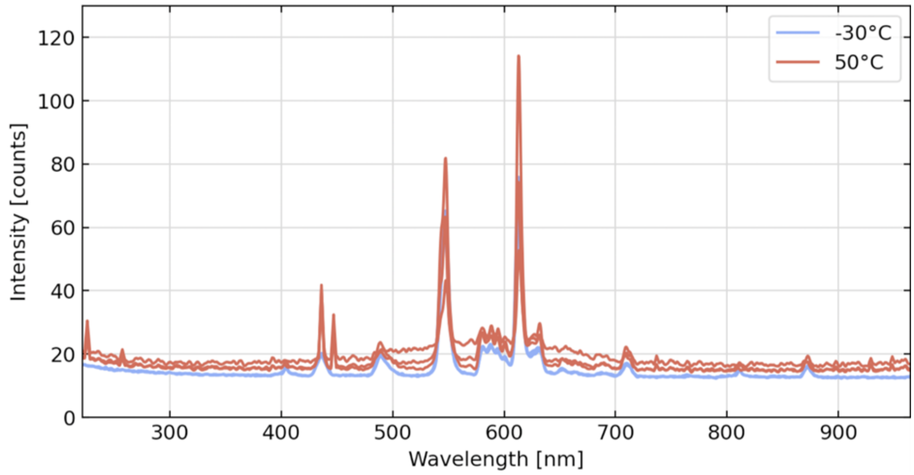


Figure 38: Spectral response for the hot and cold cases. From TVAC report in Appendix H.

The minor spectral shift displayed in Figure 36 is not considered a significant issue. In fact, a similar shift was observed during the TVAC testing of the HYPSO-1 Qualifying Model (QM). As previously mentioned, the increase in noise with rising temperatures is expected and not a major problem.

For the QM and FM of HYPSO-1, thermal straps were used to distribute heat from the payload's hot components, such as the HSI sensor, in an attempt to reduce noise. After it was calculated that the thermal straps conduct very little heat, their use for HYPSO-2 was debated. A comparison of the noise levels between HYPSO-1 and HYPSO-2, as depicted in Figure 39, reveals that the noise levels are fairly similar. As a result, thermal straps will not be employed for HYPSO-2.

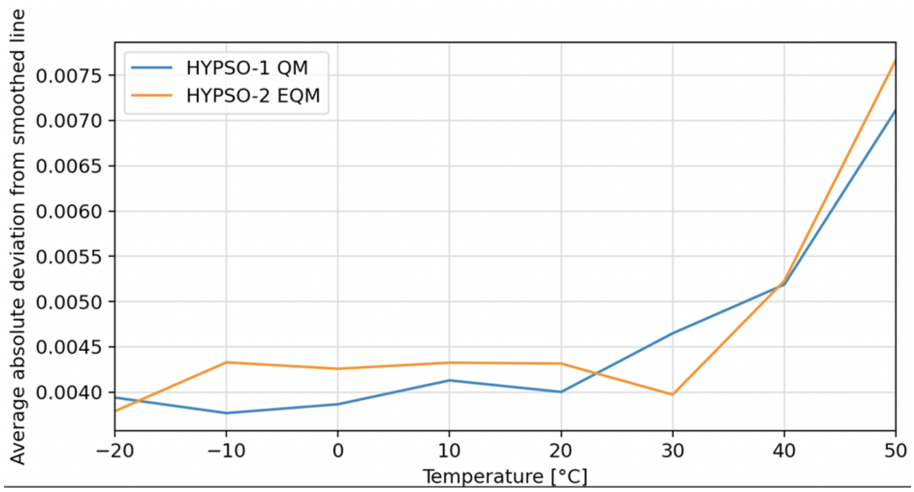
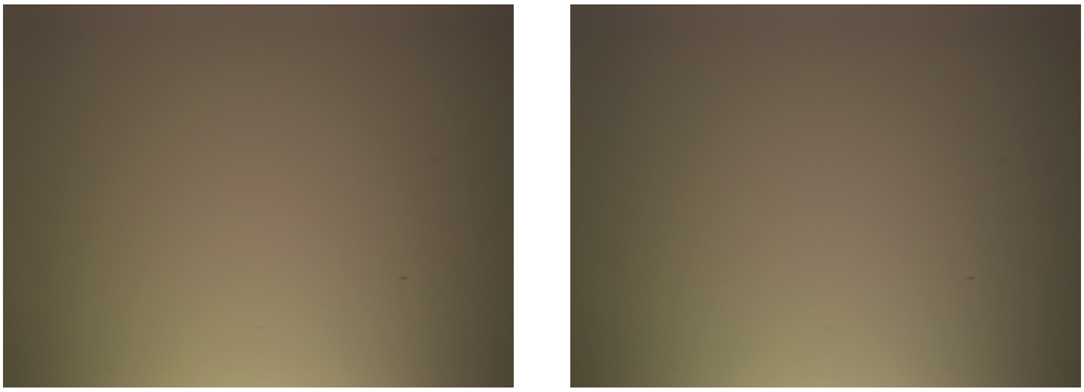


Figure 39: Noise estimations based on deviation from a smoothed spectral response. From TVAC report in Appendix H.

CP results - RGB captures

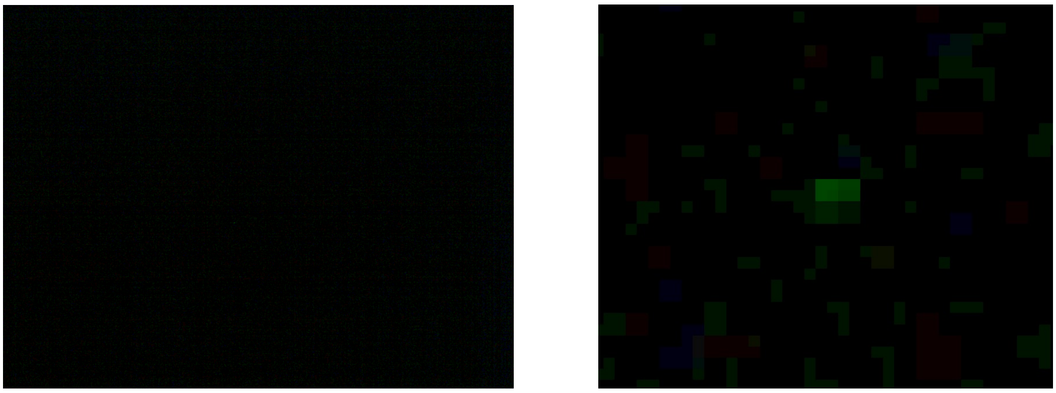
For the RGB camera, no empirical method was used to measure changes in focus or noise during testing. The primary concern of the test was to ensure that no outgassing would damage the lenses of the RGB objective. Fortunately, the validation images taken before and after the test show that no harmful outgassing has occurred. Figure 40 displays the validation images for the TVAC window test. The RGB camera is focused to infinity, so images taken inside the chamber are blurry.



(a) **Pre** (b) **Post**

Figure 40: Validation captures before and after the TVAC window test.

During testing without the window, "hot pixels" were observed in images captured at elevated temperatures. "Hot pixels" refer to image imperfections where certain pixels exhibit intensities that should not be present in the image. In Figure 41, it is noticeable that some pixels are entirely red, green, or blue. This is a common issue with imaging sensors when they are exposed to high temperatures. Hot pixels can also be observed in some images from the TVAC window test, but they are more easily detected in darker images. For further information regarding the results of the TVAC tests, refer to the TVAC EQM report in Appendix H.



(a) Entire image (b) Zoomed

Figure 41: RGB image from CP15 (50 °C). Hot pixels pixels can be observed in the image.

4.3 Changes from the EQM

Due to time restrictions and miscommunication, the EQM was produced before NanoAvionics could provide their complete feedback on the suggested design. This led to some differences between the design of the EQM and the design of the FM. Optimally a new EQM should have been produced, so that the data from acceptance tests conducted on the

EQM would better represent the FM. However, the production of parts and anodization for such a model would require approximately two months of additional work. Furthermore, it is presumed that the changes between the EQM and FM will not change the behavior and properties of the payload in a critical way. This will be discussed further in Section 6.

Repositioning of the Startracker

The most significant change to the payload involves repositioning the Startracker. NanoAvionics advised that the Startracker's position needed adjustment to enhance the satellite's slew maneuver, see Section 2.6. When capturing images with the satellite, the Startracker will be blinded by the Earth if the Earth is within 29 degrees of the boresight (the center of the line of sight for the Startracker). Figure 42 shows a projection of the Earth inhibition angle when the HSI is pointed towards the Earth. The red area represents the inhibition angle for the Startracker position of the EQM, while the green area indicates a tilted Startracker. As seen in the figure, the Earth is within the inhibition angle when the Startracker is not tilted, causing it to be blinded. For HYPSO-1 this issue was resolved by having the HSI not pointing directly towards the Earth, reducing the quality of captures. To address this issue, the Startracker is tilted 14 degrees counterclockwise on the ZX-plane and lowered 7mm in the -Y direction.

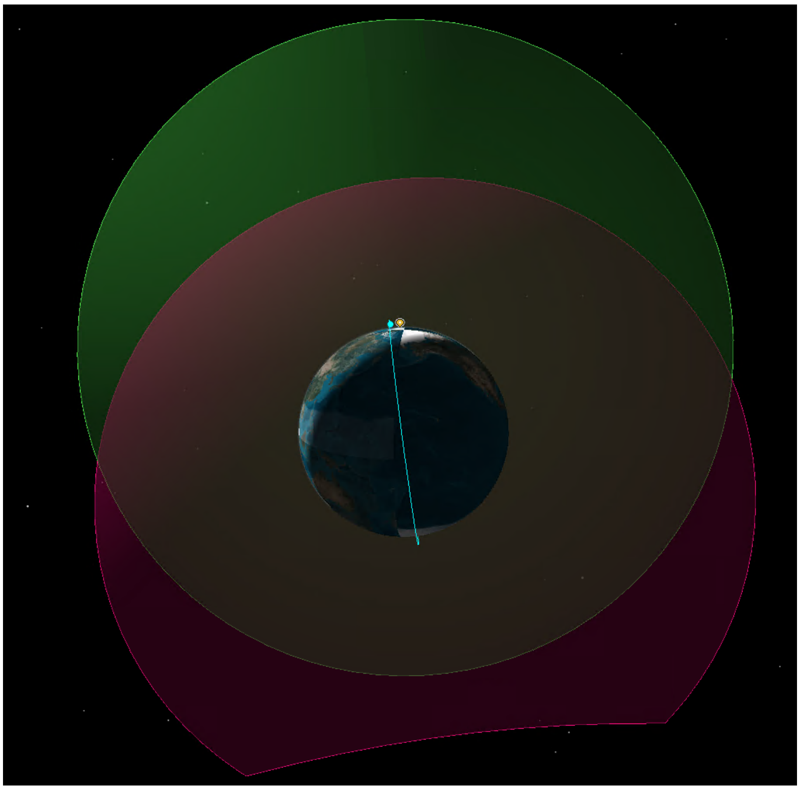
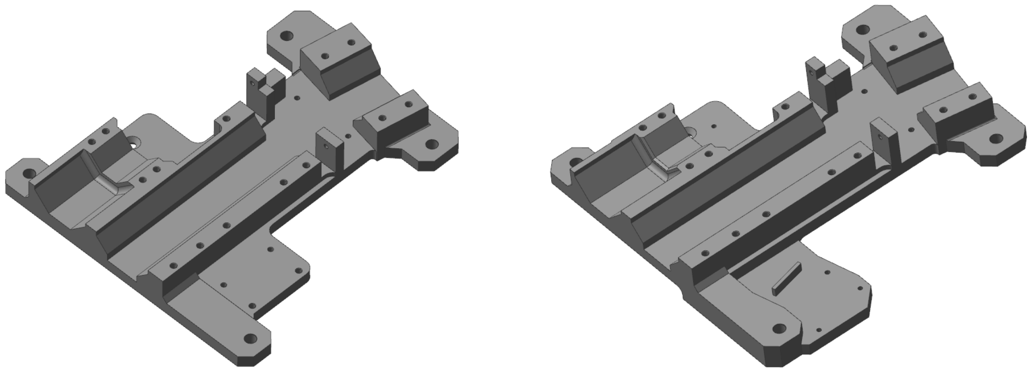


Figure 42: Earth inhibition angle of the Startracker simulated in STK by ANSYS. Green represents a tilted Startracker, Red represent a non-tilted Startracker (blinded by Earth). Figure made by HYPSO team.

The Startracker's tilt impacts the platform design. The plate on which the Startracker is mounted is lowered and extended in the -Z direction to accommodate the new mounting holes. A lip is added to the platform design, intended to be in contact with the Startracker and ensure its correct positioning.

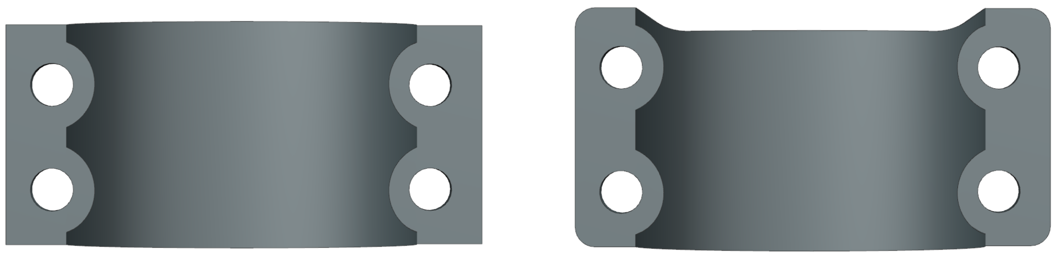


(a) **EQM** (b) **FM**

Figure 43: Payload platform of the EQM and FM.

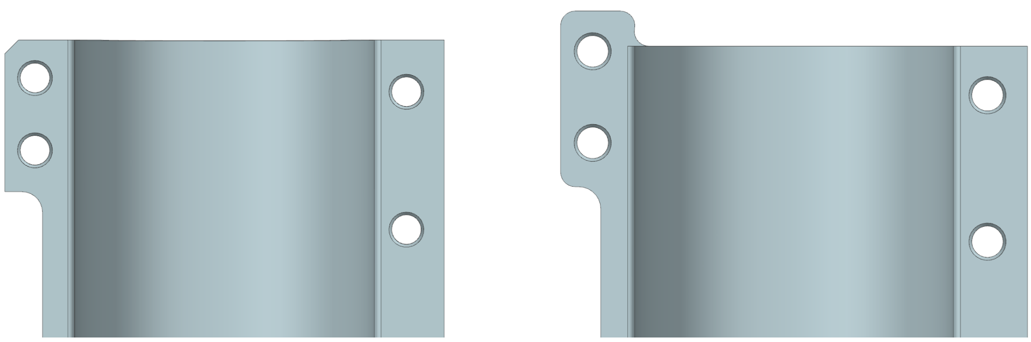
Repositioning of the RGB camera

It was found that the RGB camera protruded too far beyond the platform. Therefore, the RGB camera was repositioned so that the IR filter is parallel to the edge of the platform. This change affects the groove in the platform where the RGB is located, requiring modifications to the RGB bracket and the front bracket. The mounting holes for these components could not be moved as far back as the RGB assembly, as this would result in collisions with the satellite bus. A trapezoidal cutout was added to the RGB bracket to accommodate the conical lens of the RGB. The lip of the front bracket on the -X side was extended backward to allow the holes in the lip to move back.



(a) **EQM** (b) **FM**

Figure 44: RGB bracket of the EQM and FM.



(a) **EQM** (b) **FM**

Figure 45: Front HSI bracket of the EQM and FM.

Moving the RGB backward caused the RGB housing to collide with the HSI's middle bracket. Material was removed from the -X lip of the middle bracket, and the mounting hole was moved in the -Z direction. Some material under the middle bracket had to be removed from the platform as well.

Shield for the IMU

NanoAvionics requested a shield to protect the IMU which is positioned on the platform's underside. Both the IMU and the IMU shield are provided by NanoAvionics. Mounting holes for the shield are added to the platform. See Figure 46.

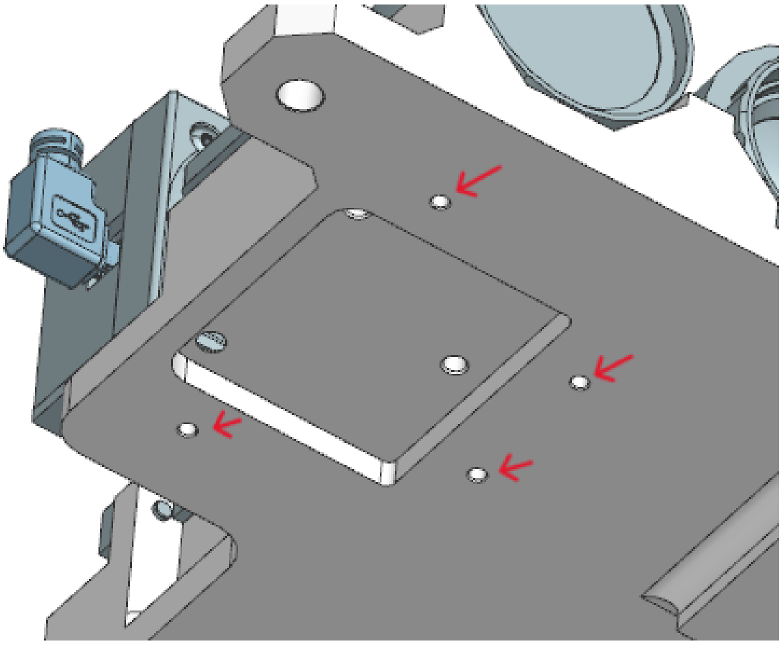


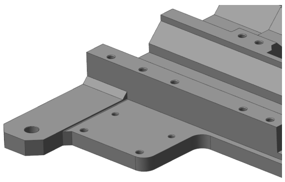
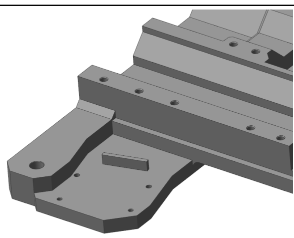
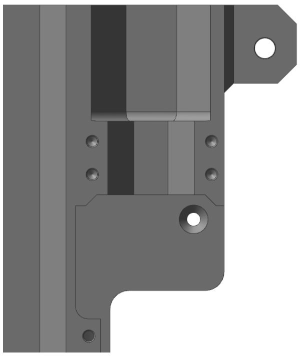
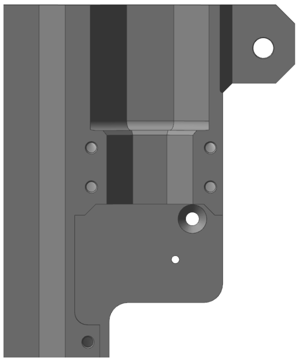
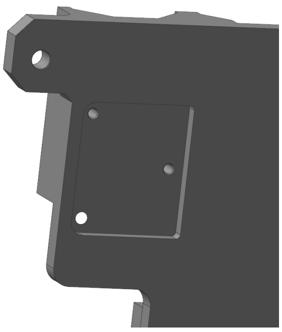
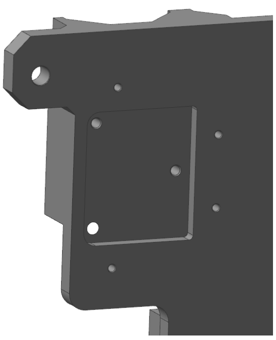
Figure 46: Mounting holes for the IMU shield.

Thickness of HSI apertures

For HYPSO-1, the apertures were created from 0.25mm aluminum sheets using a water jet cutting, which led to deformations and dents. The HYPSO-2 EQM used an Electrical Discharge Machining (EDM) manufacturing method, resulting in improved apertures. However, there was still room for enhancement. For the HYPSO-2 FM, the apertures' thickness was increased to 0.5mm, significantly reducing imperfections.

Figure 47: Custom apertures for the HSI objectives. 0.25mm thick aperture for the EQM to the left. 0.5mm thick aperture for the FM to the right.

The following table depicts all changes between the EQM and FM of HYPSO-2.

Part	**EQM**	**FM**	**Comment**
Platform - Startracker position			Mounting holes for Startracker tilted 14 degrees and lowered 7mm to improve the sleuth maneuver. Lip added for positioning of the Startracker.
Platform - RGB position			Mounting holes and cutout for the RGB assembly moved.
Platform - IMU-shield			Mounting holes for an IMU-shield added to the platform.

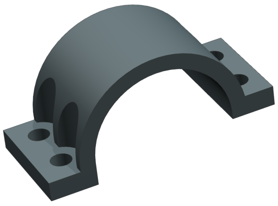
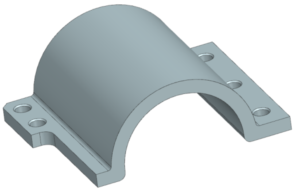
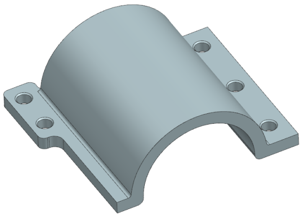
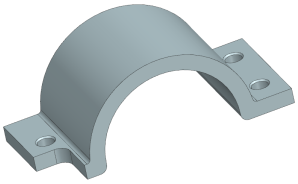
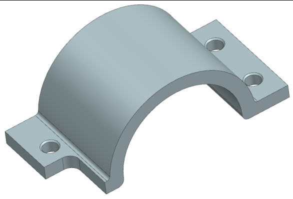
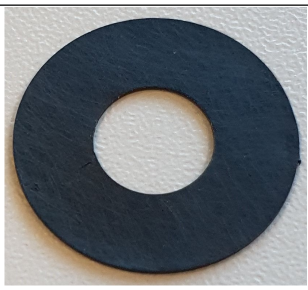
Part	EQM	FM	Comment
RGB bracket			material removed on the arc of the RGB-bracket to facilitate the repositioning of the RGB-lens.
Front bracket			-X lip of the front bracket extended in the -Z direction to move mounting holes for the RGB bracket.
Middle bracket			Material removed on the -X lip of the middle bracket to avoid crash with the RGB.
Apertures			Thickness increased from 0.25mm to 0.5mm.

Table 3: Differences between the EQM and FM of HYPSO-2.

5 Constructing the FM

This chapter explains the manufacturing, assembly, and calibration of the HYPSO-2 payload FM. Due to a delay in parts, the PicoBoB has not yet been constructed. The assembly of the PicoBoB will take place in the summer of 2023. The PicoBoB from the HYPSO-2 EQM was used to test and calibrate the HSI payload.

5.1 Manufacturing and anodization

As explained in Section 4.3, some parts of the payload had to be redesigned prior to constructing the FM. The parts were designed in the CAD software Siemens NX. CAD models and machine drawings were then sent to the workshop at Elektrobygget NTNU for manufacturing. Figure 48 shows the machined parts for the HYPSO-2 FM.

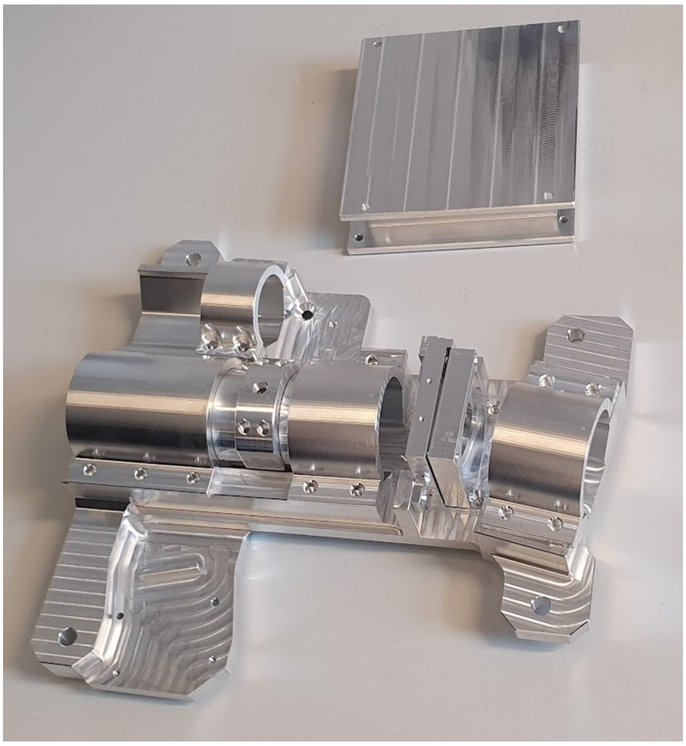


Figure 48: Machined parts for the HYPSO-2 FM.

The objectives of the HSI are delivered from the manufacturer with an adjustable aperture. From testing, it has been found that an aperture size of f/2.8 is desirable for the middle and front objectives, while the rear objective should be entirely open. With an adjustable aperture, the aperture size is likely to change when the objectives are subjected to vibrations during launch. The adjustable apertures are therefore removed. For the middle and front objectives, a custom fixed aperture is made. The apertures are manufactured using EDM. EDM is a process in which the workpiece is immersed in a dielectric fluid, commonly purified water, while a thin metal wire utilizes electrical discharges to cut the piece. Figure 47 displays the custom apertures.

Parts for the FM were anodized at Trondheim Eloksering. For the EQM, parts were anodized at NAMMO. However, due to a tight schedule and limited availability at NAMMO, Trondheim Eloksering was selected instead. Trondheim Eloksering offers the same anodization specification as used for the EQM, so there should be no concerns in using their services. The anodization specification used is MIL-A-8625 Type II, Class 2 Black. In contrast to HYPSO-1, all aluminum parts of the payload were anodized. For HYPSO-1 only the slit tube and grating cassette were anodized. Figure 49 shows the anodized parts for the FM.

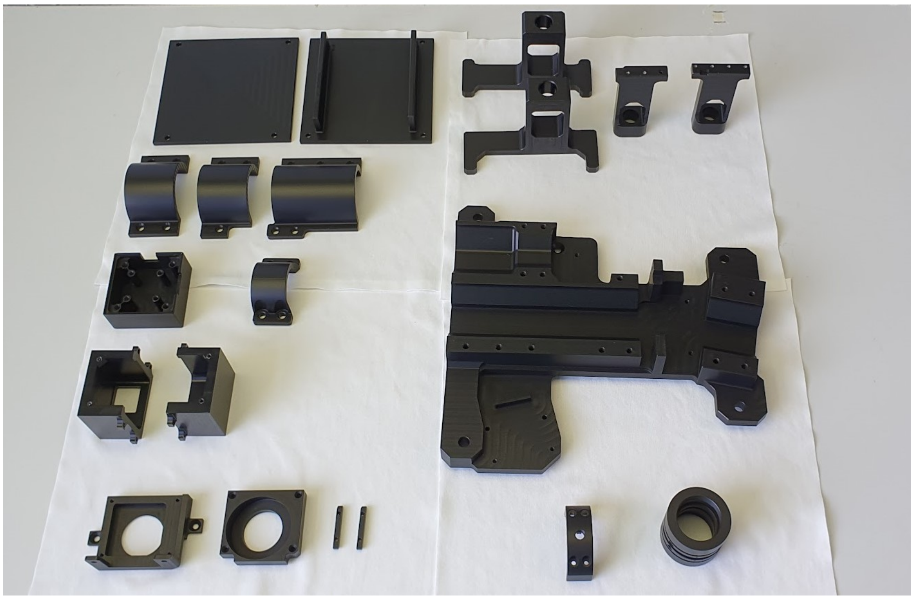


Figure 49: Anodized parts for the HYPSO-2 FM.

The updated design for the slit tube requires three holes to be drilled in the rim of the slit, as described in Tømmermo, Brovold and Vitsø [22]. These holes enable adjustments to the slit while it is in the slit tube. The holes were drilled at the Elektrobygget NTNU workshop. Moreover, the film containing the slit is capable of rotating within its housing. To prevent this rotation, the film is carefully epoxy-bonded to the housing. Great care is taken not to cause any damage to the slit during the process.

(a) Drilling at Elektrobygget NTNU

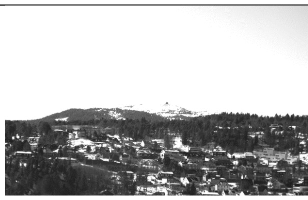
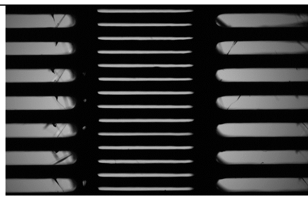
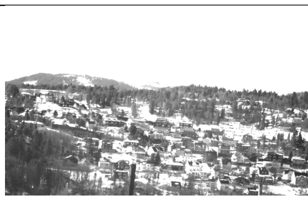
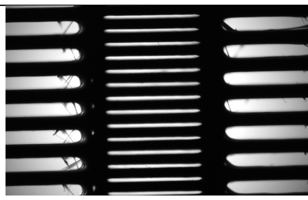
(b) Drilled slit

Figure 50: Drilling the required holes to adjust the slit in the tube.

5.2 Objectives and RGB camera

The HSI objectives are internally greased by the manufacturer to facilitate easier focus adjustment. However, the grease causes significant outgassing in a vacuum. This is explained further in Section 2.1.4. As a result, the objectives need to be disassembled and cleaned internally. This process is detailed in Appendix I and in the report ”*HSI Objective Disassembly and Cleaning: Flight Model, HYPSO-RP-039*”[14]. It is crucial not to damage the objective lenses during disassembly and assembly. The lenses are bagged immediately after removal, while the other objective parts are cleaned in the ultrasonic cleaner at the smallsat lab. It is essential to prevent dust particles from entering the objectives during assembly. Therefore, the entire disassembly, cleaning, and assembly process is carried out at the flow bench in the smallsat lab. Ideally, the process should have been conducted in a cleanroom, but this was not accessible to the HYPSO mechanical team. During assembly, the custom apertures replace the adjustable apertures for the front and middle objectives.

The three objectives of the HSI and the RGB objective need to be focused at infinity, as they will observe Earth from a low orbit. To adjust the focus, the focus set screw is loosened, and the front band of the objective is twisted, altering the focal length. The focus relies on the aperture size and the objective's focal length. Since the aperture is fixed for all objectives, the focal length determines the focus. At Elektrobygget NTNU, the objectives are mounted on a tripod and aimed towards the dome at the top of Gråkallen (a local mountain in Trondheim). A standard C-mount detector from IDS is employed to capture images with the HSI Objectives, while the RGB detector is used for the RGB objective. The uEye Cockpit software provides live video from the setup. To ensure the focus is set to infinity, a custom collimator setup is utilized. A 3D-printed grid is attached to the collimator lens and directed at a sheet of white paper. If the objectives can clearly see the grid, they are focused at infinity. The table below displays captures from focusing the objectives. Some captures are relatively bright due to the size of the apertures.

Objective	**Gråkallen**	**Collimator setup**
HSI Objective 28, front		
HSI Objective 29, collimating		
HSI Objective 30, camera		

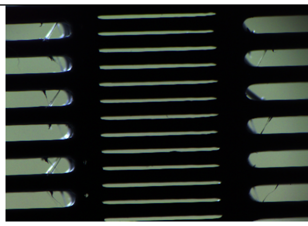
Objective	Gråkallen	Collimator setup
RGB Objective		

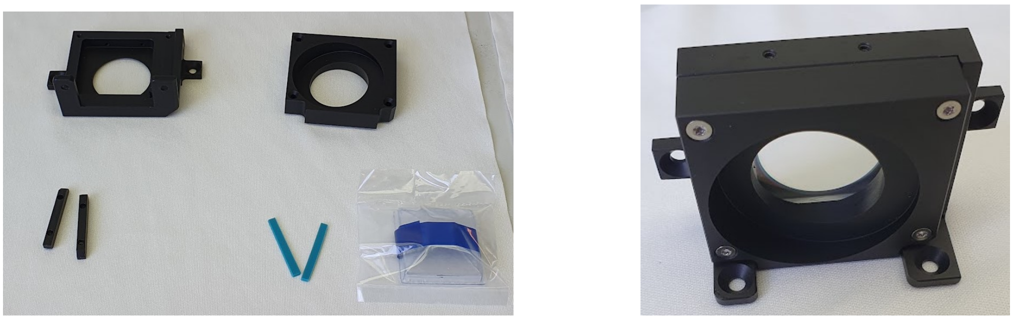
Table 4: Captures with objectives focused to infinity.

5.3 Assembly

The assembly of the payload was carried out at the smallsat lab. Ideally, it should have been performed in a cleanroom to minimize dust contamination within the assembly. To mitigate this issue, a flow bench was used to create laminar airflow, reducing the likelihood of dust particles contaminating the components. Pressurized nitrogen was initially requested for the assembly process, as it would have been used to eliminate any potential dust specks. Unfortunately, the pressurized nitrogen was not provided in time. Therefore, extra caution was required during the assembly process.

5.3.1 Grating cassette

Gaskets for the grating cassette clamp brackets were hand cut from a sheet of Turcon T05 material. These gaskets were then attached to the grating clamp brackets using epoxy. The grating clamp brackets were placed in the front of the grating cassette, followed by the careful insertion of the grating. Proper alignment of the grating is essential. For more details, refer to Appendix I. To complete the assembly, the grating cassette back was mounted, and set screws were utilized to secure the grating clamp brackets. After the grating cassette was assembled it was mounted to the platform.

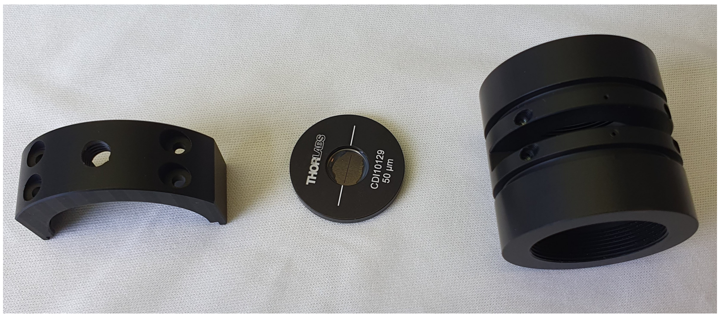


(a) Parts for the Grating Cassette (b) Grating Cassette

Figure 51: Assembly of Grating Cassette.

5.3.2 Slit tube

The slit tube assembly is composed of the slit tube bracket, the slit itself, and the slit tube base. It is important to position the slit in the correct orientation. The film is not centered within the slit housing. Therefore, the slit tube base is slightly longer on one side of the slot to ensure the slit film is located in the center of the slit tube assembly. The slit tube bracket is placed on top of the slit tube slot and secured with screws. An M6 set screw is tightened into the central hole of the slit tube bracket. To adjust the slit, the M6 set screw is removed, and a rod is used to rotate the slit. Figure 52 displays the parts and assembly of the slit tube.



(a) Parts for the Slit tube

(b) Slit tube

Figure 52: Assembly of Slit tube.

5.3.3 HSI detector and housing

The HSI detector was disassembled to remove stickers within the detector. One HSI sensor was sent to Kongsberg for coating. The coating was performed to protect it from tin whiskers (see Section 2.1.7) and to guard against outgassing. Upon its return, the coated sensor was inspected under a microscope, and it was discovered that the sensor glass was quite dirty, as illustrated in Figure 53. Due to this, an uncoated detector was used instead. This decision was discussed with the HYPSO-Electrical team, and it was determined that the coating was not absolutely necessary, since an uncoated sensor of the same type had previously passed TVAC testing and the sensor was not considered to have a great risk of tin whiskers.

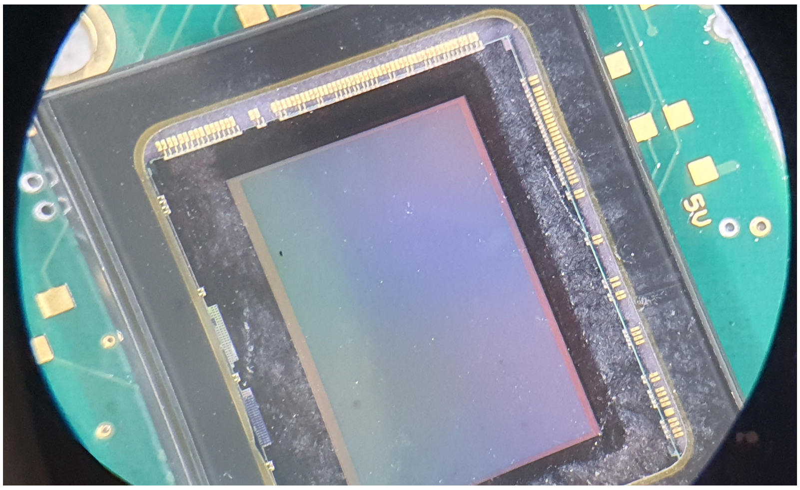


Figure 53: HSI sensor glass under a microscope.

The HSI sensor was carefully assembled. It was important to be ESD-protected during the entire assembly. The sensor was inspected for specs of dust before the two parts of the detector housing were fastened around the sensor.

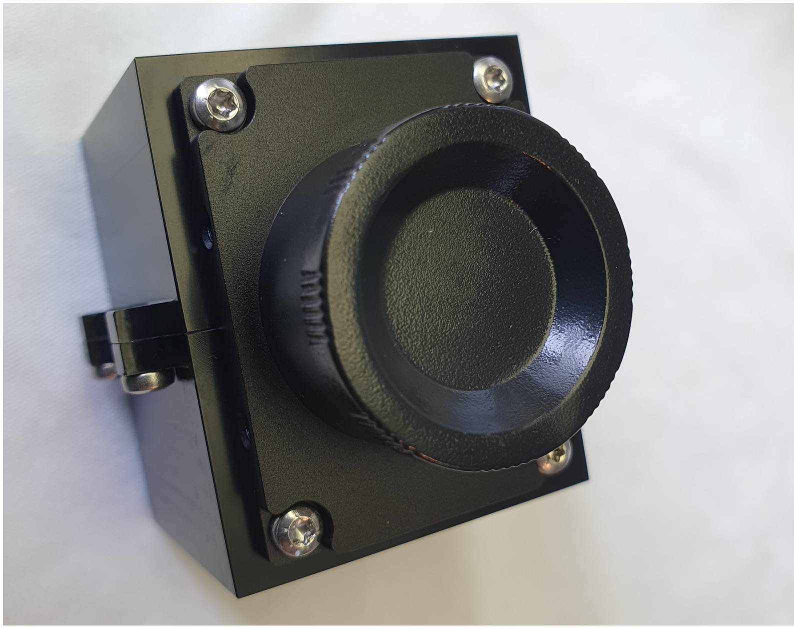


Figure 54: HSI housing assembly with lens cap.

5.3.4 HSI

The rear HSI objective was screwed onto the HSI housing. This combined piece was then securely positioned against the back of the grating cassette. The middle and front objectives were attached to the slit tube by screwing them on. It was crucial not to apply epoxy to the C-mount threads that connect the slit tube to the objectives, as spacer rings will be inserted between these components during the calibration process. This assembled section was then placed on the payload platform and pressed against the grating cassette.

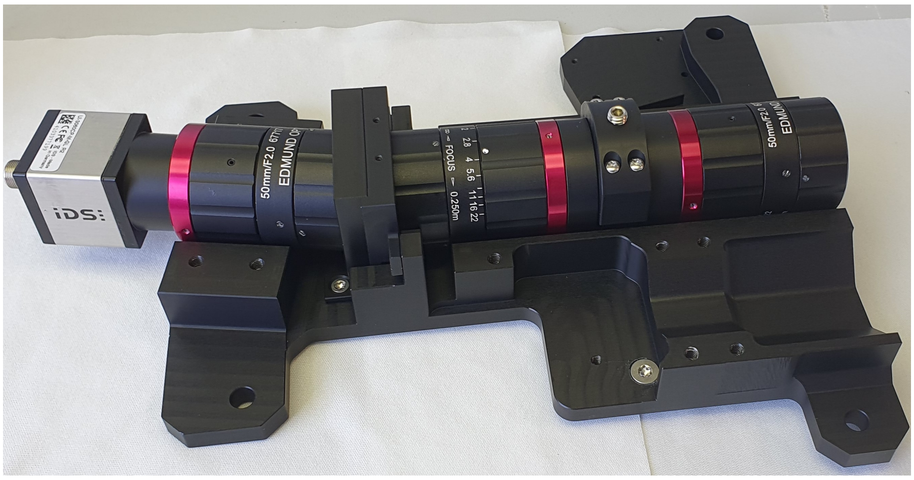
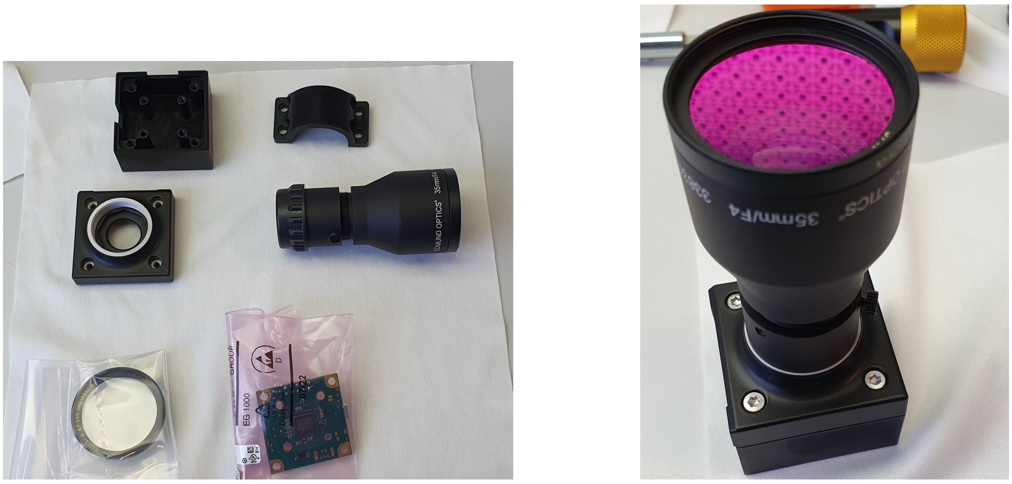


Figure 55: HSI on the platform. The IDS UI-3060CP-M-GL sensor is used in this image. This sensor is used for rapid testing.

5.3.5 RGB camera

The RGB camera consists of the RGB housing, an IDS UI-1492LE detector, a C-mount, a 35mm f/4.0, HPi Series Fixed Focal Length Lens, and an IR/UV filter. The detector was mounted to the housing using three screws, which were then epoxied. The sensor was inspected for specs of dust under a microscope before the C-mount was attached. The lens was screwed onto the C-mount and the IR filter was mounted onto the lens. A lens cap was then attached to the camera to protect the lens. Figure 56 displays the parts and assembly of the RGB camera.



(a) Parts for the RGB camera

(b) RGB camera

Figure 56: Assembly of the RGB camera.

5.3.6 Brackets

A bolt intended for the IMU was positioned prior to mounting the RGB camera onto the platform. While NanoAvionics is responsible for attaching the IMU, it is crucial to install this bolt in advance. This measure ensures that NanoAvionics won't need to remove the

RGB camera in order to install the IMU.

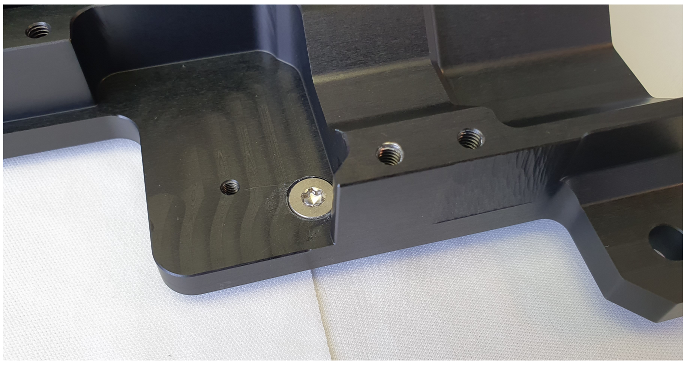


Figure 57: Bolt to fasten the IMU. The RGB is placed over this bolt.

Kapton tape was applied to all brackets, serving as a gasket between the bracket and payload components. Initially, the brackets for the HSI were positioned, followed by the placement of the RGB bracket, which overlaps the HSI bracket front. M4X10 bolts were used for all the bracket mounting holes, except for the point of overlap between the HSI bracket front and the RGB bracket, where M4X16 bolts were used. All brackets were uniformly tightened in a cross pattern to ensure the brackets exert equal pressure. When fastening the HSI rear bracket, a level was employed on the HSI detector housing to guarantee its proper alignment.

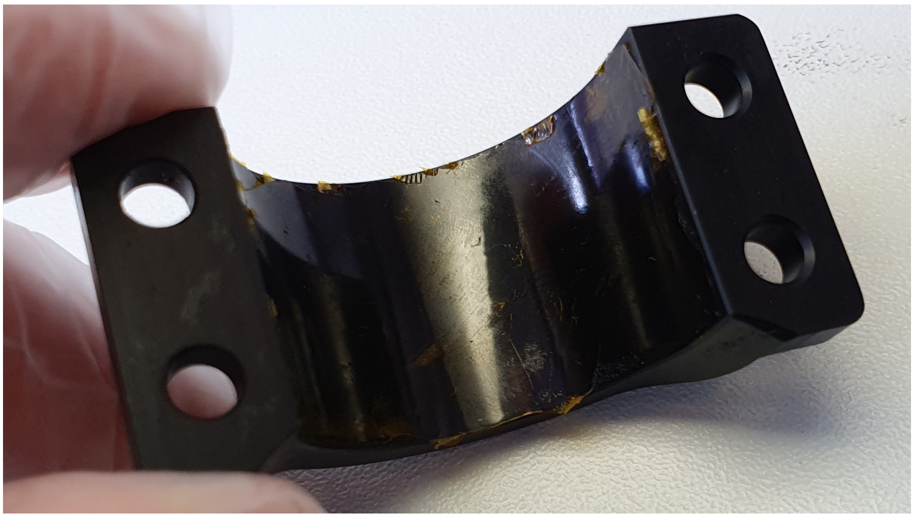
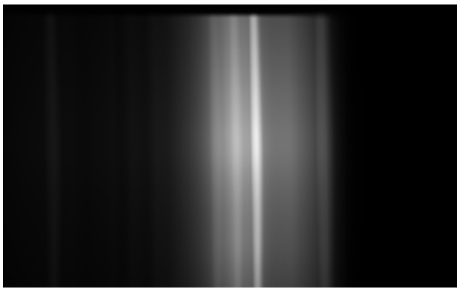


Figure 58: Kapton tape applied to the RGB bracket.

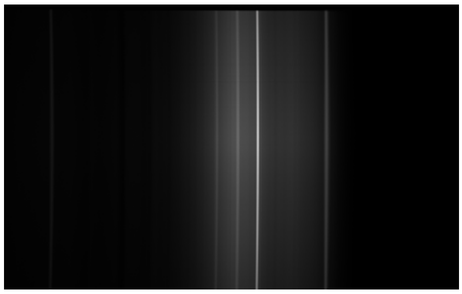
5.4 Calibration

The adjustment of the HSI focus involves adding spacer rings between the slit tube and the front and middle objectives. Changing the distance between the slit tube and the middle objective modifies the spectral focus while altering the gap between the slit tube and the front objective affects the spatial focus.

The spectral focus adjustment is carried out first. The HSI is aimed at a sheet of white paper that reflects light from a fluorescent bulb. Spacer rings are incrementally added, with a capture taken each time the spacing is increased. Appendix I presents all captures taken during this process at different spacings. Figure 59 shows the focus without spacer rings and the focus with a 0.75mm spacing.



(a) No spacing



(b) 0.75 mm spacing

Figure 59: Adjusting the spectral focus of the HSI.

A line plot is created to further evaluate the captures. Tall and narrow lines around the center of the plot are ideal. Based on the plot in Figure 60, the spacing of 0.75mm was chosen.

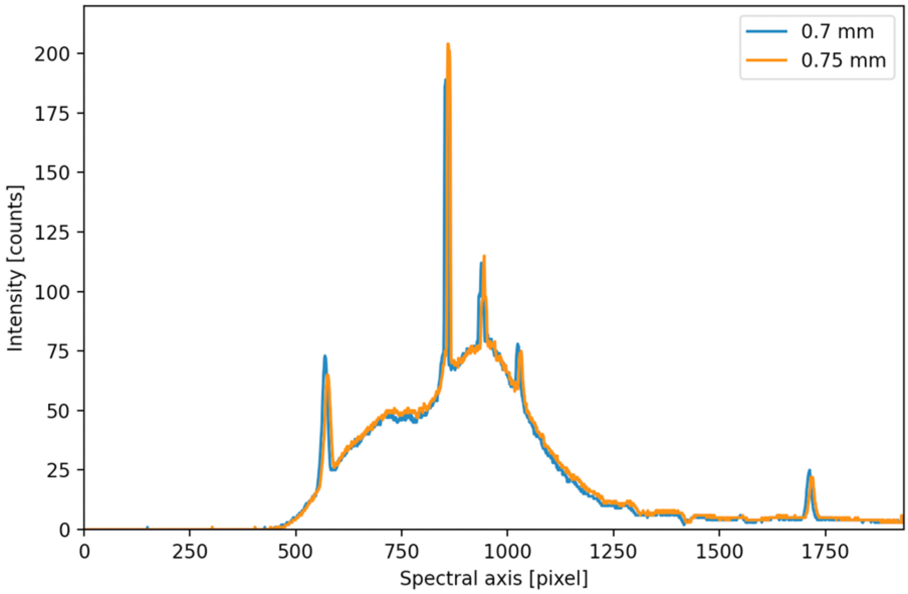


Figure 60: Line plot for adjusting the spectral focus of the HSI. The plot is only showing the best configurations of spacer rings.

For the spatial focus, a setup with the collimating lens and a Quartz Tungsten Halogen (QTH) lamp was used, see Figure 61. The QTH lamp provides a near-continuous spectrum. The sharpness of the horizontal lines generated by the striped pattern in front of the collimating lens is used to evaluate the focus. Same as for the spectral focus, the spacing was gradually increased.

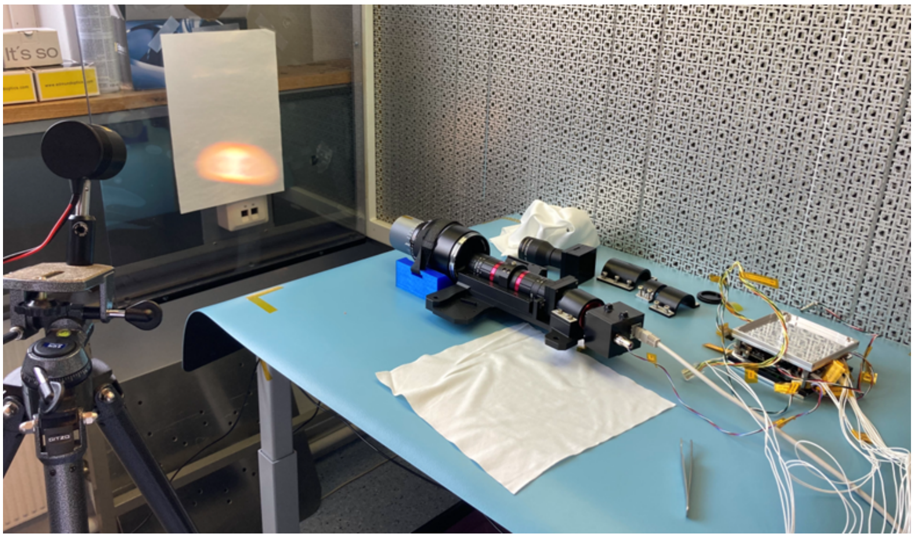


Figure 61: Setup for adjusting the spatial focus of the HSI.

(a) No spacing

(b) 0.35 mm spacing

Figure 62: Calibrating the spatial focus of the HSI.

A line plot is generated to evaluate the focus. As seen in Figure 63, the 0.35mm spacing has the highest and narrowest peaks of the spacings when evaluating the center of the plot. Based on this, the 0.35mm spacing was chosen. Brackets were mounted and torqued after the focus of the HSI was adjusted.

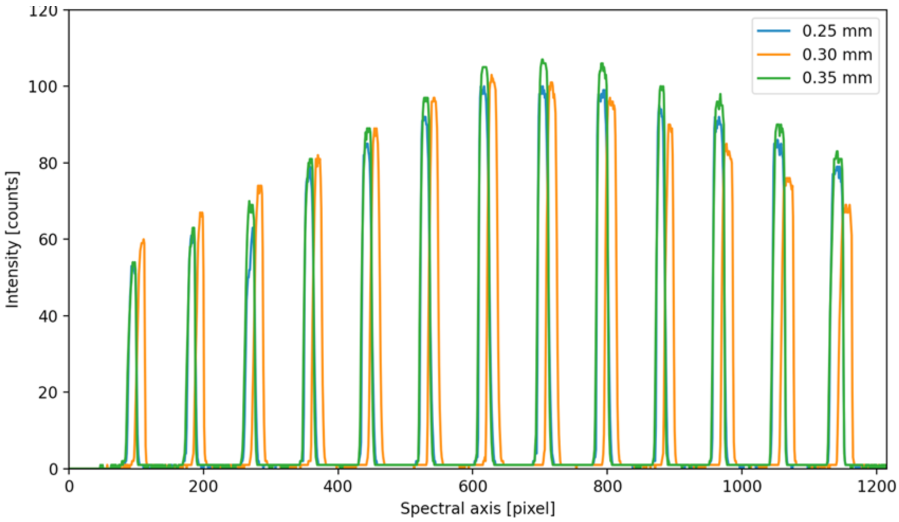


Figure 63: Line plot for spatial calibration. The plot is only showing the best configurations of spacer rings.

The slit was adjusted using a rod through the M6 hole of the slit tube bracket. A live feed from the uEye software was used when adjusting. Ideally, the slit should be completely vertical. The spectral lines from the live feed were compared to the edges of a computer window to check the alignment of the slit. When the slit was in an acceptable position, the screws on the slit tube bracket were tightened to secure the slit in its position.

Once the mechanical calibration was finalized, all bolts were secured with epoxy. The software calibrations were carried out at the calibration lab at Elektrobygget NTNU. At this location, the HSI is directed towards an integrating sphere capable of emitting light uniformly at known wavelengths [39]. The details of the software calibration process fall outside the scope of this thesis.

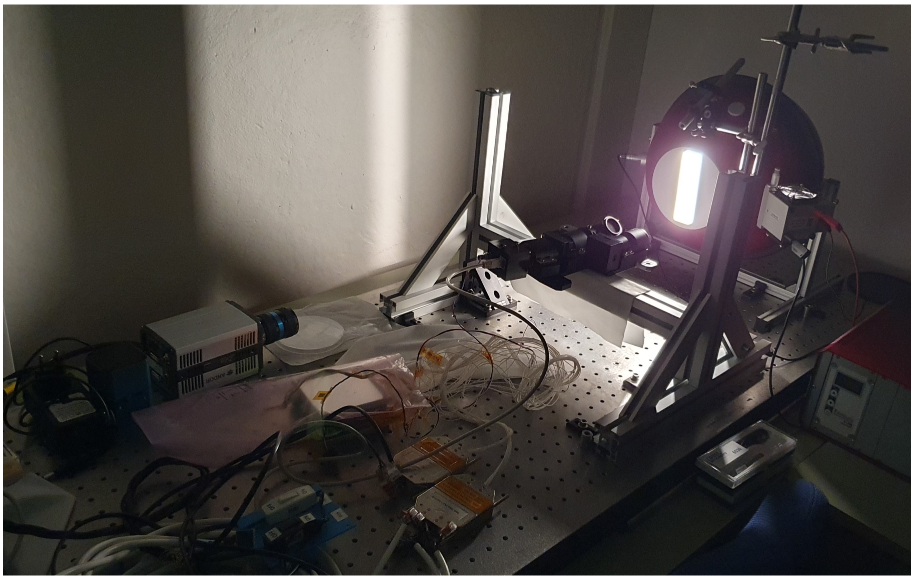


Figure 64: Calibration lab setup.

6 Discussion

This section will discuss the results from the TVAC test presented in Section 4, as well as comment on the work performed when constructing the FM for HYPSO-2, see Section 5.

6.1 TVAC test results

The outcomes of the TVAC tests are presented in Section 4.2.3. These tests were designed to assess the payload's performance under varying temperatures in a high vacuum environment. The primary focus was on the newly introduced components, meaning the new RGB camera and the ALICE breadboard. The RGB camera was of particular concern since it was discovered during TVAC testing of HYPSO-1 that the COTS objectives for the HSI were damaged from outgassing and required internal cleaning. The tests also aimed to determine if the thermal straps used in HYPSO-1 to distribute heat were necessary for HYPSO-2.

Fortunately, no damage from outgassing was found on the lenses of the RGB and HSI. This indicates that the RGB does not require internal cleaning, eliminating the danger of damaging internal parts during lens disassembly. Additionally, no issues were found relating to the ALICE breadboard.

It has been debated within the HYPSO team if the thermal straps used for HYPSO-1 were a necessity. The thermal straps were employed to distribute heat throughout the payload, to avoid the overheating of electrical components, causing noise. Figure 30 displays the variation of temperature in components during captures. Attempts to calculate the thermal conductivity of the straps indicated that little heat was transferred. Figure 39, which compares the noise of HYPSO-1 and HYPSO-2 at different temperature levels seems to confirm that the straps have no significant effect. Adding more and thicker thermal straps than those used for HYPSO-1 would probably have contributed to a reduction in noise. Considering that the straps are expensive, fragile, and complicated to install, it can be confidently stated that they will not be utilized for the HYPSO-2 FM.

As presented in the TVAC results, captures from the HSI shift with three pixels when comparing the CPs at the beginning and end of the TVAC test. This is not ideal, however, it is also not unexpected, since a similar shift occurred on HYPSO-1. The shift might suggest a change in dispersion angle, indicating a potential displacement of the grating. The shift is relatively small, and a reason for the shift could be that the chamber did not have time to stabilize before the last capture was taken, causing the payload to be at different temperatures before and after the test. Nevertheless, it is crucial to monitor this shift, ensuring that it does not escalate over time.

It was observed that noise in HSI captures changed with varying temperatures. This can be attributed to the sensor being more sensitive at high temperatures. It was also observed that the spectral shift and spectral focus vary with temperature. This is most likely due to components expanding and contracting with varying temperatures, altering the focal length. This is hard to avoid due to the focus of the HSI being mainly dependent on its length. There are temperature sensors monitoring the satellite when it is in orbit. Values from these sensors can provide an indication of the focus of the HSI at the current time.

Overall, no major issues were found when conducting the TVAC test. The payload was subjected to the non-operational temperatures of -30°C to 60°C and the operational range of -20°C to 50°C. The payload produced acceptable captures even in the non-operational range. It can therefore be concluded that the EQM passed the TVAC test.

As indicated in Section 4.3, some parts were altered between the EQM and the FM of HYPSO-2. The EQM serves as a replica model designed for performance evaluation and testing, mitigating the need for exposing the FM to the same tests. Consequently, the EQM should mimic the FM as closely as possible. As depicted in Table 3, no modifications were made to the electrical components and no new COTS parts were added. Therefore, the thermal performance of the satellite essentially remains unchanged and there is no need for conducting a TVAC test on the FM. The impact of these changes on the shock and vibration test, however, lies beyond the scope of this thesis [10].

6.2 FM assembly

The PicoBoB has not yet been built due to the postponed delivery of components. Nevertheless, it is projected to be assembled during the summer of 2023 by other members of the HYPSO team. The electrical designer of the PicoBoB will assist in the assembly process, which should ensure a construction with few issues.

The rest of the HSI payload FM has been constructed as presented in Section 5. The only issue that arose during the assembly was the contaminated HSI sensor screen. Given that the screen was undamaged prior to being sent for coating at Kongsberg, it is presumed to have been mishandled during that process. Methods of cleaning the screen were discussed, however, it is not recommended to use alcohol or rub a cloth on the screen. Therefore a new, uncoated sensor was used instead. Although the coating is not required, it does offer some degree of protection against ESD and tin whiskers. The sensor is already protected quite well against ESD, due to its connection to the HSI sensor housing which is electrically connected to the rest of the satellite. Using the new, uncoated sensor should therefore be adequate.

The payload is currently undergoing analysis to assess its performance. The PicoBoB from the EQM of HYPSO-2 is used in this process. The preliminary results of the HSI calibration indicate a satisfactory performance of the HSI, with a spectral focus as good as or even better than that of HYPSO-1, along with a reduction in spectral tilt due to a less rotated slit.

6.3 Quality of Results

By having easy access to a cutting-edge thermal vacuum chamber it has been possible to do trial-and-error tests on the chamber, to refine the process before conducting the proper TVAC test, thus improving the quality of the test results. However, the lack of a proper operator presented some challenges. When inspecting the measured temperature profiles from the TVAC tests, it is clear that the thermocouples secured by bolts achieved the target temperature more quickly than those attached with Kapton tape. A better method of mounting the thermocouples could have improved the temperature readings.

It became apparent after the TVAC tests were performed, that the chamber was not given enough time to stabilize its temperature for certain CPs. This affects the plots comparing data based on temperature since the payload could have a different temperature than intended when taking captures.

The performance of the HSI payload is influenced by certain critical dimensions. The grating diffracts light at an angle of 10.37 degrees. It is therefore critical that this angle is replicated correctly in the grating cassette and payload platform. The importance of these angles was communicated to the workshop, however, measurements should have been performed to confirm these angles. A measurement device such as a touch trigger probe measuring machine could have been used for precise measurements.

6.4 Challenges and Improvements

The challenges from the specialization project leading up to this thesis have been addressed this semester. Improved communication with the workshop has resulted in no machining errors and fewer delays. However, several challenges arose during the course of this semester.

Getting access to the proper equipment in time has been a persistent issue throughout the semester. Access to a cleanroom and pressurized nitrogen would have greatly enhanced the assembly process. Even though the laminar flow bench reduces the number of dust particles in the air, there is still a great risk of contaminating the HSI lenses during disassembly. For HYPSO-3, access to a cleanroom and pressurized nitrogen should be prioritized.

In February 2023, NanoAvionics proposed some necessary alterations to the satellite design. Given that they were provided with the new design for HYPSO-2 during the fall of 2022, these changes should have been presented earlier. This led to a difference in the design of the EQM and FM. As previously discussed, these changes do not appear to critically impact the results of the TVAC test, but ideally, the EQM and FM should share the same design.

Nanovac, the company that provided the vacuum chamber used for testing, forgot to install a window in the chamber, as requested by NTNU. This window was eventually installed, although at a severe delay. This resulted in two TVAC tests being conducted, due to the possibility of the window being installed too late.

When TVAC testing, only six thermocouples were available for measuring the temperature of the DUT. One of these sensors had to be mounted on the chamber table for proper temperature control. Additional sensors would have been useful to get a better understanding of the temperature distribution in the payload.

6.5 Project Experiences

It has been exciting to continue learning about development for satellite applications and improving the design made for the specialization project. The HYPSO team is composed of many highly skilled people in different fields and it has been a great experience learning from and with them.

The mechanical team is comprised solely of another master's student and myself. Before joining this project, we had little to no knowledge about hyperspectral imaging or space development. The design, production, assembly, and testing of the payload have been our main responsibility. This has been both exhilarating and at times somewhat overwhelming. Despite the project's success so far, it is my belief that the HYPSO team should consider expanding its mechanical team for the next project.

I am looking forward to following the project's progress in the future. My hope is that the launch of the satellite will be successful and that it will provide invaluable data for ocean research.

7 Conclusion and Further work

The primary objective of this thesis was to design, assemble and test the HSI payload for the HYPSO-2 mission. The main focus of the thesis has been on the TVAC testing of the EQM and the assembly of the FM.

Two TVAC tests were performed. One before the window was installed in the chamber and one after. The results from the tests indicate some issues such as increased noise with higher temperatures and a spectral shift. However, these issues are both minor and expected. Thus, the EQM passed the TVAC test.

The differences between the EQM and FM do not affect the thermal characteristics of the payload in a critical way. Therefore, the FM should be fit to handle the thermal vacuum conditions of launch and orbit based on the results from the TVAC tests. How the changes affect the results of the shock and vibration test performed at FFI will be discussed in the thesis of the other member of the HYPSO mechanical team.

The flight model for the payload of the HYPSO-2 mission has been constructed and is currently undergoing software calibrations. There seem to be no significant issues with the assembly.

Going forward, the PicoBoB will be assembled by other members of the HYPSO team. Once complete, the payload will be sent to NanoAvionics in Lithuania where it will be integrated into the satellite bus provided by them. NanoAvionics will perform further tests on the satellite, ensuring it is fit for launch. After this, the satellite will be handed to SpaceX, which is responsible for the launch of the satellite. The launch will hopefully take place in the fall of 2024.

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Appendix

A Scotch-Weld™ Epoxy Adhesive

Scotch-Weld™ Epoxy Adhesive
2216 B/A

Technical Data **October 2018**

Product Description

3M™ Scotch-Weld™ Epoxy Adhesive 2216 B/A is a flexible, two-part, room temperature curing epoxy with high peel and shear strength, available in three versions. 2216 B/A Gray meets DOD-A-82720.

Typical Uncured Physical Properties

Note: The following technical information and data should be considered representative or typical only and should not be used for specification purposes.

Product	3M™ Scotch-Weld™ Epoxy Adhesive					
	2216 B/A Gray		2216 B/A Tan NS		2216 B/A Translucent	
	Base	Accelerator	Base	Accelerator	Base	Accelerator
Color:	White	Gray	White	Tan	Translucent	Amber
Base:	Modified Epoxy	Modified Amine	Modified Epoxy	Modified Amine	Modified Epoxy	Modified Amine
Net Wt.: (lb/gal)	11.1-11.6	10.5-11.0	11.1-11.6	10.5-11.0	9.4-9.8	8.0-8.5
Viscosity: (cps) (Approx.) Brookfield RVF #7 sp. @ 20 rpm	75,000 - 150,000	40,000 - 80,000	75,000 - 150,000	550,000 - 900,000	11,000 - 15,000	5,000 - 9,000
Mix Ratio: (by weight)	5 parts	7 parts	5 parts	7 parts	1 part	1 part
Mix Ratio: (by volume)	2 parts	3 parts	2 parts	3 parts	1 part	1 part
Work Life: 100 g Mass @ 75°F (24°C)	90 minutes	90 minutes	120 minutes	120 minutes	120 minutes	120 minutes

Features

- Excellent for bonding many metals, woods, plastics, rubbers, and masonry products.
- Base and Accelerator are contrasting colors.
- Good retention of strength after environmental aging.
- Resistant to extreme shock, vibration, and flexing.
- Excellent for cryogenic bonding applications.
- Excellent for potting parts subject to thermal cycling.
- The tan NS Adhesive is non-sag for greater bond-line control.
- The translucent can be injected.
- Meets DOD-A-82720.

3M™ Scotch-Weld™ Epoxy Adhesive
2216 B/A

Typical Cured Physical Properties

Product	3M™ Scotch-Weld™ Epoxy Adhesive		
	2216 Gray	**2216 Tan NS**	**2216 Translucent**
Color	Gray	Tan	Translucent
Shore D Hardness ASTM D 2240	50-65	65-70	35-50
Time to Handling Strength	8-12 hrs.	8-12 hrs.	12-16 hrs.

Typical Cured Electrical Properties

Product	3M™ Scotch-Weld™ Epoxy Adhesive	
	2216 Gray	**2216 Translucent**
Arc Resistance	130 seconds	
Dielectric Strength	408 volts/mil	630 volts/mil
Dielectric Constant @ 73°F (23°C)	5.51–Measured @ 1.00 KHz	6.3 @ 1 KHz
Dielectric Constant @ 140°F (60°C)	14.17–Measured @ 1.00 KHz	—
Dissipation Factor 73°F (23°C)	0.112 Measured @ 1.00 KHz	0.119 @ 1 KHz
Dissipation Factor 140°F (60°C)	0.422–Measured @ 1.00 KHz	—
Surface Resistivity @ 73°F (23°C)	5.5 x 10^{16} ohm–@ 500 volts DC	—
Volume Resistivity @ 73°F (23°C)	1.9 x 10^{12} ohm-cm–@ 500 volts DC	3.0 x 10^{12} ohm-cm @ 500 volts DC

Typical Cured Thermal Properties

Product	3M™ Scotch-Weld™ Epoxy Adhesive	
	2216 Gray	**2216 Translucent**
Thermal Conductivity	0.228 Btu-ft/ft^2 h °F	0.114 Btu-ft/ft^2 h °F
Coefficient of Thermal Expansion	102 x 10^{-6} in/in/°C between 0-40°C 134 x 10^{-6} in/in/°C between 40-80°C	81 x 10^{-6} in/in/°C between -50-0°C 207 x 10^{-6} in/in/°C between 60-150°C

Typical Cured Outgassing Properties

Outgassing Data
NASA 1124 Revision 4

	% TML	% CVCM	% Wtr
3M™ Scotch-Weld™ Epoxy Adhesive 2216 Gray	.77	.04	.23

Cured in air for 7 days @ 77°F (25°C).

Handling/Curing Information

Directions for Use

1. For high strength structural bonds, paint, oxide films, oils, dust, mold release agents and all other surface contaminants must be completely removed. However, the amount of surface preparation directly depends on the required bond strength and the environmental aging resistance desired by user. For suggested surface preparations of common substrates, see the following section on surface preparation.
2. These products consist of two parts. Mix thoroughly by weight or volume in the proportions specified on the product label and in the uncured properties section. Mix approximately 15 seconds after a uniform color is obtained.

3M™ Scotch-Weld™ Epoxy Adhesive
2216 B/A

Handling/Curing Information *(continued)*

3. For maximum bond strength, apply product evenly to both surfaces to be joined.
4. Application to the substrates should be made within 90 minutes. Larger quantities and/or higher temperatures will reduce this working time.
5. Join the adhesive coated surfaces and allow to cure at 60°F (16°C) or above until firm. Heat, up to 200°F (93°C), will speed curing.
6. The following times and temperatures will result in a full cure:

Product	3M™ Scotch-Weld™ Epoxy Adhesive		
	2216 Gray	2216 Tan NS	2216 Translucent
Cure Temperature	Time	Time	Time
75°F (24°C)	7 days	7 days	30 days
150°F (66°C)	120 minutes	120 minutes	240 minutes
200°F (93°C)	30 minutes	30 minutes	60 minutes

7. Keep parts from moving until handling strength is reached. Contact pressure is necessary. Maximum shear strength is obtained with a 3-5 mil bond line. Maximum peel strength is obtained with a 17-25 mil bond line.
8. Excess uncured adhesive can be cleaned up with ketone type solvents.*
   Adhesive Coverage: A 0.005 in. thick bondline will typically yield a coverage of 320 sq. ft/gallon

Application and Equipment Suggestions

These products may be applied by spatula, trowel or flow equipment.

Two-part mixing/proportioning/dispensing equipment is available for intermittent or production line use. These systems are ideal because of their variable shot size and flow rate characteristics and are adaptable to many applications.

Surface Preparation

For high strength structural bonds, paint, oxide films, oils, dust, mold release agents and all other surface contaminants must be completely removed. However, the amount of surface preparation directly depends on the required bond strength and the environmental aging resistance desired by user.

The following cleaning methods are suggested for common surfaces.

Steel or Aluminum (Mechanical Abrasion)

1. Wipe free of dust with oil-free solvent such as acetone or alcohol solvents.*
2. Sandblast or abrade using clean fine grit abrasives (180 grit or finer).
3. Wipe again with solvents to remove loose particles.
4. If a primer is used, it should be applied within 4 hours after surface preparation.

*When using solvents, extinguish all ignition sources, including pilot lights, and follow the manufacturer's precautions and directions for use. Use solvents in accordance with local regulations.

3M™ Scotch-Weld™ Epoxy Adhesive
2216 B/A

Surface Preparation *(continued)*

Aluminum (Chemical Etch)

Aluminum alloys may be chemically cleaned and etched as per ASTM D 2651. This procedure states to:

1. Alkaline Degrease – Oakite 164 solution (9-11 oz/gal of water) at 190°F ± 10°F (88°C ± 5°C) for 10-20 minutes. Rinse immediately in large quantities of cold running water.
2. Optimized FPL Etch Solution (1 liter):

Material	Amount
Distilled Water	700 ml plus balance of liter (see below)
Sodium Dichromate	28 to 67.3 grams
Sulfuric Acid	287.9 to 310.0 grams
Aluminum Chips	1.5 grams/liter of mixed solution

   To prepare 1 liter of this solution, dissolve sodium dichromate in 700 ml of distilled water. Add sulfuric acid and mix well. Add additional distilled water to fill to 1 liter. Heat mixed solution to 66 to 71°C (150 to 160°F). Dissolve 1.5 grams of 2024 bare aluminum chips per liter of mixed solution. Gentle agitation will help aluminum dissolve in about 24 hours.

   To etch aluminum panels, place them in FPL etch solution heated to 66 to 71°C (150 to 160°F). Panels should soak for 12 to 15 minutes.

3. Rinse: Rinse panels in clear running tap water.
4. Dry: Air dry 15 minutes; force dry 10 minutes (minimum) at 140°F (60°C) maximum.
5. If primer is to be used, it should be applied within 4 hours after surface preparation.

Plastics/Rubber

1. Wipe with isopropyl alcohol.*
2. Abrade using fine grit abrasives (180 grit or finer).
3. Wipe with isopropyl alcohol.*

Glass

1. Solvent wipe surface using acetone or MEK.*
2. Apply a thin coating (0.0001 in. or less) of 3M™ Scotch-Weld™ Structural Adhesive Primer EC-3901 to the glass surfaces to be bonded and allow the primer to dry a minimum of 30 minutes @ 75°F (24°C) before bonding.

*When using solvents, extinguish all ignition sources, including pilot lights, and follow the manufacturer's precautions and directions for use. Use solvents in accordance with local regulations.

3M™ Scotch-Weld™ Epoxy Adhesive
2216 B/A

Typical Adhesive Performance Characteristics

A. Typical Shear Properties on Etched Aluminum
ASTM D 1002
Cure: 2 hours @ 150 ± 5°F (66°C ± 2°C), 2 psi pressure

Test Temperature	Overlap Shear (psi)		
	3M™ Scotch-Weld™ Epoxy Adhesive		
	2216 B/A Gray Adhesive	2216 B/A Tan NS Adhesive	2216 B/A Trans. Adhesive
-423°F (-253°C)	2440	—	—
-320°F (-196°C)	2740	—	—
-100°F (-73°C)	3000	—	—
-67°F (-53°C)	3000	2000	3000
75°F (24°C)	3200	2500	1700
180°F (82°C)	400	400	140

Test Temperature	Shear Modulus (Torsion Pendulum Method)
-148°F (-100°C)	398,000 psi (2745 MPa)
-76°F (-60°C)	318,855 psi (2199 MPa)
-40°F (-40°C)	282,315 psi (1947 MPa)
32°F (0°C)	218,805 psi (1500 MPa)
75°F (24°C)	49,580 psi (342 MPa)

B. Typical T-Peel Strength
ASTM D 1876

Test Temperature	T-Peel Strength (piw) @ 75°F (24°C)		
	3M™ Scotch-Weld™ Epoxy Adhesive		
	2216 B/A Gray Adhesive	2216 B/A Tan NS Adhesive	2216 B/A Trans. Adhesive
75°F (24°C)	25	25	25

3M™ Scotch-Weld™ Epoxy Adhesive
2216 B/A

Typical Adhesive Performance Characteristics (*continued*)

C. Overlap Shear Strength After Environmental Aging-Etched Aluminum

Environment	Time	Overlap Shear (psi) 75°F (24°C) 3M™ Scotch-Weld™ Epoxy Adhesive		
		2216 B/A Gray Adhesive	**2216 B/A Tan NS Adhesive**	**2216 B/A Trans. Adhesive**
100% Relative Humidity @ 120°F (49°C)	14 days 30 days 90 days	2950 psi 1985 psi 1505 psi	3400 psi 2650 psi	1390 psi
*Salt Spray @ 75°F (24°C)	14 days 30 days 60 days	2300 psi 500 psi 300 psi	3900 psi 3300 psi	1260 psi
Tap Water @ 75°F (24°C)	14 days 30 days 90 days	3120 psi 2942 psi 2075 psi	3250 psi 2700 psi	1950 psi
Air @ 160°F (71°C)	35 days	4650 psi	4425 psi	
Air @ 300°F (149°C)	40 days	4930 psi	4450 psi	3500 psi
Anti-icing Fluid @ 75°F (24°C)	7 days	3300 psi	3050 psi	2500 psi
Hydraulic Oil @ 75°F (24°C)	30 days	2500 psi	3500 psi	2500 psi
JP-4 Fuel	30 days	2500 psi	2750 psi	2500 psi
Hydrocarbon Fluid	7 days	3300 psi	3100 psi	3000 psi

*Substrate corrosion resulted in adhesive failure.

D. Heat Aging of 3M™ Scotch-Weld™ Epoxy Adhesive 2216 B/A Gray (Cured for 7 days @ 75°F [24°C])

Overlap Shear (psi)	Time aged @ 300°F (149°C)			
Test Temperature	**0 days**	**12 days**	**40 days**	**51 days**
-67°F (-53°C)	2200	3310	3120	2860
75°F (24°C)	3100	5150	4930	4740
180°F (82°C)	500	1000	760	1120
350°F (177°C)	420	440	560	—

3M™ Scotch-Weld™ Epoxy Adhesive
2216 B/A

Typical Adhesive Performance Characteristics (*continued*)

E. Overlap Shear Strength on Abraded Metals, Plastics, and Rubbers.

Overlap shear strengths were measured on 1" x 1/2" overlap specimens. These bonds were made individually using 1" by 4" pieces of substrate (Tested per ASTM D 1002).

The thickness of the substrates were: cold rolled, galvanized and stainless steel – 0.056-0.062", copper – 0.032", brass – 0.036", rubbers – 0.125", plastics – 0.125". All surfaces were prepared by solvent wiping/abrading/ solvent wiping.

The jaw separation rate used for testing was 0.1 in/min for metals, 2 in/min for plastics, and 20 in/min for rubbers.

	Overlap Shear (psi)@75°F (24°C)	
	3M™ Scotch-Weld™ Epoxy Adhesive	
Substrate	2216 B/A Gray Adhesive	2216 B/A Tan NS Adhesive
Aluminum/Aluminum	1850	2350
Cold Rolled Steel/Cold Rolled Steel	1700	3100
Stainless Steel/Stainless Steel	1900	
Galvanized Steel/Galvanized Steel	1800	
Copper/Copper	1050	
Brass/Brass	850	
Styrene Butadiene Rubber/Steel	200*	
Neoprene Rubber/Steel	220*	
ABS/ABS Plastic	990*	1140*
PVC/PVC, Rigid	940*	
Polycarbonate/Polycarbonate	1170*	1730*
Acrylic/Acrylic	1100*	1110*
Fiber Reinforced Polyester/ Reinforced Polyester	1660*	1650*
Polyphenylene Oxide/PPO	610	610
PC/ABS Alloy / PC/ABS Alloy	1290	1290

*The substrate failed during the test.

Storage

Store products at 60-80°F (16-27°C) for maximum storage life.

Shelf Life

When stored at the recommended temperatures in the original, unopened containers, the shelf life is 24 months from date of manufacture from 3M.

3M™ Scotch-Weld™ Epoxy Adhesive
2216 B/A

Precautionary Information	Refer to Product Label and Material Safety Data Sheet for health and safety information before using this product. For additional health and safety information, call 1-800-364-3577 or (651) 737-6501.
Technical Information	The technical information, guidance, and other statements contained in this document or otherwise provided by 3M are based upon records, tests, or experience that 3M believes to be reliable, but the accuracy, completeness, and representative nature of such information is not guaranteed. Such information is intended for people with knowledge and technical skills sufficient to assess and apply their own informed judgment to the information. No license under any 3M or third party intellectual property rights is granted or implied with this information.
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ISO 9001

This Industrial Adhesives and Tapes Division product was manufactured under a 3M quality system registered to ISO 9001 standards.

3M

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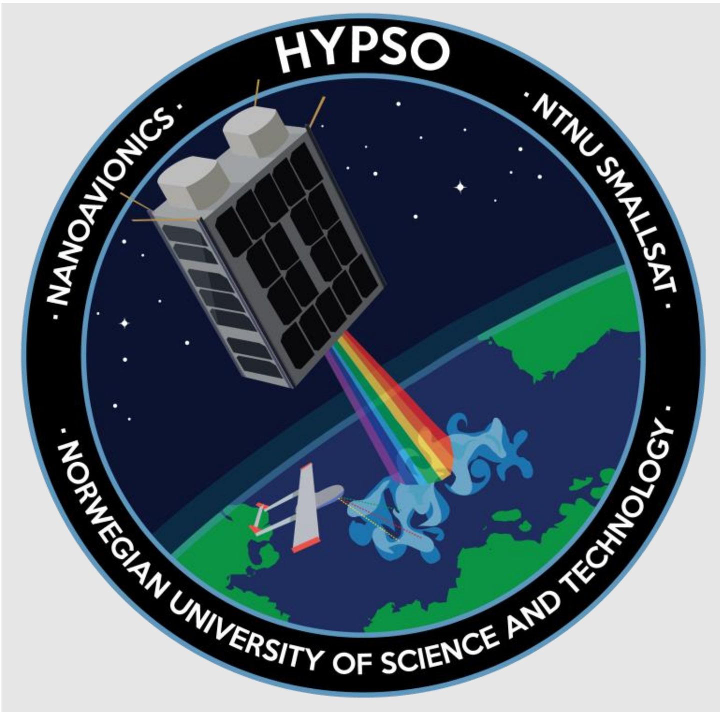
B Shock and Vibration test report

HYPSO-2 Shock, Resonance, and Vibration Test Report - EQM

HYPSO2-TPR-SHK-001



Prepared by:	HYPSO Project Team
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1. Scope

1.1 Overview

The Hyperspectral Smallsat for Ocean Observation (HYPSO) mission is a science-oriented technology demonstrator mission by the Norwegian University of Science and Technology (NTNU). It enables low-cost and high-performance hyperspectral imaging and autonomous onboard processing, fulfilling science requirements set by the ocean color remote sensing and oceanography communities.

In January 2022 the first Norwegian research satellite, HYPSO-1, equipped with a hyperspectral imager (HSI), was launched by NTNU SmallSat Lab. The second satellite, HYPSO-2, will follow shortly after with its launch planned in 2024. A vision of a constellation of remote-sensing focused cubesats as space-asset platforms added to the multi-agent architecture of UAVs, USVs, AUVs and buoys that have similar ocean characterization objectives creates a full observational pyramid observing the oceans.

The HYPSO-2 hyperspectral payload consists of a hyperspectral imager and a Red-Green-Blue (RGB) camera placed on a common payload platform, as seen in Figure 1.1. Both the HSI and RGB are powered and controlled through the electronics stack BoB. The HYPSO-2 hyperspectral payload will be similar to the HYPSO-1 hyperspectral payload, with a few changes. Most noticeable is the new slit tube design that will be tested and used for HYPSO-2 if the tests are passed. In addition, problems with the RGB camera for HYPSO-1 means more testing must be done with the RGB camera prior to launch. The RGB camera sensor and lens might be switched out, which would also mean modifications must be done to the payload platform.

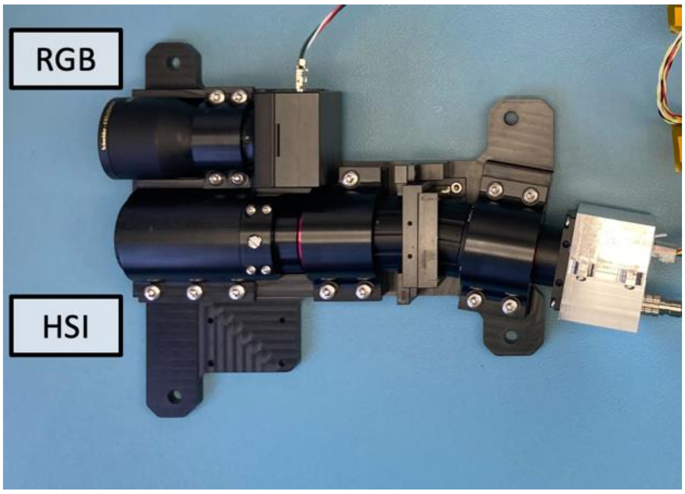


Figure 1.1: HYPSO-2 hyperspectral payload. HSI and RGB camera.

1.2 Document History

Table 1.1: Table of changes

Rev.	Summary of Changes	Author(s)	Effective Date
0	*First issue – document created*	*Simen Eger Heggelund*	*2023-02-15*
1	*Results added*	*S. E. Heggelund, M. B. Henriksen*	*2023-03-09*

1.3 Applicable Documents

Table 1.2: Applicable documents

AD	Author	Title
AD01	Space X	*RIDESHARE PAYLOAD USER'S GUIDE, October 2022*
AD02	NanoAvionics	*Satellite Mechanical Analysis Report, NA-018-SMAR-001-R001*
AD03	HYPSO Team	HYPSO-2 Shock, Resonance, and Vibration Test Plan – EQM, *HYPSO2-TPL-SHK-001*

1.4 Reference Documents

Table 1.3: Referenced documents

RD	Document ID	Rev.	Title
RD02	HYPSO2-TPL-OPT-004	1	Optical Validation Test Plan
RD03	HYPSO-TRP-VIB-003	1	Shock, Resonance, and Vibration of CLAW-1

2 Introduction

This report outlines the vibration, resonance and shock tests of the Engineering Qualification Model(EQM) of HYPSO-2 performed at Forsvarets forskningsinstitutt (FFI), Kjeller 15.-16. February 2023. The mass model used is the HYPSO-1 6U CubeSat provided by Nano Avionics.

The primary goals of the tests are to evaluate if the CubeSat will survive the launch environment and that the fundamental frequency of the components and Cubesat are above 74 Hz (40 Hz with 1.85 safety factor) [AD01]. A new slit tube design and RGB lens has been introduced, and the optical validation process will validate if the new design and component survives the launch environment. Another goal of the test is to evaluate if the payload interferes with other components during the tests. This will be done by inspecting the components when disassembling the payload.

The platform to be used for the Flight Model (FM) will be modified to tilt and to change position of the Star Tracker. Further testing will not be conducted, as discussed with NanoAvionics, as the change is relatively small. The planning and setup plan for this test can be seen in HYPSO-2 Shock, Resonance, and Vibration Test Plan – EQM [AD03].

In addition to testing the HSI and RGB payload mounted in the CubeSat, the payload will also be tested by itself. A simple eigenfrequency analysis will be performed when the platform design is set, and the team is going to compare it to the old design. The results of this testing will not be discussed in this report.

3 Test setup

3.1 Mechanical Test Setup

The CubeSat was mounted to the shaker table using mounting equipment shown in Figure 3.1.1. The equipment is explained in the test report [AD03].

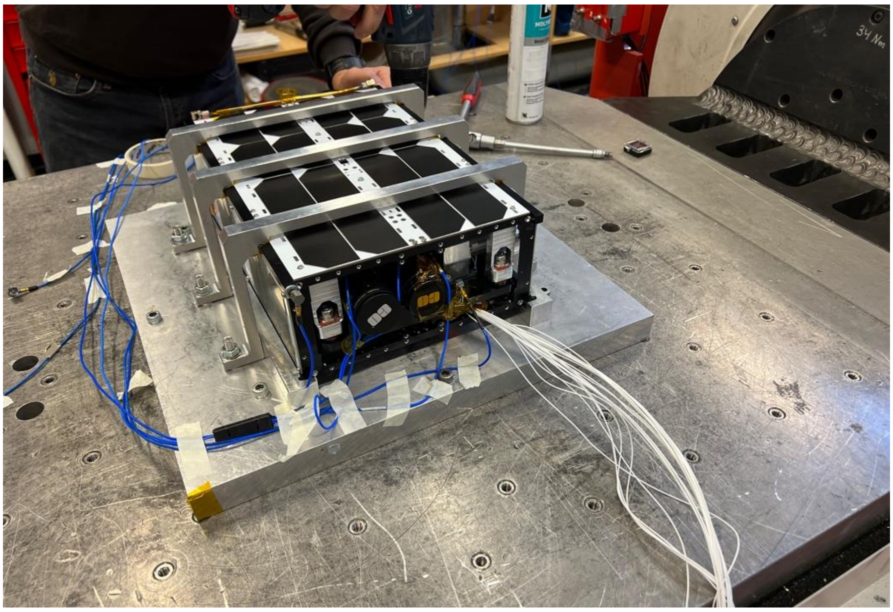


Figure 3.1.1: Mechanical setup for X- and Z-axis.

The X and Z-axis could be tested using the same table as in Figure 3.1 by rotaing the CubeSat and mounting setup 90-degrees. The Y-axis on the other hand was tested by using a different shaker setup seen in Figure 3.1.2.

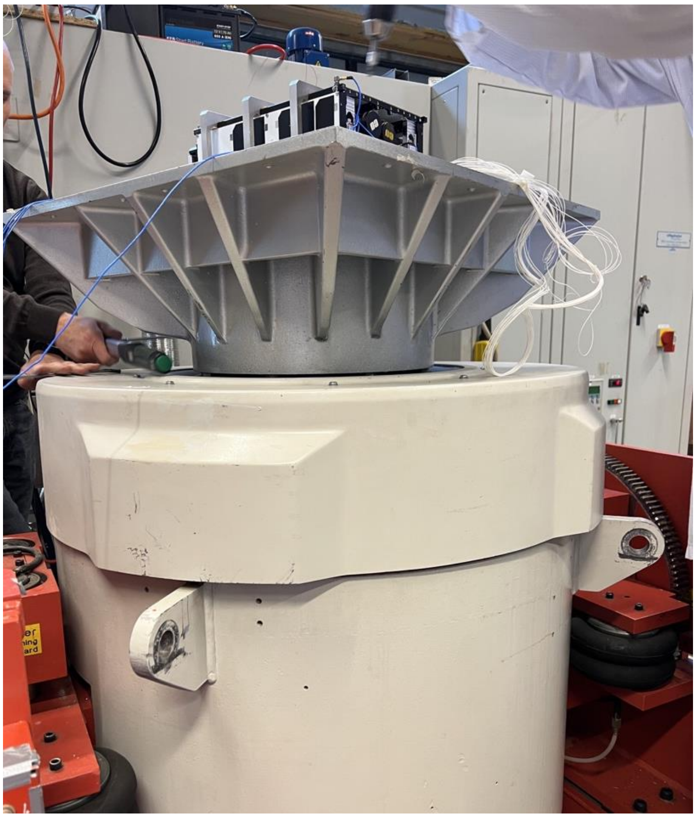


Figure 3.1.2: Mechanical setup for Y-axis.

Accelerometers sensors were mounted on the components explained in the test report [AD03]. Optical validation tests were also conducted between changing test axes. The optical validation test setup is shown in Figure 3.1.3 and 3.1.4. The optical validation process is explained in the Optical Validation Test Plan[RD02].

Figure 3.1.3: Dark box setup used

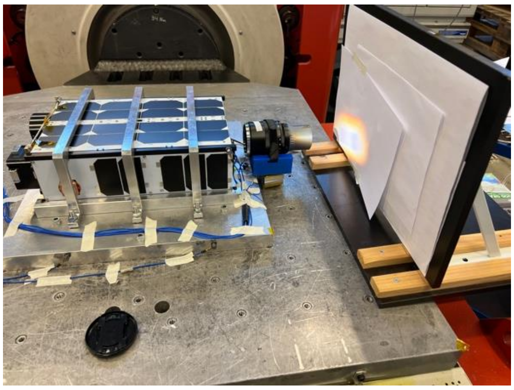


Figure 3.1.4 Optical validation using collimator

The HSI and RGB payload was also tested by itself. The test setup is shown in Figure 3.1.5. The results will not be discussed in this report.

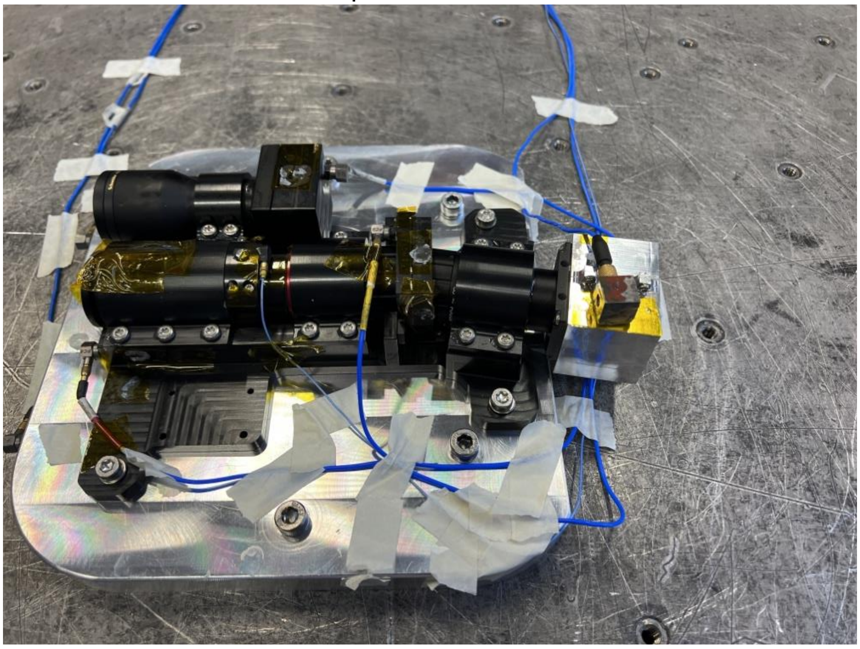


Figure 3.1.5 The HSI and RGB Payload testing

All screws were torqued according to Table 3.1.1:

Table 3.1.1 Recommended Torque

Screw	Torque (Nm)
M2	0.315 (0.4 Max)
M2.5	0.650 (0.9 Max)
M3	1.140 (1.6 Max)
M4	2.600 (2.7 Max)
M5	8.8 (9.5 Max)

3.2 Electrical Test Setup

An umbilical connected the PicoBoB to a power supply and the computer. Figure 3.2.1 shows the setup which is the same as used for HYPSO-1 testing. The equipment was placed on a separate table during vibration tests.

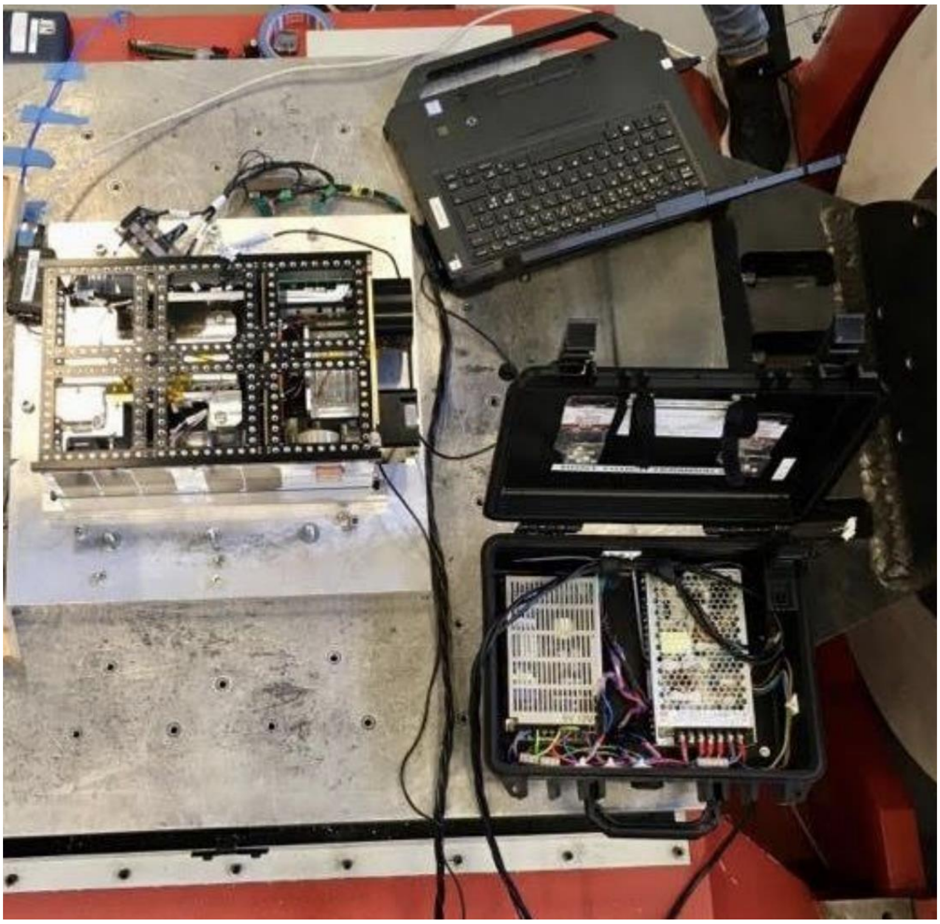


Figure 3.2.1 Electrical Setup from HYPSO-1 was used [RD03].

3.3 Image Setup

Different exposure times were tested on the first test runs. However, in consultation with Marie Henriksen, some exposure times were changed during optical validation tests when needed. The image settings are shown in Table 3.3.

Table 3.3 Image settings

Imager	**Exposure time [ms]**

HSI	100-200
RGB	10-20

3.3 Sensor Placement

A total of 6 sensors were placed on the CubeSat. This includes the RGB-housing, slit tube, grating casette, HSI detector housing, platform and the CubeSat-frame. The same components were tested in each axis.

In addition, control sensors for the shaker table were placed on the mounting plate to ensure that the output matched with the desired testing profile. The

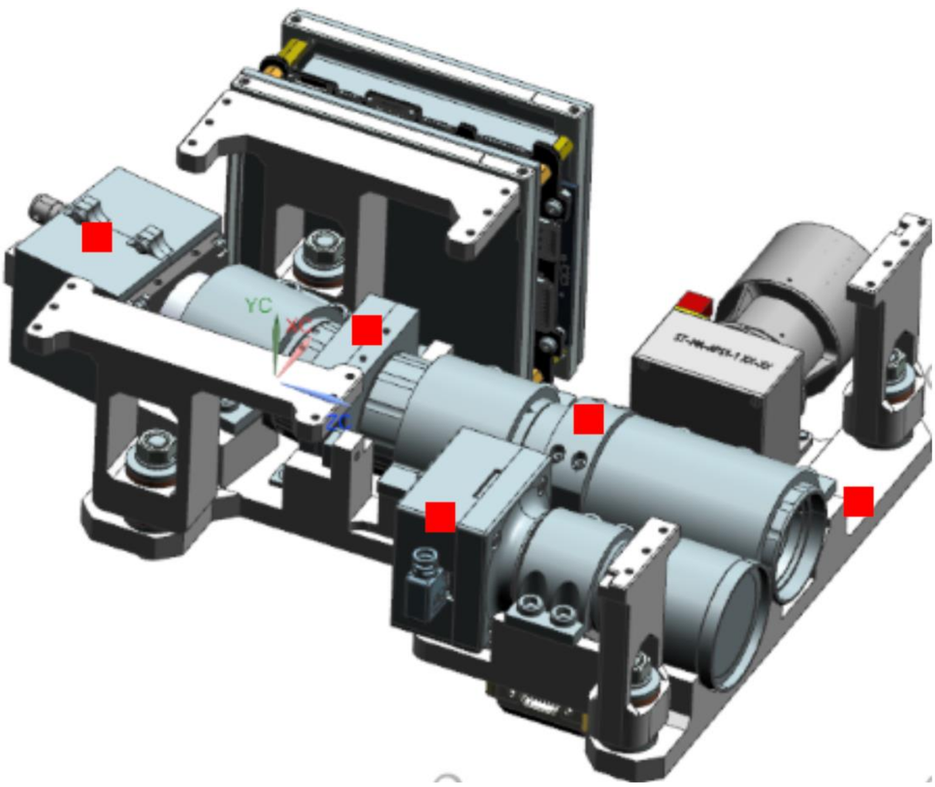


Figure 3.3.1 Sensor placement for X, Z-and Y axis.

3.4 Testing Profiles

Random vibration, shock and sine sweep tests were performed.

3.4.1 Random Vibration

The payload must be able to survive the random vibrations that are present during the flight and launch. Table 5.5.1 shows the recommended values for a random vibration test, the values are for all directions X, Y, and Z [AD02]. These values are 3 dB above acceptance values presented in [AD01].

Table 3.4.1 Random vibration test specifications.

RAND	**Qualification**	
Profile	**Frequency, Hz**	**PSD, G^2/Hz**
	20	0.02
	50	0.03
	700	0.03
	800	0.06
	925	0.06
	2000	0.01288
Acceleration, G (RMS) (g)		7.87
Duration, sec / axis		120

The values are illustrated in the profile plot in Figure 3.4.1.

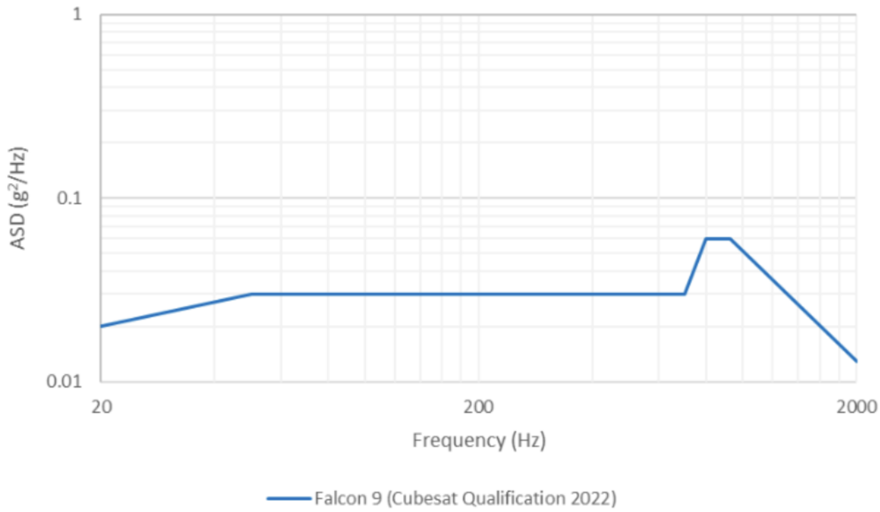


Figure 5.5.1 Random vibration profile [AD02].

3.4.2 Shock

The payload must be able to survive the shock loads present under launch. Table 3.4.2 tabulates the recommended values for a shock test according to SpaceX [AD01].

Table 3.4.2 Shock test requirements [AD01].

SHK	Test Level		
Profile	**Frequency, Hz**	**Maximum Predicted Environment (MPE) Induced by Launch Vehicle and Co-Payload(s) SRS (g)**	**Maximum Allowable Induced by Payload Separation System SRS (g)**
	100	30	30
	1000	1000	-
	1950	-	2850
	10 000	1000	2850

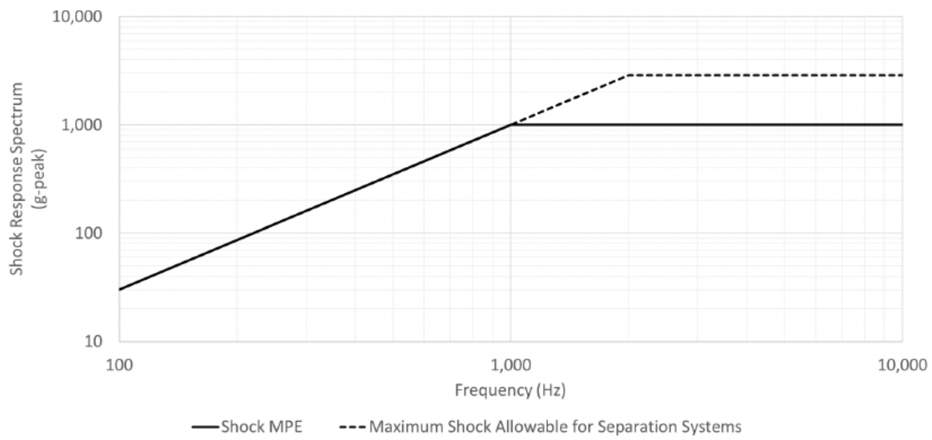


Figure 3.4.2. Payload Mechanical Interface Shock [AD01].

Due to machine constrains at FFI the shock test will be the same as for HYPSO-1 [RD03]. Table 3.4.3 tabulates the values used. The damping value Q=10 was recommended for HYPSO-2 by FFI, which is the same used for HYPSO-1.

Table 3.4.3 Shock test.

SHK	Test Level		
	Frequency, Hz	**Shock response spectrum(SRS), G**	**Slope (dB/Oct)**
Profile	100	30	7,73706
	600	300	
	2000	300	0

3.4.2 Sine Sweeps

Sine sweeps are performed between tests to check the fundamental frequency of the CubeSat tested. Sine sweep test after shock and vibration testing could also be used to check for small changes in the components by comparing the result with sine sweep results before shock and vibration testing.

Table 5.6.1. Basic sine sweep test.

SINE	Qualification

Frequency, Hz	5 - 200
Amplitude, G	0.4
Sweep Rate, octaves / min	2

3.5 Testing plan

Table 3.5 summarizes the tests performed. Nothing was changed from the test plan [AD03].

Table 3.5 Test plan

Test Name	Description	Axis	Equipment
DAY 1			
01-VAL	Validation 01	x	NTNU setup
02-SINE	Sine Sweep	x	FFI vibration table
03-RAND	Random Vibration	x	FFI vibration table
04-SHK	Shock	x	FFI vibration table
05-SINE	Sine Sweep	x	FFI vibration table
06-VAL	Validation 02	x,z	NTNU setup.
07-SINE	Sine Sweep	z	FFI vibration table
08-RAND	Random Vibration	z	FFI vibration table
09-SHK	Shock	z	FFI vibration table
10-SINE	Sine Sweep	z	FFI vibration table
11-VAL	Validation 03	z,y	NTNU setup
12-SINE	Sine Sweep	y	FFI vibration table
13-RAND	Random Vibration	y	FFI vibration table
14-SHK	Shock	y	FFI vibration table
15-SINE	Sine Sweep	y	FFI vibration table
16-VAL	Validation 04	y	NTNU setup
DAY 2 (HSI and RGB payload by itself)			
18-VAL	*Validation*	**y**	NTNU setup
19-SINE	*Sine Sweep*	**y**	FFI vibration table

20-SINE	*Sine Sweep*	**x**	FFI vibration table
21-SINE	*Sine Sweep*	**z**	FFI vibration table
22-VAL	*Validation*	**z**	NTNU setup

4 Results

Resonance, random vibration and shock tests were performed in the X, Z and Y-axis. The axes are defined as shown in Figure 4.1.

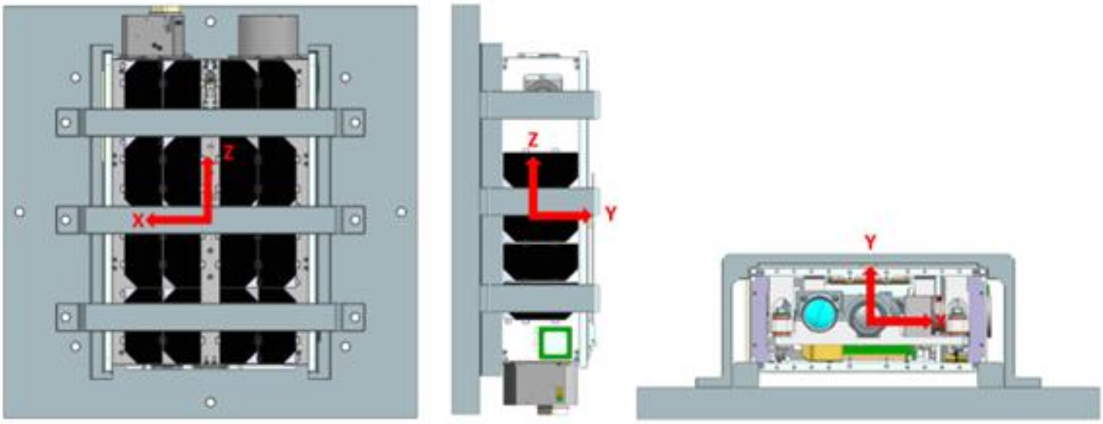


Figure 4.1 Defined satellite axes

A total of 6 accelorometers sensors were used on different componets in the CubeSat. The lines in the figures starting in Section 4.1.1 has been assigned with names. Table 4.1 shows the assigned name to these components.

Table 4.1 Explanations of the lines in the figures

Name	Description
M1	RGB-housing
M2	Slit Tube
M3	Cassette
M4	HSI Detector Housing
M5	Platform
M6	Frame

We had problems attaching the sensors to some of the components. This led to some of the sensors becoming detached during the testing. It can be seen in Figure 4.1.1 were the slit tube sensor came loose.

4.1 Sinusoidal Sweep Resonance

It is possible to determine whether resonant frequencies have changed during testing by performing a sinusoidal sweep before and after testing each axis.

The horizontal axis gives the frequency in [Hz] and the vertical axis is the force magnitude experienced in [g].

4.1.1 Sinusoidal Sweep Resonance X-direction Pre Testing

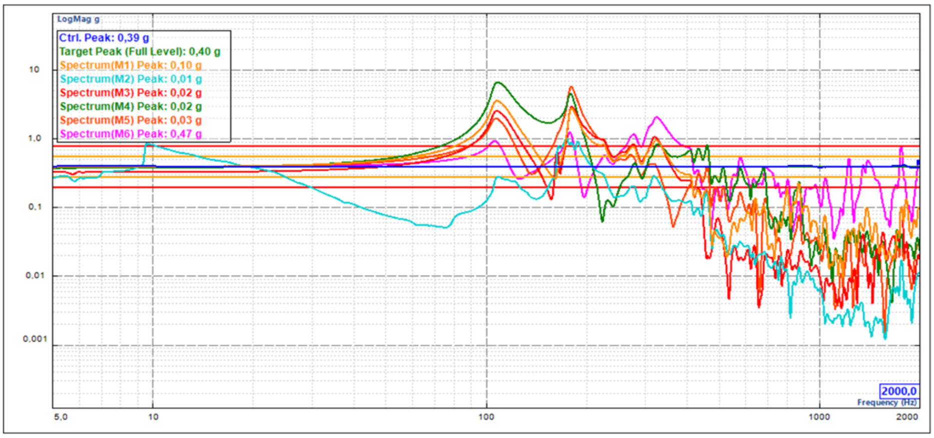


Figure 4.1.1: Component level response to sinusoidal sweep survey in the X-direction pre test.

4.1.2 Sinusoidal Sweep Resonance X-direction Post Testing

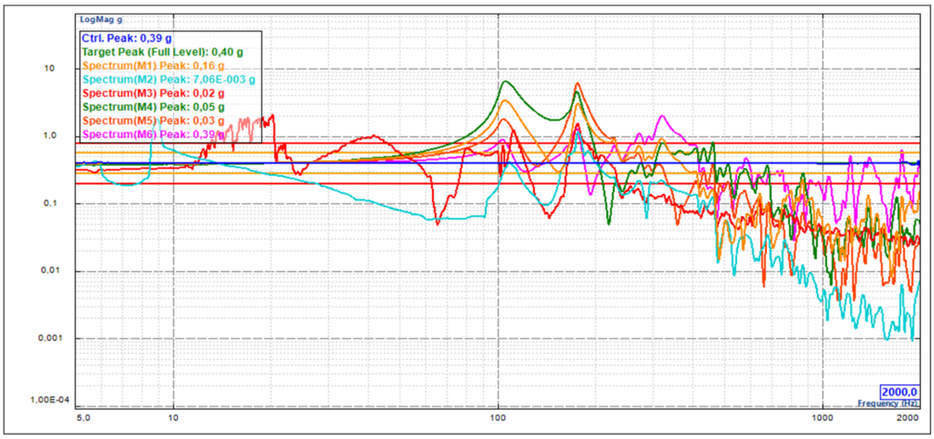


Figure 4.1.2: Component level response to sinusoidal sweep survey in the X-direction post test.

4.1.3 Sinusoidal Sweep Resonance Z-direction Pre Testing

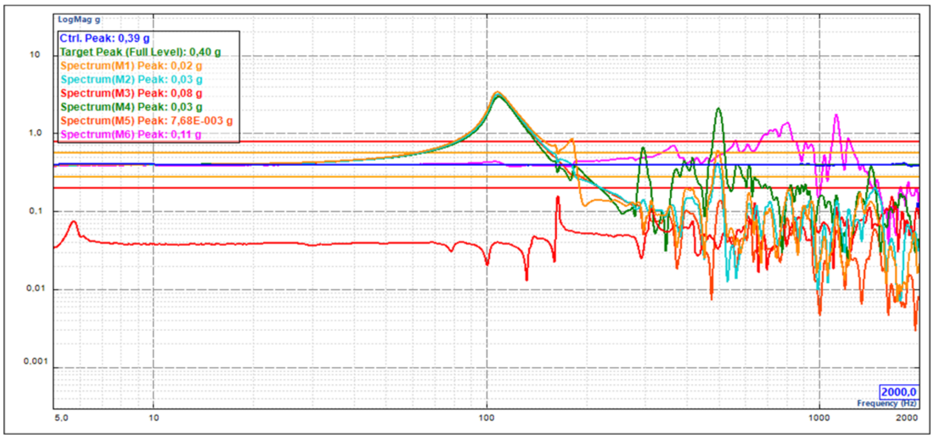


Figure 4.1.3: Component level response to sinusoidal sweep survey in the Z-direction pre test.

4.1.4 Sinusoidal Sweep Resonance Z-direction Post Testing

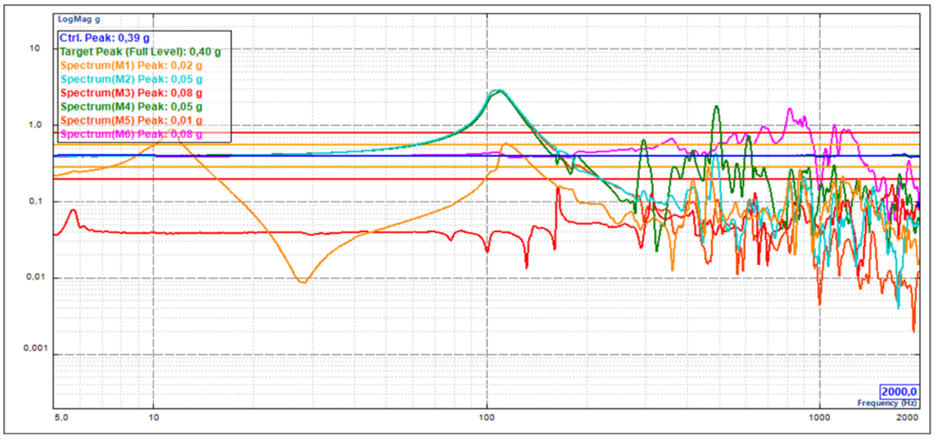


Figure 4.1.4: Component level response to sinusoidal sweep survey in the Z-direction post test.

4.1.5 Sinusoidal Sweep Resonance Y-direction Pre Testing

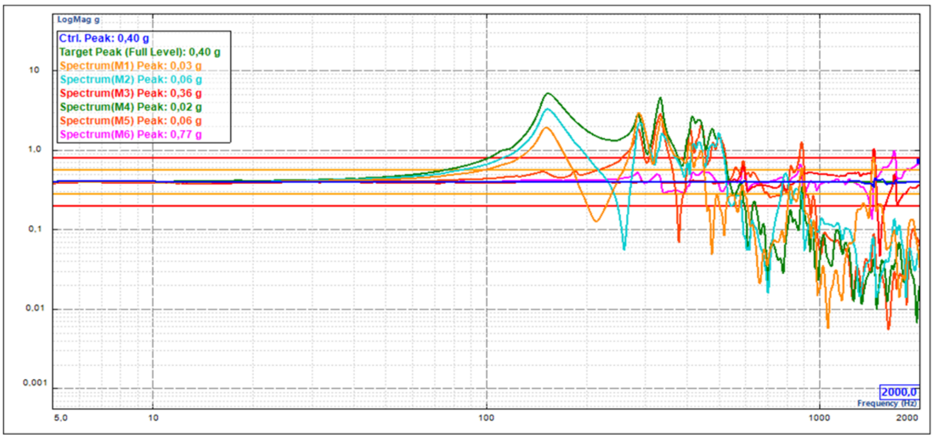


Figure 4.1.5: Component level response to sinusoidal sweep survey in the Y-direction pre test.

4.1.6 Sinusoidal Sweep Resonance Y-direction Post Testing

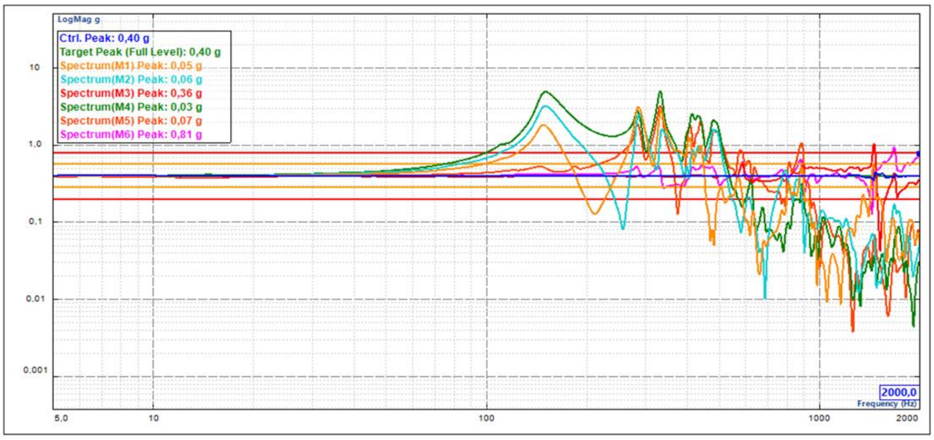


Figure 4.1.6: Component level response to sinusoidal sweep survey in the Z-direction post test.

4.1.7 Sinusoidal Sweep Resonance Summary

Table 4.1.7.1 Major sweep resonance peaks over 1g in increasing frequency for X, Z, and Y axes along with percentage change in frequency shift.

X-axis		
	Pre-test [Hz]	*Post random vibration and shock[Hz]*
RGB	118	113 (-4%)
Slit Tube	NA	NA
Grating Cassette	118	NA
HSI Detector	120	117 (-3%)
Platform	116 [0.9g]	112 [0.9g] (-4%)
Frame	116	110 (-5%)
Z-axis		
	Pre-test [Hz]	*Post random and shock[Hz]*
RGB	120	NA

Slit Tube	122	123 (1%)
Grating Cassette	NA	NA
HSI Detector	124	125 (1%)
Platform	805	815 (1%)
Frame	120	118 (-2%)
Y-axis		
	Pre-test [Hz]	*Post random and shock[Hz]*
RGB	158	156 (-2%)
Slit Tube	162	158 (-3%)
Grating Cassette	285	285 (0%)
HSI Detector	161	157 (-3%)
Platform	287	287 (0%)
Frame	1760	1780 (1%)

As shown in Table 4.1.7 the first Eigenfrequencies for the components are at 116 Hz, 120 Hz and 158 Hz for the X,Z and Y axis. This is well above Space X's requirement of 40 Hz (74 Hz with a safety factor of 1.85).

Table 4.1.7.2 First component Eigen frequency (frame not included)

Axis	First Eigenfrequency
X	116
Z	120
Y	158

4.2 Random Vibrations

The output data is given as power spectrum density plots for random vibrations. This gives the root-mean-square response for each of the channels to an acceleration base input. The base input is the acceleration power spectral density. As the sinusoidal sweep test, some of the accelerometer sensors loosened during the tests.

4.2.1 Random Vibration, X-direction

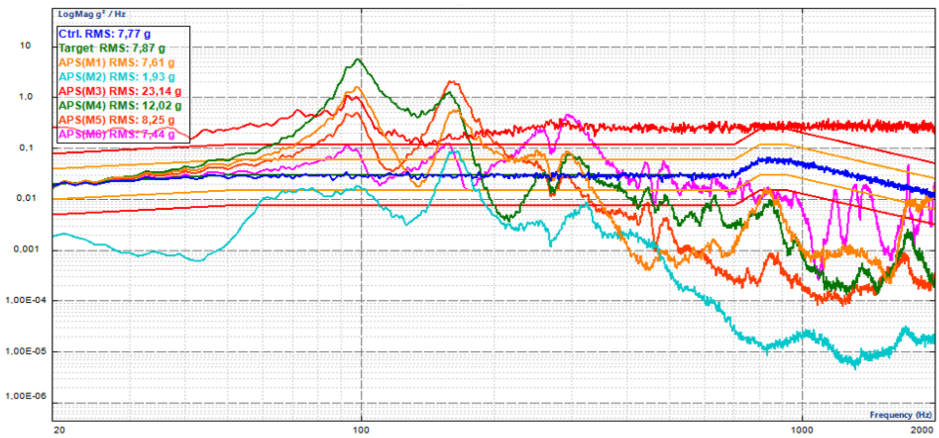


Figure 4.2.1: Random response in X-axis

4.2.2 Random Vibration, Z-direction

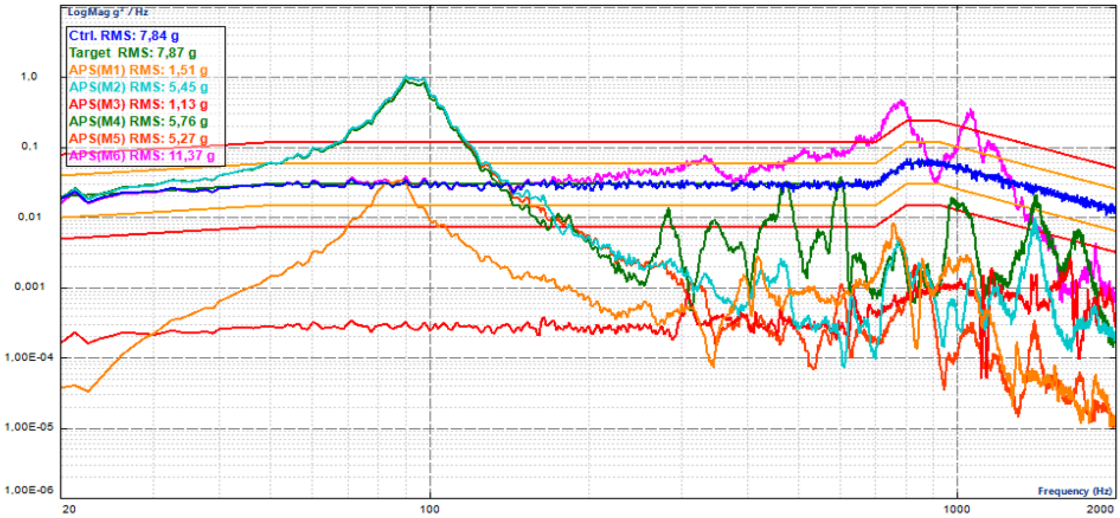


Figure 4.2.2: Random response in Z-axis

4.2.3 Random Vibration, Y-direction

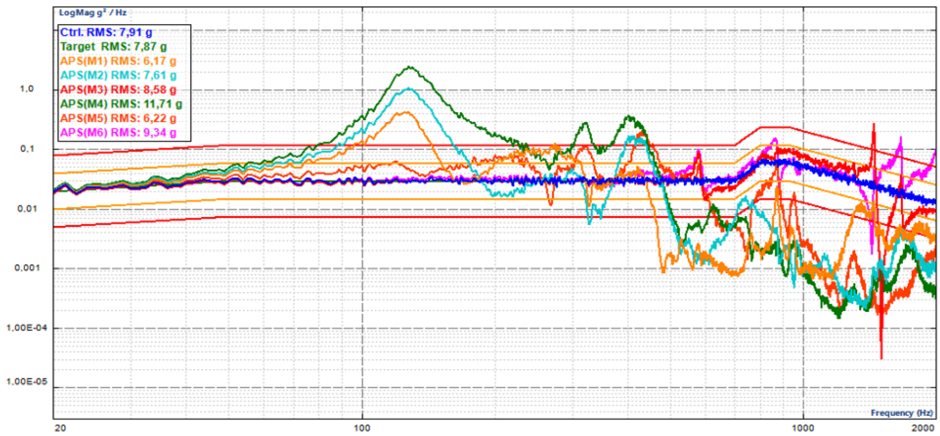


Figure 4.2.3: *Random response in Y-axis*

The lowest frequency experienced is shown in Figure 4.2.2 and is 90 Hz. This is above the 40 Hz (74 Hz with safety factor of 1.85) requirement.

4.3 Shock

Due to machine constrains at FFI the test reached 300g in the shock response spectrum (SRS). As for the previous tests, a few sensor loosened during the tests.

The general run schedule of the shock test is as follows:

Level 25%, Pulses 2
Level 50%, Pulses 2
Level 75%, Pulses 2
Level 100%, Pulses 1

4.3.1 Shock, X-direction

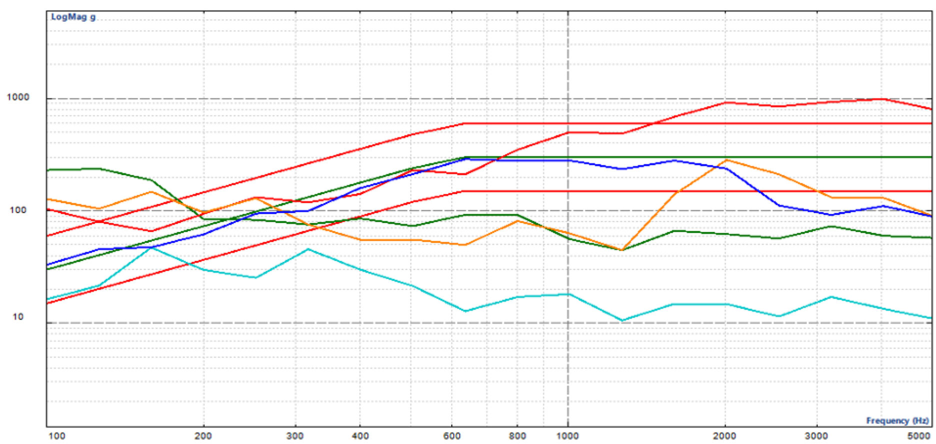


Figure 4.3.1: *Shock response in X-axis*

4.3.2 Shock, Z-direction

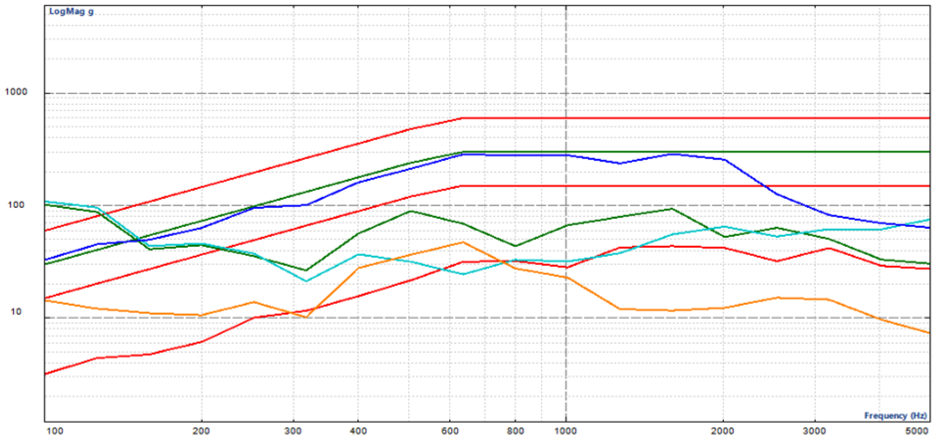


Figure 4.3.2: *Shock response in Z-axis*

4.3.3 Shock, Y-direction

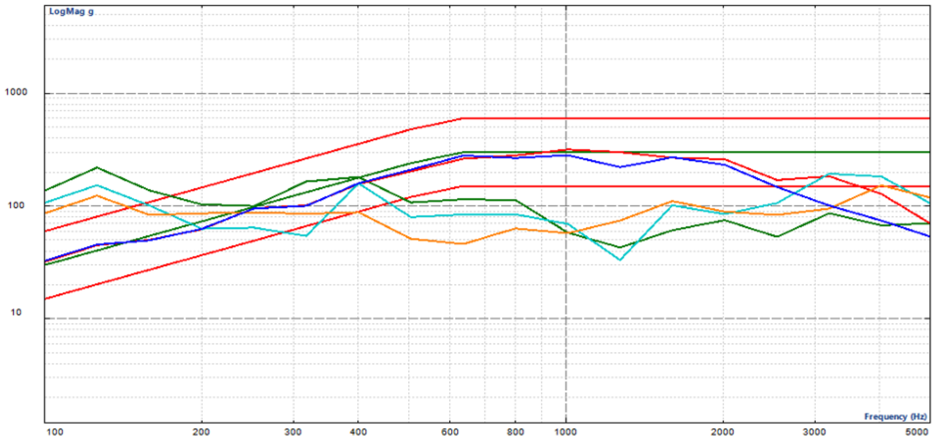


Figure 4.3.3: *Shock response in Y-axis*

All axes exceed the 6 dB margin at low frequencies. When comparing to HYPSO-1 only responses in X and Y exceed the 6 dB margin.

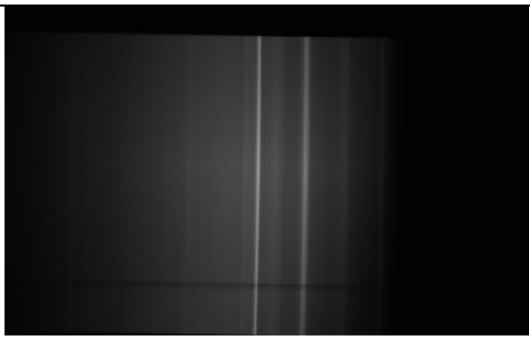
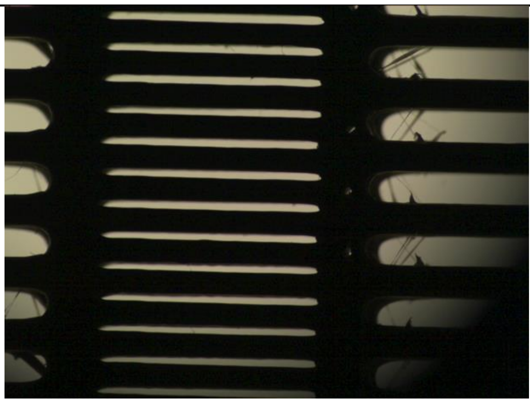
5 Optical Validation

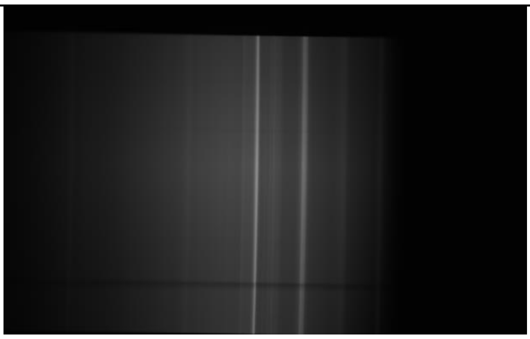
Images were captured as described in [RD02] before the testing started (pre) and after the shock and vibration test in each axis (X, Z, and Y), resulting in 20 datasets (5 optical validation tests done 4 times). For each dataset, 5 images were taken with the HSI, or 1-2 images were taken with the RGB camera. One image from each of these sets, together with the exposure time used for capture (only SW parameter varying between the captures) is shown in Table 5.1.

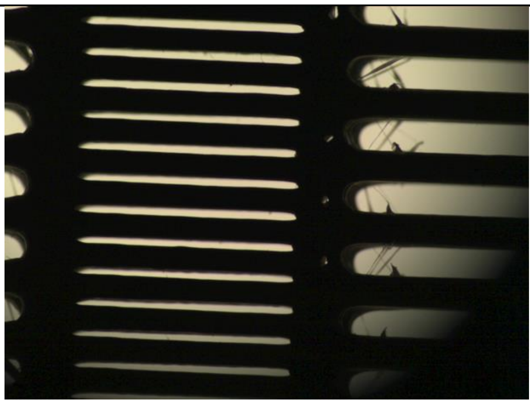
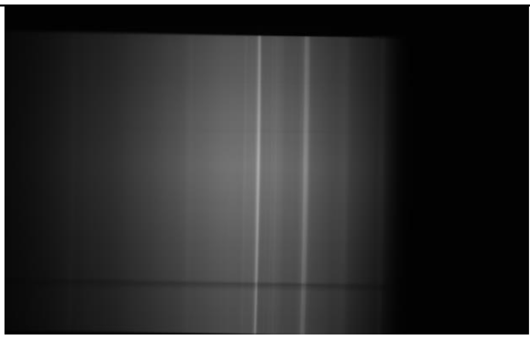
For the HSI images, intensity may vary as the light was not reflected evenly from the whole sheet of paper, so looking at different parts of the white paper target can give different amount of light. By using the fluorescent (test 1, HSI spectral) and stable lamp (test 2 and 3, HSI white and spatial) however, this should not matter as the spectrum should stay the same, and the signals can be normalized by dividing by the maximum value for analysis.
For the RGB, it was also pointed at not exactly the same part of the white sheet of paper, so the images may vary slightly. The interesting features to keep in mind are any dust/smudges on the lenses (test 4, RGB white), and how sharp the lines are when using the collimator and striped pattern (test 5, RGB spatial).

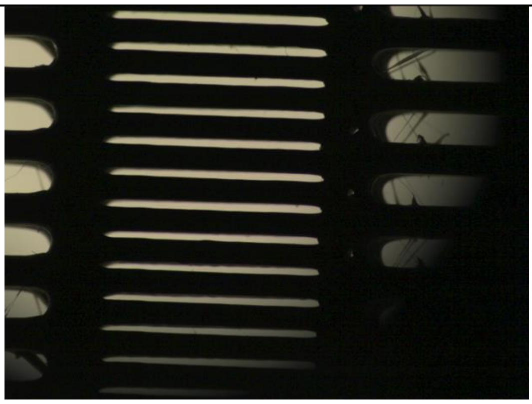
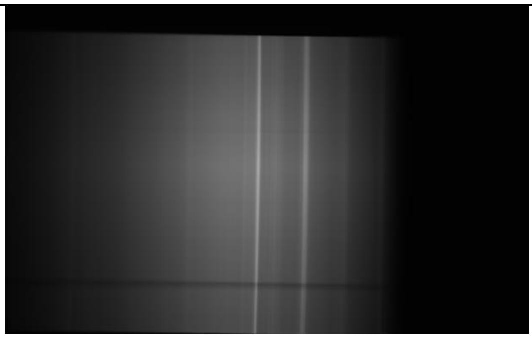
Table 5.1: Overview of optical validation data acquired during shock and vibration testing. Optical tests 1-5 are described in [RD02]. Test number ranges are 1 (pre, before shock and vibration test), 2 (after test in X-axis), 3 (after test in Z-axis) and 4 (after test in Y-axis).

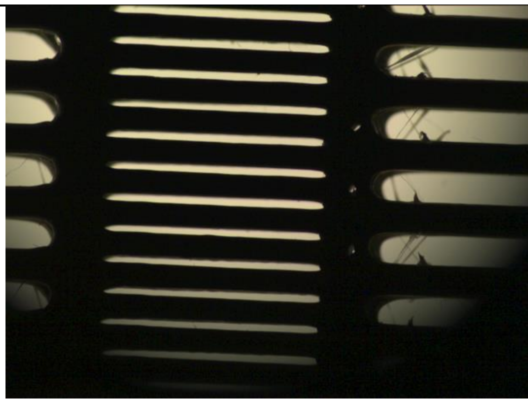
Optical test	**Test #**	**Identifier in name of folder**	**Exposure time [ms]**	**Image**
1: HSI spectral	1	1 (PRE) 01VAL01	150	

2: HSI white	1	1 (PRE) 01VAL02	200	
3: HSI spatial	1	1 (PRE) 01VAL03	200	
4: RGB white	1	1 (PRE) 01Val04	10	
5: RGB spatial	1	1 (PRE) 01VAL05	10	

1: HSI spectral	2	2 (XZ) 02VAL01	150	
2: HSI white	2	2 (XZ) 02VAL02	200	
3: HSI spatial	2	2 (XZ) 02VAL03	200	
4: RGB white	2	2 (XZ) 02VAL04	10	

5: RGB spatial	2	2 (XZ) 02VAL05	10	
1: HSI spectral	3	3 (ZY) 03VAL01	100	
2: HSI white	3	3 (ZY) 03VAL02	200	
3: HSI spatial	3	3 (ZY) 03VAL03	200	

4: RGB white	3	3 (ZY) 03VAL04	10	
5: RGB spatial	3	3 (XY) 03VAL05	10	
1: HSI spectral	4	4 (POST) 03VAL01	100	
2: HSI white	4	4 (POST) 03VAL02	200	

3: HSI spatial	4	4 (POST) 03VAL03	200	
4: RGB white	4	4 (POST) 04VAL04	10	
5: RGB spatial	4	4 (POST) 04VAL05	15	

5.1 Analysis of HSI data

When analyzing these images further, one of the most interesting things to look for here was if any spectral or spatial shifts could be detected with the HSI, indicating that any components moved during the test. When looking at the HSI spectral images (optical validation test 1), a row (horizontal line in the image) was plotted before and after the test, as seen in Figure 5.1, to see if any spectral shifts could be detected. When looking at the plot, the peaks seem to be in the exact same location before and after, indicating that no spectral shift has appeared after shock and vibration testing. The same result was found when looking at other rows as well.

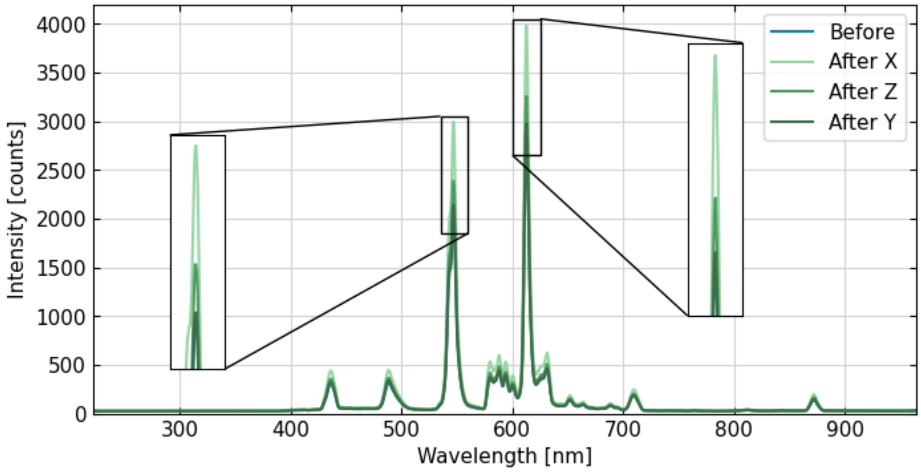


Figure 5.1: Checking for spectral shift in optical validation data (test 1) in the HYPSO-2 EQM HSI during shock and vibration testing.

When looking at the HSI white images (optical validation test 2), a column (vertical line in the image) was plotted before and after the tests and compared to see if any spatial shifts could be detected (Figure 5.2). A small shift of about 1 pixel looks visible in the plot. This is approximately the same as could be seen for the HYPSO-1 QM after shock and vibration testing, but is much less than what can be seen for the HYPSO-1 FM after launch. Here, it is hard to tell wether this small shift comes from components in different position (slit or camera sensor), or if it is simply small changes in the intensity between the images which makes it look like, the zoomed in box plot, that there has been a shift. When checking other columns, the result is the same. If a larger shift had been seen, it would have been concerning. But since the shift looks small and there are some uncertainties with the lamp intensity, the conlcusion from the optical tests is that the slit tube passes the shock and vibration tests.

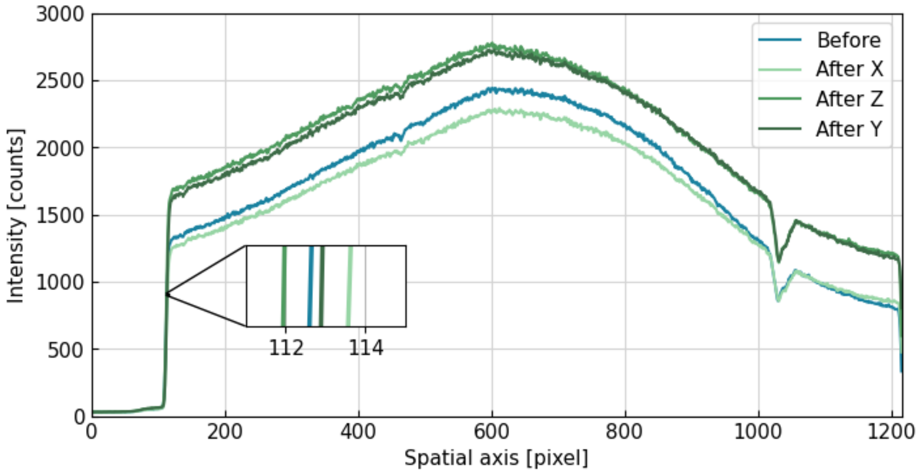


Figure 5.2: Checking for spatial shift in optical validation data (test 2) in the HYPSO-2 EQM HSI during shock and vibration testing.

6 Conclusion

Based on the results from the sine sweep tests, the fundamental frequency of the CubeSat and components are above the requirement set by Space X [AD01]. The most concerning part is the HSI Detector which is well above the 3 dB margin during random vibration in the X-axis, shown in Figure 4.2.1. The HSI Detector design is the same as for HYPSO-1 and it was expected that the most conserning axis should be the X-axis based on experiences from previous tests, and the fact that it is suspended from the C-mount objective attachment only. However, the optical validation of the HSI shows no large spectral or spatial shifts, and no large changes to the HSI detector can be found in the sine sweep tests.

No component interference and damage could be observed post test, and no issues regarding the electrical setup was recorded.

From the optical validation of the HSI, the new slit tube passes the tests since no large spectral or spatial shifts can be seen. The new slit tube design will therefore be used for the HYPSO-2 FM, if no other concerns are raised at the payload CDR.

C EQM as built report

Building HYPSO-2 EQM

HYPSO2-DR-009

Prepared by:	HYPSO Project Team
Reference:	HYPSO2-DR-009
Revision:	1
Date of issue:	Date
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Table 1: Table of Changes

Rev.	**Summary of Changes**	**Author(s)**	**Effective Date**
1	*First issue*	*S. E. Heggelund, E. Håland, M. B. Henriksen, R. Birkeland*	
A			

1 Overview

The Hyperspectral Smallsat for Ocean Observation (HYPSO) mission is a science-oriented technology demonstrator mission by the Norwegian University of Science and Technology (NTNU). It enables low-cost and high-performance hyperspectral imaging and autonomous onboard processing, fulfilling science requirements set by the ocean color remote sensing and oceanography communities.

In January 2022, the first Norwegian research satellite, HYPSO-1, equipped with a hyperspectral imager (HSI), was launched by NTNU SmallSat Lab. The second satellite, HYPSO-2, will follow shortly after with its launch planned in 2024. A vision of a constellation of remote-sensing focused CubeSats as space-asset platforms added to the multi-agent architecture of UAVs, USVs, AUVs and buoys that have similar ocean characterization objectives creates a full observational pyramid observing the oceans.

1.2 Scope

The following document describes the processes of assembling and calibrating the Engineering Qualifying Model (EQM).

1.3 Referenced Documents

The following table lists the applicable documents for this document and work.

Table 2: Referenced Documents

ID	Author	Title	Version
[RD01]	M. Hjertenæs, E. F. Prentice	HYPSO-RP-031 Objective Disassembly and Cleaning	
[RD02]	M. Hjertenæs, E. F. Prentice, T. Kaasa	HYPSO-RP-039 Objective Disassembly and Cleaning: Flight Model	
[RD03]	E. F. Prentice, M. Hjertenæs, M. B. Henriksen	HYPSO-RP-043 Flight Model As-Built	
[RD04]	M. B. Henriksen	HYPSO2-TPL-OPT-002 Focus Objectives Test Plan	
[RD05]	M. B. Henriksen	HYPSO2-TPL-OPT-003 Focus HSI Test Plan	

2 Assembly

The following sections discribes the process of assembing the EQM. During the process all screws should be epoxied.

2.1 Disassembly, cleaning, and assembly of objectives

The objectives are disassembled according to the guide [RD02]. Lenses are bagged immediately. Venting holes had to be drilled.

Figure 1: Cleaning of objectives

2.2 Assembly of grating cassette

Gaskets are cut by hand and glued to brackets with epoxy. Brackets are placed in grating cassette. Grating is placed in grating cassette; arrows indicate what direction the light should hit the grating and in what way it is bent. The brackets are tightened around the grating using M2 set screws.

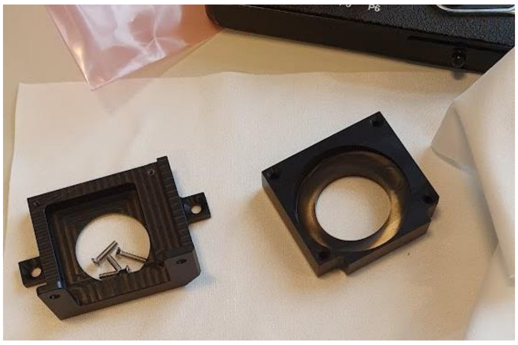


Figure 2: Grating cassette parts

2.3 Assembly of new Slit Tube

The slit arrives from the manufacturer pre-assembled. However, we found that it was still possible to rotate the slit in its housing even with the friction ring. Since this is a huge risk for getting a proper spectrogram, the slit needed to be secured in its housing. This was done by adding drops of epoxy along the inner ring of the housing

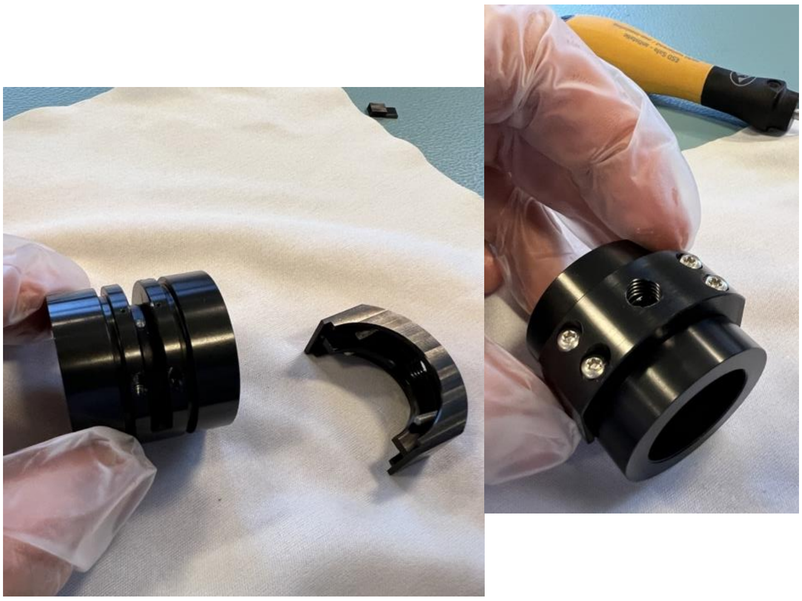


Figure 3 (a) and (b): Slit tube assembling

Figure 4: Slit tube fully assembled

When inserting the slit, a small dent was made. It is important to be very careful when handeling the slit, and is something to be aware of when assembling the Flight Model(FM) in the future.

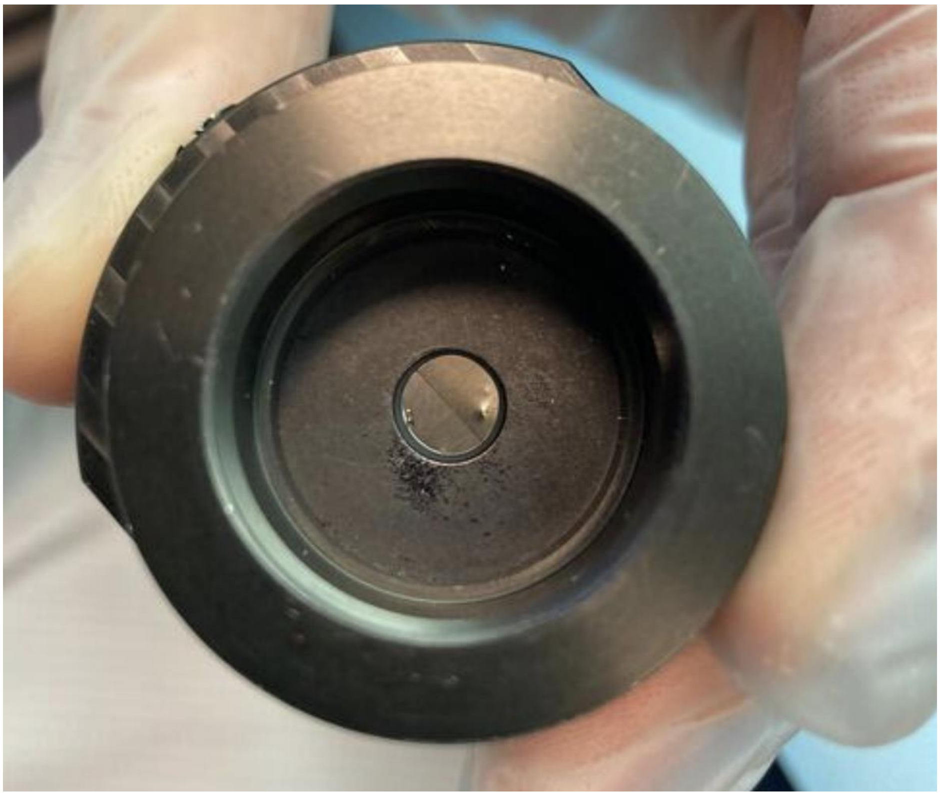


Figure 5: Dent in epoxied slit

2.4 HSI Sensor Assembly

The sensor is disassembled, and stickers are removed. Glue from stickers is cleaned with ethanol. Polymer pads are removed; plastic washers need to be replaced with metal (M2.5X3). Excess glue on power transformer is removed with a scalpel.

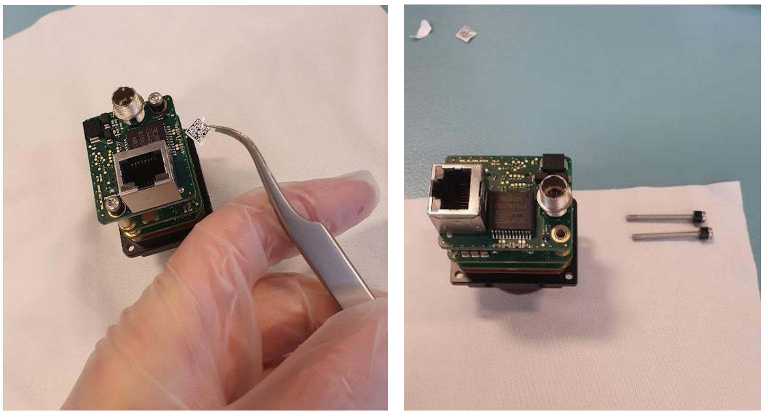


Figure 6 (a) and (b): Preparing the HSI Detector

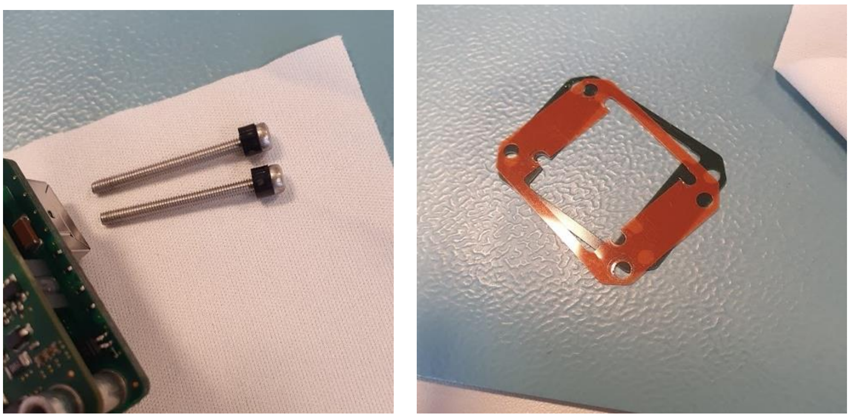


Figure 7 (a) and (b): Preparing the HSI Detector

2.5 RGB-assembly

Stickers are removed from the RGB sensor and the glue from the stickers is cleaned with ethanol.

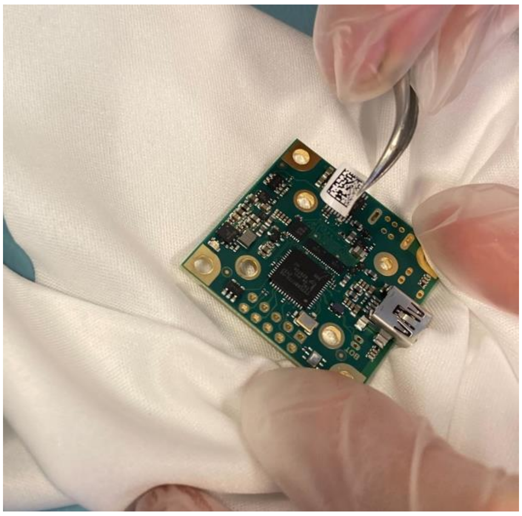


Figure 8: Preparing of the RGB sensor

Sensor is mounted in the sensor housing with 3 out of 4 screws (only 3 of the holes are possible to use). Due to the orientation of the USB2 connector, the sensor is mounted upside down in the housing (when mounted on the payload platform). Epoxy are added to the 3 screws to make sure that the sensor does not move inside the sensor housing.

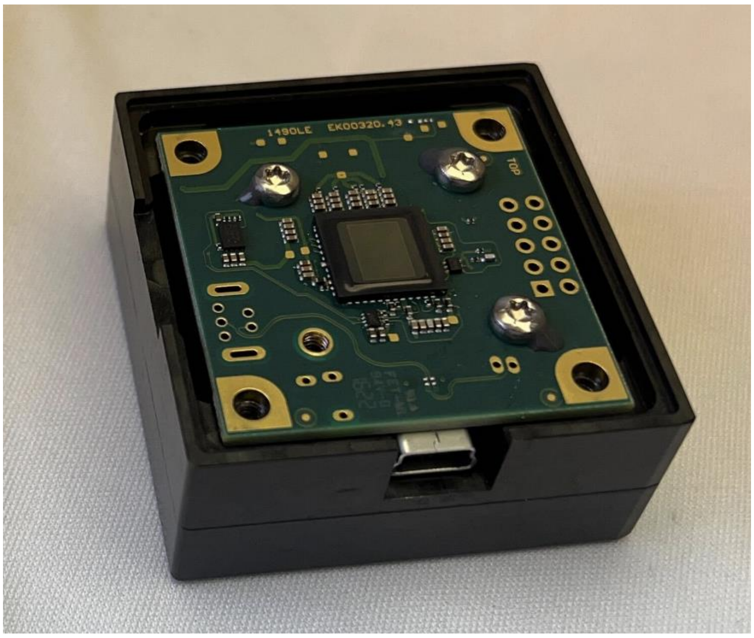


Figure 9: Sensor in RGB housing

The sensor housing is then closed using the C-mount part. An IR-filter is mounted on the end of the RGB lens and the screws are epoxied after focusing the lens, described in Section 3.1. A fully assembled RGB camera can be seen in Figure 12.

Figure 10: Epoxy ready to be applied

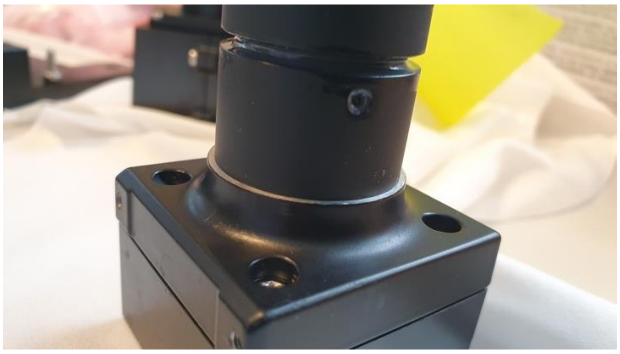


Figure 11: Epoxy applied

Figure 12: Epoxy applied, and the RGB fully assembled

2.5 Preparing the brackets

Kapton tape is used inside all of the brackets (3x HSI and 1x RGB). This tape acts as a gasket to ensure a tight fit.

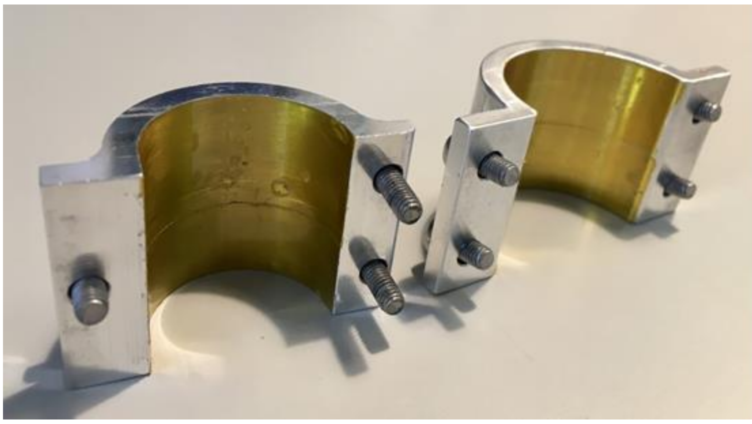


Figure 13: Kapton tape inside brackets. This picture is from a test before the parts was anodized. Kapton tape was applied after anodizing.

2.6 Building the HSI

The grating cassette is fastened with two M3X6 screws in the floor of the platform and two M3X8 screws to the wall of the platform. Grating cassette was torqued before epoxied.

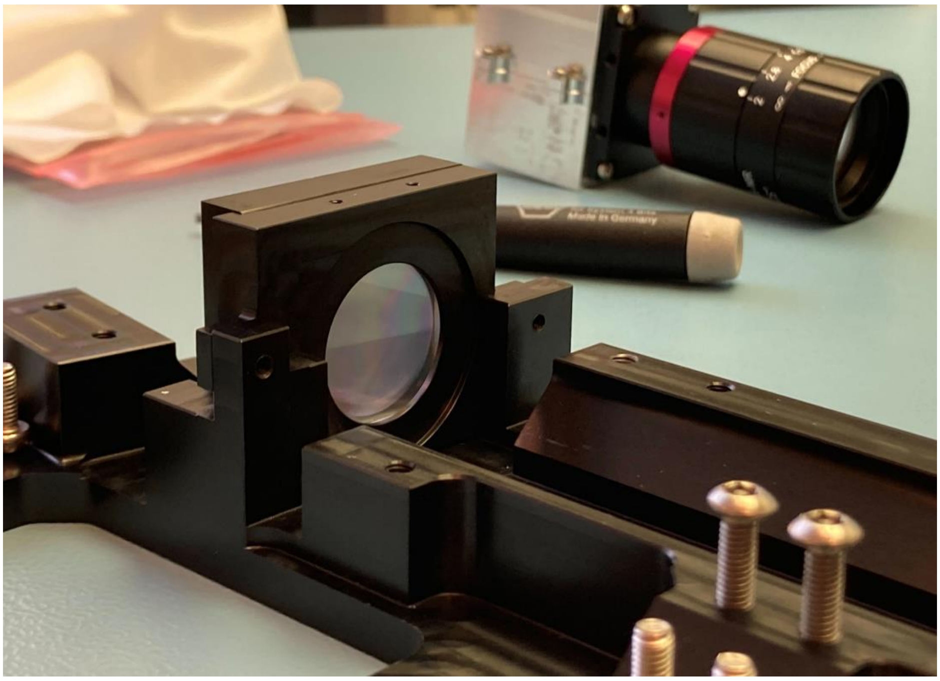


Figure 14: Grating cassette mounted to the platform

Using the USB-sensor, the objectives is individualy focused before assembling. This is shown in Section 3.2.
The rear objective (Objective 33) is fastened to the HSI sensor.

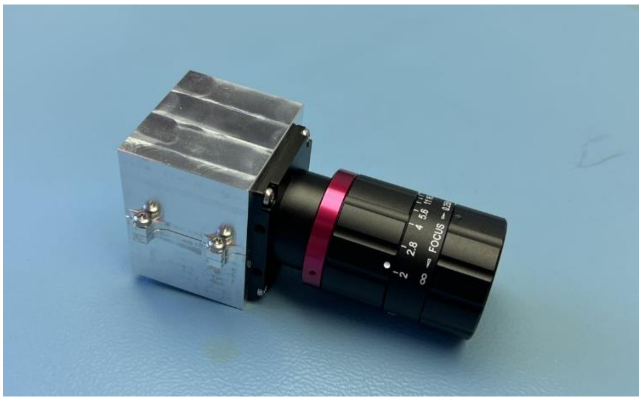


Figure 15: Rear objective epoxied and mounted to the HSI Detector.

The rear objective is placed against the back of the grating cassette. The sensor housing is torqued before mounted on the platform. A spirit level is used to make sure the sensor is leveled.

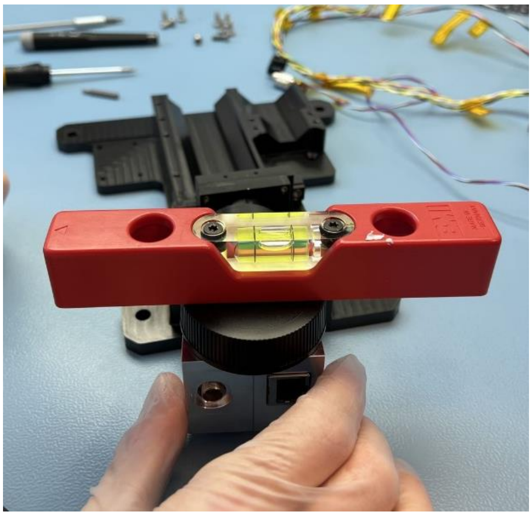


Figure 16: Rear objective leveled

The rear bracket is placed and fastened with four M4X10 bolts to secure the rear objective. The screws are tourqued.

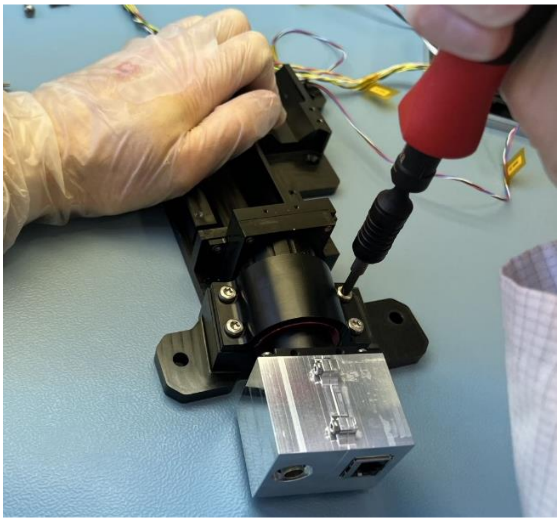


Figure 17: Torquing the rear bracket

The two front objectives (Objective 31 and Objective 32) are screwed to either side of the slit tube. It is double checked that these both have the apertures (Objective 33 has no aperture).

Figure 18: Objectives and slit tube

The objective and slit assembly is placed against the front of the grating cassette. The HSI focus is now checked, see next chapter (HSI focus, chapter 3.3). Spacer rings, 0.4 mm between the front objective and slit tube, and 0.5 mm between the slit tube and collimating/middle objective, are added.

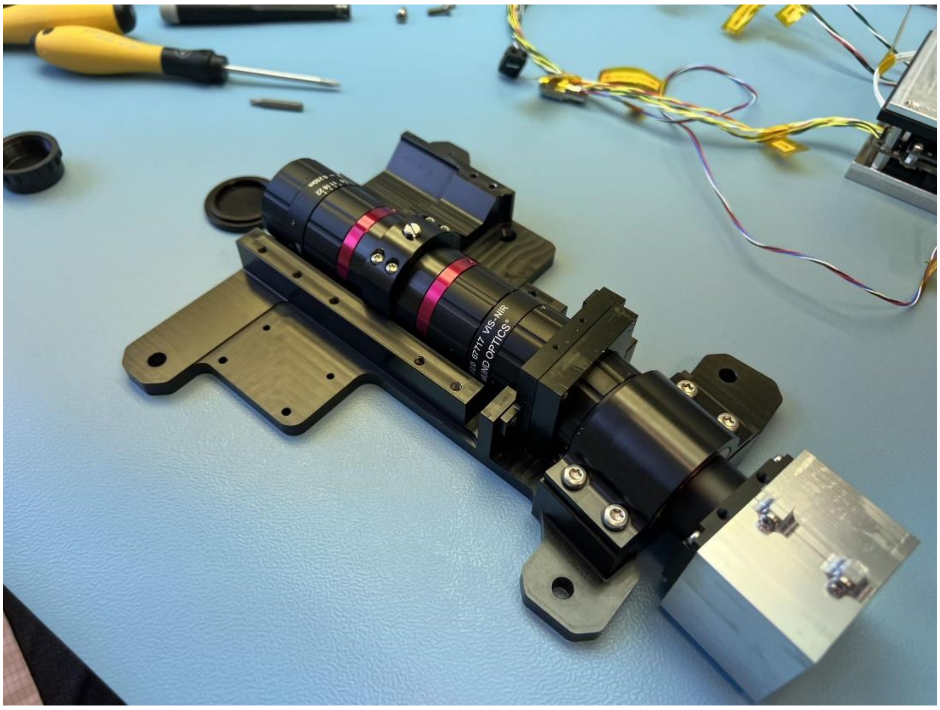


Figure 18: HSI Payload assembled

The middle HSI bracket is placed and fastened with four M4X10 bolts and the front HSI bracket is placed and fastened with three M4X10 bolts. The RGB bracket is placed and both the brackets are fastened with two M4X12 bolts. All these screws are torqued.

After focusing, the sensor was switched to a USB3 sensor. This is used when straightening the slit. To adjust the slit, the screws of the slit tube bracket are loosened and the slit is moved by using a rod. The slit is adjusted until it is straight. A simple way to confirm this is to move a computer window next to a spectral line in a captured spectrogram. The screws of the slit tube bracket are then tightened. It became apparent that the slit adjusted its position slightly after the bracket was tightened. This led to the slit position of the EQM being slightly crooked.

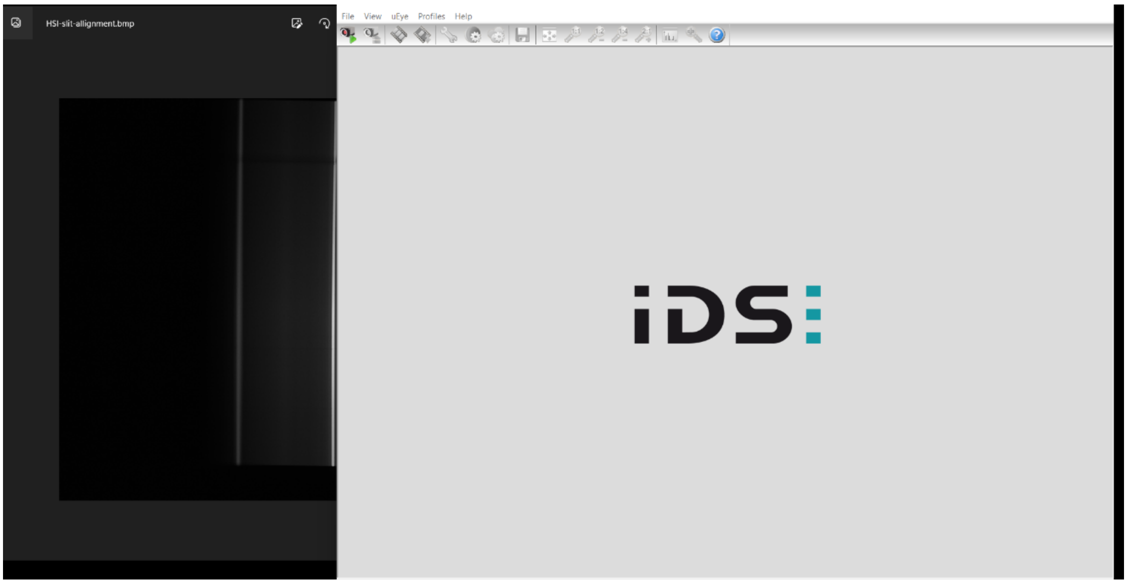


*Figure 19: Images taken in the process of s*traightening the slit

Finally, the sensor is switched back to the EQM HSI sensor. The sensor is levelled, and the bracket placed and fastened again with four M4X10 bolts, and torqued.

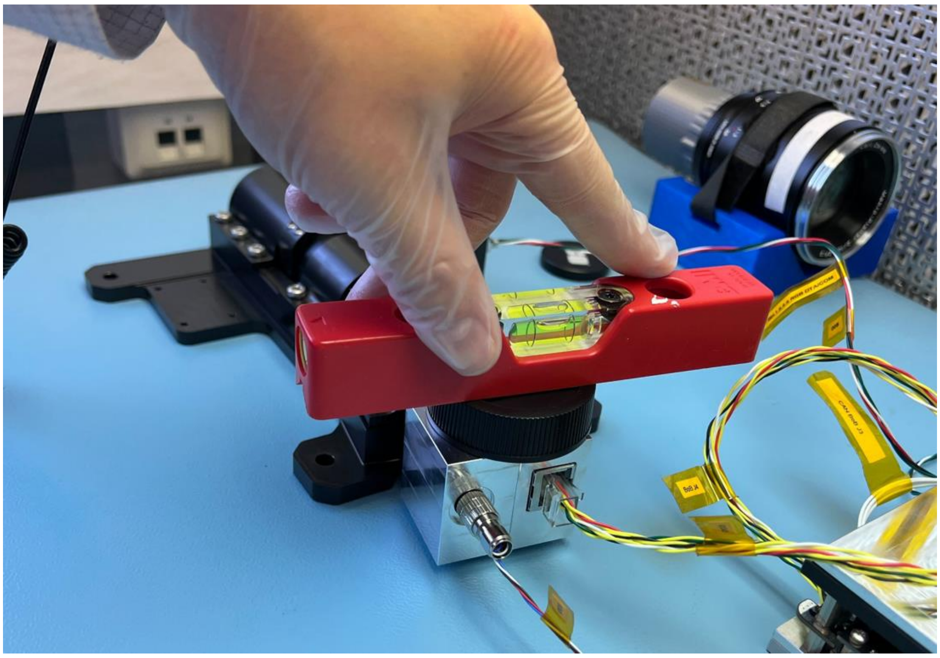


Figure 20: Leveling the HSI Detector

The RGB assembly is then placed onto the platform, and fastened using a bracket.

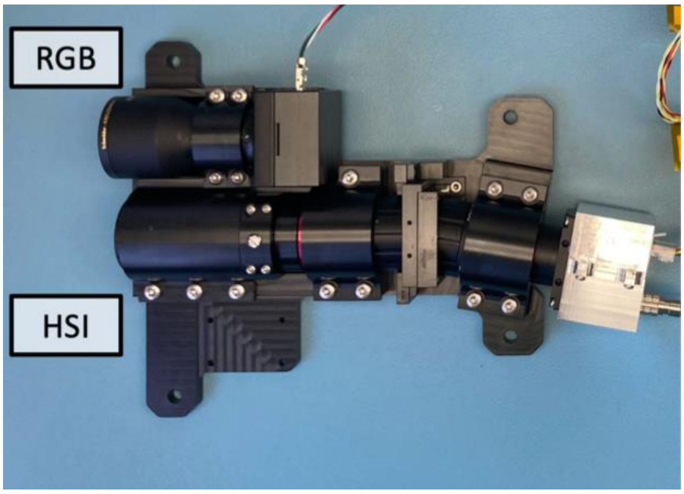


Figure 21: RGB and HSI mounted onto the platform

Connecting the EQM HSI and RGB to picoBoB, and taking a test image (see examples in chapter 6 on how to take images). The HSI was placed pointing towards the white sheet of paper, and the collimator and striped pattern put in front of the RGB when taking RGB images, as seen in Figure 22 (a) and (b) .

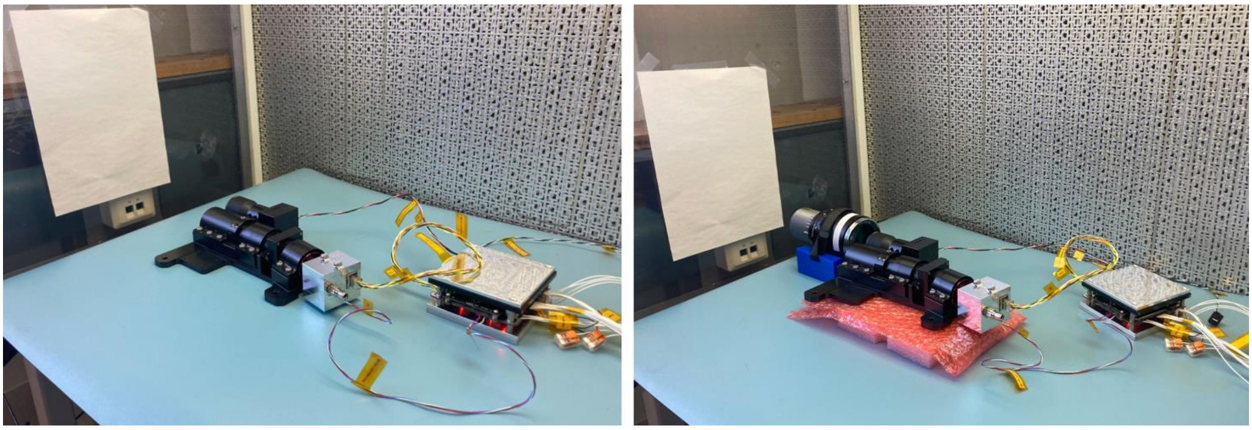


Figure 22 (a) and (b): The EQM connected to PicoBoB and power supply.

2.7 Calibration with fluorescent lamp in SmallSat Lab

The HSI was placed in the flowbench pointing towards white sheet of paper illuminated by a fluorescent lamp (the same that will be used during testing), as seen in Figure 23. Flowbench lights were turned off.

We started by trying to find a good exposure time (well exposed image should have counts of 3000-3500, well under the limit of 4095, but still as much light as possible). It was discovered that also the fps flag has to be used, to be able to use the exposure times above 100 ms. Exposure times of 200 ms, 400 ms and 600 ms were tested, as shown in Figure 23. The exposure time of 200 ms is a bit weak, while 600 ms is overexposed (seen by the flat top on the highest peak). The exposure time of 400 ms, with max count of about 3000 counts is used further for calibration. Note: the sensor is mounted upside-down (as for HYPSO-1), so the images are flipped before they are plotted here. They should also be before applying the calibration (as the calibration is based on flipped images).

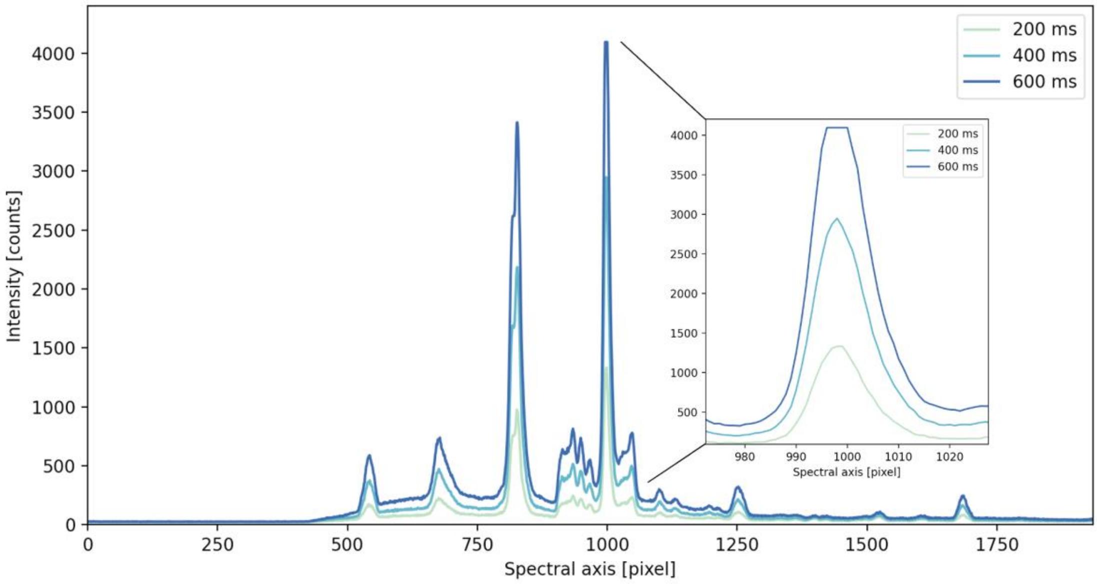
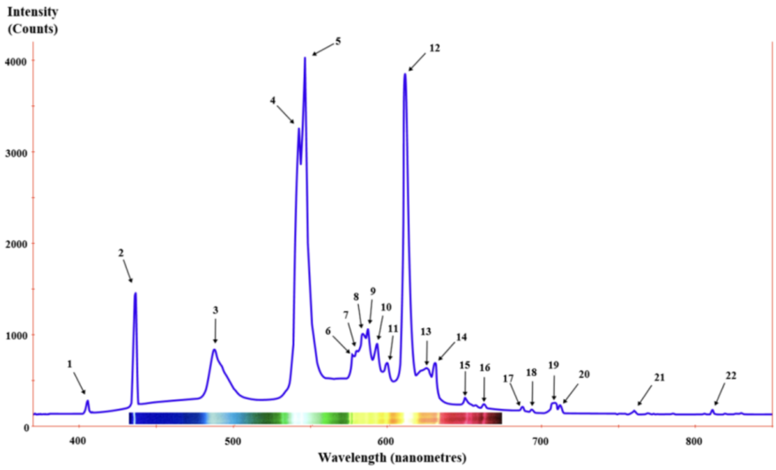


Figure 23: Middle line (center of slit) for three different exposure times (200 ms, 400 ms, 600 ms).

The spectrum is compared with the fluorescent light spectrum, seen in Figure 24. A python script is used to calculate spectral calibration coefficients, using second order polynomial fit between the pixel location and reference wavelength of the detected peaks shown in Figure 25 The spectral calibration coefficients found here are
[-7.94421348e-06, 3.99142375e-01, 2.21594608e+02]
which gives a spectral range of 221.6 nm to 964.6 nm across the full sensor.



Peak number	Wavelength of peak (nm)	Species producing peak
1	405.4	mercury
2	436.6	mercury
3	487.7	terbium from Tb^{3+}
4	542.4	terbium from Tb^{3+}
5	546.5	mercury
6	577.7	likely terbium from Tb^{3+} or mercury
7	580.2	mercury or terbium from Tb^{3+}
8	584.0	possibly terbium from Tb^{3+} or europium in $Eu^{+3}:Y_2O_3$
9	587.6	likely europium in $Eu^{+3}:Y_2O_3$
10	593.4	likely europium in $Eu^{+3}:Y_2O_3$
11	599.7	likely europium in $Eu^{+3}:Y_2O_3$
12	611.6	europium in $Eu^{+3}:Y_2O_3$
13	625.7	likely terbium from Tb^{3+}
14	631.1	likely europium in $Eu^{+3}:Y_2O_3$
15	650.8	likely europium in $Eu^{+3}:Y_2O_3$
16	662.6	likely europium in $Eu^{+3}:Y_2O_3$
17	687.7	likely europium in $Eu^{+3}:Y_2O_3$
18	693.7	likely europium in $Eu^{+3}:Y_2O_3$
19	707 and 709	likely europium in $Eu^{+3}:Y_2O_3$
20	712.3	likely europium in $Eu^{+3}:Y_2O_3$
21	760.0	likely argon
22	811.0	likely argon

Figure 24: Fluorescent light spectrum, reference (from wikipedia: https://commons.wikimedia.org/wiki/File:Fluorescent_lighting_spectrum_peaks_labeled_with_colored_peaks_added.png)

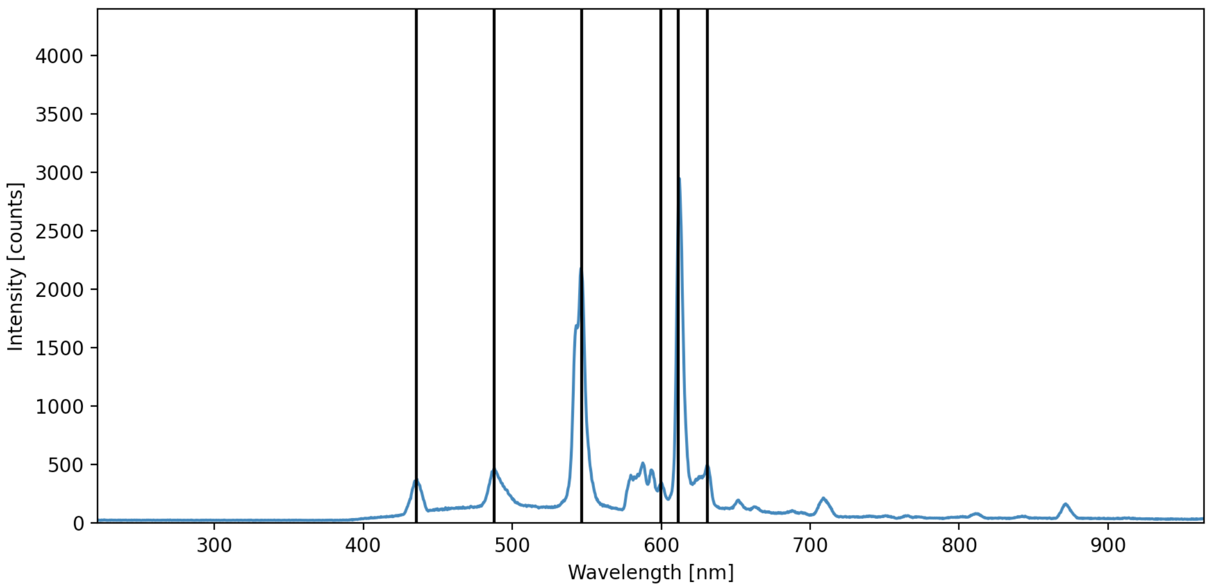


Figure 25: Middle line (center of slit) in 400 ms image. Black lines indicate the peaks used for calibration. Note: x-axis has been calibrated and now shows wavelength instead of pixel value.

3 Setting focus

Following the test procedures described in [RD03] (objectives) and [RD04] (HSI assembled).

3.1 Focusing RGB lens

Date: 2023-02-07

We noted that the RGB sensor inside the RGB sensor housing was a bit loose after dragging the cable in and out several times. The sensor was therefore fastened again in the sensor housing, 3 screws (1 of the holes are not able to use), and the RGB focused again. (After this it was epoxied, as descriped above). Only showing image from the last focusing.

The RGB was mounted and looking out the window (from Marie's office, D429) looking towards Gråkallen, as seen in Figure 26. Images were taken using the ueye cockpit software, with all automatic white balance, IR correction and individual RGB gains turned off/set to 0. We tried to focus at Gråkallen (the ball on top of the mountain), and looked at the image in zoomed in view in ueye. The focus was changed by twisting the focus ring on the objective. When we found a good focus setting, the focus set screw was fastened, and images taken at different exposure times to view different objects in the image.

The RGB camera was then moved back to the SmallSat lab, and placed in front of the collimator and striped pattern pointing towards a white sheet of paper, as seen in Figure 27. Images are seen in Table 3.

Figure 26: RGB camera pointing towards Gråkallen.

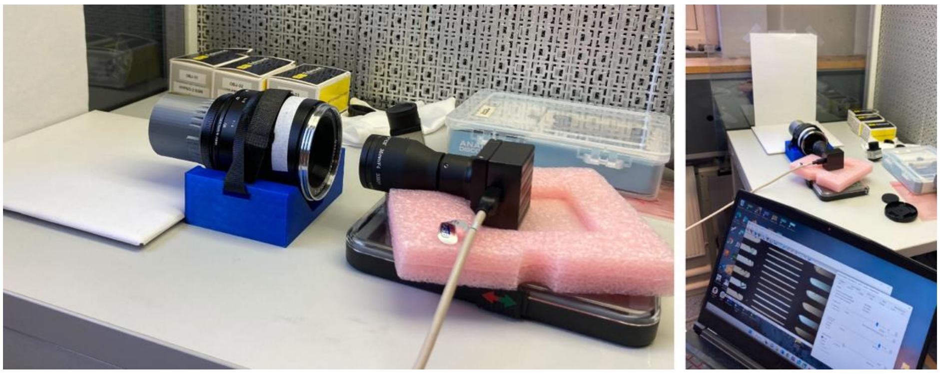
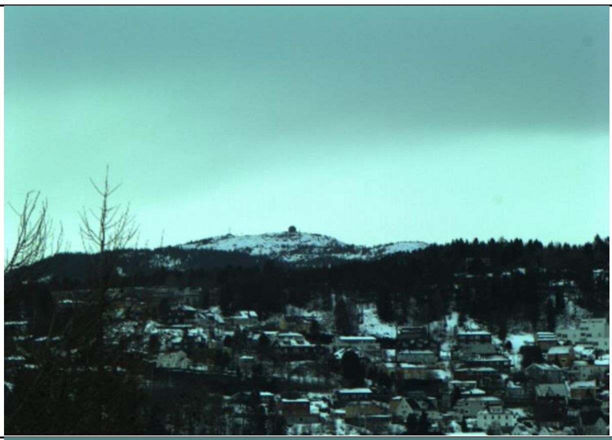
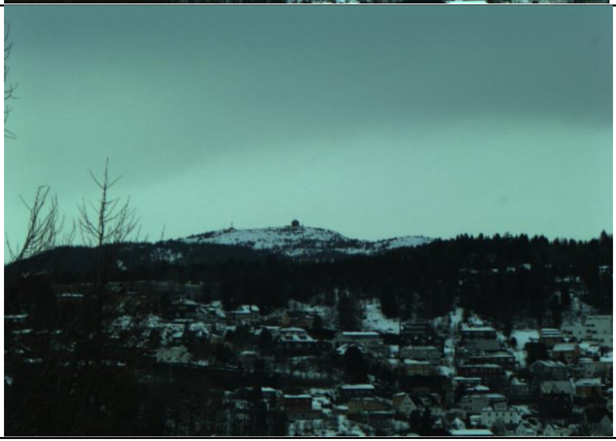
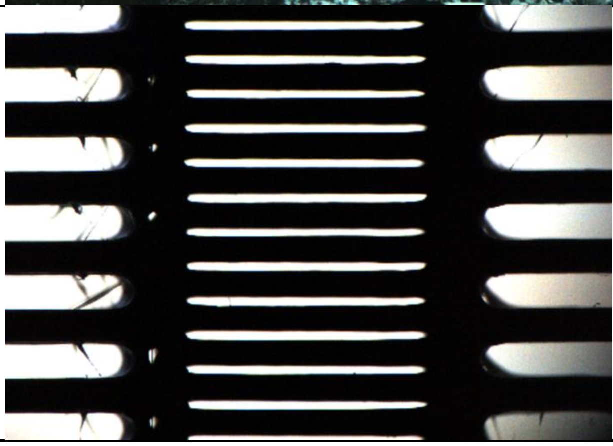


Figure 27: RGB camera placed in front of collimator and striped pattern, looking towards white sheet of paper.

Table 3: RGB images after focus was set.

Description	Image	Comment
Towards Gråkallen		Tried to focus on Gråkallen (ball on the mountain)
Towards Gråkallen, low exposure		Other masts on the mountain looks in focus, this is good

Towards Gråkallen, high exposure		Higher exposure to look at the houses
Collimator and striped pattern		

3.2 Focusing individual HSI objectives

Date: 2023-02-06 and 2023-02-07

First, each objective was focused onto the horizon when looking out the window, using an iDS UI-3060CP-M-GL Rev 2 sensor with USB3 connection and the ueye cockpit software, as seen in Figure 28. We tried to focus towards the horizon, using low exposure time so that the mountains were less overexposed. An image with higher exposure time to see focus at the tower in the city center was also taken for each objective. Images can be found in Table 4.

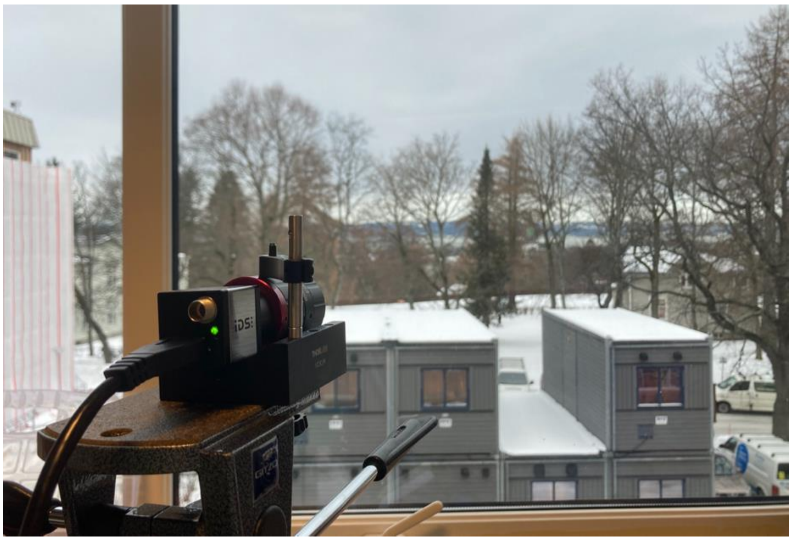


Figure 28: Focusing HSI objective connected to iDS camera, looking out the window towards the horizon.

For the back objective (camera objective, third objective) the focus was double-checked with the EQM sensor (iDS UI-5261SE-M-GL Rev. 4), to make sure the focus is right with the correct sensor (`$ hsi capture –n 1 –e 1 –h 1216 –w 1936 –b 1 –s` for full frame capture). It was also pointed towards the horizon out the window, as seen in Figure 29. The minimum exposure time that could be used when running through picoBoB is 1 ms, so the image turned out overexposed. The image can be seen in Table 5.

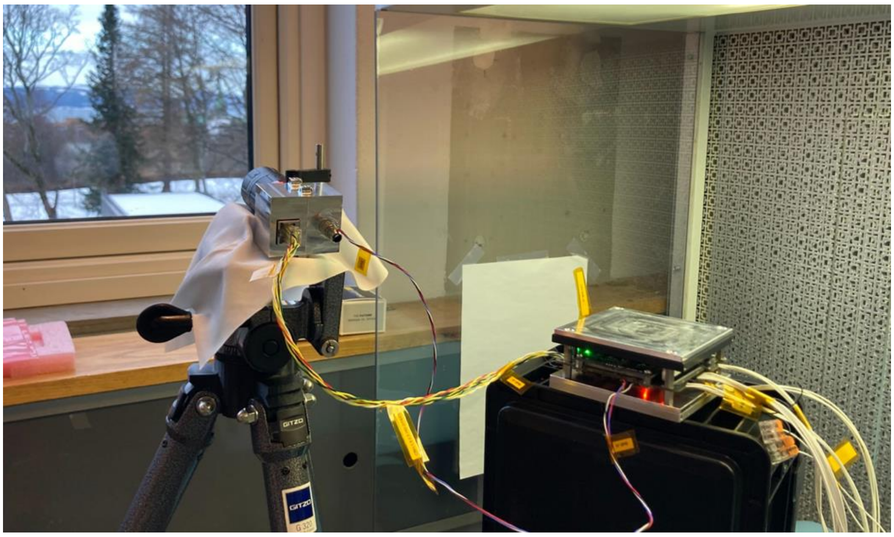


Figure 29: Focusing HSI objective connected to HYPSO-2 EQM (old HYPSO-1 EM) camera sensor, run with picoBoB, looking out the window towards the horizon.

Table 4: Images with the HSI objectives and the USB3 camera sensor.

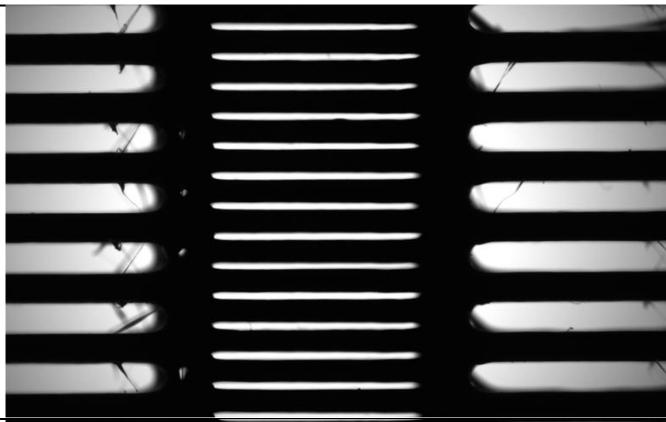
HSI lens	Comp. #	Low exp (horizon)	Higher exp (tower)	Comment
Front objective	OBJ-31			Hard to twist, makes it hard to adjust focus in small steps
Middle/ collimating objective	OBJ-32			
Back/ camera objective	OBJ-33			

Table 5: Image with the HSI objective and the EQM camera sensor, run through picoBoB.

HSI lens	Comp. #	Focused image	Comment
Back/ camera objective	OBJ-33		1 ms was the lowest exposure time available, hard to see whether focus is great or not. Also think there is some smearing from looking through the corner of the window..

The front and middle objective were also checked with the collimator and striped pattern set-up, watching a white sheet of paper illuminated by light from the room and flowbench. Images can be seen in Table 6.

Table 6: HSI objectives and USB3 camera sensor, with collimator and striped pattern set-up.

HSI lens	Comp. #	Focused image	Comment (pass/fail)
Front objective	OBJ-31		Pass
Middle/ collimating objective	OBJ-32		Pass
Back/ camera objective	OBJ-33	Not taken due to testing with picoBoB at the time	-

3.3 Focusing the HSI (after assembly)

Date: 2023-02-07 and 2023-02-08

The HSI was assembled, as described in chapter above. The first test was to take a test image with the correct sensor and picoBoB. The test set-up (as seen Figure 30) was under the flowbench, with the HSI pointing towards a white sheet of paper on the wall, with lights in the room on, and the flowbench lights off or on (when they're off we could see the fluorescent lamp lines more clearly). All pictures taken when setting the EQM HSI focus are shown in Table 7.

The first image was clearly out of focus, so spacer rings are needed. To adjust spectral focus, the distance between the slit and the middle objective should be changed/increased. To check and adjust the spatial focus, the collimator and the striped pattern can be used, and the distance between the slit and the front objective should be adjusted/increase (described in the second part of this subchapter).

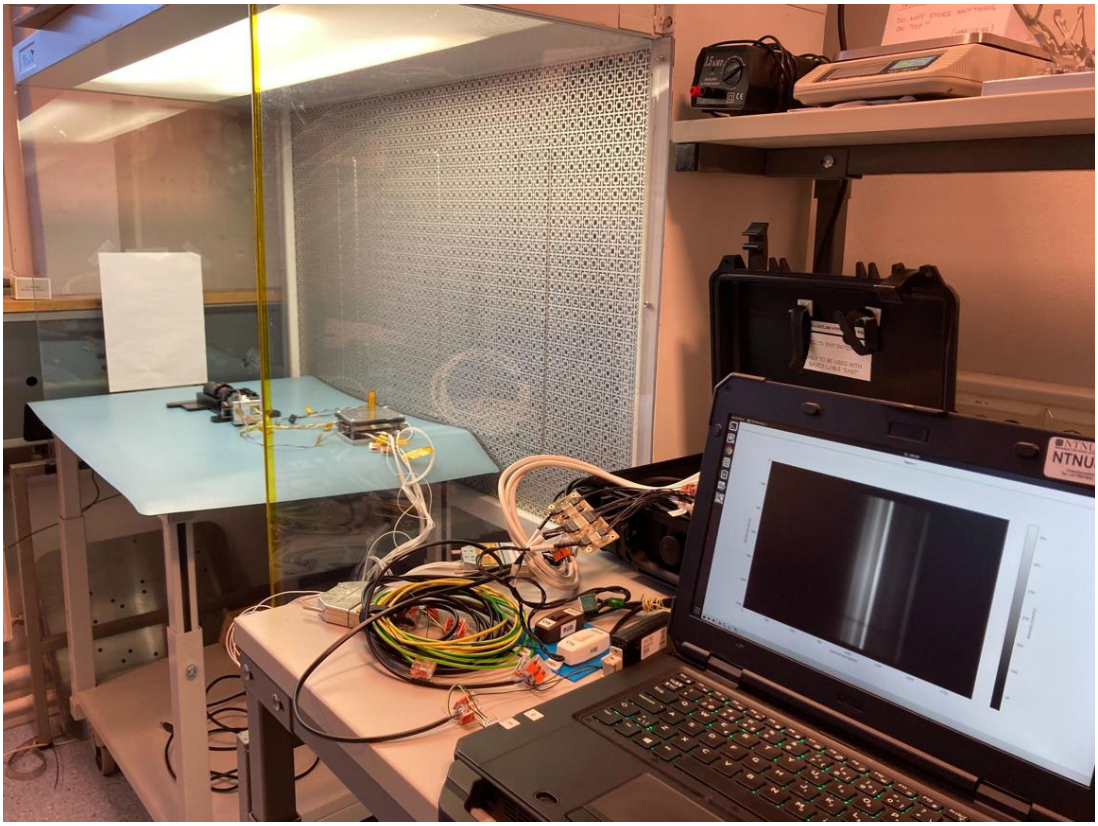
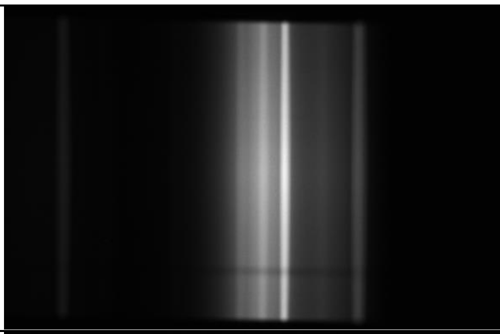
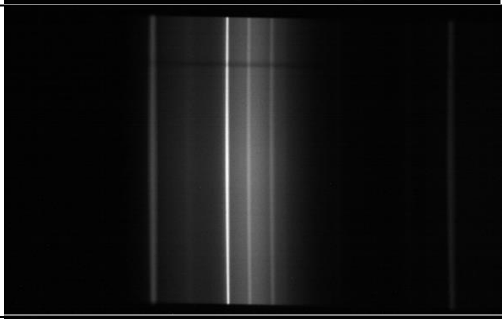
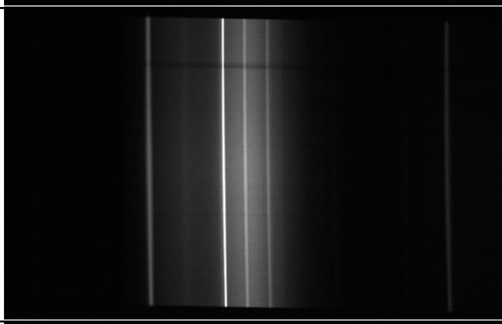
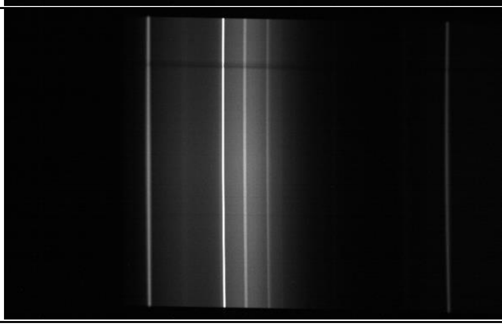
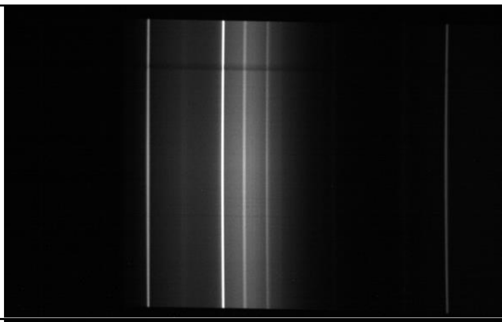
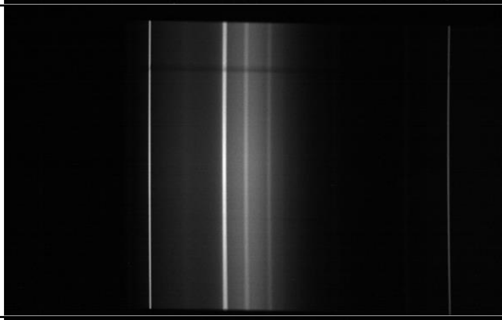
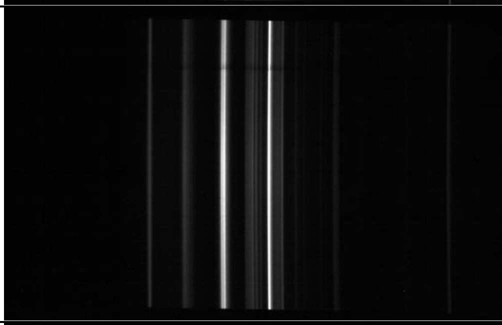
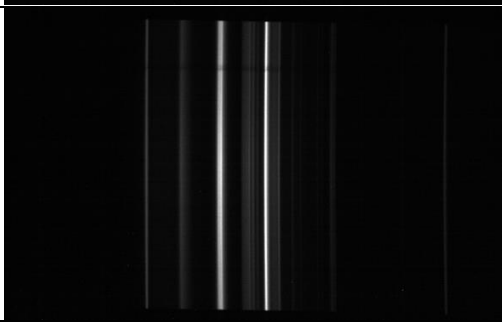


Figure 30: Test set-up with assembled HSI, in front of white sheet of paper illuminated by roof lamps and flowbench lamp (shows first EQM image – unfocused).

Taking images with picoBoB takes time, so we switched back to the USB3 camera. The ueye cockpit software with liveview was used to get continuous updates on the image, while untwisting the middle objective until it looked sharper. We tried to measure the distance between the slit tube and the objective (increase from twisting it). It looked like 0.7 mm or 1 mm, but was really hard to tell, so we tried with 1 mm spacer ring first – not good. We then tried smaller and smaller distances, from 0.75 mm to 0.45 mm, images seen in Table 7.The best focus looks to be at 0.5 mm. Some images were also taken with the flowbench lamp off (and increasing the exposure time used). We can then see the fluorescent lines better.

Table 7: Images with HSI assembled with USB3 sensor, looking at white sheet of paper to find spacer rings for spectral focus.

Description	Spacer ring distance [mm]	Image	Comment
First image, running with EQM sensor and picoBoB	none		Upside-down because of sensor upside down when mounted on payload platform
USB3 sensor, flowbench lamp on	0.25		Not focused
USB3 sensor, flowbench lamp on	0.4		Ok focus
USB3 sensor, flowbench lamp off	0.5		Good focus

USB3 sensor, flowbench lamp off	0.6		Good focus, maybe bit less good than 0.5 mm
USB3 sensor, flowbench lamp on	0.75		Blurry, but the edges (lower/ shorter and higher/ longer wavelengths) seem better
USB3 sensor, flowbench lamp off	0.5		Really good, can see double peaks!
USB3 sensor, flowbench lamp off	0.6		Can see double peaks, but a bit more blurry than 0.5 mm?

To determine which spacer ring to use, some of the images were further investigated in a python script. The images taken with the flowbench lamp off was used. The middle line/row (center of slit) was plotted, and is shown in Figure 31. The spectra are a bit shifted, this is ok (this happens when moving the slit assembly in front of the grating which we do when changing spacer rings). It’s a bit hard to tell from the plot which line is better (and FWHM is not accurate to use when the images are overexposed as they are here – max value of 255 with 8-bit images). However, when looking at the double peak at about spectral pixel 420, the dip seems more prominent in the blue peak (0.5 mm) than for orange (0.6 mm). From this, 0.5 mm seems like the better match (at least at this wavelength). For the EQM, this investigation is deemed good enough. For the FM, the FWHM should be measured with the calibration lamps in the calibration lab.

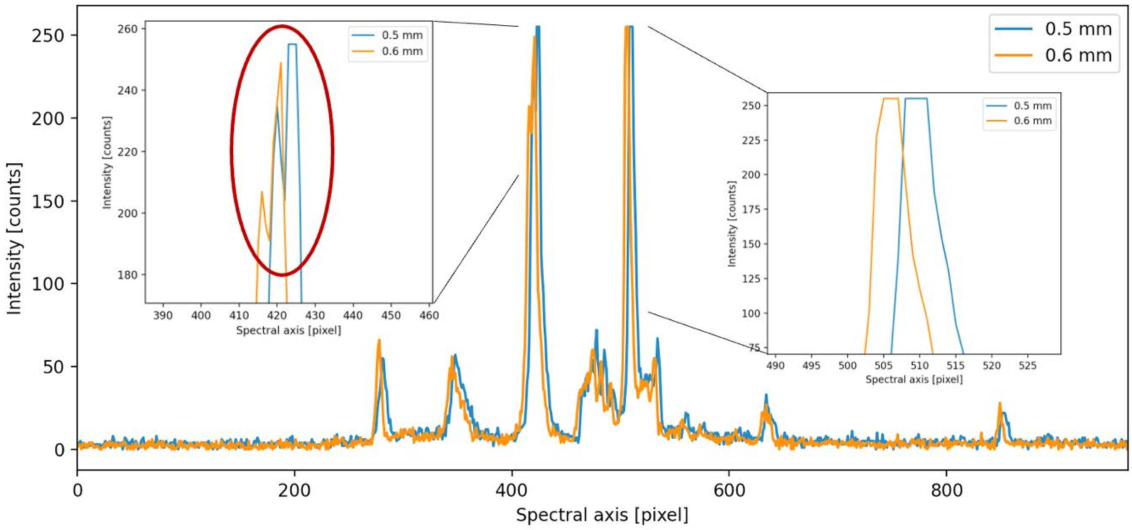


Figure 31: Middle row (center of slit) of HSI images with 0.5 mm and 0.6 mm spacer rings, with flowbench lights off.

Next step is looking at the spatial focus. The HSI is placed in front of the collimator and striped pattern (flowbench lights on), as seen in Figure 32. The goal was to get the striped in the center of the image/spectrogram as well focused as possible. We first tried to unscrew the front objective from the slit tube to increase the distance, but it was hard to tell any difference in the images. We took one image before we started (first image), then tightened it again after unscrewing it (0 mm). We then to place tried a set of different spacer rings, 0.25 mm, 0.5 mm and 0.75 mm, one at the time, between the front lens and the slit tube. The resulting images are shown in Table 8.

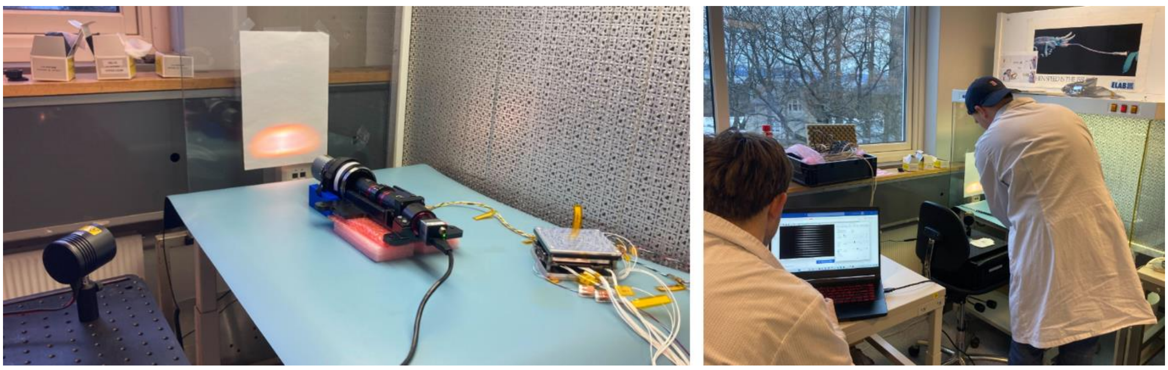


Figure 32: Set-up when adjusting spatial focus.

Table 8: Images with HSI assembled and USB3 sensor, looking through collimator to find spacer rings for spatial focus.

Description	**Spacer ring distance (mm)**	**Image**	**Comment**
First image	0		Looks a bit out of focus
Tightened after unscrewing	0		Looks a bit more out of focus than first image..
0.25 mm spacer ring	0.25		Best focus approx in the center, maybe a bit to the left

0.1+0.3 mm spacer ring	0.4		(Last try, we chose this), best focus approx in the center
2x0.25 mm spacer ring	0.5		Best focus a bit right from the center
3x0.25 mm spacer ring	0.75		Best focus too far to the right

The images were then further investigated in python. We looked at one line/column (wavelength) along the slit, for each image. We also tried to look at several lines/columns (wavelengths), as the best focus differs between the wavelengths. There is a small shift, this is normal as we moved the slit tube assembly when adding new spacer rings. The light intensity might also change a bit due to unstable light source or different placement in front of the collimator. The shape of the lines are therefore more important, lines should be step response (sharp edges, box-shaped) if perfectly in focus.

In the end, 0.25 mm and 0.5 mm looked like the best options. We added 0.4 mm (0.1 mm + 0.3 mm) spacer ring to get good focus around spatial pixel 500 here. (Note: the images saved with ueye here seems to be 2x2 binned, as the dimensions are half of what is normal for the full frame images for this sensor). The 0.4 mm was chosen as it looked like a good compromise between the 0.25 mm and 0.5 mm spacer rings. In hindsight, maybe 0.3 mm should have been tested as well.

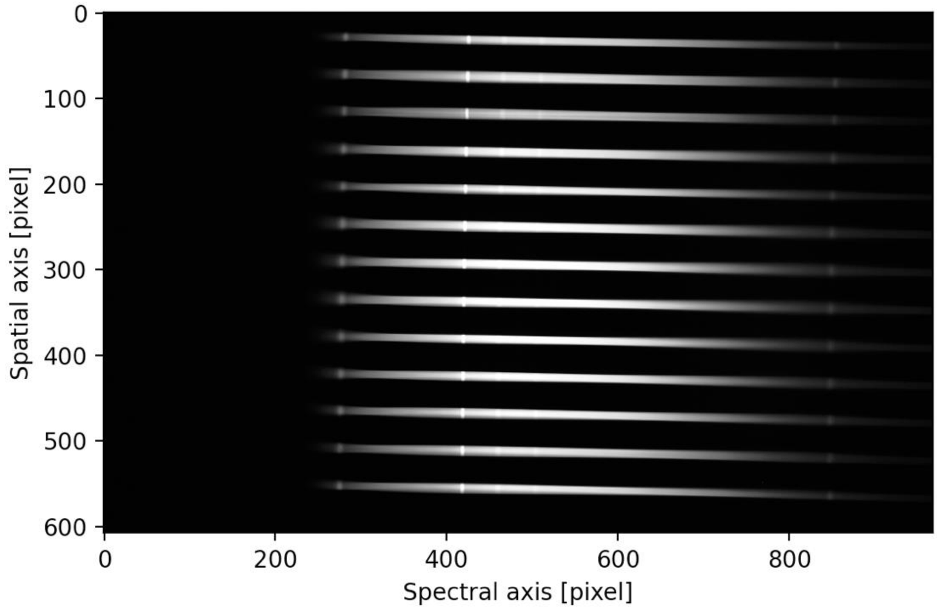


Figure 33: Image/spectrogram (with 4 mm spacer ring) with x and y axis, for reference for the column numbers.

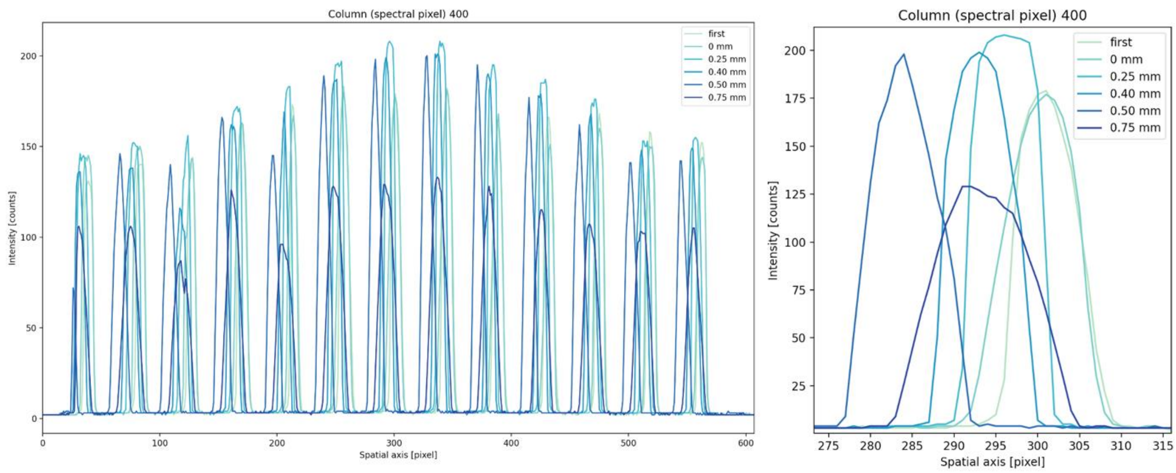


Figure 34: Line plot for column 400 (bit to the left from the center).

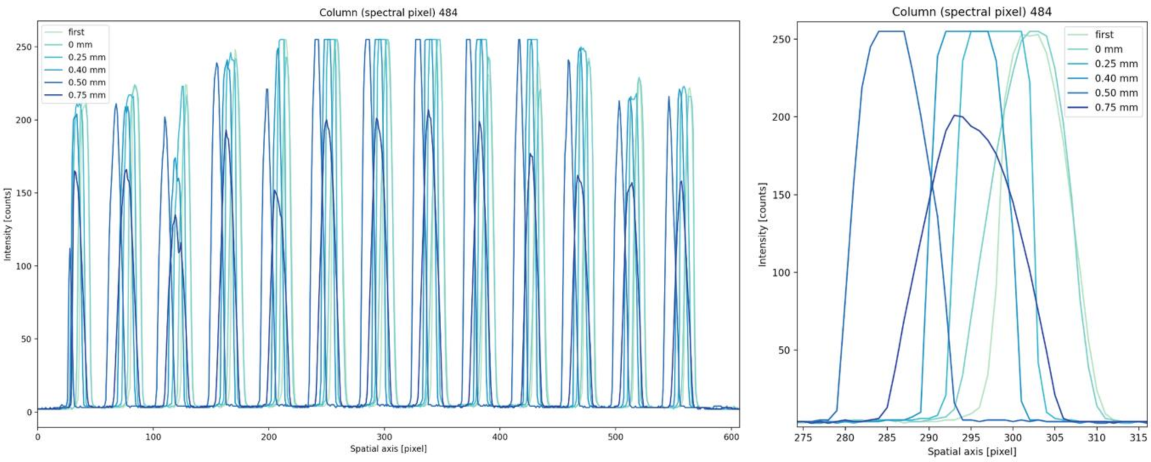


Figure 35: Line plot for column 484 (center).

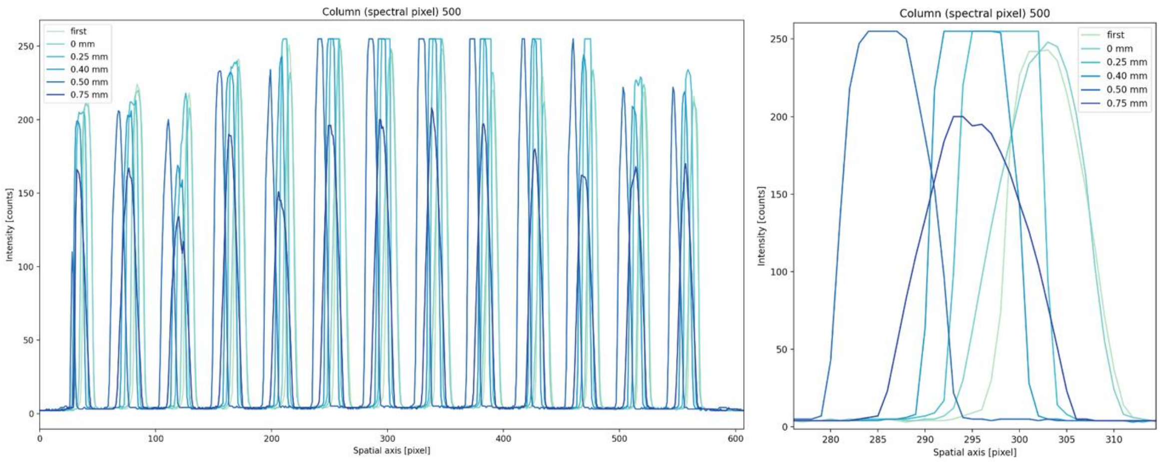


Figure 36: Line plot for column 500 (bit to the right from the center).

Finally, the brass rings were replaced with black spacer rings from Edmund Optics (same as used for the HYPSO-1 FM), and a final test image taken in front of the collimator set-up, as seen in Figure 37 and of the white sheet of paper illuminated by a fluorescent lamp (flowbench lamp off), as seen Figure 38.

Figure 37: Spatial focus with 0.4 (0.1+0.3) mm spacer ring between front objective and slit tube (and spacer ring 0.5 mm between slit tube and middle objective) (USB3 sensor).

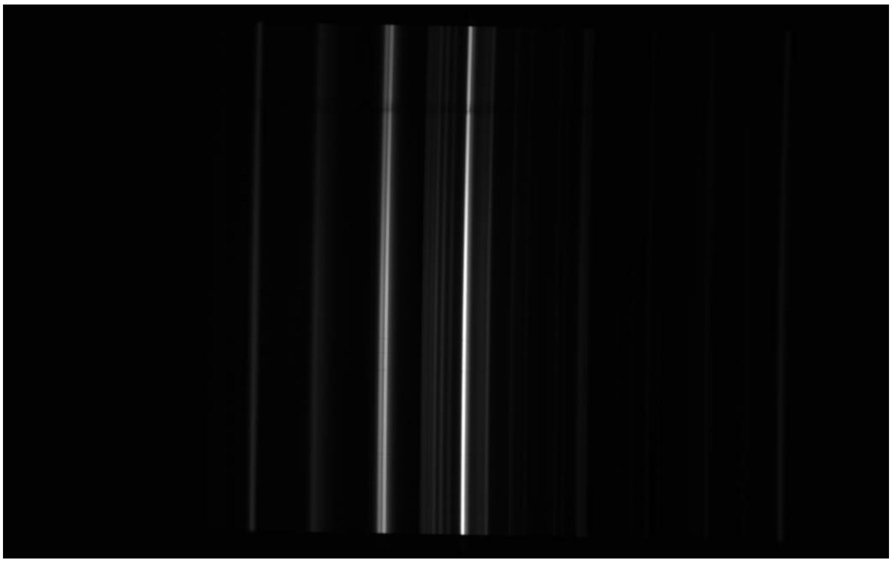


Figure 38: Spectral focus with 0.5 mm spacer ring between slit tube and middle objective (and spacer ring 0.4 mm between front objective and slit tube).

4 Updating firmware for cameras

Some of the steps are also described in chapter 10.2 in the flight model as-built report [RD03]. You don't need to do everything described in each subsection; the subsections are here to help in case you need to do any of these things. We only need to configure the cameras first time they're used, after that they should be fine.

Note: This was done using the HYPSO-1 HSI QM sensor, which has already been used and configured with the correct IP address. When configure unused HSI sensor, the IP address also needs to be set. We need the steps for this, must be done for the HYPSO-2 FM.

4.1 Configure HSI first time: update driver/firmware

1) Download ueye driver 4.96
    a) You can find this by looking at the file "setup_ueye_drivers.sh" in the "scripts" folder. There is an address in the section called "x86-64", download driver from this web address
2) Uninstall previous version (VERY IMPORTANT) <- step 1 in chapter 10.2 in [RD03]
    a) $ sudo /usr/bin/ueyesetup -r eth
    b) $ sudo /usr/bin/ueyesetup -r usb
3) Unzip the downloaded file
    a) $ tar –xf [filename]
4) Make sure the HSI has power, plug the ETH cable directly into the laptop from the HSI, turn on the power supply (connected to the camera via BoB)
5) Install the new driver (in the ueye folder)
    a) $ sudo sh ./[file] <- step 4a in chapter 10.2 in [RD03]
6) <- Step 5 in chapter 10.2 in [RD03]
7) Start ids cameramanager <- step 6 in chapter 10.2 [RD03]
    a) $ idscameramanager
    b) Press button "upload starter firmware"
8) Switch back to ETH via BoB, turn on power
9) Take test image
    a) $ hsi capture -n 1 –s

4.2 HSI: Get IP address (BoB)

1) Connect the camera via ETH to BoB
2) Turn on power
3) In terminal
    a) $ opu caminfo
    b) HYPSO-1 QM (now HYPSO-2 EQM) ip: 129.241.2.140

4.3 HSI: Set IP address to be used with computer (mech wiki)

1) Open ids camera manager (camera connect to computer with ETH)
2) Activate expert mode
    a) Note the “IP address” and “IP subnetmask” under “Local network adapters IP”
3) Open the “Manual ETH configuration” menu, and set the IP address to xxx.xxx.xxx.nnn
    a) 129.241.2.nnn
    b) nnn should be something unique
4) Subnetmask should be 255.255.254.0
5) Update firmware if needed by pressing the “upload starter firmware” button

4.4 Configure RGB first time

1) Turn on power on the RGB
2) In terminal
    a) $ opu caminfo
    b) On lidsat, cam id for RGB is 5, so it should be that here as well
3) Change id
    a) $ opu setid [old id] [new id]
        i) Here: $ opu setid 1 5
    b) Check that it’s correct
        i) $ opu caminfo
4) Check that it works
    a) $ rgb init
5) Take test image
    a) $ rgb capture [something more]
6) Download images (HSI and RGB)
    a) $ opu list
    b) $ opu download hsi0/compressed_cube.bip.cmpr [local_name]
    c) $ opu download rgb/h2-rgb-eqm-first.png [local_name]

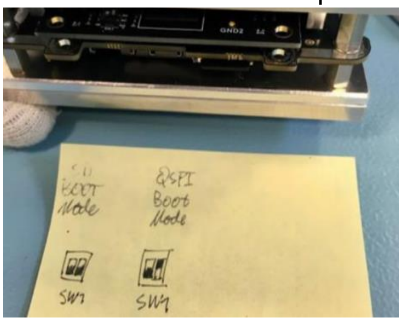
5 Testing BoBs

We’re testing 2 BoBs. Using the shield plates and cables from HYSPO-1 QM. Removing the thermal straps from HYPSO-1 QM.

The two BoBs that are tested for HYPSO-2 are called 10801 and 10802. One of them is for the HYPSO-2 EQM, the other for the HYPSO-2 FM.

5.1 BoB 10801 (FM BoB)

Date: 2023-02-06

1. Taking one and one cable from the HYPSO-1 QM BoB over to the 10801 BoB
2. Moving stand-offs from HYPSO-1 QM BoB to 10801 BoB
3. (Might have swapped the SD cards)
4. Connecting to computer, power on GSE
    a. Letting it boot
    b. Shutting it down
        i. $ opu shutdown
    c. Turn off power
    d. Flip both boot switches to down position
        i. 

    e. Turn on power again
    f. Turn power back off
        i. $ opu shutdown
    g. Flip the one both switch back up
    h. Turn back on, let it boot
    i. See that it was not started from golden
        i. $ opu git
            1. Is primary
    j. Turn back off
        i. $ opu shutdown
    k. Turn back on
        i. Can't boot kernel image, this is ok
        ii. But something went wrong, might be missing some files (will look into this tomorrow)
    l. Turn back off
5. Connect to cameras (HSI and RGB) to check that it works
    a. Power on
    b. Check camera id
        i. $ opu caminfo
    c. Take hsi image
        i. $ hsi capture –n 1 –e 100 –s
            1. Couldn't take without specifying exposure time, is this normal?

            2. First one error msg saying – is invalid, then second error msg says we need to specify exposure time, then third time it works
    d. Take RGB image
        i. $ rgb init
        ii. $ rgb capture n rgb png bob-10801-test
        iii. $ rgb deinit
    e. Turn off power of cameras
    f. Download images
        i. $ opu list
        ii. $ opu download hsi2/compressed_cube.bip.cmpr hsi-10801-test.bip.cmpr
            1. This was fast
        iii. $ opu download rgb/bob-10801-test.png bob-10801-test.png
6. Look at images
    a. Looks ok
    b. Shut down opu and turn off power
7. Disassemble and putting it in flight hardware box in smallsat lab

5.2 BoB 10802 (EQM BoB)

Date: 2023-02-06

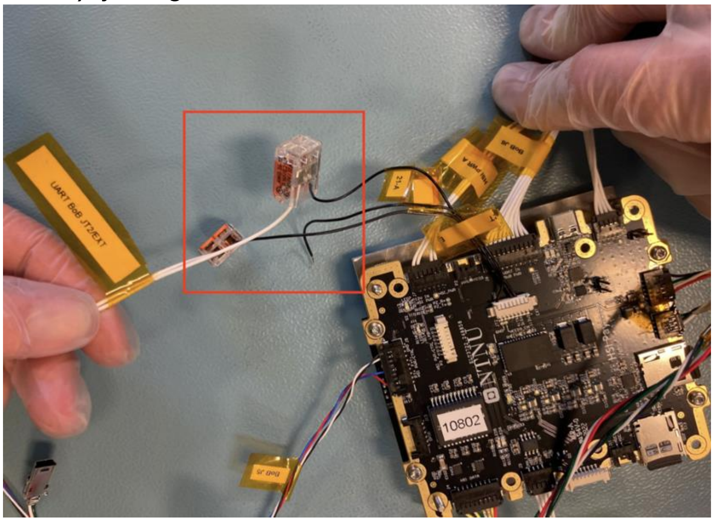
1. Moving all cables from 10801 to 10802
2. BoB doesn't fit, almost, but it works (phuu)
3. We're not torquing, because the cables will be switched before shock/vibe testing
4. Repeat steps as for BoB 10801 (but skipping golden image for now)
    a. Turn on power supply, let it boot
    b. Connect cameras
    c. Turn on cameras
    d. Take HSI image
    e. Take RGB image
    f. Turn off cameras
    g. Download images
    h. Look at images – ok, nice!

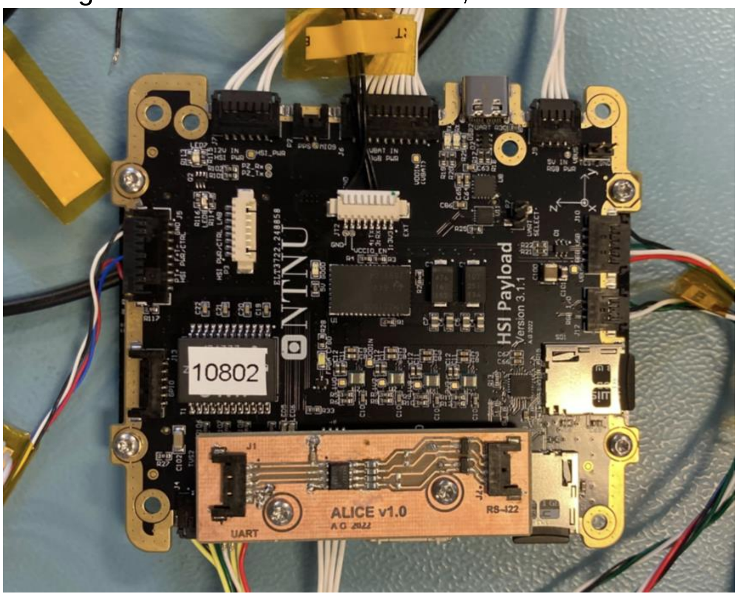
Date: 2023-02-07

Replacing GSE harness with TVAC harness, and mounting ALICE.

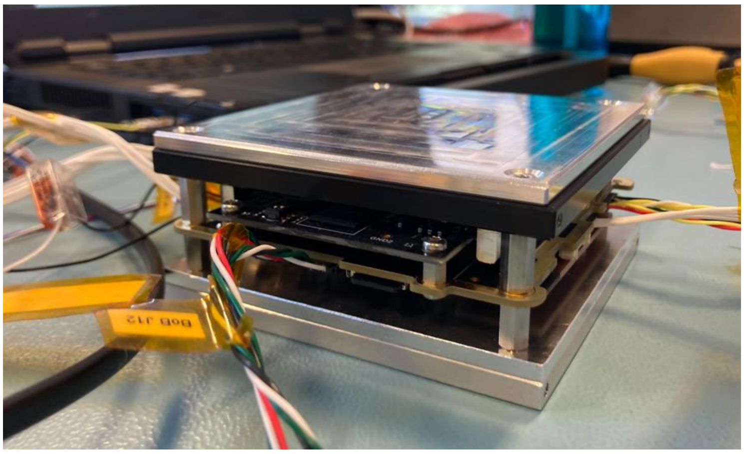
- UART cable cables loosened from connector, Roger re-attached them hopefully in the right place. They keep on loosening when trying to connect to BoB.

- If dragging in the UART cable it might loosen again, and we'll lose contact with the terminal = not good, so be careful with these.

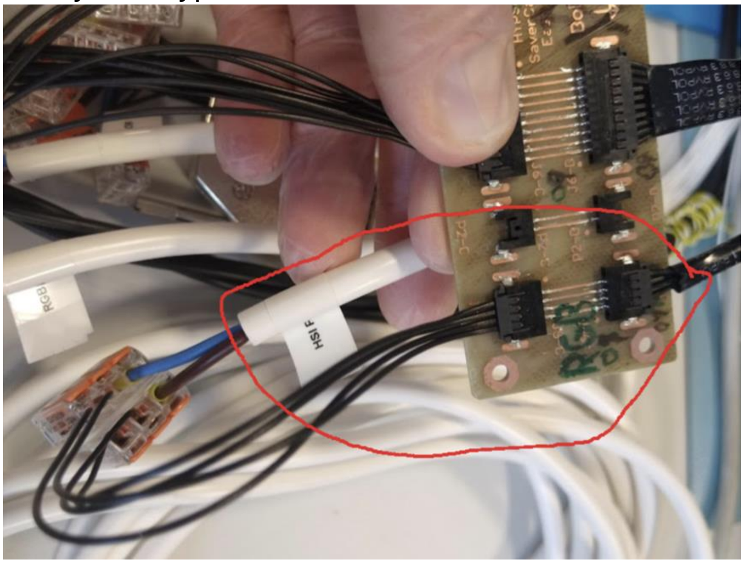
- It doesn't work. Cheating and cutting off the UART connector from GSE (and from the TVAC cables), joining the GSE connector with the TVAC cables with wago clip for now
  - 

- Mounting ALICE, using 5 mm spacers
  - Noticed holes on BoB and ALICE are M3, while the spacers and screws are M2.5. So there is wiggle room, ALICE can move a bit while mounted on BoB. Can tighten them and it should work, but would be nicer with M3.
  - 

- PicoBoB assembly, everything else seems to fit fine

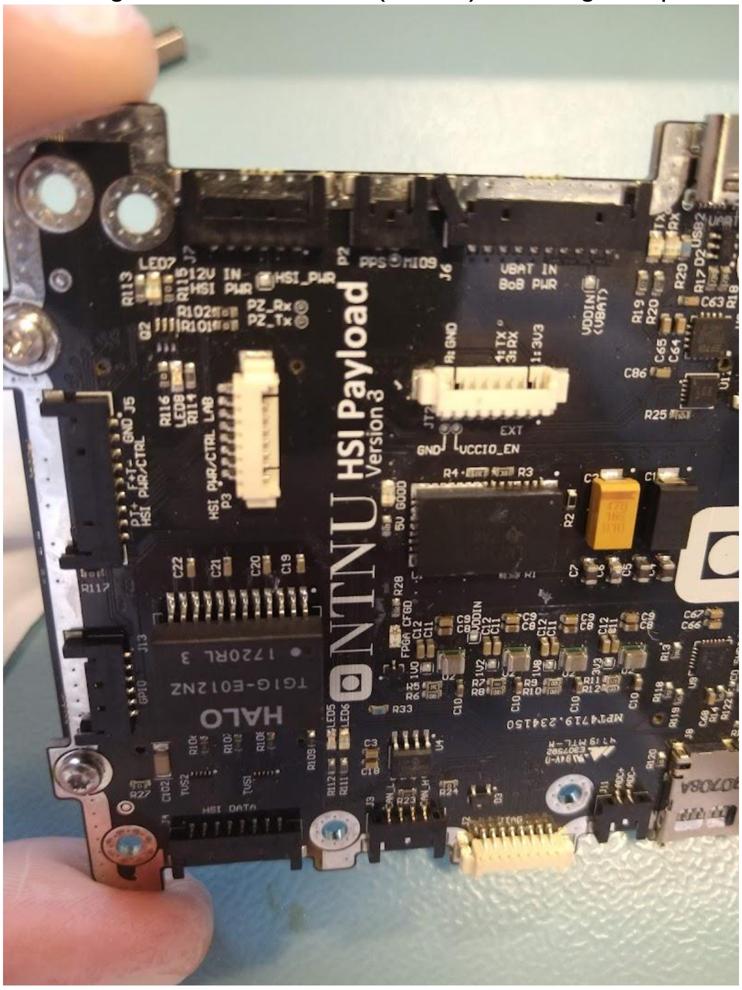


- Testing if it works
    - Boots fine
    - Turning on HSI power -> SMOKE
- Found the mistake
    - Name on cable saver cards not double checked, HSI 12V power was connected to RGB.. Only dummyproof on one side..



    - RGB was not connected, so that was good, only the BoB got fried
- Using HYPSO-1 QM BoB instead, at least for shock and vibe test
    - Considered using HYPSO-1 EM BoB, but it is too dirty (should be cleaned and tested before use)

- See image. White substance (oxide?) covering component pins.:



6 Set-up and run SW on fieldwork laptop

To run test scripts, there are some functionalities that is nice to have set-up beforehand. Images can be acquired by command line and stored on BoB. They must then be downloaded to the computer. These steps can be automated through a test script.

In addition, functionality to decompress the .bip.cmpr files (compressed hyperspectral cubes), and functionality to show an image (either black and white or an RGB image created from three bands) from a .bip file is nice to have.

6.1 Take image with command line via BoB - manually

1. Connect HSI and RGB to BoB, turn on power

2. Take image with HSI:
   - Make sure HSI power is on
   - $ hsi capture -n 1 -e 100 -s
   - (for full frame image: $ hsi capture -n 1 -e 100 -h 1216 -e 1936 -b 1 -s)
3. Take image with RGB:
   - Make sure RGB power is on
   - $ rgb init
   - $ rgb capture n rgb png [filename, no type]
   - $ rgb deinit
4. Download images from BoB to computer
   - $ opu list
   - Download hsi image
     - $ opu download [hsi folder/filename] [local filename]
       - Ex $ opu download hsi1/...
   - Download rgb image
     - $ opu download rgb/[filename] [local filename]
       - Ex $ opu download rgb/rgb-marie-test-png marie-rgb-test.py

6.2 Decompress .bip.cmpr (from scratch)

1) Go to github, clone the fpga-modules repository
2) Navigate into folder compression/ccsdc123/SOFTWAREA (in terminal)
3) In terminal (in folder)
   a) $ make
4) You will then get a program called main.out (can change the name of this if necessary, ex. to ccsds123)
5) Decompress:
   a) $ ./ccsds123 --DECOMPRESSION -i [filename.bip.cmpr]

6.3 Show .bip image

Make a python script with the lines shown below and give it a name such as "show_image_from_bip_cube.py". Adjust filename and/or width/height in the script according to the settings that were used when capturing the cube (can use text editor for this).

1. To avoid changing filename in the script all the time, just copy the cube and call it cube.bip
   a. $ cp [filename] cube.bip
2. Run the script from command line (from the folder where the script and cube are located):
   a. $ python show_image_from_bip_cube.py

Content of script:

```
import numpy as np
import matplotlib.pyplot as plt

def main():
	# Read bip cube
	filename = ‘cube.bip’ # path and filename of bip cube
	width = 1936 # number of pixels on x-axis
	height = 1216 # number of pixels on y-axis
	cube = np.fromfile(filename, dtype=np.uint16)
	size_im_flat = width*height
	num_images = int(len(cube)/size_im_flat)
	cube.shape = (num_images, height, width)

	# Choose one image (one frame/spectrogram)
	im = cube[0]

	# Show image
	fig = plt.subplots()
	plt.imshow(im, cmap = 'gray', aspect='auto')
	cbar = plt.colorbar()
	plt.xlabel('Spectral axis [pixel]')
	plt.ylabel('Spatial axis [pixel]')
	cbar.set_label('Intensity [counts]', rotation=90)
	plt.show()

	return none

if __name__ == ‘__main__’:
main()
```

6.4 Test scripts

7 Things to remember when building HYPSO-2 FM

- When focusing the objectives, it's nice to be in D-blokka, looking out a window towards Gråkallen. The radar dome is an easy object to target for setting focus. The distance from Gløshaugen to Gråkallen is about 10 km (straight line in the air), this should be far enough for both the HSI objectives and the RGB objective.
- When images are saved using the uEye Cockpit software, some more testing should be done beforehand to figure out how to save the full images. Maybe save as .png, or open the software in expert mode from the beginning. It is possible storing the full frame, and not 2x2 binned (as we have done for EQM).
- Be very careful with the slit, to ensure no dents or dust.
- Don't let any components lay "open" more than necessary, let them stay in a bag if they are not in use. Specially for the grating and slit, but also the objectives and sensor.
- Use the flowbench when handling all FM optical components, don't take them out of the box/bag if not under the flowbench.
- Use calibration lab and calibration lamp when/after setting HSI spectral focus to check that FWHM is acceptable (less than 5 nm for all wavelengths). Do final calibration after HSI brackets have been assembled and epoxied.
- Test both the RGB and HSI pointing out the window after final assembly. If possible, do a scan with the HSI to obtain a cube (looking out the window) - functional testing.
- Should we make bigger holes (or something else) in slit tube to avoid problems after anodizing?
- When mounting slit inside slit tube, try to make sure that the slit edge is only barely visible in the image. For EQM there is about a 100 pixels wide dark edge in the image from the slit blocking light. We want this edge to be smaller, maybe 10-50 pixels max. It' still nice that the edge of the slit is visible, this makes it easy to see if the slit moves during/after launch.
- When taking images when setting spectral and spatial focus (adding spacer rings to the HSI), make sure the images are not overexposed!
- For HSI focus: 1) make sure sensor is straight/levelled, look through collimator and get straight lines, 2) set spatial focus (add spacer ring) with the collimator set-up, 3) set spectral focus (add spacer ring) with fluorescent lamp, 4) torque brackets over slit assembly and RGB, 5) check that RGB is levelled, look through collimator, 6) straighten slit (make sure spectral lines are straight). Not sure which one should be first of 2 and 3, don't think it is important. But please do step 1 first to get nice data, and step 4 before 5 to make sure we don't have to take the brackets off again to adjust the RGB and then straighten the slit tube again (since it takes time..)
- Make sure to level the sensor properly, it is very important that the edge of the slit (black line in the top or bottom of the spectrogram) is straight (horizontal)! If not we get a lot of error in the measurements, it can be corrected but it is troublesome, we're not correcting for this with HYPSO-1 at the moment..
- Save image after spacer rings are added on both sides + sensor and slit are straight: 1) with collimator and striped patter, 2) with fluorescent lamp

8 List of Abbreviations

Table X: List of Abbreviations

Abbrv.	Description
ABD	Aided Blind Deconvolution
AC	Atmospheric Correction
AIT	Assembly, Integration and Test
ADC	Analog to Digital Converter
ADCS	Attitude Determination and Control System
AOCS	Attitude and Orbit Control System
AoI	Area of Interest
API	Application Programming Interface
AxV	Autonomous Vehicles
BB	Breadboard
BER	Bit Error Rate
CAD	Computer Aided Design
CAN	Controlled Area Network
CCSDS	Consultative Committee for Space Data Systems
CDR	Critical Design Review
CoG/COG	Centre of Gravity
COM	Communication
CoM	Center of Mass
COTS	Commercial Off-The-Shelf
CPU	Central Processing Unit
CSP	Cubesat Space Protocol
CTE	Coefficient of Thermal Expansion
DAC	Digital to Analog Converter
DN	Digital Number
DSP	Digital Signal Processor

ECEF	Earth Centered Earth Fixed
ECI	Earth Centered Inertial
EEE	Electrical, Electronic and Electro-mechanical
EM	Engineering Model
EPS	Electric Power System
ESA	European Space Agency
FC	Flight Computer
FEM	Finite Element Method
FFT	Fast Fourier Transform
FM	Flight Model
FOV	Field of View
FPGA	Field Programmable Gate Array
FPS	Frames Per Second
FRR	Flight Readiness Review
FWHM	Full-Width Half-Maximum
GMSK	Gaussian Minimum Shift Keying
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSE	Ground Support Equipment
HSI	HyperSpectral Imager
HW	Hardware
HYPSO	HYPer-spectral Smallsat for Ocean observation
ICD	Interface Control Document
IMU	Inertial Measurement Unit
IOCCG	International Ocean-Colour Coordinating Group
IOD	In Orbit Demonstration
IOP	Inherent Optical Properties
IR	InfraRed
I2C	Inter-Integrated Circuit

LEO	Low-Earth Orbit
LEOP	Launch and Early Orbit Phase
LNA	Low Noise Amplifier
LQR	Linear-Quadratic Regulator
Lw	Water Leaving Radiance
MM	Mass Model
MoI/MOI	Moment of Inertia
MPC	Model Predictive Control
MTF	Modular Transfer Function
NASA	National Aeronautics and Space Administration
NTNU	Norwegian University of Science and Technology
OBPG	Ocean Biology Processing Group
OTFP	On-The-Fly-Processing
PA	Power Amplifier
PCB	Printed Circuit Board
PDR	Preliminary Design Review
PID	Proportional-Derivative-Integral
PSD	Power Spectral Density
PSF	Point Spread Function
QAR	Qualification and Acceptance Review
RAM	Random Access Memory
RF	Radio Frequency
RGB	Red-Green-Blue
RMS	Root-Mean-Square
RW	Reaction Wheel
RX	Receive
SD	Secure Digital
SDR	Software Defined Radio
SNR	System to Noise Ratio

SOC	System-on-Chip
SOM	System-on-Module
SST	NX Space Systems Thermal
STM	Structural Thermal Models
SW	Software
SWIR	Short-Wave Infrared
TBC	To Be Confirmed
TBD	To Be Determined
TM/TC	Telemetry/Telecommand
TRL	Technology Readiness Level
TRB	Test Review Board
TRR	Test Readiness Review
TX	Transmit
UART	Universal Asynchronous Receiver-Transmitter
UHF	Ultra High Frequency
UxV	Unmanned Vehicles
WCS	World Coordinate System

D payload-parts

HYPSO-2 Payload parts (DRAFT)

HYPSO-XXX-XXX

Prepared by:	HYPSO Project Team
Reference:	HYPSO-XXX-XXX
Revision:	1
Date of issue:	14.12.2022
Status:	Preliminary
Document Type:	XXX

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3 List of Abbreviations.................................... **Error! Bookmark not defined.**

Table 1: Table of Changes

Rev.	Summary of Changes	Author(s)	Effective Date
1	*First issue*	*Eirik Sundby Håland* *Simen Eger Heggelund*	*14.12.2022*
2	*Updated*		22.05.2023

1 Overview

The HYPSO Mission will primarily be a science-oriented technology demonstrator. It will enable low-cost & high-performance hyperspectral imaging and autonomous onboard processing that fulfill science requirements in ocean color remote sensing and oceanography. NTNU SmallSat Lab launched the first research CubeSat developed at NTNU in January 2022, the HYPSO-1, followed by a second mission later. Furthermore, vision of a constellation of remote-sensing focused SmallSat will constitute a space-asset platform added to the multi-agent architecture of UAVs, USVs, AUVs and buoys that have similar ocean characterization objectives.

1.1 Purpose

The HYPSO-2 payload parts document provides a reference to the parts included in the HSI payload of HYPSO-2. The layout of the part list is based on the layout in [RD01].

1.2 Scope

The HYPSO-2 payload parts document is an overview of the parts included in the payload of HYPSO-2. The document is based on the design for the payload as of December 2022 and will be updated as development continues. The document only includes parts that are to be assembled at the Smallsat NTNU lab.

1.3 Summary

The document consists of the following:

- Chapter 2: Table of parts included in the HSI payload of HYPSO-2

1.4 Applicable Documents

The following table lists the applicable documents for this document and work.

Table 2: Applicable Documents

ID	Author	Title	Version
[AD01]	ECSS Secretariat	ECSS-M-ST-10C: Space management: Project planning and implementation (tailored)	
[AD02]	Norwegian Space Agency	NSC-Payload-PAQA (tailored)	

1.5 Referenced Documents

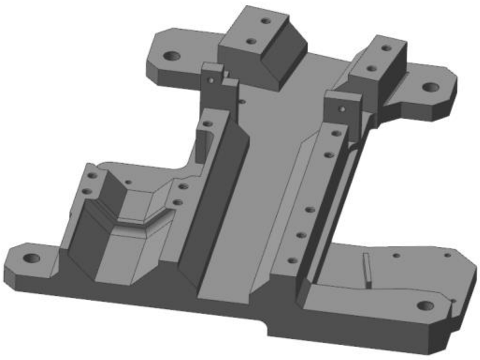
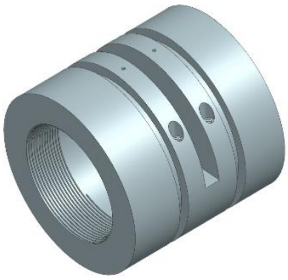
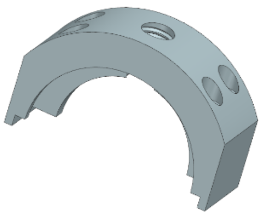
The documents listed in have been used as reference in creation of this document.

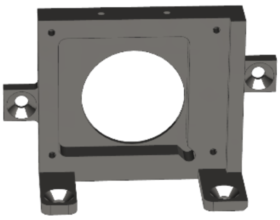
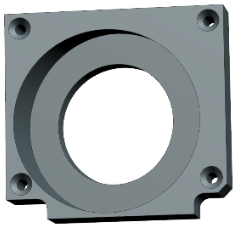
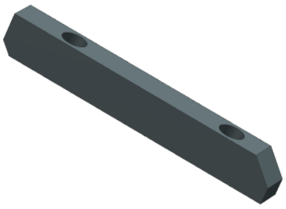
Table 3: Referenced Documents

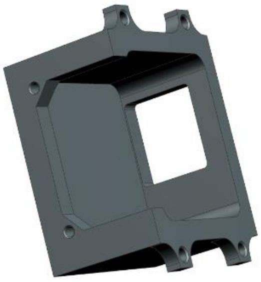
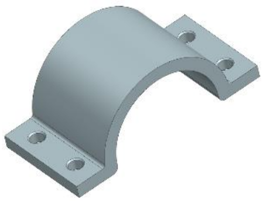
ID	Author	Title
[RD01]	Martine Hjertenæs Tord Hansen Kaasa Elizabeth Prentice	CLAW-1 Assembly, Integration and Test Plan

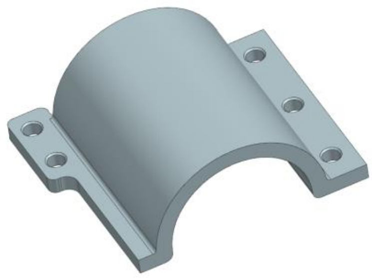
2 Part list

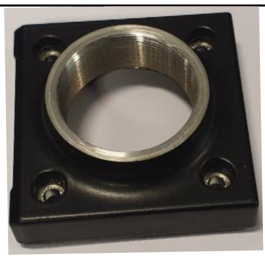
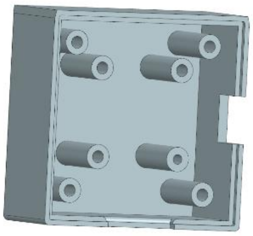
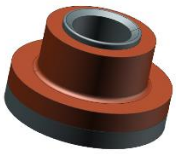
Table 4: List of full payload components CLAW

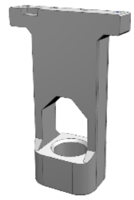
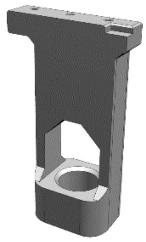
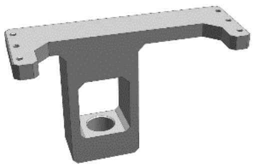
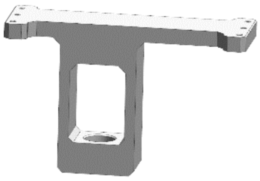
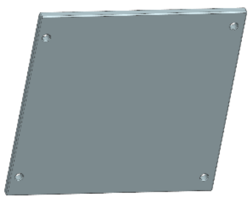
HSI Hyperspectral Imager				
	Description	**Image**	**#**	**COTS?**
1	Platform		1	Machined at NTNU
2	Slit tube		1	Machined at NTNU
3	Slit tube bracket		1	Machined at NTNU
4	Slit		1	S50RD

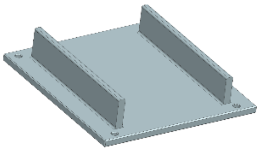
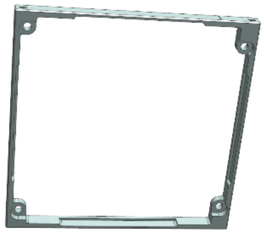
				
5	Cassette - Front		1	Machined at NTNU
6	Cassette - Back		1	Machined at NTNU
7	Clamp Bracket		2	Machined at NTNU
8	Bracket Gasket		2	Cut from sample material at NTNU
9	Grating		1	EO#49-579

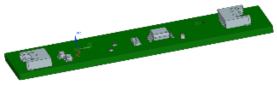
10	Detector Housing ETH		1	Machined at NTNU
11	Detector Housing Hi-Rose		1	Machined at NTNU
12	Detector		1	UI-5261SE
13	Platform Bracket Back		1	Machined at NTNU
14	Platform Bracket Mid		1	Machined at NTNU

15	Platform Bracket Front		1	Machined at NTNU
16	Objective		3	EO#67-717
		RGB Camera		
	Description	**Image**	**#**	**COTS?**
1	Detector		1	UI-1492LE
2	Objective		1	#33-831
3	C-Mount		1	UI-1250ML

				
4	Detector Housing		1	Machined at NTNU
5	RGB Bracket		1	Machined at NTNU
6	IR Filter		1	#49-810
	PLD Payload Structure			
	Description	**Images**	**#**	**COTS?**
1	Dampers		8	2151S

2	Front Crosslink +X		1	Machined at NTNU
3	Front Crosslink -X		1	Machined at NTNU
4	Back Crosslink +X		1	Machined at NTNU
5	Back Crosslink -X		1	Machined at NTNU
		PLD PicoBoB		
	Description	**Image**	**#**	**COTS?**
1	Shield Plate		1	Machined at NTNU

2	Shield Plate w/Rails		1	Machined at NTNU
3	Ring1U		2	COTS
4	MicroSD Card - Primary		1	[RP-SMSC08]()
5	MicroSD Card – Backup		1	[1052-1259-ND]()
	PicoZed		1	[7Z015 /7Z030SOM]()
	BoB		1	Designed at NTNU

	ALICE		1	Designed at NTNU

E Risk analysis

RISIKOANALYSE (alternativ til bruk av RiskManager)

Enhet/Institutt:	MTP	**Dato opprettet:**	13.9.2022
Ansvarlig linjeleder (navn):		**Sist revidert:**	
Ansvarlig for aktiviteten som risikovurderes (navn):	Bjørg Margrethe Granly and Marie Henriksen		
Deltakere (navn):	Simen and Erik		

Beskrivelse av den aktuelle aktiviteten, området mv.:

The risk analysis includes various tasks that Simen and Eirik will do during their project and master's thesis.

Aktivitet/arbeidsoppgave	**Mulig uønsket hendelse**	**Eksisterende risikoreduserende tiltak**	**Vurdering av sannsynlighet (S)**	**Vurdering av konsekvens (K)** *Vurder en konsevenskategori om gangen. Menneske skal alltid vurderes.*				**Risikoverdi (S x K)**	**Forslag til forebyggende og/eller korrigendene tiltak** *Prioriter tiltak som kan forhindre at hendelsen inntreffer (sannsynlighetsreduserende tiltak) foran skjerpet beredskap (konsekvensreduserende tiltak)*	**Restrisiko etter tiltak (S x K)**
			(1-5)	Menneske (1-5)	Øk/materiell (1-5)	Ytre miljø (1-5)	Omdømme (1-5)			
Eksempel: *Bruk av vinkelsliper*	*Øyeskade p.g.a. sprut av slipestøv/partikler*	*Vernebriller er alltid tilgjengelig i verkstedet*	*3*	*3*				9	*Før oppstart: Gjennomføre dokumentert HMS-opplæring med studentene (bruk av håndverktøy og pålagt verneutstyr)*	3 (S = 1)
Update CAD design with new RGB components	N/A	N/A	0					0	N/A	
Verify new design fits with rest of components inside satellite (also with SDR)	N/A	N/A	0					0	N/A	
Machine new platform	Machine breaking down or being damaged	Need to use glasses, safety shoes and appropriate clothes	3	1	2			9	Careful planning of tool path	
Build EQM and FM with new platform	Pinching from getting stuck between parts, damaging parts, getting parts dirty, shorting of components	Gloves, ESD equipment	2	1	2			6	Caution	
Test RGB vs HSI placement in new platform	Pinching from getting stuck between parts, damaging parts, getting parts dirty, shorting of components	Gloves, ESD equipment	2	1	2			6	Caution	
Test sensor placement in new platform	Pinching from getting stuck between parts, damaging parts, getting parts dirty, shorting of components	Gloves, ESD equipment	2	1	2			6	Caution	
Clean platform and brackets	Allergic reaction from cleaning detergent on skin	Need to use gloves.	2	1				2	Read Safety data sheet	
Machine grating cassette	Splinter in eyes, cuts from metal shavings, pinching from machinery	Need to use glasses, safety shoes and appropriate clothes	3	1	2			9	Careful planning of tool path	
Anodize grating cassette	Done remotely. Part can be incorrectly anodized	Clear communication with supplier	2		1			2	None needed	
Clean grating cassette	Allergic reaction from cleaning detergent	Need to use gloves.	2	1				2	Read Safety data sheet	
Machine housing for RGB sensor	Machine breaking down or being damaged	Need to use glasses, safety shoes and appropriate clothes	3	1	2			9	Careful planning of tool path	
Anodize RGB housing	Done remotely. Part can be incorrectly anodized	Clear communication with supplier	2		1			2	None needed	
Clean RGB housing	Allergic reaction from cleaning detergent	Need to use gloves.	2	1				2	Read Safety data sheet	
Machine housing for HSI sensor	Machine breaking down or being damaged	Need to use glasses, safety shoes and appropriate clothes	3	1	2			9	Careful planning of tool path	
Anodize HSI housing	Done remotely. Part can be incorrectly anodized	Clear communication with supplier	2		1			2	None needed	
Clean HSI housing	Allergic reaction from cleaning detergent	Need to use gloves.	2	1				2	Read Safety data sheet	
Update CAD, remove 2 of the 3 holes	N/A	N/A	0					0	N/A	
Machine new slit tube	Machine breaking down or being damaged	Need to use glasses, safety shoes and appropriate clothes	3	1	2			9	Careful planning of tool path	
Machine old slit tube for backup	Machine breaking down or being damaged	Need to use glasses, safety shoes and appropriate clothes	3	1	2			9	Careful planning of tool path	
Anodize all slit tubes	Done remotely. Part can be incorrectly anodized	Clear communication with NANO Avionics	2		1			2	None needed	
Clean slit tubes that will be used	Allergic reaction from cleaning detergent	Need to use gloves.	2	1				2	Read Safety data sheet	
Machine/cut new aperture	Machine breaking down or being damaged	Need to use glasses, safety shoes and appropriate clothes	3	1	2			9	Careful planning of tool path	
Anodize new aperture	Done remotely. Part can be incorrectly anodized	Clear communication with supplier	2		1			2	None needed	
Test EQM assembly before cleaning lenses	Damaging parts, getting parts dirty, shorting of components	Gloves, ESD equipment	2	1	3			8	Caution	
Disassemble objectives	Finger cuts and damaging parts.	Need to use gloves.	2	1	2			6	Caution	
Drill venting holes	Cuts from drill and clothing getting caught in machinery	Need to use glasses, safety shoes and appropriate clothes	2	2	2			8	Conduct HSE course (required protective equipment)	
Clean objective parts (except lenses)	Allergic reaction from cleaning detergent	Need to use gloves.	2	1				2	Read Safety data sheet	
Clean lenses	Allergic reaction from cleaning detergent	Need to use gloves.	2	1				2	Read Safety data sheet	
Assemble objectives	Finger cuts and damaging parts.	Need to use gloves.	2	1	2			6	Caution	
Focus objectives to infinity	Damaging parts, getting parts dirty	Need to use gloves.	2		2			4	Caution	
Test EQM assembly to check performance after dissasembly of objectives	Finger cuts and damaging parts.	Need to use gloves.	2	1	3			8	Caution	
Operating the Nanovac vacuum chamber	Finger pinching and damaging parts	Follow the chamber guidelines, use gloves and ESD equipment	2	1	3			8	Caution	
Performing shock and vibration test on a shaker table	Finger pinching and damaging parts	Use gloves, ESD equipment, listen to the operator at FFI	2	1	3			8	Caution	

F RGB-vacuum-test

HYPSO-2 RGB Vacuum Test

HYPSO2-XXX-XXX

Prepared by:	HYPSO Project Team
Reference:	HYPSO2-XXX-XXX
Revision:	1
Date of issue:	DD.MM.YYYY
Status:	Preliminary
Document Type:	XXX

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Table 1.1: Table of Changes

Rev.	Summary of Changes	Author(s)	Effective Date
1	*First issue*	*Eirik S. Håland*	
A	Changes after PDR: *Sec XX.XX - changed variable in response to RID-XX-XX*		

1 Overview

The Hyperspectral Smallsat for Ocean Observation (HYPSO) mission is a science-oriented technology demonstrator mission by the Norwegian University of Science and Technology (NTNU). It enables low-cost and high-performance hyperspectral imaging and autonomous onboard processing, fulfilling science requirements set by the ocean color remote sensing and oceanography communities.

In January 2022 the first Norwegian research satellite, HYPSO-1, equipped with a hyperspectral imager (HSI), was launched by NTNU SmallSat Lab. The second satellite, HYPSO-2, will follow shortly after with its launch planned in 2024. A vision of a constellation of remote-sensing focused CubeSats as space-asset platforms added to the multi-agent architecture of UAVs, USVs, AUVs and buoys that have similar ocean characterization objectives creates a full observational pyramid observing the oceans.

For HYPSO-2, a new RGB-lens and sensor were selected. To ensure the lens and detector could withstand vacuum without components outgassing and compromising the quality of the RGB images, the camera was tested in a vacuum chamber. This document describes the testing of the new RGB lens and sensor in the homemade Orbit vacuum chamber.

1.1 Applicable Documents

Table 1.1 below lists the applicable documents for this document and work.

Table 1.1: Applicable Documents

ID	Author	Title	Version
[AD01]	ECSS Secretariat	ECSS-M-ST-10C: Space management: Project planning and implementation (tailored)	
[AD02]	Norwegian Space Agency	NSC-Payload-PAQA (tailored)	
[AD03]			
[AD04]			
[AD05]			

1.2 Referenced Documents

The documents listed in Table 1.2 have been used as reference in creation of this document.

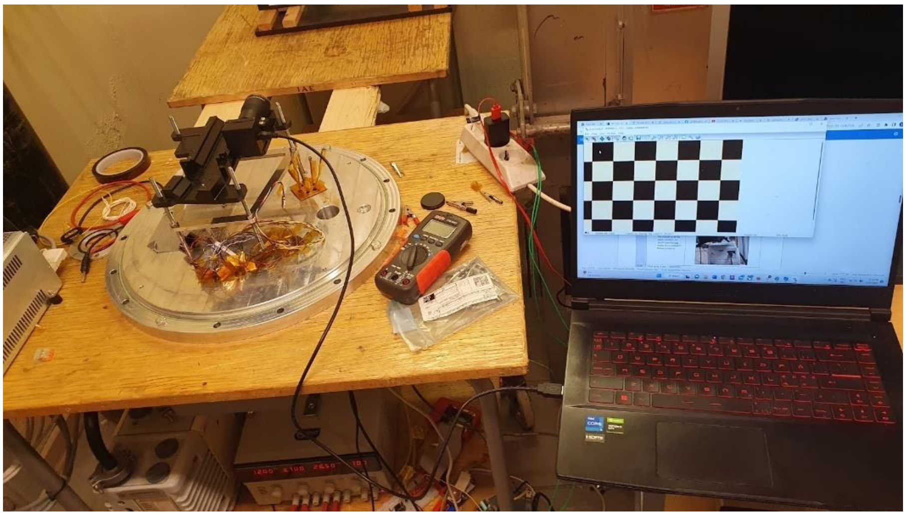
Table 1.2: Referenced Documents

ID	Author	Title
[RD01]	Fermin Navarro Medina, Esmèe Oudijk	Orbit TVAC guide
[RD02]		
[RD03]		
[RD04]		
[RD05]		

2 Test setup

The RGB-camera assembly is to be placed on the HSI-platform and fastened with a bracket. This is done to keep the camera in the same position before and after the testing. The platform is elevated using threaded rods to be able to point the RGB-lens through the window in the vacuum chamber.

The camera is pointing and focused on a checkerboard pattern. This is done to compare the focus before and after vacuum, and to detect potential warping and outgassing. The checkerboard pattern is placed at a different table than the chamber. The two tables are connected using planks and screws to ensure the RGB is in the same position during the entire test.



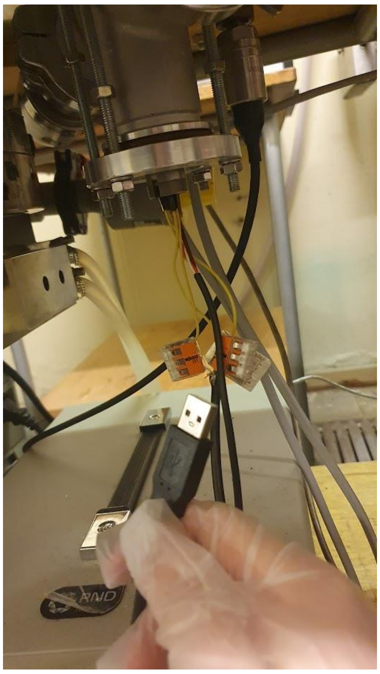
Test setup without the chamber dome

The camera is connected to a laptop using a USB-cable. The cable is connected on each side of the feedthrough pins of the chamber.

3 Preparations

3.1 Cables

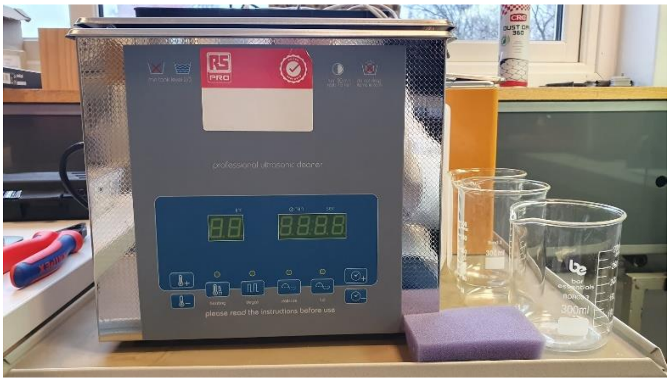
We wanted the opportunity to take pictures within the chamber while the vacuum pump was running. Therefore, we needed to split a USB mini-A cable. The Cable was split using a wire stripper and a pico-lock crimp tool. The cable can then be used in the chamber by connecting it to the chamber's feedthrough pins.



Cable connected to feedthrough pins

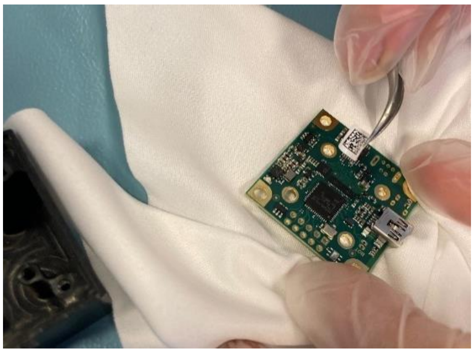
3.2 Cleaning

To reduce outgassing, cleaning of all the parts that are to be placed in the chamber is necessary. The cleaning of the machined aluminum parts is done with a wipe and alcohol. For testing in the Nanovac chamber, cleaning of the aluminum parts is to be done in the ultrasonic bath.



Ultrasonic bath

The sensor, IDS UI-1492el, contains stickers that need to be removed to reduce outgassing. The sensor is handled with care and the stickers are removed using tweezers. The glue from the stickers is cleaned using alcohol and wipes.



Removal of sticker from RGB-sensor

3.3 Software

To capture images with the RGB-camera, the "uEye Cockpit" software from IDS is used. The software can be downloaded for free from the IDS webpage: https://en.ids-imaging.com/downloads.html. Live video is used when testing the camera.

4 Conducting the test

Prior to placing the vacuum chamber over the camera, pictures were taken of the checker pattern, the T-21 / USAF focus calibration pattern and a white paper. These pictures were taken to be able to compare the state of the camera before and after the test.

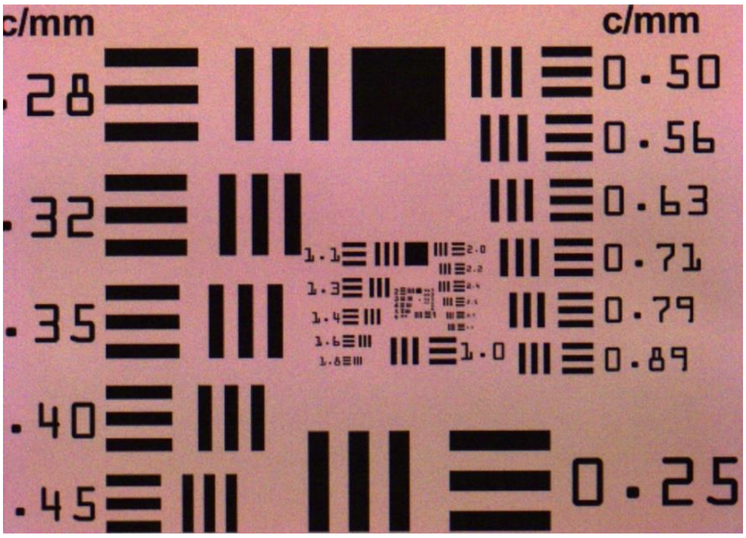


Image of the USAF pattern prior to placement of the chamber

The vacuum chamber was placed over the camera and the chamber was turned on and operated in accordance to [RD01]. Several pictures were taken from inside of the chamber. These were not in focus due to the thick glass of the chamber. The camera was turned off and sat in the chamber overnight.

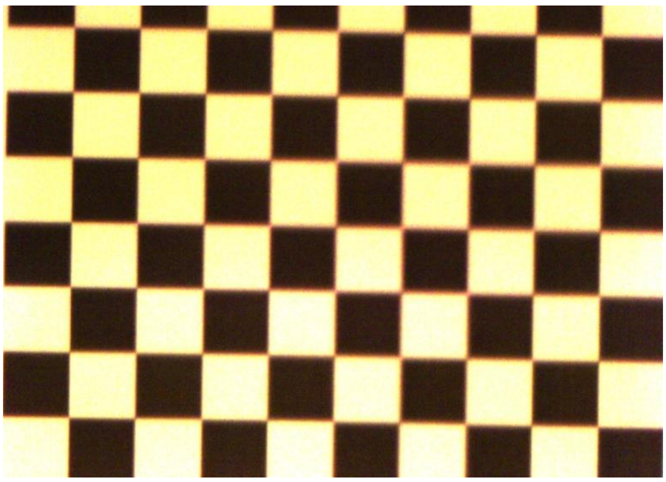
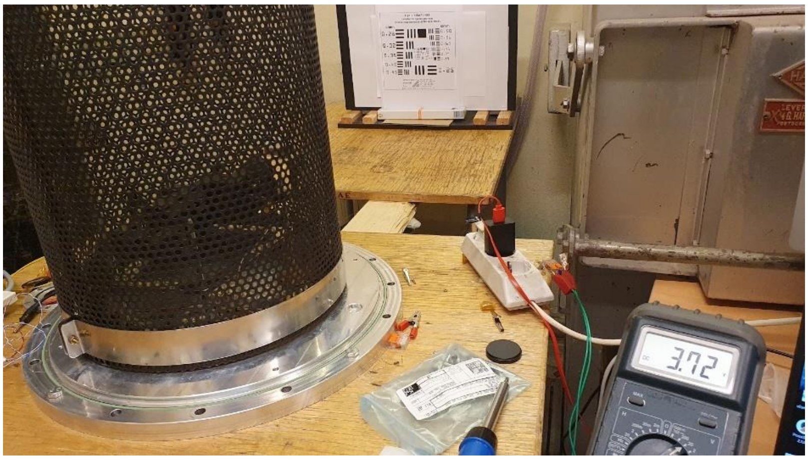


Image of the checker pattern during vacuum. Note that the image is not in focus due to the glass of the chamber.

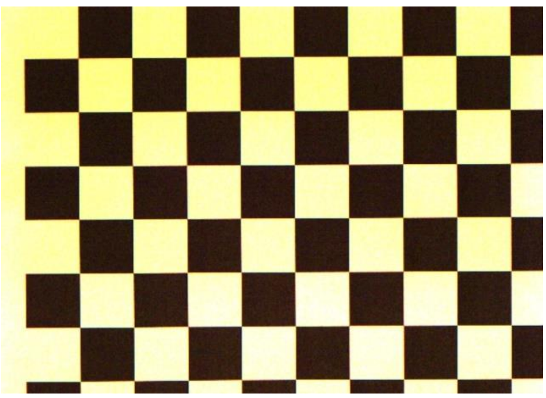
The camera was in the chamber for a total of 23 hours before the vacuum was turned off. A peak minimal pressure of 7.72*10^-6 mbar was achieved. When the chamber lid was lifted a distinct smell was present, indicating some outgassing had occurred. After the vacuum chamber was removed, more pictures of the checker pattern, T-21 / USAF focus calibration pattern, and the white paper were taken.

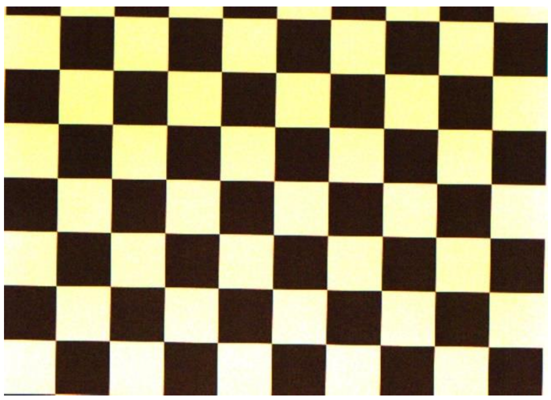


*The multimeter indicates a pressure of 7.72*10^-6 mbar*

5 Results

No major issues emerged prior to the vacuum testing. Although some outgassing was detected by smell, this did not seem to affect the image quality. It was noted that the noise in the images increased the longer the camera was turned on, although this seemed to occur due to overheating of the sensor.





Checker pattern prior to vacuum *Checker pattern after vacuum*

Note that the camera was slightly shifted when removing the chamber. All of the captures can be found on the HYPSO-Sharepoint.

6 Discussion

The results indicates that no disassembly and internal cleaning of the lens is necessary. This is positive, since as little handling of the lenses as possible reduces the chance to damage the optics.

7 List of Abbreviations

Table 7.1: List of Abbreviations

Abbrv.	**Description**
ABD	Aided Blind Deconvolution
AC	Atmospheric Correction
AIT	Assembly, Integration and Test
ADC	Analog to Digital Converter
ADCS	Attitude Determination and Control System
AOCS	Attitude and Orbit Control System
AoI	Area of Interest
API	Application Programming Interface
AxV	Autonomous Vehicles
BB	Breadboard
BER	Bit Error Rate
CAD	Computer Aided Design

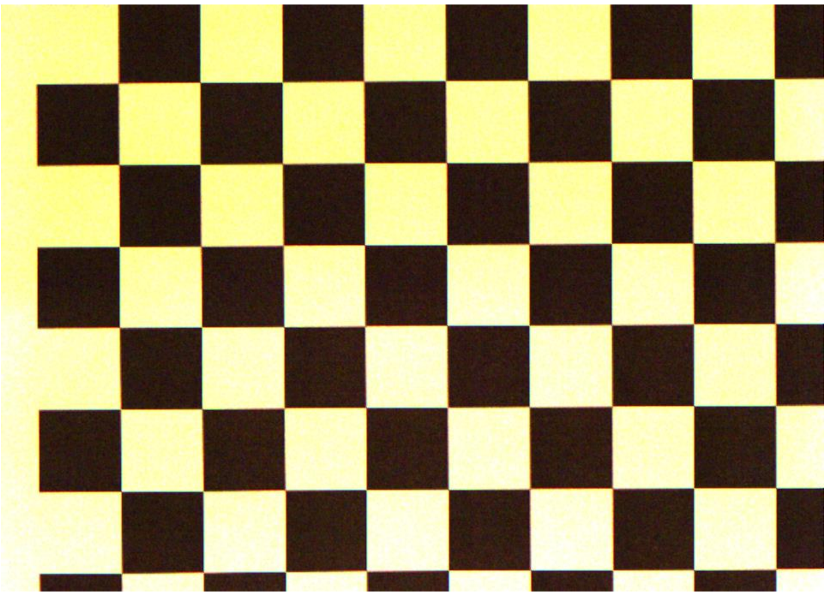
CAN	Controlled Area Network
CCSDS	Consultative Committee for Space Data Systems
CDR	Critical Design Review
CoG/COG	Centre of Gravity
COM	Communication
CoM	Center of Mass
COTS	Commercial Off-The-Shelf
CPU	Central Processing Unit
CSP	CubeSat Space Protocol
CTE	Coefficient of Thermal Expansion
DAC	Digital to Analog Converter
DN	Digital Number
DSP	Digital Signal Processor
ECEF	Earth Centered Earth Fixed
ECI	Earth Centered Inertial
EEE	Electrical, Electronic and Electro-mechanical
EM	Engineering Model
EPS	Electric Power System
ESA	European Space Agency
FC	Flight Computer
FEM	Finite Element Method
FFT	Fast Fourier Transform
FM	Flight Model
FOV	Field of View
FPGA	Field Programmable Gate Array
FPS	Frames Per Second
FRR	Flight Readiness Review
FWHM	Full-Width Half-Maximum

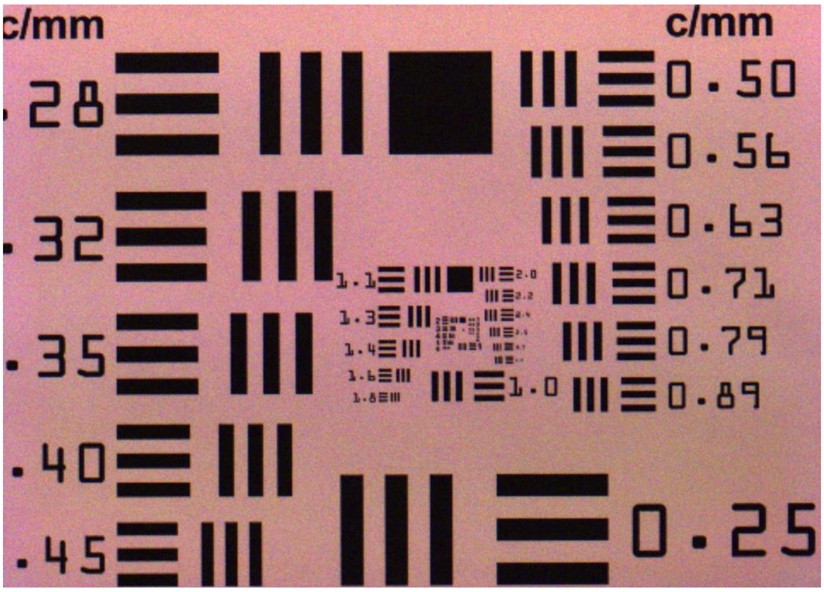
GMSK	Gaussian Minimum Shift Keying
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSE	Ground Support Equipment
HSI	HyperSpectral Imager
HW	Hardware
HYPSO	HYPer-spectral Smallsat for Ocean observation
ICD	Interface Control Document
IMU	Inertial Measurement Unit
IOCCG	International Ocean-Colour Coordinating Group
IOD	In Orbit Demonstration
IOP	Inherent Optical Properties
IR	InfraRed
I2C	Inter-Integrated Circuit
LEO	Low-Earth Orbit
LEOP	Launch and Early Orbit Phase
LNA	Low Noise Amplifier
LQR	Linear-Quadratic Regulator
Lw	Water Leaving Radiance
MM	Mass Model
MoI/MOI	Moment of Inertia
MPC	Model Predictive Control
MTF	Modular Transfer Function
NASA	National Aeronautics and Space Administration
NTNU	Norwegian University of Science and Technology
OBPG	Ocean Biology Processing Group
OTFP	On-The-Fly-Processing
PA	Power Amplifier

PCB	Printed Circuit Board
PDR	Preliminary Design Review
PID	Proportional-Derivative-Integral
PSD	Power Spectral Density
PSF	Point Spread Function
QAR	Qualification and Acceptance Review
RAM	Random Access Memory
RF	Radio Frequency
RGB	Red-Green-Blue
RMS	Root-Mean-Square
RW	Reaction Wheel
RX	Receive
SD	Secure Digital
SDR	Software Defined Radio
SNR	System to Noise Ratio
SOC	System-on-Chip
SOM	System-on-Module
SST	NX Space Systems Thermal
STM	Structural Thermal Models
SW	Software
SWIR	Short-Wave Infrared
TBC	To Be Confirmed
TBD	To Be Determined
TM/TC	Telemetry/Telecommand
TRL	Technology Readiness Level
TRB	Test Review Board
TRR	Test Readiness Review
TX	Transmit

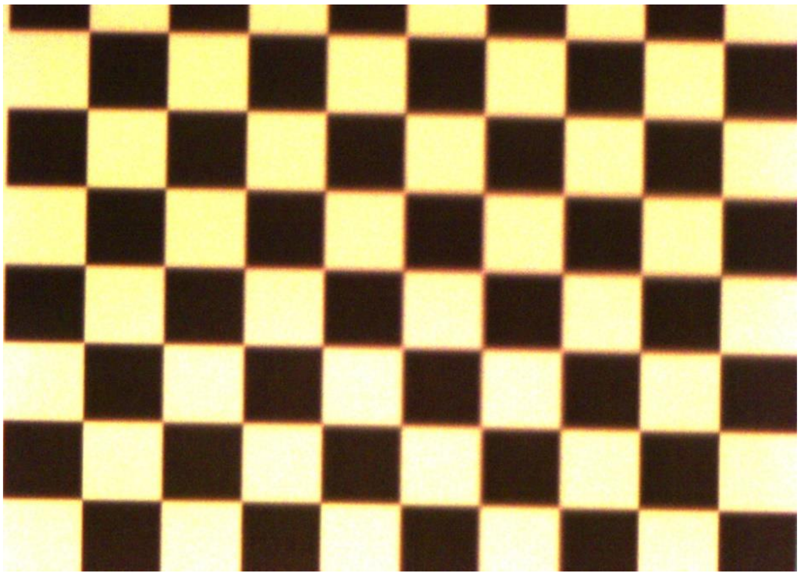
UART	Universal Asynchronous Receiver-Transmitter
UHF	Ultra-High Frequency
UxV	Unmanned Vehicles
WCS	World Coordinate System

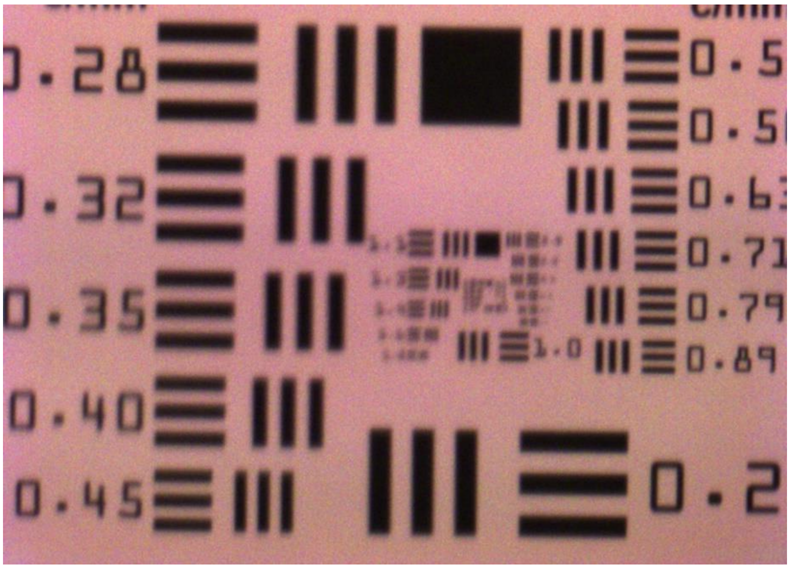
Appendix A Captures before vacuum



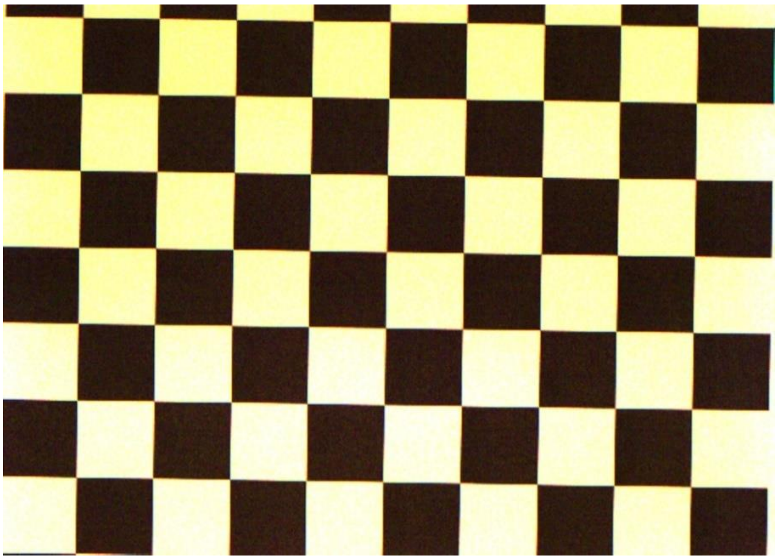


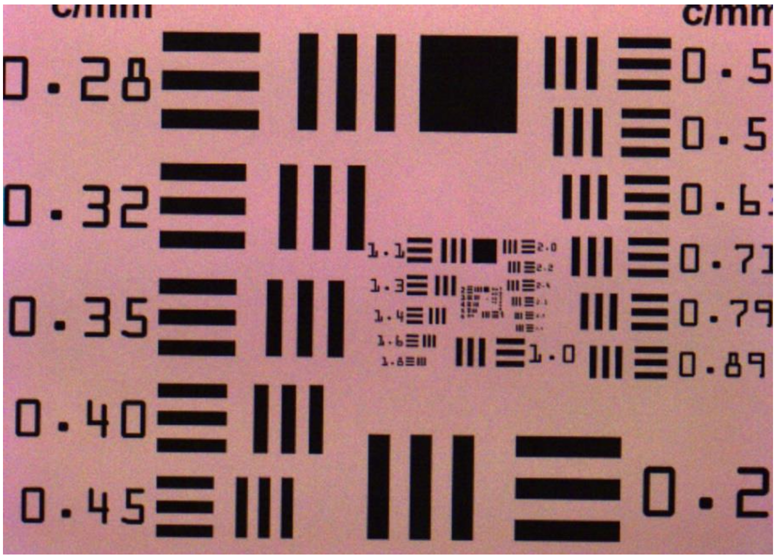
*Appendix B Captures during vacuum (7.72*10^-6 mbar)*

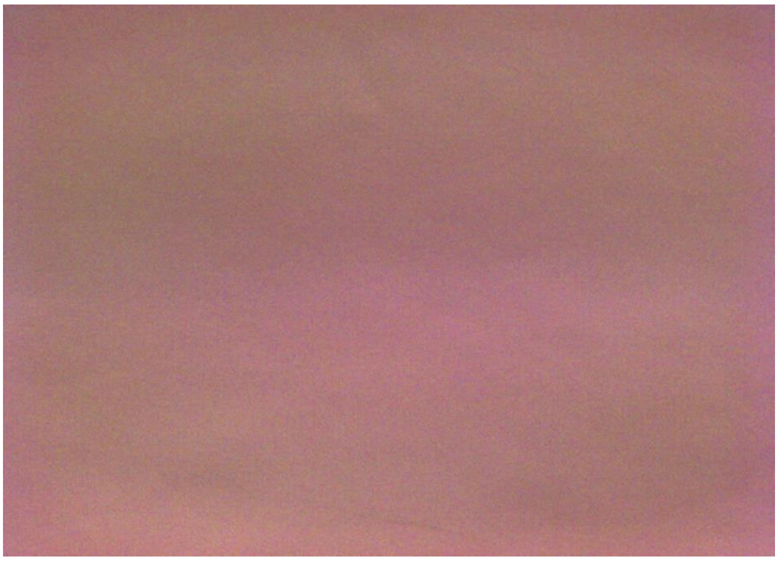



0.35
0.40
0.45
0.79
0.89
1.0
0.2

Appendix C Captures after vacuum







G Recipe for creating a temperature profile

Temperature profile guide for Nanovac chamber

HYPSO-XXX-XXX

Prepared by:	HYPSO Project Team
Reference:	HYPSO-XXX-XXX
Revision:	1
Date of issue:	Date
Status:	Preliminary
Document Type:	XXX

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Table 1: Table of Changes

Rev.	**Summary of Changes**	**Author(s)**	**Effective Date**
1	*First issue*	*Eirik Sundby Håland*	*28.04.23*

1 Overview

This document is a guide on how to create a temperature profile on the software for Nanovac chambers. A temperature profile is a recipe that provides the vacuum chamber with instructions on which temperature the table of the chamber and the shroud of the chamber should be at for a given time.

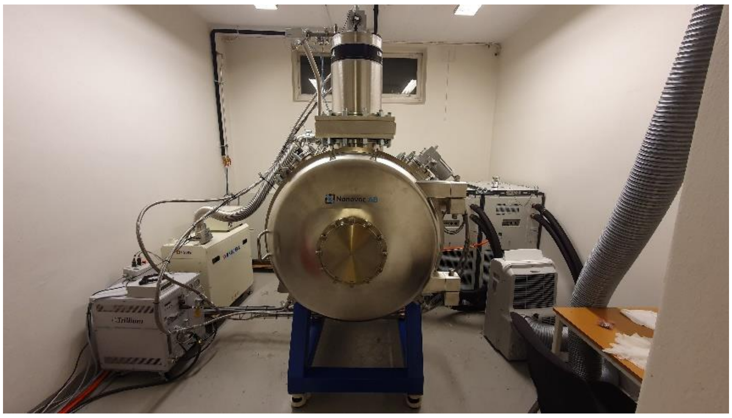


Figure 1.1 Nanovac AB vacuum chamber at NTNU

Within the chamber there are several thermocouples that are used to measure the temperature on the DUT (device under test), chamber table and the shroud.

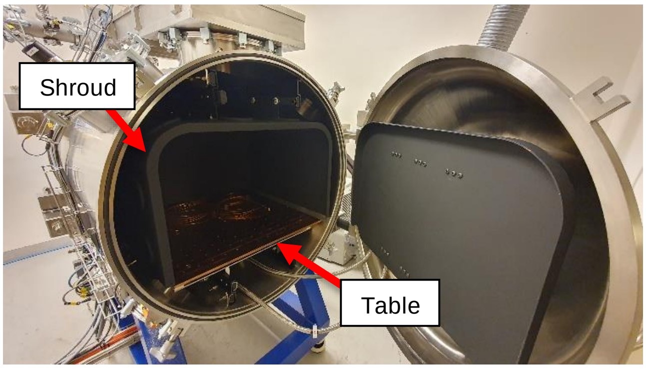


Figure 1.2 Inside the Nanovac AB vacuum chamber

The measurements from these thermocouples are used to regulate the temperature of the chamber.

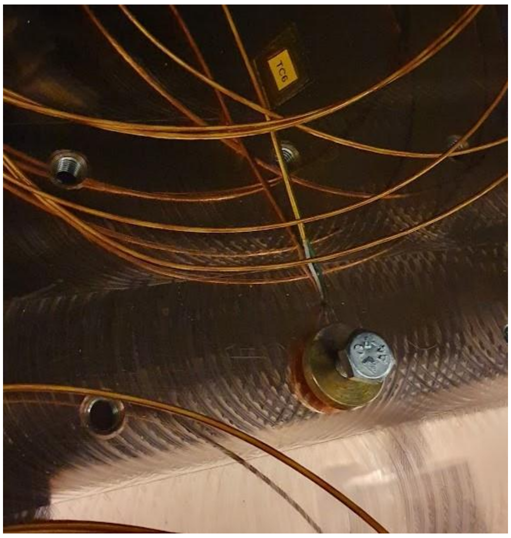
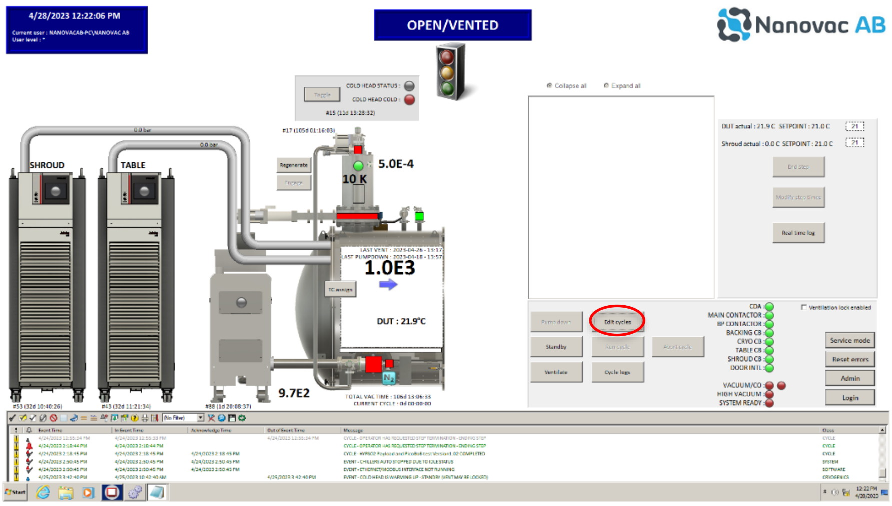


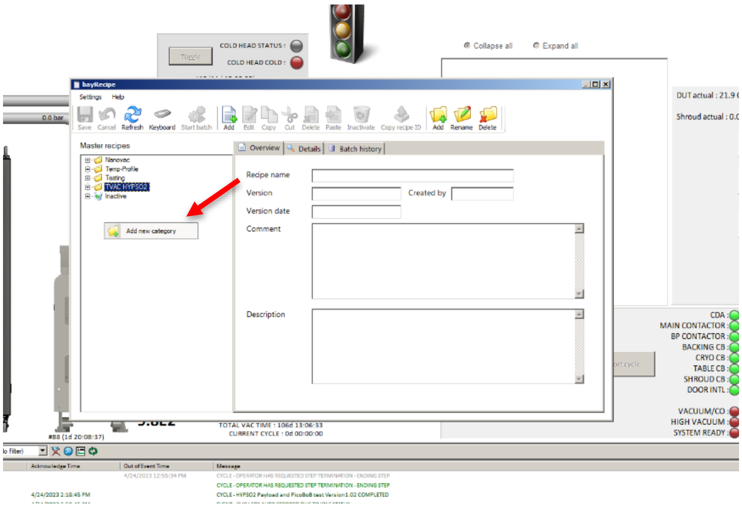
Figure 1.3 Thermocouple

2 How to create a temperature profile

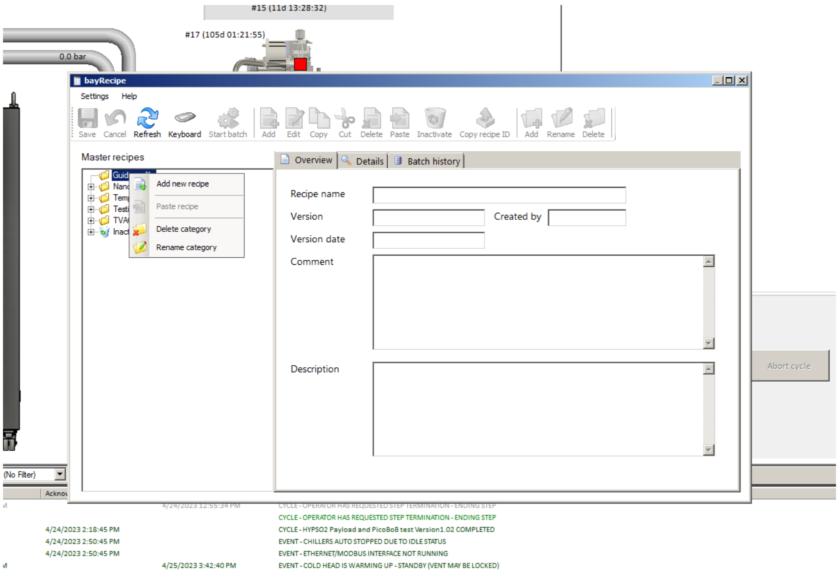
From the Nanovac AB software main page, press “Edit cycles”.



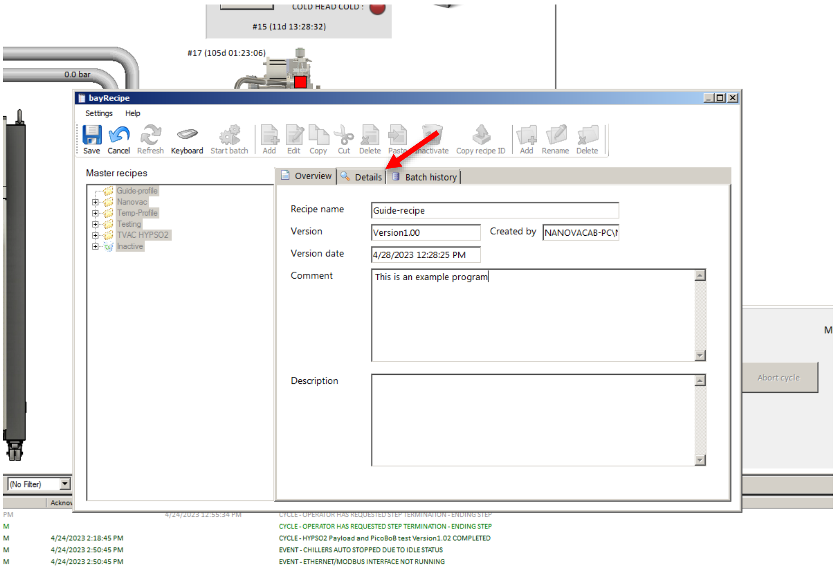
This takes you to the recipe edit page. Right-click in the Master recipes column and select “Add new category”.



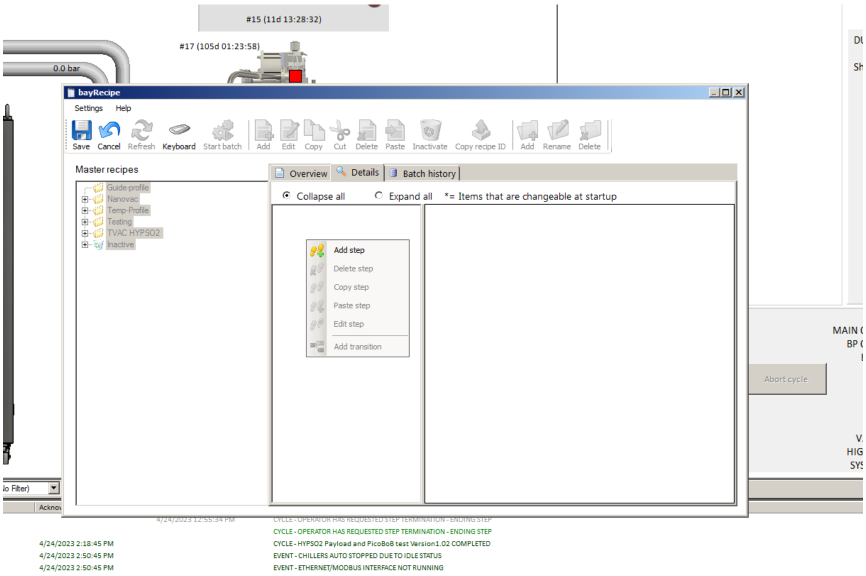
Give the new category a proper name. After this, right click on the category and select "Add new recipe"



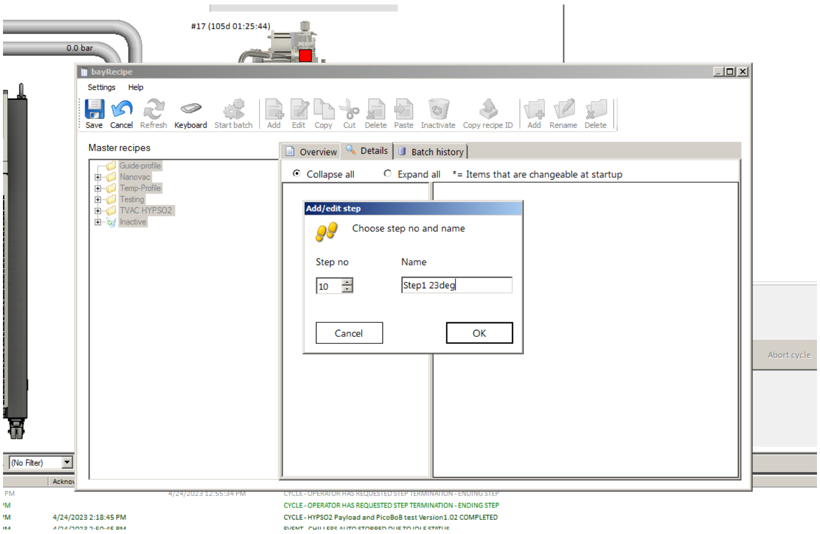
Give the new recipe a proper name. After this, select "Details".



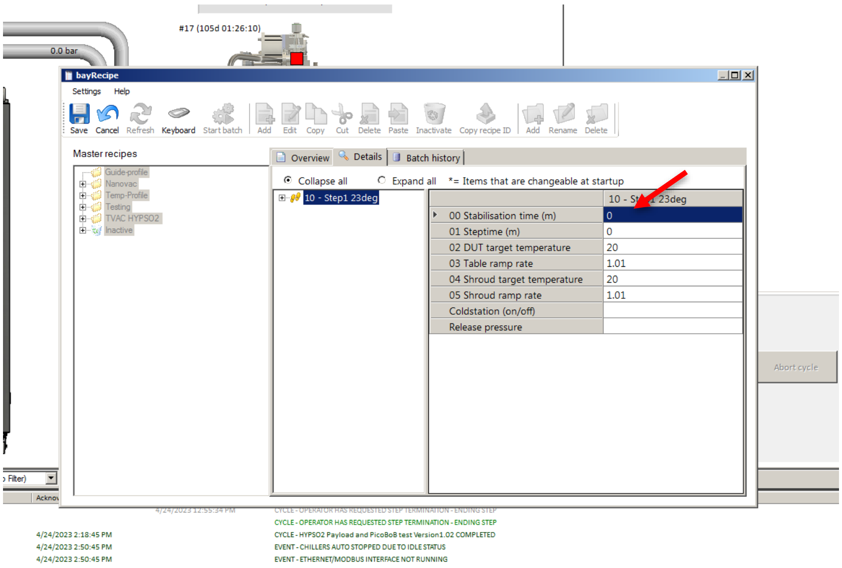
Right-click on the left window of the Details section and select “Add step”.



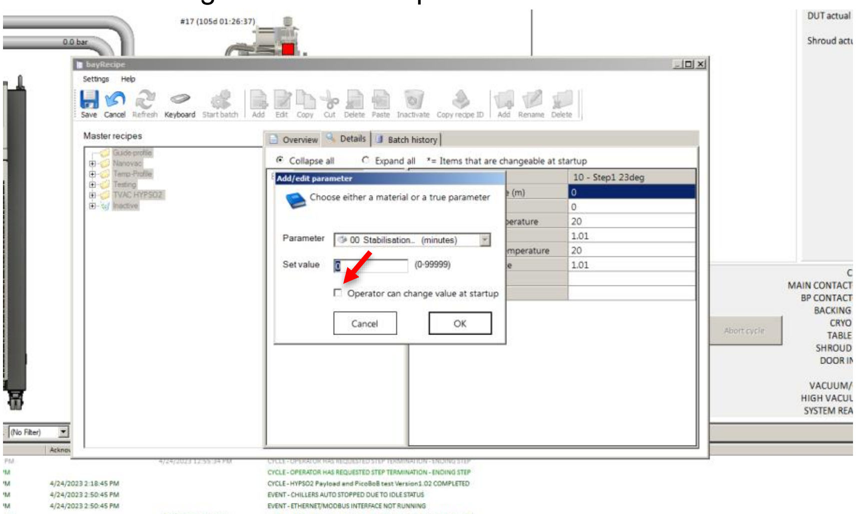
Give the new step a fitting name.



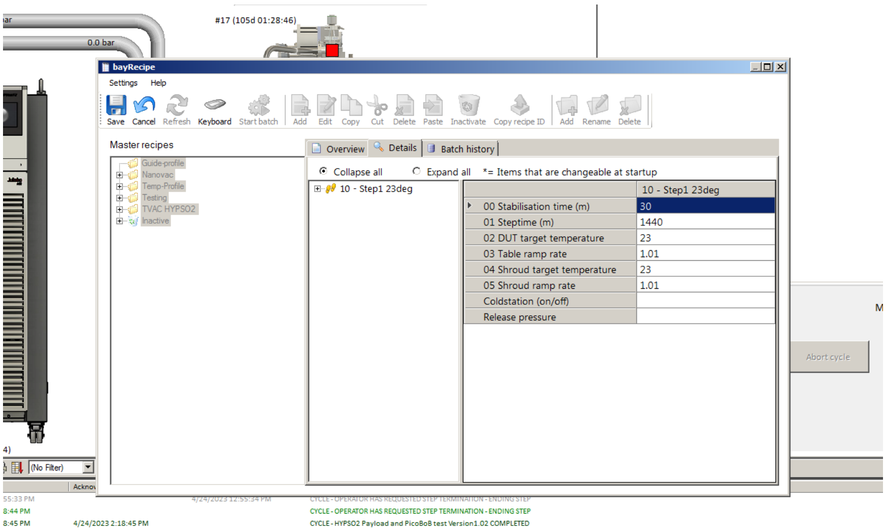
Each step contains settings that decide the behaviour of the chamber during that step. The different variables that can be altered are Stabilisation time [min], Steptime [min], DUT target temperature [C], Table ramp rate [C/min], Shroud target temperature [C] and Shroud ramp rate [C/min]. Stabilisation time is a timer that starts when the temperature is within +/-5C of the target temperature. This timer allows for the temperature to stabilise before the steptime timer is initiated. The steptime is the length of the step in minutes after the chamber has reached its target temperature. Table and shroud ramp rate decides how many degrees per minute the chamber should ramp at when altering temperature between steps. If the ramp rate is set to 0, the machine will attempt to run at a maximum rate change. Around 1C/min is usually a fitting ramp rate. Each variable can be altered by double clicking on a cell in the recipe table.



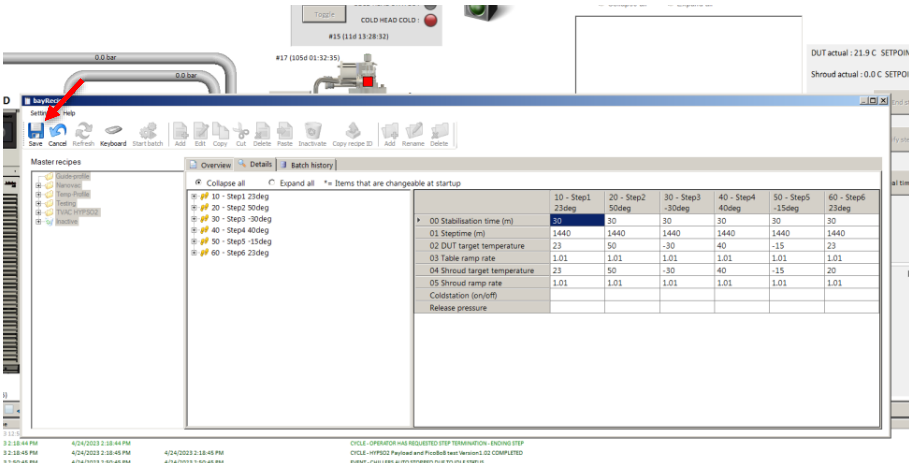
The values of the variables of a step can be altered when the program is running if the checkbox “Operator can change value at startup” is checked.



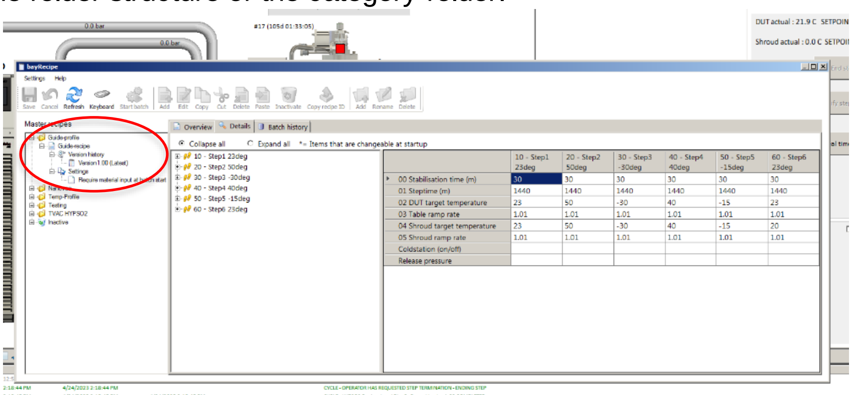
Each step runs until the steptime timer is completed. However, it is also possible to force the program to go to the next step by pressing “End step” in the main GUI while running a cycle. Therefore, by setting the steptime high, the program can be left in a steady state overnight and data can be gathered over several days without the need to constantly be in the vicinity of the chamber.



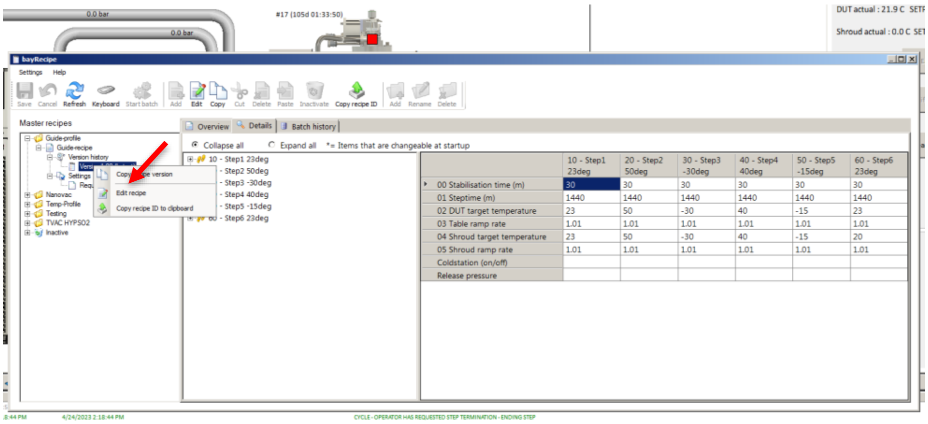
Repeat the process and add as many steps as needed. When the program is completed press the “Save” button.



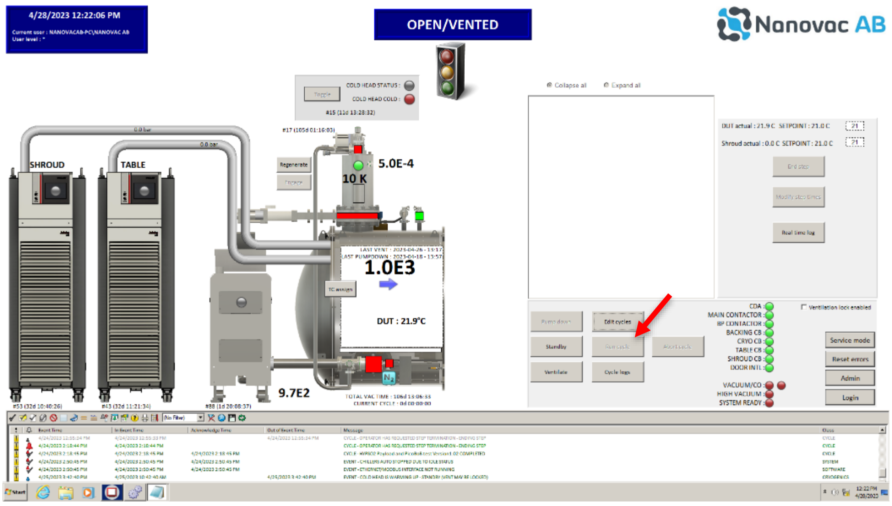
This creates the folder structure of the category folder.



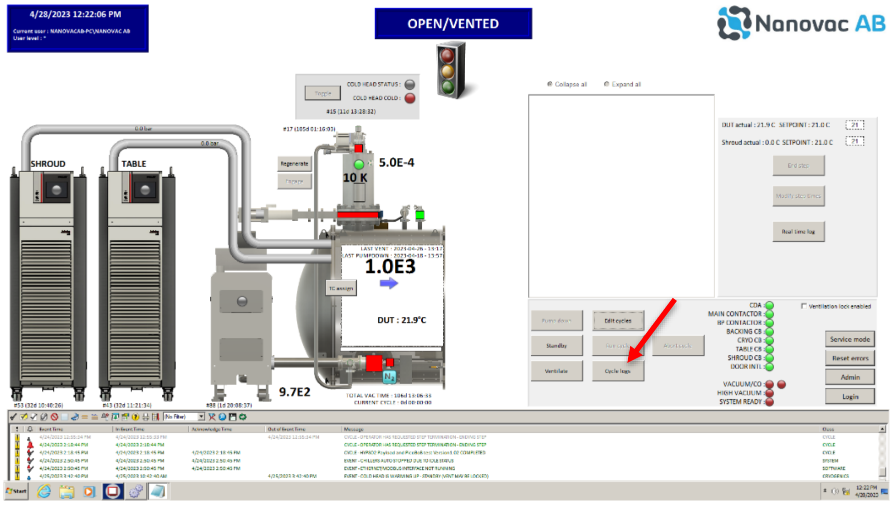
To alter the program, right click on the latest version of the program and select “Edit recipe”. This will create a new version of the program.



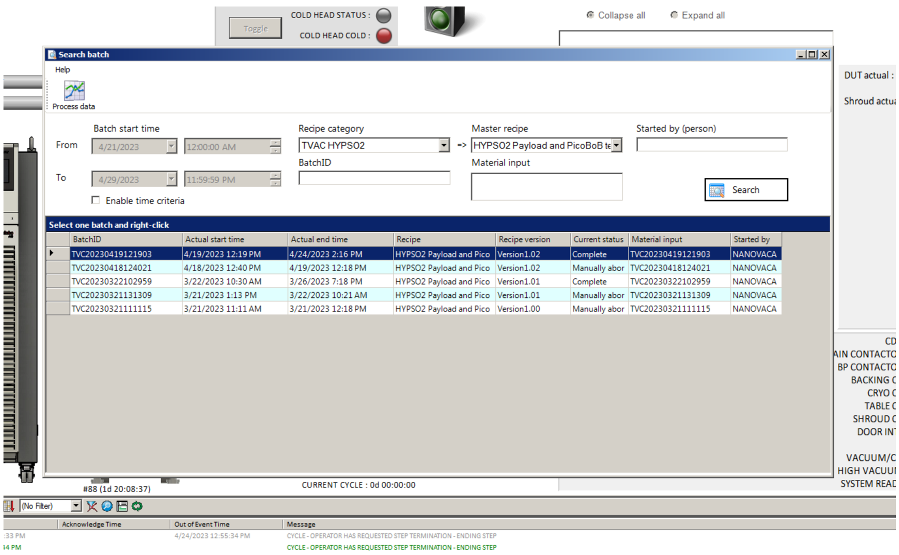
To run the program, click the “Run cycles” button on the main GUI page and select the recipe you want to run (This can not be done when the chamber is Open/Vented)



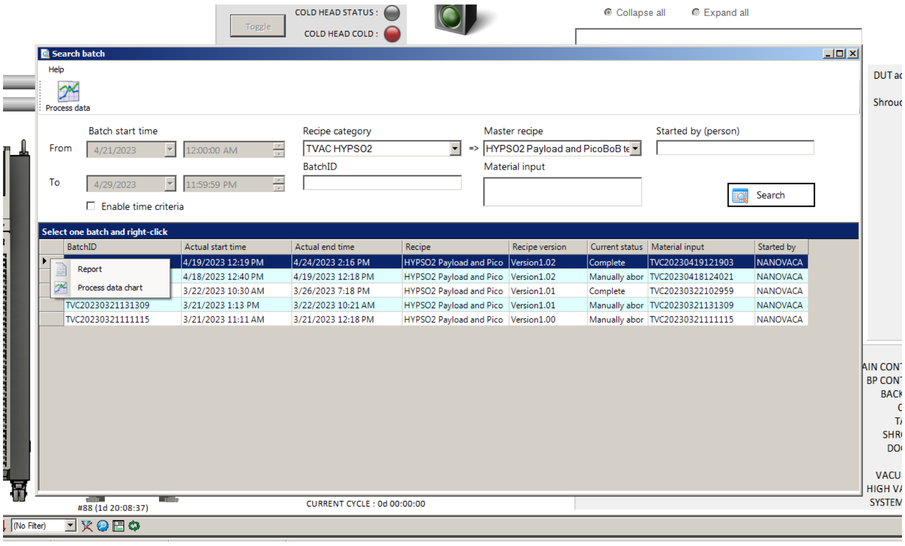
After a program is finished running, the data from the program can be found by clicking “Cycle logs” on the main GUI page.

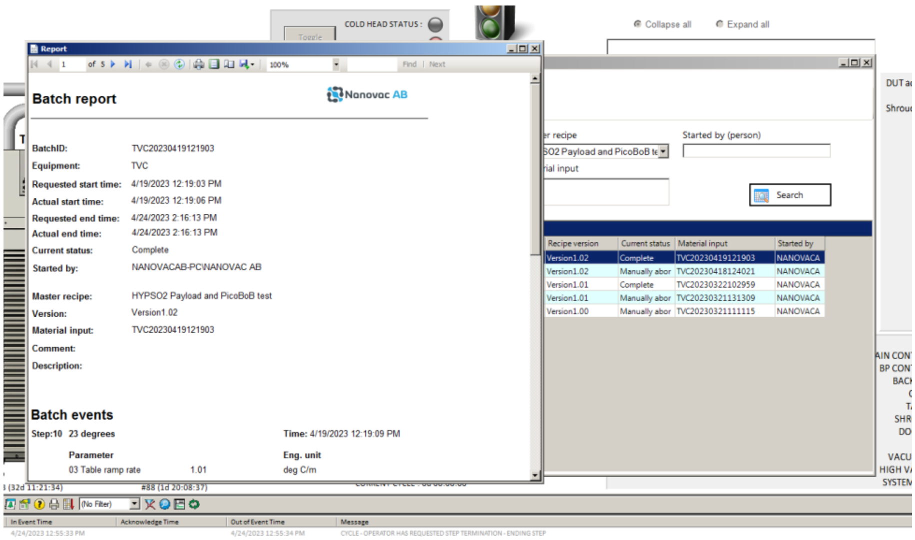


By selecting the category and recipe of interest and pressing search, previously run cycles from this program is displayed.



Right click on the cycle of interest and press either “Report” to get a PDF file with data from the cycle, or “Process data chart” which provides csv data of the cycle.





H HYPSO-2 TVAC report EQM

HYPSO-2 EQM TVAC Test Report

HYPSO2-TRP-TVAC-XXX

Prepared by:	HYPSO Project Team
Reference:	
Revision:	1
Date of issue:	04.05.2023
Document Type:	Test Report
Author(s):	Eirik S. Håland, Marie B. Henriksen

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1 Scope

1.1 Overview

This report outlines the TVAC tests performed at the newly installed Nanovac chamber at NTNU. The device under test (DUT) was the payload engineering qualification model (EQM) of HYPSO-2. The test was performed in order to characterize the CubeSats response to the high and low temperatures in vacuum. Evaluation is based on temperature sensor data, mechtest.py script results, plotted spectrograms, and RGB images measured before, during, and after each test. The primary test goals are as follows:

- Evaluate HYPSO-2 payload performance in high and low temperature
- Evaluate HYPSO-2 payload functionality in high and low temperature
- Compare performance at different temperatures
- Identifying issues with recently added components, such as the new RGB lens and sensor, as well as the ALICE breadboard.
- Evaluate if thermal straps are necessary

The testing was conducted in two stages. During the first test, there was no window installed in the chamber, resulting in all images being black. This test aimed to identify any potential issues that could be addressed prior to the installation of the window in the chamber. Additionally, it served as an opportunity to familiarize ourselves with the operation of the chamber.

Four full cycles were run on each of the two tests, with the first reaching non-operational extremes, -30 to 60 degC, and the following three cycling between -30 to 50 degC. On the ramp up of the first operational test, temperature was increased by 10 degree increments. The test script was run at the Characterization Points as noted in the Test Plan. There were initially some difficulties with controlling the chamber temperature. Due to poor connection between the thermocouples of the chamber and the DUT, the chamber overshot its temperature. This led to the DUT being exposed to temperatures of up to 90 degC, before the chamber aborted its test program. This was fixed by improving connections and after resetting the program, the test was completed without issues. The script ran without errors for all CPs and spectrograms and images show no major changes between runs. It was concluded that the payload EQM passes qualification.

1.2 Document History

Table 1.1. Table of changes

Rev.	Summary of Changes	Author(s)	Effective Date
1	First issue	E. Håland, M. B. Henriksen	

1.3 Applicable Documents

Table 1.2: Applicable documents

AD	Document ID	Rev.	Title
AD01	NA-ETR-002	1	Environmental Test Requirements for Falcon 9 Auxiliary Nanosatellites
AD02			
AD03			
AD04	HYPSO-TPL-OPT-001	1	Optical Validation Test Plan
AD05			
AD06	HYPSO-DR-003	5	HSI Design Report
AD07	HYPSO-TRP-TVAC-001	2	Thermal Vacuum Test Plan QM

AD08	Inspecting tightening torque. Tohnichi torque handbook vol. 9		https://www.tohnichi.com/pdf/03-inspecting-tightening-torque.pdf

1.4 Reference Documents

Table 1.3: Referenced documents

RD	Document ID	Rev.	Title
[RD01]	YAWE0028	2015	Lauda temperature controller manual Integral XT 20 W
[RD02]	HYPSO-TRP-TVAC-002	1	TVAC CLAW-1 QM

2 Validation

The validation for the first test was performed in the smallsat lab. For the test with the window, the validation was performed when the payload was mounted in the chamber and before the vacuum was turned on.

2.1 Validation setup

The validation setup at the smallsat lab is shown in the following figure. We used one of the ESD boxes to put the payload plate on and aligned the corners with the toolbox for a repeatable setup. This matters most for RGB validation since the data is spatial, not spectral. Note: the RGB was focused to infinity and no collimator lens was used. The RGB images will therefore show blurry results of targets close to the camera.

Figure 2.1: Validation overview side view.

.

A cardboard box was placed over the whole setup to block external light sources. The box had a fluorescent light mounted at the top, which was turned on more than 10 minutes before the test started for warm up.

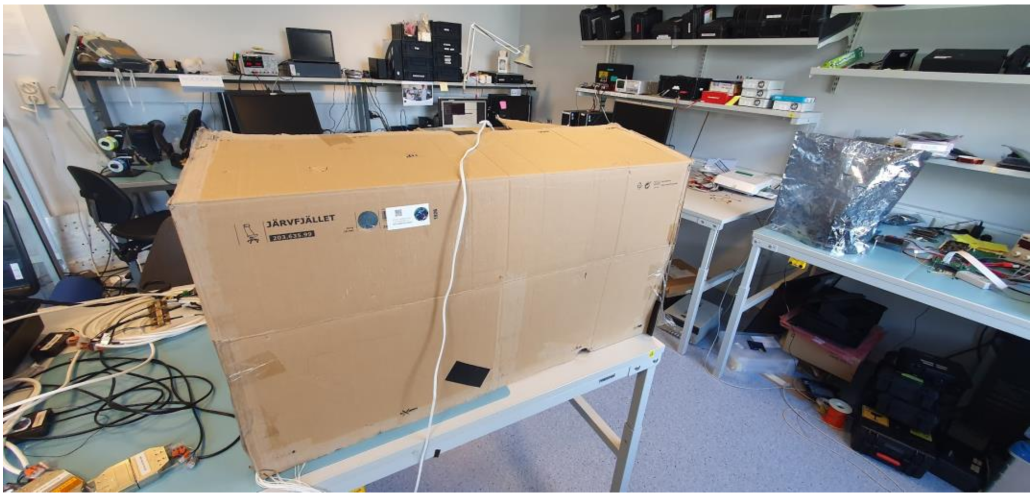


Figure 2.1: Validation overview with box.

The setup for the validation of the window test is shown in the following two figures. Cardboard and a piece of cloth was used to block out other light sources. The fluorescent light was placed directly in front of the window. This was also the setup when taking captures for the CPs.

Imager settings are summarized in Table 2.1 and Table 2.2. These same settings were used pre and post TVAC testing for consistency in the image comparisons.

Table 2.1: Imager settings for on-table validation.

Imager	Exposure Time [ms]	Frame Rate [FPS]
HSI	300	1
RGB	15	-

Table 2.2: Imager settings for on-table validation.

Imager	Exposure Time [ms]	Frame Rate [FPS]
HSI	1000	1
RGB	100	-

3 Test Setup

The test setup followed the guidelines in the TVAC test plan. There were two umbilical cords from the payload, through the chamber, to the power supply and the laptop.

3.1 Mechanical Test Setup

The payload was mounted on an interface plate to the TVAC chamber. For the first test, no light source was present.

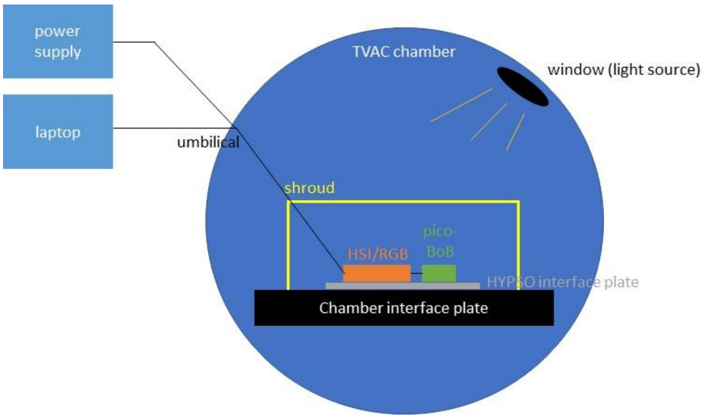


Figure 3.1: TVAC chamber test setup schematic.

3.1.1 Instrumentation

The TVAC chamber is a Nanovac AB vacuum chamber. Can provide a pressure below 1*10^-7 mbar. A dry pump is used to pump the pressure down to 1*10^-5 mbar before a cryogenic pump is employed to pump the pressure down further. The cryogenic pump operates at a temperature of 10K. It is cooled using liquid helium. A helium compressor is therefore located next to the chamber. The shroud and table of the chamber are temperature controlled and can vary between –50C to +90C.

Figure 3.2: Nanovac AB thermal vacuum chamber at NTNU.

3.1.2 Torque applied

The torque was applied according to the table in the TVAC test plan, as shown below. Screws M2, M2.5, and M3 torque values were recommended by NanoAvionics.

Table 3.1: Torque table.

Screw Diameter [mm]	Torque [Nm]	Notes
M2	0.315 (0.4 max)	everything else
M2.5	0.7	
M3	1.140 (1.6 max)	
M4	2.600 (2.7 max)	
M5	4.0	
M6	8.800 (9.5 max)	for mounting plate

3.1.3 Mounting in the Chamber

The payload was mounted to an aluminum plate machined specifically for the TVAC test. A drawing of the plate is attached in Appendix A. That plate was attached to the TVAC interface plate using M6 screws.

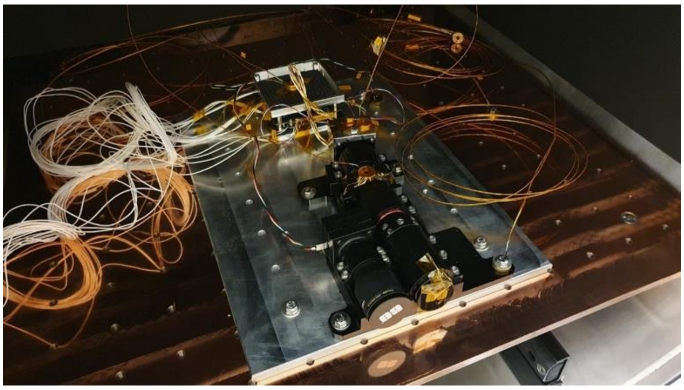


Figure 3.3: Payload mounted inside chamber. Thermocouples attached.

3.2 Electrical Test Setup

Two umbilical cords are brought through the chamber via a sealed adapter.

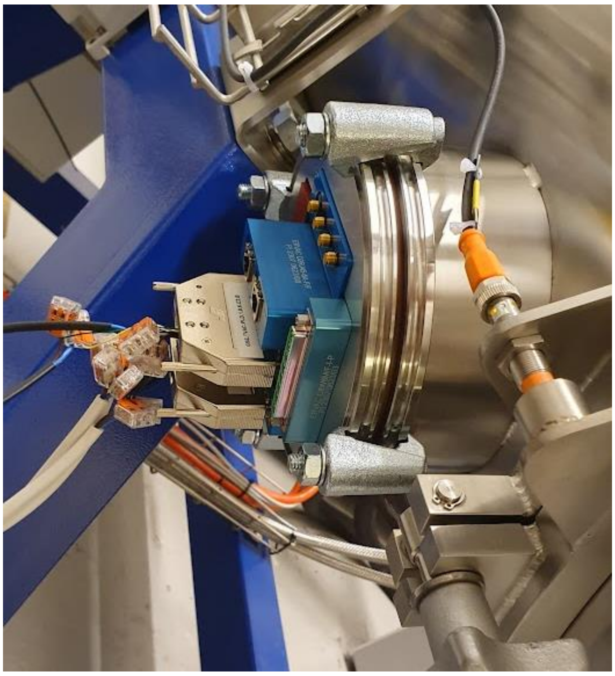


Figure 3.4: Cables through the chamber

3.3 Imager settings

The exposure time and frame rate of the HSI was set after taking test images inside the TVAC chamber [see AD04 for more info on the procedure]. The only light source was a fluorescent lamp in the chamber window, see the schematic in §3.1. These settings were changed in the initialization file of the script prior to testing and set to be default.

Table 3.2: Imager settings for inside the TVAC chamber.

Imager	Exposure Time [ms]	Frame Rate [FPS]
HSI	1000	1
RGB	100	-

3.4 Sensor Placement

There are 8 thermocouples present in the chamber. Two are permanently fixed on the shroud and table. During testing it became apparent that another thermocouple needed to be placed on the table for proper temperature regulation. Figure 3.5 and 3.6 shows the placement of the rest of the sensors. Figure 3.7 and 3.8 shows the sensor placement for the TVAC test of HYPSO-1.

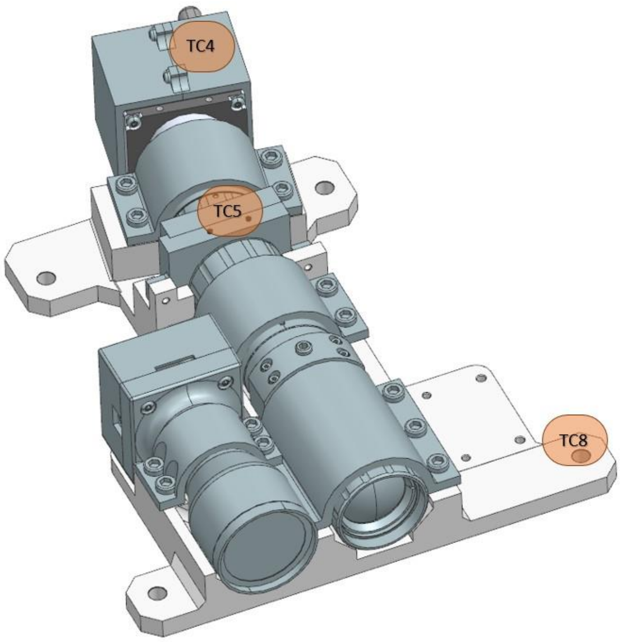


Figure 3.5: Sensor placement on the HSI payload.

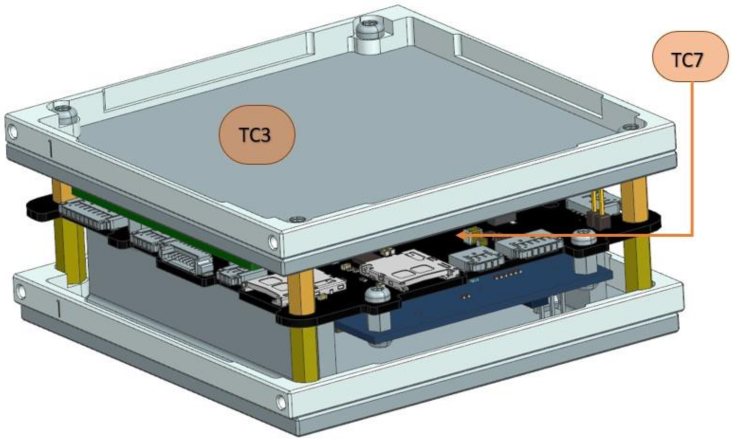


Figure 3.6: Sensor placement on the PicoBoB.

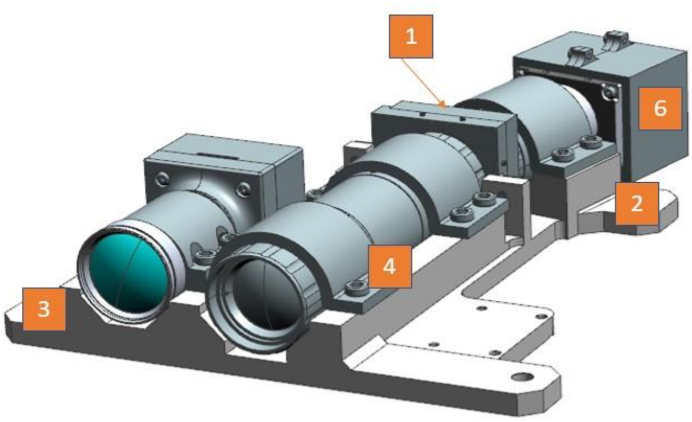


Figure 3.7: Sensor placement on the payload for the TVAC test of HYPSO-1.

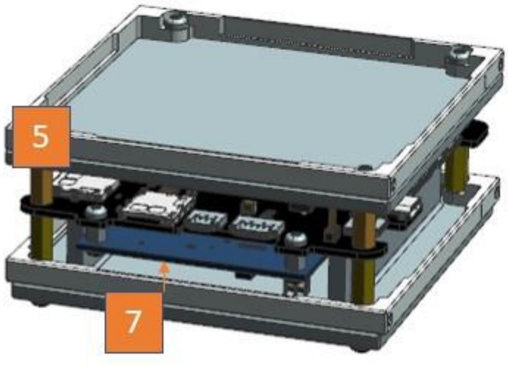


Figure 3.8: Sensor placement on the PicoBoB for the TVAC test of HYPSO-1.

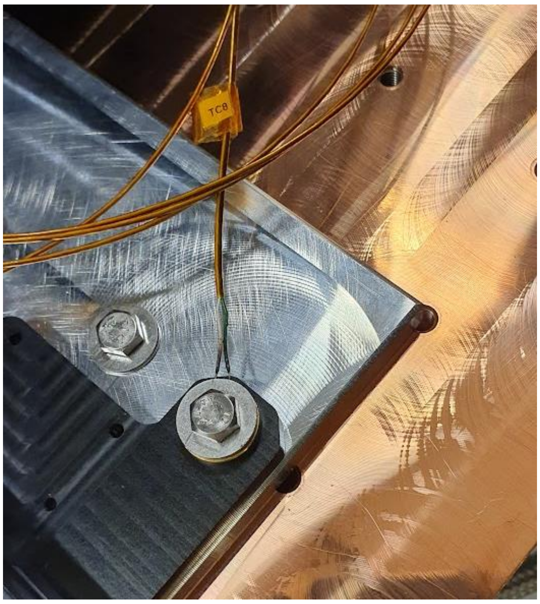


Figure 3.9: Sensor TC8.

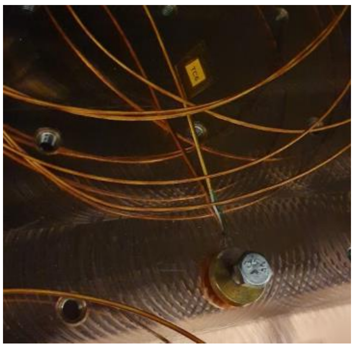


Figure 3.10: Sensor TC6.

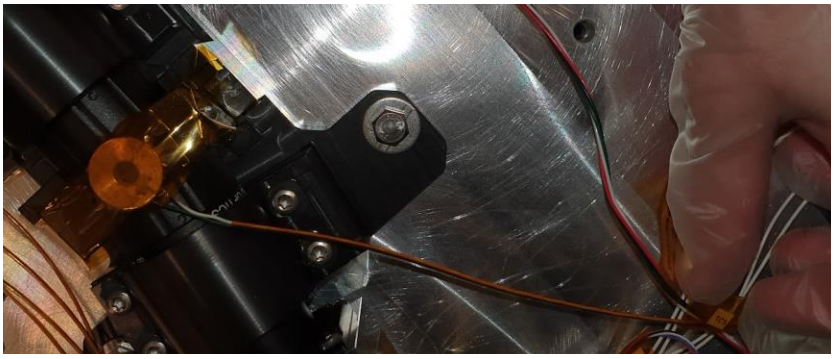


Figure 3.11: Sensor TC5 grating cassette.

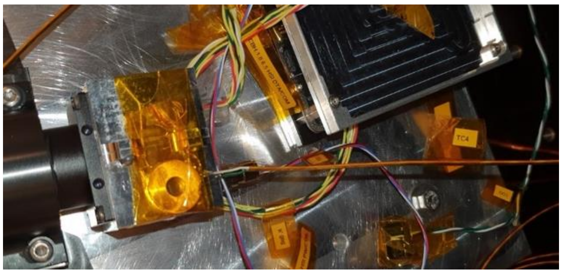


Figure 3.12: Sensor TC4 HSI sensor.

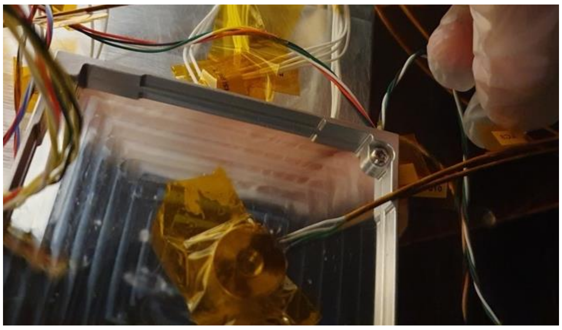


Figure 3.13: Sensor TC3 outside BOB shield plate.

TC7 is placed on the 5V regulator of the PicoBoB.

3.5 Testing Profiles

We followed the testing profile outlined in the Test Plan [AD07].

Figure 3.14: Followed temperature profile from test plan.

The output temperature readings of the Nanovac chamber are shown in Figure 3.14. Dwell is elongated in the plot since the testing occurred over several days (overnight).

4 Results

At each Characterization Point (CP), the test script was run to capture one RGB image and five HSI spectrograms. Two temperature readings from the HSI sensor are output- one just as the HSI is turned on and one right before it's turned off. If images are saved, the test is considered a 'pass' for rebooting and compression. A failed test will have no data for that specific CP.

4.1 Measured temperature profiles

The following plots show the measured temperature profile from individual sensors, first the full profile, then the steps, and finally the final cycles.

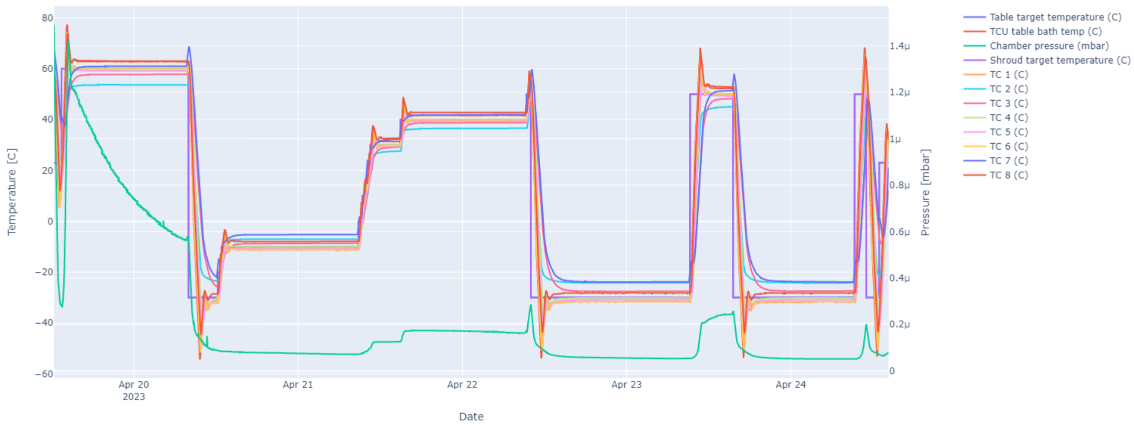


Figure 4.1: Measured temperature profile – window

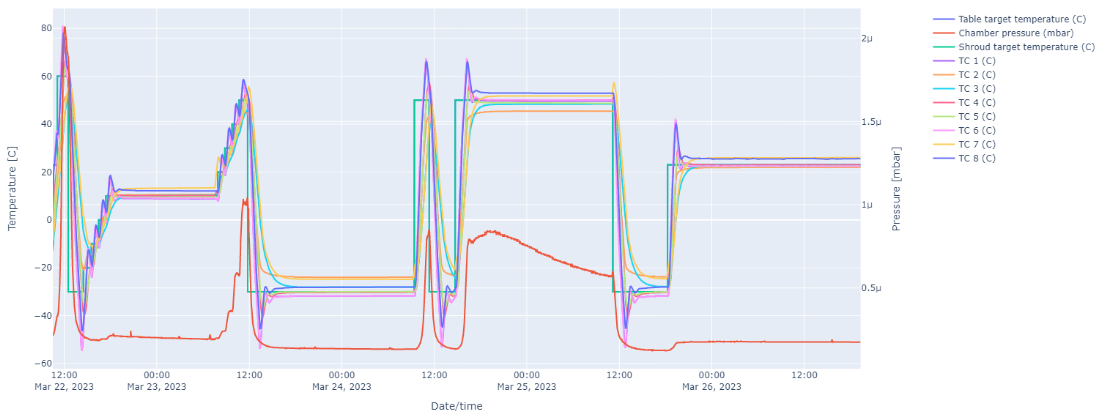


Figure 4.2: Measured temperature profile – no window

By inspecting the measured temperature profile closer, we can see that some components heat up when captures are taken. The following figure is a closeup of CP2. As explained in section 4.4, sensor TC5 is placed on the grating cassette, TC6 is placed on the table and TC7 is placed on the 5V regulator of the PicoBoB. All sensors deviate slightly before the mechtest script is run. This might be due to differences in the thermocouples, or the chamber might not have had enough time to stabilize. It Is clear from the figure that the PicoBoB has a significant rise in temperature (approx. 8 degrees), compared to the other components.

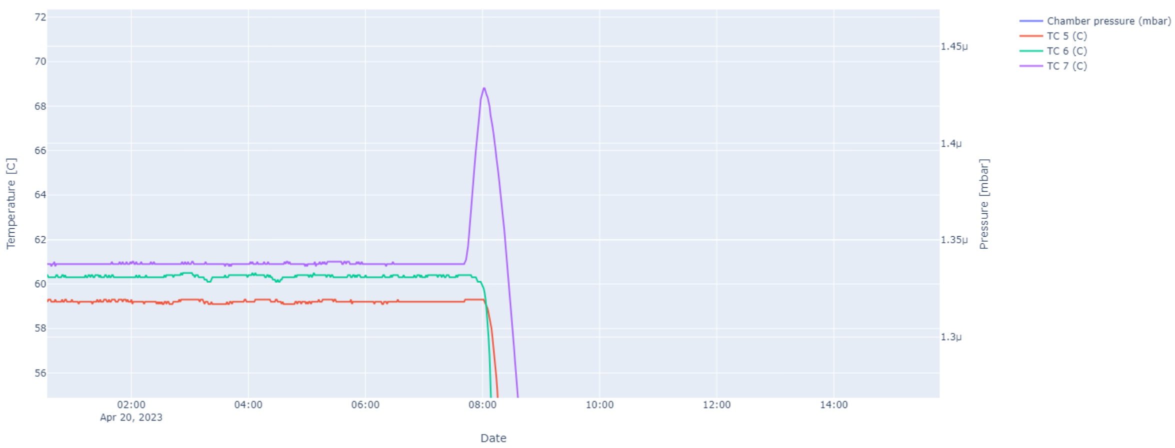


Figure 4.3: Temperature rise of PicoBoB. Closeup of CP2 - window

The same effect can be seen on the sensor that is placed on the HSI housing (TC4), although not to the same extent. From the telemetry readings of CP2, we can see that the HSI sensor temperature rises with 5 degrees, however the rise of temperature is not as significant on the housing.

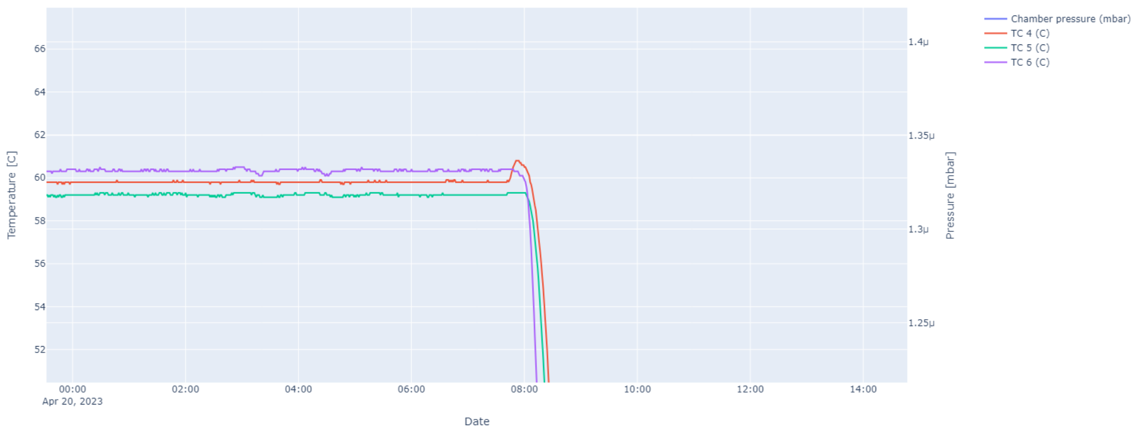


Figure 4.4: Temperature rise of HSI housing. Closeup of CP2 - window

The following figure gives an overview of how the pressure changes with the changes in temperature. The most significant rise in temperature is at CP2 where the pressure rises from around 3*10^-7 mbar to 1.4* 10^-6 mbar before gradually decreasing. The quick rise and gradual decrease of pressure is a clear sign of outgassing. The pressure rises every time the temperature increases, although not to the same extent as for CP2. This could indicate that most of the outgassing occurred at the beginning of the test. The fluctuations in pressure are even more evident for the first TVAC test (no window). This is also a clear sign that some outgassing occurred during testing in the chamber. Luckily, the outgassing did not seem to affect the results or damage the instruments.

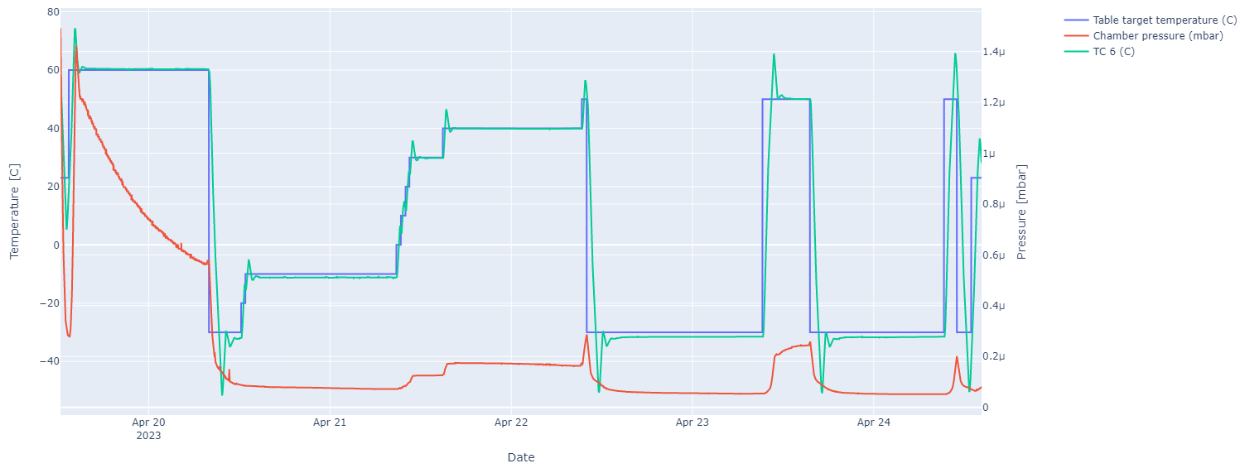


Figure 4.5: Temperature profile, table measurements and chamber pressure of the TVAC test – window

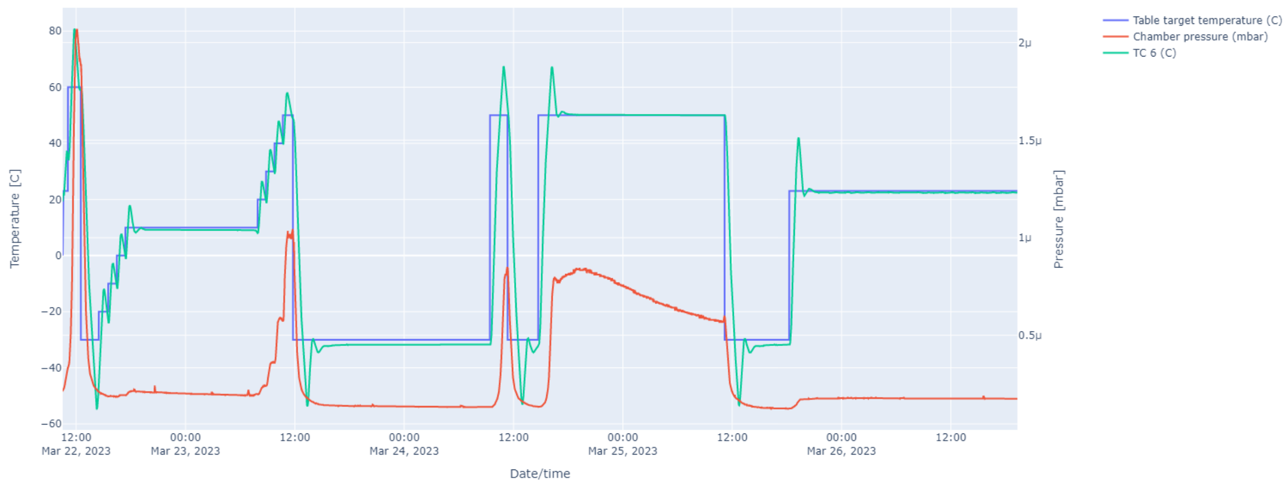


Figure 4.6: Temperature profile, table measurements and chamber pressure of the TVAC test – no window

4.2 CP Results first test – no window

4.2.1 HSI Spectrograms

For the first TVAC test in the dark (no window), data/images were not saved at all temperature steps. Only spectrograms of three temperature steps (-30, 10 and 50 degrees) and the hot (50 degrees) and cold (-30 degrees) cases are therefore plotted here.
Note: exact values may be inaccurate due to black level setting being active (adding a possible count value of 12 or something like that).

Due to there being no window in the TVAC chamber, the environment is dark. This is convenient to investigate the dark current/ noise in the sensor at different temperatures. Five images were saved at each step. Histograms were plotted to show the distribution of values in the image, each shade of blue in the plot corresponding to one of the five images taken. On the x-axis is the counts, so further to the right means higher pixel value, while the y-axis shows how many pixels that have this value (on a logarithmic scale).

First, images from the three temperature steps (step 3 with –30 degrees, step 7 with 10 degrees and step 11 with 50 degrees) were plotted. It can be seen that most values in the cold case (step 3, -30 degrees) are centered around 20-30 counts, while higher values appear for the higher temperatures.

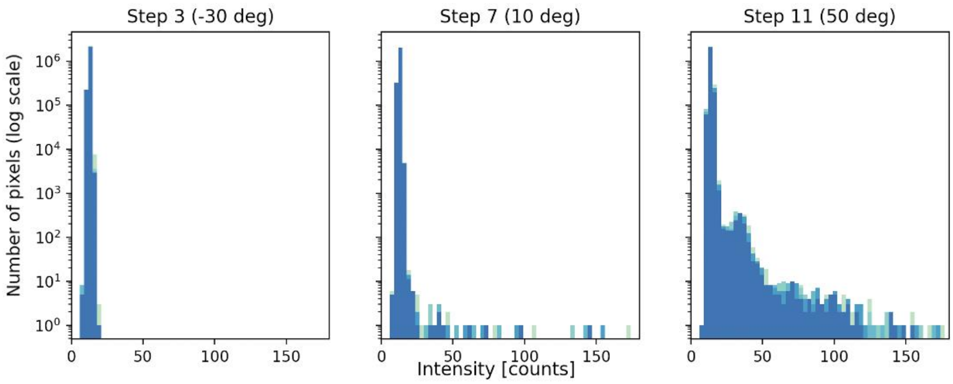


Figure 4.7: Histograms of the HSI images from steps 3 (-30 degrees), 7 (10 degrees) and 11 (50 degrees), showing the distribution of values recorded by the image sensor.

The same trend can also be seen in the hot and cold cases from steps 11-16. Step 11, 13 and 15 are from the hot case (top plots), and step 12, 14 and 16 are from the cold case (bottom plots). The values are clearly different between the two, with lower values centered around 20-30 counts again for the cold case, and higher values for the warm case. This is as expected, as the sensor will get more noisy with higher temperatures.

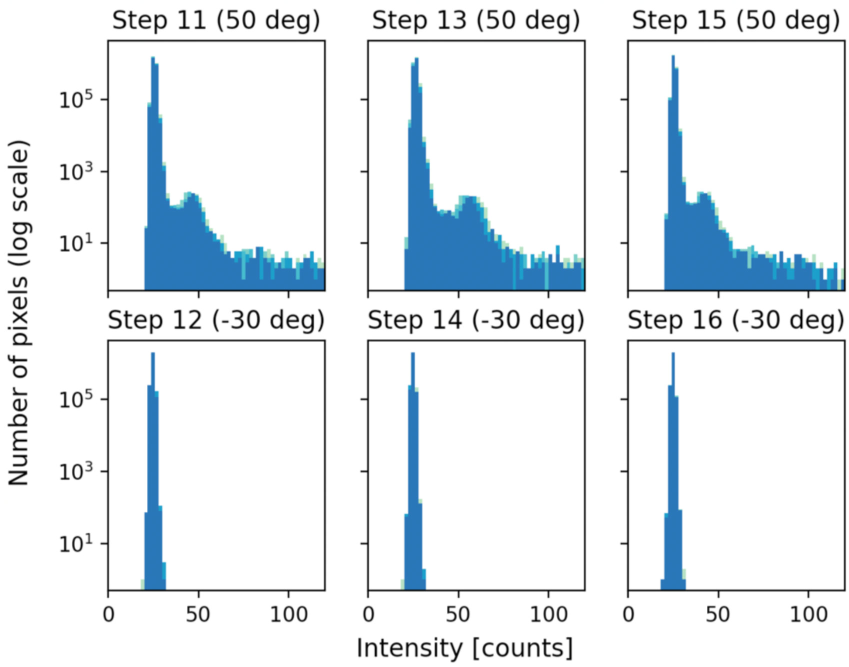


Figure 4.8: Histograms of the HSI images from the hot (50 degrees, steps 11, 13 and 15) and cold (-30 degrees, steps 12, 14 and 16) cases, showing the distribution of values recorded by the image sensor.

4.2.2 Telemetry

Table X: Mechtest.py script output telemetry readings at each CP.

4.2.3 RGB Sample Image

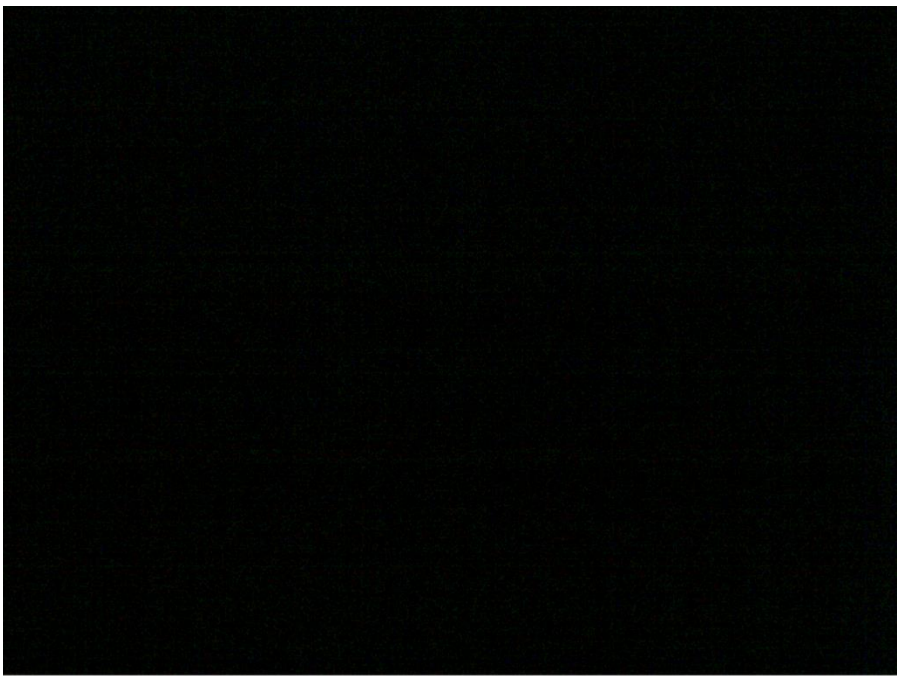


Figure 4.9: Example of RGB image captured at step 1 (23 degrees), completely black as expected.

4.3 CP Results second test – window

4.3.1 HSI Spectrograms

For the five HSI images taken, these were first averaged to reduce noise. Further, the center line (row in the middle of the spectrogram) is used when plotting the spectral response. For some lines (noted in the figure description), the line is smoothed to reduce the noise further, and easier see trends or changes in the spectral response.
Note: exact values may be inaccurate due to black level setting being active (adding a possible count value of 12 or something like that).

First, the spectrum before (step 1, 23 degrees) and after (step 17, 23 degrees) the TVAC test were compared. They look quite similar, but a small spectral shift of about 3 pixels (1 nm) can be seen, with the spectrum shifting towards the right (higher wavelengths) after the TVAC test. This could for example be due to changes in the materials with temperature during the tests, and the temperature of the materials not being the exact same before as after at the time of measurement.

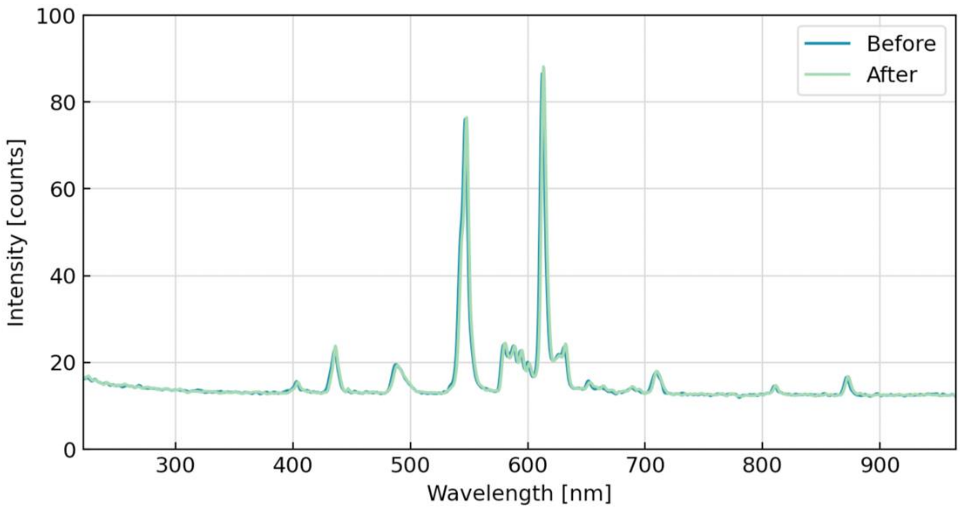


Figure 4.10: HSI spectral response before (step 1, 23 degrees) and after (step 17, 23 degrees) the TVAC test. Signal is smoothed to reduce noise.

Further, the spectral response at increasing temperature (step 3 to 11) are plotted together, to show the change in response with changing temperature. The colder temperatures are barely visible in the plot as they are in the back, but they are fairly similar with low noise floor (compared to the higher temperatures). The peaks get gradually higher (and a bit more narrow), indicating better focus, at temperatures around 30-40 degrees (steps 9-10), then decreases again at 50 degrees (step 11), indicating the the focus gets worse. This is natural as the exact focus depends on the focal length, and the exact lengths may change with temperature as the materials shrink or expands. The noise and noise floor increases with increasing temperature as expected, since higher temperatures leads to more noise in the sensor.

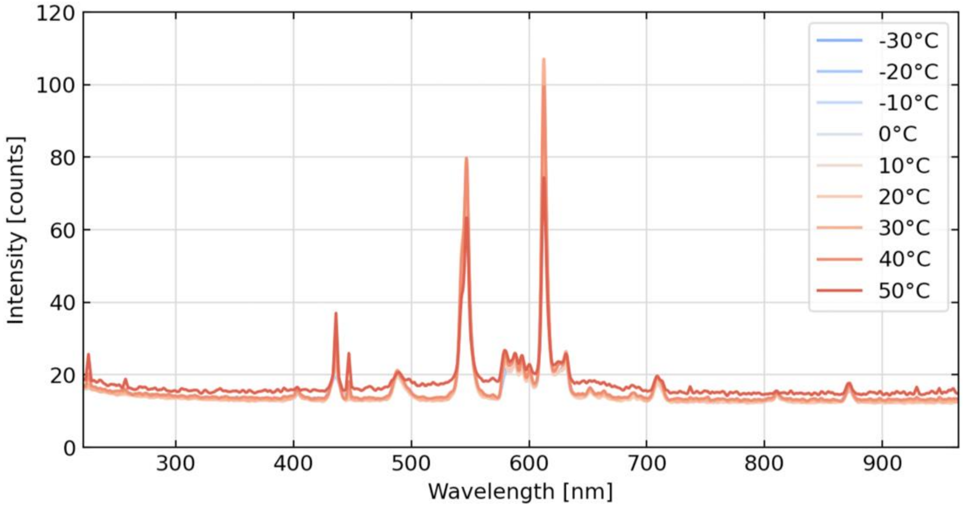


Figure 4.11: HSI spectral response with increasing temperature (step 3, -30 degrees to step 11, 50 degrees), during the TVAC test. Signal is smoothed to reduce noise.

The hot (50 degrees) to cold (-30 degrees) cold cases, steps 11-16, are also plotted. A clear distinction can be seen between the two cases, mostly based on the noise and the noise floor. The cold cases (steps 12, 14 and 16) gives similar responses, while the hot cases (steps 11, 13 and 15) vary more. This can be due to the noise not being distributed evenly, giving different results when averaging and smoothing the signal, or due to the temperatures not being the exact same for the different steps. As seen in the previous plot, the spectral response varies more for the higher temperatures than for the lower temperatures. So seeing more variation in the hot case seems reasonable.

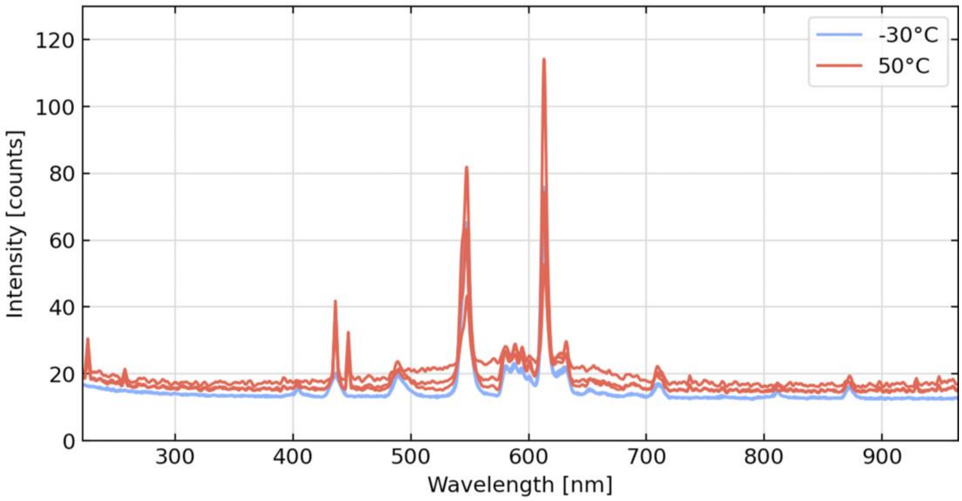
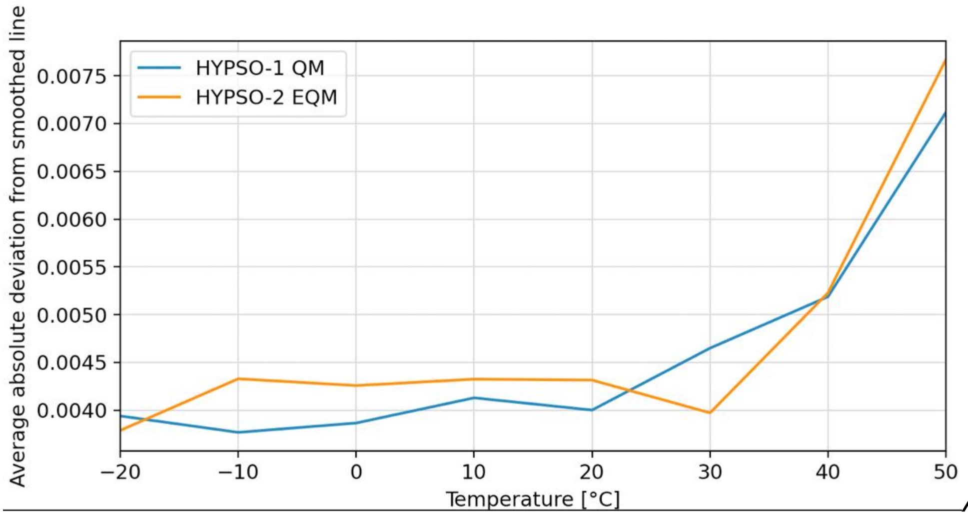


Figure 4.12: HSI spectral response for hot and cold cases (steps 11-16) during the TVAC test. Signal is smoothed to reduce noise.

To investigate the noise levels and compare them to those seen when testing the HYPSO-1 QM (see [RDxx]), noise was estimated as the absolute deviation from the smoothed signal. The average noise for each temperature was found, and plotted for both HYPSO-1 QM data and HYPSO-2 EQM data (with light). It can be seen that the estimated noise levels and trends with temperature are comparable between the two. From this, it is concluded that removing the thermal straps is not expected to increase the noise significantly for HYPSO-2.



AA

Figure 4.13: Noise, estimated as the average absolute deviation from the smoothed spectral response (center line) at different temperatures for HYPSO-1 QM and HYPSO-2 EQM. The signals were first normalized (by dividing by maximum value), then compared with the smoothed line.

5.3.2 Telemetry

Table X: Mechtest.py script output telemetry readings at each CP.

4.3.3 RGB Sample Image

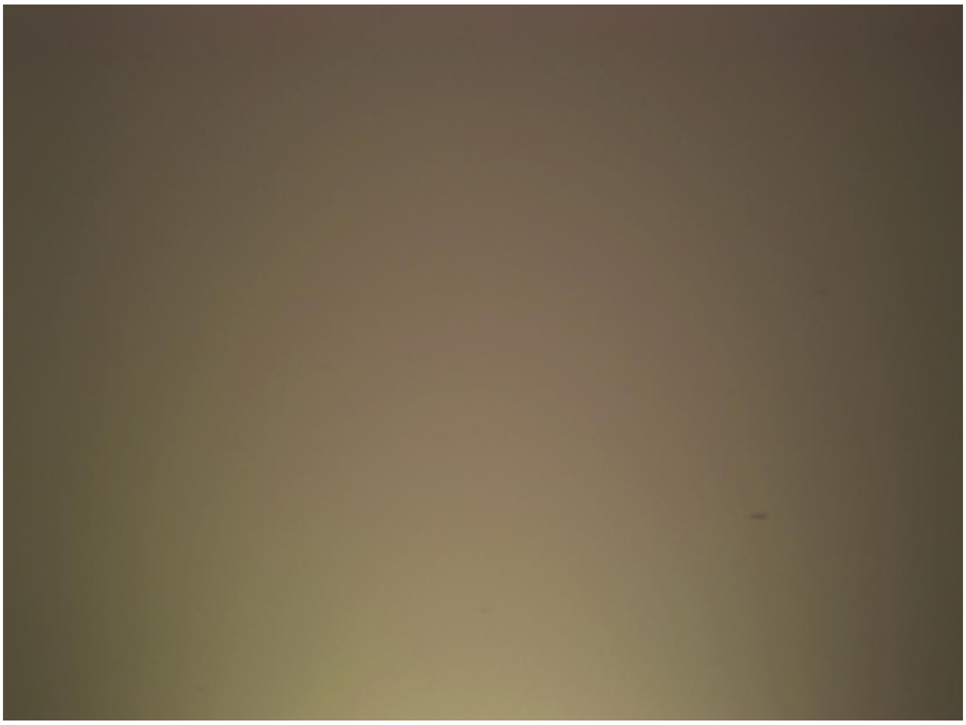
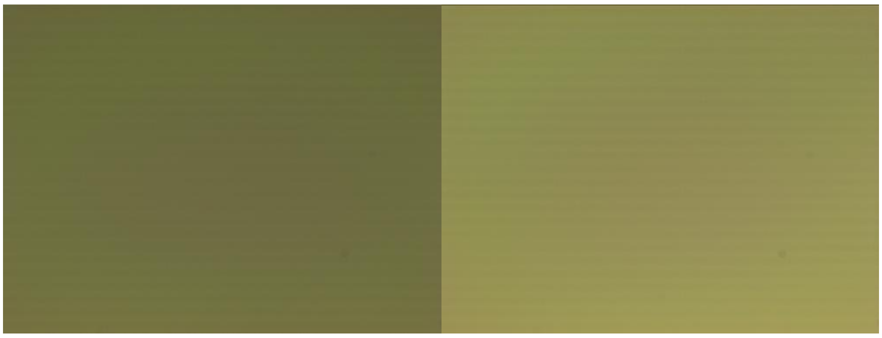


Figure 4.14: Example of RGB image captured at step 1 (23 degrees), blurry (as expected), one small "blob" can be seen.

4.4 Pre and post validation first test – no window

4.4.1 RGB Images

The resulting images from testing are shown in Figure 4.15. One image was taken before and after the TVAC testing. A small blob is visible in both images. Different intensity could be due to a small difference in the target/what the camera observes, or could be do to differences in lenses/coating on the lens/filter.



PRE **POST**

Figure 4.15: RGB images of checkerboard target pre- (left) and post- (right) TVAC testing

4.4.2 HSI images

The spectrograms taken with the validation bench setup (cardboard box + fluorescent lamp) are shown in Figure 4.16. A line plot is shown below to better compare them.

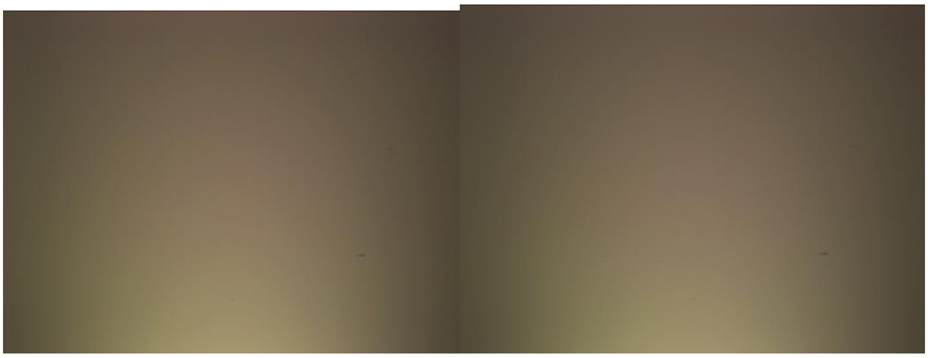
PRE **POST**

Figure 4.16: HSI spectrograms of white paper target (fluorescent light) pre- (left) and post- (right) TVAC testing

4.5 Pre and post validation second test – window

4.5.1 RGB Images

The resulting images from testing are shown in Figure 4.17. One image was taken before and after the TVAC testing. Again the small blob can be seen in both images.

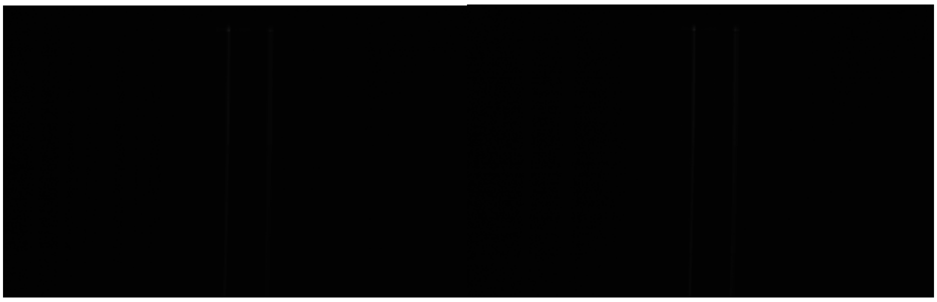


PRE **POST**

Figure 4.17: RGB images taken inside the vacuum chamber pre- (left) and post- (right) TVAC testing

4.5.2 HSI images

The spectrograms taken with the validation bench setup (cardboard box + fluorescent lamp) are shown in Figure 4.18. A line plot is shown below to better compare them.



PRE **POST**

Figure 4.18: HSI spectrograms from inside of the fluorescent light pre- (left) and post- (right) TVAC testing

5 Discussion

The primary test goals were as follows:

- Evaluate HYPSO-2 payload performance in high and low temperature
- Evaluate HYPSO-2 payload functionality in high and low temperature
- Compare performance at different temperatures
- Identifying issues with recently added components, such as the new RGB lens and sensor, as well as the ALICE breadboard.
- Evaluate if thermal straps are necessary

5.1 Performance changes

5.1.1 HSI spectrogram

The spectrograms change very little for different control points, although as mentioned in section 4, a slight pixel shift is noticeable with increasing/decreasing temperature. This was no surprise, since a pixel shift of 2 pixels was present when TVAC testing for HYPSO-1. A pixel shift of 3 pixels had occurred when comparing spectrograms before and after testing. This might indicate a change in dispersion angle, meaning the grating could have shifted. This was also the case for HYPSO-1, so it was no surprise, although it is not desirable.

It was also noticed that noise increases with increasing temperature. This is expected, since the focus of the HSI depends on the focal length. Materials expand with increasing temperatures, causing the focus to change.

Thermal straps were used for HYPSO-1. After it was calculated that these straps transfer way less heat than expected, it was decided to try a TVAC test without these straps. From the last figure of section 4.3.1, it can be seen that the noise levels are about the same for HYPSO-1 and HYPSO-2. Therefore, we can conclude that thermal straps are not necessary for the flight model.

5.1.2 RGB pictures

Since the RGB was focused to infinity, it is not possible to determine if the focus of the RGB changed with increasing/decreasing temperature. There seemed to be no damage from outgassing, which was our main concern.

Noise can be detected from the TVAC test with no window. Here we can notice Hot Pixels in high temperatures. This was also noticed during the bakeout of the RGB, when the camera was turned on for longer periods of time. This indicates that overheating of the sensor causes noise. This is not a major issue for the RGB, however a heat sink or another way of cooling the sensor should be considered for a potential HYPSO-3.

5.2 Sources of error

The following summarizes the sources of error we noted during testing.

- As can be seen in the measured temperature profiles in section 4, we did not wait long enough for the temperature to stabilize for several of the steps.
- It was not measured how long the fluorescent light was on for before captures were taken. The lamp needs 5-10 minutes to warm up. This could affect the spectrograms.
- Not all light was blocked by the setup for the window test.
- Poor connections between thermocouples and the components could affect measurements.

5.3 Further Improvements

After testing, the following suggestions are noted for improving thermal vacuum testing in the future:

- Some of the temperature sensors were fastened with Kapton tape. A better way of fastening the sensors which provides better heat transfer should be found.
- The spectrograms were quite dark, even though we placed the fluorescent light directly in front of the window. Another lightbulb could be used to provide more light.
- A setup that can evaluate the focus of the RGB should be made.

6 Conclusion

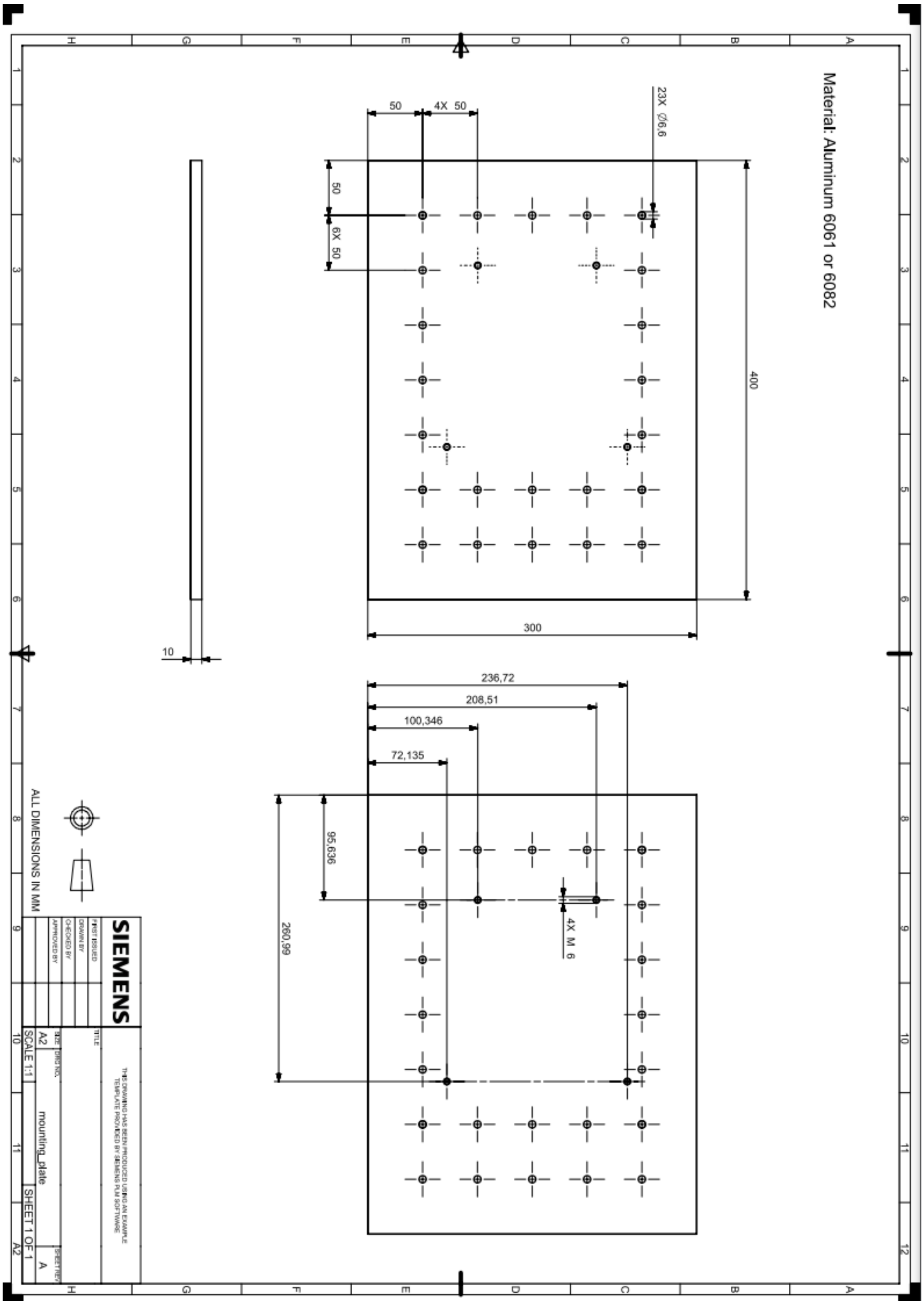
The files that have been stored from each CP are what we expect to downlink during the commissioning of the payload, this was as expected. There were no unexpected performance changes during the vacuum testing. There was a spectrum shift for the HSI in pre- and post-validation. Thermal straps will not be necessary for the flight model of HYPSO-2. No issues with the newly added ALICE breadboard or the RGB camera were found, except for ?? Pixels in captures with the RGB camera in high temperatures. This is not a major problem.

7 Abbreviations

Abbrev.	Description
CP	Characterization Point
DUT	Device Under Test
EM	Engineering Model
FM	Flight Model
GSE	Ground Support Equipment
HSI	Hyperspectral imager
KOG	Kongsberg Gruppen
QM	Qualification Model
TVAC	Thermal Vacuum

8 Appendices

8.1 Appendix A: Machine drawing of mounting plate


Material: Aluminum 6061 or 6082
23X ⌀6.6
50
4X 50
6X 50
400
300
10
236,72
208,51
100,346
72,135
95,636
260,99
4X M 6
ALL DIMENSIONS IN MM
SIEMENS
mounting_plate
A2
SCALE 1:1
SHEET 1 OF 1
A

I HYPSO-2 Flight Model (FM) as built report

HYPSO-2 Flight Model As-Built

HYPSO2-RP-XXX

Prepared by: HYPSO Project Team
Reference: HYPSO2-RP-XXX
Revision:
Date of issue:
Document Type: Report

Author(s): M. B. Henriksen, S. E. Heggelund, E. S. Håland, R. Birkeland, A. Gjersvik

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1 Introduction

1.1 Overview

The HYPSO Mission will primarily be a science-oriented technology demonstrator. It will enable low-cost & high-performance hyperspectral imaging and autonomous onboard processing that fulfill science requirements in ocean color remote sensing and oceanography. NTNU SmallSat is prospected to be the first SmallSat developed at NTNU with launch planned for Q4 2020 followed by a second mission later. Furthermore, vision of a constellation of remote-sensing focused SmallSat will constitute a space-asset platform added to the multi-agent architecture of UAVs, USVs, AUVs and buoys that have similar ocean characterization objectives.

This report documents all procedures and steps taken to assemble the payload flight model (FM) of the HYPSO-2 satellite.

1.2 Document History

Table 1.1: Table of changes.

Rev.	Summary of Changes	Author(s)	Effective Date
1	First issue	S. E. Heggelund, E. Håland, M. B. Henriksen, R. Birkeland, A. Gjersvik	2023-05-09

1.3 Reference Documents

Table 1.2: Referenced Documents.

RD	Document ID	Rev.	Title
RD01	HYPSO-DL-001A	3.0	Declared Lists for Parts, Materials and Processes
RD02	https://drive.google.com/drive/u/0/folders/1GmaVV4XF31KaKnOOluVJBUCHYztcHFj7	-	Turcon T05 Material Specification (Gasket Material)
RD03	HYPSO-DR-013	2.0	Cable Harness Design
RD04	HYPSO-DR-011	3.1	BoB V3.1 Design Report
RD05	HYPSO-ICD-003	2.0	Breakout Board V3 ICD
RD06	HYPSO-DR-003	5.0	HSI Design Report
RD07	HYPSO-RP-039	1.0	Objective Disassembly and Cleaning: Flight Model

RD08	HYPSO-RP-046	1.0	Figuring out FM spectral focus
RD09	HYPSO2-DR-009	1.0	Building HYPSO-2 EQM
RD10			

2 Manufacturing

The first step is gathering all components. Some were commercial off-the-shelf (COTS), some were machined from aluminum 6082 in the cybernetics (ITK) workshop, others were modified or created in the SmallSatellite Lab through various methods. Table 4 shows an overview and a discussion follows for each type.

Table 2.1: Overview of machined parts.

HYPSO Code	Part	Manufacturing?
PLD 1.8.1	**Hyperspectral Imager**	
HSI 1.8.1.1	HSI Mechanical Parts	
HSIM 1.8.1.1.1	HSI Platform	y (ITK)
HSIM 1.8.1.1.2	Slit Tube	y (ITK)
HSIM 1.8.1.1.3	Slit Tube bracket	y (ITK)
HSIM 1.8.1.1.3.1	Spacer rings	y (cut w/ dremel in the lab)
HSIM 1.8.1.1.4	Cassette Front	y (ITK)
HSIM 1.8.1.1.5	Clamp Bracket (x2)	y (ITK)
HSIM 1.8.1.1.6	Bracket Gasket (x2)	y (cut w/ razor in the lab)
HSIM 1.8.1.1.7	Cassette Back	y (ITK)
HSIM 1.8.1.1.8	Detector Housing1	y (ITK)
HSIM 1.8.1.1.9	Detector Housing2	y (ITK)
HSIM 1.8.1.1.10	Platform Bracket Front	y (ITK)
HSIM 1.8.1.1.11	Platform Bracket Middle	y (ITK)
HSIM 1.8.1.1.12	Platform Bracket Rear	y (ITK)
HSIM 1.8.1.1.13	Fixed Aperture	y (cut at Perleporten)
HSI 1.8.1.2	HSI Optical Parts	
HSIO 1.8.1.2.1	Objective - front	y (COTS - holes drilled at ITK)
	Objective - collimating	y (COTS - holes drilled at ITK)
	Objective - camera	y (COTS - holes drilled at ITK)
HSIO 1.8.1.2.2	Slit	y (COTS - holes drilled at ITK)
HSIO 1.8.1.2.3	Grating	COTS
HSI 1.8.1.3	HSI Detector	
HSID 1.8.1.3.1	Detector	COTS
PLD 1.8.2	**PicoBoB**	
PBB 1.8.2.1	BoB v3	COTS
PBB 1.8.2.2	PicoZed	COTS

PBB 1.8.2.3a	MicroSD Card	COTS
PBB 1.8.2.3b	MicroSD Card (backup - not used)	COTS
PBB 1.8.2.4	Shield w/ hole	y (ITK)
PBB 1.8.2.5	Shield w/ rails	y (ITK)
PBB 1.8.2.6	Alice	y
FRM 1.7.2	1U ring frame (x2)	COTS
PLD 1.8.4	**RGB Camera**	
RGB 1.8.4.1	Detector	COTS
RGB 1.8.4.2	Objective Lens	COTS
RGB 1.8.4.3	C-Mount	COTS
RGB 1.8.4.4	Detector Housing	y (ITK)
RGB 1.8.4.5	Platform Bracket	y (ITK)
RGB 1.8.4.6	IR-Filter	COTS
PLD 1.8.5	**Payload Structure**	
STR 1.8.5.1	Dampers	COTS
STR 1.8.5.2	Front Crosslink +X	y (ITK)
STR 1.8.5.3	Front Crosslink -X	y (ITK)
STR 1.8.5.4	Back Crosslink +X	y (ITK)
STR 1.8.5.5	Back Crosslink -X	y (ITK)
Other		
Cables		y (fabricated in the lab)
Objective Screws		COTS
M2-4 Screws		COTS
M6 Screws, Nuts, Washers		COTS
PCB Standoffs		COTS

2.1 COTS components

Lens objectives, electronics, and hardware were purchased as is. They are commercially available off-the-shelf components. Some were modified, details on the modifications can be found in Section 3 “COTS Modifications”. Hardware including screws, nuts, washers, and standoffs are all made from stainless steel A2.

2.2 ITK Machine Shop

One large piece of Aluminum 6082 was ordered from Astrup - a local raw materials supplier [RD01]. T10 tolerances were used in general. Components in the optical train were anodized - see Section 4.1.

2.3 Gaskets

Gaskets (for the grating) were cut from a sample piece of Turcon T05 material provided by Trelleborg. It is a high grade composition of virgin PTFE compounded with Turcon®. See the product Data Sheet [RD02]. The gaskets were measured with a ruler and cut with a razor blade in the SmallSatellite lab.

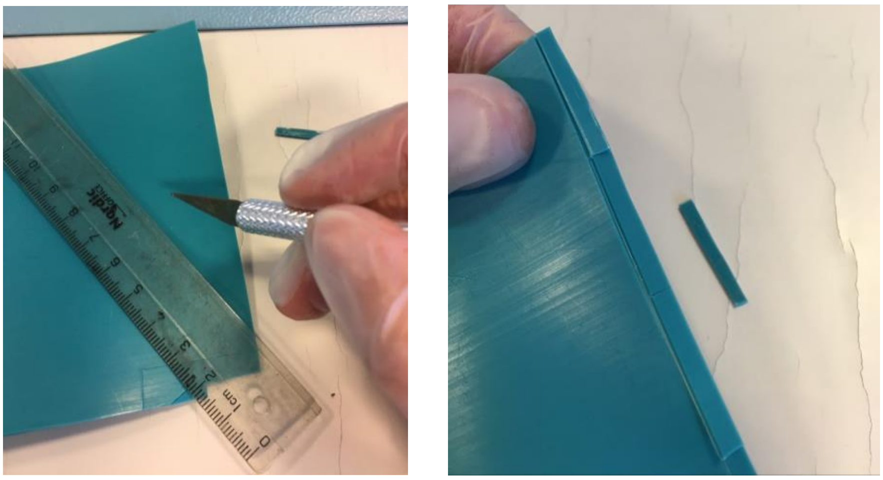


Figure 2.1: Manufacturing the gaskets in the lab (picture from HYPSO-1).

2.4 Fixed Aperture

The standard aperture consists of eight tiny moving parts. These have a high risk of breaking or falling out during launch or during the mission. Also, once they are taken out for cleaning, it is not possible to assemble the mechanism again. Therefore a custom, fixed aperture is necessary. The fixed, circular baffle, Figure 2.2, has the same outer and inner diameter as the adjustable aperture. This gives the same f-number, so that the ratio between the effective focal length of the lens to the effective aperture diameter is the same as the original design.

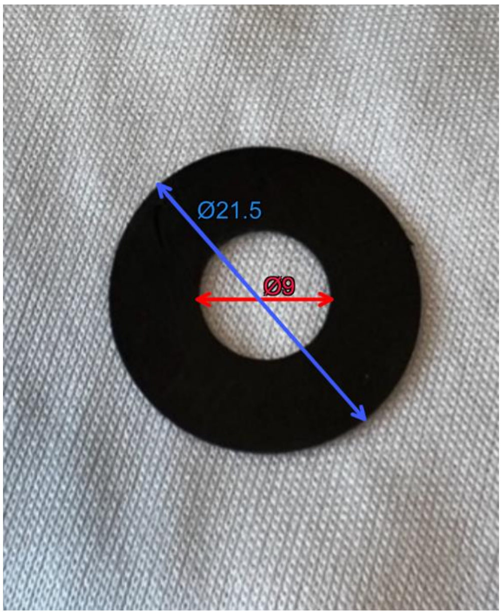


Figure 2.2: The fixed aperture.

The aperture is cut from a sheet of 0.50 mm thick aluminum with a EDM-machine at Perleporten Workshop, NTNU. (0.25 mm as used for HYPSO-1 were also cut, but these did not turn out nice, and the 0.5 mm option was therefore used instead). It is then anodized. The fixed apertures are added to the f/2.8 objectives (front and collimating) and all apertures are removed for the f/2.0 objective (camera).

2.5 Cables

The cable harness is described in detail in the Cable Harness Design Report [RD03]. The cables are labeled with Dymo Industrial labels. The Dymo labels are covered on both sides with acrylic adhesive Kapton tape to minimize the risk of outgassing from the labels.

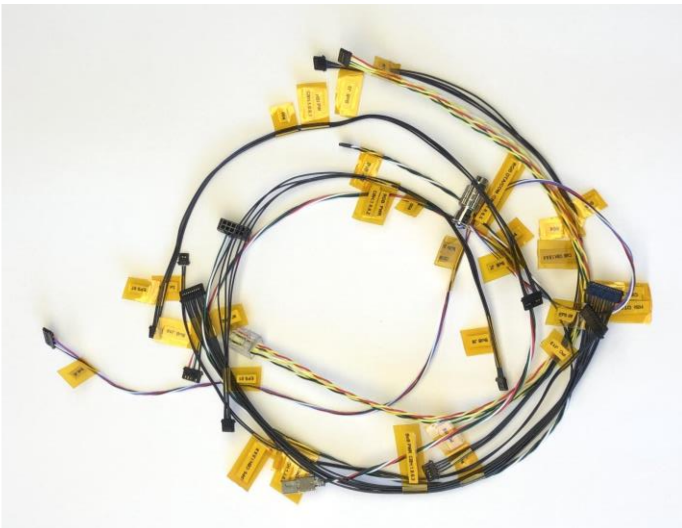


Figure 2.3: Cables with cable labels wrapped in Kapton for vacuum safety (picture from HYPSO-1).

2.6 Breakout Board (BoB)

The Breakout Board (BoB) is carrying and powering the OPU and acting as the OPU interface to the satellite platform and to the rest of the payload. The design is developed at NTNU. The PCB fabrication and the component assembly is done by external contractors. Details of the design can be found in [RD04]. A detailed ICD can be found in [RD05].

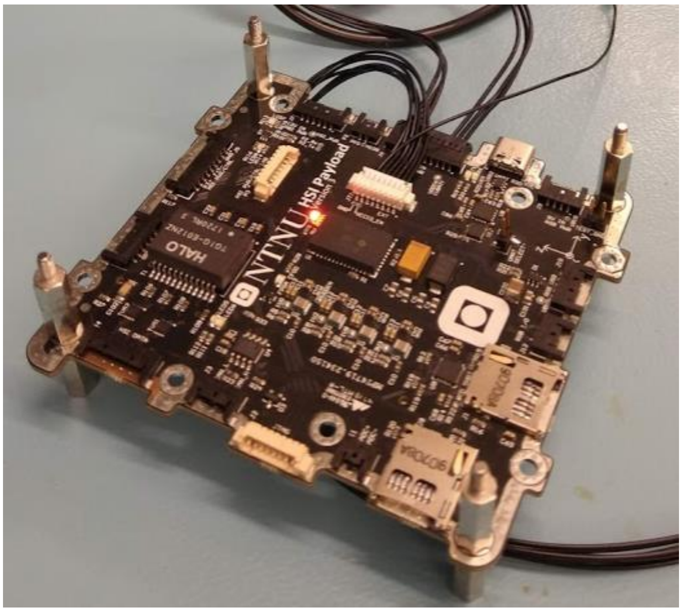


Figure 2.4: One of the finished v3.1 Breakout Boards. The OPU is mounted on the bottom (picture from HYPSO-1).

3 COTS Modifications

Of the commercial off-the-shelf components ordered, some needed modifications for space. Table 3.1 outlines which components these were and what was done. Details follow in the next sections.

Table 3.1: Overview of modifications on COTS parts.

HYPSO Code	Part	COTS Modified?
PLD 1.8.1	**Hyperspectral Imager**	
HSI 1.8.1.1	HSI Mechanical Parts	
HSIM 1.8.1.1.1	HSI Platform	NA
HSIM 1.8.1.1.2	Slit Tube	NA
HSIM 1.8.1.1.3	Slit Tube bracket	NA
HSIM 1.8.1.1.3.1	Spacer ring	Y (cut to fit threading)
HSIM 1.8.1.1.4	Cassette Front	NA
HSIM 1.8.1.1.5	Clamp Bracket (x2)	NA
HSIM 1.8.1.1.6	Bracket Gasket (x2)	NA

HSIM 1.8.1.1.7	Cassette Back	NA
HSIM 1.8.1.1.8	Detector Housing1	NA
HSIM 1.8.1.1.9	Detector Housing2	NA
HSIM 1.8.1.1.10	Platform Bracket Front	NA
HSIM 1.8.1.1.11	Platform Bracket Middle	NA
HSIM 1.8.1.1.12	Platform Bracket Rear	NA
HSIM 1.8.1.1.13	Fixed Aperture	NA
HSI 1.8.1.2	HSI Optical Parts	
HSIO 1.8.1.2.1	Objective - front	y (custom aperture, epoxied)
	Objective - collimating	y (custom aperture, epoxied)
	Objective - camera	y (custom aperture, epoxied)
HSIO 1.8.1.2.2	Slit	y (holes drilled, epoxied)
HSIO 1.8.1.2.3	Grating	n
HSI 1.8.1.3	HSI Detector	
HSID 1.8.1.3.1	Detector	y (conformal coated)
PLD 1.8.2	**PicoBoB**	
PBB 1.8.2.1	BoB v3	y (conformal coated)
PBB 1.8.2.2	PicoZed	y (conformal coated)
PBB 1.8.2.3a	MicroSD Card	n
~~PBB 1.8.2.3b~~	~~MicroSD Card~~	~~n~~
PBB 1.8.2.4	Shield w/ hole	NA
PBB 1.8.2.5	Shield w/ rails	NA
PBB 1.8.2.6	Alice	NA
FRM 1.7.2	1U ring frame (x2)	n
PLD 1.8.4	**RGB Camera**	
RGB 1.8.4.1	Detector	y (conformal coated)
RGB 1.8.4.2	Objective Lens	y (epoxied)
RGB 1.8.4.3	C-Mount	y (plastic removed)
RGB 1.8.4.4	Detector Housing	NA
RGB 1.8.4.5	Platform Bracket	NA
RGB 1.8.4.6	IR-filter	NA
PLD 1.8.5	**Payload Structure**	
STR 1.8.5.1	Dampers	n
STR 1.8.5.2	Front Crosslink +X	NA

STR 1.8.5.3	Front Crosslink -X	NA
STR 1.8.5.4	Back Crosslink +X	NA
STR 1.8.5.5	Back Crosslink -X	NA
Other		
Cables		NA
Objective Screws		n
M2-4 Screws		n
M6 Screws, Nuts, Washers		n
PCB Standoffs		n

3.2 Slit

The slit arrives from the manufacturer pre-assembled. However, during the assembly of HYPSO-1 it was found that it was still possible to rotate the slit in its housing. Since this is a huge risk for getting a proper spectrogram, the slit needed to be secured in its housing. This was done by adding drops of epoxy along the inner ring of the housing, Figure 3.3. The slit and friction ring are then press fit into the epoxy and excess epoxy is scraped off with a toothpick.

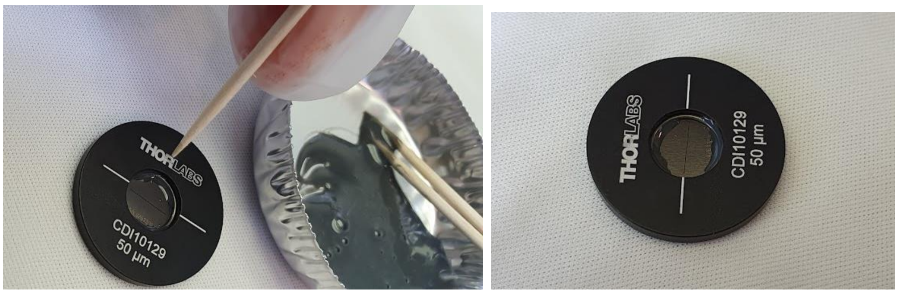


Figure 3.3: Disassemble slit (left) and reassemble with dots of epoxy (right) (pictures from HYPSO-1).

Removable tape was placed over either side of the exposed slit to protect it during the assembly - it is countersunk so the tape did not touch the surface of the slit.

Holes were drilled in the rim of the slit to be able to adjust the allignment of the slit. This was done at the workshop at Elektrobygget NTNU

Figure 3.4: Holes drilled to help align slit in the slit tube.

3.3 Spacer ring

The spacer ring was too small to fit over the threadings on the objective, as the inner dimensions of the spacer ring is 25.00 mm and the outer diameter of the threads on the objective (and general C-mounts) is 25.40 mm. A small cut therefore had to be made so that the spacer ring could be twisted around the threads. A dremel with a 0.8 mm cutting disc was used. The cut was then gently filed to ensure no small pieces of metal around the cut that could loosen, and then cleaned to remove any metal dust left on the ring.

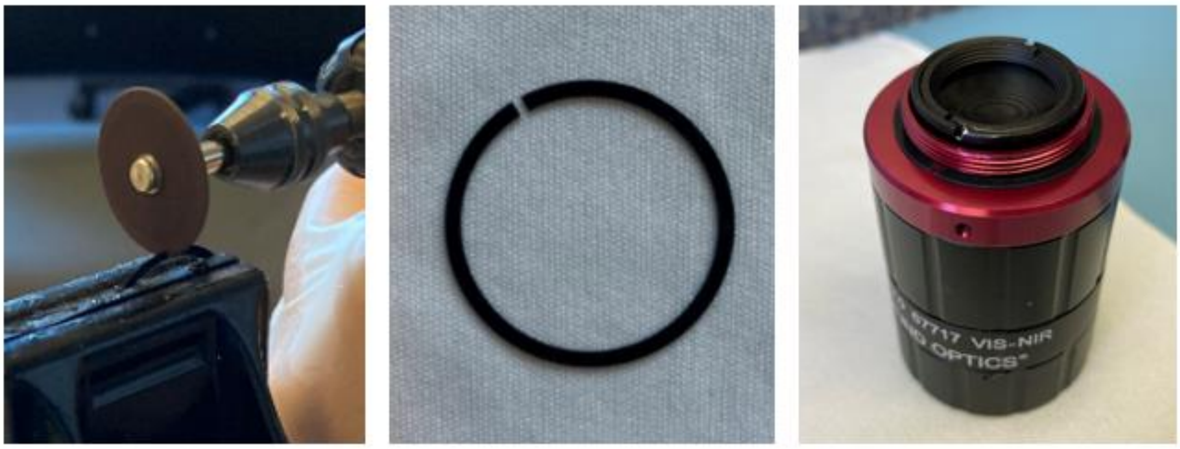


Figure 3.5: Spacer ring cut with dremel to fit on the objective (pictures from HYPSO-1).

3.4 Electronics

The RGB and HSI detector, as well as BoB and PicoZed were conformal coated. The Printed Circuit Boards (PCBs) were coated at Norspace, with Mapsil 213-B. It is used as a varnish for PCB-boards, to protect from contaminants inside the electronics that may cause outgassing. In addition, it is added to avoid electrical conductivity between the components that may cause short circuiting.

When receiving the components back, however, it was noticed that the HSI detector looked dirty. The coated and an uncoated sensor were compared under the microscope, as seen in Figure 3.6. Since there has been an ongoing discussion if conformal coating of the components is necessary or not (with the conclusion being that it didn't harm on HYPSO-1, so we'll do it), it was decided to use the uncoated HSI sensor in the HYPSO-2 HSI FM.

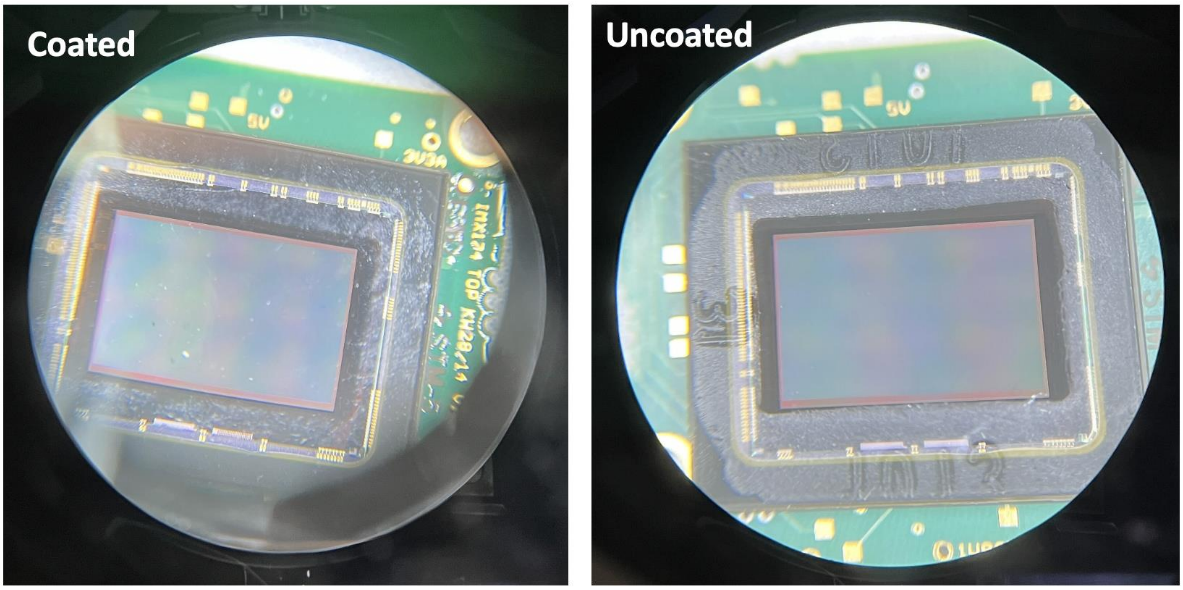


Figure 3.6: Coated (to the left) and uncoated (to the right) HSI sensors. The uncoated to the right was chosen and used for the HYPSO-2 HSI FM.

3.5 C-Mount

The RGB C-mount is actually a part of an entire COTS camera ordered from iDS (UI-1250ML). Since we only need the C-mount for the payload RGB, it was removed. See Figure 3.7. The C-mount is machined aluminum and is already anodized. After cleaning it is ready to use.

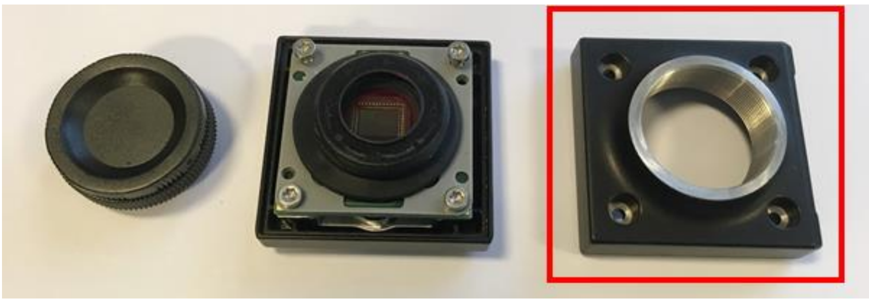


Figure 3.7: Lens cap and electronics removed (left) and C-mount reserved for RGB (right) (picture from HYPSO-1).

4 Treatment and Cleaning

The raw aluminum parts need treatment and cleaning depending on their function. Treatment was done by anodizing the surface of the optical machined components. Cleaning was done by wiping the components with optical cloth and ethanol. Component treatment is summarized in Table 4.1.

Table 4.1: Overview of treatment and cleaning of parts.

HYPSO Code	Part	Ultrasonics w/ ElmaClean in SmallSat Lab	Ultrasonics w/ ethanol in Fume Hood
PLD 1.8.1	**Hyperspectral Imager**		
HSI 1.8.1.1	HSI Mechanical Parts		
HSIM 1.8.1.1.1	HSI Platform	anodized	y (cleaned with ethanol wipes)
HSIM 1.8.1.1.2	Slit Tube	anodized	y
HSIM 1.8.1.1.3	Slit Tube bracket	anodized	y
HSIM 1.8.1.1.4	Cassette Front	anodized	y
HSIM 1.8.1.1.5	Clamp Bracket (x2)	anodized	y
HSIM 1.8.1.1.6	Bracket Gasket (x2)	anodized	y
HSIM 1.8.1.1.7	Cassette Back	anodized	y
HSIM 1.8.1.1.8	Detector Housing1	anodized	y
HSIM 1.8.1.1.9	Detector Housing2	anodized	y
HSIM 1.8.1.1.10	Platform Bracket Front	anodized	y
HSIM 1.8.1.1.11	Platform Bracket Middle	anodized	y
HSIM 1.8.1.1.12	Platform Bracket Rear	anodized	y
HSIM 1.8.1.1.13	Fixed Aperture (x2)	anodized	y
HSI 1.8.1.2	HSI Optical Parts		
HSIO 1.8.1.2.1	Objective - front	y (not glass)	y (not glass)
	Objective - collimating	y (not glass)	y (not glass)
	Objective - camera	y (not glass)	y (not glass)
HSIO 1.8.1.2.2	Slit	NA	n (but hand clean)
HSIO 1.8.1.2.3	Grating	NA	NA
HSI 1.8.1.3	HSI Detector		
HSID 1.8.1.3.1	Detector	conformal coated	NA
PLD 1.8.2	**PicoBoB**		
PBB 1.8.2.1	BoB v3	conformal coated	NA
PBB 1.8.2.2	PicoZed	conformal coated	NA
PBB 1.8.2.3a	MicroSD Card	NA	NA
PBB 1.8.2.3b	MicroSD Card	NA	NA
PBB 1.8.2.4	Shield w/ hole	y	y
PBB 1.8.2.5	Shield w/ rails	y	y
PBB 1.8.2.6	Alice	conformal coated	NA

FRM 1.7.2	1U ring frame (x2)	anodized	n (at NA)
PLD 1.8.4	**RGB Camera**		
RGB 1.8.4.1	Detector	conformal coated	NA
RGB 1.8.4.2	Objective Lens	can't disassemble	NA
RGB 1.8.4.3	C-Mount	anodized	y
RGB 1.8.4.4	Detector Housing	anodized	y
RGB 1.8.4.5	Platform Bracket	y	y
RGB 1.8.4.6	IR-filter	can't disassemble	NA
PLD 1.8.5	**Payload Structure**		
STR 1.8.5.1	Dampers	NA	NA
STR 1.8.5.2	Front Crosslink +X	y	y
STR 1.8.5.3	Front Crosslink -X	y	y
STR 1.8.5.4	Back Crosslink +X	y	y
STR 1.8.5.5	Back Crosslink -X	y	y
Other			
Cables		NA	NA
Objective Screws		y	y
M2-4 Screws		y	y
M6 Screws, Nuts, Washers		y	y
PCB Standoffs		y	y

4.1 Anodizing

All machined parts of the payload were anodized as to be non-reflective and to function as a passive thermal control. This process removes a very thin top layer of the material and deposits back the anodizing on the surface. The parts were sent to Trondheim Eloksering for the Mil-A-8625, Type II, Class 2, black lustreless coating procedure.

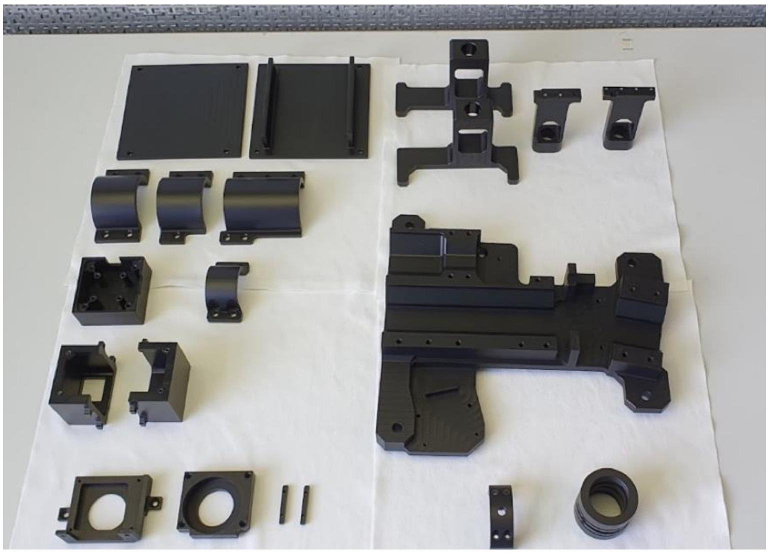


Figure 4.1 Anodized parts for HYPSO-2 HSI FM.

The anodized layer on some parts of some of the components had to be removed to ensure an electrical connection between all parts of the payload. The reason this is done is for ESD protection. This is not visible in Figure 4.1, but is visible in later images such as Figure 4.2 and when the FM is assembled, and can be seen on the surfaces were screws are fastening the HSI and RGB brackets to the platform. A connection between the RGB bracket surface and the crosslinks will be added to ensure connection between the payload and the satellite.

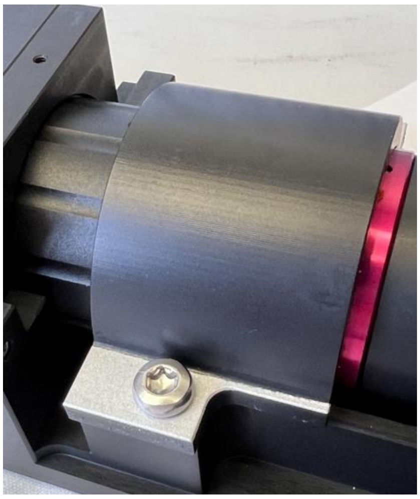


Figure 4.2 Anodized layer removed on the lip of the brackets.

4.2 Cleaning components

All raw machined aluminum parts may have traces of oil on their surface from the machining process and small particles. Oils need to be removed before vacuum so it does not outgas - especially on to the lenses. Grease and oils were removed from the surfaces using an ultrasonic bath with a mix of ELMA Clean70 (20-50 ml/L) for (20-80 degrees) for solvent, as recommended on the product label. The bath was heated to 40 degC and left to run for 30 minutes. Several parts were washed together if they fit the 500 mL beakers, but the water solution was switched out between washings. Parts were left to air dry in a flow bench and individually bagged. The same procedure as for HYPSO-1 reported in [RD07] was used.

Figure 4.2 Disassembled HSI objective parts for cleaning (picture from HYPSO-1).

The objectives, as seen in Figure 4.2, were disassembled and cleaned. They are the biggest concern as each of the individual components are particularly greasy. Extra grease is added on purpose by the manufacturer to ensure that the focus and aperture can be changed smoothly. Since we modify the objectives to be completely fixed, the grease is no longer necessary. All other parts were thoroughly cleaned with ethanol and air dried.

4.3 Glass Lenses

FM lenses (3x per HSI objective) were removed in a flow bench while objectives were disassembled for cleaning, see Figure 19. They were wrapped in dry cleanroom wipes and bagged immediately.

Figure 4.3: Three HSI glass lens components removed before cleaning (picture from HYPSO-1).

Figure 4.4: All lenses are bagged separately after being disassembled and cleaned (picture from HYPSO-1)

After a vacuum test of the HYPSO-1 RGB-assembly it was decided that the RGB lens did not need internal cleaning and therefore was not disassembled. It was therefore not disassembled for HYPSO-2 either.

5 Assembly

First some the objectives were assembled, and focus was set to infinity as described in Section 5.2. When the components were all ready, the main components of the HSI, RGB and PicoBoB were assembled.

To make sure the slit was straight (as described in Section 5.7), cables were connected and the software (see Section 7) was updated and tested before the platform assembly was finished. After the slit was positioned to satisfaction, epoxy was applied to finalize the assembly.

5.1 Objective Assembly

The objective assembly is performed inside the flow bench on a lens tissue. Remember to wear a coat that limits particle contamination, as well as ESD gloves and face-masks. The same procedure as from HYPSO-1 was used, and is described in Table 5.1.

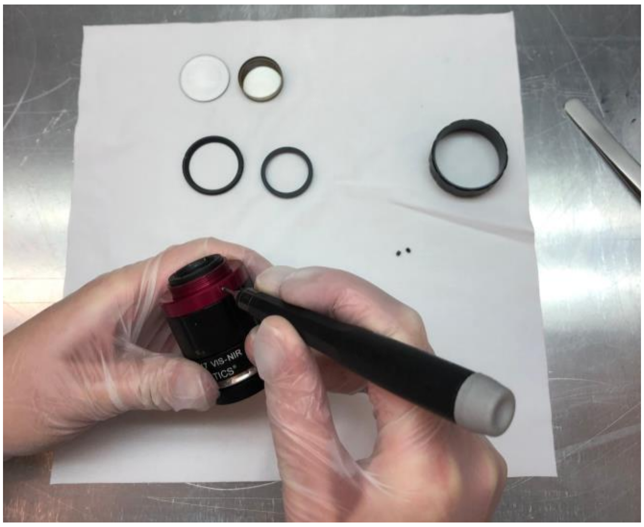
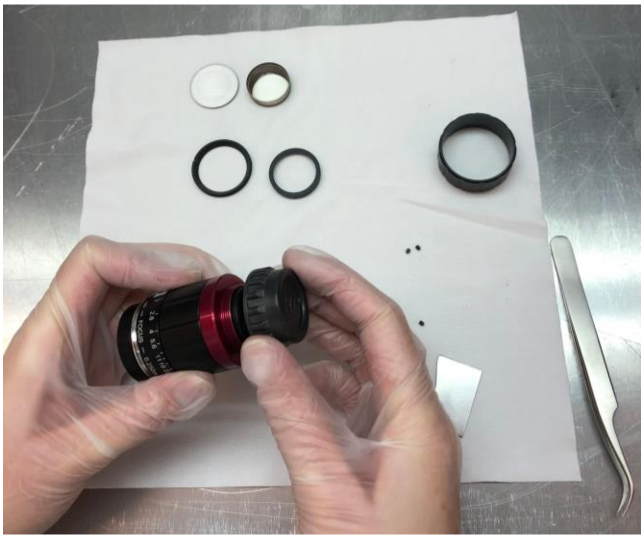
Figure 5.1: Overview of objective parts for assembly. Picture from HYPSO-1

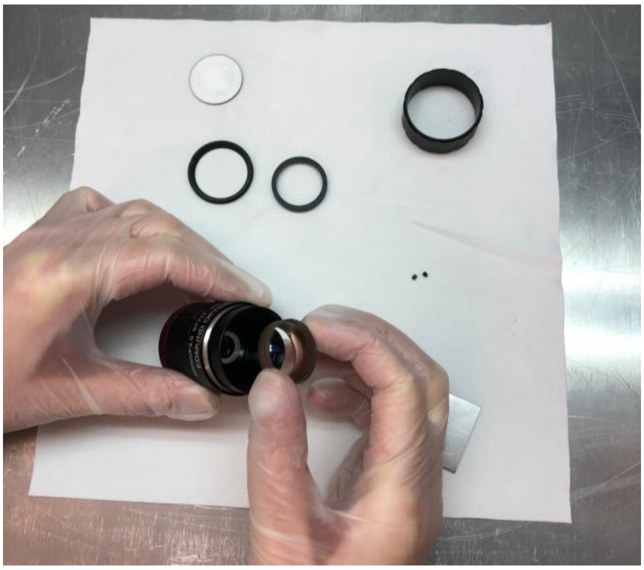
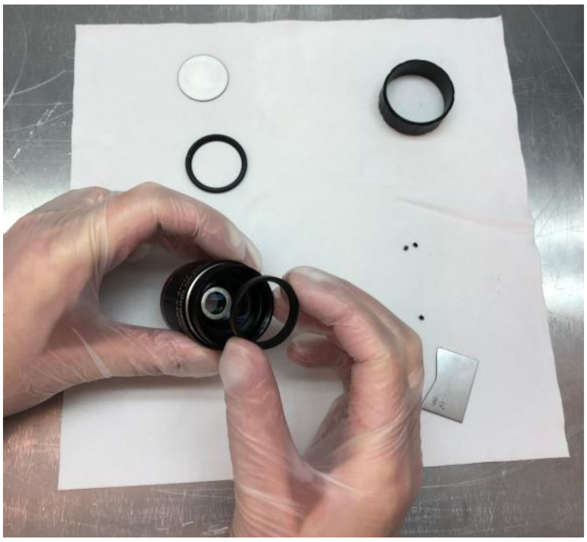
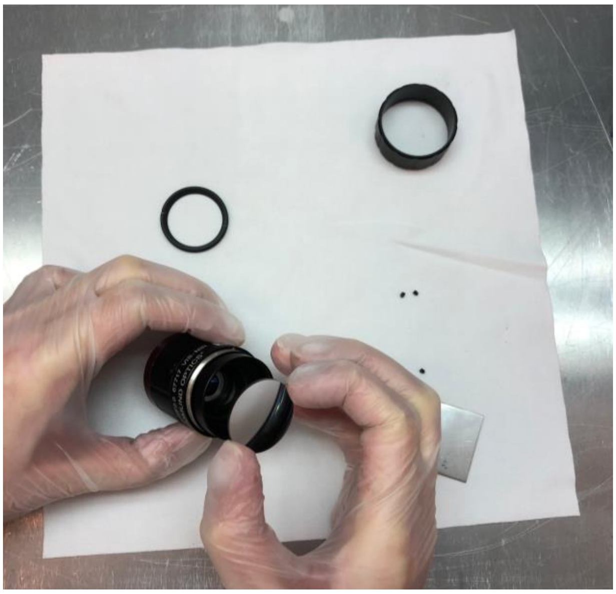
Table 5.1: HSI objective assembly (with pictures from HYPSO-1).

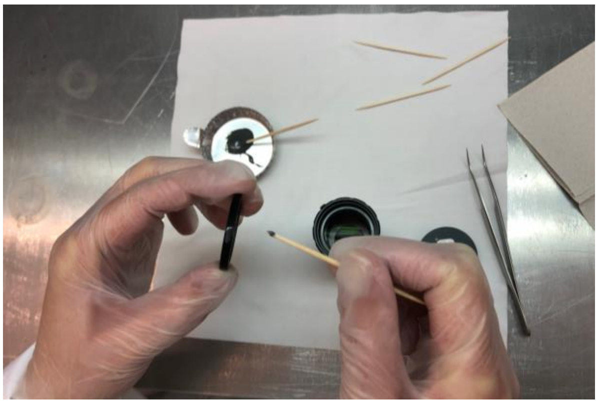
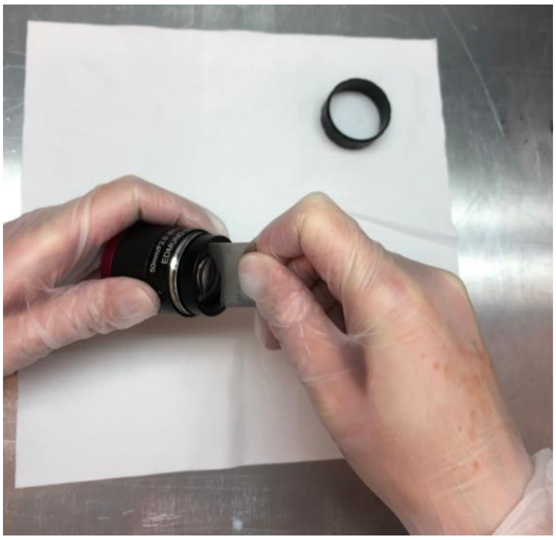
Step	Description	Images
	HSI	
1	Twist the two largest components together.	
2	Add the custom aperture (for f/2.8 objectives) or skip this step (for f/2.0 objective). (The aperture used in this figure is not the same as for the FM of HYPSO-2. The aperture used for HYPSO-2 FM is black anodized).	

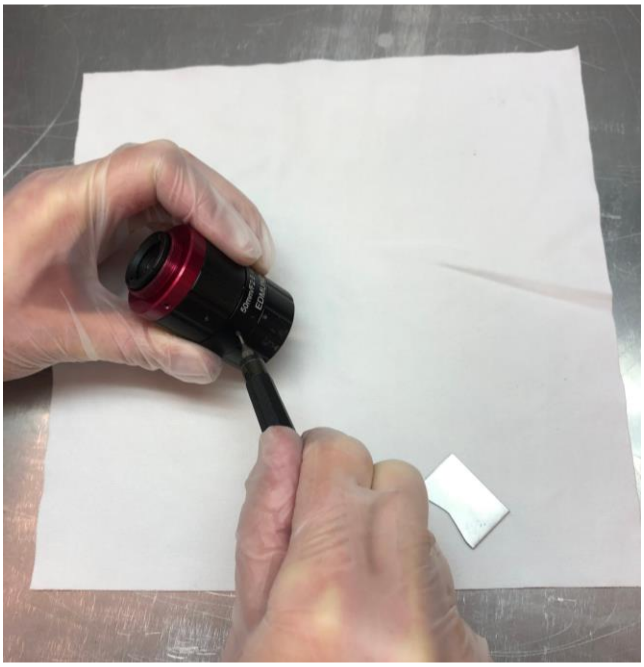
3	Add the tube component that secures the aperture.	
4	Secure the tube with the long set screw in the slot.	
5	Add the two short screws in the slots on the sides of the center slot. Be sure to remove the plastic spacers.	

6	Twist in the back composite lens stack.	
7	Add the back outer ring that is used to set f/#.	
8	Add small set screw to secure the ring at the correct f/# position based on the fixed aperture installed.	

9	Add the pink outer ring to secure the lens stack.	
10	Add 2x set screws to secure the pink ring with epoxy.	
11	Replace the back lens cap to keep the optics clean throughout the rest of assembly.	

12	Add the thicker lens to the front of the objective. It can be positioned by tapping the objective on the table.	
13	Add the spacer ring on top of the thinker lens. This should give a flush surface to support the thinner front lens.	
14	Add the thin front lens.	

15	Add a drop of epoxy to the threads in the retaining ring and spread it around.	
16	Twist the retaining ring until it rests on the front lens.	
17	Add the final front outer ring.	

18	Screw in the 3x front set screws with epoxy.	
19	Screw in the final focus set screw.	

5.2 Setting Objective Focus

There are four objectives in the HYPSO-2 HSI payload: 3x HSI objectives and 1x RGB. Each objective must be focused at infinity since they will be used in low earth orbit (approximated by infinite focus). This section outlines the procedure for setting objective focus for both types of objectives, and how they are verified with a second set-up.

5.2.1 HSI Objectives

The HSI objectives have two settings each: the aperture (f/#) and the focal length. The apertures are fixed as demonstrated in Section 2.4. The focal length is set by removing the locking set screw in the center band of the objective, Figure 5.2, and twisting the front band.

Figure 5.2: Setting the focus of the HSI objectives (picture from HYPSO-1).

The focus changes as the front band is twisted. Each objective is attached to a standard c-mount detector, mounted on a tripod for repeatable viewpoints, and pointed out the window to targets beyond 50m (e.g. buildings in the distance). The detector is plugged into a laptop running Ueye cockpit for a real-time feed of images the camera is capturing. As the focus band is twisted, the image comes into better or worse focus. The clearest focus is set when houses at a distance are in focus, see Figure 5.3. This simulates infinity.

Figure 5.3: Setup for setting HSI objective focus out the window (picture from HYPSO-1).

To verify that the objectives are indeed set at infinity, a custom setup was developed. This setup includes (from left to right in Figure 5.4): a white paper target with fluorescent light source, a patterned reticle, a collimating objective, an adjustable mount for the HSI lens, a standard C-mount detector from iDS, and a laptop running uEye Cockpit. The collimating objective is set at infinity and oriented backwards to the HSI objective being set. The mount centers the HSI objective to both the collimating objective and reticle so the pattern can be seen. The view of the pattern is then displayed in uEye on the laptop. The image on the computer screen then shows if the objective is set at best focus and can be adjusted if necessary.

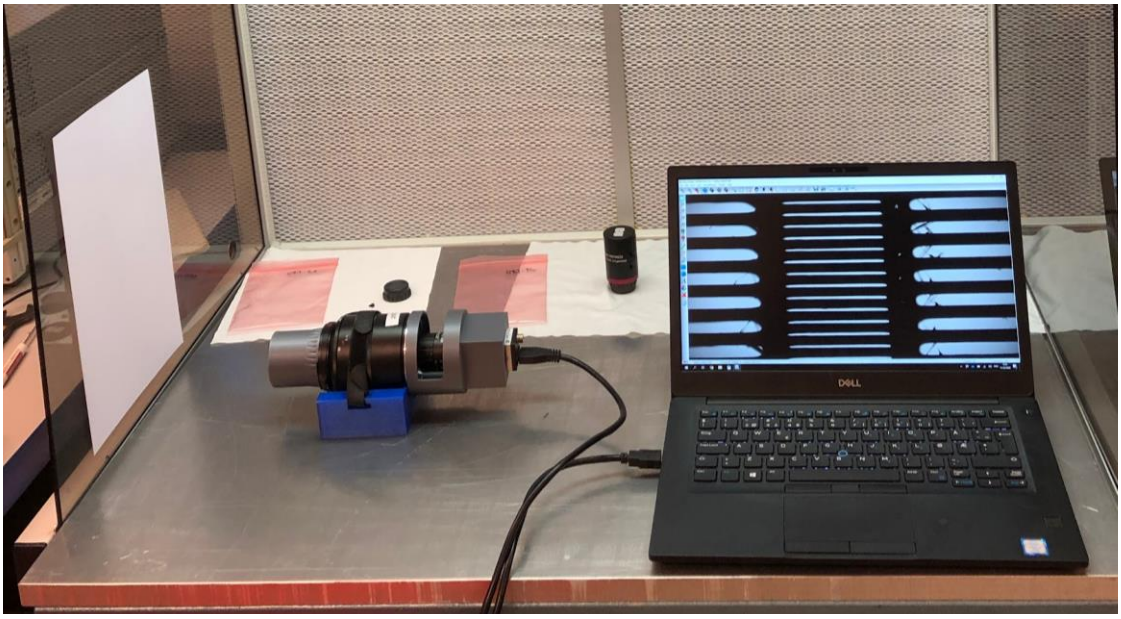
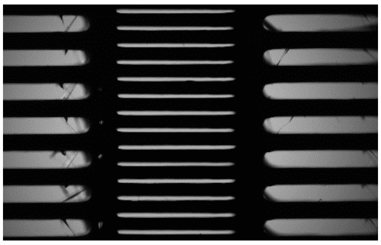
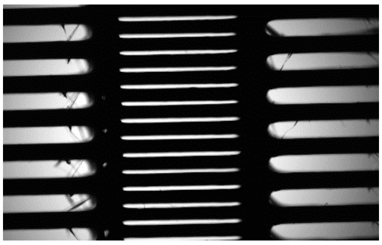
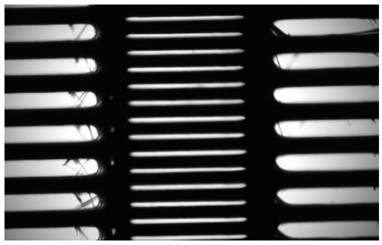


Figure 5.4: Setup for setting HSI objective focus in the lab (picture from HYPSO-1).

The resulting focused images for each HSI objective are shown in Table 8, the top row showing the view from the Elektro building facing Gråkallen. Gråkallen is used instead of the trees and buildings seen from the SmallSat lab due to a greater distance and clear view of Gråkallen and the buildings, compared to the view being obstructed by trees quite close by from the SmallSat lab. Distant buildings / the dome on the top of Gråkallen are the focal point. The bottom row are pictures from the custom in-lab setup.

Table 5.2: Sample focus setting images with HSI objectives.

Objective 28 front	**Objective 29 collimating**	**Objective 30 camera**
		
		

When both scenes are in focus, the HSI objective is removed from the detector, without twisting any parts. Epoxy was immediately added to the focus set screw as demonstrated in Figure 5.5.

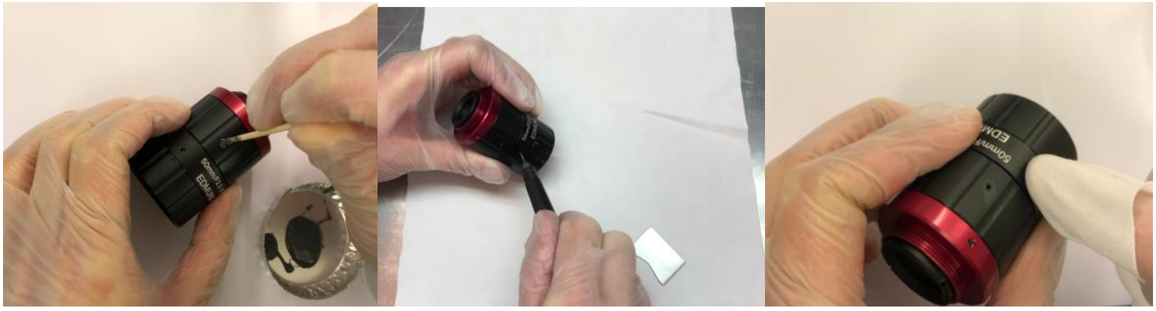


Figure 5.5. Left to right: adding epoxy to the screw hole controlling the focus; screwing the set screw into this hole; wiping off the excess epoxy. Images from HYPSO-1

Lens caps were replaced at this point to keep the lenses clean until final assembly. The objectives were then left to cure (epoxy) in un-sealed bags in the flow bench for 24 hours.

5.2.2 RGB Objective

The RGB objective only has one setting: the focal length. It is set by removing the three set screws on the c-mount collar and twisting the front of the objective, as shown in Figure 5.6.

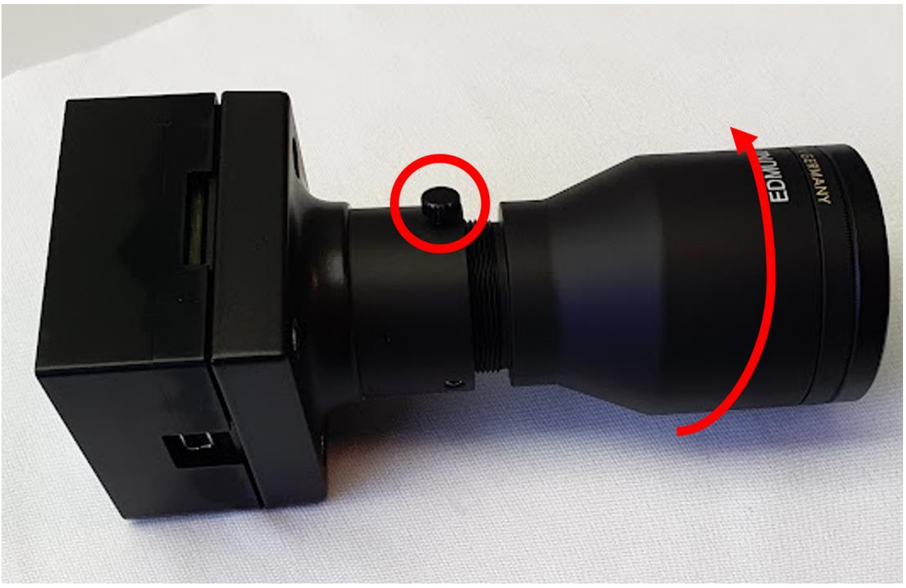


Figure 5.6: Setting the focus of the RGB objective.

A similar setup was used to set the focus of the RGB at infinity, see Figure 5.7. Only the mount was modified to fit the slightly different sized camera, but the method was the same.

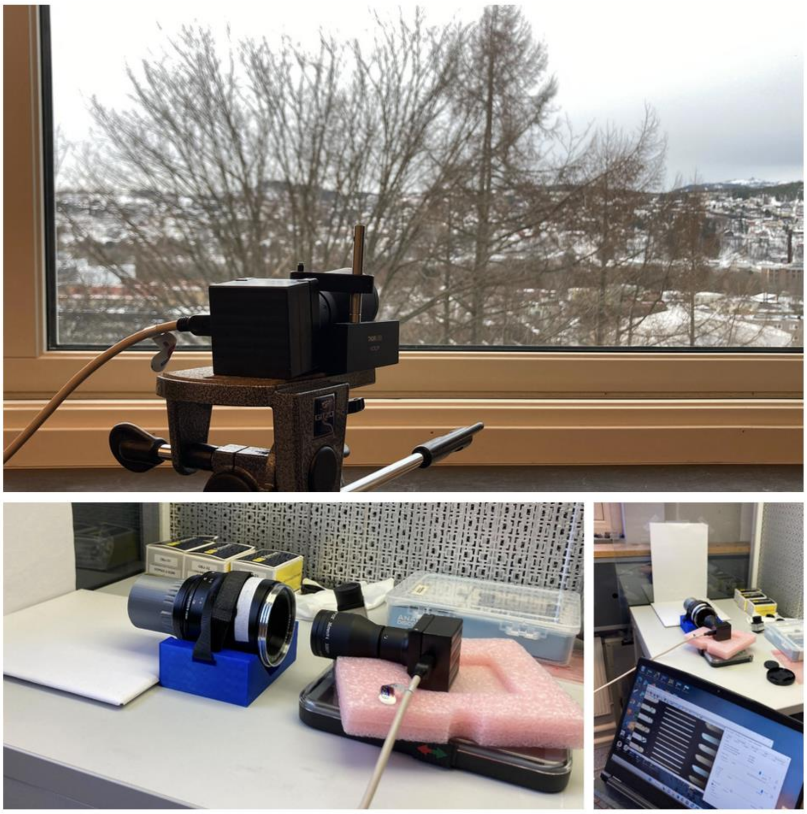
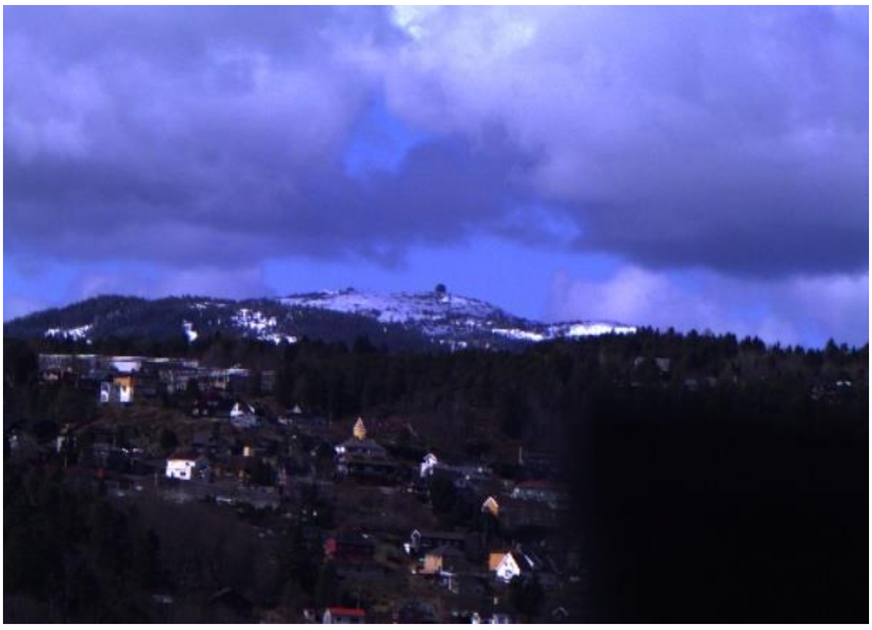
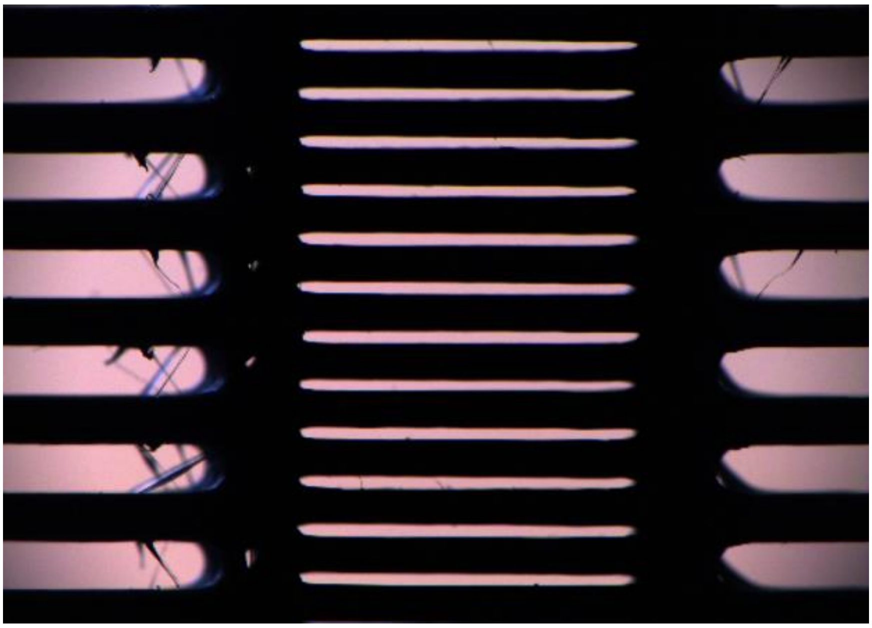


Figure 5.7: Setup for setting RGB focus. Top: Out the window pointing towards Gråkallen. Bottom: Collimator set-up in the lab (pictures from HYPSO-2 EQM).

Again, resulting images of both the focus setting taken out the window towards Gråkallen and the verification images in the lab with the collimator set-up taken with uEye Cockpit are shown in Table 5.3.

Table 5.3: Sample focus setting images with RGB objective.

RGB Objective




When the general setting for the RGB was noted, the objective was taken apart. Epoxy was added to the objective threading at the point it comes in contact with the C-mount collar. The focus setting procedure was repeated and the epoxy was pushed into the threading by screwing in the objective. In addition, the three set screws were added with epoxy.

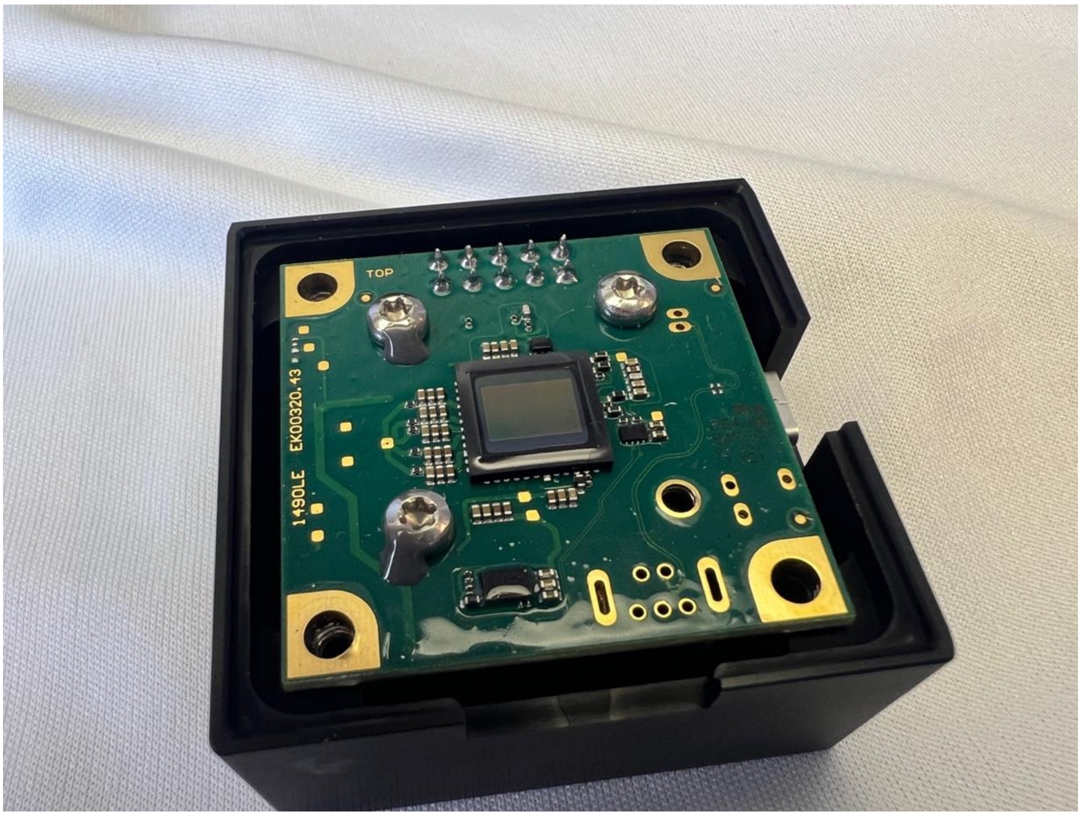


Figure 5.8: Epoxy added to the three screws holding the RGB-sensor to the RGB housing.

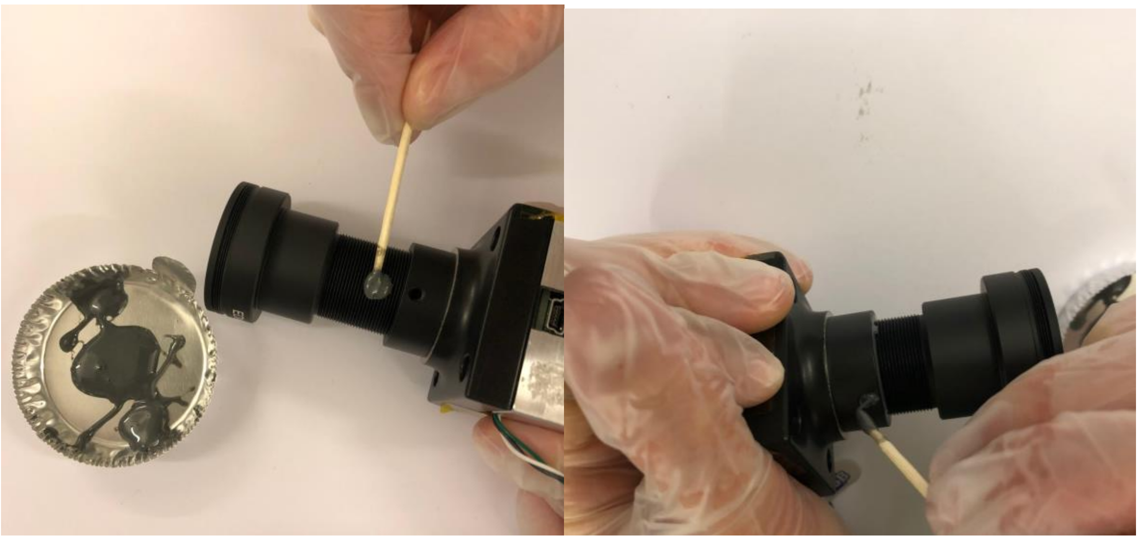


Figure 5.9: Epoxy added to the threading that controls the focus (left). Epoxy added to the set screw holes (x3) and then filled with the secured set screws (right) (pictures from HYPSO-1).

The epoxy takes 7 days to cure at room temperature (24 degrees Celsius), see Appendix B.

The RGB on HYPSO-2 has an IR-filter connected (with threads) to the lens. Epoxy was added to secure the IR-filter.

5.3 Bracket Gaskets

Immediately after ethanol cleaning and drying with nitrogen, all four platform brackets (3x HSI and 1x RGB) were taped with kapton as shown in Figure 5.10. This tape layer acts as a gasket to ensure a tight fit between the brackets and objectives.

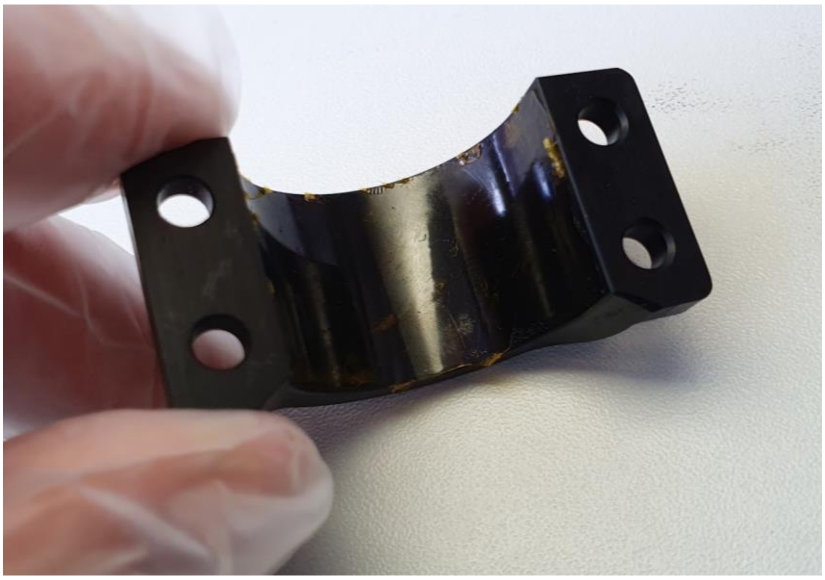


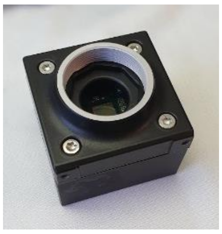
Figure 5.10: Kapton tape added as a 'gasket' to 3x HSI and 1x RGB platform brackets.

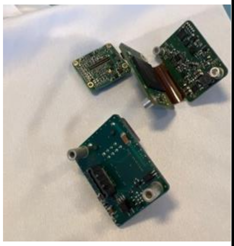
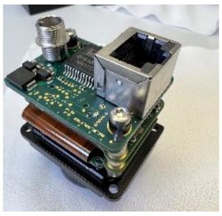
The brackets are covered with two strips of tape (one is not wide enough) and no overlap in the center. Tape edges are trimmed with a razor blade to limit the change of the tape accidentally peeling off. Kapton tape is vacuum safe and approved for use in space.

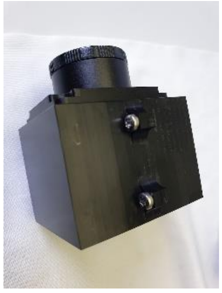
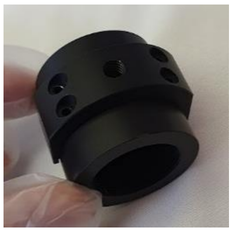
5.4 Payload Platform Assembly

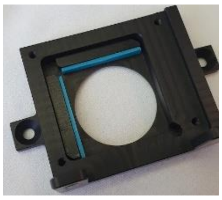
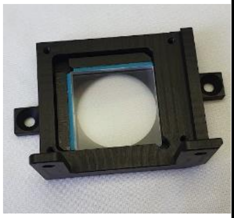
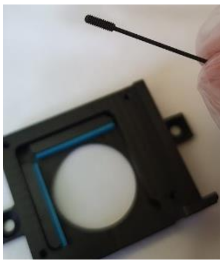
This section describes the steps involved in assembling the payload platform. Additionally, the table summarizes the torques that were applied to all screws in the payload during assembly. Torque values were recommended by engineers at NanoAvionics and tested during shock & vibe. Screws are in metric units [mm] unless otherwise stated. Screw heads are labeled as follows: CH = cheese head, CSK = countersunk, SET = set screw. Screwdriver bits are also listed for reference below the required screws.

Table 5.4: How the payload platform was assembled.

Screw [mm]	Torque [Nm]	From part	To part	Image	Notes (what should be done)	Notes (what was done)
RGB Sub-Assembly						
M2.5x4 CH (x1) Torx T8	0.600	RGB 1.8.4.1 Detector	RGB 1.8.4.4 Detector Housing		Be careful not to damage PCB components with the screw. Add epoxy to screws.	
M3x12 CH (x4) T9	1.100	RGB 1.8.4.3 C-mount	RGB 1.8.4.4 Detector Housing		Check that sensor is centered.	
-	-	RGB 1.8.4.2 RGB Objective	RGB 1.8.4.3 C-mount		Add epoxy to threading.	
		RGB 1.8.4.6 IR-filter	RGB 1.8.4.2 RGB Objectiv e			

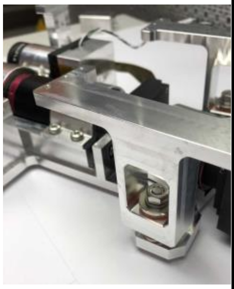
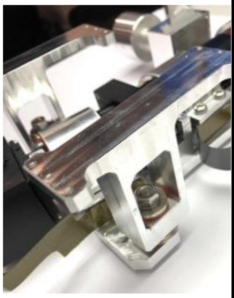
						
		PLD 1.8.4 RGB Camera	HSIM 1.8.1.1.1 HSI Platform			
HSI Sub-Assemblies						
					Carefully assemble the HIS detector after coating	
M2.5x30 CH (x2) Torx ?	0.600	HSID 1.8.1.3.1 Detector	-		Be careful not to damage PCB components with screw	
M2.5x4 CH (x4) Torx T8	0.500	HSID 1.8.1.3.1 Detector	HSIM 1.8.1.1.8 Detector Housing ETH HSIM 1.8.1.1.9 Detector Housing Hi-Rose			Screws epoxied.

M2.5x6 CH (x4) Torx T8	0.600	HSIM 1.8.1.1.8 Detector Housing ETH	HSIM 1.8.1.1.9 Detector Housing Hi-Rose		Only ETH side is threaded.	Screws epoxied.
-	-	HSIO 1.8.1.2.1 HSI Objective (camera)	HSID 1.8.1.3.1 Detector		Add epoxy to threading. Keep front lens cap on.	Hand tightened, one small drop of epoxy added to threading.
-	-	HSIO 1.8.1.2.1 Slit	HSIM 1.8.1.1.2 Slit Tube			
-	-	HSIM 1.8.1.1.3 Slit Tube Bracket	HSIM 1.8.1.1.2 Slit Tube			
M2.5x1 0 CH (x4) Torx T8 M6X6 Setscre w	0.600				Screws do not need to be torqued until the slit is adjusted in the final assembly	
-	-	HSIO 1.8.1.2.1 HSI Objective (collimator)	HSIM 1.8.1.1.3 Slit Tube			

		HSIO 1.8.1.2.1 HSI Objective (front)				
-	-	HSIM 1.8.1.1.6 Bracket Gasket	HSIM 1.8.1.1.5 Clamp Bracket		Add epoxy to interface. Check orientation.	
-		HSIM 1.8.1.1.5 Clamp Bracket	HSIM 1.8.1.1.4 Cassette Front		Allign the clamp brackets correctly	
-		HSIO 1.8.1.2.3 Grating	HSIM 1.8.1.1.4 Cassette Front		Arrows point in direction of incoming light path and diffraction angle bend, respectively.	
M2x6 SET (x4) Hex 0.9	0.300	-	HSIM 1.8.1.1.4 Cassette Front		Screw in evenly. Apply epoxy to threads. Be careful not to strip the threading.	Screws epoxied.
M2x12 CSK (x4) Torx T6	0.300	HSIM 1.8.1.1.7 Cassette Back	HSIM 1.8.1.1.4 Cassette Front			Screws epoxied.
M3x10	1.100	HSIM	HSIM		Apply epoxy to	

CSK (x4) Torx T8		1.8.1.1.4 Cassette Front	1.8.1.1.1 HSI Platform		threads.	
Platform Assembly						
-	-	HSIO 1.8.1.2.1 HSI Objective (collimator)	HSIM 1.8.1.1.1 HSI Platform		Use level to check positioning of slit tube.	To check positioning of slit tube, this step was redone after the rest of the payload was assembled and connected, but before the brackets and epoxy was applied. Rotation of the slit tube is described in Section 8.8.
M4x10 CH (x4) Torx T20	2.600	HSIM 1.8.1.1.11 Platform Bracket Middle	HSIM 1.8.1.1.1 HSI Platform			

		HSIM 1.8.1.1.10 Platform Bracket Front	HSIM 1.8.1.1.1 HSI Platform			
		RGB 1.8.4.5 Platform Bracket	HSIM 1.8.1.1.1 HSI Platform		Place the RGB bracket over the HSI Bracket Front	
M4x10 CH (x5) M4x16 CH (x2) Torx T20	2.600	HSIM 1.8.1.1.10 Platform Bracket (front) RGB 1.8.4.5 Platform Bracket	HSIM 1.8.1.1.1 HSI Platform		Tighten evenly with	M4x16 CH screws used for the mounting holes where the HSI bracket front and the RGB bracket overlap
-	-	HSIO 1.8.1.2.1 HSI Objective (camera)	HSIM 1.8.1.1.1 HSI Platform		Use level for positioning.	IDS UI-3060CP-M-GL sensor used in the image. Will be changed during calibration
M4x10 CH (x4) Torx T20	2.600	HSIM 1.8.1.1.10 Platform Bracket (back)	HSIM 1.8.1.1.1 HSI Platform		Keep level for positioning. Tighten evenly.	
NanoAvionics		IMU	HSIM 1.8.1.1.1 HSI Platform		Apply epoxy to threads	[Not yet done]

NanoAvionics		Star Tracker	HSIM 1.8.1.1.1 HSI Platform		Apply epoxy to threads	[Not yet done]
Bus Interface Structure						
Dampers (x2) M6 nut (x1) M6 washer (x1)	-	STR 1.8.5.1 Dampers STR 1.8.5.2 Front XLink +X	HSIM 1.8.1.1.1 HSI Platform		Press dampers into place in crosslinks, vertically. Attach each crosslink to the platform using stated hardware. The screw is inserted up. A 90deg bent wrench can be used to tighten once payload is integrated in bus.	[Not yet done]
Dampers (x2) M6 nut (x1) M6 washer (x1)	-	STR 1.8.5.1 Dampers STR 1.8.5.3 Front XLink -X	HSIM 1.8.1.1.1 HSI Platform			
Dampers (x2) M6 nut (x1) M6 washer (x1)	-	STR 1.8.5.1 Dampers STR 1.8.5.4 Back XLink +X	HSIM 1.8.1.1.1 HSI Platform			
Dampers (x2) M6 nut (x1) M6 washer	-	STR 1.8.5.1 Dampers STR 1.8.5.5 Back XLink -X	HSIM 1.8.1.1.1 HSI Platform			

(x1)						
M6x35 CH (x4) Torx ?	8.800	STR 1.8.5.2-5 Crosslinks (x4)	HSIM 1.8.1.1.1 HSI Platform			[Not yet done]

5.5 PicoBoB Assembly

This section describes the steps involved in assembling the PicoBoB electronics stack.

Table 5.5: How PicoBoB was assembled.

Screw [mm]	Torque [Nm]	From part	To part	Image	Notes (what should be done)	Notes (what was done)
PicoBoB Assembly						
	Will be added when the PicoBoB is built					

5.7 Setting up for testing

Assembly and calibration of the HSI was done the week of May 9th 2023. The FM picoBoB was not yet available, and the picoBoB used for HYPSO-2 EQM testing (with HYPSO-1 QM PicoZed and HYPSO-2 EQM BoB and no ALICE) was therefore used for testing.

The table under the workbench was set-up with a clean ESD mat, and checked as seen in Figure 5.11 before being used.

Figure 5.11: Testing ESD mat set-up.

The HYPSO-2 FM HSI sensor was first directly connected to the fieldwork laptop with an ETH cable (but with power from picoBoB), and configured. This made it possible to use uEye cockpit with the ETH sensor. Note: If the sensor doesn't appear in the uEye software, press the computer wifi button in the top right corner (where you normally connect to wifi), choose the wired option and select UAV. The sensor should then appear in uEye cockpit (iDS camera manager). If not, ask Roger.

5.8 Confirm focus on back lens

A few test images were then taken with only the HSI sensor and the back lens, to check if the focus looked good with the correct sensor, and to check for any dust/smudges on the sensor (or the back lens). The focus, with the correct sensor (and not the USB3 sensor used when setting focus of the lenses), using the same collimator set-up as described before, can be seen in Figure 5.12. It looks ok, it is hard to determine visually where the exact focus is the best, if it is on the back or in the middle of the pattern (thickness of the 3D print), which is an uncertainty that should be considered in future test set-ups. Figure 5.13 shows an image of a white sheet of paper (with the wall visible at the top). This was mainly to check for any dust/smudges visible in the image before calibration. No smudges can be seen.

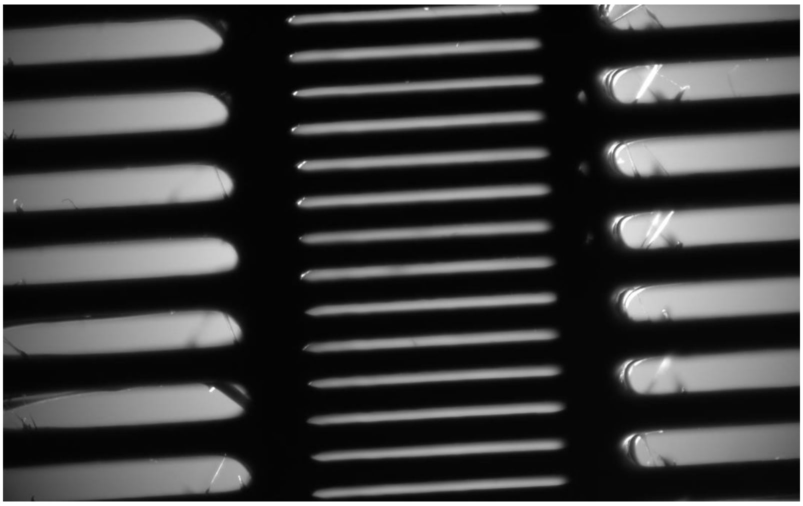


Figure 5.12: HYPSO-2 HSI sensor and back lens only, with the collimator set-up in the lab to check focus of the back lens.

Figure 5.13: *HYPSO-2 HSI sensor and back lens only, pointing towards a white sheet of paper to look for dust/smudges.*

5.9 Level sensor

The HSI sensor and back lens assembly were then mounted to the rest of the optical train. When tightening the bracket screws, a level (placed on top of an old bracket to avoid the screws in the HSI sensor box) was used to make sure the HSI sensor was levelled. To ensure the platform being level as well, it was placed on two smaller metal rods (since the platform is not flat underneath and therefore would not be level when placed directly on a flat surface).

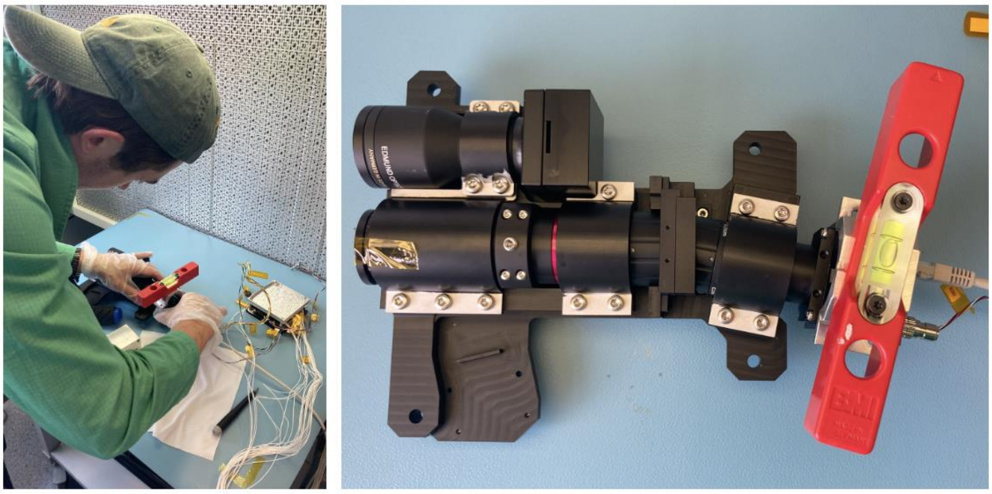


Figure 5.14: HYPSO-2 HSI sensor being levelled.

5.10 Adding spacer rings

When adding spacer rings, the procedure as described when building the HYPSO-2 EQM [RD09] was followed. The HSI was set-up in the flowbench and placed in front of a white sheet of paper, illuminated by the flowbench lights. The HSI sensor was still connected via ETH to the computer directly, so uEye cockpit could be used.

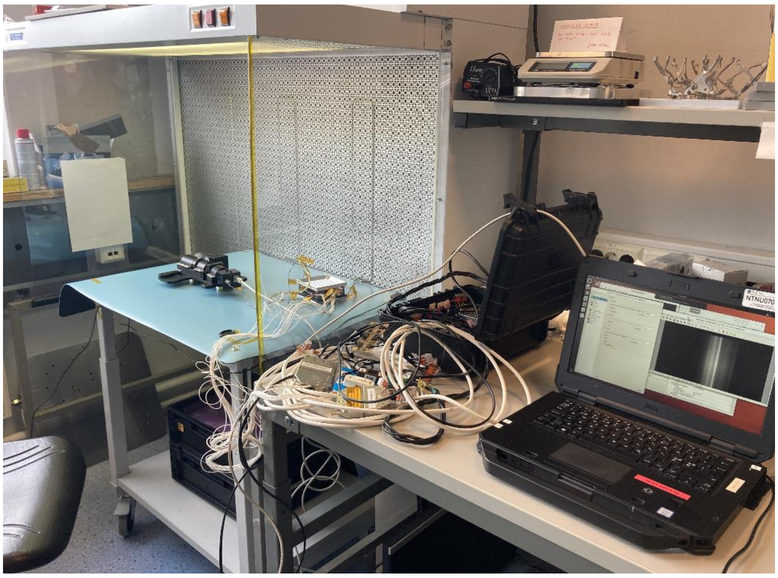
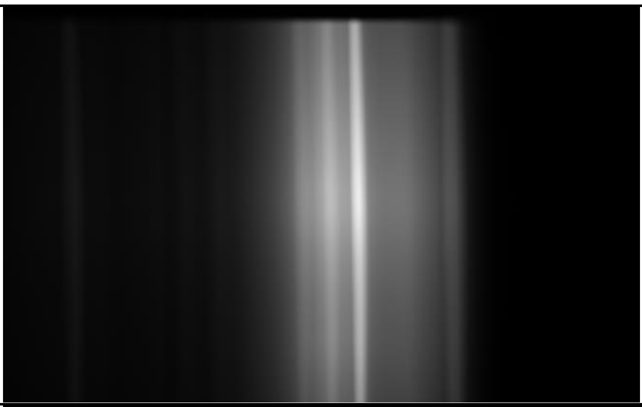
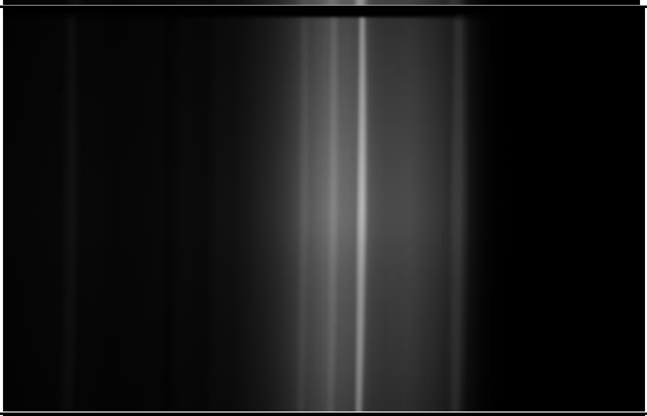
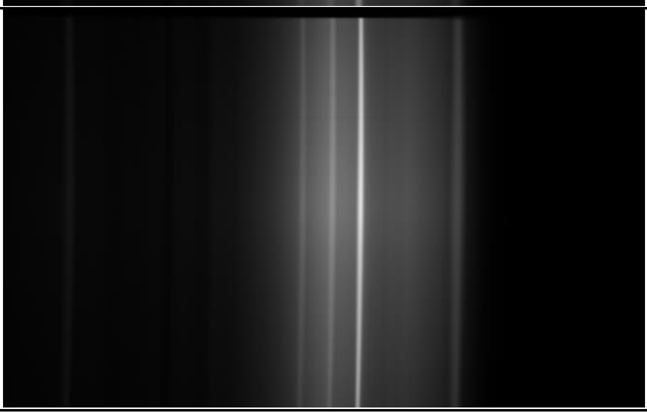
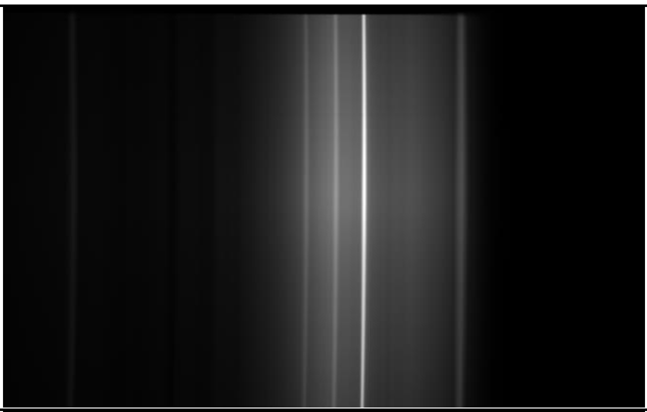
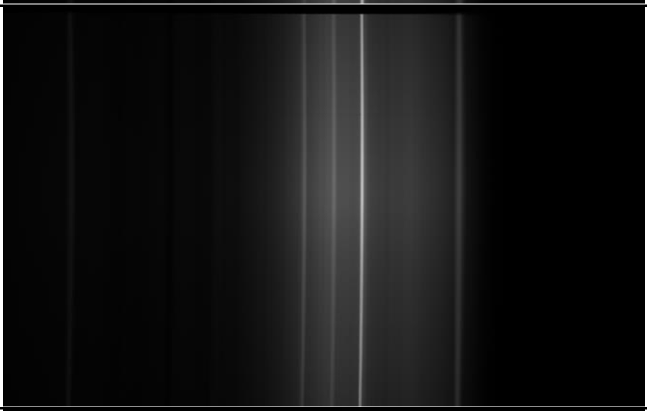
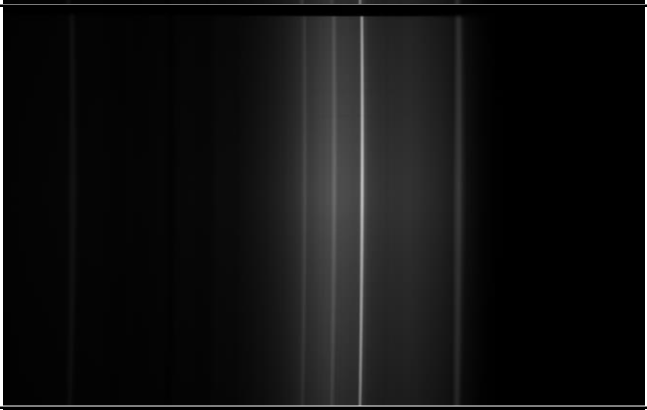
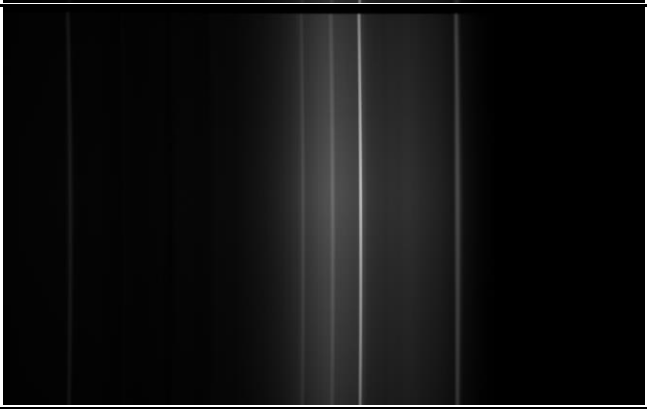


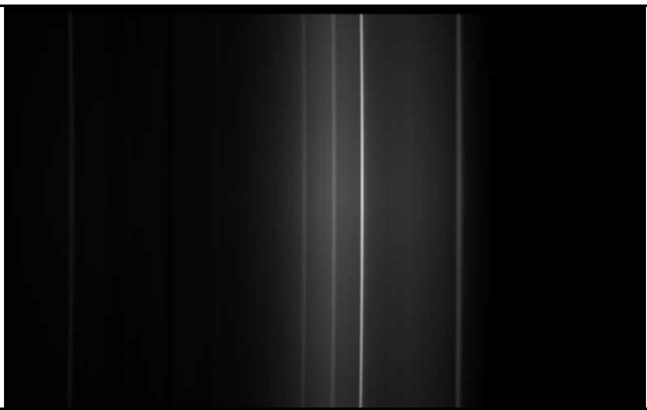
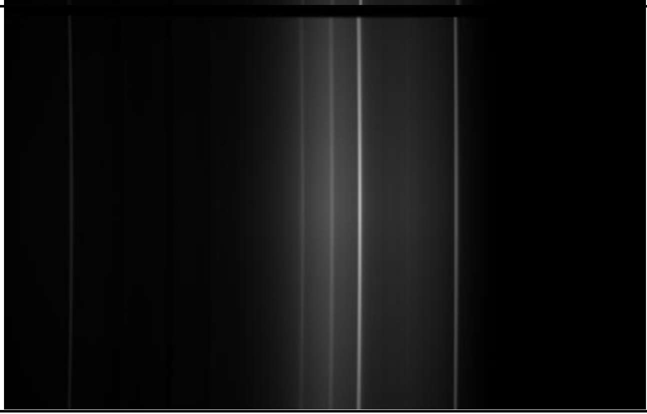
Figure 5.15: Set-up when adjusting spacer rings.

5.10.1 Spectral focus

First, the spectral focus was adjusted by adding spacer rings between the slit and the middle objective. The images were first visually inspected, then line plots were made, as seen in Figure 5.16. The 0.75 mm spacer ring was chosen, as this gave the sharpest lines in the middle of the image. The 0.5 mm + 0.25 mm spacer rings were used.

Spacer ring distance [mm]	Image	Comment
none		Very blurry
0.25		Less blurry
0.4		Even less blurry

0.5		Getting sharper
0.6		Even better
0.65		Better
0.7		This looks good

0.75		This is also good
0.8		This is worse again

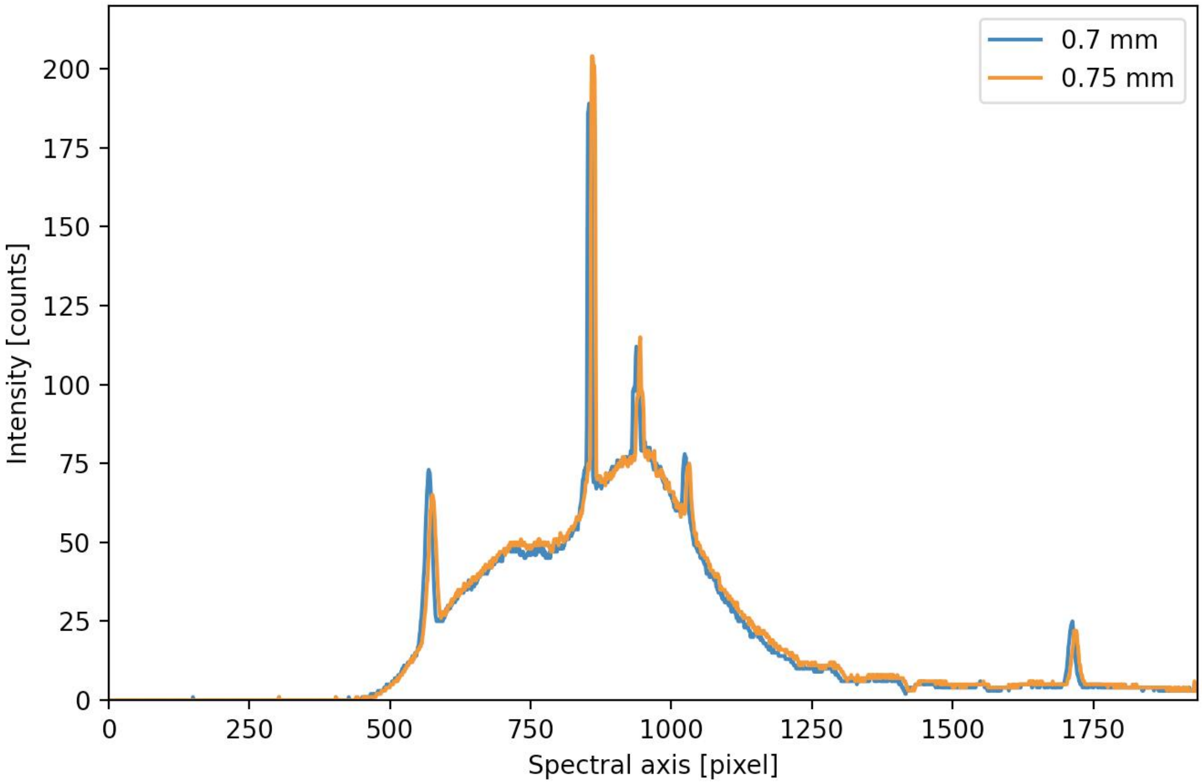


Figure 5.16: Line plot for 0.7 mm and 0.75 mm spacer rings between the slit tube and mid objective to adjust spectral focus.

5.10.2 Spatial focus

The spatial focus was then adjusted by adding spacer rings between the slit tube and the front objective. The collimator and striped pattern were placed in front of the HSI, to look at spatial lines in the spectrogram, and the stable QTH lamp was used for illumination as the spectrum here is broader.

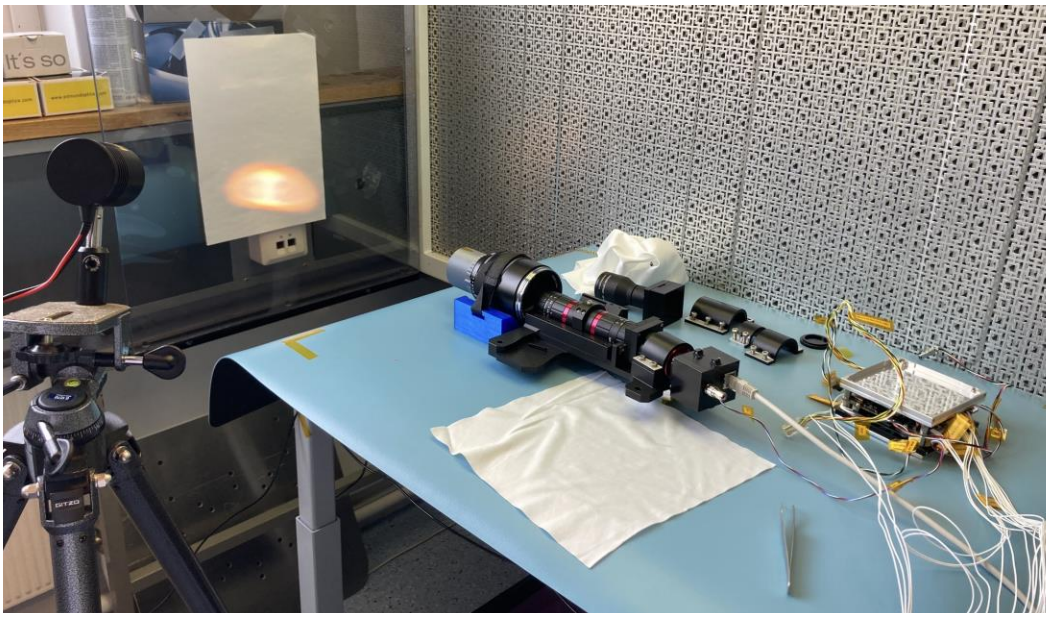
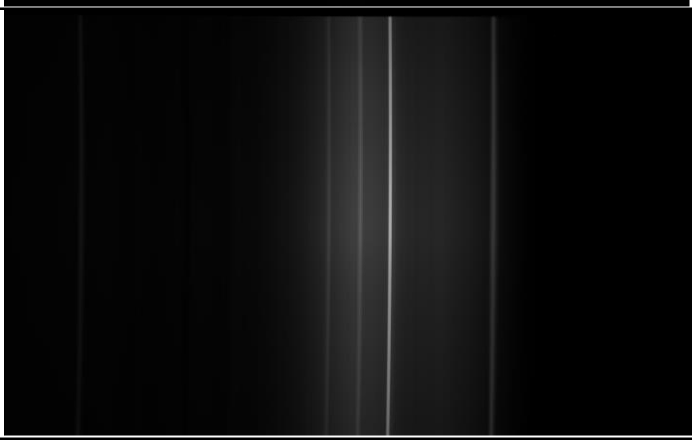


Figure 5.17: Set-up with collimator and QTH lamp when adjusting spatial focus.

The sharpness of the spatial stripes was first evaluated visually, then plotted as seen in Figure 5.18. The options of 0.25 mm, 0.3 mm and 0.35 mm all looked very good, but after looking at the plot the 0.35 mm option was chosen (combining 0.25 mm + 0.1 mm).

Spacer ring distance [mm]	**Image**	**Comment**
none		Blurry

0.2		Better
0.25		Top 3
0.3		Top 3
0.35		Top 3

0.45		
0.5		
0.6		Blurry again
0.35		Final image taken, with correct combination of 0.25 + 0.1 mm

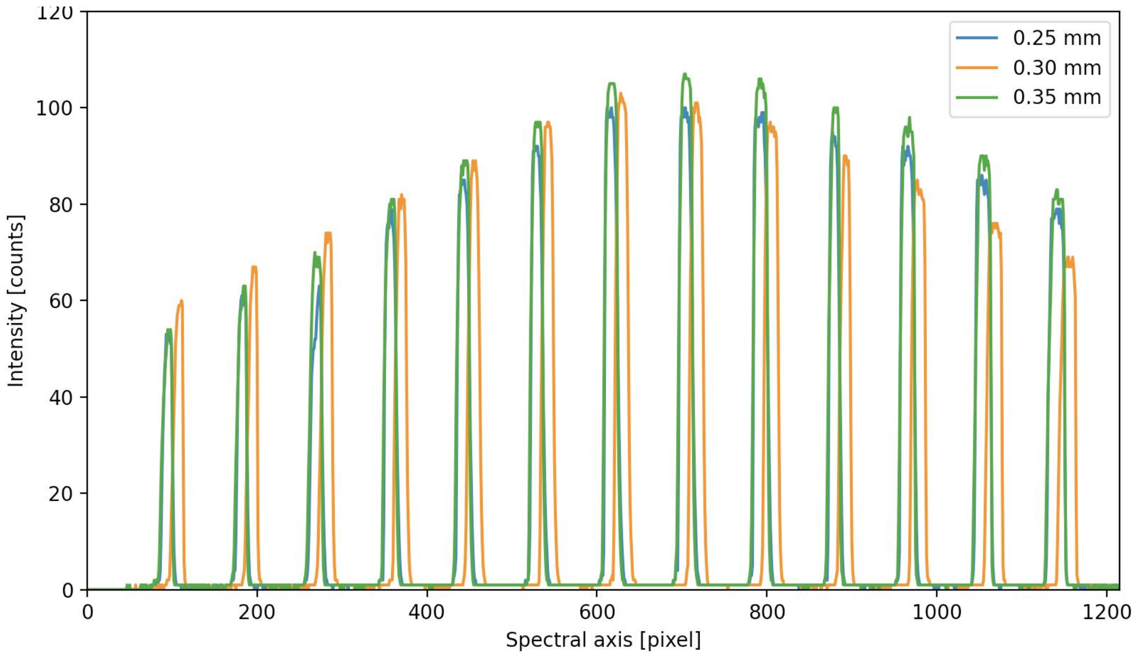


Figure 5.18: Line plot for 0.25, 0.3 and 0.35 mm spacer rings between the slit tube and front objective to adjust spatial focus.

5.11 Straighten slit tube

After adding the spacer rings, the brackets (and RGB) are mounted to the platform again, and all the screws torqued. The slit is then adjusted (still using the uEye software with livefeed which is nice), and tightened, then torqued, when the spectral lines were as straight as possible, see Figure 5.20. As seen in the figure, using the edge of a different window in front of the image gives a nice visual on whether the spectral line is straight or not. The movement of the slit when tightening was minimal (compared to for the EQM when it moved slightly every time the slit tube was tightened).

Figure 5.19: Straightening the slit tube.

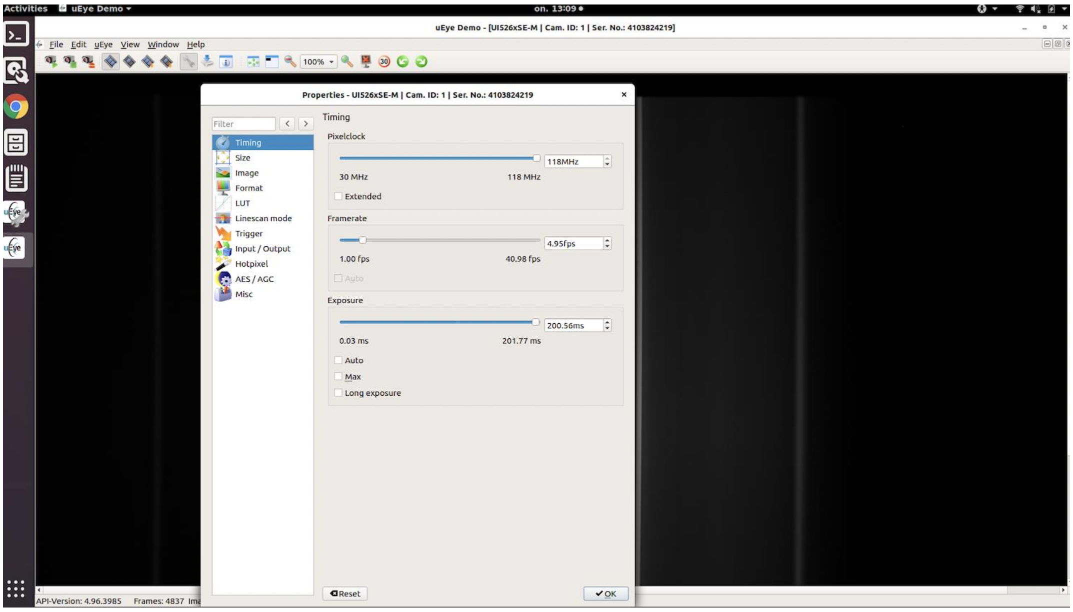
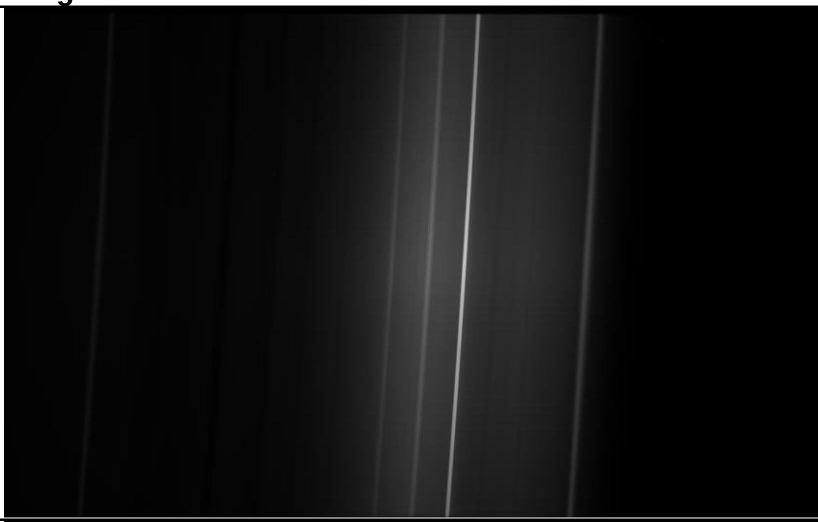
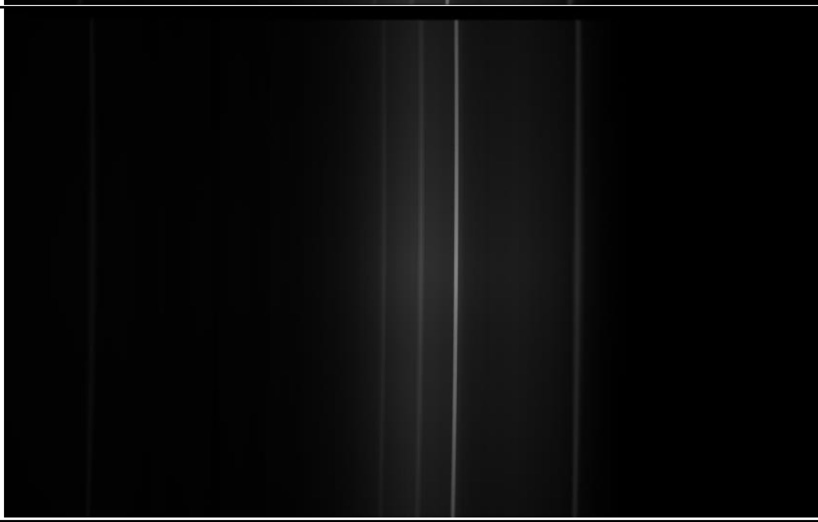


Figure 5.20: Visually determining if spectral line is straight by comparing with edge of other window (here settings window), using the iDS uEye cockpit software at the same time as adjusting the slit position inside the slit tube.

	Image
Before adjustment	
After adjustment	

5.12 Pre-calibration

After all screws were torqued, a pre-calibration was done in the calibration lab. Spectral images (with argon and mercury) were acquired to investigate the FWHM, and an image with the radiometric source (not warmed up) was taken to check if there were any noticeable dust stripes or smudges in the image.
Note: The images acquired with the picoBoB (EQM or FM) are upside-down compared to the ones captured with the uEye software. The frames presented here are there "backwards" (400 nm to the right and 800 nm to the left in the image). During image processing and calibration, the images will be flipped.

The radiometric frame in Figure 5.21 shows that there are some small dust stripes (seen as horizontal lines in the spectrogram). These are, however, quite weak and few, and will be corrected by radiometric calibration. No big blobs/smudges are easily visible in the frame.

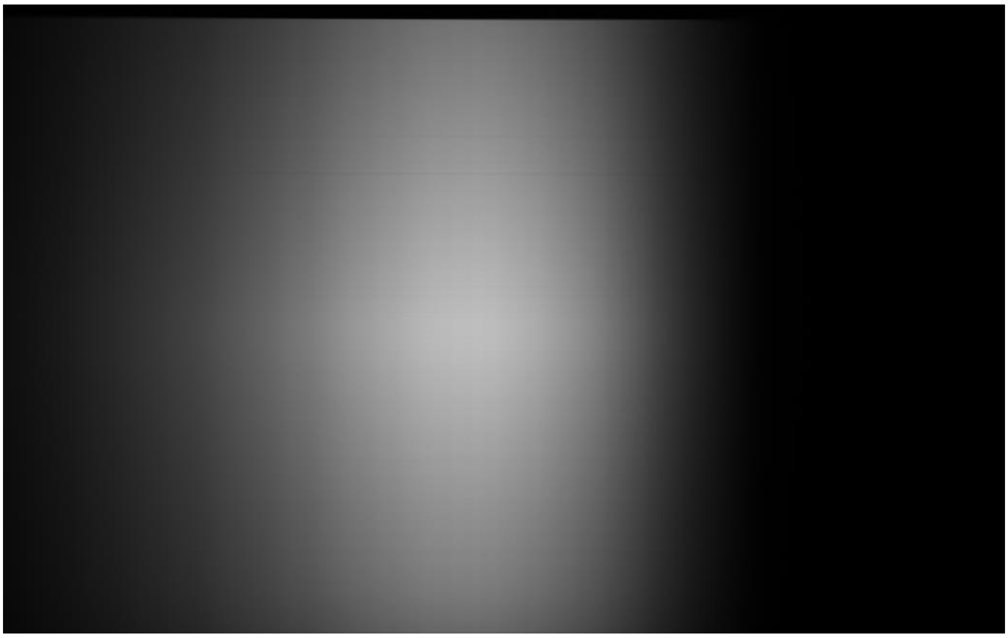


Figure 5.21: Radiometric pre-calibration frame (400 nm is to the right in the image, 800 nm to the left).

The spectral calibration frames can be seen in Figure 5.22 and 5.23 for the argon lamp and mercury lamp, respectively. The images were merged, and the middle line (middle row in the image) used to investigate the FWHM of the lines, as seen in 5.24. This was only done as a preliminary check, and a full analysis will be done and presented in the calibration report after the proper calibration has been performed. The peak widths calculated was width (in nm): 5.28, 3.66, 4.56, 3.54, 3.62, 3.69, 3.85, 3.75, 3.70, 3.91, 4.27, 4.13, 4.69, 4.69, 4.87, and the average value overall 4.15 nm, and average value in the 400-800 range 3.99 nm. The only value above the requirement (5 nm) is the first peak at around 430 nm. Since the signal between 400-450 nm is (from experience with HYPSO-1) very low, and it can be seen that the peak widths at higher wavelengths also approaches 5 nm, it was decided that this result was acceptable. The best focus can only be in one part of the spectrum, where we are aiming for the center part (around 600 nm), and the focus seems to be good here.

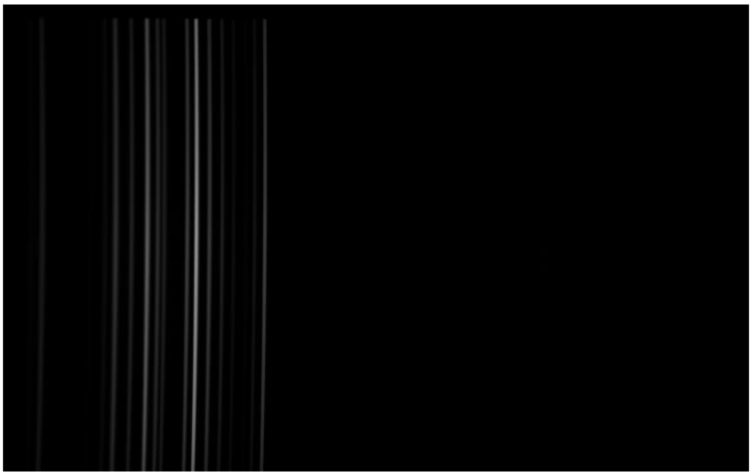


Figure 5.22: Spectra pre-calibration frame with the argon spectral lamp (400 nm is to the right in the image, 800 nm to the left).

Figure 5.23: Spectra pre-calibration frame with the mercury spectral lamp (400 nm is to the right in the image, 800 nm to the left).

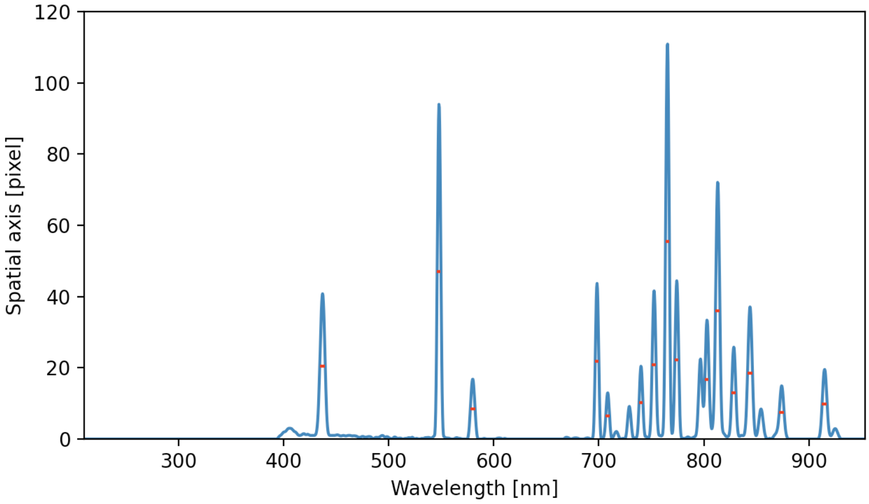


Figure 5.24: FWHM of the pre-calibration, width of the peaks are (in nm): 5.28, 3.66, 4.56, 3.54, 3.62, 3.69, 3.85, 3.75, 3.70, 3.91, 4.27, 4.13, 4.69, 4.69, 4.87, and the average value overall 4.15 nm, and average value in the 400-800 range 3.99 nm.

5.13 Epoxy

After investigating the images from the pre-calibration, the screws were epoxied. The RGB and IR filter were also epoxied.

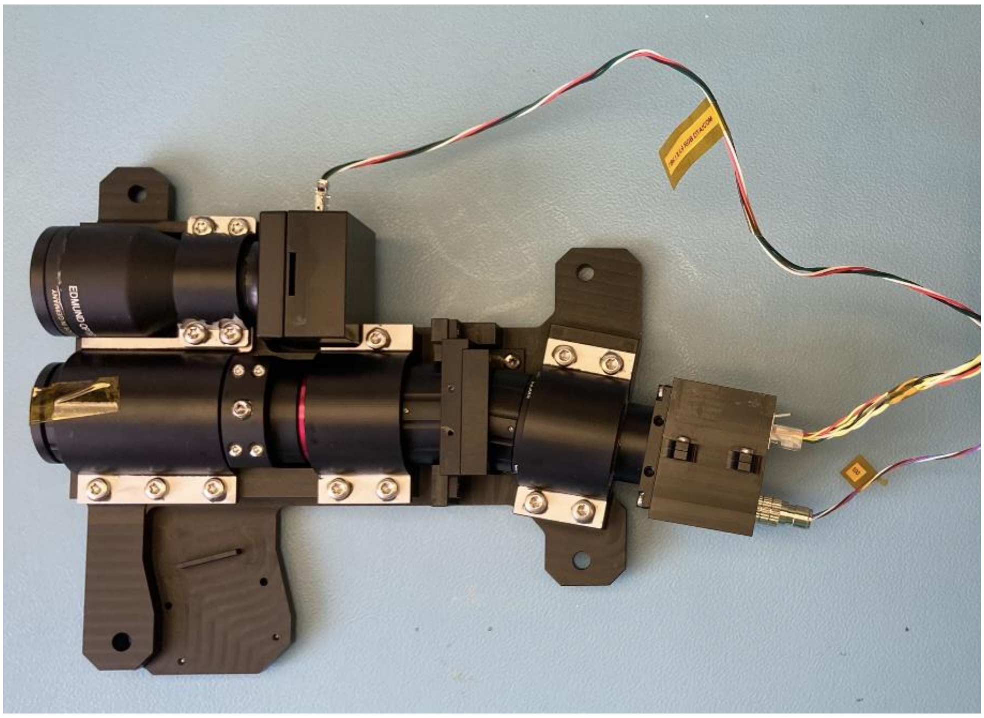


Figure 5.25: HYPSO-2 HSI FM assembled and epoxied.

5.14 Configure sensor with picoBoB

Switching from using ETH connection directly to the computer and running uEye cockpit with running through BoB. First, the EQM picoBoB was used (during calibration). When FM picoBoB is built, the same steps must be followed to configure the sensors with this picoBoB.

5.14.1 With EQM picoBoB for calibration

Following steps from HYPSO-2 EQM as-built report [RD09], chapter 4 (with some additional steps). Software was updated to release 2.0.0. Ask Roger if you have any questions.

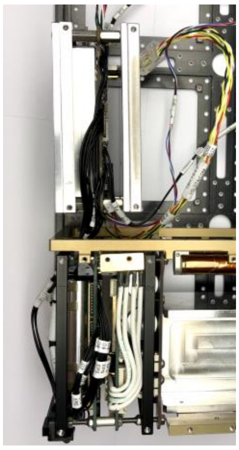
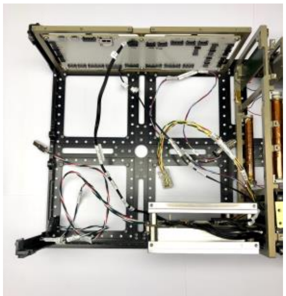
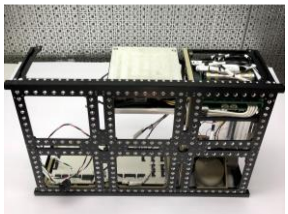
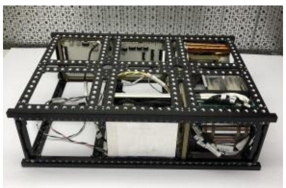
5.14.2 With FM picoBoB

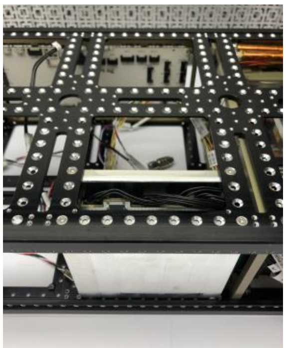
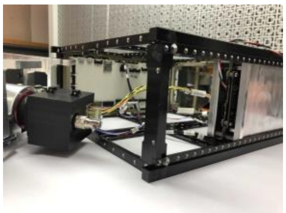
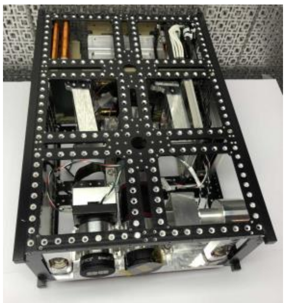
To be written.

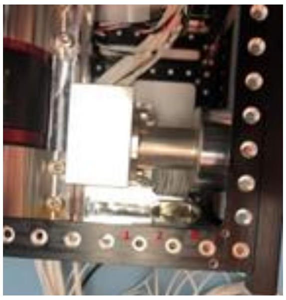
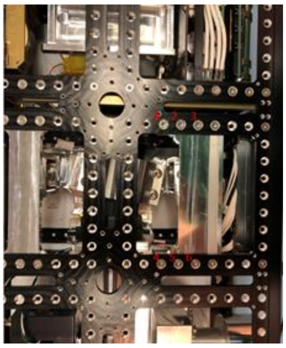
6 Integration - TBD

The integration was tested with the mass model, as detailed below, at NTNU to verify fit. The cables have to be connected between the payloads before bus integration. The final integration will happen at NanoAvionics. Epoxy will be added to all screw threading at that point. It is assumed that all panels (and tuna cans) and the top (+Y) frame are removed from the bus before integration occurs.

Table 14. How the payload should integrate to the satellite bus.

Screw [mm]	Torque [Nm]	From part	To part	Image	Notes
Payload Integration					
Cable	-	CBH 1.8.6.2 RGB PWR	PWR 1.2.2 EPS		Route cables carefully so they do not get in the way of the frame.
Cable	-	CBH 1.8.6.3 BOB PWR	PWR 1.2.2 EPS		
Cable	-	CBH 1.8.6.1 HSI PWR	PWR 1.2.2 EPS		
Cable	-	CBH 1.8.6.4 CAN	PCS 1.4.1 Payload Controller		Route cables such that they will go under the payload platform.
Cable	-	CHB 1.8.6.8 PPS	PCS 1.4.1 Payload Controller		
M2.5x6 CSK (x4) Torx T8	0.600	FRM 1.7.2 Ring Frame1-1 FRM 1.7.2 Ring Frame1-2	FRM 1.7.1 External 6U Frame -Y		Easiest if balanced on -X frame.
M2.5x8 CSK (x4) Torx T8	0.600	FRM 1.7.1 External 6U Frame +Y	FRM 1.7.1 External 6U Frame ALL		The four screws attach the top frame at each corner on the side frames.

M2.5x6 CSK (x4) Torx T8	0.600	FRM 1.7.2 Ring Frame1-1 FRM 1.7.2 Ring Frame1-2	FRM 1.7.1 External 6U Frame +Y		
Cable	-	CBH 1.8.6.7 HSI Hirose	HSID 1.8.1.3.1 Detector		For the HSI.
Cable	-	CBH 1.8.6.5 RJ45	HSID 1.8.1.3.1 Detector		
-	-	HSIM 1.8.1.1.1 HSI Platform	FRM 1.7.1 External 6U Frame		Slide payload platform into satellite bus.
Cable	-	CBH 1.8.6.6 USB mini	RGB 1.8.4.4 Detector Housing		Plug in usb cable to RGB and flash cable to BoB.
Cable	-	CBH 1.8.6.9 Flash	PBB 1.8.2.1 BoB - J12		
M2.5x4 CH (x3) Torx T8	0.600	FRM 1.7.1 External 6U Frame (+Y)	STR 1.8.5.3 Front Crosslink (-X)		

M2.5x4 CH (x3) Torx T8	0.600	FRM 1.7.1 External 6U Frame (+Y)	STR 1.8.5.2 Front Crosslink (+X)		
M2.5x4 CH (x6) Torx T8	0.600	FRM 1.7.1 External 6U Frame (+Y)	STR 1.8.5.5 Back Crosslink (-X)		
M2.5x4 CH (x6) Torx T8	0.600	FRM 1.7.1 External 6U Frame (+Y)	STR 1.8.5.4 Back Crosslink (+X)		

7 Software

In the 1.2.0 release used in the satellite, you will find `hypso-cli` and of `opu-services`, as well as `image.ub`, `bitstream.bit`, `BOOT.BIN`, `BOOT_QSPI.BIN`, `image_golden.ub`, `bitstream.bit.bin` and `full_bitstream.bif`.

The software is associated with a specific commit, That is

- https://github.com/NTNU-SmallSat-Lab/hypso-sw/commit/044903ab27a950f622953b9a6c1cb33eed54a493 for hypso-sw, e.g. `hypso-cli` and `opu-services`
- https://github.com/NTNU-SmallSat-Lab/opu-system/commit/a637149ae499d3bca4afd96cdffb6393f462c092 for opu-system, e.g. `image.ub`, `bitstream.bit`, `BOOT.BIN`, `BOOT_QSPI.BIN`, `image_golder.ub`, `bitstream.bit.bin` and `full_bitstream.bif`

The opu-system files are intended to be deployed on picozed with static IP: 129.241.2.42 To deploy the opu-system put the files in the opu-system partition on the SD card that will be inserted into the picozed.

The deployment instructions found in the README of the opu-system shall be followed. So that the eMMC is flashed with a golden image from the SD-card, and the booting switches are in QSPI mode so that the SD-card is used as the primary booting source.

See [AD06] for more information on the software.

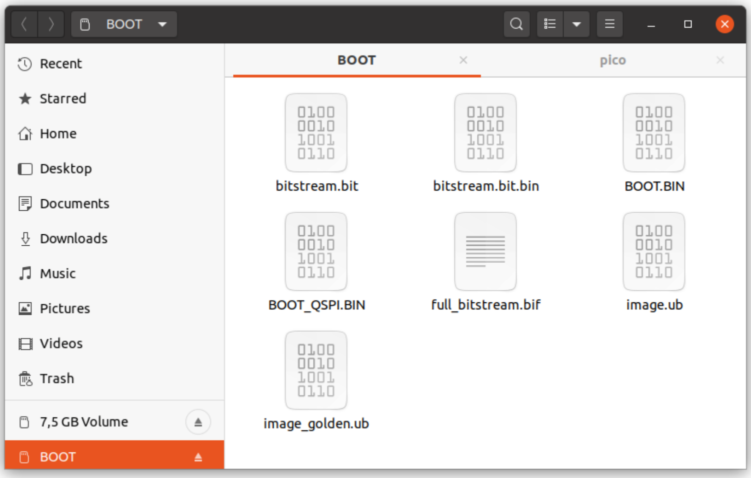
7.1 Flash PicoBoB with updated SD card

When taking into use a PicoBoB and a PicoZed for the first time, perform the two following checks:

1. Prepare zip-file from github
   For HYPSO-1 flight release: https://github.com/NTNU-SmallSat-Lab/assembly-integration-test/releases/tag/1.2.0
2. Put SD card in reader and plug into laptop

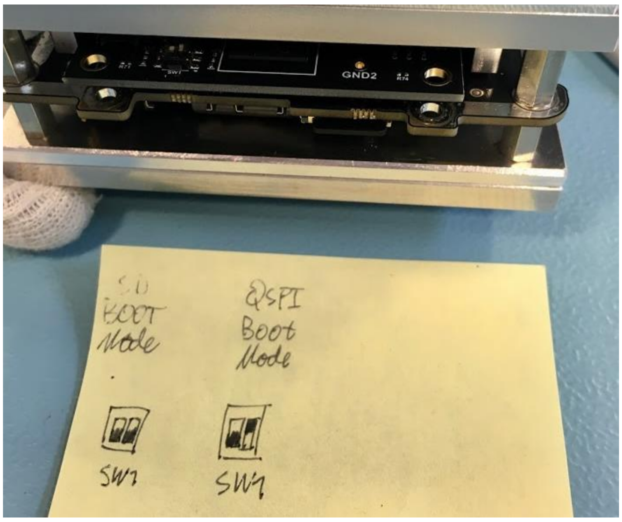
3. Prepare SD card
   a. Search for ubuntu program called 'Disks' (it's a GUI, so need to be started from the graphical menu)
   b. ~~*Select sd card in the list on the left*, then [...] (top right) button, format the disk~~
   c. ~~Select options: 'don't overwrite', 'compatible with all sys and devices'~~
   d. ~~format, yes~~
   e. - to remove existing partition(s)
   f. + to make partition, make 2 according to release notes of opu (https://github.com/NTNU-SmallSat-Lab/opu-system) use deployment/system testing
   g. 200 MB, called BOOT, "for use with all systems and devices (FAT)", create
   h. Select unallocated space, +
   i. All remaining, PAYLOAD, "Internal disk for use with Linux systems only (Ext4)"
   j. Wait for program to finish, then click "eject this disk" and close Disks
4. Insert SD Card in laptop again

a. Pick an ip.zip file (42)
b. Extract zip file on laptop
c. Move folder (7 files) to sd card BOOT partition



d. Unmount with eject button
e. Take out SD card from laptop

5. Insert SD in PicoBoB
    a. Insert in short side of picozed
6. Make sure the UART selector header is in place. This is needed in order to have access to the USB-to-UART port of the PicoBoB to have direct cli access to the payload.
7. Make sure that boot pins are in flashing position
    a. Position the bootstrap micro switches on the bottom side of the PicoZed into SD boot mode (both towards SW1 label on the pcb). Bent tweezers work well for this.



8. Open picoBoB terminal and turn on PicoBoB
    a. picocom -b 115200 /dev/ttyUSB0
9. Power on OPU
10. When message in terminal window says that it flashed ok 'flashing finished, you can turn off the device', keep picocom open
11. Turn off PSU
12. Switch pins to QSPI card booting position (see image above - black indicates the pin)

13. Turn on PSU, creating 'swap file' may take several minutes during first power-on.
14. Booting is finished when you see the text '[started] telemetry service'

7.2 Upgrade HSI camera firmware

A camera to be used in the payload shall have firmware version 4.93.0.989. The firmware will be flashed to the camera by use of iDS cameramanager. If the cameramanager itself needs to be updated, follow these steps:

1. Uninstall old version (VERY IMPORTANT)
    a. sudo /usr/bin/ueyesetup -r eth
    b. sudo /usr/bin/ueyesetup -r usb
2. Download or get the new version of cameramanager and put it into a folder on the computer
    a. If the file is copied from an USB-stick, the file might not have executable permissions:
       ls -al `ueye_4.93.0.989_amd64.run`
    b. The permissions must read something like: -rwxrwxrwx (it's the 'x'-es that must be present. If the permissions looks like: -rw-rw-rw-, do this: chmod a+x `ueye_4.93.0.989_amd64.run`
3. Make sure HSI has power (hi-rose cable) and connect to laptop
    a. Plug HSI ethernet directly into laptop ethernet port
    b. toggle power 'on' to HSI
4. Install the new driver:
    a. `sudo sh ./ueye_4.93.0.989_amd64.run`
5. Start the deamons (the driver)
    a. `sudo systemctl stop ueyeethdrc`
    b. `sudo systemctl stop ueyeusbdrc`
    c. `sudo systemctl start ueyeethdrc`
    d. `sudo systemctl start ueyeusbdrc`
6. Start the camera manager. If a firmware update does not happen automatically, do it manually.

Then the camera can be used as normally. See http://folk.ntnu.no/elizabep/mech/doku.php?id=mech:other:ip on how to set the IP so it can be used for the computer.

Note:
- You can probably not set the IP the camera needs to have to function in the payload from the computer. That has to be done while the camera is plugged into the PicoBoB.
- On the field laptop, click the wireless icon, and select wired connection. Make sure that it's the network UAV that is selected
- The camera manager on the field laptop might misbehave. This happened when upgrading HSI firmware on the FM. This was solved by updating firmware from a different computer (in Linux).

7.3 Camera configurations

Brand new sensors must be configured with correct IP-address (HSI only) and camera ID. Observe the steps below.

7.3.1 Setting the HSI camera ID and IP-address

Find the connected cameras (power on OPU and HSI-camera power channel)
opu caminfo – see that there is a camera listed with device ID 1001. Observe that “in use” is “yes” and “Cam ID” is 1 (indicates that the camera will not work…)
set new IP
opu setip 1001 129.241.142.142 255.255.254.0
opu caminfo
observe that IP has changed and that “in use” changed from “yes” to “no”
Also change the cam ID from 1 to 2
opu setid 1 2
opu caminfo
Observe that the camID now is 2, and “in use” should say “no”. If so, you can try take a image with hsi capture.

7.3.2 Setting the RGB camera ID

Power on the OPU, and then (after the OPU has booted properly) power on the RGB channel.
opu caminfo
Observe that OPU lists one camera. It should have “Cam ID” 1. This must be changed to 5.
opu setid 1 5
opu caminfo
Observe that “Cam ID” now is 5.
Try take an image.
rgb init
rgb capture …
rgb deinit

7.3 Testing boot from SD card and golden image

To test if the booting worked properly, both normal boot from SD card and booting from golden image was tested several times. Booting from the golden image was both tested by removing the SD card and starting the system, and by toggling the power switch for the OPU quickly 5 times (with the SD card in).

The logs from these tests can be found in https://drive.google.com/drive/folders/1isa8PO569sTMEZMVQSNOVr_ekdG91Uij.

All tests indicate normal performance using the golden image.

Appendix

Appendix A: Part Numbers

See Checklist or BOM

HYPSO Code	Part	Company	Part Number / Spec	Order Date	Delivery Date	Notes
PLD 1.8.1	**Hyperspectral Imager**					
HSI 1.8.1.1	HSI Mechanical Parts					
HSIM 1.8.1.1.1	HSI Platform	Astrup	Al skinne 6082-T6, 200x40x4300 mm	23.04.2020	27.04.2020	
HSIM 1.8.1.1.2	C-Mount Adapter	Thorlabs	SM1A10	13.01.2020	17.01.2020	
HSIM 1.8.1.1.3	Slit Tube	Astrup	Al skinne 6082-T6, 200x40x4300 mm	23.04.2020	27.04.2020	
HSIM 1.8.1.1.3.1	Spacer ring 0.25 mm	Edmund Optics	0.25mm Thick Inner Spacer Ring #11-190	17.02.2021	03.03.2021	
HSIM 1.8.1.1.4	Cassette Front	Astrup	Al skinne 6082-T6, 200x40x4300 mm	23.04.2020	27.04.2020	
HSIM 1.8.1.1.5	Clamp Bracket (x2)	Astrup	Al skinne 6082-T6, 200x40x4300 mm	23.04.2020	27.04.2020	
HSIM 1.8.1.1.6	Bracket Gasket (x2)	Trelleborg	Turcon T05, 75x1x75 mm	02.05.2019	24.06.2019	TTH ordered so I can't be sure, the reciept says a different material
HSIM 1.8.1.1.7	Cassette Back	Astrup	Al skinne 6082-T6, 200x40x4300 mm	23.04.2020	27.04.2020	

HSIM 1.8.1.1.8	Detector Housing1	Astrup	Al skinne 6082-T6, 200x40x4300 mm	23.04.2020	27.04.2020	
HSIM 1.8.1.1.9	Detector Housing2	Astrup	Al skinne 6082-T6, 200x40x4300 mm	23.04.2020	27.04.2020	
HSIM 1.8.1.1.10	Platform Bracket (x3)	Astrup	Al skinne 6082-T6, 200x40x4300 mm	23.04.2020	27.04.2020	
HSIM 1.8.1.1.11	Retaining Ring	Thorlabs	SM1RR	13.01.2020	17.01.2020	
HSIM 1.8.1.1.12	Fixed Aperture	ThermoFisher Scientific	11335067, Al foil, annealed, 100x100x0.25 mm	11.06.2020	15.06.2020	
HSI 1.8.1.2	HSI Optical Parts					
HSIO 1.8.1.2.1	Objective - front	Edmund Optics	EO#67-717, 6mm Ci Series Lens, F1.4	15.01.2020	17.01.2020	
	Objective - collimating	Edmund Optics	EO#67-717, 6mm Ci Series Lens, F1.4	05.02.2020	07.02.2020	
	Objective - camera	Edmund Optics	EO#67-717, 6mm Ci Series Lens, F1.4	05.02.2020	07.02.2020	
HSIO 1.8.1.2.2	Slit	Thorlabs	S50RD, custom slit, 7mm	19.11.2019	20.01.2020	
HSIO 1.8.1.2.3	Grating	Edmund Optics	EO#49-579, Grating Trans 300 Gr 17.5 deg 25 Sq	29.01.2020	01.02.2020	
HSI 1.8.1.3	HSI Detector					
HSID 1.8.1.3.1	Detector	iDS	UI-5261SE-M-GL Rev. 4 (S/N 4103337325)	30.03.2020	30.03.2020	
PLD 1.8.2	**PicoBoB**					
PBB 1.8.2.1	BoB v3		10742			Amund??
PBB 1.8.2.2	PicoZed	Avnet	PicoZed 7015/7Z030 RevE (S/N			Who ordered this??

			4000130 1401 1950 004019)			
PBB 1.8.2.3a	MicroSD Card	Farnell (Panasonic)	RP-SMSC08	12.02.2020	14.02.2020	
PBB 1.8.2.3b	MicroSD Card	DigiKey (Swissbit)	SFSD016GN3BM1TO-I-HG-2CP-STD	12.02.2020	19.02.2020	This was not added after all
PBB 1.8.2.4	Shield w/ hole	Astrup	Al skinne 6082-T6, 200x40x4300 mm	23.04.2020	27.04.2020	
PBB 1.8.2.5	Shield w/ rails	Astrup	Al skinne 6082-T6, 200x40x4300 mm	23.04.2020	27.04.2020	
FRM 1.7.2	1U ring frame (x2)	NanoAvionics				Not sure, they were here before I started on the project
PLD 1.8.4	**RGB Camera**					
RGB 1.8.4.1	Detector	iDS	UI-1252LE-C (S/N 4103694284)	31.01.2020	19.02.2020	
RGB 1.8.4.2	Objective Lens	Edmund Optics	EO#86-591, FA CFF 6mm, F1.4	31.01.2020	10.02.2020	
RGB 1.8.4.3	C-Mount	iDS	UI-1250ML-M-GL (S/N 4103694358)	31.01.2020	19.02.2020	
RGB 1.8.4.4	Detector Housing	Astrup	Al skinne 6082-T6, 200x40x4300 mm	23.04.2020	27.04.2020	
RGB 1.8.4.5	Platform Bracket	Astrup	Al skinne 6082-T6, 200x40x4300 mm	23.04.2020	27.04.2020	
PLD 1.8.5	**Payload Structure**					
STR 1.8.5.1	Dampers					
STR 1.8.5.2	Front Crosslink +X	Astrup	Al skinne 6082-T6, 200x40x4300 mm	23.04.2020	27.04.2020	

STR 1.8.5.3	Front Crosslink -X	Astrup	Al skinne 6082-T6, 200x40x4300 mm	23.04.2020	27.04.2020	
STR 1.8.5.4	Back Crosslink +X	Astrup	Al skinne 6082-T6, 200x40x4300 mm	23.04.2020	27.04.2020	
STR 1.8.5.5	Back Crosslink -X	Astrup	Al skinne 6082-T6, 200x40x4300 mm	23.04.2020	27.04.2020	
Other						
	Cables					Not sure, didn't order them
	Objective Screws					see BOM
	M2-4 Screws					see BOM
	M6 Screws, Nuts, Washers					see BOM
	PCB Standoffs					see BOM

Appendix B: Epoxy

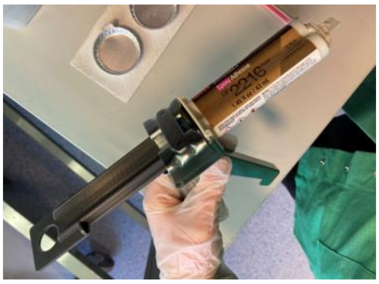
B.1 Applying epoxy

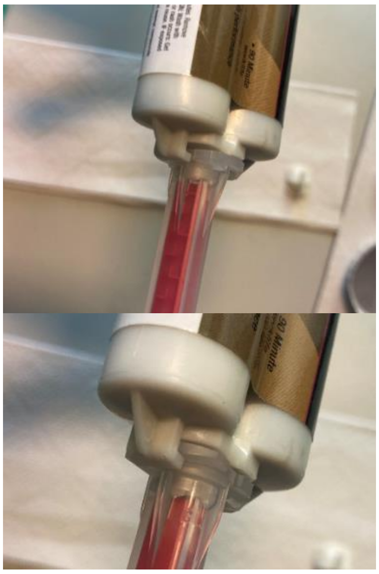
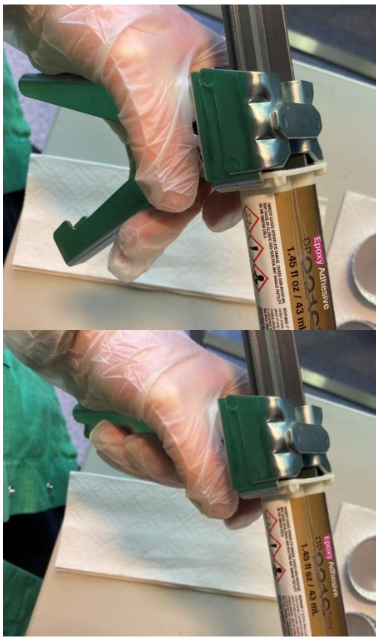
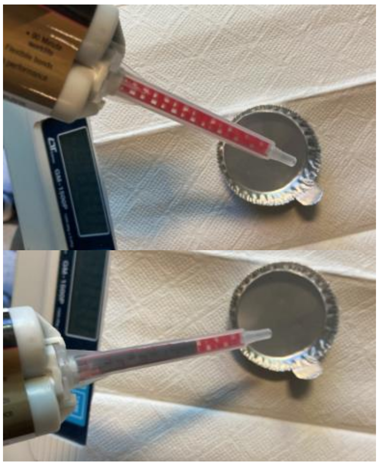
The equipment used to apply the epoxy can be seen in Figure B.1.1. The procedure for applying epoxy is described in Table B.1.1.

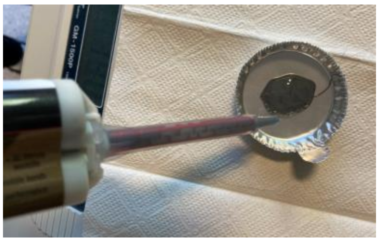
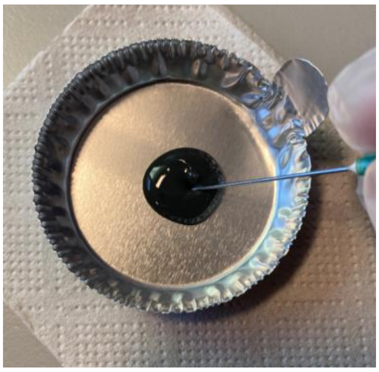
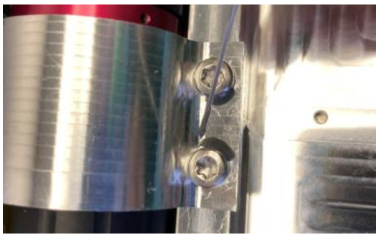
Figure B.1.1: Equipment needed for applying epoxy.

Table B.1.1: Procedure on how to prepare and apply epoxy.

Step	**Picture**	**Notes**
Press the release button on (4) and insert (3).		The “stripes” on (3) are pointing down. Push it all the way in.

		
Add the epoxy tube (5).		There is a small tube and a big tube, make sure they're matching with the small and big circles on (3).
Open the tube cap.		Twist it and pull it off.

Add the mixing “needle” (6) by twisting it onto the epoxy tip.		
Push the plastic piece (3) by pressing the handle on (4) so that it presses the stamps on the epoxy tube.		Usually about 5-6 pushes.
Continue pressing so that epoxy comes out of the tip (6). Fill 1.75 grams in a container (1).		Throw this away, this is to make sure that the epoxy you use is properly mixed.

		
Fill a new container (1) with the amount of epoxy you think you need.		
Stir the epoxy with the needle (2).		If just testing, a toothpick can be used instead of the needle.
Apply the epoxy with the needle (2).		
Clean up.		Clean the needle when done with it. It’s usually nice to leave the container with the remaining epoxy to cure to make sure that the mixture cures properly.

B.2 Epoxy curing time

Product	3M™ Scotch-Weld™ Epoxy Adhesive		
	2216 Gray	2216 Tan NS	2216 Translucent
Cure Temperature	Time	Time	Time
75°F (24°C)	7 days	7 days	30 days
150°F (66°C)	120 minutes	120 minutes	240 minutes
200°F (93°C)	30 minutes	30 minutes	60 minutes

B.3 Removing epoxy

The epoxy can be removed from the screws by heating up the epoxy so that it starts melting a bit, then it should be possible to rub it off. When it is only a small blob of epoxy, it is also possible to loosen the screw by force. This could then crack the epoxy and leave tiny particles, which is not desired. Heating the epoxy was therefore the preferred option.

Heating the epoxy was first attempted by using a soldering iron to heat up the screw. But this was very slow, and only the thinner parts of the epoxy blob started to get softer after 30 minutes. So only a small part of the epoxy blob was removed from one screw, as seen in Figure B.3.1.

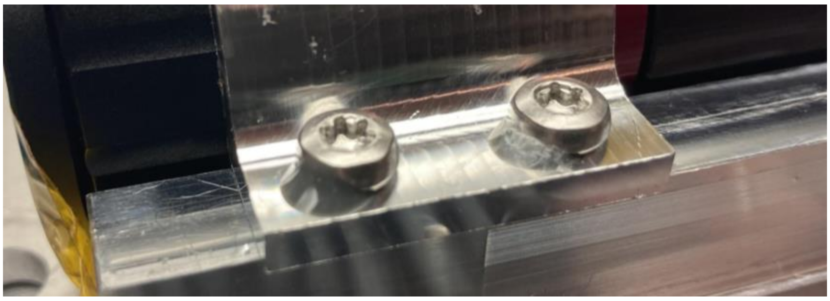


Figure B.3.1: FM HSI front bracket screws, where some of the epoxy of the screw to the right has been removed by using a soldering iron to heat up the screw and a tweezer.

Heating the epoxy using a heat gun was then attempted. One with a smaller tip was preferred to avoid hot air all over the payload. Since the screws were torqued they were quite tight, so to get a feeling on how much force was needed to untighten the screws this was practiced on the QM beforehand. The heat gun was then held a few centimetres from the screw, as seen in Figure B.3.2, and the torque screw (with correct torque) was used to loosen the screw at the same time. After a few seconds most of the screws would be able to loosen from the epoxy, so that the screw could be taken off while the epoxy blob was still on the bracket. All screws were loosened, then all screws removed, the brackets were taken off and then the epoxy was removed by the brackets by applying a bit more heat above the epoxy and then removing it using tweezers.

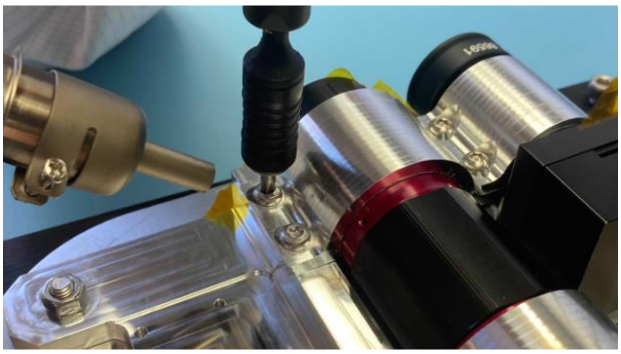
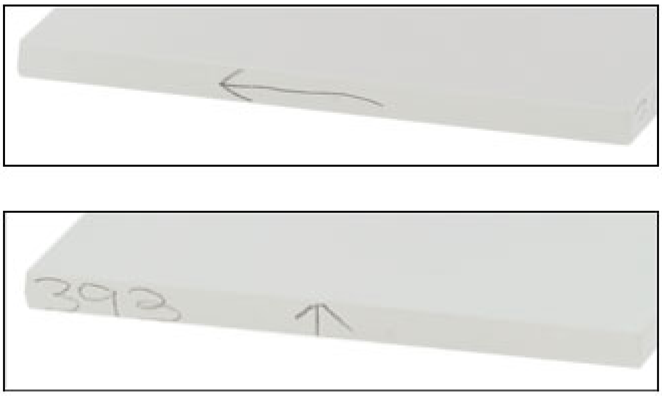


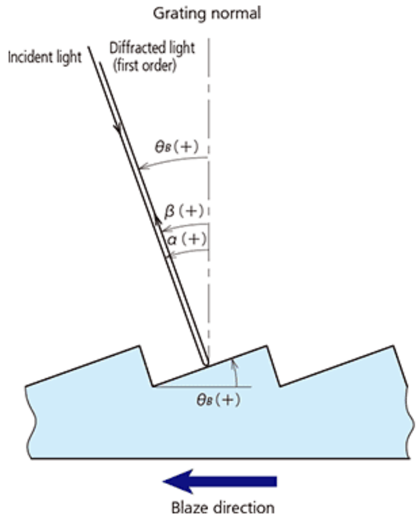
Figure B.3.2: Epoxied screws being loosened then removed from FM using a heat gun and torque screwdriver.

Appendix C: Grating direction

Followed the conventions for grating orientation relative to transmission direction of throughput light. The top arrow should point in the direction light goes eg. toward the sensor.



Click to Enlarge
Top Image: On one edge of the grating, an arrow parallel to the grating's surface indicates the blaze direction.
Bottom Image: On the opposite edge of the grating, an arrow perpendicular to the grating's surface indicates the transmission direction.



[image from ThorLabs]

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