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FRAMSAT-1: THE FIRST NORWEGIAN SATELLITE FROM NORWEGIAN SOIL

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Abstract

In 2024, the first orbital launch from Andøya Spaceport is scheduled. This will open for new launch providers and an expected increased access-to-space capacity, especially from the European mainland. Hopefully, this also increase the capacity and opportunities for cheap access to space for university space projects. For many university projects, the launch cost is on the same order – or larger – than the monetary cost of a satellite, which often consist of "self made" parts. National and international programs and competitions like NASA ELaNa and ESA "Fly your satellite" has made the dream of reaching space come true for many young students for more than 15 years. We hope that the new launch sites – both at Andøya and at other locations – as well as the new families of launchers will lead to even more successful student and university projects being flown. In this paper, we describe the precursor mission, FramSat- 1, that slated to be onboard this first launch attempt. The idea of "the first satellite from Norwegian soil" is decades old, and now the satellite is finally built and launched/awaiting launch. FramSat-1 was officially started right after the Norwegian Government first secured the first financing of the Spaceport. The satellite is built by students from the Norwegian University of Science and Technology (NTNU), through a joint effort between NTNU, the student organization Orbit NTNU, Norwegian industry and with support from the Norwegian Space Agency. FramSat-1 is the manifestation of many projects and ideas, into what was intended to be a simple and small satellite. FramSat-1 was started during the finalization of the first satellite from Orbit NTNU, the SelfieSat, which was launched in 2022. It was intended to be a "scaled-down" copy, a decision that saw unpredicted challenges that lead to a change of scope and ambition several times. In this paper we describe the project's progress and challenges from the idea creation, the consolidation of a consortium and up to finalizing with hardware and software integration and the environmental test campaign (as well as the launch and early operations). Emphasis will be put on how the project has been maintained through changing teams and a dynamic timeline.

Acronyms/Abbreviations

Local Time of Descending Node (LTDN)
Sun-Synchronous Orbit (SSO)
Low-Earth-Orbit (LEO)
Automatic Identification System (AIS)
Attitude Determination and Control System (ADCS)
Electric Power Supply (EPS)
Random Access Memory (RAM)
Raspberry PI (RPI)
European Space Agency (ESA)
Deutsches Zentrum für Luft- und Raumfahrt (DLR)
Interface Control Document (ICD)
Thermal Vacuum Chamber (TVAC)
Operating System (OS)

1. Introduction and Background

The FramSat-1[·] is a 1U CubeSat intended to be onboard the first launch attempt by an orbital class rocket from the new launch facility at Andøya Space Port, Andøya, Norway. Historically, the rocket range at Andøya has a 60-year long history of serving sub-orbital launchers from the sub-orbital launch site "Oksebåsen", near Andenes. From 2024, the new orbital launch site is planned to be operational. Once the first orbital launch attempt is

[·] The name is a nod to the famous arctic expedition ship "Fram", used by Norwegian polar explorers from the late 1800s to the early 1900s. We also note that this is the name used for the first crewed orbital mission with the Dragon capsule later this year.

successful, FramSat-1 will enable the dream "*A Norwegian satellite launched from Norwegian soil*".

The FramSat-1 is mainly designed and built by students at the Norwegian University of Science and Technology (NTNU) as an extracurricular project. The students are volunteers in the student organization Orbit NTNU which aims to offer exciting projects for the Norwegian space engineers of tomorrow.

A Norwegian satellite on the first orbital launch from Andøya is a long-held idea for many, including NTNU, the Norwegian Space Agency, Andøya Space, and others. When the announcement of the intent of funding and construction of the launch site was confirmed by the Norwegian government in May 2020 [1], the Orbit students and NTNU took the initiative to start this project. By utilizing existing partners within the Norwegian industry and educational sector, NTNU and Orbit NTNU created an efficient consortium with the intent to build the first satellite to be launched from Norwegian soil.

Note: This paper mainly concerns the first satellite, the FramSat-1. In addition, a second "flight spare" was built, dubbed the FramSat-1.5. Some references to the FramSat-1.5 are provided, when relevant. This includes the timeline and some test activities as well as clarification of the funding.

1.1 The idea and the consortium

The micro-launchers have seen an increasing popularity in the past ten years, as a response to the maturing newspace industry and an increasing demand for launch capacity. Combined with the lack of European launch capacity both concerning launch vehicles and sites, many prospective spaceports and launch vehicle manufacturers alike have seen the dawn.

Andøya Space has been an operative rocket range for launching sounding rockets for more than 60 years. In 2023 Andøya Space officially opened as a Spaceport that aims to serve launch vehicles designed to deliver payloads up to 1.5 metric tons to Low-Earth-Orbit (LEO). Andøya Space can offer launch inclinations ranging from 87.4 to 108 degrees. These are favorable for both sun-synchronous (SSO) and polar orbits. The flightpath ensures a trajectory whose ground track does not cross populated areas. The large impact and dispersion area in the Norwegian Sea enables us to safely dispose of the spent stages.

The CubeSat community at NTNU has always had the intent to find a way to be a part of the spaceport adventure, based on the early involvement in both student-driven CubeSat projects and also research satellite projects for the past 20 years.

Even if the funding decision from the Norwegian government in May 2020 for the new spaceport was not definitive, the FramSat project was initiated during the summer of 2020. This was under the assumption that the final funding would be secured and more importantly, that there were one or more launch providers that would provide a service in the near future. The final challenge would be to secure a spot onboard the first launch opportunity. The development of the satellite itself was seen as a lesser challenge, due to the ongoing SelfieSat project with Orbit NTNU.

Figure 1 shows the overall timeline of the FramSat project, from the start up until the time of writing. To save time and resources, FramSat-1 was decided to be a scaled-down satellite based on most central sub-systems from the "SelfieSat" [2], the first CubeSat developed and launched by the Orbit NTNU students. Therefore, it was (intended to be) relatively easy for the Orbit students to build and complete the satellite within a short amount of time, the original estimate being around $1\frac{1}{2}$ years from funding was acquired in early 2021. NTNU supported the mission by providing partial funding, lab and testing facilities, as well as project management support.

To also include a more industrial perspective, the NTNU students teamed up with the Norwegian technology company EIDEL[†], which has a long history of developing high-end electronics for space and defense. EIDEL, in cooperation, with the University of Oslo (UiO) through a master's thesis project, supplied a novel high-rate solar sensor made for sounding rockets and satellites [3].

This solar sensor operates using an event-based, asynchronous topology that differs significantly from traditional sun sensors, see the payload section of this paper.

Benefiting from the historically close collaboration between NTNU and Andøya Space Education, it was possible to facilitate interaction with the rocket launcher company ISAR at an early stage. This happened just after the agreement between Andøya Space and ISAR was announced in April 2021 [4]. The NTNU team expressed a desire to "join" the first launch, and ISAR was open to discussing how this could be facilitated already from May 2021.

In parallel with these discussions, ESA and DLR announced a flight opportunity call [5]. The call was a competition for a free ride on the first orbital launch from Andøya. This was announced in early the fall of 2021. Further advances towards a launch were taken through this competition, and in December 2021, FramSat-1 was selected as one of the satellites for the maiden launch [6].

[†] `www.eidel.no`

Fig. 1. FramSat project timeline, showing several of the important processes and decision points fundamental for the project's progress, until the start of the construction of the satellite(s) itself. ASP: Andøya Space Port. NoSA: Norweigan Space Agency.

2. The short history of Norwegian CubeSats

The idea of a *"Norwegian satellite from Norwegian soil"*, aiming to exploit the technology edge of the Norwegian universities to build a student satellite as well as the potential of orbital launches from Andøya, dates back to at least 1999 [7]. This was about the same time as the advent of the CubeSats, by professors Puig-Suari and Twiggs from Cal. Poly and Stanford universities [8]. Norwegian universities were among the first to adopt the CubeSats.

2.1 The nCube satellites

From 2000 to 2006, two 1U CubeSats (nCube1 and nCube2) were developed by students at Norwegian University of Science and Technology (NTNU) in Trondheim, the Norwegian University of Life Sciences (NMBU)[‡] at Ås, University of Oslo (UiO) and The Arctic University of Norway (UiT), campus Narvik[§]. The satellites were equipped with VHF receivers intended to register Automatic Identification System (AIS)-messages from reindeer collars, enabling tracking of the animals from orbit [9, 10]. Unfortunately, none of the satellites made it into orbit successfully or confirmed manner. The nCube2 was launched first, with the larger European student satellite SSETIExpress [11] on a Cosmos 3M-rocket from Plesetsk in Russia on the the 27^{th} of October 2005. The satellite was to be deployed from inside SSetiExpress, but it was never heard from. It is uncertain when the satellite was deployed.

nCube1 was launched on the 26^{th} of July 2006, with a Dnepr-rocket from Baikonour Cosmodrome, Kazakhstan. The rocket experienced an anomaly during the main stage burn and was terminated [12]. In total, around 100 students participated in the development of the two satellites. Later, the idea of AIS-receivers in space were demonstrated by the Norwegian AIS-1 satellite in 2010, and later made a service by several service providers [13].

[‡]At the time known as Norwegian Agricultural University College.
[§]At the time known as Narvik University College.

2.2 The Norwegian Student Satellite Program - ANSAT

In the period 2007 – 2017, NTNU was partaking in the Norwegian National Student Satellite Project (ANSAT), managed by NAROM, the Norwegian Center for space-related education[¶] [14–16]. Participants were Narvik University College and UiO, with their HiNCube[17] and CubeStar[18] satellites, respectively. The NTNU team aimed at building a 2U CubeSat, the NTNU Test Satellite (NUTS). Around 80 students worked with NUTS during the project period. The project was led and driven by NTNU staff, but the students were organized in a volunteer student organization with their management and budget. Most of them carried out their project and master theses as part of the project [16, 19–21].

In 2017, the development of the NUTS-satellite was canceled, and the team structure was changed. Students could now join the organization from their first or second year of study. This counteracted the dramatic turnover by having only students involved for one year. The student then could contribute over several years compared to the previous organizational form where most students contributed during their fifth year. This re-organization enabled more long-term commitment and gave a better organizational structure. The volunteer student organization was re-branded into "Orbit NTNU"[‖].

Eventually, only the HiNCube [17] was launched but never made contact with. However, all three projects made a mark. The high-rate multi-Needle Langmuir Probe (m-NLP) payload from CubeStar was further developed and integrated into several satellites [22]. At NTNU, the Orbit NTNU organization found its form, and the NTNU Small Satellite Lab[††] was established for research satellite activities. Their HYPSO-1 was successfully launched on the 13^{th} of January 2022 [23, 24] and is now operational. The follow-up, the HYPSO-2, was launched in August of 2024. There are also CubeSat projects at other universities today.

[¶]Now known as Andøya Space Education
[‖]`http://www.orbitntnu.com`
[††]`www.ntnu.edu/smallsat`

3. FramSat-1 mission objective and design

The FramSat-1 can be said to be a scaled-down version of the "SelfieSat" which was launched 25^{th} of May 2022. The development was managed by the Orbit NTNU students with the following project objectives.

3.1 Primary objectives

The primary objectives reflect the main goal of the project, as well as the desire to put a working satellite, based on an in-house design, into orbit. The primary objectives remain unchanged since the project started.

1. FramSat-1 should become the first Norwegian satellite launched from Norwegian soil.
2. FramSat-1 should demonstrate the satellite bus developed by Orbit NTNU.

3.2 Original secondary objectives

As FramSat was delayed, and Orbit NTNU as an organization changed, the secondary objectives were updated during the project. The original objectives below were decided in early 2020 but were later iterated in 2021.

1. EIDEL and UiO shall deliver a newly developed sun sensor that is to be integrated by Orbit NTNU.
2. At least one solar panel is developed by Melkelle University in Ethiopia and integrated in the satellite bus by Orbit NTNU.

Some of the project members were in contact with Mekelle University and wanted to establish cooperation. The objective was a nice-to-have so if Mekelle was not able to deliver, it would not impact the development of the satellite. Tragically, the project with Mekelle came to an abrupt end, with the start of the Tigray war in November 2020.

3.3 Current secondary objectives

After both the changes in the situation with Mekelle and other changes in the organization, the secondary objectives were changed. These are still valid:

1. Successfully integrate the EIDEL sun sensor and validate EIDEL experimental sun sensor.
2. Enable students to get in contact with space-related industry and gain experience with engineering methods and standards that are applied in the space engineering field.

Justification of objectives: At the time of definition, the SelfieSat had not yet been launched so Orbit NTNU had yet to prove its satellite design. So, the FramSat-1 second main objective was thus the same as the main objective of the SelfieSat: to demonstrate the satellite design developed by Orbit NTNU. Successful demonstration of the bus was consequently given less priority after the SelfieSat became partly operational in the late summer of 2022.

The inclusion of the EIDEL sun-sensor was made to increase the chances of receiving funding from Norwegian Space Agency (NoSA), which viewed industry participation as a main pillar for providing monetary support to the project. The inclusion of a partner from the industry also further anchored the project as a national endeavor and not just a NTNU initiative.

3.4 Concept of operations

To relax the work and resource demands, the mission was devised to be simple to carry out, also since the orbital lifetime may be relatively short. The final orbital parameters are not confirmed, but it is assumed that the orbital height will be between 300 km to 500 km, in an Sun-Synchronious Orbit (SSO), with an at the time un-known Local Time of Decending Node (LTDN). For FramSat-1, the LTDN does not have any impact of the mission utility.

After the launch and following the insertion into orbit, the satellite would deploy the UHF antennas and start transmitting beacons. As soon as contact between the satellite and the ground station is established the satellite would be tasked with collecting data from the EIDEL and the reference Gomspace sun-sensors. The collected data would be transmitted to the ground during ground station passes over Trondheim or KSAT's ground stations at Svalbard. The data would then be compared on the ground to analyze the performance of the novel EIDEL sensor in comparison to the COTS Gomspace sensor.

4. The FramSat-1 System Design

The FramSat-1 system design is based on the previously developed satellite SelfieSat thus which defined most of the baseline design. The most notable change to the FramSat-1 bus compared to the SelfieSat design was "compressing" the satellite from a 2U to fit a 1U. The desire to reduce the size of the satellite was motivated by the high uncertainties related to project funding and launch opportunities, as this was defined before the launch opportunity call (see Fig. 1).

A small size should ensure launch costs are kept at a minimum and that the small size would allow the satellite to be fitted inside a deployer with other satellites. A 1U satellite would also reduce hardware costs for solar panels and the satellite frame itself.

From a technical perspective, this was already at the start of the project seen as a challenge and perhaps a risk

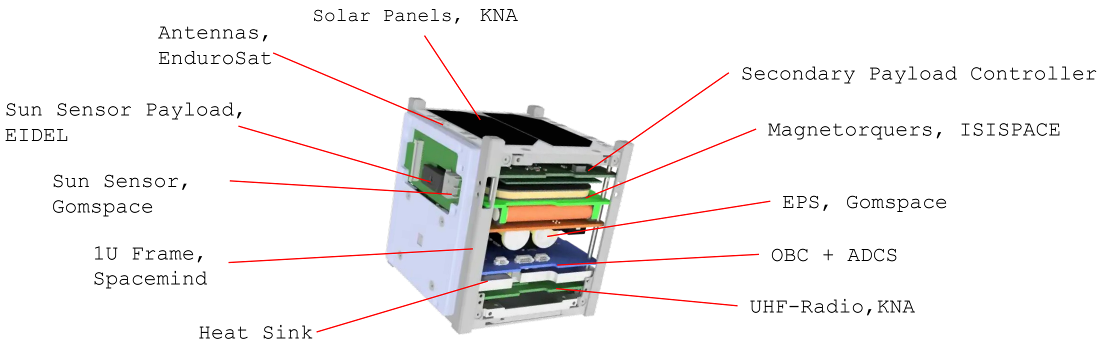

Fig. 2. FramSat Subsystem Overview. FramSat is a scaled-down version of the 2U SelfieSat.

for the operational viability of the satellite. Notably, the reduction of solar panels means that the design is barely power-positive, which in turn leads to the OBC and ADCS-systems having to run on the same computer board to save volume and energy. This is further discussed in the Lessons Learned section in this paper.

4.1 Satellite bus

The FramSat-1 bus and consequently the SelfieSat bus consist of a set of subsystems defined below. The bus is a conventional CubeSat design designed in-house by Orbit NTNU, combining both COTS and in-house built subsystems, see Figure 2.

1. **OBC** - On-Board Computer, developed by Orbit NTNU. It is based on affordable COTS components and an in-house developed OS called ErlendOS, named after the creator.

2. **ADCS** - Attitude Determination and Control System (ADCS). Software and control system designed and developed on the same hardware and OS as the OBC. The ADCS was intended to run an in-house designed Extended Kalman Filter, EKF, using five sun sensors, two three-axis gyroscopes, and two three-axis magnetometers. The control system consisted of a magnetorquer from ISISPACE, the Netherlands, and an in-house developed PD-controller. For SelfieSat, this was implemented on a separate PCB, for FramSat-1 it was the intention that the OBC should run the ADCS functionality.

3. **EPS** - The Electrical Power System was purchased from GomSpace, Denmark. It consisted of two 8 V batteries with a total of 20 Wh capacity and a photovoltaic power conversion up to 30 W. The solar panels were from Kongsberg NanoAvionics, Lithuania.

4. **SatCom** - Satellite Communications, is ensured by a UHF system in the HAM radio band, based on an SAT2RF1-1B radio module from Kongsberg NanoAvionics, Lithuania, with a HAM radio stack developed by Orbit NTNU. The deployable antennas, model UHF Antenna III, were purchased from Bulgarian EnduroSat.

5. **Payload Controller** - The payload controller was developed in-house using a Raspberry Pi, with the RPI-OS.

6. **Mechanical Frame** - The 1U-Frame was purchased from Spacemind, Italy. All other mechanical components were designed in-house.

4.2 How to down-scale a bus

The restructuring of the bus into the 1U format led to several changes. Due to the ”merge” of the OBC and the ADCS processor cards, the team met several challenges. The lack of available RAM had been a problem for both the OBC and the ADCS subsystems on the SelfieSat. The ADCS system on the FramSat-1 was thus quite restricted by the processing hardware. The lack of a middle frame also made it unfeasible to attach sun sensors outside of the payload face which further restricted advanced attitude control.

This meant that the satellite did not have the means to execute controlled sun-pointing. To meet the objective of delivering test data for the EIDEL sun sensor, sun-pointing events would be required. Several strategies were investigated and partially simulated, such as relying on uncontrolled rotation to ensure that the payload would eventually point toward the sun. In addition, an effort to achieve a more reliable semi-random rotation based on attitude control utilizing movement to the ”tennis racket principle” [25] was investigated. The objective of both strategies was to ensure that the sun-sensors face the sun at an arbitrary time. Ultimately, the effort to implement the tennis racket theorem had to be canceled due to both on-board resources as well as lack of personnel.

4.3 Payloads

The FramSat-1 is equipped with two payloads. The first is an in-house developed camera module equivalent to the secondary SelfieSat payload with two Raspberry Pi cameras, in addition to the novel sun sensor from EIDEL and UIO.

4.3.1 RPI camera

The camera was mounted on the payload face so it also could be used to confirm if the sun-sensor was pointing towards the sun during testing. Because of the aforementioned RAM issues, the camera payload software had to be removed and is currently not planned to be operated in orbit even if the hardware is in place.

4.3.2 Industrial hosted payload

EIDEL, in cooperation with the University of Oslo (UiO), supplied a novel high-rate solar sensor made for sounding rockets and satellites [3]. Traditional sun-sensors typically measure the accumulated charge of each pixel over a fixed time period, producing continuous data readouts. In contrast, EIDEL’s novel sun sensor employs individual pixels acting as ”masters” that trigger events asynchronously once they accumulate a threshold amount of charge from photon exposure. Each event corresponds to a specific pixel sending its address via an asynchronous data bus, significantly increasing the sensor’s temporal resolution and allowing it to react much faster to changes in light conditions.

With an expected data output rate of 11,000 events per second in direct extraterrestrial sunlight, the sensor is particularly well-suited for high-speed, dynamic environments such as space missions. This high data rate allows for the detection of minute changes in illumination and angular position, enabling more precise attitude determination for satellites and sounding rockets. The design is compact and optimized for low power consumption, making it a valuable tool in space applications where size, weight, and energy efficiency are crucial factors. Moreover, the sensor’s asynchronous nature reduces the need for constant polling, allowing systems to process data more efficiently [3].

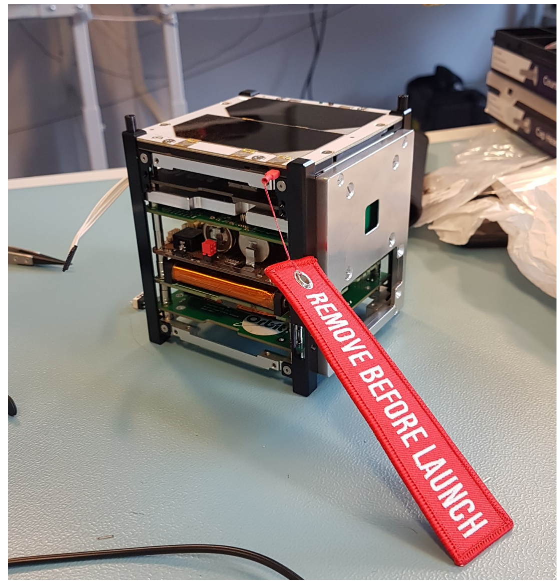

Fig. 3. First full FRAMSat-1 test assembly, 28.09.2021

4.4 Funding

The satellite and launch were in part funded by many different actors. The satellite bus was mainly funded by NTNU and NoSA, with Orbit contributing with their in-house developed systems. EIDEL provided the reference sun sensor and development hours for the readout system for the industry sun sensor, while UiO provided the actual sensor ASIC from an earlier proof-of-concept tape-out.

Andøya Space Education also funded a substantial part of the FramSat project. This was through their project “Space Education 2.0” (SE 2.0). The aim of SE 2.0 was to determine how the new spaceport at Andøya could open new opportunities for higher education in Norway and Europe. How to provide launches through the work package *Access to Space* has been one of the initiatives that have been supported. Through this activity, Andøya Space Education supported FramSat-1 by covering the launch-pod costs and vibration testing at Andøya. For FramSat-1.5 the launch pod cost was covered.

In-kind contributions from industry and also the ESA Fly Your Satellite! program contributed to environmental testing. The launch itself (for both satellites) is funded by ESA and DLR through their flight opportunity call.

5. Assembly and Testing

As with all satellites, the FramSat-1 was subject to test campaigns to prove flightworthiness after assembly. Figure 3 shows the first test-assembly. Testing is required both to ensure verification of functionality as well as necessary environmental tests as defined by the launch provider. Figure 4 shows the progress and milestones for the later stages of the project.

Several test campaigns were planned and conducted. As part of a contribution to the project (see the section on funding), Andøya Space invested in an upgrade of their shaker table for it to be used for vibration tests.

5.1 FramSat-1 assembly

FramSat-1's final assembly took place the week before its first environmental test campaign, with the Orbit NTNU team assembling the satellite between 13.02.23 and 16.02.23. The assembly team consisted of two mechanical engineers and one electrical engineer, supported by the project manager. Despite facing time pressure due to the tight schedule, the team managed to follow the established checklists effectively, ensuring that the assembly was completed on time and according to specifications.

5.2 Function testing and verification

Development and tests are often carried out in parallel for university systems, often with success. However, it is important to strive for integrated end-to-end tests as soon as possible, to exclude any integration and/or ICD discrepancies at an early stage [26]. For FramSat, the lack of complete integration and early system tests became an issue: Individual sub-systems and parts of payload functionality ended up being tested individually, and therefore it seemed like the software for the satellite was (almost) finished at an early stage. However, when the software integration was finally carried out, the aforementioned RAM issue surfaced and it became clear that even if all parts of the satellite were individually, a full software integration was not possible and this is still undergoing development.

5.3 Environmental testing

FramSat-1 has undergone two environmental tests: random vibration, and thermal vacuum (TVAC) test. The random vibration test was performed at Andøya in the spring of 2023, and TVAC testing was done at Kongsberg Gruppen at Kongsberg, in March 2022.

5.3.1 Engineering model TVAC

The TVAC test was performed on engineering versions (EM) of the hardware before the final assembly of a flight model. The purpose of the was mainly to ensure that the satellite design could handle transmitting data over UHF continuously over 12 minutes without overheating. The 12-minute duration was chosen since it is equal to the expected maximum time the satellite would pass over a ground station. The test was also performed for educational purposes as TVAC testing of the SelfieSat had previously been successful. The test was successful and confirmed that the more compact FS-1 design did not pose any new issues in terms of overheating during radio operations.

The Orbit students were supported by Kongsberg during the tests, and also the research team at the NTNU SmallSat Lab in preparation for the tests. Although four thermal cycles were planned, the team was only able to complete two. This was the minimum requirement, and the test campaign was therefore considered successful.

5.3.2 Random Vibration

The random vibration test campaign was carried out the week after the final assembly. As stated in the Funding section of this paper, Andøya Space was to provide the test facilities. Due to a lack of internal communication amongst the team, the Framsat team also applied for and got accepted for the ESA Fly! test program. Unfortunately, the team had to withdraw from the ESA test campaign for FramSat-1 for two reasons; to honor the agreement with Andøya as well as that the object for the test was not ready in time (see lessons learned).

The test campaign took place from 20.02.23 to 23.02.23, approximately a year after the first TVAC test. FramSat-1 was tested on all three axes and two non-conformances were discovered.

The first anomaly was that two screws came loose during testing of the Y-axis. This followed the successful completion of testing the Z-axis. These screws were for the EIDEL payload and had not been glued properly. The reason was found to be miscommunication between the project management team and the assembly team. The screws were put back in place and taped down to be able to conclude the test. They were to be glued upon return to Trondheim, and the anomaly was concluded as a *non-critical* failure.

The second non-conformance was software-related, and no solution was found during the test campaign. During the functionality checks between test series, it was discovered that the EPS was not able to communicate through the I2C bus. To fix this, a disassembly was needed.

FramSat-1 was fully disassembled the 21.03.23. During inspection and debugging, it was found that the 3V3-power rail saw a 5 V voltage. Finally, it was concluded that a component that not was intended for the flight version of the hardware had been placed and soldered due to a mistake. This particular component was intended for earlier versions of the OBC but was not meant to be mounted for the flight version. Following this finding, the component was removed.

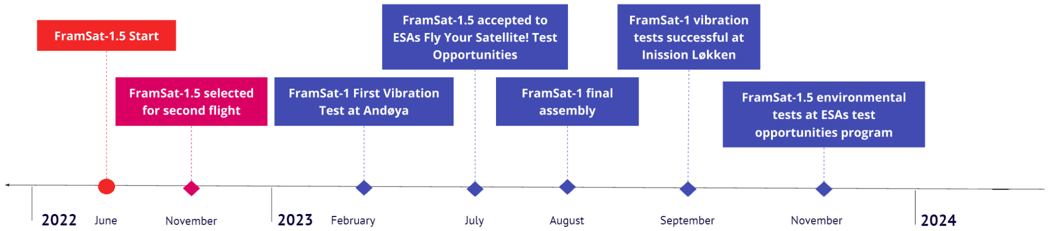

Fig. 4. FramSat project timeline, showing the progress and development of the satellite(s).

5.3.3 A second vibration test

Isar Aerospace was included in the non-conformance handling and advised the Orbit team to re-test the satellite, applying qualification levels and acceptance durations. Consequently, a new qualification random vibration test for the re-assembled satellite was performed in August 2023. This time at Inission's facilities at Løkken Verk, outside Trondheim. All test items were successfully completed this time, and there were no unexpected events.

5.3.4 FramSat-1.5 testing

FramSat-1's twin, FramSat-1.5, was tested through the ESA Fly Your Satellite! program in a two-week test campaign from 6.11.23 to 17.11.23. The satellite underwent random vibration testing during the first week to the same specifications as FramSat-1, and TVAC testing during the second week. See Figures 5, 6. This time, one non-conformance item was discovered. FramSat-1.5 was found to be too wide in the X+ plane, leading to the need for the test pod to be able to complete the shaking.

FramSat-1.5 will be re-assembled and re-tested during the fall of 2024. Overall, the testing and assembly of FramSat-1 and its twin satellite, FramSat-1.5, was critical in identifying and addressing key issues, ultimately ensuring that both satellites are well-prepared for their respective missions.

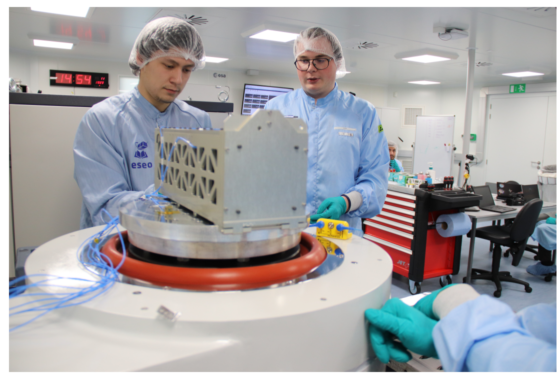

Fig. 5. FramSat-1.5 inside a test-pod on a shaker.

Fig. 6. FramSat-1 in a vacuum chamber prior to a test.

6. Lessons learned

Even if FramSat-1 was intended to be a "very simple project", in the end, it became evident that it was not the case. A selection of lessons learned, both from a technical side and organizational perspective is presented in the following.

6.1 FramSat, a down-scaled SelfieSat

FramSat was developed based on a scaled-down model of SelfieSat. Unfortunately, this led to unforeseen implementation and integration consequences. Some, which maybe could have been identified earlier with a proper risk analysis.

6.1.1 The operating system

A significant factor contributing to this issue was the use of the custom-built *Erlend OS* [27]. This started as a hobby project by a former Orbit NTNU member. At an early stage, it was decided to attempt to use Erlend OS for SelfieSat, and thus, consequently, for FramSat-1. Erlend OS lacks certain functionalities, such as multi-threading and synchronization/memory protection to avoid race conditions. Resulting, this requires complex workarounds to achieve the desired results. Additionally, the ADCS system demands extensive calculations, further straining the system's resources. The build-system and how subprograms are organized and flashed also is constrained and different compared to other more common operating systems. The OS also loads all programs from persistent memory into RAM at run-time. This leads to a much higher demand of RAM, compared to other OSs.

6.1.2 Joining the OBC software and ADCS software

An early decision was made to attempt integration of the ADCS software on the onboard computer (OBC), primarily motivated due to a limited power margin. At the same time, as part of risk mitigation defined under the initial project review. it was determined the ADCS functionality was "nice to have". ADCS should be removed if any major issues or development delays occur.

However, due to delays in the software development process, the ADCS development was continued even if it faced major challenges and ADCS design changes. Due to insufficient software integration testing it was not discovered until after the final assembly was completed that the RAM capacity was exceeded. FramSat could not run both the main programs for the OBC and the ADCS programs simultaneously. Finally, it was concluded that including any ADCS implementation was infeasible.

The initial design rationale of defining ADCS as a "nice-to-have" was lost to the design team over the years. This happened partly due to turnover and also a lack of documentation. Therefore, in the following years, this was taken into consideration. As a result of this loss of rationale, the problems faced with the ADCS development was not properly evaluated and removed.

The impossible development effort thus caused a significant development delay and reduced team motivation when it was (re)-discovered by a new team that the work they had performed could not be included in the satellite after all. Some of the lacking documentation routines are mentioned in subsection 6.4.

6.1.3 Software re-design

Additionally, the preceding SelfieSat mission also experienced design problems due to limited RAM. This called for a redesign of the OBC software. The core design problem was not communicated to the FramSat project group, even if the satellite was using the same OBC platform, with an intent to accommodate an increased processor workload.

This could partially be mitigated by establishing a design problem register based on the SeflieSat design problem register as a basis. This may have aided the identification of the issues, and most likely limited the impact of the RAM problem. The consequence was instead a very delayed SW development caused by the organic problem discovery very late in the project cycle.

6.1.4 A new software attempt?

Currently, the team is considering whether there is sufficient time to replace ErlendOS with the Zephyr operating system. Zephyr will be used in other satellite projects within the organization, meaning that there is already a solid foundation of expertise available to support this transition. The embedded team also assesses that changing to Zephyr will make it easier to resolve the bugs the team is struggling with now. The unsure aspects are whether time will allow us to do this, and ensuring that changing operating systems leave us with so many tasks that it would be easier to resolve original the issues at hand instead. The decision has not yet been taken, as more analysis needs to be done before making such a large change.

6.2 The project's foundation in the organization

The organizational growth of Orbit NTNU has also affected the progress of the FramSat project. From 2021 to 2023, Orbit grew from 60 to 120 members. Tight deadlines for Orbit's projects resulted in reduced training for many of the new personnel. Consequently, multiple of the new members did not have the training required to work on the FramSat project. Senior team members therefore experienced a higher work pressure. This led to decreased motivation for some key members and therefore reduced morale in periods.

Overall, the project has faced periods with varying foundation within the Orbit NTNU organization. During 2022 and early 2023 when the project was delayed multiple times and the issues with RAM were at high intensity, the overall motivation was relatively low. Many teams were also split into a few persons working on FramSat-1, and most members on Orbit's new project, the BioSat.

Today the situation has improved significantly as many team leaders are good at involving the whole team in discussions or work around FramSat. The foundation for the FramSat satellites sees a better situation in the organization now, compared to the past years. This is probably also helped by that the satellites are nearing completeness and launch.

6.3 Management

The FramSat project spans several generations of team members, including several management groups. There is therefore regularly need to train new leaders. In general, it is a heavy task to assign a student to become a project manager for a satellite project, since this is not what the general student would be experienced in. To support new leaders, considerable time and effort should be put into allowing them to learn about both management and the necessary technical aspects of the project. Tight deadlines within Orbit lead to a decreased ability to follow up with the project managers, and also affected the training of new leaders in the organization.

It is theorized that a primary part of the problem stems from the fact that a focus on team management and support was not a core value imparted to the management. As a result, management of workload, project coordination, and support for leaders were less prioritized. One tool that has worked well for onboarding new project managers and leaders, is discussion forums between the previous and new leaders. The session provided valuable support and guidance on how to move forward with projects. It offered training and created a safe space for learning and collaboration.

6.4 Communication and documentation

Teams spanning a large number of members from broad backgrounds and levels of experience require a well-selected range of tools for communications and documentation. This includes both the day-to-day informal (or formal) communications within or across teams and between teams and management, but also how to formalize proper curating of design documents of all sorts.

6.4.1 Slack

Slack has been an essential tool for communication within Orbit by centralizing discussions and making collaboration more efficient. It allows for real-time messaging across various channels dedicated to specific teams, projects, or tasks, which helps reduce email clutter and ensure quick access to relevant information. Slack's search functionality allowed users to retrieve past conversations, documents, or decisions efficiently, providing easier access to historical data. Additionally, the platform supported file sharing, which facilitated the exchange of documents within the same communication space. The use of threaded discussions helped maintain organization within channels by keeping related conversations grouped, contributing to greater clarity in ongoing discussions.

However, Slack also introduced challenges. With many channels and constant notifications, it often led to information overload, making it difficult for team members to keep track of important messages. The real-time nature of Slack could also cause distractions, hindering deep focus and productivity. Important communications were sometimes buried in informal chats, leading to misunderstandings or overlooked information. Proper guidelines were necessary to mitigate these issues and ensure Slack was used effectively.

6.4.2 Meetings

Each team in Orbit had responsibility for their expertise in the different projects. Once a week all teams gathered to work at the same time. These workshops enabled the teams to work together interdisciplinary and to find solutions for FramSat that could affect the different teams' work. "Big Workshops" made communication easier since all members were gathered in the same room. This can be compared with having core working hours in a normal job. Since Orbit consists of students building satellites in their spare time, the time working simultaneously is limited. In addition to the "Big Workshops", each of the teams had their separate workshops. Having dedicated time slots for working with FramSat and the other projects in Orbit, ensured progression and follow-up on their work.

Involving external stakeholders Biweekly meetings with externals (NTNU, EIDEL, Andøya, ISAR) was fundamental to to update everyone involved on the project's progress. This was also a forum for sharing experiences and issues and served as a meeting place to get help and tips on issues raised. For the Orbit team members, it has been a great work opportunity closely with experienced engineers and scientists on how they have handled similar issues previously.

Leadership meetings In these meetings, all team leaders presented their progress and plans for the upcoming week, which were valuable for coordinating efforts and providing a clear overview of the project status. These meetings were also used to give important information from the top management of Orbit to the rest of the teams.

An approach that may have further strengthened these meetings could be if project managers take a more active role in guiding these meetings. This could have transformed the gatherings into a platform for not only reviewing progress but also presenting and discussing project plans in greater detail, as well as exploring opportunities for enhancing inter-team collaboration. However, this would have increased the meeting duration, which is why it was not implemented yet.

6.4.3 Documentation

Google Drive is used by Orbit for managing internal documentation. All members have access and editing rights, making it easy to find project-related information. Google Drive is commonly used by students at NTNU making the platform easy to use. However, new documents are often added, or existing ones are updated without proper revision logging. In some cases, instead of updating an existing document, a new copy was created, leading to confusion about which version was the most current. This has resulted in uncertainty and loss of traceability, often requiring team members to contact the subsystem owners to determine which document is valid. A solution to this issue could be to establish a strong documentation culture, supported by clear revision management standards. This could include mandatory training and verification steps each time a document is revised.

For project management documentation and NTNU-related documents, Microsoft Teams was used. This is the primary allowed platform for data sharing for NTNU. Fewer people had access to these files compared to those on Google Drive. Managing documentation across two platforms made it difficult to keep files synchronized and up-to-date in both locations when necessary.

Another issue we faced with documentation was the assumption that since FramSat was based on SelfieSat, much of the necessary documentation for the project did not need to be created separately for FramSat. This assumption that the projects were similar enough, led to gaps in FramSat's documentation. Even when issues arose that required modifications, updates were never made because the documentation had not been created in the first place. This problem can largely be attributed to Orbit being a relatively new organization comprised of inexperienced members, unfamiliar with the importance of thorough documentation practices from the start. Revision logging has since been a highlighted theme in the organization.

6.5 The impact of project delays

The delays (both from external factors and also internal factors) significantly impacted and are still impacting both the technical progress and team dynamics of FramSat-1. Initially planned for completion within 1.5 years, unforeseen challenges in design and implementation, particularly with the ADCS system, caused setbacks. The most significant delays came from the uncertainties regarding the launch date. These external delays led to short-term plans rather than good long-term plans, rushed testing, and the need to reprioritize certain features. Additionally, the prolonged timeline strained team morale and disrupted knowledge transfer, further complicating the project's execution. One example is that it is challenging to foster motivation to work with ErlendOS. The OS is not maintained any longer, nor does it have a user base outside of Orbit. Therefore, some of the team members working with it feel that it is not relevant or something they want to learn.

6.6 Having multiple projects at the same time

In 2022 and 2023, Orbit's leadership focused on emulating the structure and processes of a professional organization. The aim was to adopt tools, guidelines, and methodologies similar to those used by established companies, as well as by organizations like ESA and NASA. This approach resulted in the work sometimes becoming more complex than necessary. It did however lead to an improvement in how Orbit documents decisions and design. But the effective implementation across the organization still saw some shortfalls, as explained above.

After the launch of SelfieSat in May 2022, there was room to initiate a new project, the BioSat. The thought of having parallel projects was initiated to ensure a student could get experience within the whole process from designing to operating a satellite. For example, this way, a mechanics student could work on the design of BioSat one month, and then the assembly of FramSat-1 the next. This strategy did place a higher work burden on some teams, especially the smaller ones.

Another strategy of limiting the development of new components to a minimum, as opposed to developing a full satellite design, could have been an effective middle ground between improving and maintaining ongoing satellite projects and initiating new initiatives. This strategy was partially implemented with the early and comprehensive design process surrounding a new OBC which was initiated during spring 2022.

7. Future mitigation strategies and changes to meet the original vision

While this topic deserves separate and extensive analysis, some observations can be made. The original intention of FramSat as a bus with significant heritage from SelfieSat was risky and premature, as the SelfieSat design was not stable. This could have been handled by delaying FramSat-specific SW development until the SelfieSat SW reached an MVP state, opening for SW reuse in combination with early design and prototyping of other components, such as the electrical and mechanical system components.

Concurrent projects are likely beneficial for a continuous organization with high turnover. Parts of the FramSat development and the following satellite development provide clues to the successful implementation of concurrent projects. Strictly allocating most resources to the established and ongoing missions would secure long-term continuation and a more reliable increase, instead of a decrease, in development speed and total team capacity for these projects. This strategy could also slow the development of the most recent project, slowing the transition from one satellite mission to the next while sustaining overlap that facilitates knowledge transfer.

The successful implementation of such an operating scheme depends on at least two factors, as in Orbit's case. Recruitment is done at known times during the year, with one fall recruitment and supplementing recruitment during the spring. These events provide regular and known opportunities for resource allocation that can set good fundamental conditions for handling ongoing projects.

Continuing to support and strengthen the management team and team leads and refocusing towards maximizing benefits from ongoing missions could set the conditions for successful resource management throughout the year, including setting the right expectations and team culture for this goal.

8. Conclusions

The FramSat project has met many challenges and setbacks during development. However, the mission is positioned to meet the original primary objective of having an academia-industry collaborative satellite ready for the first rocket launch from Norway. It has provided countless learning opportunities for Orbit's members, and many lessons will hopefully be brought on to Orbit's future projects. Many of the core challenges persist. The turnover of members will never end, so the focus and ambitions of the organization (especially the board) may influence how technical challenges are tackled in the future. If properly disseminated across the whole Orbit NTNU organization, the lessons learned from the FramSat projects may strengthen the team and culture.

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