SED

Student Experiment Documentation

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Mission: BEXUS 26

Team Name: TUBULAR

Experiment Title: Alternative to AirCore for Atmospheric Greenhouse Gas Sampling

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CHANGE RECORD

Version	Date	Changed chapters	Remarks
0	2017-12-20	New Version	Blank Book 2017
1-0	2018-01-15	All	PDR
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1-2	2018-03-07	2.1, 2.3, 2.4, 2.5, 3.5, 4.1, 4.4, 4.6, 4.8, 5.2, 6.1.4, 6.2, 6.3, 6.4, appendix: B, C.	
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Abstract: Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are three main greenhouse gases emitted by human activities. Developing a better understanding of their contribution to greenhouse effects requires more accessible, flexible, and scalable air sampling mechanisms. A balloon flight is the most cost-effective mechanism to obtain a vertical air profile through continuous sampling between the upper troposphere and the lower stratosphere. However, recovery time constraints due to gas mixture concerns geographically restrict the sampling near existing research centers where analysis of the recovered samples can take place. The TUBULAR experiment is a technology demonstrator for atmospheric research supporting an air sampling mechanism that would offer climate change researchers access to remote areas by minimizing the effect of gas mixtures within the collected samples so that recovery time is no longer a constraint. The experiment will include a secondary sampling mechanism that will serve as reference against which the proposed sampling mechanism can be validated.

Keywords: Balloon Experiments for University Students, Climate Change, Stratospheric Air Sampling, AirCore, Sampling Bags, Greenhouse Gas, Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O).

Contents

PREFACE

The Rocket and Balloon Experiments for University Students (REXUS/BEXUS) program is realized under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB). The Swedish share of the payload has been made available to students from other European countries through a collaboration with the European Space Agency (ESA).

EuroLaunch, a cooperation between the Esrange Space Center of SSC and the Mobile Rocket Base (MORABA) of DLR, is responsible for the campaign management and operations of the launch vehicles. Experts from DLR, SSC, ZARM, and ESA provide technical support to the student teams throughout the project.

The Student Experiment Documentation (SED) is a continuously updating document regarding the BEXUS student experiment TUBULAR - Alternative AirCore for Atmospheric Greenhouse Gas Sampling (TUBULAR) and will undergo reviews during the preliminary design review, the critical design review, the integration progress review, and final experiment report.

The TUBULAR Team consists of a diverse and inter-disciplinary group of students from Luleå University of Technology's Masters programme in Atmospheric Studies, Space Engineering, and Spacecraft Design. The idea for the proposed experiment stems from two concerns over the realities of climate change as a result of human activity coupled with the complexity and limitations in obtaining greenhouse gas profile data to support climate change research.

Based above the Arctic circle in Kiruna, Sweden, the TUBULAR Team is exposed to Arctic science research with which it will interact with in order to produce a research detailing the air sampling methodology, measurements, analysis, and findings.

File Naming

The naming convention for the SED is as follows:

- BX for BEXUS or RX for REXUS, plus number of flight
- Experiment name
- SED, plus version (e.g. 3 for CDR) and issue number (beginning with 0 and increasing number when a new issue is sent)
- Date of issue in format ddmmmyy

e.g. BX26_TUBULAR_SEDv1-0_15Jan18.pdf

Acknowledgements

The TUBULAR team wishes to acknowledge the invaluable support received by the REXUS/BEXUS organizers, SNSB, DLR, ESA, SSC, ZARM, Esrange Space Centre, and ESA Education. In particular, the team's gratitude extends to the following project advisers who show special interest in our experiment:

- **Dr. Rigel Kivi**, Senior Scientist at the Finnish Meteorological Institute (FMI). A key project partner, Dr. Kivi's research and experience in Arctic atmospheric studies serves as a knowledge-base reference that ensures proper design of the experiment.
- **Dr. Uwe Raffalski**, Associate Professor at the Swedish Institute of Space physics (IRF) and the project's endorsing professor. Dr. Raffalski's research and experience in Arctic atmospheric studies serves as a knowledge-base reference that ensures proper design of the experiment.
- **Dr. Thomas Kuhn**, Associate Professor at Luleå University of Technology (LTU). A project course offered by Dr. Kuhn serves as a merited university module all while providing the team with guidance and supervision.
- **Mr. Olle Persson**, Operations Administrator at Luleå University of Technology (LTU). A former REXUS/BEXUS affiliate, Mr. Persson has been providing guidance based on his experience.
- **Mr. Grzegorz Izworski**, Electromechanical Instrumentation Engineer at European Space Agency (ESA) in the Engineering Services Section, ESTEC Test Centre Division, Mechanical Department with is within the Directorate of Tech, Eng. Quality. Mr. Izworski is the team's mentor supporting design and development of the project to ensure launch success.
- **Mr. Koen Debeule**, Electronic Design Engineer at European Space Agency (ESA). Mr. Debeule is the team's supporting mentor.

1 Introduction

1.1 Scientific Background

The ongoing and increasingly rapid melting of the Arctic ice cap has served as a reference to the global climate change. Researchers have noted that "the Arctic is warming about twice as fast as the rest of the world" [8] and projecting an ice-free Arctic Ocean as a realistic scenario in future summers similar to the Pliocene Epoch when "global temperature was only 2–3°C warmer than today" [1]. Suggestions that additional loss of Arctic sea ice can be avoided by reducing air pollutant and CO_2 growth still require confirmation through better climate effect measurements of CO_2 and non-CO_2 forcings [1]. Such measurements bear high costs, particularly in air sampling for trace gas concentrations in the region between the upper troposphere and the lower stratosphere which have a significant effect on the Earth's climate. There is little information on distribution of trace gases at the stratosphere due to the inherent difficulty of measuring gases above aircraft altitudes.

Trace gases, are gases which makes up less than 1% by volume of the Earth's atmosphere. They include all gasses except Nitrogen, and Oxygen. In terms of climate change, the main concern of the scientific community, focuses on CO_2 and CH_4 which make up less than 0.1% of the 1%, and are referred to as Greenhouse gases. Greenhouse gas concentrations are measured in parts per million (ppm), and parts per billion (ppb). They are the main offenders of the greenhouse effect, released by human activity as they trap heat into the atmosphere. Larger emissions of greenhouse gases lead to higher concentrations of those gases in the atmosphere thus contributing to climate change.

1.2 Mission Statement

There is little information on distribution of trace gases at the stratosphere due to the inherent difficulty and high cost of air sampling above aircraft altitudes [1]. The experiment seeks to contribute to and support climate change research by proposing and validating a low-cost air sampling mechanism that reduces the current complexities and limitations of obtaining data on stratospheric greenhouse gas distribution.

1.3 Experiment Objectives

Beyond providing knowledge on greenhouse gas distributions, the sampling obtained from the experiment will serve as a reference to validate the robustness and reliability of proposed sampling system through comparative analysis of results obtained with a reference sampling system.

The primary objective of the experiment consists of validating the proposed sampling system as a reliable mechanism that enables sampling of stratospheric greenhouse gases in remote areas.

The secondary objective of the experiment will be to analyze the samples by both systems in a manner that will contribute to climate change research in the Arctic region. The trace gas profiles to be analyzed are that of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

1.4 Experiment Concept

The experiment seeks to test the viability and reliability of a proposed cost-effective alternative to the The AirCore Sampling System. The AirCore Sampling System consists of a long and thin stainless steel tube shaped in the form of a coil which takes advantage of changes in pressure during descent to sample the surrounding atmosphere and preserve a profile (see Figure 29 in Appendix A). Sampling during a balloon's descent phase will result in a profile shape extending the knowledge of distribution of trace gases for the measured column between the upper troposphere and the lower stratosphere [3]. The proposed experiment will consist of two sampling subsystems: a conventional implementation of AirCore as described above, henceforth referred to as CAC, and a proposed alternative, henceforth referred to as Alternative AirCore (AAC).

The proposed AAC system is primarily motivated by the CAC sampling mechanism lacking flexibility in choice of coverage area due to the geographical restriction imposed by the irreversible process of gas mixing along the air column sampled in its stainless tube. Because of this, the sampling region for the CAC system needs to remain within proximity to research facilities for post-flight gas analysis. The AAC sampling system is a proposed alternative configuration to the CAC sampling system that has been designed to address this limitation all while improving cost-effectiveness. The AAC sampling system consists of a series of small independent air sampling bags (see Figure 30 in Appendix A) rather than a single long tube as for the CAC. The air sampling bags will be opened and closed in series to ensure continuous sampling in which analysis can then be merged into a single profile. Each sampling bag is to be allocated a small vertical sampling size of 500 meters in which mixing of gases becomes a lesser concern.

The use of sampling bags in series rather than a single long tube is meant to tackle limitations of CAC by 1) reducing system implementation cost inherent to the production of a long tube and 2) enabling sampling of remote areas by reducing the effect of mixing of gases in post-analysis. Overall design of AAC will be approached with miniaturization, cost-effectiveness, and design for manufacturability (DFM) in mind with the purpose of enabling ease of replication.

1.5 Team Details

The TUBULAR team consists of diverse and inter-disciplinary team members

Georges L. J. Labrèche - Management Division

Education: BSc in Software Engineering with experience in technical leadership and project management in software development.

Responsibilities: Acting as Systems Engineer and managing overall implementation of the project. Establishing and overseeing product development cycle. Coordinating between different teams, project stakeholders, and documentation efforts.

Nuria Agües Paszkowsky - Scientific Division

Education: BSc in Aerospace Engineering.

Responsibilities: Defining experiment parameters; data analysis; interpreting and documenting measurements; research on previous AirCore experiments for comparative analysis purposes; contacting researchers or institutions working on similar projects; exploring potential partnership with researchers and institutions, evaluating the reliability of the proposed AAC sampling system; conducting measurements of collected samples; documenting and publishing findings.

Kyriaki Blazaki - Scientific Division

Education: BSc in Physics.

Responsibilities: Coordinating between the team and the Project Manager; defining experiment parameters; data analysis; interpreting and documenting measurements; research on previous AirCore experiments for comparative analysis purposes; evaluating the reliability of the proposed AAC sampling system; conducting measurements of collected samples; documenting and publishing findings.

Jordi Coll Ortega - Mechanical Division

Education: BASc in Aerospace Vehicle Engineering.

Responsibilities: Designing or redesigning cost-effective mechanical devices using analysis and computer-aided design; developing and testing prototypes of designed devices; analyzing the test results and changing the design as needed in collaboration with the team lead; integrating and assembling final design.

Gustav Dyrssen - Software Division

Education: MSc in Space Engineering (4th Year).

Responsibilities: Leading quality assurance and testing efforts; Enforcing software testing best practices such as continuous integration testing and regression testing; reviewing requirements and specifications in order to foresee potential issues; provide input of functional requirements; advising on design; formalizing test cases; tracking defects and ensuring their resolution; facilitating code review sessions; supporting software implementation efforts.

Natalie Lawton - Electrical Division

Education: MEng in Aerospace Engineering. Previous experience in UAV avionic systems and emissions measurement techniques.

Responsibilities: Supporting designing and implementing cost-effective circuitry using analysis and computer-aided design; Reviewing and testing proposed designs; recommending modifications following prototype test results; assembling designed circuitry.

Pau Molas Roca - Mechanical Division

Education: BSc in Aerospace Technology Engineering, Mechanical experience.

Responsibilities: Coordinating between the team and the Project Manager; designing or redesigning cost-effective mechanical devices using analysis and computer-aided design; producing details of specifications and outline designs; overseeing the manufacturing process for the devices; identifying material and component suppliers; integrating and assembling final design.

Muhammad Ansyar Rafi Putra - Software Division

Education: BSc in Aerospace Engineering.

Responsibilities: Coordinating between the team and the Project Manager; gathering software requirements; formalizing software specifications; drafting architecture design, detailed design; leading software implementation efforts.

Hamad Siddiqi - Electrical Division

Education: BSc in Electrical Engineering with experience in telecommunication industry and electronics.

Responsibilities: Coordinating between the team and the Project Manager; designing and implementing cost-effective circuitry using analysis and computer-aided design; producing details of specifications and outline designs; developing, testing, and evaluating theoretical designs; identifying material as well as component suppliers.

Ivan Zankov - Thermal Division

Education: BEng in Mechanical Engineering.

Responsibilities: Thermal analysis of proposed designs and Recommending modifications following thermal analysis results..

2 Experiment Requirements and Constraints

2.1 Functional Requirements

F.1 ~~The experiment *shall* collect air samples.~~[1]

F.2 The experiment *shall* collect air samples by the CAC.

F.3 The experiment *shall* collect air samples by the AAC.

F.4 ~~The experiment's AAC System *shall* be able to collect air samples during the ascent phase.~~[1]

F.5 ~~The experiment's AAC System *shall* be able to collect air samples during the descent phase.~~[1]

F.6 The altitude from which a sampling bag will start sampling *shall* be programmable.

F.7 The altitude from which a sampling bag will stop sampling *shall* be programmable.

F.8 ~~The experiment *shall* pump air into the AAC Sampling Bags.~~[1]

F.9 The experiment *should* collect data on the air intake flow to the AAC.

F.10 The experiment *shall* collect data on the air pressure.

F.11 The experiment *shall* collect data on the temperature.

F.12 The experiment *shall* collect data on the humidity.

F.13 ~~The experiment *shall* measure the temperature inside the AAC Valve Box.~~[1]

F.14 ~~The experiment *should* measure the humidity inside the AAC Valve Box.~~[1]

F.15 ~~The experiment *shall* collect data on the time.~~[2]

F.16 ~~The experiment *shall* accept telecommand instructions to program AAC sampling altitudes for each sampling bag.~~[1]

F.17 ~~The experiment *shall* accept telecommand instructions to open designated valves.~~[1]

F.18 ~~The experiment *shall* accept telecommand instructions to close designated valves.~~[1]

F.19 ~~The experiment *may* accept telecommand instructions to change the sampling rate of the ambient pressure sensor.~~[1]

F.20 ~~The experiment *may* accept telecommand instructions to change the sampling rate of the ambient temperature sensor.~~[1]

F.21 ~~The experiment *may* accept telecommand instructions to change the sampling rate of the AAC Valve Box temperature sensor.~~[1]

F.22 ~~The experiment *may* accept telecommand instructions to turn on the air pump.~~[1]

F.23 ~~The experiment *may* accept telecommand instructions to turn off the air pump.~~[1]

[1]Unnecessary requirement that has been removed.
[2]Unverifiable requirement that has been removed.

F.24 ~~The experiment *may* accept telecommand instructions to turn on the Valve Heater.~~[1]

F.25 ~~The experiment *may* accept telecommand instructions to turn off the Valve Heater.~~[1]

F.26 ~~The experiment *may* accept telecommand instructions to turn on the Electronics Box Heater.~~[1]

F.27 ~~The experiment *may* accept telecommand instructions to turn off the Electronics Box Heater.~~[1]

2.2 Performance Requirements

P.1 ~~The telecommand data rate *shall* be 10Kb/s.~~[3]

P.2 ~~The default sampling rate of the ambient pressure sensor during Standby mode *shall* be 0.1 Hz.~~[4]

P.3 ~~The default sampling rate of the ambient pressure sensor during Normal operation ascent mode *shall* be 0.2 Hz.~~[4]

P.4 ~~The default sampling rate of the ambient pressure sensor during Normal operation descent mode *shall* be 10 Hz.~~[4]

P.5 ~~The default sampling rate of the AAC Valve Box temperature sensor *shall* be 1 Hz.~~[4]

P.6 ~~The programmable sampling rate of the ambient pressure sensor *shall* not be lesser than 0.1 Hz.~~[4]

P.7 ~~The programmable sampling rate of the ambient pressure sensor *shall* not be greater than 100 Hz.~~[4]

P.8 ~~The programmable sampling rate of the Electronics Box temperature sensor *shall* not be lesser than 1Hz.~~[4]

P.9 ~~The programmable sampling rate of the Electronics Box temperature sensor *shall* not be greater than 7Hz.~~[4]

P.10 ~~The programmable sampling rate of the AAC Valve Box temperature sensor *shall* not be lesser than 1 Hz.~~[4]

P.11 ~~The programmable sampling rate of the AAC Valve Box temperature sensor *shall* not be greater than 7 Hz.~~[4]

P.12 The accuracy of the ambient pressure measurements *shall* be -1.5/+1.5 mbar for 25°C.

P.13 The accuracy of temperature measurements *shall* be +3.5/-2°C (max) for condition of -55°C to 150°C.

P.14 The accuracy of the ambient humidity measurements *shall* be ±3%. [6]

P.15 ~~The accuracy of the AAC Valve Box temperature measurements *shall* be +3.5/-~~[5]

P.16 The air intake rate of the air pump *shall* be minimum 3L/min.

P.17 The temperature of the Electronics Box *shall* be between 0°C and 25°C.

P.18 ~~The temperature of the Electronics Box *shall* not exceed 25°C.~~[6]

P.19 The temperature of the AAC Valve Box *shall* be between 0°C and 25°C.

P.20 ~~The temperature of the AAC Valve Box *shall* not exceed 25°C.~~[7]

[3] Moved to design requirements.
[4] Replaced by P.23
[5] Combined with P13
[6] Combined with P17
[7] Combined with P19

P.21 The air sampling systems *shall* filter out all water molecules before filling the sampling containers.

P.22 ~~The CAC air sampling *shall* filter out all water molecules before filling the tube.~~[8]

P.23 The sensors sampling rate *shall* be 2Hz.

P.24 The temperature of the Pump Box *shall* be between 5°C and 25°C.

[8]Combined with P21

2.3 Design Requirements

D.1 The experiment *shall* operate in the temperature profile of the BEXUS flight.

D.2 The experiment *shall* operate in the vibration profile of the BEXUS flight.

D.3 ~~The experiment *shall* not disturb or harm the launch vehicle.~~[1]

D.4 The experiment's communication system *shall* be compatible with the gondola's E-link system.

D.5 The experiment's power supply *shall* be compatible with the gondola's provided power.

D.6 ~~The experiment *shall* not disturb other experiments on the gondola.~~[1]

D.7 The total DC current draw *should* be below 1.8 A.

D.8 The total power consumption *should* be below 374 Wh.

D.9 The experiment *shall* be able to operate in low pressure conditions (10-15 mbar) up to 30 km altitude.

D.10 ~~The components of the experiment *shall* operate within their temperature ranges.~~[1]

D.11 ~~The OBC *shall* be able to autonomously control the heaters.~~[1]

D.12 ~~The ground station GC *shall* be able to display some of the received data.~~[1]

D.13 ~~The experiment *shall* be able to survive and operate between -30°C and 60°C.~~[1]

D.14 ~~The external components that are directly exposed to the outside environment *shall* be able to operate at -70°C.~~[1]

D.15 ~~The watchdog *should* be able to reset the system.~~[1]

D.16 The experiment *shall* be able to autonomously turn itself off just before landing.

D.17 The experiment box *shall* be placed with at least one face exposed to the outside.

D.18 The experiment *shall* operate in the pressure profile of the BEXUS flight.

D.19 The experiment *shall* operate in the vertical accelerations profile of the BEXUS flight.

D.20 The experiment *shall* operate in the horizontal accelerations profile of the BEXUS flight.

D.21 The experiment *shall* be attached to the gondola's rails.

D.22 The telecommand data rate *shall* not be over 10kb/s.

2.4 Operational Requirements

O.1 ~~The TUBULAR Team *shall* send telecommands from the ground station to the experiment before and during the flight.~~[1]

O.2 ~~The TUBULAR Team *shall* receive telemetry from the experiment during the flight.~~[1]

O.3 ~~The experiment *shall* change modes autonomously.~~[1]

O.4 ~~The heating mechanism *shall* work autonomously.~~[1]

O.5 ~~The experiment *shall* store data autonomously.~~[1]

O.6 ~~The Air sampling control system *shall* work autonomously.~~[1]

O.7 ~~The valves in air sampling control system *should* be controllable from the ground station.~~[1]

O.8 ~~The experiment *should* be able to handle a timeout or drop in the network connection.~~[1]

O.9 ~~The heaters *should* be controllable from the ground station.~~[1]

O.10 ~~The watchdog[9] *should* be able to reset the system.~~[1]

O.11 ~~The system *should* be able to be reset with a command from the ground station.~~[1]

O.12 ~~The experiment *should* enter different modes with a telecommand from the ground station.~~[1]

O.13 The experiment *should* function automatically.

O.14 The experiment's air sampling mechanisms *shall* have a manual override.

[9]Explained in subsection 4.8. Software Design

2.5 Constraints

C.1 Constraints specified in the BEXUS User Manual.

C.2 ~~The person-hours allocated to project implementation is limited by university related factors such as exams, assignments, and lectures.~~[1]

C.3 ~~Budget limited to TBD.~~[1]

C.4 ~~The dimensions show a minimum print area of 50 x 50 cm and 65cm height experiment box.~~[1]

3 Project Planning

3.1 Work Breakdown Structure

The team is categorized into different groups of responsibilities with dedicated leaders who will report to and coordinate with the project manager. Leadership may be organized on a rotational basis should the need arise. The formation of these subteams constitute a work breakdown team structure in which a simplified version is illustrated in Figure 1:

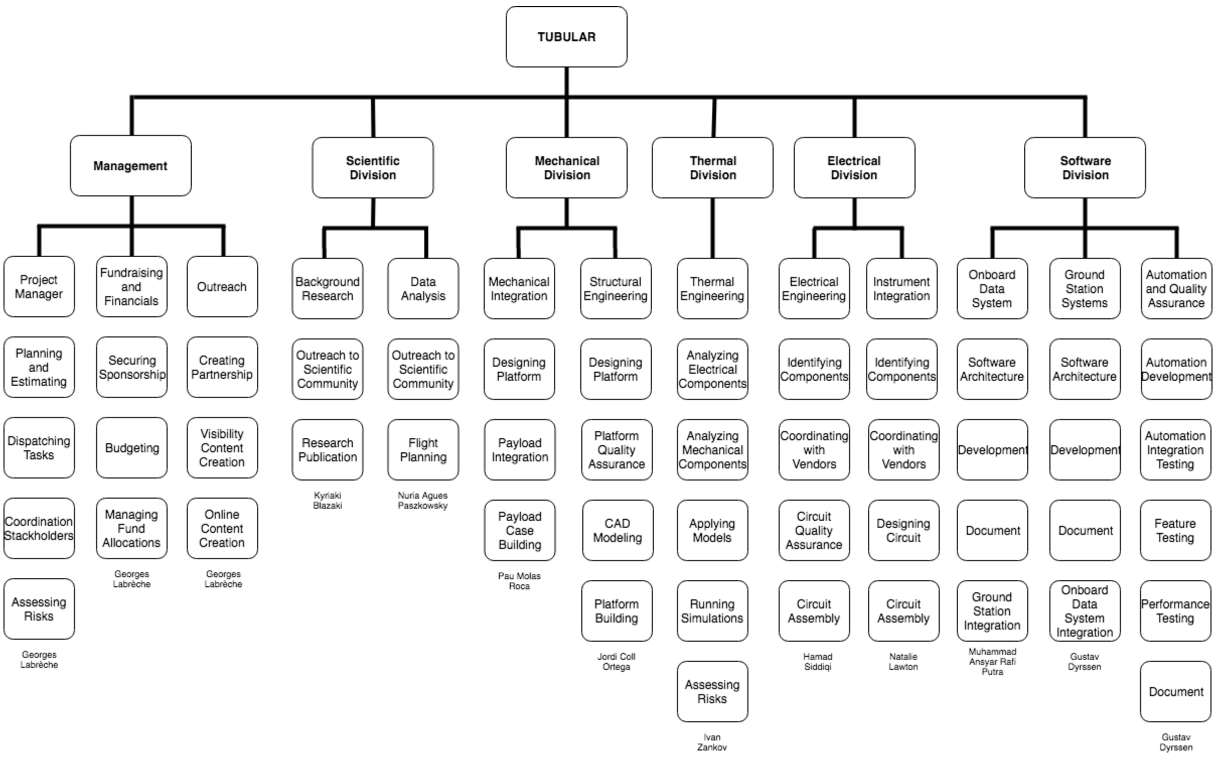


Figure 1: Work Breakdown Structure

The interaction between the subteams will be refined over the course of project implementation to acknowledge the interdisciplinary nature of the experiment around a Payload / Platform scheme.

The Management is composed of a Project Manager acting as the Systems Engineer and managing overall implementation of the project. The Project Manager is responsible for establishing and overseeing product development cycle; coordinating between different teams, project stakeholders, and documentation efforts; outreach and public relations; Fundraising; monitoring and reporting; system integration; and quality assurance.

The Scientific Division is responsible for defining experiment parameters; data analysis; interpreting and documenting measurements; researching previous AirCore experiments for comparative analysis purposes; evaluating the reliability of the proposed AAC sampling system;

conducting measurements of collected samples; documenting and publishing findings; defining experiment parameters; contacting researchers or institutions working on similar projects; exploring potential partnership with researchers and institutions; documenting and publishing findings.

The Mechanical Division is responsible for designing or redesigning cost-effective mechanical devices using analysis and computer-aided design; producing details of specifications and outline designs; overseeing the manufacturing process for the devices; identifying material and component suppliers; developing and testing prototypes of designed devices; analyzing test results and changing the design as needed; and integrating and assembling final design.

The Electrical Division is responsible for designing and implementing cost-effective circuitry using analysis and computer-aided design; producing details of specifications and outline designs; developing, testing, and evaluating theoretical designs; identifying material as well as component suppliers; reviewing and testing proposed designs; recommending modifications following prototype test results; and assembling designed circuitry.

The Software Division is responsible for gathering software requirements; formalizing software specifications; drafting architecture design; leading software implementation efforts; leading quality assurance and testing efforts; enforcing software testing best practices such as continuous integration testing and regression testing; reviewing requirements and specifications in order to foresee potential issues; providing input for functional requirements; advising on design; formalizing test cases; tracking defects and ensuring their resolution; facilitating code review sessions; and supporting software implementation efforts.

3.2 Schedule

Scheduling of the project is presented in a Gantt Chart overview on Figure 2. Exam period constraints have been included in order to evaluate risks in person-day allocations to project implementation:

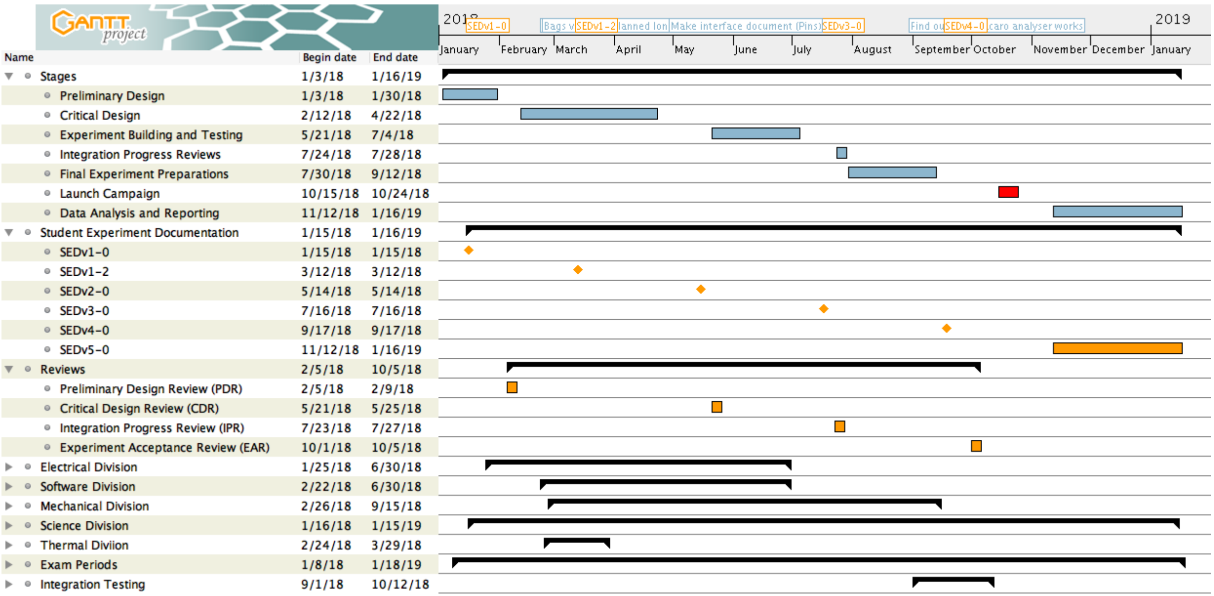


Figure 2: Project Schedule Gantt Chart

Deadlines of the five Student Experiment Documentations (SED) versions have been estimated based on past REXUS/BEXUS Cycles. A complete Gantt Chart listing tasks for each division is shown in Appendix F.

3.3 Resources

3.3.1 Manpower

The TUBULAR team is categorized into divisions as summarized in Table 3:

Management	Scientific	Mechanical	Electrical	Thermal	Software
Georges Labrèche*	Kyriaki Blazaki*	Pau Molas Roca*	Hamad Siddiqi*	Ivan Zankov	Muhammad Ansyar Rafi Putra*
	Nuria Agues Paszkowsky	Jordi Coll Ortega	Natalie Lawton		Gustav Dyrssen

Table 3: Project Divisions and Members (Asterisks Denote Division Leaders)

The experience of TUBULAR team members are listed in Table 4:

Team Member	Project Related Experience
Georges Labrèche	BSc in Software Engineering with experience in technical leadership and project management in software development.
Nuria Agues Paszkowsky	BSc in Aerospace Engineering.
Kyriaki Blazaki	BSc in Physics.
Jordi Coll Ortega	BSc in Aerospace Vehicle Engineering.
Gustav Dyrssen	MSc in Space Engineering (4th Year).
Natalie Lawton	MEng in Aerospace Engineering. Previous experience in UAV avionic systems and emissions measurement techniques.
Muhammad Ansyar Rafi Putra	BSc in Aerospace Engineering.
Pau Molas Roca	BSc in Aerospace Technology Engineering, Mechanical experience.
Hamad Siddiqi	BSc in Electrical Engineering with experience in telecommunication industry and electronics.
Ivan Zankov	BEng in Mechanical Engineering.

Table 4: Project Related Experience of Team Members

The initial projected effort to be contributed by each team member is of an average of 1.5 hour per person per day corresponding to a team total of 15 hours per day. Taking into account all team members, the efforts projected to be allocated to each stages of the project is summarized in Table 5:

Stage	Duration (days)	Effort (hours)
Preliminary Design	28	420
Critical Design	70	1050
Experiment Building and Testing	45	675
Final Experiment Preparations	45	675
Launch Campaign	10	150
Data Analysis and Reporting	66	990
Total:	**264**	**3960**

Table 5: Project Effort Allocation per Project Stages

All TUBULAR team members are based in Kiruna, Sweden, just 40 kilometers from Esrange Space Center. Furthermore, all team members are enrolled in LTU Master programmes in Kiruna and thus expected to remain in Kiruna during the entire project period. Special attention will have to be made for planning during the summer period where many team members are expected to travel abroad. An initial timeline of team member availability until January 2019 is available in Appendix D. A significant risk can be observed during the summer months from June to August where most members will only be partially and some completely unavailable. Team member availability and work commitments over the summer still need to be negotiated and finalized across team members in order to reduce incurred risks to the project. Furthermore, the Project Manager role will have to be assigned to another team member due to extended unavailability and partial availability.

As part of their respective Master programmes, all TUBULAR team members are enrolled in a project course at LTU. The TUBULAR project acts as the course's project for all team members from which they will obtain ECTS credits. This course is supervised by Dr. Thomas Kuhn, Associate Professor at LTU.

3.3.2 Budget

LTU will provide financial assistance for part of the hardware expenses, approximately 250 EUR per team member. This brings the total budget to 2 500 EUR thus far. However, the total cost of the project is 8 376.65 EUR[10]. In order to fill this budget gap, the following potential sources of funding are to be explored throughout the first stages of the project implementation:

- The Swedish National Space Board, SNSB, will be reached out to during their next open call to researchers in Sweden to apply for funding for Space Research, including Earth Observation Research.
- The Swedish Research Council typically opens calls for "Proof of Concept Grant – Life science" as well as "Natural and Engineering Sciences" research grants to which an application will be sent to during the upcoming 2018 calls.
- Meteorological institutes, research initiatives, researchers, academic institutions, and institutional donors involved in climate change will be reached out to for contributions based on the interest of collaborating in the experiment.
- Third-party providers of required equipment, components, and materials will be approached with an opportunity for these providers to sponsor the project through donation before considering the related expenses. Visibility of the experiment through the planned outreach programs will serve as a visibility incentive to encourage such contributions.
- A small online crowdfunding campaign will be organized that will primarily target contributions from the team members' first and second degree contacts.

The project budget is detailed in Table 6. The budget table does not include costs related to component redundancy and as such consist of the minimum cost to build the experiment. Not included in the total are components supplied by partners and potential sponsors (e.g. the CAC tube supplied by FMI). Funding from LTU covers 28% of the total costs while it is projected that a SNSB grant will cover 31%. The remaining costs are associated with the air sampling bags for which sponsorship will actively be sought from a manufacturer (at the time of writing, discussions with the manufacturer Restek Corporation are ongoing regarding sponsorship of air sampling bags).

[10] The cost of some items have been estimated due to lack of direct quotes from vendors. A total error margin of 5% has been included in the final budget to account for possible estimation errors.

	Quantity	Mass/Unit [g]	Cost/Unit [€]	Mass [g]	Cost [€]
1 STRUCTURE				**8,306.14**	**€543.10**
1.1 Aluminum bar	9.6	428.62	n/a	4,114.75	€146.90
1.2 Aluminum plate	2.12	2.70	€25.00	1,144.80	€53.00
1.3 Styrofoam	0.0212	37,790.00	n/a	801.15	€80.00
1.4 Screw	160	5.00	€0.62	800.00	€99.20
1.5 Corner joint	52	5.00	€0.75	260.00	€39.00
1.6 Polyethylene foam	0.0212	37,790.00	€0.00	801.15	€80.00
1.7 Flange	50	2.00	€0.10	100.00	€5.00
1.8 Bar	1	2.70	€20.00	244.29	€20.00
1.9 Handle	4	10.00	€5.00	40.00	€20.00
2 ELECTRONIC BOX				**257.14**	**€260.00**
2.1 Arduino Due	1	36.00	€35.00	36.00	€35.00
2.2 Ethernet Shield	1	36.00	€30.00	36.00	€28.00
2.3 Heater	3	2.28	€40.00	6.84	€120.00
2.4 DC/DC converter	2	16.90	€25.00	33.80	€50.00
2.5 MicroSD	1	0.50	€20.00	0.50	€20.00
2.6 Logic CAT5E Network	1	90.00	€7.00	90.00	€7.00
2.7 Electronics shielding box	0.1	2.70	€0.00	54.00	€0.00
3 CABLES AND SENSORS				**157.00**	**€245.50**
3.1 Temperature sensor	10	1.00	€4.00	10.00	€40.00
3.2 Pressure sensor	6	5.00	€11.00	30.00	€66.00
3.3 Airflow sensor	1	14.00	€106.00	14.00	€106.00
3.4 Humidity sensor	3	5.00	€1.00	15.00	€3.00
3.5 Wires	30	1.00	€0.50	30.00	€15.00
3.6 Heat Sinks	5	5.00	€1.00	25.00	€5.00
3.7 Resistors	3	5.00	€0.50	15.00	€1.50
3.8 Transistors	18	1.00	€0.50	18.00	€9.00
4 CAC				**12,320.00**	**€246.29**
4.1 Coil	1	12,000.00	€0.00	12,000.00	€0.00
4.2 CAC ext pipe	10	0.00	€5.00	0.00	€50.00
4.3 magnesium filter	1	100.00	€25.00	100.00	€25.00
4.4 valve	1	220.00	€146.29	220.00	€146.29
4.5 flushing process (nitrogen)	1	0.00	€25.00	0.00	€25.00
5 AAC				**4,450.00**	**€5,989.19**
5.1 Bag	12	150.00	€290.00	1,500.00	€3,480.00
5.2 Valve center box (Mechanical)	1	0.00	€250.00	0.00	€250.00
5.3 AAC ext pipe	1	0.00	€250.00	0.00	€250.00
5.4 Air pump	1	430.00	€350.00	430.00	€350.00
5.5 Valve	10	220.00	€146.29	2,200.00	€1,462.90
5.6 Flushing valve	1	220.00	€146.29	220.00	€146.29
5.7 Manifold	1	0.00	€0.00	0.00	€0.00
5.8 Magnesium filter	1	100.00	€25.00	100.00	€25.00
5.9 Flushing process (nitrogen)	1	0.00	€25.00	0.00	€25.00
5.10 Plastic tube	5	0.00	€0.00	0.00	€0.00
5.11 Pump shielding box (Mechanical)	0	0.00	€0.00	0.00	€0.00
6 OTHER				**2,549.03**	**€1,092.61**
6.1 Shipping costs	n/a	n/a	n/a	n/a	€728.41
6.2 Error margin	n/a	n/a	n/a	2,549.03	€364.20
			TOTAL	**28,039.31**	**€8,376.69**

Table 6: Project budget table. Values highlighted in yellow have yet to be determined/estimated. Number values in red have been estimated rather than determined by vendor quotes. Shipping cost is estimated at 10% of total cost. Total cost error margin is set to 5% of projected total cost. Total mass error margin is set to 10% of projected total mass.

3.3.3 External Support

Partnership with the Finnish Meteorological Institute (FMI), and the Swedish Institute of Space Physics (IRF) will provide the team with technical guidance in implementing the sampling system. FMI's experience in implementing past AirCore sample systems provide invaluable lessons learned towards conceptualizing, designing, and implementing the proposed AAC sampling system.

FMI is a key partner in the TUBULAR project, its scientific experts will advise and support the TUBULAR project by sharing knowledge, experience, and granting accessibility of equipment. As per the agreement shown in Appendix G, FMI will provide the TUBULAR team with the AirCore stainless tube component of CAC subsystem as well as the post-flight gas analyzer. This arrangement requires careful considerations on the placement of the experiment in order to minimize hardware damage risks. These contributions will result in significant cost savings regarding equipment and component procurement.

Daily access to LTU's Space Campus in Kiruna will expose the team to scientific mentorship and expert guidance from both professors and researchers involved in the study of greenhouse gases and climate change. Dr Uwe Raffalski, Swedish institute of Space physics (IRF), Associate professor (Docent) is one of many researchers involved in climate study who is mentoring the team.

3.4 Outreach Approach

The experiment as well as the BEXUS programme and its partners will be promoted through the following activities:

- Research paper published in partnership with the Finnish Meteorological Institute (FMI) detailing the sampling methodology, measurement result, analysis, and findings.
- Collected data will be licensed as open data to be freely available to everyone to use and republish as they wish, without restrictions from copyright, patents or other mechanisms of control.
- A website will be launched that will summarize the experiment and provide regular updates. Backend web analytics included to gauge interest on the project through number of visitors and their origins.
- Dedicated Facebook page used as publicly accessible logbook detailing challenges, progress, and status of the project. Open for comments and questions (See Figure 46 in Appendix E).
- Two Instagram accounts for short and frequent image and video focused updates. A primary Instagram account will be dedicated to project updates. A secondary account will reach out to a broader audience by focusing on space instruments in general and cross-reference TUBULAR related activities when relevant (See Figures 47, 48, and 49 in Appendix E).
- GitHub account to host all project software code under free and open source license (See Figures 50 in Appendix E). Other REXUS/BEXUS teams will be invited to host their code in this account in what will hopefully become a centralized GitHub account and code archive for present and future REXUS/BEXUS projects.
- Reddit Ask Me Anything (AMA) thread to discuss the project with community of online enthusiasts.
- "Show and Tell" trips to local high schools and universities. Team members will be responsible to organize such presentations through any of their travel opportunities abroad.
- In-booth presentation and poster display in the seminars or career events at different universities.
- A thoroughly documented and user-friendly manual on how to build replicate and launch CAC and AAC sampling systems will be produced and published.

3.5 Risk Register

Risk ID

TC – technical/implementation

MS – mission (operational performance)

SF – safety

VE – vehicle

PE – personnel

EN – environmental

OR - Outreach

BG - Budget

Adapt these to the experiment and add other categories. Consider risks to the experiment, to the vehicle and to personnel.

Probability (P)

A Minimum – Almost impossible to occur

B Low – Small chance to occur

C Medium – Reasonable chance to occur

D High – Quite likely to occur

E Maximum – Certain to occur, maybe more than once

Severity (S)

1. Negligible – Minimal or no impact
2. Significant – Leads to reduced experiment performance
3. Major – Leads to failure of subsystem or loss of flight data
4. Critical – Leads to experiment failure or creates minor health hazards
5. Catastrophic – Leads to termination of the BEXUS programme, damage to the vehicle or injury to personnel

The rankings for probability (P) and severity (S) are combined to assess the overall risk classification, ranging from very low to very high and being coloured green, yellow, orange or red according to the SED guidelines.

ID	Risk (& consequence if)	P	S	P * S	Action
TC10	Software fails to store data	B	4	Low	Acceptable Risk: Extensive testing will be done
TC20	Failure of several sensors	B	3	Low	Acceptable Risk: Thermal test to approve the functionality of the experiment.
TC30	Critical component is destroyed in testing	B	1	Low	Acceptable risk: Spare components can be ordered but for expensive ones, they will be ordered and tested early in the project in case we need to order more.
TC40	Electrical connections dislodges or short circuits because of vibration or shock	B	3	Low	Unacceptable risk. Careful soldering and extensive testing will be applied.
TC50	Experiment electronics fail due to long exposure to cold or warm temperatures	B	3	Low	Unacceptable Risk: Thermomechanical and thermoelectrical solutions will be simulated and tested in detail to help prevent this from happening.
TC60	Software and electrical fail to control heaters causing temperature to drop or rise below or above operational range	B	2	Very Low	Unacceptable risk: Tests will be performed prior to the flight to detect and minimize the risk of occurrence.The system will be monitored during flight and handled manually if necessary.
TC70	Software fails to enter safe mode (may result in loss of data)	B	3	Low	Acceptable Risk: Extensive testing will be done.
TC80	On-board memory will be full (flight time longer than expected)	A	2	Very Low	Acceptable Risk: The experiment shall go through testing and analysis to guarantee the onboard memory size is sufficient.
TC90	Connection loss with ground station	A	4	Very Low	Acceptable Risk: Experiment will be designed to operate autonomously.
TC100	Software fails to control valves autonomously	B	4	Low	Acceptable Risk: Extensive testing will be done. Telecommand will also be used to manually control the valves.
TC110	Software fails to change modes autonomously	B	4	Low	Acceptable Risk: Extensive testing will be done. Telecommand will also be used to manually change experiment modes.
TC120	Complete software failure	B	4	Low	Acceptable Risk: Watchdog timer will be applied to reset software if it freezes.
TC130	Failure of fast opening system	B	2	Very Low	Acceptable risk: the box could also be opened but a little bit slower.

TC140	The gas analyzer isn't properly calibrated and returns inaccurate results	B	4	Low	Acceptable risk: Calibrate the gas analyzer before use.
MS10	Down link connection is lost prematurely	B	2	Very Low	Acceptable Risk: Data will also be saved on SD card.
MS20	Condensation on experiment PCBs which could causes short circuits	A	3	Very Low	Acceptable risk: Circuit box will be sealed to prevent condensation.
MS30	Temperature sensitive components that are essential to full the mission objective might be below their operating temperature.	C	3	Low	Acceptable Risk: Safe mode to prevent the components to operate out of its operating temperature range.
MS40	Experiment lands in water causing electronics failure	B	1	Very Low	Acceptable risk: Check if SD card needs waterproof shell or is waterproof in itself. Also, all the necessary data will be downloaded during the flight.
MS50	Interference from other experiments and/or balloon	A	4	Very Low	Acceptable risk: no action.
MS60	Balloon power failure	C	1	Very Low	Acceptable risk: Valves default state is closed so if all power is lost valves will automatically close preserving all samples collected up until that point.
MS70	Bags disconnect	C	3	Low	Acceptable Risk: The affected bags could not collect samples. A proper fixing of the flanges must be double checked.
MS71	Bags puncture	B	3	Low	Acceptable Risk: The affected bags could not collect samples. Proper protection will be placed in order to avoid puncture from external elements.
MS72	Bags' hold time is typically 48h	C	3	Low	Acceptable risk: Validation studies can demonstrate longer stability.
MS80	Pump failure	C	4	Medium	Unacceptable risk: The bags would not be filled and thus the AAC system would fail. The pump will be properly chosen based on past research and extensively tested before the flight.
MS90	Intake pipe blocked by external element	C	3	Low	Unacceptable Risk: The bags would not be filled and thus the AAC system would fail. An air filter will be placed in both intake and outlet of the pipe to prevent this.
VE10	SD-card is destroyed at impact	B	3	Low	Acceptable Risk: All data will be transmitted to the ground.

VE20	Gondola Fixing Interface	B	4	Low	Unacceptable Risk: The experiment box could detach from the gondola's rails and the two boxes could detach one from the other. Proper fixing has been designed to prevent it.
VE30	Structure damage due to bad landing	B	3	Low	Acceptable Risk: Landing directly on a hard element could break the structure or the protective walls. Consistent design implemented to prevent it.
VE40	Hard landing damages the CAC equipment	C	3	Low	Acceptable risk: Proper protection will be placed in order to avoid damage from hard landing.
VE50	Hard landing damages the AAC equipment	C	3	Low	Acceptable risk: Proper protection will be placed in order to avoid puncture from hard landing.
EN10	Vibrations	C	1	Very Low	Acceptable risk: Vibrations do not affect the sampled air.
EN20	The air samples must be protected from direct sunlight and stored above 0 °C to prevent condensation	D	4	High risk	Unacceptable risk: Further test regarding insulation performance and humidity levels in the bags will be done.
PE10	The Project Manager is no longer available to manage the project.	E	1	Low	Acceptable risk: The Deputy Project Manager will take over as Project Manager.
PE20	Team members from the same division are unavailable during the same period over the summer.	C	4	Medium risk	Unacceptable risk: Summer travel schedules to be coordinated among team members and approved by Project Manager.

Table 7: Risk Register

4 Experiment Design

4.1 Experiment Setup

The experiment consists of AAC ten sampling bags subsystem, and the CAC coiled tube subsystem. The principal aim is to validate the AAC sampling method and to do so, it is necessary to sample during descent phase in order to compare the results with the ones obtained from the CAC. All speeds mentioned in this section have been obtained from the BEXUS manual as well as through analysis of past flights.

The primary concern regarding the AAC air sampling subsystem is that after cut-off the gondola will tumble and fall at an average speed of 50 m/s for approximately 2 minutes [5]. This falling speed is too fast in order to sample air at the desired vertical resolution that is targeted to be 500m. This means that only after the gondola is stabilized at a descent rate of 8 m/s [5] the sampling can be done. The tumbling phase will span approximately for 6km and considering a floating phase at 25km, the sampling can be started from 19km in altitude. Nevertheless, the main region of interest is the stratosphere, especially between 19km and 25km of altitude. It is for this reason that the team has decided to sample during ascent phase as well. Ten sampling bags will be filled up, six during ascent phase approximately between 18-24km, and four during descent phase below 19km. The desired vertical resolution is 500 m at a falling speed of 8 m/s which means that using bags with a volume of 3L, an air pump with at least 3L/min intake rate is necessary for the sampling bags.

The maximum pressure that the sampling bags can withstand has to be taken into account in order to avoid bursting. During ascent phase, due to the decreasing pressure, the bags with the air samples , will expand which may have risk of bursting. To avoid this, the bags should not be fully sampled. The providers recommend not to fill more than 80% (2psi/0.14bar) for Multi-Layer Foil bags. The opposite applies for descent phase. The bags with the air samples, will be compressed, and in order to assure that the samples are enough for analysis, they should be fully filled. It has to be mentioned that it has been found from past research [2] that the same bags can withstand a difference in pressure between outside and inside of 310hPa at 30km of altitude, which is equivalent to 0.31bar. Therefore, future test will confirm the maximum pressure for the bags.

Depending on the altitude of sampling, the range of the sample size is between 0.2L and 0.8L, with 0.2L being the minimum amount required for the chromatographer to analyze.

The AAC will need an air pump for sampling, due to low ambient pressure at stratospheric altitudes. The air pump is also needed in order to assure the intake flow rate and obtain a good resolution. A control valve will be used to flush the pump after each bag is filled and make sure that the next bag will be filled with fresh air from the corresponding altitude. Each sampling bag will be assigned a 500 meter altitude sampling range from which to collect air samples. At an ascent speed of 5 m/s during the Ascent Phase and at a descent speed of 8 m/s during the Descent Phase.

Shortly after the launch, the CAC valve will be opened in order to allow flushing the inert gas that is inside the tube, while the AAC valves will be closed until reaching the sampling altitude. Flushing of the CAC tube happens passively through the progressive decrease in air pressure during the balloon's ascent phase. The CAC valve will remain open at all time during ascent, floating, and descent phases. The tube will empty itself due to pressure gradient during the ascent phase and it will be filled passively during descent. The valve will close just after hitting the ground in order to preserve the sample. The AAC will need an air pump for sampling, due to low ambient pressure. The air pump is also needed in order to assure the intake flow rate and obtain a good resolution.

After sampling for a given bag is complete, the pump will be flushed and prior to the subsequent sampling bag valve being opened. This process continues until the last sampling bag is filled.This procedure occurs twice, the first time during the Ascent Phase for the 6 first sampling bags and the second time during the descent phase for the remaining 4 sampling bags.

The ambient pressure will be measured by three pressure sensors located inside the experiment box. Only one of them is necessary for AAC and CAC, but three sensors will be used for redundancy reasons. The pressure inside the AirCore is assumed to be the same as the ambient pressure, therefore no sensor is needed. To measure the pressure inside the bags, three more sensors will be allocated inside the valve center. To measure ambient temperature in the AirCore, three sensors will be allocated in the styrofoam whereas three more for the bags will be placed in the valve center. Temperature inside the bags/AirCore is assumed to quickly adjust to the ambient temperature, therefore there will not be differentiation in between inside/outside temperature. In total, there will be six pressure sensors and six temperature sensors.

The sampling of the AAC will be triggered by the pressure reading from the sensors inside the valve center. When the required pressure is reached, the valve will open and the sampling will start. The closing of the valve depends on two conditions and it will be triggered when either one of the conditions is true. These conditions are: maximum sampling time or maximum pressure difference between inside/outside the bags. They are determined from past research but in the future will be determined by testing.

The emptying and sampling sequence is represented in Figures 3 and 4. It should be kept in mind that the different pressures are what triggers the opening of the valves.

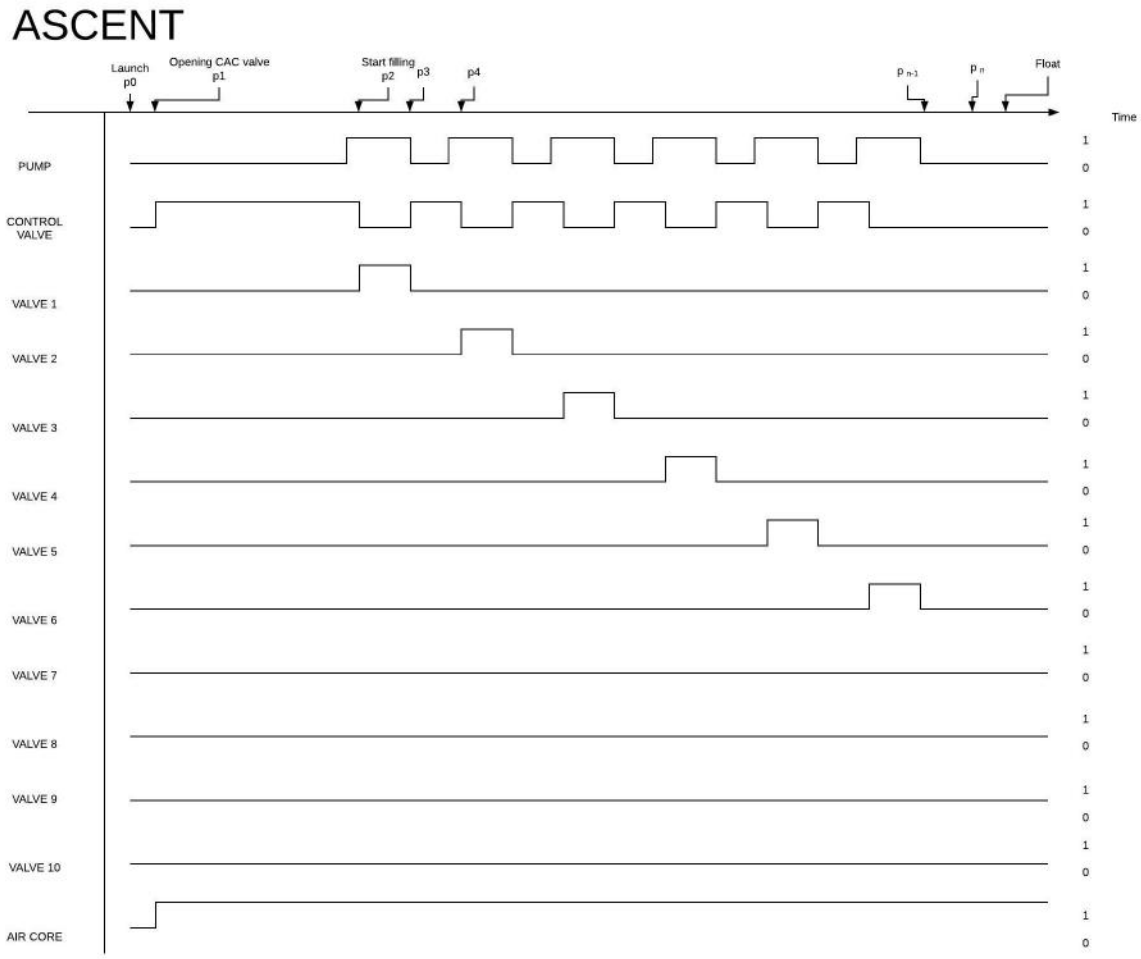


Figure 3: The emptying and sampling sequence-Ascent Phase

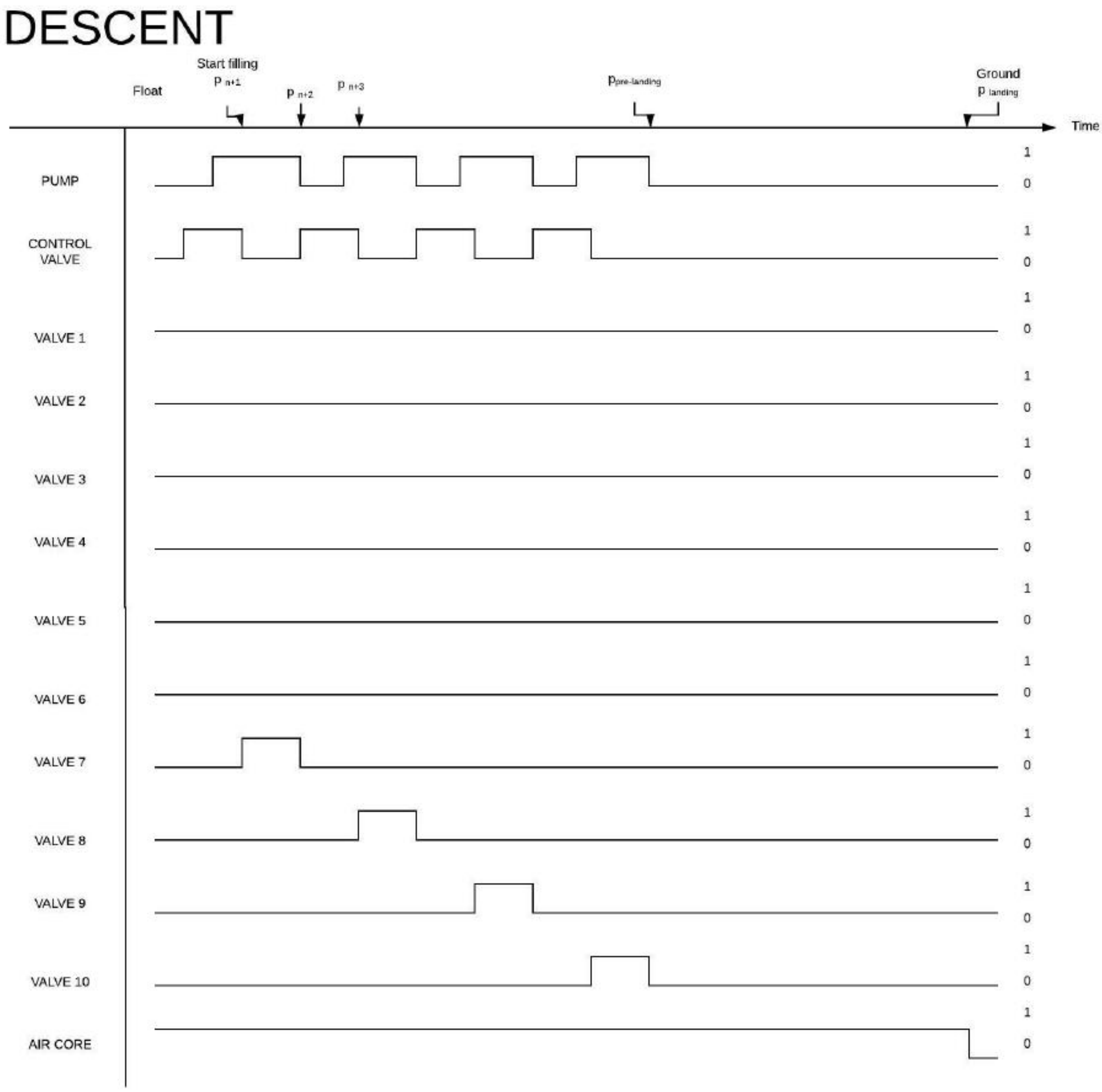


Figure 4: The emptying and sampling sequence-Descent Phase

In the diagrams, 0 denotes closed/off and 1 denotes opened/on.

The general timeline of the experiment is as follow:

Ascent Phase:

$p_0 - p_1$

- CAC valve shall be closed.
- AAC valves shall be closed.
- AAC' control valve shall be closed.

$p_1 - p_2$

- CAC valve shall be opened.
- AAC valves shall be closed.
- CAC tube shall be flushed.
- AAC' control valve shall be open.

$p_2 - p_3$

- Sampling bags' control valve shall be closed.
- Sampling bag valve 1 shall be opened, allowing for air to enter the first bag.
- CAC valve remains open.

$p_3 - p_4$

- Sampling bag valve 1 shall be closed
- Sampling bags' control valve shall be opened, allowing the system to flush.

p_4 - p_{n-1}

- The above procedures shall repeat itself until the remaining five bags have collected air samples for their assigned altitudes.

$p_{n-1} - p_n$

- Sampling bag valve 6 shall be closed.
- Sampling bags' control valve shall be closed.

Float Phase:
No action taken other than continued telemetry. Air pump is off.

Descent Phase:

Note: Before sampling starts again, the system has to be flushed.

$p_{n+1} - p_{n+2}$

- Sampling bags' control valve shall be closed.
- Sampling bag valve 7 shall be opened, allowing for air to enter the first bag.

$p_{n+2} - p_{n+3}$

- Sampling bag valve 7 shall be closed
- Sampling bags' control valve shall be opened, allowing the system to flush.

In between, same procedure shall repeat itself until all the remaining bags have collected air samples for their assigned altitudes.

$p_{pre-landing}$

- System Sampling bag valve 10 shall be closed.

- Sampling bags' control valve shall be closed
- CAC valve shall be opened.

$p_{landing}$

- CAC valve shall be closed.

Note: The AAC system's air pump is only on during sampling into the air sampling bags and flushing of the system.

4.2 Experiment Interfaces

4.2.1 Mechanical Interfaces

The experiment box will be fixed to the gondola rails by means of 4 screws interfacing the experiment outside structure with the hammer nuts in the rails. 90-degree aluminum angles will be used to provide this interface.This method is secure as well as fast enough to provide an accessible and easy recuperation for the later analysis.

Lateral and top handles will be mounted to facilitate the experiment box manipulation when moving it in and out of the gondola.

In order to collect reliable air samples, the experiment requires to be mounted at least with one side exposed to the outside. The later will reduce the pipe length used to collect clean air. Three tubes will extend from the experiment box face, see Figure 5. One for the CAC sampling and two, input and output, for the AAC sampling. The one-way selected method will provide a proper flushing of the pipe and thus ensure a reliable sampling as explained in section 4.1.

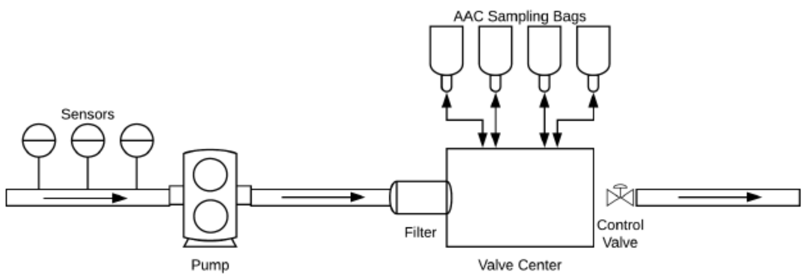


Figure 5: Schematic of air sampler pipe.

4.2.2 Electrical Interfaces

The experiment will connect to the gondola electrically via a 4 pin, male, box mount receptacle MIL - C-26482P series 1 connector with an 8-4 insert arrangement (MS3112E8-4P) [5]. It will connect to one 28.8V/1mA battery pack which consists of eight SAFT LSH20 batteries in series where each has a 5A fuse[5]. The expected maximum current is 1.33A.

The E-Link connection shall be made between the experiment and the E-Link system using a RJ45 connection which will be supplied by SSC and an Ethernet protocol. The Amphenol RJF21B connector will be mounted on either the front or the side of the experiment[5].

The expected data rate is 2kbit/s with 10kbit/s peak downlink and 5kbit/s peak uplink.

4.3 Experiment Components

4.3.1 Electrical Components

Table 8 shows all required electrical components with mass and price.

ID	Components	Specs (size,weight)	No.	Cost	Note	Availability	Status
1	Arduino Due	101.52 mm x 53.3 mm, 36 g	1	35 Euro	Fast and has many analog, and digital pins	Easily ordered online	Ordered
2	W5500 Ethernet Shield	36 g	1	28 Euro	Easily, connected on top of the board	Easily ordered online	Ordered
3	KNF 850.1.2. KNDC B Miniature Diaphragm Pump	30 x 54.3 x 77.5 mm, 430g	1	350 Euro	Low power, small size	Easily ordered online	Ordered
4	Barometric Pressure Sensor MS5607-02BA03	5.0 x 3.0 x 1.0 mm, 1g	3	11 Euro	High resolution, large measuring range	Easily ordered online	To be ordered online
5	Electromagnetically controlled valve	1-1/4", 2640 g	12	1756 Euro	Cascaded/series of valves	Easily ordered online	One ordered for testing
6	Airflow sensor AWM40000 Series	14 g	1	106 Euro	good temperature range, high accuracy	Easily ordered online	To be ordered online
7	Polyimide Thermofoil Heaters HK5161R78.4L12	12.7 x 101.6 mm, 6.84g	1	40 Euro	Easy to mount, compact size	Easily ordered online	To be ordered online
8	Polyimide Thermofoil Heaters HK5160R157L12	12.7 x 50.8 mm, 6.84g	1	40 Euro	Easy to mount, compact size	Easily ordered online	To be ordered online

9	Temperature sensor VSSOP-8, LM75A, Texas Instruments	5.3 x 3.4 x 1.4 mm	12	4 Euro	I2C digital output interface, temperature range down to - 55 ℃	Easily ordered online	To be ordered online
10	DC-DC Converter TEN 5 Series, 6 W, 12 V	20.3 x 31.8 mm, 33.8 g	3	50 Euro	Provides required output voltage and power	Easily ordered online	To be ordered online
11	HDC2010 Low Power Humidity Digital Sensors	1.5 x 1.5 x 0.675 mm, 15g	1	3 Euro	I2C interface, good temperature range, high accuracy	Easily ordered online	To be ordered online
12	Industrial temperature microSD XCUHS-I 8GB	15 x 11 x 1 mm, 0.5 g	1	20 Euro	Small, good temperature range, sufficient storage	Easily ordered online	Ordered
13	Logic CAT5E Network (2m)	2 m, 90g	1	7 Euro	Will be used for testing	Easily ordered in the nearest store	To be bought
14	Electrical wires	30g	30	15 Eur	For use in testing and the final PCB board and circuitry	Easily ordered online	To be ordered
15	Heat sinks	25g	5	5 Eur	For dissipating heat generated from components	Easily ordered online	To be ordered
16	Resistors	15g	3	1.5 Eur	For use in valve switching circuit	Easily ordered online	To be ordered
17	Transistors	18g	18	9 Eur	For use in valve switching circuit	Easily ordered online	To be ordered

Table 8: Table showing all required electrical components

4.3.2 Mechanical Components

Table 9 shows all required mechanical components with mass and price. Table cells highlighted in yellow denote values that have yet to be determined.

ID	Components	Specs (size,weight)	No.	Cost	Note	Availability	Status
1	Aluminum Bar	45cm	12	TBD[11]	Railed geometry, Structural element	Online	To be ordered
2	Aluminum Bar	40cm	8	TBD[11]	Railed geometry, Structural element	Online	To be ordered
3	Aluminum Bar	25cm	4	TBD[11]	Railed geometry, Structural element	Online	To be ordered
4	Aluminum Plate	50 x 40 x 0.2 cm	4	TBD[11]	Wall, Protective element	Store	To be ordered
5	Aluminum Plate	50 x 25 x 0.2 cm	4	TBD[11]	Wall, Protective element	Store	To be ordered
6	Aluminum Plate	50 x 50 x 0.2 cm	2	TBD[11]	Wall, Protective element	Store	To be ordered
7	Aluminum Plate	40 x 40 x 0.2 cm	2	TBD[11]	Wall, Protective element	Store	To be ordered
8	Styrofoam	2 m^2, 1cm thick	1	TBD[11]	Wall, Protective element	Store	To be ordered
9	Polyethylene foam	2 m^2, 1cm thick	1	TBD[11]	Wall, Thermal insulation	Store	To be ordered
10	Corner joint	0.2 x 0.2 cm	52	TBD[11]	Join structure bars, 90-degree angle	Online	To be ordered
11	Flange	Small	50	TBD[11]	Join tubes with valves	Store	To be ordered
12	Bar	45 x 0.8 cm	2	TBD[11]	Anchor point fro bags	Store	To be ordered
13	Handle	TBD[12]	4	TBD[11]	Experiment box manipulation	Store	To be ordered
14	Screw	TBD[12]	160	TBD[11]	Fixing elements	Store	To be ordered

Table 9: Table showing all required mechanical components

[11] Budget in Table 3.3.2 has estimated values. TBD here until exact values are figured out.
[12] Exact size depending on availability.

4.3.3 Other Components

Other components are included in the full budget previously presented in Table 6.

4.4 Mechanical Design

4.4.1 Structure

The experiment consists on two cubic boxes, one stacked next to the other. The smallest box -in red in Figure 8- allocates the heaviest element, the CAC. The main box-in grey in Figure 8- contains the AAC system as well as the general Electronic Box (EB). The frame of these two boxes will be made of aluminum bars which have a characteristic cross-section of 20x20 mm, see Figure 6. The rails will allow an easy interface between bars and other elements. Bars will be joined together by using 90-degree angles and corner cubes, see Figure 7.

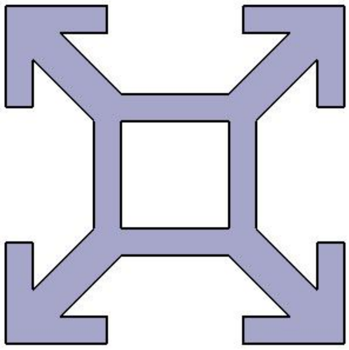


Figure 6: Cross section of the structural bars.

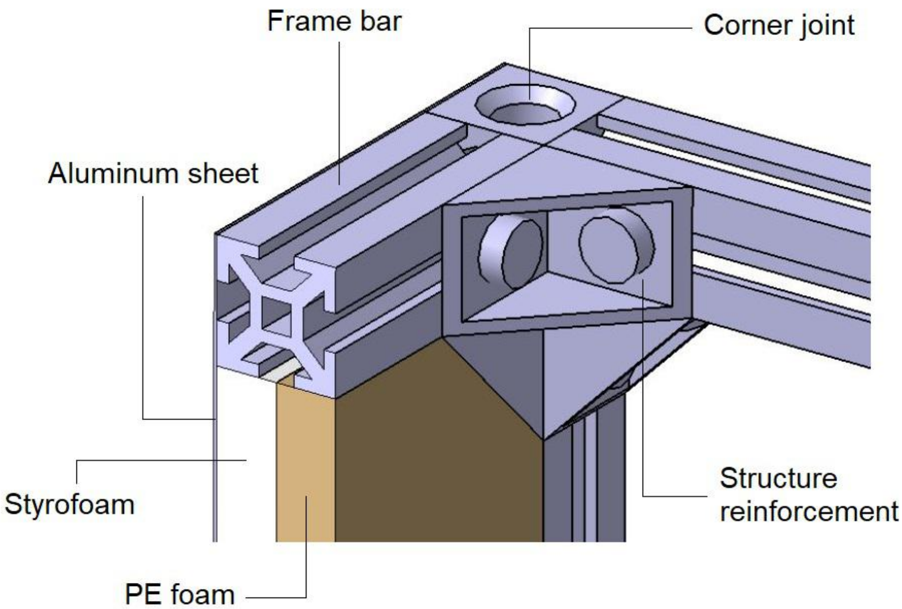


Figure 7: Interface between structural bars.

The frame is designed to withstand all vibrations and ensure a reliable stability of the entire system. Further tests will help to confirm and update the design if necessary.

The two-box design will allow ease of access and manipulation of both the CAC and AAC subsystems, see Figure 8. In addition, the AAC sampling system is designed to be re-usable for future handover to FMI, as such, it will be mountable on any standard balloon flight without having to introduce major design changes. The latter would imply to introduce a battery as a power unit, hence less bags could be carried (around 6 bags) in this potential future setup.

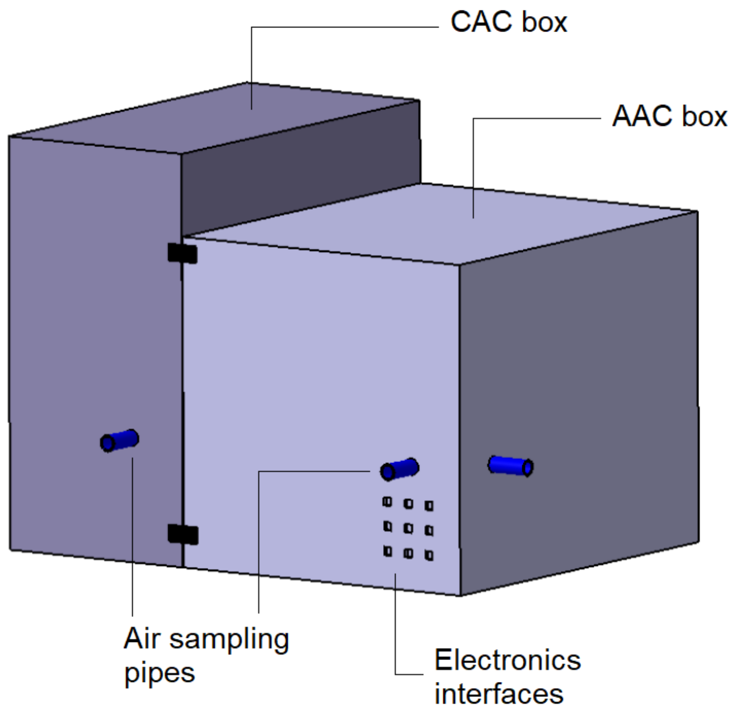


Figure 8: General configuration of the experiment.

4.4.2 CAC Subsystem

The CAC subsystem is designed to fit a 300-meter coiled tube, the valve governing it and a temperature sensor. To determine its positioning inside the gondola and the experiment box, some mechanical issues and gondola constraints must be considered.

Firstly, it is possible to identify the interface to attach the experiment box to the gondola as one of the most critical points in terms of mechanics performance. In the worst case scenario, with a heavy experiment and without a proper study of the aforesaid interface, shear in the screws could be produced after a violent landing stress. Since the CAC will be the heaviest component in the whole experiment, its location and orientation will affect directly the stress analysis of the structure. The larger the distance to the fixed points, the bigger the momentum produced by the component. Nevertheless, due to fast recovery implementation, the CAC tube will be placed vertically. Therefore, its dedicated box will be properly attached to the AAC box by means of 4 anchor points, in black in Figure 8. The fast recovery then will only imply unscrewing 4 screws and disconnecting a wire.

In order to command the valve, a wire will go out from the box and connected to the electronics interface panel located on an AAC box wall.

In addition, to avoid sample contamination with standstill air inside the gondola, the coil will have a direct outside inlet and outlet by means of an extension tube reaching further from the gondola's limits, in blue in the red box in Figure 8.

4.4.3 AAC Subsystem

The AAC Subsystem consists of 10 three-liter sampling bags. Each bag will have a dedicated valve in the Valve Center (VC) to allow emptying and filling processes as well as to close the bag when needed. The bags will be placed vertically and will have two anchor points: on the top through a multiple anchor interface (see Figure 9) and on the bottom by means of the tubes connecting them to the valves.

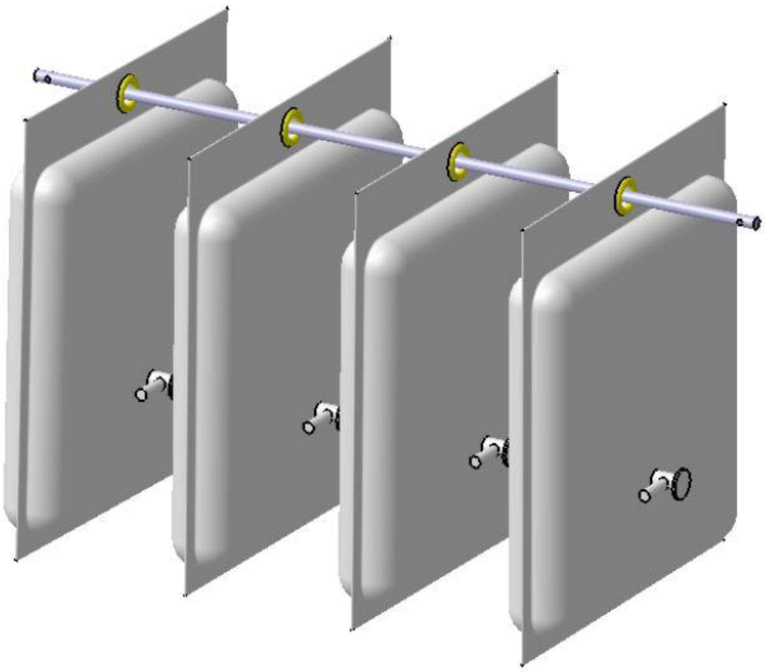


Figure 9: Sampling bags with fixing interface.

4.4.4 Electronics Box

The OBC and its external elements will be allocated in a bottom corner of the experiment box, inside AAC box, and on the opposite side of the CAC box. This will allow an easy access and manipulation as well as the required external interfaces, holes in Figure 8. The smallest side of the EB will have the outer connections interfaces. Hence, the wall will have the necessary holes. The EB will be fixed to the AAC box structure bars in 3 different points.

4.4.5 Valve Center

The valve center consists of a coated box to which the AAC's 10 air sampling bags will be attached to. This box will serve as airflow chamber. It will be connected to a pipe from which outside air will be pumped and also enable pre-sample collection flushing. The pump providing the airflow will be allocated on the inlet side and protected by an air filter. It will be allocated inside a shielding box, more detailed information in section 4.6. The pipes used for both intake and outlet can be seen in blue in the grey box in Figure 8.

Both the pump box and the valve center will be allocated above the EB so all the command center is at the same place. Having them together will provide as well a proper cooling system monitored by several temperature sensors.

4.4.6 Protection

In order to protect the components from all kind of external elements, the experiment box will be shielded with removable aluminum walls along with a thick layer of Styrofoam combined with Polyethylene foam attached to each wall. No internal space will be lost since the total foam thickness is the same as that of the structural bars. Isolating sheets will also be glued in the walls to reinforce the temperature shielding.

The walls will properly protect both the CAC coiled tube and the AAC sampling bags from any external element, unexpected rapid movements, and a probable hard landing impact.

The front walls, face of the experiment box exposed to the outside, will have several holes: to allow the tubes providing air flow to collect clean air from the outside, and to manipulate the electric connections.

Bolts shall be used to attach all walls to the structure's railed bars.

4.4.7 Fixing Interface

The two experiment box subsystem structures will be joined together by four anchor points, in black in Figure 8. On the front and back side, two flat plates with two bolts each will interface both structures.

This method will allow for easy and fast recovery of the CAC box.

4.4.8 Manipulation Interface

The two-box system will be fixed to the gondola rails by using four 90-degree angles, 2 per rail. All the anchor points to the gondola will be in the AAC box since the CAC box will be already attached to it. The latter also ensures that the AAC box will remain properly fixed in the gondola after the CAC fast recovery.

In order to access the experiment once fixed in the gondola, the walls could be removed when necessary providing access in all three directions. They can be screwed in again once the manipulation is done.

Several handles will be placed to allow an easy and safe manipulation of both the CAC and the AAC boxes.

4.4.9 Mechanical Components

All the components used in the mechanical design can be found in Table 9. Spare elements are not included.

4.5 Electrical Design

4.5.1 Block Diagrams

The electronics design can be seen in Figure 10 and the interfaces this requires can be seen in Figure 11. There will be four distinct areas, the Electronics box, the valve centre, the pump box and the CAC system. All connections to the outside of the box are located in the electronics box. These are the voltage regulators for the external power source and the Ethernet shield with an SD data storage which will connect to the Telemetry, Tracking, and Command (TT&C). Additionally one pressure sensor, one heater and one temperature sensor will be placed in this area. The CAC system area will contain three temperature sensors to monitor its ambient temperature and one electronic valve to be closed before landing. In the AAC system area there will be eleven valves, one airflow sensor, one pressure sensor, five temperature and one humidity sensor and a heater. In the pump box there will be the miniature diaphragm air pump, one temperature sensor and one heater.

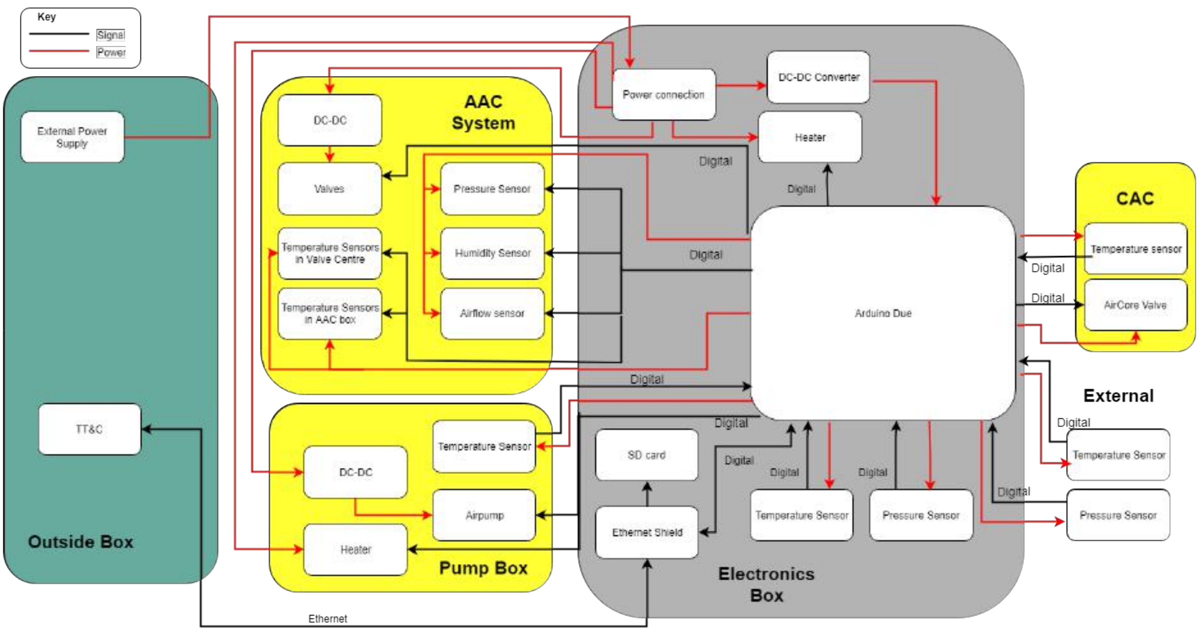


Figure 10: Block Diagram for all Electronic Components Showing the Signal and Power Connections

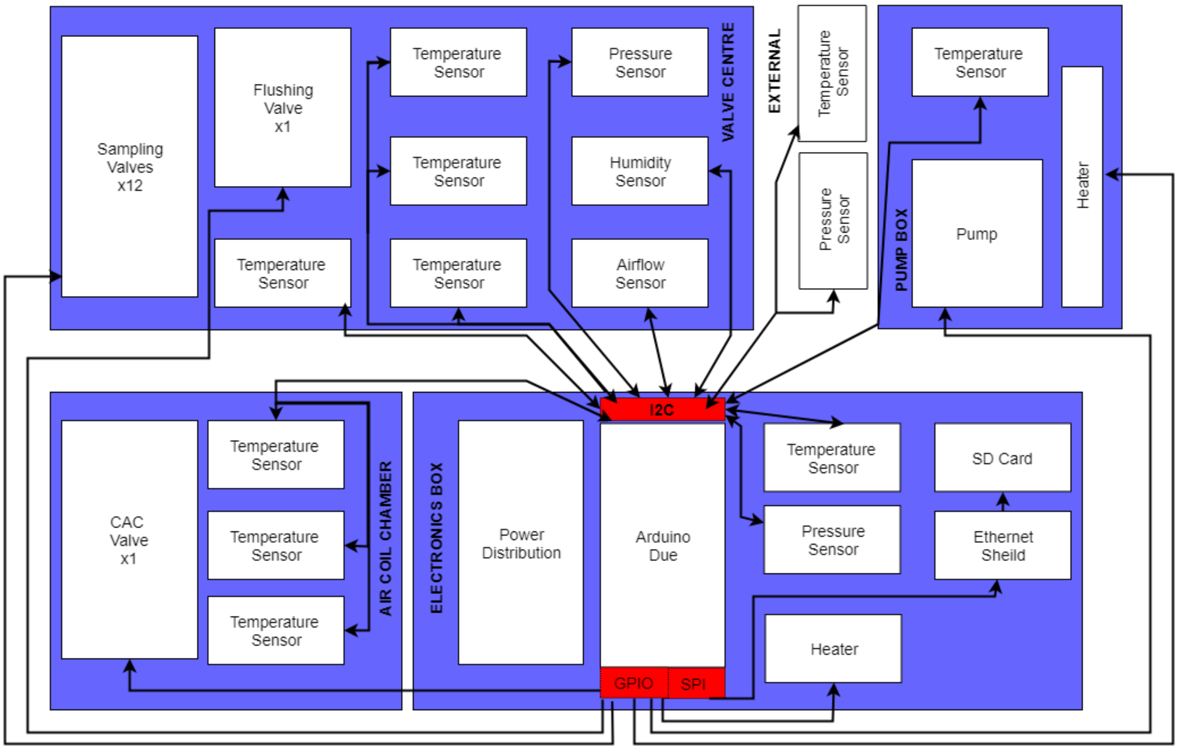


Figure 11: Block Diagram Showing the Interfaces Between All Electrical Components.

Three DC-DC converters will be used to step down the voltage from the 28.8V provided by the gondola down to:

- $28.8V \implies 12V$ for the Arduino.
- $28.8V \implies 24V$ for the valves.
- $28.8V \implies 24V$ for the pump.

The heaters will not require the voltage to be stepped down and so will be powered directly from the gondola battery.

4.5.2 Miniature Diaphragm Pump

The pump which has been selected is the KNF 850.1.2. KNDC B, Figure 12, which is manufactured by KNF. One of the reasons this pump has been selected is that it has successfully been flown on a similar flight in the past [2]. On this flight it managed to pump 180mL of air at 25km altitude. However, to ensure the pump will operate as intended several low pressure and low temperature tests will be completed.

The pump has a maximum flow rate of 8.0LPM when at ambient pressure. This is in excess of the required flow rate as the flow rate will decrease as the altitude increases. As the pressure decreases the current required by the pump will increase until it hits a peak current draw of 340mA. However as seen in Figure 13 the peak current then decreases as the pressure continues to decrease. It is also worth noting that whilst the flow rate appears to decrease too much Figure 13 is assuming that this is the pressure differential. Our bags will not be at vacuum and they will not be pressurized therefore the expected flow rate performance is higher.

Figure 12: KNF 850.1.2. KNDC B Miniature Diaphragm Pump

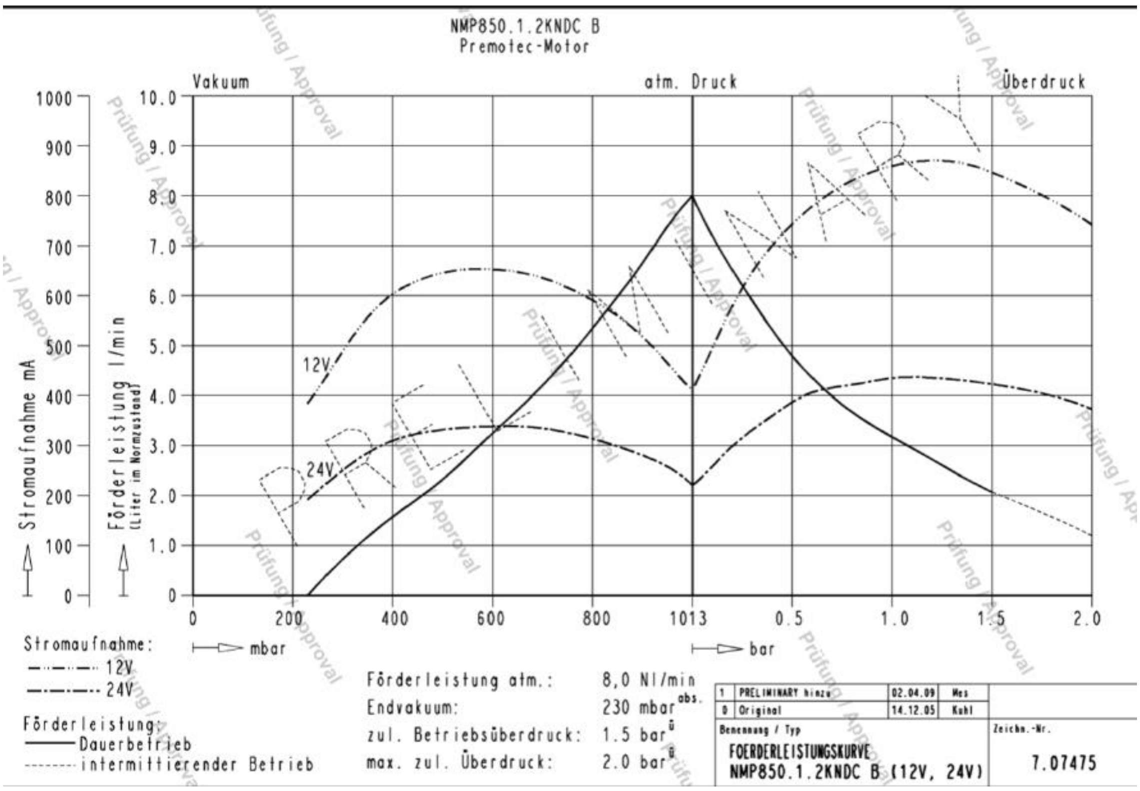


Figure 13: KNF 850.1.2. KNDC B Flow Rate and Current Draw to Pressure Graph.

4.5.3 Electromagnetically Controlled Valves

Filling of the air bags will be controlled by the solenoid valves. For this purpose Parker solenoid valve 121K63, Figure 14, with the 24 VDC input, Figure 15, has been selected after careful consideration of the different options available in the market and keeping the experiment requirements in mind. The valves will be normally closed through out the experiment with zero power consumption and will be open, when given power, to fill up the air bags at specific altitudes or to flush the tubes.

Figure 14: Valve

Figure 15: Coil

The port size of the valve is 1/4" which is compatible with the gas analyzer. The coil can withstand temperature from -40 to 50 °C which is suitable for flight operations at high altitudes. Although the valve can operate under a maximum pressure drop of 100 bar it also needs to be tested at intended low pressure values. For this purpose one valve with the motor and a shield, Figure 16, has already been ordered.

Figure 16: Shield

4.5.4 Valve Driving Circuit

The valves will be powered through a 50W DC-DC converter that will step down the 28.8V to 24V. They will also have a connection to the Arduino so that they can be controlled. In order to allow this connection a switching circuit has been devised using a power MOSFET and a BJT. This circuit is detailed in Figure 17.

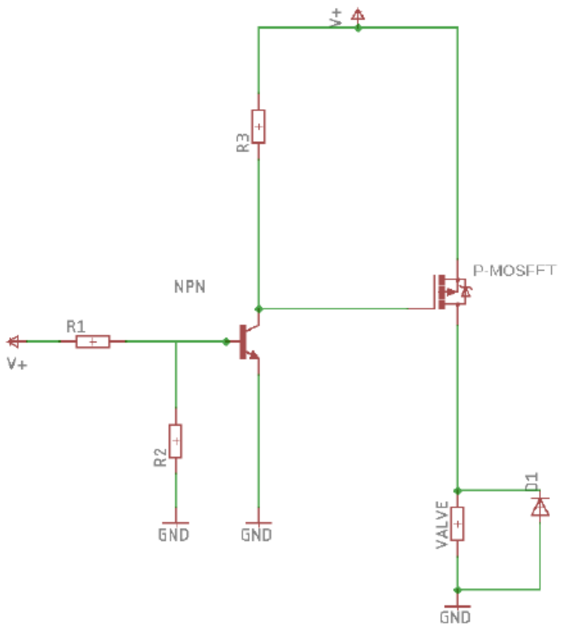


Figure 17: Schematic showing the switching circuit to drive the valves through the Arduino

The power MOSFET will control the valves ON-OFF state whilst the BJT will connect directly to the Arduino and ensure that the valve is only turned on when a true signal is given. The power MOSFET will be on when the BJT is on. The BJT will be on when a signal of 3.3V is given and off when a signal of 0V is given. Three resistors will also be used.

4.6 Thermal Design

4.6.1 Thermal Environment

The experiment will experience a wide range of temperatures during the flight and it must be able to continue to operate despite these changes. As seen in Figure 18 the coldest point of the flight will be between 15km and 20km where the air temperature can drop to -80°C and temperatures on the gondola have been recorded as low as -40°C during the float phase in the past [5]. In addition launching from Kiruna in late October means the temperature on the ground could be as low as -15°C. As our lowest operating temperature component must be at a minimum of 0°C this could mean heaters may need to be switched on while the experiment is still on the ground.

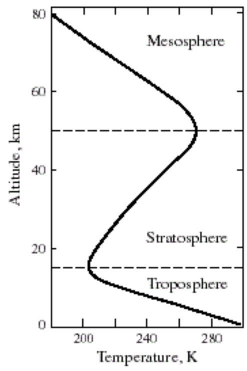


Figure 18: Diagram showing the temperature profile of the atmosphere [7]

4.6.2 Overall Design

To protect the components against the cold two heaters will be included. One of these will be placed close to the Arduino, which is anticipated to be able to keep the controller area warm enough, and the second will be placed close to the valves to ensure they continue to operate as expected. To control these heaters two temperature sensors will also be onboard in similar locations. If the reading from one of the temperature sensors is lower than the predefined value then the heater will turn on.

In addition to using electrical heaters the experiment will also be thermally insulated. The Styrofoam casing which will be used to protect the CAC from impact forces will also serve as insulation. It is also planned to add additional insulation around the components.

It is also important to consider heating from the sun which could raise the temperature of the experiment considerably. Sufficient insulation should be included to ensure the inside of the box stays within the operating temperature range. This will be investigated at a later date when a full CFD thermal analysis is completed.

ID	Components	Operating T (°C)		Survivable (°C)	
		Min.	Max.	Min.	Max.
1	Arduino Due	-40	85	-60	150
2	Arduino Ethernet Shield 2	-40	85	-65	150
3	KNF 850.1.2.KNDC BMiniature Diaphragm Pump	5	50	-20	100
4	Barometric Pressure Sensor MS5607-02BA03	-40	85	-40	125
5	Electromagnetically controlled valve	-40	50	-40	50
6	Airflow sensor AWM40000 Series	-40	125	-40	125
9	Temperature sensor VSSOP-8, LM70, LM70CIMM-5/NOPB	-55	150	-65	150
10	DC-DC step converter	-40	85	-50	125
11	HDC2010 Low Power Humidity Digital Sensors	-40	85	-40	125
12	Industrial temperature microSD XCUHS-I 8GB	-40	85	-40	85

Table 10: Thermal Table

4.6.3 Internal Temperature

As the current experiment model stands, an enclosed partition has been reserved in the lower front-right corner of the AAC section of the TUBULAR experiment. This partition will house all of the electronic components not required to be situated in specified locations throughout the experiment setting, such as some of the sensors.

Inside this partition will be three separate insulated boxes. The first of these is the Electronics box which will occupy a space measuring 20 cm in length, 10 cm in width, and 20 cm in height, and will be insulated from inside to outside with polyethylene, polystyrene, and finally aluminum. The infrastructure within this enclosure shall be such that the electronics are fitted together to in turn be bound within another box of insulated material (likely made from PVC).

Above the electronics box will be the second internal box, the pump box, where the pump will be situated and the third internal box, the valve centre, where the valves will be situated. The valves will be routed together by several tubes to form a compact structure aiding the thermal control over this area.

One heater will be included in the electronics box with its main priority being keeping the Arduino Due board within operational temperatures whilst delivering the remaining heat to peripheral electronics. The other heater will be fitted between the pump and the entrances to the valve center and will keep its lateral neighbors within their respective operational temperature ranges.

The pump has the most critical temperature range as it is the only component that cannot operate below freezing temperatures. It's data sheet states it must always be no colder than 5°C, or the EPDM diaphragm may not be able to expand and contract sufficiently to maintain the desired airflow of 8L/min. However as this pump has been used successfully on flights before, [2], tests will be conducted on the pump to find its true performance at lower temperatures. The valves are also crucial to the experiment's function, as they enable each and every sampling bag onboard to be used. For this reason, while the valves can operate down to -43°C, it is desirable to be keep them above this limit whenever in use.

Given the thermal conductivity of EPDM ($0.2W/(m.K)$), the pump's diaphragm experiences a minimal temperature drop across itself when one side is subject to the heater's temperature while the other end of the pump is leveled with the ambient temperature. Through calculation it was found that at an ambient temperature of -50°C and a heater temperature at 10°C, the center of the pump, the far end of the diaphragm, measured 9.35°C. Reassessing the equation yielded the most energy-conserving temperature that would keep the pump's diaphragm above the minimum requirement to be 7°C. This held whether the temperature was as it could be on ground level (-10°C), or in floating phase (-50°C).

Symbols used are the following:

- T_{inlet} = Temperature at the pump inlet face
- T_{heated} = Temperature at the pump's diaphragm face (directly heated)
- L_{inlet} = Length of the pump inlet valve(s)
- L_{phragm} = Length of the pump's diaphragm
- k_{PPS} = Thermal conductivity of the pump's inlet valve(s) made of PPS
- k_{EPDM} = Thermal conductivity of the pump's diaphragm made of EPDM
- k_{air} = Thermal conductivity of the air entering the pump
- k_{phragm} = Averaged thermal conductivity of the pump's diaphragm (Assumed 4 parts air to 1 part EPDM)
- T_{med} = Temperature halfway across the pump (start of the diaphragm)

$$
\begin{aligned}
T_{inlet} &= 263K \\
T_{heated} &= 283K \\
L_{inlet} &= 0.038m \\
L_{phragm} &= 0.038m \\
k_{PPS} &= 2\frac{W}{m \cdot K} \\
k_{EPDM} &= 0.2\frac{W}{m \cdot K} \\
k_{air} &= 0.024\frac{W}{m \cdot K} \\
k_{phragm} &= \frac{(k_{EPDM} + 4_{air})}{5} = 0.06\frac{W}{m} \\
T_{med} &= \frac{(k_{phragm} \cdot L_{inlet} \cdot T_{inlet}) + (k_{PPS} \cdot L_{phragm} \cdot T_{heated})}{(k_{phragm} \cdot L_{inlet}) + (k_{PPS} \cdot L_{phragm})} \\
T_{med} &= \frac{(0.06 \cdot 0.038 \cdot 263) + (2 \cdot 0.038 \cdot 283)}{(0.06 \cdot 0.038) + (2 \cdot 0.038)} \\
T_{med} &= 282.35K \longrightarrow 9.35°C
\end{aligned}
$$

Reworking the equation to fit the inlet face at the true ambient temperature of -50°C and the reduced heater temperature of 7°C gives the following:

$$
\begin{aligned}
T_{inlet} &= 223K \\
T_{heated} &= 280K \\
T_{med} &= \frac{(k_{phragm} \cdot L_{inlet} \cdot T_{inlet}) + (k_{PPS} \cdot L_{phragm} \cdot T_{heated})}{(k_{phragm} \cdot L_{inlet}) + (k_{PPS} \cdot L_{phragm})} \\
T_{med} &= \frac{(0.06 \cdot 0.038 \cdot 223) + (2 \cdot 0.038 \cdot 280)}{(0.06 \cdot 0.038) + (2 \cdot 0.038)} \\
T_{med} &= 278.28K \longrightarrow 5.28°C
\end{aligned}
$$

4.6.4 Box Analysis

For the box temperature to be properly estimated, the other two divisions within the component enclosure need to be taken into account. The manifold comprising the valve center is made of a compound of nylon (assumed to be nylon-6) and kynar. It has also been assumed they are used equally in mass and distribution at this stage of the thermal estimation.

Symbols used are the following:

- T_{outlet} = Temperature at the manifold's outlet(s)
- T_{heated} = Temperature of the pump at its diaphragm face
- $L_{outhalf}$ = Length of the outer half of the manifold
- L_{inhalf} = Length of the inner half of the manifold
- $k_{Nylon-6}$ = Thermal conductivity of Nylon-6
- k_{Kynar} = Thermal conductivity of Kynar
- $k_{manifold}$ = Averaged thermal conductivity of manifold

$$
\begin{aligned}
T_{outlet} &= 263K \\
T_{heated} &= 283K \\
L_{outhalf} &= 0.038m \\
L_{inhalf} &= 0.038m \\
k_{Nylon-6} &= 0.24\frac{W}{m \cdot K} \\
k_{Kynar} &= 0.162\frac{W}{m \cdot K} \\
k_{manifold} &= \frac{k_{Nylon-6} + k_{Kynar}}{2} = 0.201\frac{W}{m \cdot K} \\
T_{med} &= \frac{(k_{manifold} \cdot L_{inhalf} \cdot T_{heated}) + (k_{manifold} \cdot L_{outhalf} \cdot T_{outlet})}{(k_{manifold} \cdot L_{inhalf}) + (k_{manifold} \cdot L_{outhalf})} \\
T_{med} &= \frac{(0.201 \cdot 0.040 \cdot 223) + (0.201 \cdot 0.040 \cdot 280)}{(0.201 \cdot 0.040) + (0.201 \cdot 0.040)} \\
T_{med} &= 251.59K \longrightarrow -21.41°C
\end{aligned}
$$

Below, in Figure 19 is a theoretical general arrangement of the components within the enclosure, seen from the front of the experiment inward.

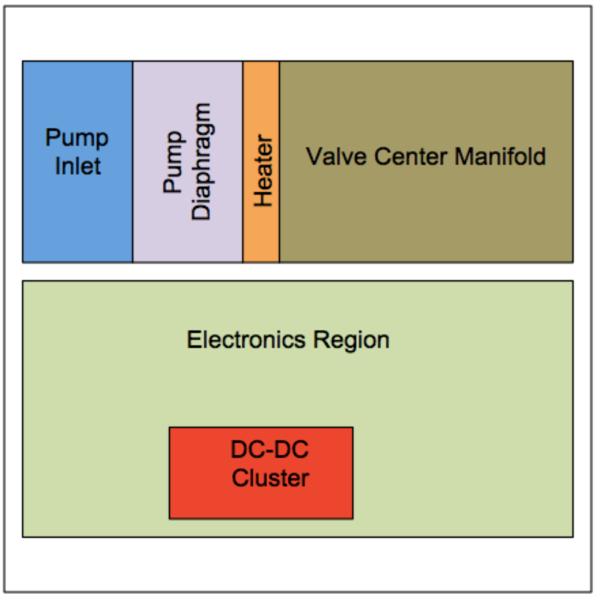


Figure 19: Diagram showing a general layout of the AAC components

A rough estimation of temperature gradients can thus be shown in Figure 20:

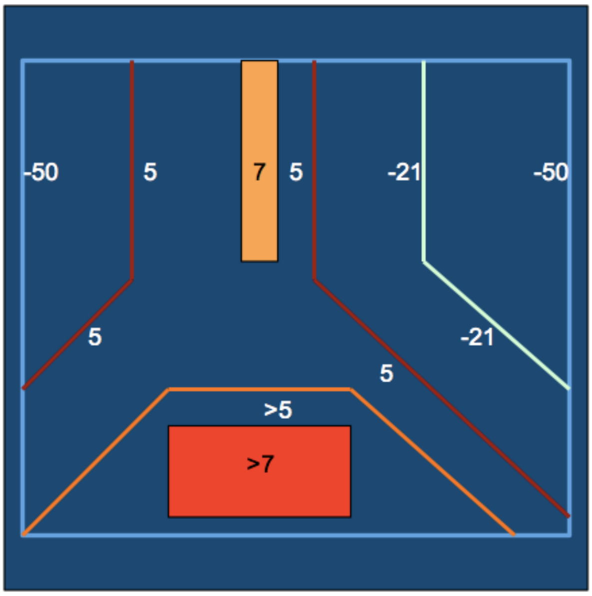


Figure 20: Diagram of the previous layout now showing temperature contours

4.7 Power Design

4.7.1 Power System Requirements

The Gondola provides 28.8 V or 13 Ah battery with a recommended maximum current draw of 1.8A [5]. The experiment must run on external power from 4 hours before launch during the countdown phase and for the entire flight duration, lasting approximately 4 hours. As a factor of safety the experiment should be able to run for an additional 2 hours.

ID	Component	Voltage [V]	Current [mA]	Power [W]	Total [Wh]
1	Arduino Due	12	30	0.36	36
3	KNF 850.1.2.KNDC BMiniature Diaphragm Pump	24	320	7.68	7.68
4	Barometric Pressure Sensor MS5607-02BA03	3.3	1.4	0.00462	0.1
5	Electromagnetically controlled valve	24	458	11	75
6	Airflow sensor AWM40000 Series	10	6	0.060	0.6
7	Polyimide Thermofoil Heaters HK5161R78.4L12	28	357	10	100
8	Polyimide Thermofoil Heaters HK5160R157L12	28	179	5	50
9	Temperature sensor VSSOP-8, LM70, LM70CIMM-5/NOPB	5.5	0.49	0.002695	0.054
10	DC-DC step converter	28	500 (output)	0.09	0.9
11	HDC2010 Low Power Humidity Digital Sensors	3.3	0.0005	1.65×10^{-6}	16.5×10^{-6}
-	**Total**	-	1811	44.77	270
-	**Available from gondola**	-	-	-	374

Table 11: Power Design Table

4.7.2 Power System Control and Regulation

The power on board will be split using three DC-DC converters. The pump and valves both have a high peak current. Therefore it was decided to use two DC-DC converters to step down from 28.8V to 24V giving the pump its own dedicated DC-DC converter. This is as the pump and valves both have a high peak current draw. The Arduino will also have its own DC-DC converter stepping the voltage down from 28.8V to 12V. It is thought using three DC-DC converters will provide the best compromise between efficiency, cost and heating.

4.8 Software Design

4.8.1 Purpose

The purpose of the software is to automatically control the valves so that they will be opened/-closed at the designated altitude. Moreover, the software will store housekeeping data from sensors, pump and valves states to the on-board memory storage device. To determine a vertical profile, the acquisition of sensor data is required. From Olivier's research:

> "In order to determine the vertical profiles of CO_2 and CH_4 from the analysis of sampled air, measurements of several atmospheric parameters are needed (see Sect. 2.3). The two most important parameters are the ambient pressure and the mean coil temperature. Those parameters are recorded by the AirCore-HR electronic data package. Mean coil temperature is obtained by taking the mean of three temperatures recorded by independent probes located at different positions along the AirCore-HR".[4]

The next purpose is to transmit such data to the ground. It will allow the team to monitor the real-time condition of the experiment. Telecommand is also needed to take over the experiment if the software automation fails, since this experiment is highly dependent on the software. It will also be used to test the system, especially valves and heaters.

4.8.2 Design

(a) Process Overview
The software which run on Arduino Due reads from the sensors through the I2C interface. The sensors provides temperature, pressure, airflow and humidity data. The acquired data will be time-stamped and stored on the on-board SDcard and transmitted via the E-Link System to the ground station. Then according to the pressure/altitude, the software controls the valves which will allow the air to flow inside the tube and bags. Figure 21 visually explain the process flow.

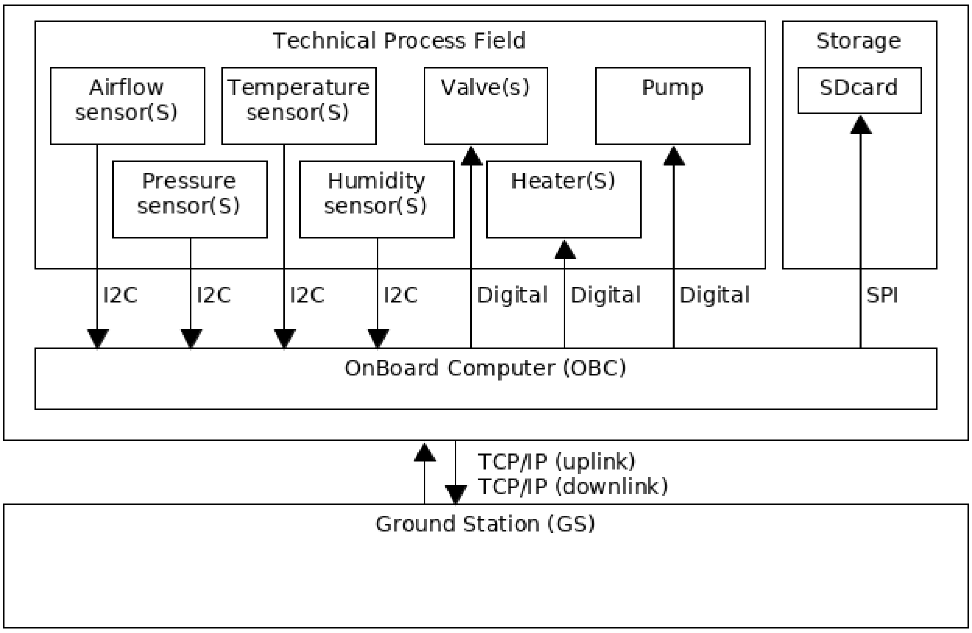


Figure 21: The process overview of the experiment

(b) General and Safety related concepts
Watchdog timer, which is an electronic countdown timer that causes an interrupt when it reaches 0, will be used to avoid failure because of a freezing software. During normal operations, the software will regularly reset the the watchdog timer to prevent it from elapsing, or "timing out". Telecommands will also be used as backup in case the automation fails or otherwise become unresponsive. Telemetry will be utilized to transmit housekeeping data and the state of the valves to get conformation of operation. Rigorous testing will be performed during the development of the project and before the launch phase to insure that that the software is capable to control the experiment.

Watchdog has been suggested to be removed in Preliminary Design Review. However, it is still a good feature for automatic reset in case the software freeze/stuck. Therefore, the watchdog will be kept and shall be tested before Critical Design Review.

(c) Interfaces
Table 12 demonstrates how the components will interact with the onboard computer (OBC). Components that use SPI, will share MISO, MOSI, and CLK pins on the Arduino board. Each of them will also be connected to general pins input output (GPIO) for slave select. Furthermore, components using I2C protocol, will share Serial Data pin (SDA) and Serial Clock pin (SCL).

Components interacting	Communication protocol	Interface
Pressure Sensors-OBC	I2C	Arduino I2C
Temperature sensors-OBC	I2C	Arduino I2C
Airflow sensor-OBC	I2C	Arduino I2C
Heaters-OBC	Digital	GPIO pins
Air pump-OBC	Digital	GPIO pins
Valve-OBC	Digital	GPIO pins
OBC-microSD Storage	SPI	Arduino Ethernet shield
OBC - E-Link	Ethernet	Ethernet port

Table 12: Communication and interface protocols

Every transmission to/from the ground will utilize the E-link connection. The data packet which will be used is Ethernet Packet with a header contains the address of destination, followed by the data, and at the end there is a frame check sequence (FCS). The uplinked data packet will have the same structure, with header followed by commands and ended with FCS.

(d) Data Acquisition and Storage
Data will be stored on the SD memory card on the Arduino Ethernet Shield. It is estimated that for the entire flight, all the sensors will produce 650 kilo bytes or 5.2 mega bits of data. The sampling rates of the sensors are dependent on the modes (see Figure 22). In standby mode, the sampling rate is 1 per 10 seconds, since this is not the essential part. The sampling rate is increased in the Normal Operation (ascent) mode to 1 per seconds. Moreover, in the the descent phase of the experiment, the sampling rate will be increased significantly to 10 per one second.

The data will be collected and presented as a matrix, where the first column is the time frame, the following columns are the sensors data. After the sensors data, there will also be housekeeping data, that keeps track of the valves, and heaters states. However, the size of the housekeeping data is not expected to surpass 20 bits per sampling.

Data will be continuously down-linked and the total telemetry size is 4.788 MB for 5 hours of flight.

(e) Process Flow
The process flow can be explained with the mode diagram in figure 22. The software will start with Standby Mode, in which the software will get samples from all sensors. When the software got reading of pressure changes (decrease), it will change to Normal - Ascent mode, where the software will empty the tube and bags by opening the valves. Then, at certain altitudes, air sampling will be conducted during ascending phase. During floating phase, there will be nothing conducted. The software will go to Normal - Descent mode when it sense when the pressure reduction is considerably big, where the software will sample the air by opening the valves for each bag in their designated altitude. The air sampling during descent phase will only be started after the gondola stabilize after cut-off. The software will know this by the reduction of pressure value readings. The experiment goes to SAFE mode about $500\,m$ before the landing, where all the valves will be closed.

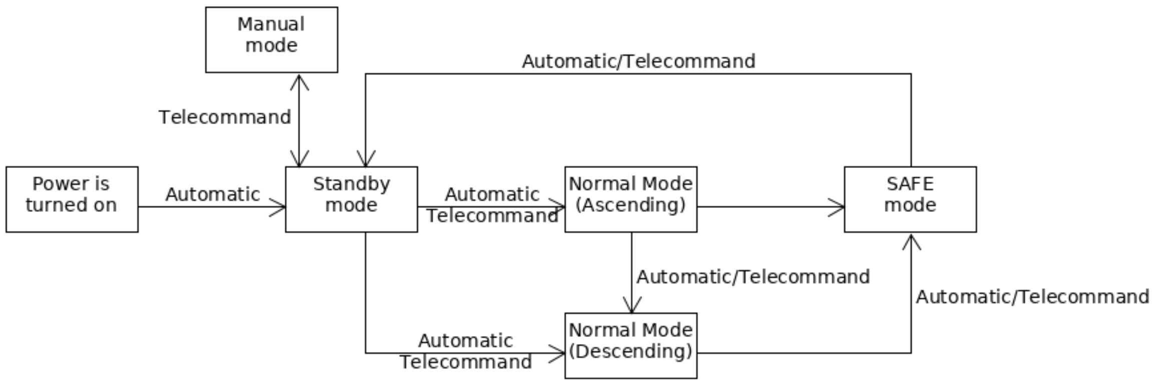


Figure 22: Process diagram for the modes

(f) Modularization and Pseudo Code

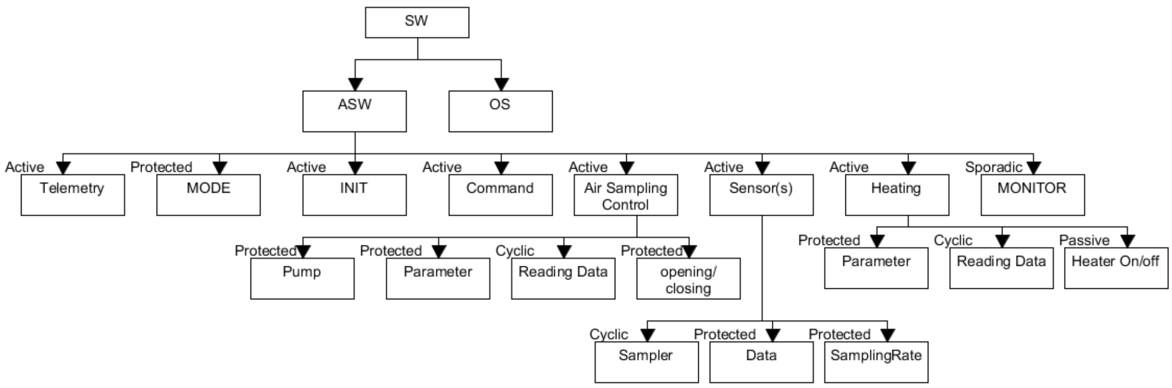


Figure 23: Onboard Software Design Tree

The software design is produced by using object oriented approach. The functionality of the experiment has been divided into several objects and their children. The design tree is shown in Figure 23.

The Telemetry object is responsible to format the sensor/housekeeping data, and to transmit it. MODE is responsible for controlling the four modes of software. INIT will initialize the necessary software programs. COMMANDS reads the telecommands and execute their commands. The AIR SAMPLING CONTROL object have the four children objects. The first child is responsible for controlling the pump. The second child contains the parameters for the valves and pump. The third child reads the data from the sensors, a fourth child is responsible for manipulating the valves.

The SENSOR object have two children objects. One for sampling the sensors and another for recording and storing the housekeeping data. The HEATER object have three children objects. One for reading the temperature sensor data, another for deciding if the heaters should be turn on/off. And the third child for turning it on/off.

Each of the objects interacts with each others fulfilling mutually exclusive interaction. It means that any shared variables can only be accessed by one object at time. This is important considering the program is be fully automatic and to prevent unnecessary data lost. The objects interface diagrams and their sequence diagrams can be found in Appendix B and C.

4.8.3 Implementation

The C/C++ programming language is used when programming the platform. Software's as Arduino IDE will be used, other software will be used if necessary. A real-time operating system is under consideration and might be implemented if its use is found warranted.

4.9 Ground Support Equipment

One personal computer will be used to connect to the E-Link through the Ethernet port. A GUI will be created to display the sensors data and a feature to change the parameters in the experiment. The GUI for the ground station shall be with MATLAB programming language and IDE.

The data shall be recorded and stored on the computer.

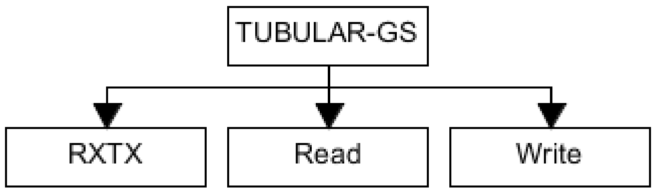


Figure 24: The ground control software design tree

Figure 24 shows the preliminary design of the ground station. The RXTX object is responsible for receiving and transmitting data over the provided Ethernet connection. The READ object takes the input received from the user, and the DISPLAY object takes data received from the RXTX object and show the data to the user through the GUI.

5 Experiment Verification and Testing

5.1 Verification Matrix

The verification matrix is made following the standard of *ECSS-E-10-02A*. [9]

There are four established verification methods:
A - Verification by analysis or similarity
I - Verification by inspection
R - Verification by review-of-design
T - Verification by testing

Currently, no verification has yet transpired due to the hardware and software components potentially fitting the requirements still being sought and ordered and/or requested. As the project advances and the parts for each division arrive or are developed, the verification methods will be revised, and test numbers and status will be assigned.

ID	Written requirement	Verification	Test number	Status
F.1	~~The experiment *shall* collect air samples.~~[1]	-	-	
F.2	The experiment *shall* collect air samples by the CAC.	A, R	-	
F.3	The experiment *shall* collect air samples by the AAC.	A, T	2, 16	
F.4	~~The experiment's AAC System *shall* be able to collect air samples during the ascent phase.~~[1]	-	-	
F.5	~~The experiment's AAC System *shall* be able to collect air samples during the descent phase.~~[1]	-	-	
F.6	The altitude from which a sampling bag will start sampling *shall* be programmable.	A,T	10	
F.7	The altitude from which a sampling bag will stop sampling *shall* be programmable.	A,T	10	
F.8	~~The experiment *shall* pump air into the AAC Sampling Bags.~~[1]	-	-	
F.9	The experiment *should* collect data on the air intake flow to the AAC.	A, T	21	
F.10	The experiment *shall* collect data on the air pressure.	A, T	21	
F.11	The experiment *shall* collect data on the temperature.	A, T	21	
F.12	The experiment *shall* collect data on the humidity.	A, T	21	
F.13	~~The experiment *shall* measure the temperature inside the AAC Valve Box.~~ [1]	-	-	

F.14	~~The experiment *should* measure the humidity inside the AAC Valve Box.~~[1]	-	-	
F.15	~~The experiment *shall* measure the time.~~ [2]	-	-	
F.16	~~The experiment *shall* accept telecommand instructions to programme AAC sampling altitudes for each sampling bag.~~[1]	-	-	
F.17	~~The experiment *shall* accept telecommand instructions to open designated valves.~~[1]	-	-	
F.18	~~The experiment *shall* accept telecommand instructions to close designated valves.~~[1]	-	-	
F.19	~~The experiment *may* accept telecommand instructions to change the sampling rate of the ambient pressure sensor.~~[1]	-	-	
F.20	~~The experiment *may* accept telecommand instructions to change the sampling rate of the Electronics Box temperature sensor.~~[1]	-	-	
F.21	~~The experiment *may* accept telecommand instructions to change the sampling rate of the AAC Valve Box temperature sensor.~~[1]	-	-	
F.22	~~The experiment *may* accept telecommand instructions to turn on the air pump.~~[1]	-	-	
F.23	~~The experiment *may* accept telecommand instructions to turn off the air pump.~~[1]	-	-	
F.24	~~The experiment *may* accept telecommand instructions to turn on the Valve Heater.~~[1]	-	-	
F.25	~~The experiment *may* accept telecommand instructions to turn off the Valve Heater.~~[1]	-	-	
F.26	~~The experiment *may* accept telecommand instructions to turn on the Electronics Box Heater.~~[1]	-	-	
F.27	~~The experiment *may* accept telecommand instructions to turn off the Electronics Box Heater.~~[1]	-	-	
P.1	~~The telecommand data rate *shall* not be over 10Kb/s.~~[3]	-	-	
P.2	~~The default sampling rate of the ambient pressure sensor during Standby mode *shall* be 0.1 Hz.~~[13]	-	-	
P.3	~~The default sampling rate of the ambient pressure sensor during Normal operation ascent mode *shall* be 0.2 Hz.~~[13]	-	-	
P.4	~~The default sampling rate of the ambient pressure sensor during Normal operation descent mode *shall* be 10 Hz.~~[13]	-	-	

[13] Replaced by P.23

P.5	~~The default sampling rate of the AAC Valve Box temperature sensor *shall* be 1 Hz.~~[13]	-	-	
P.6	~~The programmable sampling rate of the ambient pressure sensor *shall* not be lesser than 0.1 Hz.~~[13]	-	-	
P.7	~~The programmable sampling rate of the ambient pressure sensor *shall* not be greater than 100 Hz.~~[13]	-	-	
P.8	~~The programmable sampling rate of the Electronics Box temperature sensor *shall* not be lesser than 1Hz.~~[13]	-	-	
P.9	~~The programmable sampling rate of the Electronics Box temperature sensor *shall* not be greater than 7Hz.~~[13]	-	-	
P.10	~~The programmable sampling rate of the AAC Valve Box temperature sensor *shall* not be lesser than 1 Hz.~~[13]	-	-	
P.11	~~The programmable sampling rate of the AAC Valve Box temperature sensor *shall* not be greater than 7 Hz.~~[13]	-	-	
P.12	The accuracy of the ambient pressure measurements *shall* be -1.5/+1.5 mbar for 25°.	I, T	5, 10	
P.13	The accuracy of the temperature measurements *shall* be +3.5/-2°C(max) for condition of -55°C to 150°C.	I, T	5	
P.14	The accuracy of the ambient humidity measurements *shall* be +-3%.	I [14]	-	
P.15	~~The accuracy of the AAC Valve Box temperature measurements *shall* be +3.5/-2°C(max).~~[5]	-	-	
P.16	The air intake rate of the air pump *shall* be 3L/min.	A, T [14]	18	
P.17	The temperature of the Electronics Box *shall* be between 0°C and 25°C.	A, T	5	
P.18	~~The temperature of the Electronics Box *shall* not exceed 25°C.~~[6]	-	-	
P.19	The temperature of the AAC Valve Box *shall* be between 0°C and 25°C.	A, T	5	
P.20	~~The temperature of the AAC Valve Box *shall* not exceed 25°C.~~[7]	-	-	
P.21	The AAC air sampling *shall* filter out all water molecules before filling the sampling bags.	A, T	17	
P.22	~~The CAC air sampling *shall* filter out all water molecules before filling the tube.~~[8]	-	-	

[14] The other elements still need to be found either in the store or online.

P.23	The sampling rate shall be 2Hz.	A,T	10	
P.24	The temperature of the Pump Box *shall* be between 5°C and 25°C.	A, T	5, 23	
D.1	The experiment *shall* operate in the temperature profile of the BEXUS vehicle flight and launch.	A, T	5	
D.2	The experiment *shall* operate in the vibration profile of the BEXUS vehicle flight and launch.	A, T	9	
D.3	~~The experiment *shall* not disturb or harm the launch vehicle.~~[1]	-	-	
D.4	The experiment's communication system *shall* be compatible with the gondola's E-link system.	A, T	8	
D.5	The experiment's power supply *shall* be compatible with the gondola's provided power.	A	-	
D.6	~~The experiment *shall* not disturb other experiments on the gondola.~~[1]	-	-	
D.7	The total DC current draw *should* be below 1.8 A.	A, T	11	
D.8	The total power consumption *should* be below 374 Wh.	A,T	11	
D.9	The experiment *shall* be able to operate in low pressure conditions (300mbar) up to 30 km altitude.	A, T	4, 18	
D.10	~~The components of the experiment *shall* operate within their temperature ranges.~~[1]	-	-	
D.11	~~The OBC *shall* be able to autonomously control the heaters.~~[1]	-	-	
D.12	~~The ground station GC *shall* be able to display some of the received data.~~[1]	-	-	
D.14	~~The experiment *shall* be able to survive and operate between -30°C and 60°C.~~[1]	-	-	
D.15	~~The external components that are directly exposed to the outside environment *shall* be able to operate in -70°C.~~[1]	-	-	
D.16	The watchdog *should* be able to reset the system.	R, T	10	
D.17	The experiment *shall* be able to autonomously turn itself off just before landing.	R, T	7, 10	
D.18	The experiment box *shall* be placed with at least one face exposed to the outside.	R, A	-	
O.1	~~The TUBULAR Team *shall* send telecommands from the ground station to the experiment before and during the flight.~~[1]	-	-	

O.2	~~The TUBULAR Team *shall* receive telemetry from the experiment during the flight.~~[1]	-	-	
O.3	~~The experiment *shall* change modes autonomously.~~[1]	-	-	
O.4	~~The heating mechanism *shall* work autonomously.~~[1]	-	-	
O.5	~~The experiment *shall* store data autonomously.~~[1]	-	-	
O.6	~~The Air sampling control system *shall* work autonomously.~~[1]	-	-	
O.7	~~The Air sampling control system *shall* work autonomously.The valves in air sampling control system *should* be controllable from the ground station.~~[1]	-	-	
O.8	~~The experiment *should* be able to handle a timeout or drop in the network connection.~~[1]	-	-	
O.9	~~The heaters *should* be controllable from the ground station.~~[1]	-	-	
O.10	~~The watchdog[15] *should* be able to reset the system.~~[1]	-	-	
O.11	~~The system *should* be able to be reset with a command from the ground station.~~[1]	-	-	
O.12	~~The experiment *should* enter different modes with a telecommand from the ground station.~~[1]	-	-	
O.13	The experiment *should* function automatically.	R, T	8, 10	
O.14	The experiment's air sampling mechanisms *shall* have a manual override.	R, T	8, 10	
C.1	Constraints specified in the BEXUS User Manual	I	-	
C.2	~~The person-hours allocated to project implementation is limited by university related factors such as exams, assignments, and lectures.~~ [1]	-	-	
C.3	~~Budget limited to TBD.~~ [1]	-	-	

Table 13: Verification Matrix

[15] An electronic timer that is used to detect and recover from computer malfunctions

5.2 Test Plan

The planned tests are as follows:

1. Valves test in Table 14.
2. Data collection test in Table 15.
3. Weight verification in Table 16.
4. Low pressure test in Table 17.
5. Thermal test in Table 18.
6. Experiment assembly and disassembly test in Table 19.
7. Bench test in Table 20.
8. E-Link test in Table 21.
9. Vibration test in Table 22.
10. Software operation test in Table 23.
11. Power systems test in Table 24.
12. Experiment removal test in Table 25.
13. Ground station - OBC connection test in Table 26.
14. Ground station - OBC parameters reprogram test in Table 27.
15. Ground station invalid commands test in Table 28.
16. Sampling test in Table 29.
17. Samples' condensation test in Table 30.
18. Pump low pressure test in Table 31.
19. PCB operations test in Table 32.
20. Switching circuit testing and verification in Table 33.
21. Arduino sensor operation test in Table 34.
22. Arduino, pump and valves operation test in Table 35.
23. Pump thermal test in Table 36.
24. Software and electronics integration testing in Table 37.
25. Mechanical structural testing in Table 38.
26. Insulating foam low pressure test in Table 39.
27. Mechanical interfaces test in Table 40.

Test Number	1
Test Type	Calibration and Verification
Test Facility	Kiruna Space Campus laboratory
Tested Item	Valve system
Test Level/ Procedure and Duration[12]	Test procedure: Test valves work at different air pressures and temperatures. Check valves respond to commands as expected. Ensure valve series are properly connected and properly seal. Test duration: 2 hours
Test Campaign Duration	Recurrent test until and during the launch campaign
Test Campaign Date	April
Test Completed	NO

Table 14: Test 1: Valves calibration and verification

[12] All test procedure and duration's are subject to change.

Test Number	2
Test Type	Software
Test Facility	Kiruna Space Campus laboratory
Tested Item	Arduino, sensors, valves and pump
Test Level/ Procedure and Duration[12]	Test procedure: Run software for full flight duration and ensure data collection proceeds as expected. Particularly watch for error handling and stack overflow. Test duration: 5 hours. Based on previous BEXUS flight duration's.
Test Campaign Duration	2 days (1 day build-up, 1 day testing)
Test Campaign Date	June
Test Completed	NO

Table 15: Test 2: Data collection test description

Test Number	3
Test Type	Weight Verification
Test Facility	Kiruna Space Campus laboratory
Tested Item	The entire experiment
Test Level/ Procedure and Duration[12]	Test procedure: Use scales to measure the weight of the entire experiment. Test duration: 1 minute
Test Campaign Duration	1 day
Test Campaign Date	July-August
Test Completed	NO

Table 16: Test 3: Weight verification description

Test Number	4
Test Type	Vacuum
Test Facility	Esrange Space Centre TBC
Tested Item	The entire experiment
Test Level/ Procedure and Duration[12]	Test procedure: Take experiment down to at least stratospheric pressures and verify all systems work. Ensure valves and pump still perform as expected. Test duration: 5 hours
Test Campaign Duration	1 week
Test Campaign Date	July-August
Test Completed	NO

Table 17: Test 4: Low pressure test description

Test Number	5
Test Type	Thermal
Test Facility	Esrange Space Centre
Tested Item	The entire experiment
Test Level/ Procedure and Duration[12]	Test procedure: Place experiment in thermal chamber and take the temperature down to at least $-40°C$ but preferably $-80°C$ and verify all systems still work. Test duration: 5 hours
Test Campaign Duration	1 week
Test Campaign Date	July-August
Test Completed	NO

Table 18: Test 5: Thermal test description

Test Number	6
Test Type	Assembly and disassembly
Test Facility	Kiruna Space Campus
Tested Item	The entire experiment
Test Level/ Procedure and Duration[12]	Test procedure: All components are laid out and the experiment is assembled. A timer is used to determine how long is required to assemble the experiment. Once the experiment is assembled the procedure is reversed to find the disassemble and replace components. Test duration: 1 hour
Test Campaign Duration	2 days
Test Campaign Date	July-August
Test Completed	NO

Table 19: Test 6: Assembly and disassembly test description

Test Number	7
Test Type	Verification
Test Facility	Kiruna Space Campus
Tested Item	The entire experiment
Test Level/ Procedure and Duration[12]	Test procedure: Assemble experiment and set up any desired monitoring sensors. Run through simulated countdown. Run through simulated launch and flight, include simulated e-link drop outs. Potentially run experiment for longer to simulate wait time before recovery. Test duration: 10 hours
Test Campaign Duration	2 days (1 day build-up, 1 day testing)
Test Campaign Date	August-September
Test Completed	NO

Table 20: Test 7: Bench test description

Test Number	8
Test Type	Verification
Test Facility	Kiruna Space Campus
Tested Item	The entire experiment
Test Level/ Procedure and Duration[12]	Test procedure: Assemble experiment and set up any desired monitoring sensors. Run through simulated countdown. Run through simulated launch and flight, include simulated e-link drop outs. Potentially run experiment for longer to simulate wait time before recovery. Test duration: 10 hours
Test Campaign Duration	2 days (1 day build-up, 1 day testing)
Test Campaign Date	August-September
Test Completed	NO

Table 21: Test 8: E-link test description

Test Number	9
Test Type	Vibration
Test Facility	Kiruna Space Campus
Tested Item	Entire experiment
Test Level/ Procedure and Duration[12]	Test procedure: Either use a shake table to test both random and sinusoidal vibrations or mount the experiment on the back of a car/trailer and drive over bumpy or rough terrain. After check the experiment for functionality and structural integrity. Test duration: 2 hours
Test Campaign Duration	1 week
Test Campaign Date	July-August
Test Completed	NO

Table 22: Test 9: Vibration test description

Test Number	10
Test Type	Software
Test Facility	Kiruna Space Campus
Tested Item	Ardunio, sensors, pump and valves
Test Level/ Procedure and Duration[12]	Test procedure: Ensure software responds well to all possible commands including entering and exiting safe mode. Ensure experiment can be shut down manually. Perform simulated flight using previous BEXUS flight data. Test duration: 10 hours
Test Campaign Duration	2 days
Test Campaign Date	July-August
Test Completed	NO

Table 23: Test 10: Software operation test description

Test Number	11
Test Type	Electronics
Test Facility	Kiruna Space Campus
Tested Item	Electronic systems
Test Level/ Procedure and Duration[12]	Test procedure: Ensure all electronic connections function at all phases of the flight, simulate a full flight with all possible loading. Test duration: 8 hours, to reproduce flight from pre-launch to post-landing.
Test Campaign Duration	2 days (1 day build-up, 1 day testing)
Test Campaign Date	July-August
Test Completed	NO

Table 24: Test 11: Electronics test description

Test Number	12
Test Type	Verification
Test Facility	Kiruna Space Campus
Tested Item	Entire experiment
Test Level/ Procedure and Duration[12]	Test procedure: Mount the experiment as it would be mounted in the gondola. Using a timer find the time required to remove the experiment, or part of the experiment, from the gondola. Test duration: 1 hours
Test Campaign Duration	1 day
Test Campaign Date	July-August
Test Completed	NO

Table 25: Test 12: Experiment removal test description

Test Number	13
Test Type	Software
Test Facility	Kiruna Space Campus
Tested Item	Ardunio, ground station
Test Level/ Procedure and Duration[12]	Test procedure: Ensure communication between ground station and OBC work. Perform simple data transfer. Test duration: 15 minutes
Test Campaign Duration	1 day
Test Campaign Date	May-June
Test Completed	NO

Table 26: Test 13: Ground station-OBC connection test description

Test Number	14
Test Type	Software
Test Facility	Kiruna Space Campus
Tested Item	Ardunio, ground station
Test Level/ Procedure and Duration[12]	Test procedure: Ensure ground station can reprogram some parameters on OBC. Perform parameter changes. Test duration: 15 minutes
Test Campaign Duration	1 day
Test Campaign Date	May-June
Test Completed	NO

Table 27: Test 14: Ground station-OBC parameters reprogram test description

Test Number	15
Test Type	Software
Test Facility	Kiruna Space Campus
Tested Item	Ardunio, ground station
Test Level/ Procedure and Duration[12]	Test procedure: Ensure OBC still works perfectly even after receiving invalid commands. Perform invalid commands. Test duration: 30 minutes
Test Campaign Duration	1 day
Test Campaign Date	May-June
Test Completed	NO

Table 28: Test 15: Ground station-OBC invalid commands test description

Test Number	16
Test Type	Verification
Test Facility	Kiruna Space Campus laboratory
Tested Item	Valves, pump, bags, pressure and temperature sensors
Test Level/ Procedure and Duration[12]	Test procedure: Test the filling of the bags at different pressure and different airflow intake. Test duration: 2 hours.
Test Campaign Duration	2 days (1 day build-up, 1 day testing)
Test Campaign Date	April
Test Completed	NO

Table 29: Test 16: Sampling system verification

[12] All test procedure and duration's are subject to change.

Test Number	17
Test Type	Verification
Test Facility	Kiruna Space Campus
Tested Item	Bags
Test Level/ Procedure and Duration[12]	Test procedure: Test the holding times of the bags and potential condensation of the samples. Test duration: 3 days.
Test Campaign Duration	3 days
Test Campaign Date	April
Test Completed	NO

Table 30: Test 17: Bags' holding times and samples' condensation verification

[12] All test procedure and duration's are subject to change.

Test Number	18
Test Type	Vacuum
Test Facility	Esrange Space Centre TBC
Tested Item	Pump
Test Level/ Procedure and Duration[12]	Test procedure: Pump shall be placed in a low pressure testing chamber and a bag with a known volume attached to its output. The pump shall then be run at several different pressures that will be encountered during flight. The time taken to fill the bag will be recorded and the flow rate extrapolated. Test duration: 1 day
Test Campaign Duration	2 days (1 day build-up, 1 day testing)
Test Campaign Date	April
Test Completed	NO

Table 31: Test 18: Pump low pressure test

Test Number	19
Test Type	Electronics
Test Facility	Kiruna Space Campus
Tested Item	Electronics PCB
Test Level/ Procedure and Duration[12]	Test procedure: As PCB board is soldered check using a multimeter for shorts. Check that the circuit operates as intended by checking the voltages at test points using a multimeter. Test duration: 1 week
Test Campaign Duration	2 weeks
Test Campaign Date	June
Test Completed	NO

Table 32: Test 19: PCB board operations check.

Test Number	20
Test Type	Electronics
Test Facility	Kiruna Space Campus
Tested Item	Valves, Arduino, Switching Circuit
Test Level/ Procedure and Duration[12]	Test procedure: Using a bread board test the switching circuit proposed in Figure 17. Check that the resistor values chosen produce the expected current output. Test duration: 1 hour
Test Campaign Duration	2 days
Test Campaign Date May	Recurrent test through April
Test Completed	NO

Table 33: Test 20: Switching circuit testing and verification.

Test Number	21
Test Type	Operation and Verification
Test Facility	Kiruna Space Campus
Tested Item	Arduino and sensors
Test Level/ Procedure and Duration[12]	Test procedure: Sensors will be connected to the arduino in turn and their operation tested. Once all sensors have been verified to work using a bread board all sensors will be connected as the will be in the final design and tested again. Test duration: 1 week
Test Campaign Duration	2 weeks
Test Campaign Date	May
Test Completed	NO

Table 34: Test 21: Arduino sensor operation test

Test Number	22
Test Type	Operation and Verification
Test Facility	Kiruna Space Campus
Tested Item	Arduino, valves and pump
Test Level/ Procedure and Duration[12]	Test procedure: The arduino will be connected via a bread board to first one valve and then the system will be tested to see if it operates as expected. Then the pump will be connected and tested in the same way. Finally all valves and the pump will be connected as they will be in the final design and tested for operation. Test duration: 1 week
Test Campaign Duration	2 weeks
Test Campaign Date	May
Test Completed	NO

Table 35: Test 22: Arduino, pump and valves operation test

Test Number	23
Test Type	Thermal
Test Facility	Esrange Space Centre TBC
Tested Item	Pump
Test Level/ Procedure and Duration[12]	Test procedure: The pump will be placed in a temperature chamber and tested from +40 to at least -40 and its operation will be recorded. This test will happen once to simulate the operation of the pump during testing where it will cycle between on and off. The test will be repeated but this time the pump will be off for long enough that the internal temperature of the pump is the same as the ambient temperature of the chamber. Then it will be attempted to turn the pump on. This is to simulate the reaction of the pump to being off during the float phase. Test duration: 2 days
Test Campaign Duration	1 weeks
Test Campaign Date	April-May
Test Completed	NO

Table 36: Test 23: Pump thermal test

Test Number	24
Test Type	Verification and integration
Test Facility	Kiruna Space Campus
Tested Item	All electronics, groundstation and arduino
Test Level/ Procedure and Duration[12]	Test procedure: After all individual parts and components have been tested and verified all the electronics shall be connected in their final positions and all software shall be run. This test will systematically go through all software commands and check that the electronics and software operates as expected. Test duration: 1 week
Test Campaign Duration	2 weeks
Test Campaign Date	June-July
Test Completed	NO

Table 37: Test 24: Software and electronics integration testing

Test Number	25
Test Type	Verification
Test Facility	Kiruna Space Campus
Tested Item	Mechanical box structure
Test Level/ Procedure and Duration[12]	Test procedure: The mechanical structure will be tested under different loads to ensure it can withstand the expected stresses and strains during flight. Test duration: 2 days
Test Campaign Duration	1 weeks
Test Campaign Date	June-July
Test Completed	NO

Table 38: Test 25: Structural test

Test Number	26
Test Type	Vacuum
Test Facility	Esrange Space Centre TBC
Tested Item	Insulating foam
Test Level/ Procedure and Duration[12]	Test procedure: A sample of the insulating foam intended for use in the experiemnet box will be placed inside a low pressure chamber. The reaction of the foam to the low pressure and its behaviour upon returning to ambient pressure will be recorded. Test duration: 5 hours
Test Campaign Duration	2 days (1 day build up, 1 day test)
Test Campaign Date	June-July
Test Completed	NO

Table 39: Test 24: Insulating foam low pressure test

Test Number	27
Test Type	Mechanical
Test Facility	Kiruna Space Campus
Tested Item	Mechanical interfaces
Test Level/ Procedure and Duration[12]	Test procedure: The mechanical interfaces will be tested under different loads to ensure it can withstand the expected stresses and strains during flight. Test duration: 2 days
Test Campaign Duration	1 weeks
Test Campaign Date	June-July
Test Completed	NO

Table 40: Test 25: Mechanical interfaces test

5.3 Test Results

As testing has yet to be done, no test results exist currently. As the project advances, and all requirements are assigned verification methods, the testing environments can be set up, and the experiment components tested.

6 Launch Campaign Preparations

6.1 Input for the Campaign / Flight Requirements Plans

The TUBULAR experiment consists of one box with two air sampling systems inside. It shall be positioned with at least one side exposed to the outside.

6.1.1 Dimensions and Mass

The data shown in Table 41 below is based on the design presented in section 4.4. The mass for the electronics is estimated to be 1.5 kg.

Experiment mass	$26.5\ kg$ [13]
Experiment dimensions	0.25 x 0.50 x $0.50\ m$ and 0.40 x 0.50 x $0.40\ m$
Experiment footprint area	$0.325\ m^2$
Experiment volume	$0.1625\ m^3$

Table 41: Experiment summary table.

6.1.2 Safety Risks

Table 42 contains the risks of all stages of the whole campaign and project.

Risk	Key Characteristics	Mitigation
Flammable substances	Styrofoam Brand Foam is oil based and is highly flammable	Extensive testing will be performed to make sure there is no heat/fire source
Sharp or cutting edges	Edges along the experiment	File down edges

Table 42: Experiment safety risks

[13] To be refined in future SED versions.

6.1.3 Electrical Interfaces

Please refer to Table 43 for details on the electrical interfaces with the gondola.

BEXUS Electrical Interfaces		
E-link Interface: Yes		
	Number of E-link interfaces	1
	Data rate - Downlink	10 kbps
	Data rate - Uplink	5 kbps
	Interface type (RS232, Ethernet)	Ethernet
Power system: Gondola power required? Yes		
	Peak power (or current) consumption:	44.3W
	Average power (or current consumption)	26.9W
Power system: Experiment includes batteries? No		

Table 43: Electrical Interface Table

6.1.4 Launch Site Requirements

A laptop PC will be used to monitor the experiment. Therefore, a desk and a chair are needed for this station. A total of 13 chairs need to be rented: 10 chairs for all members of team TUBULAR and an additional 3 for visiting collaborators from FMI. One power outlet and one Ethernet cable for E-link connection are also essential for the laptop PC.

6.1.5 Flight Requirements

Floating altitude is desired to be as high as possible in order to sample air from the stratosphere both in ascent and decent phase. The duration of the float phase is not relevant for the experiment performance.

No conditions for visibility are required for this experiment.

With respect to a swift recovery and transport for fast data analysis, a launch time in the early morning hours would be favorable.

6.1.6 Accommodation Requirements

The experiment involves two cubic boxes inside the gondola environment. The only requirement is to allocate the box with at least one face exposed to the outside. The latter will also facilitate the fast experiment recovery for the later analysis of the collected samples. The design allows full adaptability regarding the interface with the gondola's rails, for more detail see section 4.4. The current location of the experiment in Figure 25 is the one arranged with RXBX Coordinator during the Training Week in Esrange.

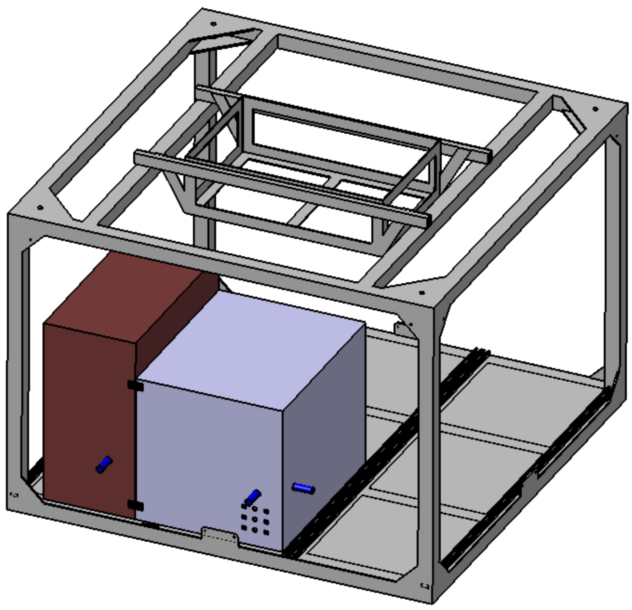


Figure 25: Example of experiment box accommodation inside the gondola.

6.2 Preparation and Test Activities at Esrange

The ground station laptop PC will need to be put in place and operational. The communication through E-link with the experiment shall be tested. The air sampling itinerary has to be checked before flight.

What is more, in a preparation phase, short (15 cm) lengths of stainless steel tubing, will be filled with fresh magnesium perchlorate powder [3] and will be attached to either end of the CAC tubing, to ensure that no moisture will enter the tubing during any testing or sampling.

Magnesium perchlorate powder will be used for the AAC. As seen in Figure 5 the filter, in front of the valve center, will be coated with magnesium perchlorate to prevent moisture from entering while sampling.

Before the launch, both CAC and AAC will be filled with an inert gas. All the bags will be manually emptied before flight. Flushing of the CAC tube will be done passively through the progressive decrease in air pressure during the balloon's ascent phase. Nitrogen will be used as the inert gas. Nitrogen's triple bond is very strong and requires a lot of energy to break those bonds and participate in a reaction. That is why nitrogen is used, despite the fact that is not truly inert like most noble gases.

In a laboratory phase, tests under monitored conditions will be done to evaluate the overall consistency of the CAC and the AAC. In particular, the CAC and the AAC shall be tested for leaks at the junctions and at the valves.

Should a gas chromatograph be made available on site, pre-flight testing will be made to ensure sample concentration preservation. To do so, calibrated dry standard gases of two different values for both CO_2 and CH_4 will be used. One with high CO_2 and CH_4 concentrations, i.e high-concentration calibration standard, and one with lower concentrations, i.e low-concentration standard. Should a gas chromatograph not be available, this activity will be incorporated in the latter part of the Experiment Building and Testing stage.

6.3 Timeline for Countdown and Flight

Table 44 is the estimated timeline during countdown and flight. It may undergo updates in future versions of the SED.

The desired altitudes in which air samples are to be collected with the air sampling bags are associated with specific air pressure values. Thus, the valve operations to sample air during the balloon ascent and descent phases are to be triggered by readings from the ambient pressure sensor. The time values presented in Table 44 merely serve as an indicative estimate of when the sampling will take place as sampling will not be programmed based on flight time.

Time	Altitude	Events
T-45min	0	Experiment is switched on
T-45min	0	Experiment goes to Standby mode
T=0	0	Lift-off
T+1s	~5 meter	Experiment goes to Normal - Ascent mode
T+15 min	1 km	Experiment starts to empty the CAC's tube and AAC's bags
T+45 min	15 km	Experiment stops emptying the tube and bags
T+~1H	~18 km	Take air samples with AAC until ~24 km
T+~1.5H	~25 km	Floating phase
T+~2.5H	~25 km	Cut-off
T+~2.6H	~25 km	Experiment goes to Normal - Descent mode
T+~2.75H	~20 km	Parachute is deployed
T+~2.8H	~19 km	Take air samples with AAC and CAC until 1 km above ground
T+3.5H	~1 km	Experiment goes to SAFE mode

Table 44: Countdown and flight estimated timeline

6.4 Post Flight Activities

To ensure minimize the length of time in which mixing of the gas occurs in the collected CAC samples, is necessary that the they be analyzed as soon as possible after the experiment landing. Measurements will be made in partnership with the Finnish Meteorological Institute (FMI) thus it is necessary that the experiment can be transported to the measurement equipment provided by FMI. To make measurements at the landing site would be unfeasible due to the size of the gas analyzer hence measurements are to be made at the Esrange Space Centre.

The FMI team would begin their travel to Esrange as soon as the balloon landing site has been located. Once the experiment has been recovered to Esrange the samples will be analyzed by the FMI equipment and the preliminary results will be found. The disadvantages of this option are that additional time in between the gas collection and the analysis means a loss of vertical resolution in the sample and the transportation of the equipment from Sodankylä to Esrange may result in calibration loss due to equipment vibrations caused by transportation. The ideal scenario for would be to have the FMI team be at Esrange the day before the launch despite the possibility of waiting time in case of short notice launch cancellations. This would give margins to react to unforeseen problems such as trouble on the road due to bad weather as well as missing equipment and/or tools. Furthermore, this would allow additional time to install and calibrate their lab equipment at Esrange prior to the launch.

Special consideration will be put into designing the experiment so that the recovery team can easily remove the experiment from its enclosure for possible transportation back to Esrange via helicopter. Detailed instructions will be provided on operating the detachable mechanism that will be designed. In addition, instructions will be provided to ensure that the system is completely shut down and the valves secured. Shutdown will be automated however a manual shutdown mechanism will be included should the automation fail.

The analysis results that will then be used for the post flight meeting. Further analysis will then be carried out to fully understand the data. Once a full analysis of the data has been completed there is the potential for publication of research findings.

7 Data Analysis and Results

7.1 Data Analysis Plan

After the flight the collected samples, from the CAC and the AAC, will be analyzed with a Picarro gas analyzer. The end of the CAC that remains closed during sampling, will be opened first, and connected to the gas standard with the higher CO_2 and CH_4 concentrations. The reason for that, is to have a notable difference between the standard gas and the stratospheric air sample. The other end of the CAC will be connected to the analyzer. The analyzer pump will pull the sample through the analyzer with both ends of the CAC open, so that the standard gas will be pulled through after the sample finish, [3], [4]. After the sample has been analyzed, the time trace of analysis will be converted into a mole fraction profile as a function of atmospheric pressure, using the ideal gas law,

$$PV = nRT <=> n = \frac{PV}{RT} \tag{1}$$

where P is the ambient pressure, V is the inner volume of the CAC/AAC, n the fraction of moles, R is the universal gas constant in $JK^{-1}mol^{-1}$ and T the ambient temperature in Kelvin, [4]. A constant unit of pressure in the atmosphere is represented by a unit of length in the CAC tube, due to the method that the CAC will sample the ambient air. During the analysis the number of moles that will go through the analyzer will increase linearly with time. So, the number of moles at any time during the analysis will be

$$n_i = n^{max} \frac{t_i}{\Delta t} \tag{2}$$

where n^{max} is the maximum number of moles i.e when the CAC reaches the Earth's surface, and Δt is the total time duration of the analysis between the top and bottom of the CAC sample. Finally, the vertical profiles will be obtained by using equations 1 and 2, and relate a specific pressure point with every Picarro measurement of the sample.

The AAC sampling system will be analyzed, in the same manner as the CAC, using the same Picarro gas analyzer. The vertical profiles for CO_2 and CH_4 are going to be obtained using again, equations 1 and 2.

7.2 Launch Campaign

No launch campaign activities are currently defined. This will be elaborated on in future SEDs.

7.3 Results

No results for now. More will come after the launch campaign in an updated version of the SED.

7.3.1 Expected Results

After the analysis of the samples, the expected results are the vertical profiles of CO_2 and CH_4. The profiles will be similar to that of Figure 26. The continuous profile (dashed line) belongs to the CAC while the discrete values (black dots) belongs to the AAC ([3]). Both profiles are decreasing with increasing altitude.

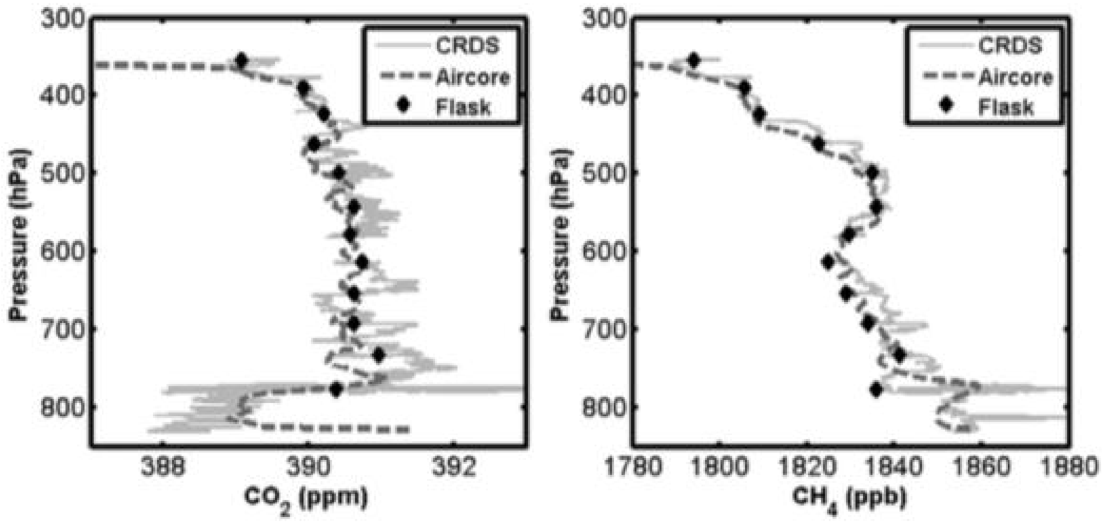


Figure 26: Pressure profiles for (left) CO_2 and (right) CH_4 by three different methods.[3]

The experiment's goal is to achieve the higher vertical resolution possible. Since the vertical resolution is determined by the length and the diameter of the tube [4], for the experiment a 300m long tube will be used, consisting of 2 smaller tubes. One of 200m length with 3×10^{-3} m outside diameter and 1.3×10^{-4} m wall thickness, and another one of 100m length with 6×10^{-3} m outside diameter and 1.3×10^{-4} m wall thickness. For achieving higher stratospheric resolution, the tube with the smaller diameter will be used to sample the higher altitudes and the one with the bigger diameter for the lower ones. Figure 27 by Olivier Membrive [4] compares the vertical resolution that can be expected with three different AirCores.

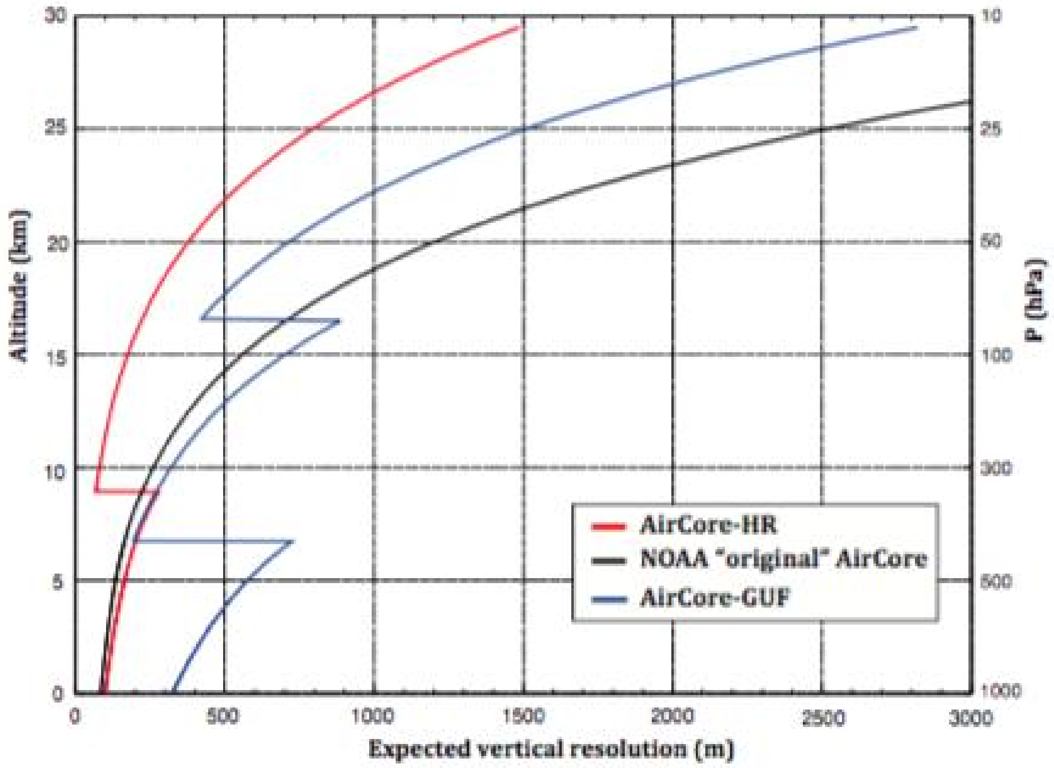


Figure 27: Comparison of the vertical resolutions that can be expected with different AirCores, after 3h storage time before analysis.[4]

The AirCore-HR (red line),[4], is a combination of two tubes. One of 200m and one of 100m.

The NOAA 'original' CAC, [3], (black line) is a 152m long tube and the AirCore-GUF (designed and developed at Goethe University Frankfurt), (blue line) is a combination of three tubes, 100m long in total.

The longer AirCore, AirCore-HR, achieved a higher resolution throughout the whole sampled air.

In addition, the vertical resolution depends on the the mixing inside the tube.

The experiment takes into account two types of mixing. Molecular diffusion and the shear flow diffusion, known as Taylor dispersion. The effect of molecular diffusion is described by the root-mean-square of the distance of molecular travel,

$$X_{rms} = \sqrt{2Dt} \tag{3}$$

where, D is the molecular diffusivity of the molecule in the surrounding gas, and t is the time over which travel occurs, [3]. For the tubing dimension that will be used in this experiment, the flow of air through the AirCore, will be laminar. In such a flow, a parabolic velocity profile exists inside the tube, causing longitudinal mixing (Taylor dispersion). Before the experiment is recovered, only molecular diffusion will affect the sample, but during analysis both molecular diffusion and Taylor dispersion will affect the sample. Combining both of them, an effective diffusion coefficient can be calculated as,

$$Deff = D + \frac{a^2\overline{V^2}}{48D} \tag{4}$$

where D is the molecular diffusivity, a is the tube's inner radius, and $\overline{V}$ is the average velocity [4]. The first term translates into the longitudinal direction, while the second one is the Taylor dispersion.

The exact flow rates are going to be decided at a later stage of the experiment.

Finally, storage time (time from the moment the tube is sealed until the end of the analysis) is a key factor that affects the experiment's results in terms of resolution. Figure 28 shows the effect of time delay between landing and analysis, on the expected vertical resolution.

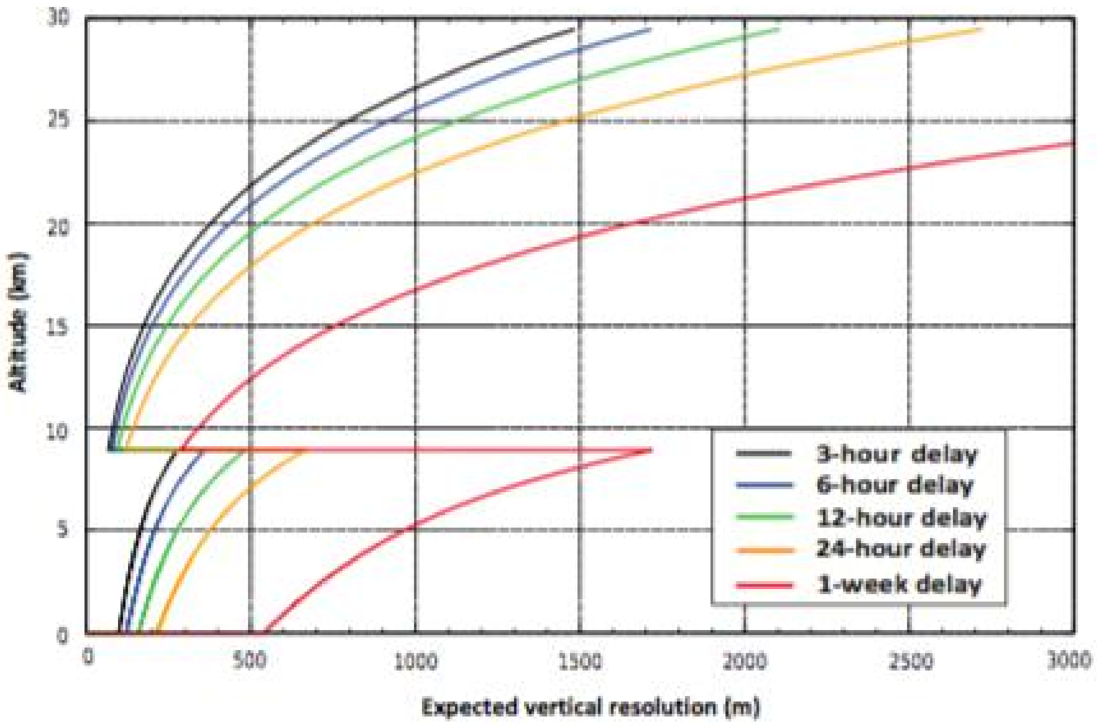


Figure 28: Expected vertical resolution of AirCore-HR, for a storage time of 3h (black), 6h (blue), 12h (green), 24h (orange) and 1 week (red). [4]

It is clear that the sooner the samples are going to be analyzed, the better the results for the vertical resolution of the CAC sample. At an altitude of 20km the resolution decreases significantly from 300m to 500m for 6h and 12h of delay, respectively, [4]. But even after a week of storage, a vertical profile can still be achieved with lower resolution.

Based on past BEXUS projects, the time to experiment recovery is estimated at 12 to 24 hours if not multiple days. As such, it is expected that the desired vertical resolution of gas analysis will favour AAC configuration over that of CAC due to mixing of gases in the latter configuration, resulting in poorer vertical resolution.

The targeted vertical resolution for the AAC is 500m. This will be achieved assuring the airflow intake rate. For ascent phase, a nominal speed of 5m/s is considered, which means that it will take 100 seconds to fill up a 3L sampling bag while ascending 500m, and therefore the airflow intake rate should be of approximately 1.8L/min. For descent phase, the nominal speed is assumed to be 8m/s. While descending 500m a 3L sampling bag will be filled in 62 seconds. But considering the fact that the pump will not have the same efficiency at higher altitudes, the sampling time may be longer and the airflow intake rate may be higher. The exact numbers will be included in the upcoming version of the SED.

For a 500m of vertical displacement, the horizontal resolution of the AAC has been approximated based on past BEXUS flights data obtained from the BEXUS manual [5]. The average horizontal resolution obtained for ascent phase is 588m and for descent phase is 186.5m. This means that the square area covered by the sample will be 500m x 588m and 500m x 186.5m for ascent and descent phases respectively.

It is expected that the AAC will serve as model enabling a cost-effective large scale deployment scheme for regular high altitude greenhouse gas measurement. Unlike CAC, the design of AAC will not impose experimental restrictions based on the proximity of infrastructure for shipping and analysis. As such, a successful proof of concept of AAC sampling system will serve as a basis to enable reliable cost-effective measurements in remote areas.

7.4 Lessons Learned

At this early stage of the experiment, and having already submitted an accepted experimental proposal, the TUBULAR team has learned important lessons regarding document creation as well as learning how to build an idea into a project.

The TUBULAR team expects that the BEXUS programme will be rewarding in terms of experience regarding balloon craft design and development, with real deadlines, published documents, and team work. This part of the document will be updated in later SEDs to reflect what the team members have learned.

7.4.1 Science

After an extended research in trace gases and climate change, as well as in atmospheric sampling methods, the science team has gained so far:

- General knowledge in climate change.
- General knowledge in the different sampling methods of the atmosphere; its characteristics and applications.
- Study scientific papers in detail.
- Outreach to scientific community.
- Translating scientific concepts to technical teams.

7.4.2 Electrical Division

The electrical team has thus far enhanced its understanding of the electronics design as well as gained confidence in selecting appropriate components as per requirements. Some of the points team improved as their general understanding are listed below:

- Gained confidence in designing electronics circuitry.
- Familiarized with the selection of the electrical components.
- By reading through large number of data sheets, team is now able to easily extract and understand technical details.
- Learned and developed power calculation skills.

7.4.3 Software Division

- Learned more about version control in the form of Git.
- Learned how to implement RTOS in an Arduino micro-controller.
- Learned how to translate experiment requirements to software design.

7.4.4 Mechanical Division

- Come up with real design solutions starting from conceptual problems.
- Make a proper use of both space and mass.
- Learn mechanical *tricks* when designing.

7.4.5 Management Division

- Coordination between multiple project stakeholders.
- Task definition, estimation, and management.
- Task integration.
- Conflict management and resolution.
- Communication flows.
- Funding research and outreach.

8 Abbreviations and References

8.1 Abbreviations

AAC	Alternative to the Air Coil
BEXUS	Balloon Experiment for University Students
CAC	Conventional Air Coil
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CH_4	Methane
CLK	Serial Clock
CO_2	Carbon Dioxide
COG	Center of Gravity
DC	Direct Current
DFM	Design for Manufacturability
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EB	Electronic Box
ESA	European Space Agency
FCS	Frame Check Sequence
FMI	Finish Meteorological Institute
GC	Ground Control Station
GPIO	Goethe University Frankfurt
GUI	Graphical User Interface
HOOD	Hierarchic Object-Oriented Design
I2C	Inter-Integrated Circuit
IDE	Integrated Software Environment
I/O	Input/Output
IRF	Institutet för rymdfysik (Swedish Institute for Space Physics)
LTU	Luleå University of Technology
MB	Mega Byte
MISO	Master Input Slave Output
MORABA	Mobile Rocket Base
MOSI	Master Output Slave Input
MSc	Master of Science
N_2O	Nitrous Oxide
NOAA	National Oceanographic and Atmospheric Administration
OBC	Onboard Computer
ppb	parts per billion
ppm	parts per million
REXUS	Rocket Experiment for University Students
RJ45	Registered Jack 45
RTOS	Real-time operating system
SAFT	Société des Accumulateurs Fixes et de Traction
SCP	Serial Clock Pin
SD	Secure Digital (Storage)

SDP	Serial Data Pin
SED	Student Experiment Documentation
SNSB	Swedish National Space Board
SPI	Serial Peripheral Interface
SSC	Swedish Space Corporation
TBC	To Be Confirmed
TBD	To Be Determined
TT&C	Telemetry, Tracking, and Command
ZARM	Zentrum für angewandte Raumfahrttechnologie und Mikrogravitation

8.2 References

[1] Hansen James et al. *Climate Change and Trace Gases*. The Royal Society Publishing, 2007.

[2] Hooghiem Joram J.D. et al. Lisa: a lightweight stratospheric air sampler. *Atmoshperic Measurement Techniques*, Pending, 26th January 2018.

[3] Karion et al. Aircore: An innovative atmospheric sampling system. 2010.

[4] O. Membrive et al. Aircore-hr: a high-resolution column sampling to enhance the vertical description of ch4 and co2. 2017.

[5] EuroLaunch. *BEXUS User Manual*. Version 7.2. 31 Nov 2017.

[6] Texas Instruments. *HDC2010 Low Power Humidity and Temperature Digital Sensors*. Texas Instruments, Texas Instruments, Post Office Box 655303, Dallas, Texas 75265, Jul 2017.

[7] Daniel J. Jacob. *Atmospheric Chemistry*, chapter 2.3. Princeton University Press, 1999.

[8] Sid Perkins. Arctic warming twice as fast as rest of world. *ScienceShot*, 2013.

[9] ECSS Secretariat. *Space Engineering: Verification*. ESA-ESTEC, Requirements Standards Division, ESTEC, P.O. Box 299, 2200 AG Noordwijk, The Netherlands, Nov 1998.

A APPENDIX A

A1 - CAC Coiled Tube

Figure 29: CAC Coiled Tube

A2 - Example Air Sampling Bag

Figure 30: Example Air Sampling Bag

B APPENDIX B

B1 Air Sampling Control Object Sequence diagrams

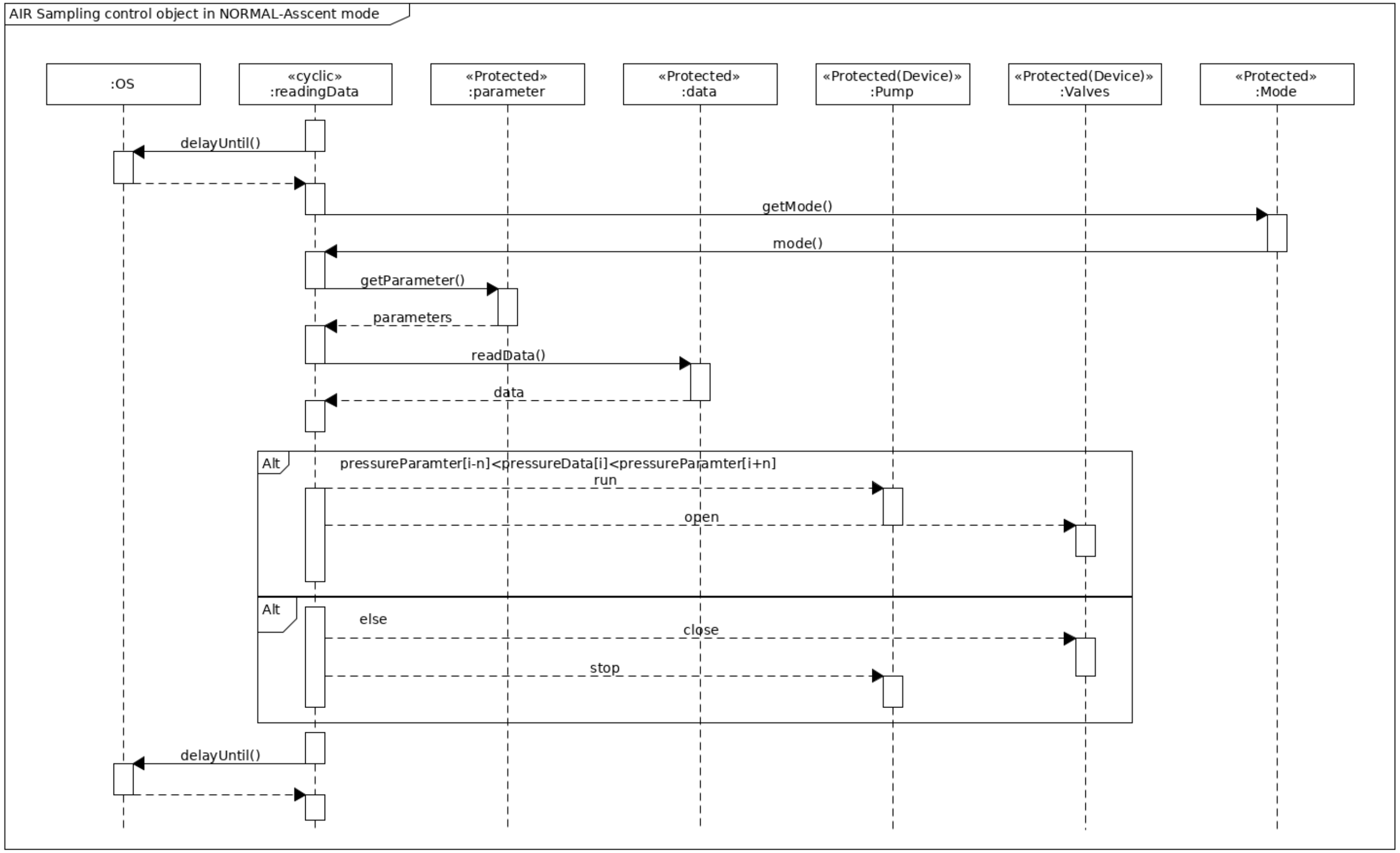


Figure 31: ASC object in normal mode -Ascent.

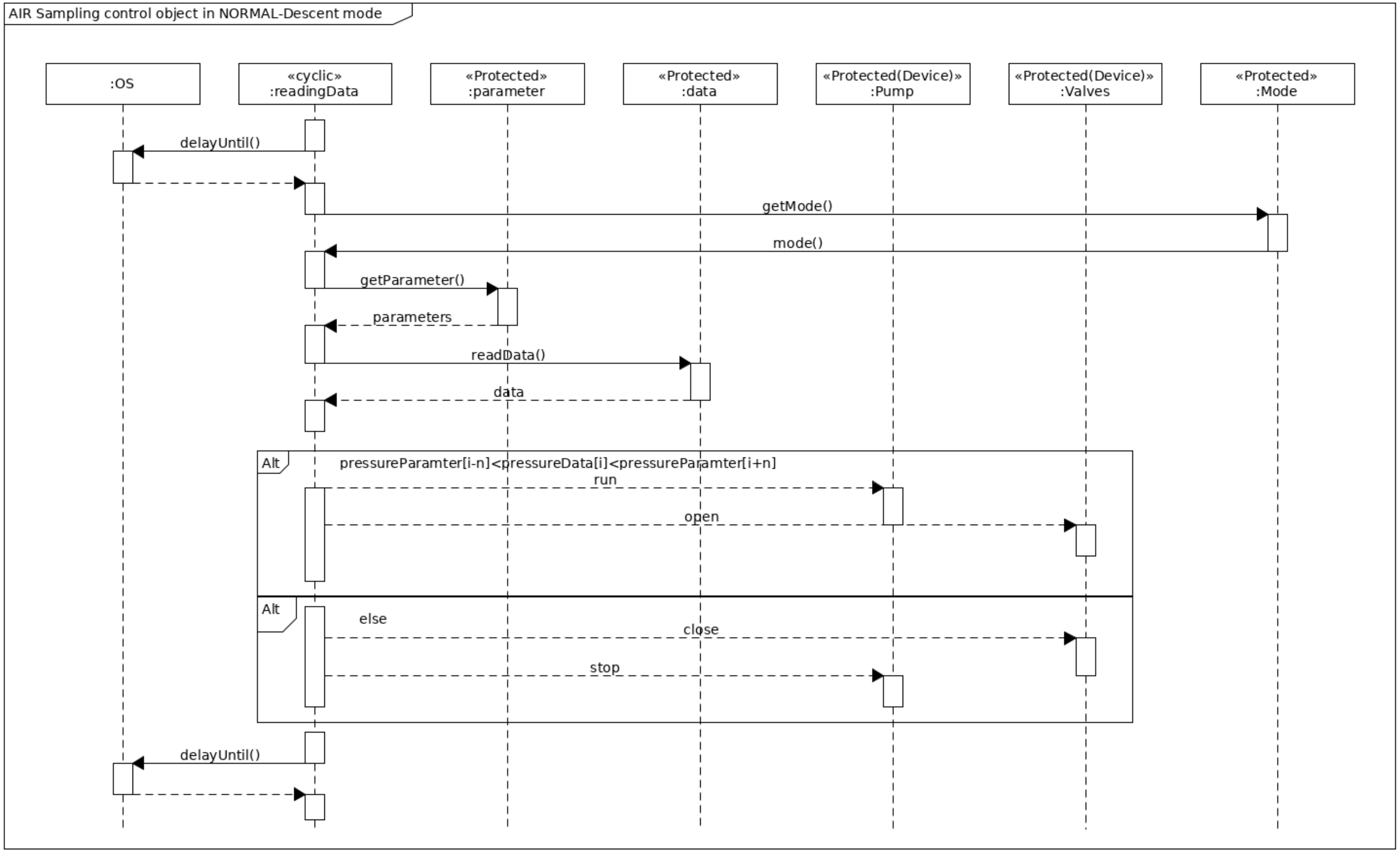


Figure 32: ASC object in normal mode -Descent.

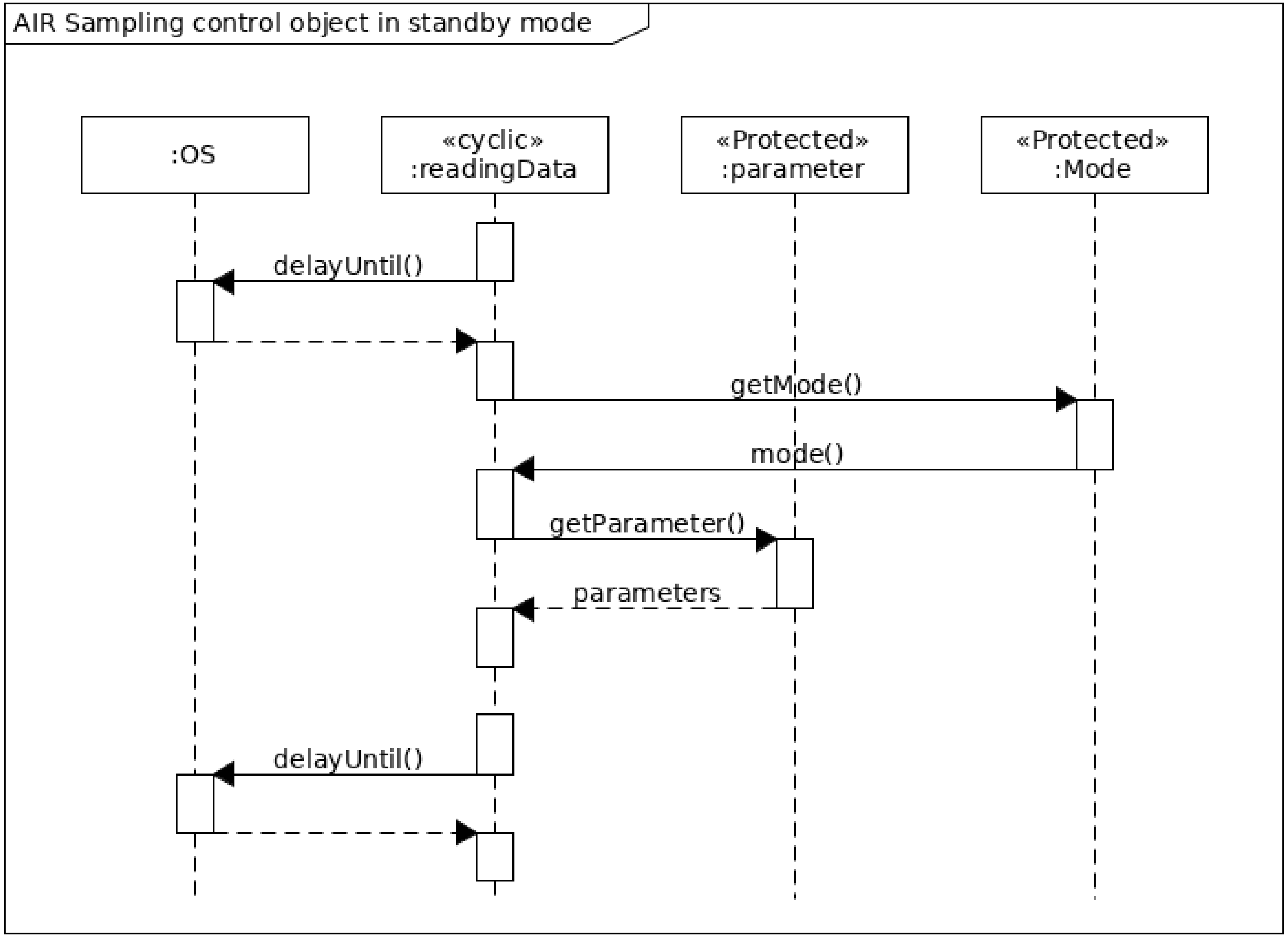


Figure 33: ASC object in standby mode.

B2 Heating Object Sequence Diagrams

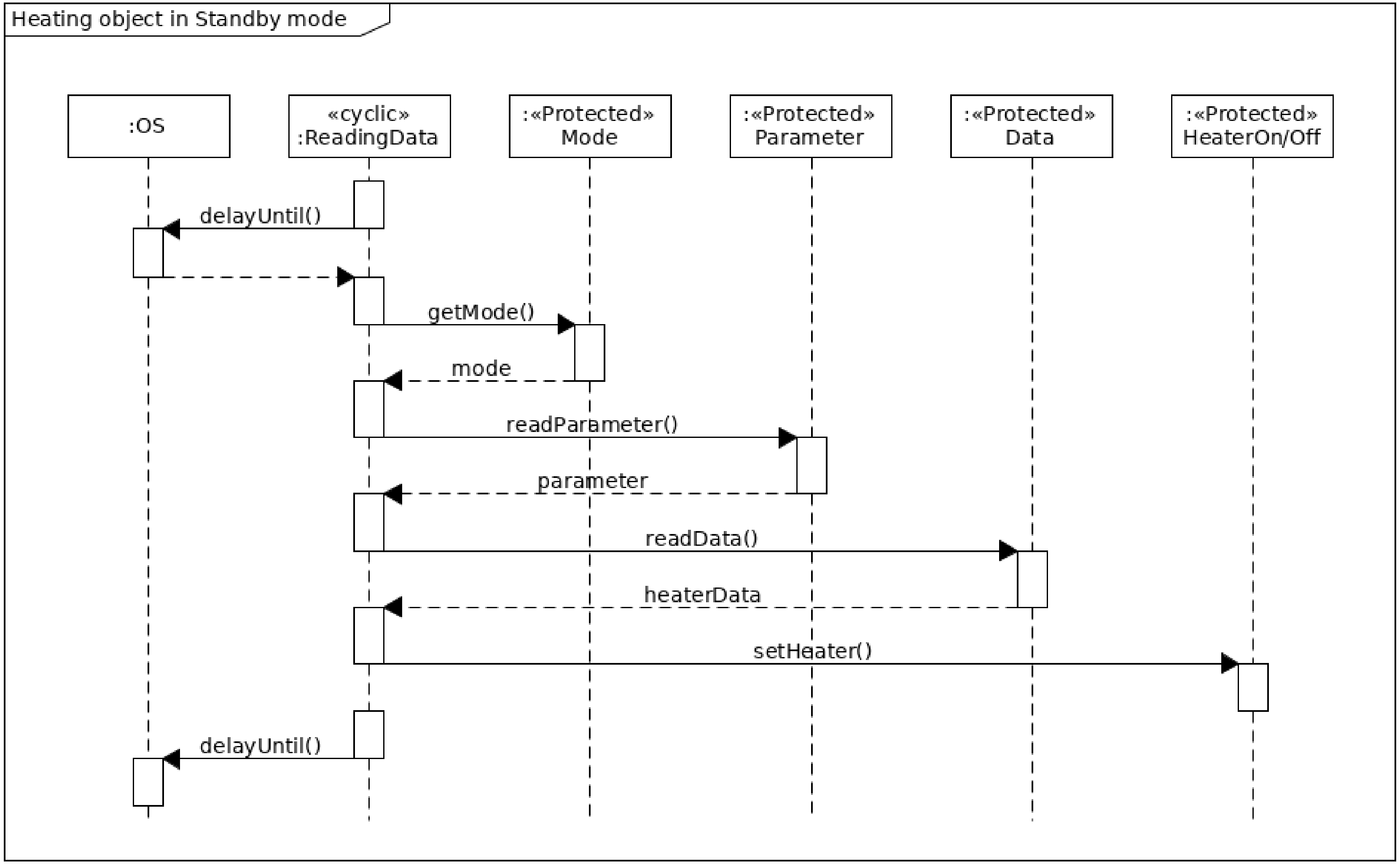


Figure 34: Heating object in standby mode.

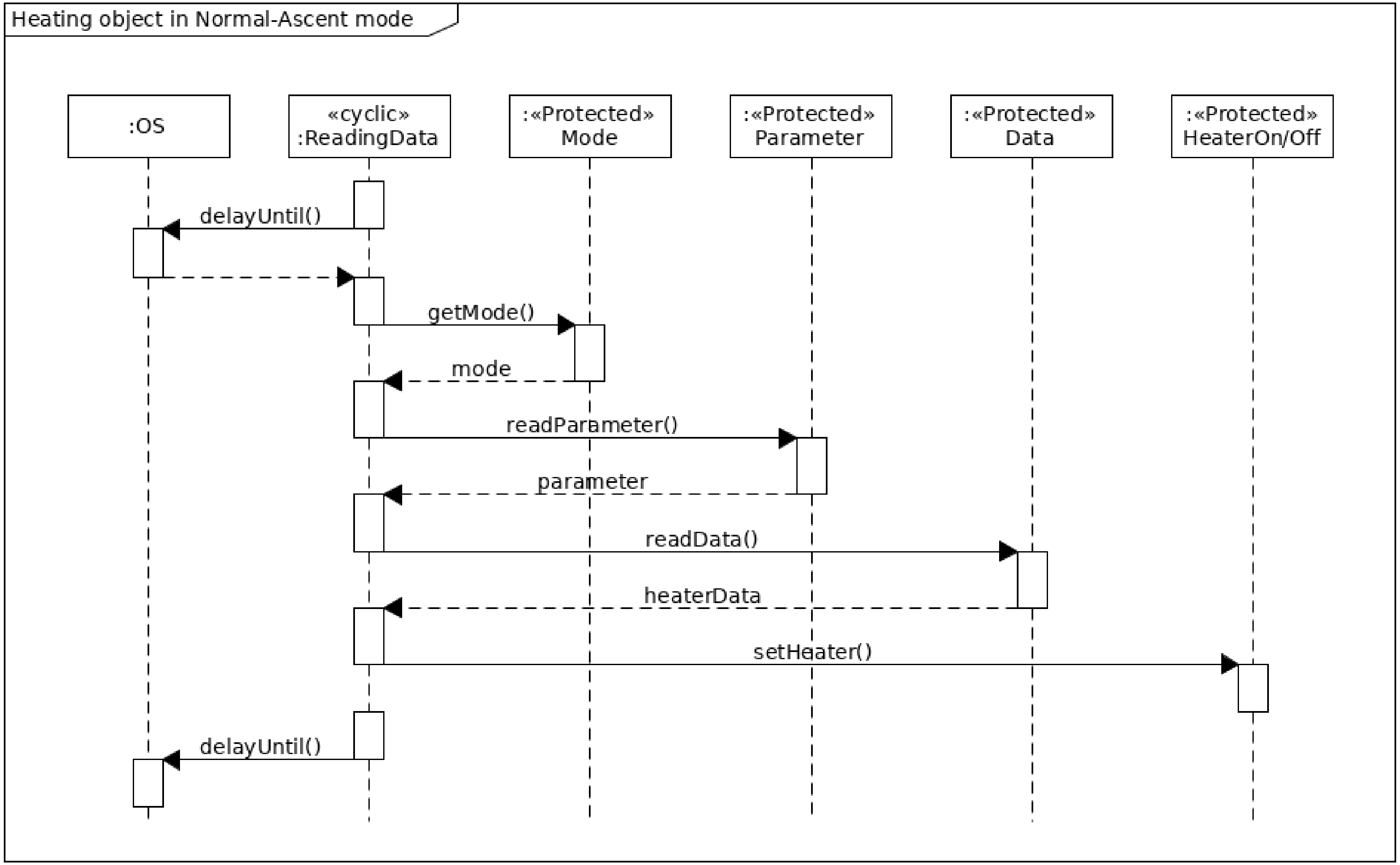


Figure 35: Heating object in normal mode -Ascent.

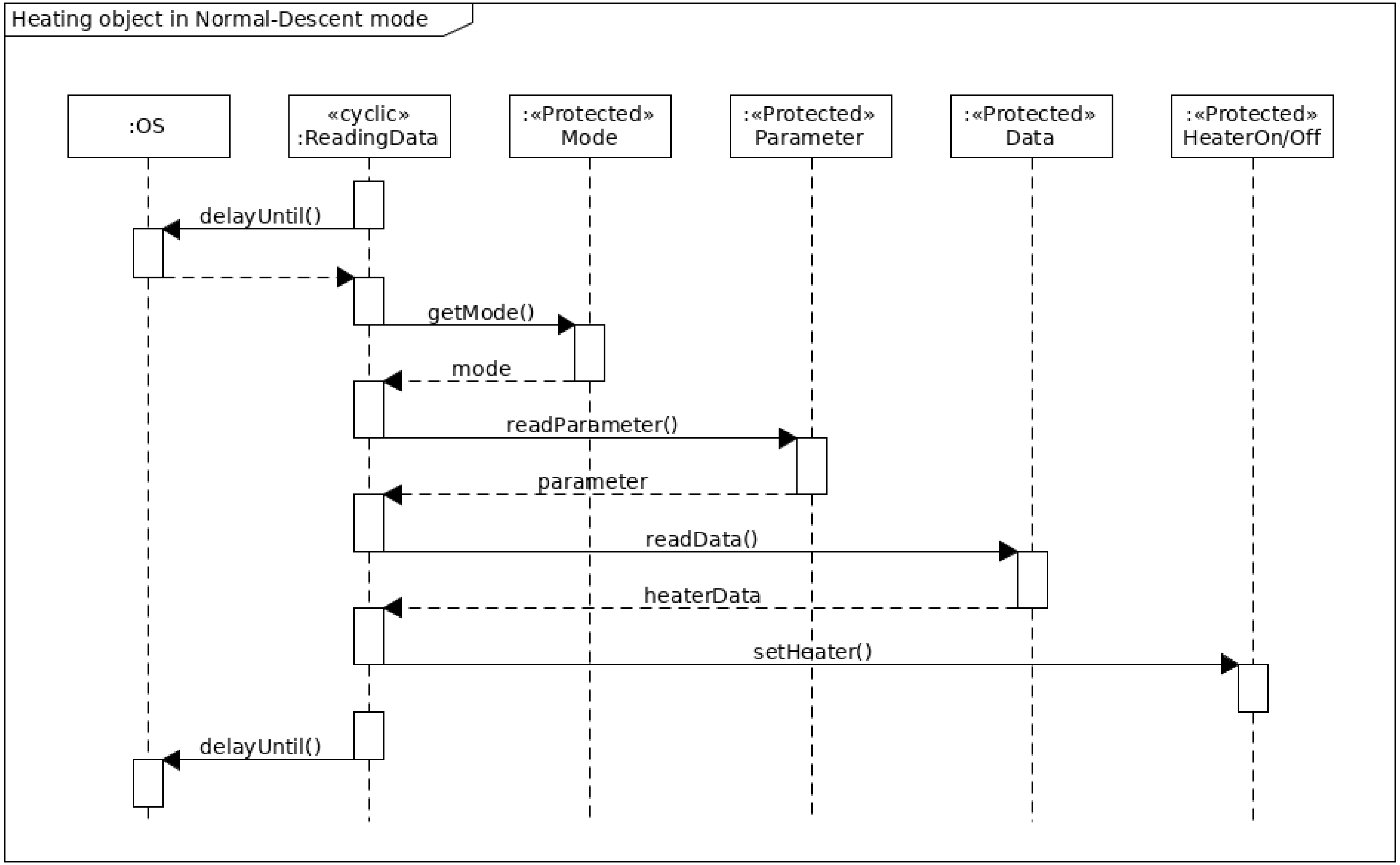


Figure 36: Heating object in normal mode -Descent.

B3 Sensor Object Sequence Diagrams

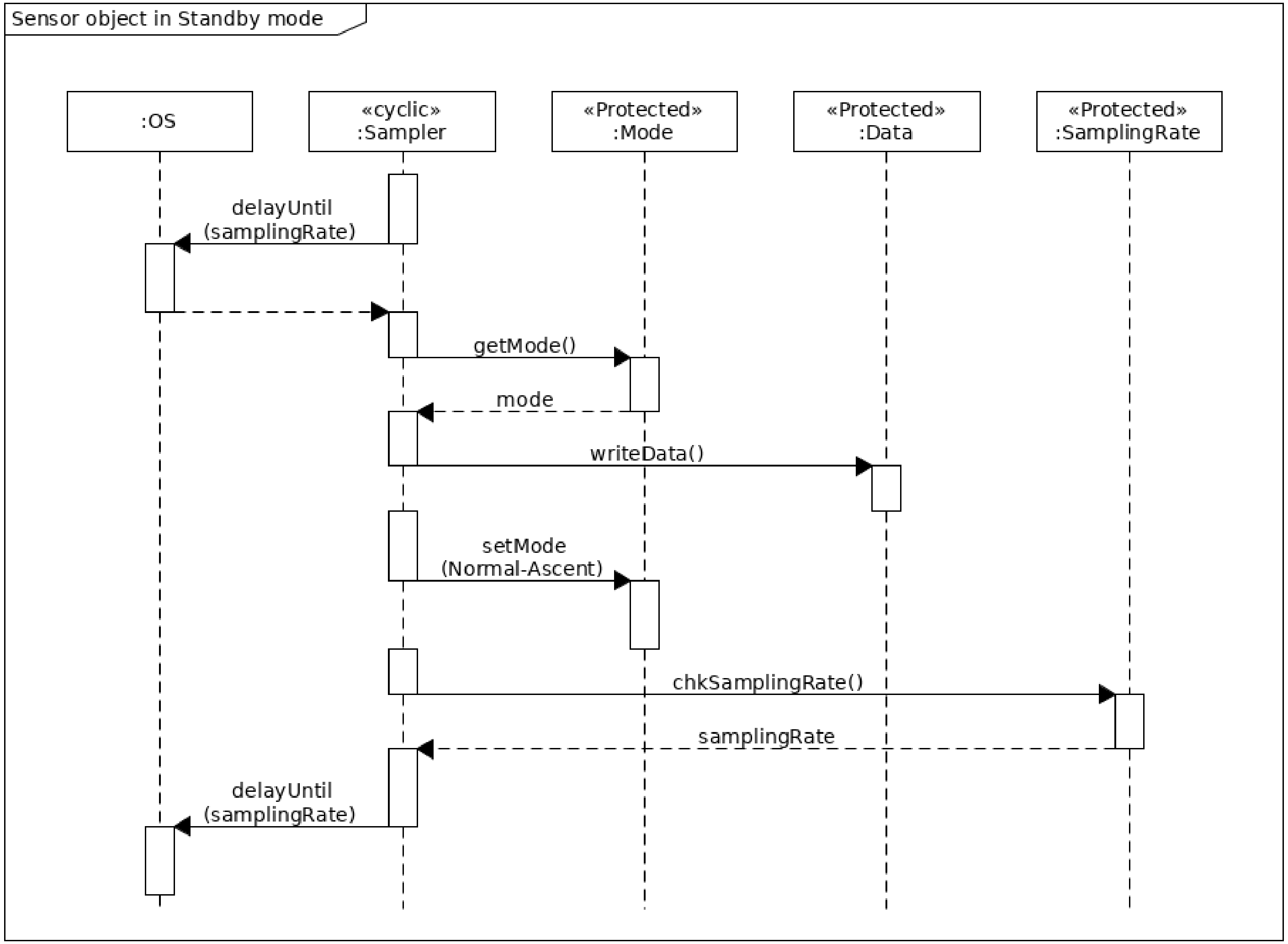


Figure 37: Sensor object in standby mode

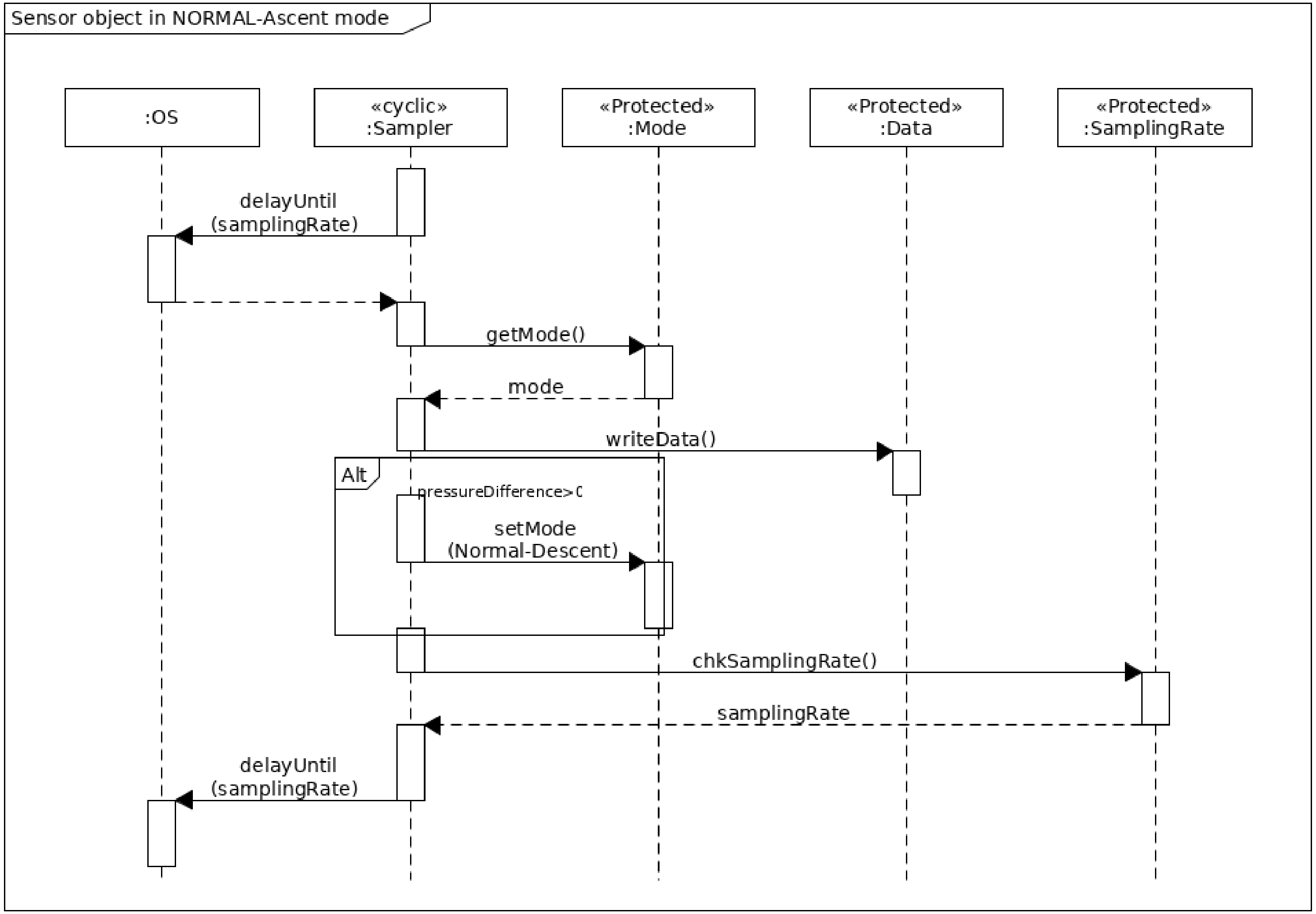


Figure 38: Sensor object in normal -Ascent mode

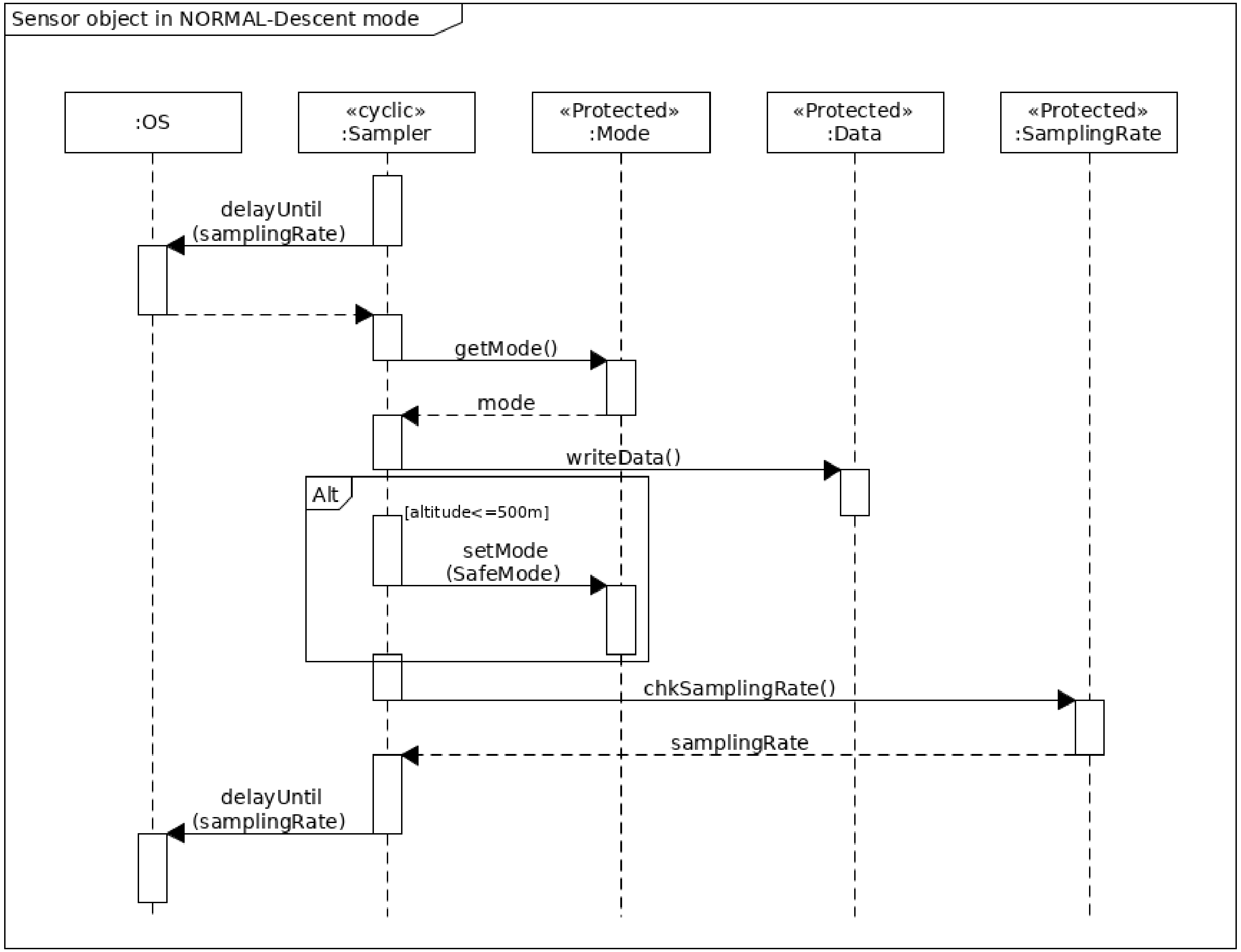


Figure 39: Sensor object in normal -Descent mode

C APPENDIX C

C1 - Sensor Object Interface Diagram

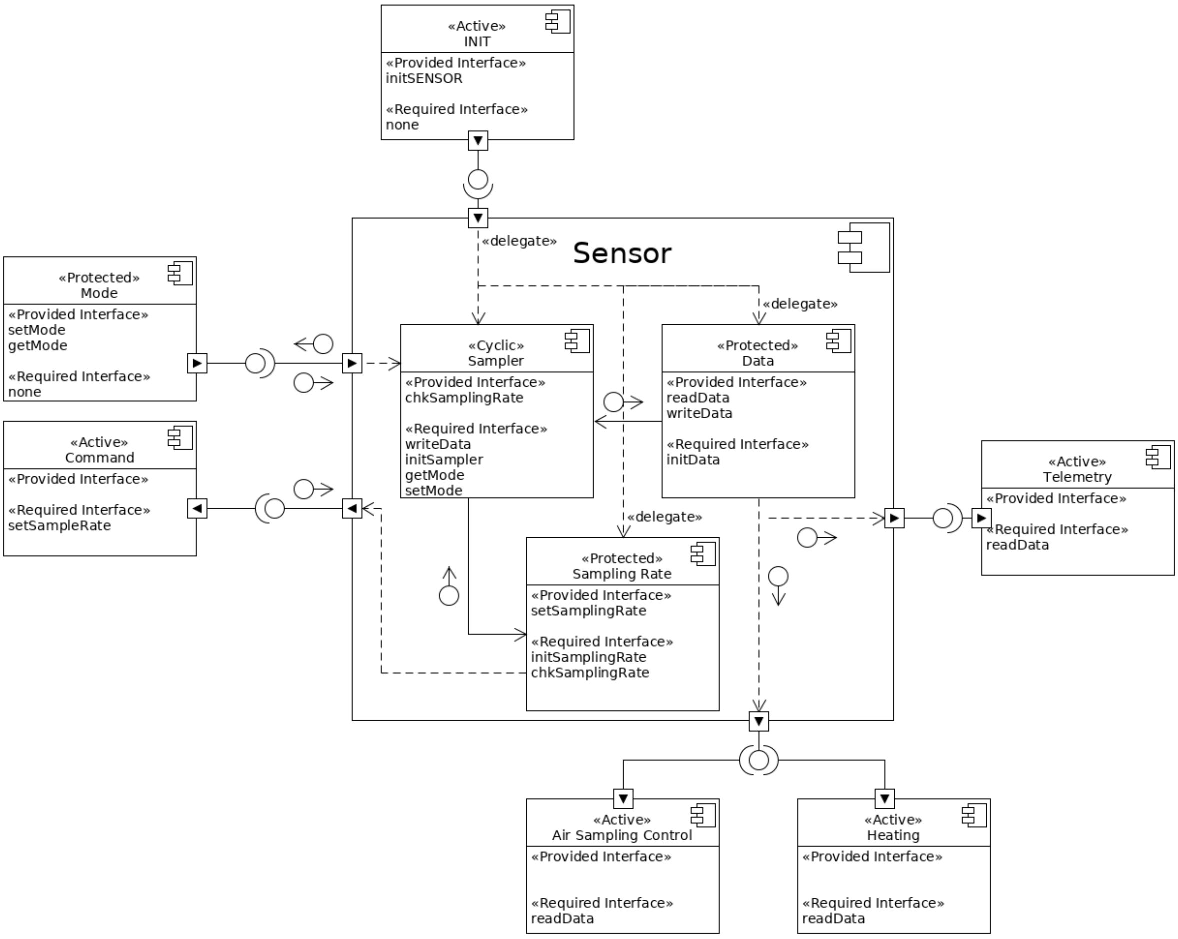


Figure 40: Sensor Object Interface Diagram

C2 - Air Sampling Control Object Interface Diagram

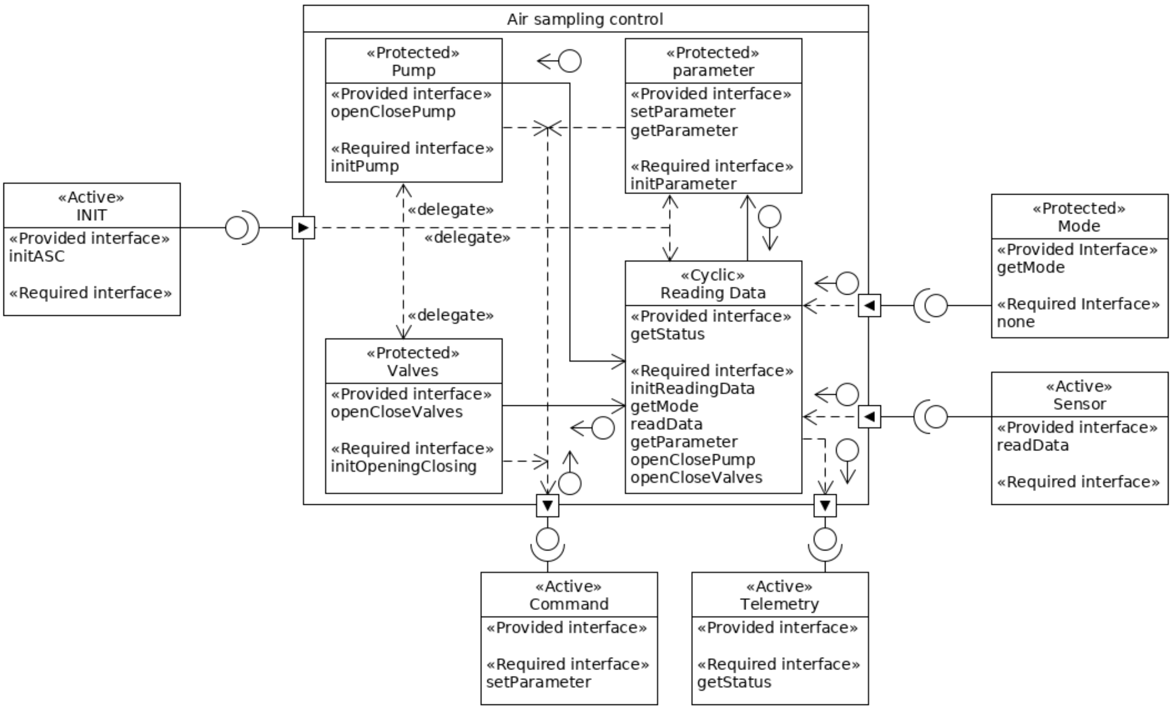


Figure 41: Air Sampling Control Object Interface Diagram

C3 - Heating Object Interface Diagram

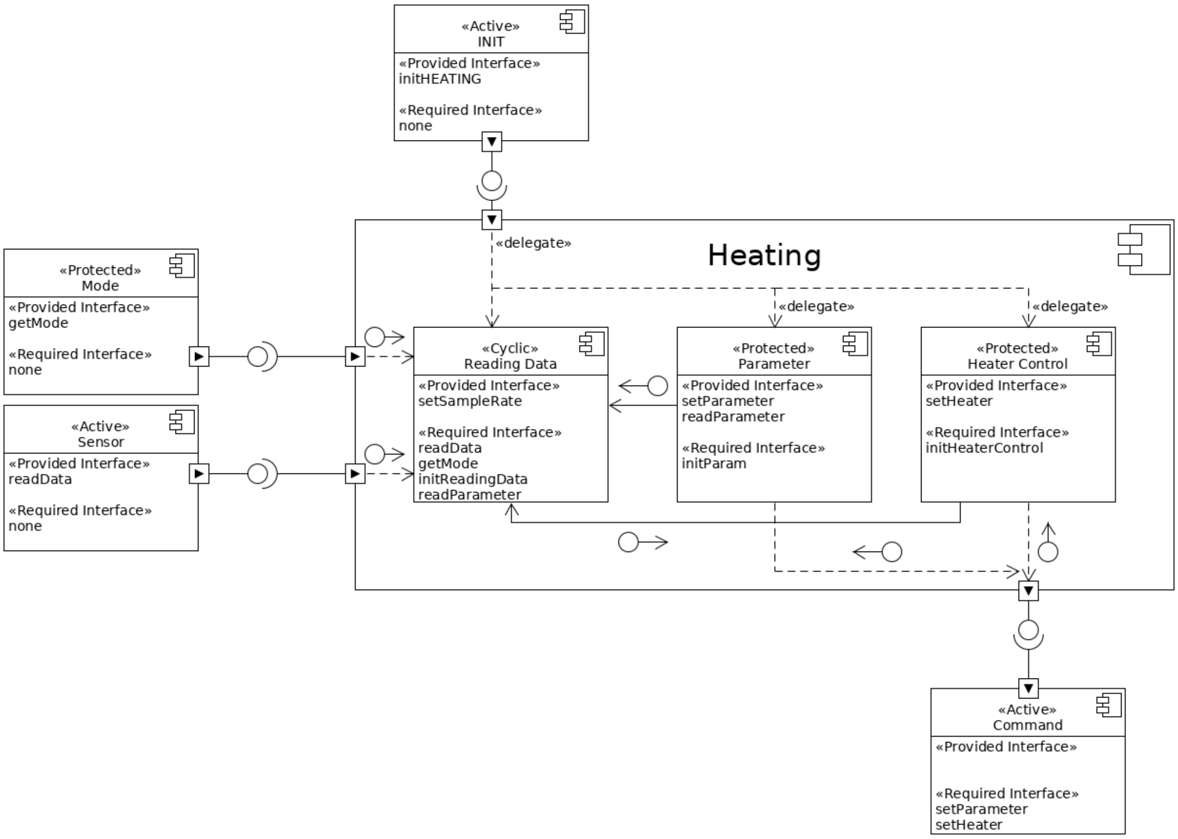


Figure 42: Heating Object Interface Diagram

D APPENDIX D

D1 - Team availability from February 2018 to July 2018

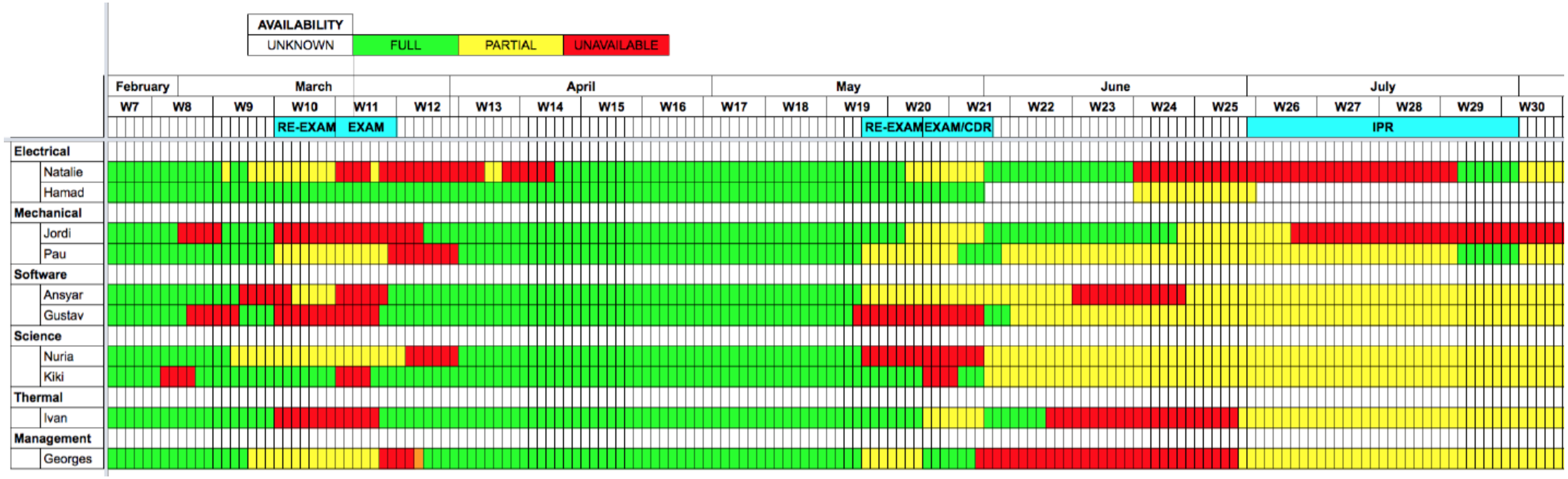


Figure 43: Team availability from February 2018 to July 2018.

D2 - Team availability from August 2018 to January 2019

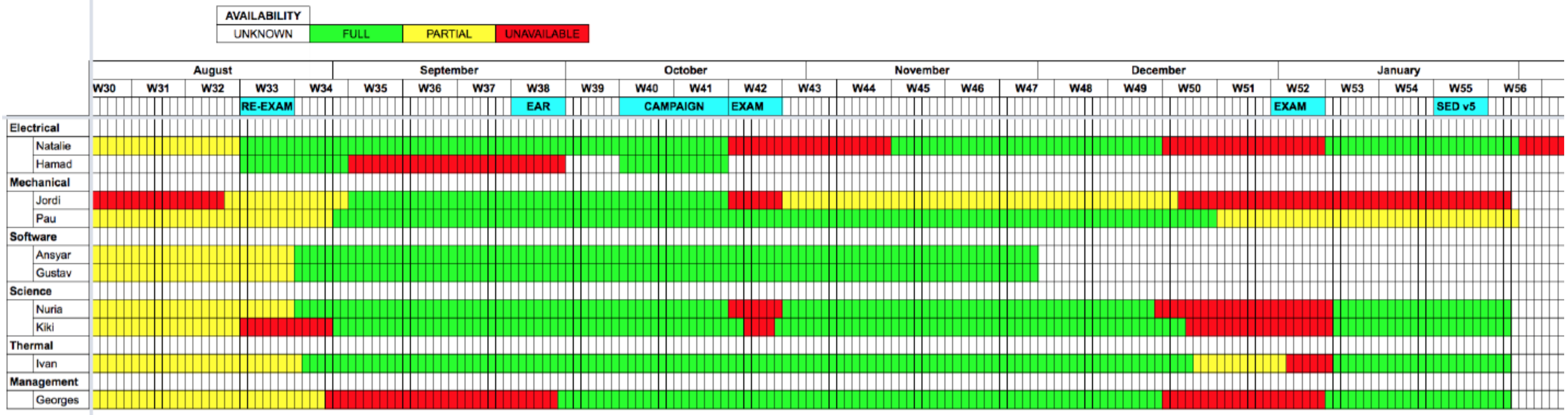
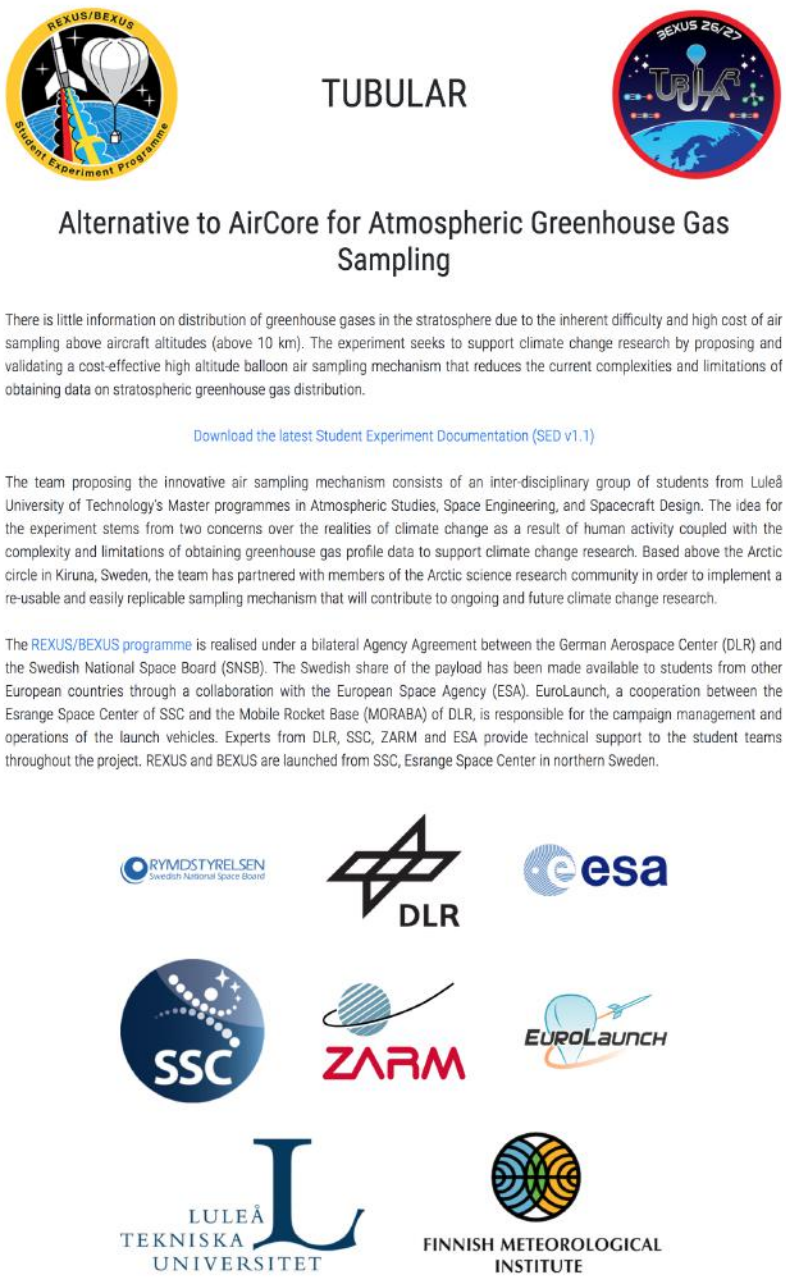


Figure 44: Team availability from August 2018 to January 2019.

E APPENDIX E

E1 - Outreach on Project Website



TUBULAR

Alternative to AirCore for Atmospheric Greenhouse Gas Sampling

There is little information on distribution of greenhouse gases in the stratosphere due to the inherent difficulty and high cost of air sampling above aircraft altitudes (above 10 km). The experiment seeks to support climate change research by proposing and validating a cost-effective high altitude balloon air sampling mechanism that reduces the current complexities and limitations of obtaining data on stratospheric greenhouse gas distribution.

Download the latest Student Experiment Documentation (SED v1.1)

The team proposing the innovative air sampling mechanism consists of an inter-disciplinary group of students from Luleå University of Technology's Master programmes in Atmospheric Studies, Space Engineering, and Spacecraft Design. The idea for the experiment stems from two concerns over the realities of climate change as a result of human activity coupled with the complexity and limitations of obtaining greenhouse gas profile data to support climate change research. Based above the Arctic circle in Kiruna, Sweden, the team has partnered with members of the Arctic science research community in order to implement a re-usable and easily replicable sampling mechanism that will contribute to ongoing and future climate change research.

The REXUS/BEXUS programme is realised under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB). The Swedish share of the payload has been made available to students from other European countries through a collaboration with the European Space Agency (ESA). EuroLaunch, a cooperation between the Esrange Space Center of SSC and the Mobile Rocket Base (MORABA) of DLR, is responsible for the campaign management and operations of the launch vehicles. Experts from DLR, SSC, ZARM and ESA provide technical support to the student teams throughout the project. REXUS and BEXUS are launched from SSC, Esrange Space Center in northern Sweden.

Figure 45: Outreach on project website (tubularbex.us).

E2 - Social Media Outreach on Facebook

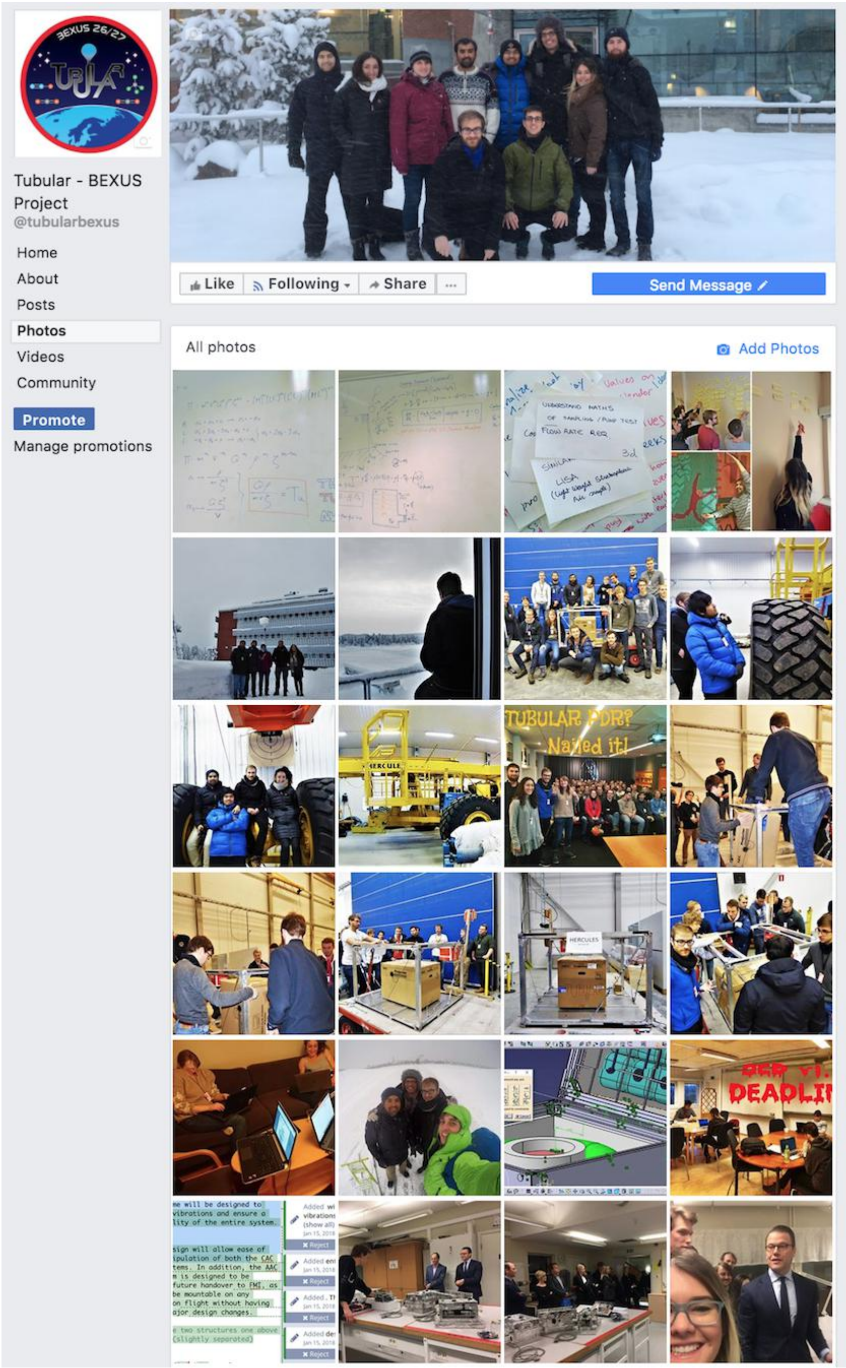


Figure 46: Social media outreach on Facebook.

E3 - Social Media Outreach on Instagram

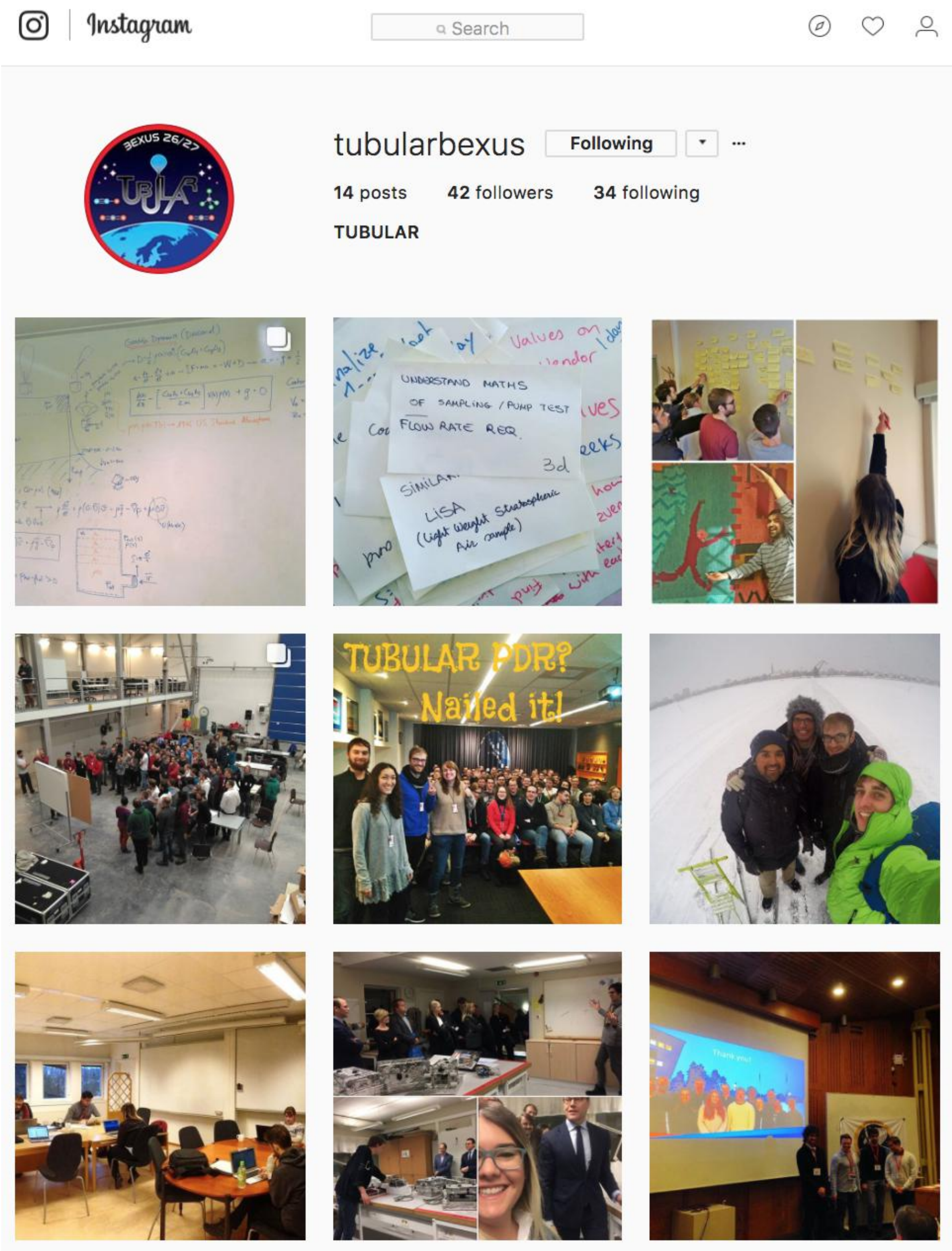


Figure 47: Social media outreach on Instagram.

E4 - Social Media Outreach on Space Instrument Themed Instagram (1/2)

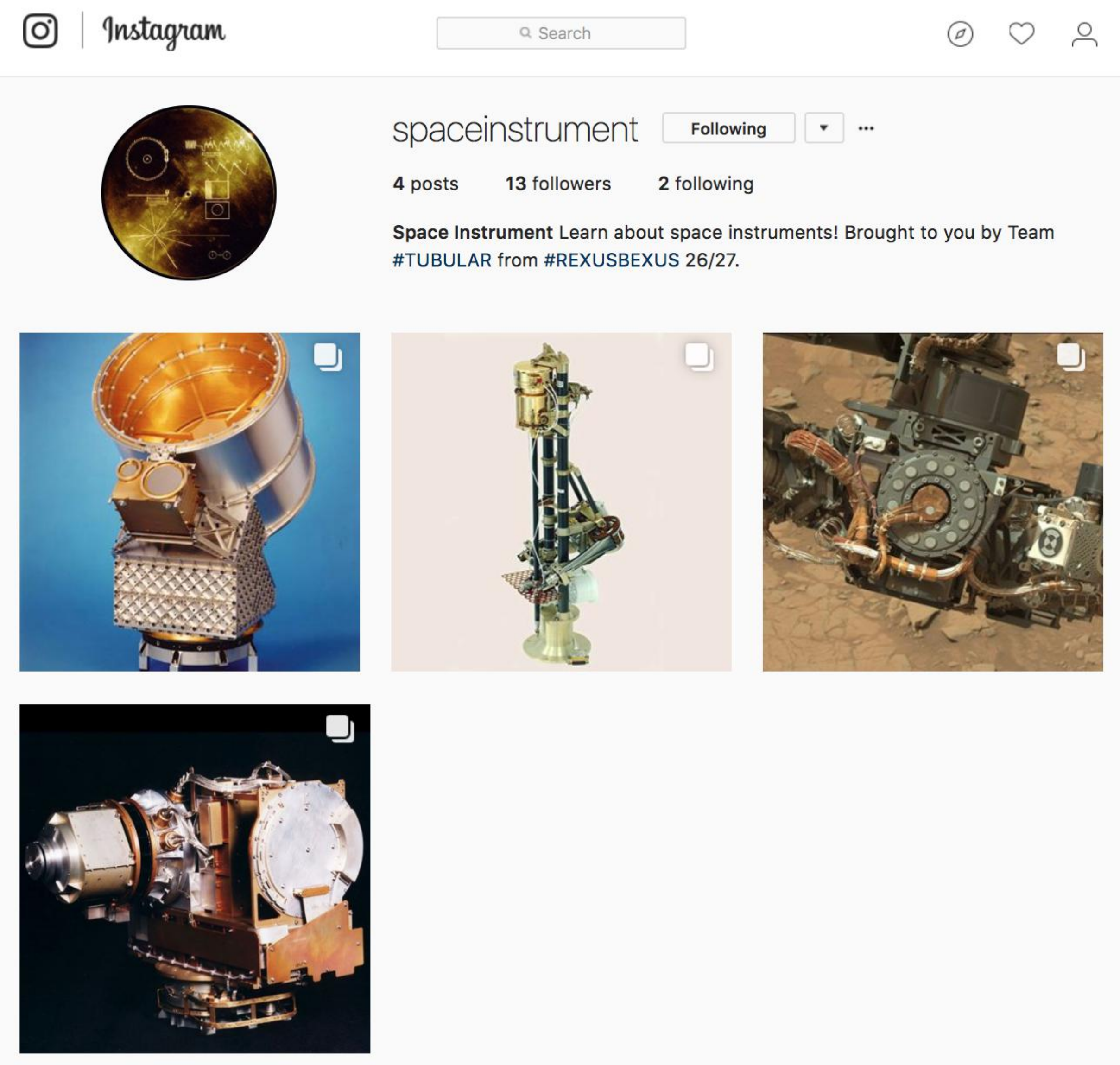


Figure 48: Social media outreach on space instrument themed Instagram (1/2).

E5 - Social Media Outreach on Space Instrument Themed Instagram (2/2)

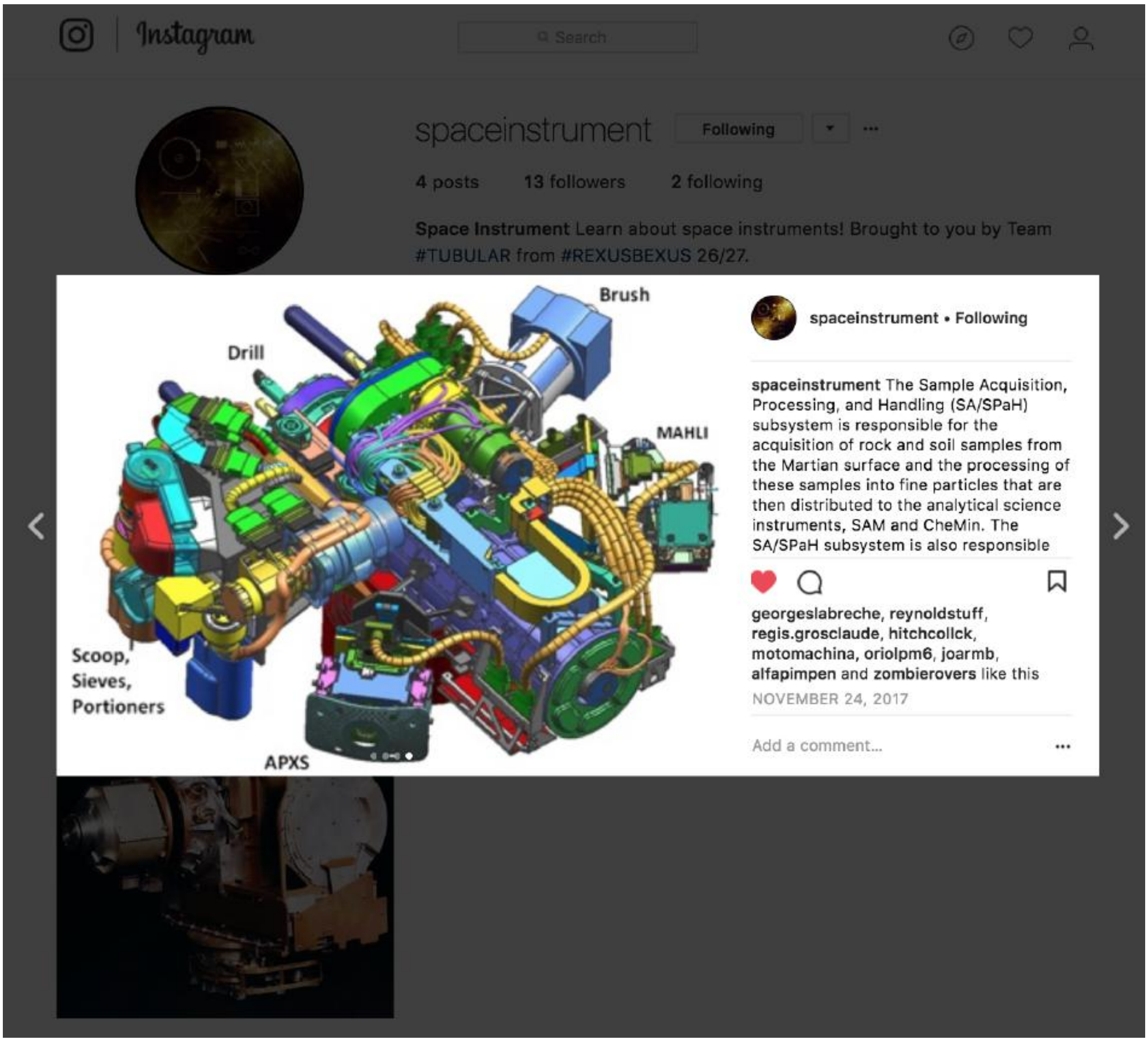


Figure 49: Social media outreach on space instrument themed Instagram (2/2).

E6 - Outreach with Open Source Code Hosted on a REXUS/BEXUS GitHub Repository

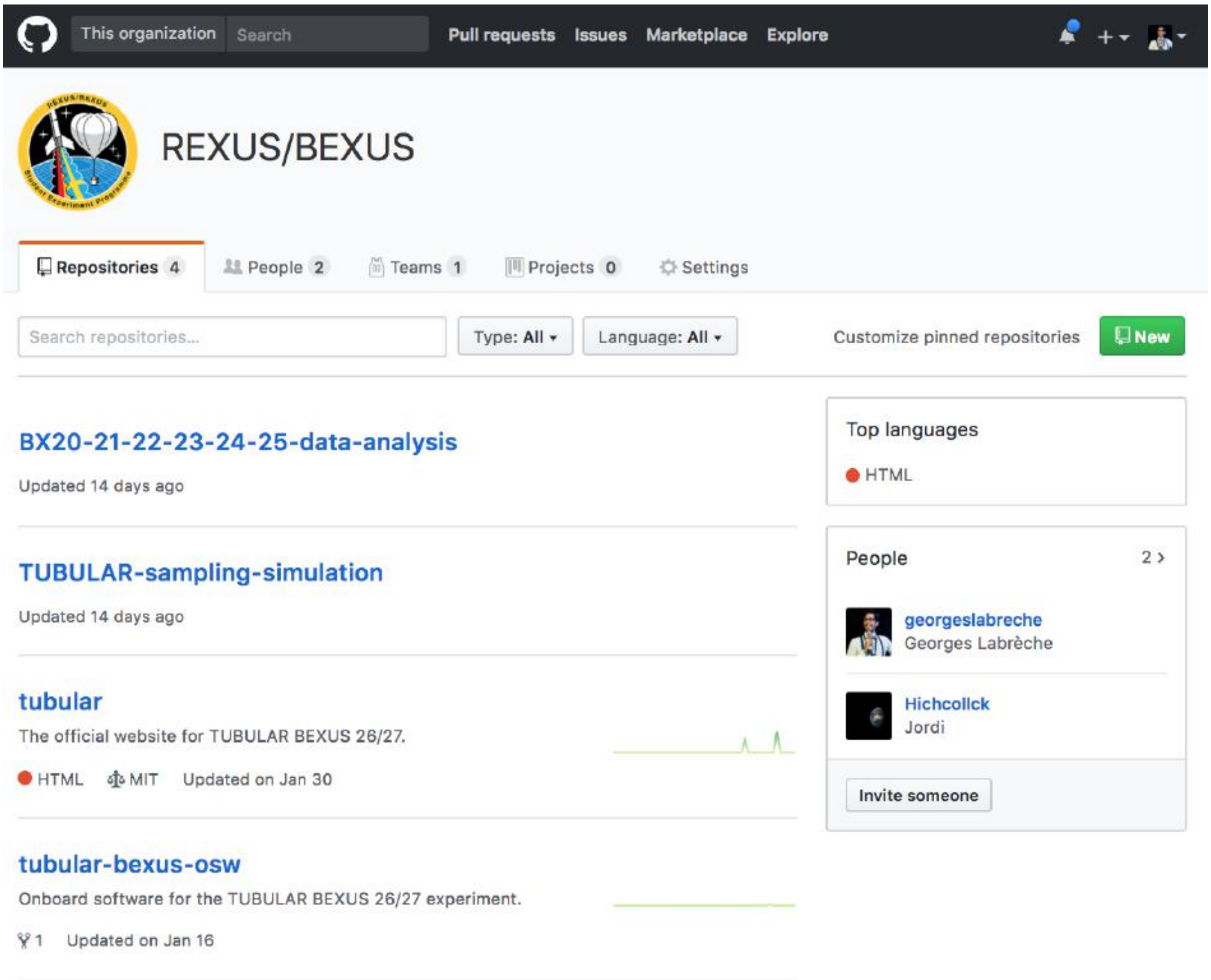


Figure 50: Outreach with open source code hosted on a REXUS/BEXUS GitHub repository.

F APPENDIX F

F1 - Gantt Chart (1/2)

Figure 51: Gantt Chart (1/2)

F2 - Gantt Chart (2/2)

Name	Begin date	End date
Mechanical Division	2/26/18	9/15/18
Design the new configuration	2/26/18	3/8/18
Decide on locations of external connecti...	2/26/18	3/8/18
Agree on new designs with programme ...	2/26/18	3/8/18
Design pipes	2/26/18	3/2/18
Find valves	2/26/18	3/2/18
Order valves	3/5/18	3/19/18
Label all figures in SED	2/26/18	2/26/18
Acquire styrofoam walls (payload protec...	5/11/18	5/21/18
Acquire aluminium sheet for the walls	5/11/18	5/21/18
Acquire polyethylene foam (thermal insu...	5/11/18	5/21/18
Acquire experiment building component...	5/11/18	5/21/18
Acquire frame bars REXROTH	5/11/18	5/21/18
Join the frame bars build structure	6/1/18	6/21/18
Build valve center (drill holes, attach valv...	6/1/18	6/21/18
Attach the pipes	6/25/18	6/29/18
Build the walls (aluminium sheet, PE FOA...	7/25/18	7/29/18
Make holes in the walls for the external ...	7/25/18	7/29/18
Attach the walls to the structure	7/25/18	7/29/18
Testing	8/1/18	9/15/18
Test: vibration	8/1/18	9/15/18
Test: shock	8/1/18	9/15/18
Test: thermal	8/1/18	9/15/18
Test: styrofoam in vacuum	8/1/18	9/15/18
Test: mechanical interfaces	8/1/18	9/15/18
Science Division	1/16/18	1/15/19
Bags vs Canisters decision	2/23/18	2/23/18
Understand maths of sampling/test. Flo...	2/22/18	2/24/18
Similarity with LISA (the paper Lightweigh...	2/22/18	2/22/18
Calculate endothermal analysis (i.e. atm...	2/22/18	2/22/18
Obtain empirical model	3/2/18	3/12/18
MATLAB simulation of flight	3/12/18	3/18/18
Model/simulation of sampling	3/25/18	4/15/18
Determing sampling altitudes	5/1/18	5/1/18
Understand how chromatographer works	5/14/18	5/20/18
FMI site visit / AirCore tube retrieval	7/1/18	7/7/18
Find out how Piacaro analyser works	8/30/18	9/2/18
Post-flight analysis	10/22/18	11/18/18
Write research paper	11/19/18	1/15/19
Publish research paper	1/16/18	1/31/18
Testing	4/9/18	5/15/18
Test: planning / sampling methodology	4/9/18	4/15/18
Test: sampling	4/16/18	4/22/18
Analyse sampling test results	4/30/18	5/15/18
Test: bag condensation test	4/23/18	4/29/18
Thermal Diviion	2/24/18	3/29/18
Calculate exothermal analysis	2/24/18	2/26/18
Update thermal design	3/1/18	3/4/18
Onboard new thermal team member	3/15/18	3/25/18
Planned long term thermal tasks	3/30/18	3/30/18
Exam Periods	1/8/18	1/18/19
Exam Period 1 (EX1)	1/8/18	1/12/18
Exam Period 2 (EX2)	3/12/18	3/21/18
Exam Period 3 (EX3)	5/23/18	5/30/18
Exam Period 4 (EX4)	8/13/18	8/22/18
Exam Period 5 (EX5)	10/15/18	10/24/18
Exam Period 6 (EX6)	12/17/18	12/21/18
Exam Period 7 (EX7)	1/14/19	1/18/19
Integration Testing	9/1/18	10/12/18
Integration Testing	9/1/18	10/10/18
Pre-flight testing	10/8/18	10/12/18

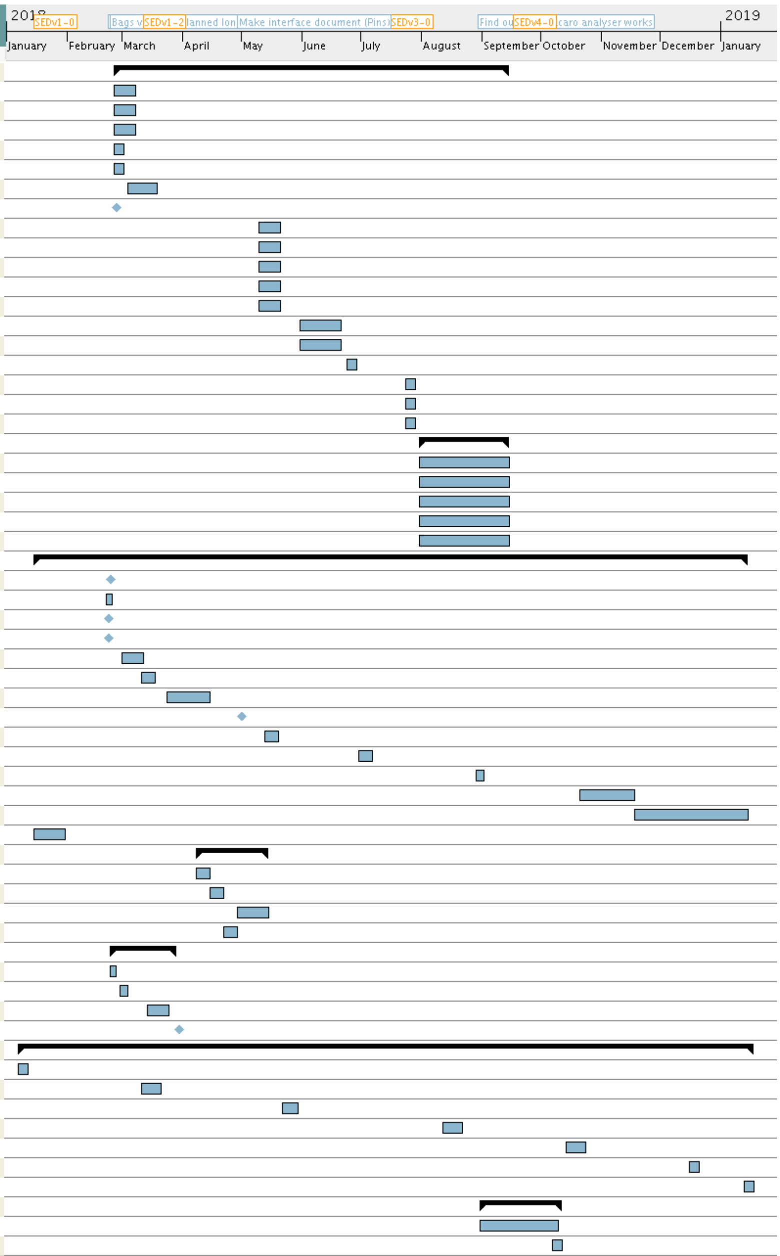


Figure 52: Gantt Chart (2/2)

G APPENDIX G

Equipment Loan Agreement

I. Lender Information
Institution: Finnish Meteorological Institute (FMI)
Address: Tähteläntie 62, 99600 Sodankylä, Finland
Representative: Dr. Rigel Kivi
E-Mail: rigel.kivi@fmi.fi
Telephone Number: +358 405 424 543

Hereinafter referred to as "the Lender."

II. Borrower Information
Group: Team TUBULAR (BEXUS 26/27)
Address: Luleå University of Technology, Rymdcampus, 981 28, Kiruna, Sweden.
Representative: Georges L. J. Labrèche
E-Mail: geolab-7@student.ltu.se
Telephone Number: +4670 577 23 87

Hereinafter referred to as "the Borrower."

III. Equipment Information
The borrowed Equipment, hereinafter referred to as "the Equipment," is a coiled 300 meters long stainless steel tube. The tube is coated and has wall thickness of 0.005 inches. The coil can be damaged if not packed properly, using some kind of shock absorbing material, for example soft styrofoam material. The Borrower is to use the Equipment as part of an AirCore experimental setup that will collect air samples during a high altitude balloon flight under the REXUS/BEXUS programme[1] scheduled to launch in October, 2018. After the payload landing and gas analysis the Equipment will be returned to the Lender.

[1] REXUS/BEXUS – Rocket and Balloon Experiments for University Students, http://rexusbexus.net/.

IV. Borrower Responsibilities

This Agreement and the responsibilities as outlined hereunder are not transferable without the written approval of the Lender. By executing this Agreement, the Borrower agrees to comply with the terms set forth below:

1. *Use/Disclaimer*
   - 1.1. The Borrower is responsible for the proper use and deployment of the Equipment.
   - 1.2. The Borrower is responsible for training anyone using the Equipment on the proper use of the Equipment in accordance with any Equipment use procedures.
   - 1.3. The Borrower agrees to use the Equipment for academic or research use only and not for any commercial use of application.
   - 1.4. If the Equipment is lost, stolen, or damaged, the Borrower agrees to promptly notify the Lender Representative designated above.

2. *Proper Care and Protection*
   - 2.1. The Borrower is responsible for proper care, maintenance, and protection of the Equipment.
   - 2.2. The Borrower is responsible for designing experiments using the Equipment with protection of the Equipment as the primary requirement.
   - 2.3. The Borrower is responsible for testing the designed Equipment protection measures.
   - 2.4. The Borrower is responsible for communicating the Equipment protection test results to the Lender Representative designated above.
   - 2.5. The Borrower is not responsible for Equipment damage related to hard landings. Nominally, the landing is gentle with no damage to the experiments however, on rare occasions, landing shocks up to 35g have been recorded when landing in rocky terrain.
   - 2.6. The Borrower is not responsible for Equipment damage related to the unlikely event of a water landing since the experiment gondola is not watertight.

3. *Delivery and Return*
   - 3.1. Title to the Equipment is to remain with the Lender.
   - 3.2. The Borrower is responsible for the safe packaging, proper import, export, and receiving of the Equipment.
   - 3.3. The Equipment is to be returned within a reasonable amount of time after the Loan Period end date agreed between the Lender and the Borrower.
   - 3.4. The Equipment shall be returned to the Lender in as good a condition as when received by the Borrower.

4. *Indemnification*
   - 4.1. In consideration for the Equipment loan, the Borrower agrees to indemnify, defend, and hold Lender harmless from any and all damages, losses, claims, causes of actions, expenses, and liability of any nature whatsoever associated with its use of the Equipment while under care, custody, and control of the Borrower unless due to the negligence of Lender.

5. *Amendment/Modification*
   5.1. This Agreement cannot be amended or modified except by an instrument in writing signed by both parties. Any attempt to do so except in accordance with this paragraph shall be void.

6. *Force Majeure*
   6.1. The Borrower is not responsible to Lender for any loss, damage, or failure to perform if occasioned by fire, flood, explosion, windstorm, riot, war, transportation difficulty, or any other cause beyond the reasonable control of the Borrower.

In witness whereof, the parties have executed this Agreement effective as of the date of the last party to sign this Agreement below.

Authorized Borrower Representative

Signature: DocuSigned by: Georges L. J. Labrèche 6326A4DA9B2F4D0...

Name: Georges L. J. Labrèche

Title: Project Manager (Team TUBULAR)

Date: 3/12/2018

Authorized Lender Representative

Signature: Rigel Kivi

Name: Dr. Rigel Kivi

Title: Senior Scientist

Date: March 12, 2018