SED

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Team Name: TUBULAR

Experiment Title: Alternative to AirCore for Atmospheric Greenhouse Gas Sampling

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CHANGE RECORD

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1-0	2018-01-15	All	PDR
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Abstract: Carbon dioxide (CO_2), methane (CH_4), and carbon monoxide (CO) 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.

Contents

PREFACE

The Rocket and Balloon Experiments for University Students (REXUS/BEXUS) programme 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 to AirCore for Atmospheric Greenhouse Gas Sampling 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 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 collaborate in order to produce a research detailing the air sampling methodology, measurements, analysis, and findings.

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.

- **Mr. Pauli Heikkinen**, Scientist at FMI. A key project partner, Dr. Heikkinen'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). 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.

- **Mr. Vince Still**, LTU alumni and previous BEXUS participant with project EXIST. Mr Still assists the team as a thermal consultant.

The TUBULAR Team would also like to acknowledge component sponsorship from the following manufacturers and suppliers all of which showed authentic interest in the project and provided outstanding support:

- **Restek** develops and manufactures GC and LC columns, reference standards, sample prep materials, and accessories for the international chromatography industry.

- **SMC Pneumatics** specializes in pneumatic control engineering to support industrial automation. SMC develops a broad range of control systems and equipment, such as directional control valves, actuators, and air line equipment, to support diverse applications.

- **SilcoTek** provides coatings solutions that are corrosion resistant, inert, H2S resistant, anti-fouling, and low stick.

- **Swagelok** designs, manufactures, and delivers an expanding range of fluid system products and solutions.

- **Teknolab Sorbent** provides products such as analysis instruments and accessories within reference materials, chromatography and separation technology.

- **Lagers Masking Consulting** specializes in maintenance products and services for industry, construction, and municipal facilities.

- **Bosch Rexroth** manufactures products and systems associated with the control and motion of industrial and mobile equipment.

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" [16] 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 make up less than 1% of the Earth's atmosphere. They include all gasses except Nitrogen, and Oxygen. In terms of climate change, the main concern for the scientific community is that of CO_2 and CH_4 concentrations which make up less than 0.1% of the trace gases 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 caused 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 the 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 the 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. Achieving this objective consists of developing a cost-effective and re-usable stratospheric air sampling system (i.e. AAC). Samples collected by the proposed mechanism are to be compared against samples collected by a proven sampling system (i.e. CAC). The proven sampling system is to be part of the experimental payload as a reference that will validate the proof-of-concept air sampling system.

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 carbon oxide (CO)[1]. The research activities will culminate in a research paper written in collaboration with FMI.

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 69 in Appendix C.2). 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 to 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 70 in Appendix C.2) rather than the CAC's single long and coiled tube. Each sampling bag is to be allocated a vertical sampling range capped at 500 meters so that mixing of gases becomes a lesser concern.

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[1]The third gas being sampled has been changed from N_2O to CO. The main reason for changing this is that the model of analyzer used is only able to detect CO_2, CH_4 and CO.

The use of sampling bags in series rather than a single long tube is meant to tackle limitations of the 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. However, the AAC comes with its own limitations as its discrete sampling will not allow for a the type of continuous profiling made possible by the CAC coiled tube. 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 all of which are studying at the Masters level at LTU's space campus in Kiruna, Sweden.

Georges L. J. Labrèche - Management Division

Current Education: MSc in Spacecraft Design.

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

Responsibilities: Acting as Systems Engineer / Project Manager and managing overall implementation of the project until the Critical Design Review (CDR). Establishing and overseeing product development cycle. Coordinating between different teams, project stakeholders, and documentation efforts.

Natalie Lawton - Management and Electrical Division

Current Education: MSc in Spacecraft Design.

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

Responsibilities: Acting as Deputy Systems Engineer / Project Manager until the CDR. Assuming role of System Engineer / Project Manager after the CDR until end of project. 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.

Nuria Agües Paszkowsky - Scientific Division

Current Education: MSc in Earth Atmosphere and the Solar System.

Previous Education: BSc in Aerospace Engineering.

Responsibilities: Defining experiment parameters; data analysis; interpreting and documenting measurements; research on previous CAC 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

Current Education: MSc in Earth Atmosphere and the Solar System.

Previous Education: BSc in Physics.

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

Emily Chen - Mechanical Division

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

Responsibilities: Mechanical designing and assembly of CAC subsystem; analyzing the test results and changing the design as needed in collaboration with the team leader; integrating and assembling final design.

Jordi Coll Ortega - Mechanical Division

Current Education: MSc in Spacecraft Design.

Previous 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

Current 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.

Erik Fagerström - Thermal Division

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

Responsibilities: Coordinating between the Thermal Division and the Project Manager. Planning project thermal analysis and testing strategy. Thermal simulations of proposed designs and analyze results.

Pau Molas Roca - Mechanical Division

Current Education: MSc in Spacecraft Design.

Previous Education: BSc in Aerospace Technology Engineering, Mechanical experience.

Responsibilities: Coordinating between the Mechanical Division 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.

Emil Nordqvist - Electrical Division

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

Responsibilities: Quality assurance of circuit design and implementation. Developing, testing, and evaluating theoretical designs.

Muhammad Ansyar Rafi Putra - Software Division

Current Education: MSc in Spacecraft Design.

Previous Education: BSc in Aerospace Engineering.

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

Hamad Siddiqi - Electrical Division

Current Education: MSc Satellite Engineering.

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

Responsibilities: Coordinating between the Electrical Division 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

Current Education: MSc in Spacecraft Design.

Previous Education: BEng in Mechanical Engineering.

Responsibilities: Thermal analysis of proposed designs and analysis result based recommendations.

2 Experiment Requirements and Constraints

Requirements in this section does not list obsolete requirements. For a complete list of requirements that include obsolete ones, refer to Appendix N.

2.1 Functional Requirements

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

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

F.9 The experiment *should* measure the air intake flow to the AAC.

F.10 The experiment *shall* measure the air pressure.

F.11 The experiment *shall* measure the temperature.

2.2 Performance Requirements

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/-3°C (max) for condition of -55°C to 150°C.

P.23 The temperature sensor sampling rate *shall* be 1 Hz.

P.24 The temperature of the Pump *shall* be between 5°C and 40°C.

P.25 The minimum volume of air in the bags for analysis *shall* be 0.18 L at ground level.

P.26 The flow rate of the pump *shall* be between 8 to 3 L/min from ground level up to 24 km altitude.

P.27 The accuracy range of the sampling time, or the resolution, *shall* be less than 52.94 s, or 423.53 m.

P.28 The pressure sensor sampling rate *shall* be 1 Hz.

P.29 The airflow sensor sampling rate *shall* be 1 Hz.

P.30 The accuracy of the pressure measurements inside the tubing and sampling bags *shall* be -0.005/+0.005 bar for 25°C.

2.3 Design Requirements

D.1 The experiment *shall* operate in the temperature profile of the BEXUS flight[6].

D.2 The experiment *shall* operate in the vibration profile of the BEXUS flight[6].

D.3 The experiment *shall* not have sharp edges or loose connections to the gondola that can harm the launch vehicle, other experiments, and people.

D.4 The experiment's communication system *shall* be compatible with the gondola's E-link system with the RJF21B connector over UDP for down-link and TCP for up-link.

D.5 The experiment's power supply *shall* have a 24v, 12v, 5v and 3.3v power output and be able to take 28.8v input through the Amphenol PT02E8-4P connector supplied from the gondola.

D.7 For the supplied voltage of 28.8 V, the total continuous DC current draw *should* be below 1.8 A.

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

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[6].

D.19 The experiment *shall* operate in the vertical and horizontal accelerations profile of the BEXUS flight[6].

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

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

D.23 The air intake rate of the air pump *shall* be minimum 3 L/min at 24 km altitude.

D.24 The temperature of the Brain[2] *shall* be between -10°C and 25°C.

D.26 The air sampling systems *shall* filter out all water molecules before filling the sampling bags.

D.27 The total weight of the experiment *shall* be less than 28 kg.

D.28 The AAC box *shall* be able to fit at least 6 air sampling bags.

D.29 The CAC box *shall* take less than 3 minutes to be removed from the gondola without removing the whole experiment.

D.30 The AAC *shall* be re-usable for future balloon flights.

D.31 The altitude from which a sampling bag will start sampling *shall* be programmable.

D.32 The altitude from which a sampling bag will stop sampling *shall* be programmable.

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[2]The Brain is a central command unit which contains Electronic Box and pneumatic sampling system.

2.4   Operational Requirements

O.13 The experiment *should* function automatically.

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

2.5   Constraints

C.1 Constraints specified in the BEXUS User Manual.

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 divisions constitute a work breakdown structure in which is illustrated in Figure 1.

The interaction between the divisions 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 and a Deputy Project Manager, both acting as 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. Once all subsystems have been assembled, the Project Manager will be responsible for overseeing the integration processes leading to the final experiment setup and will put emphasis on leading quality assurance integration testing efforts. The Deputy Project Manager assists the Project Manager in all management duties in a manner that ensures replaceability when necessary.

The Scientific Division is responsible for defining experiment parameters; data analysis; interpreting and documenting measurements; researching previous CAC 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.

The Thermal Division is responsible for ensuring thermal regulation of the payload as per operational requirements of all experiment components; evaluating designs against thermal simulation and propose improvements; managing against mechanical design and electrical power limitations towards providing passive and active thermal control systems.
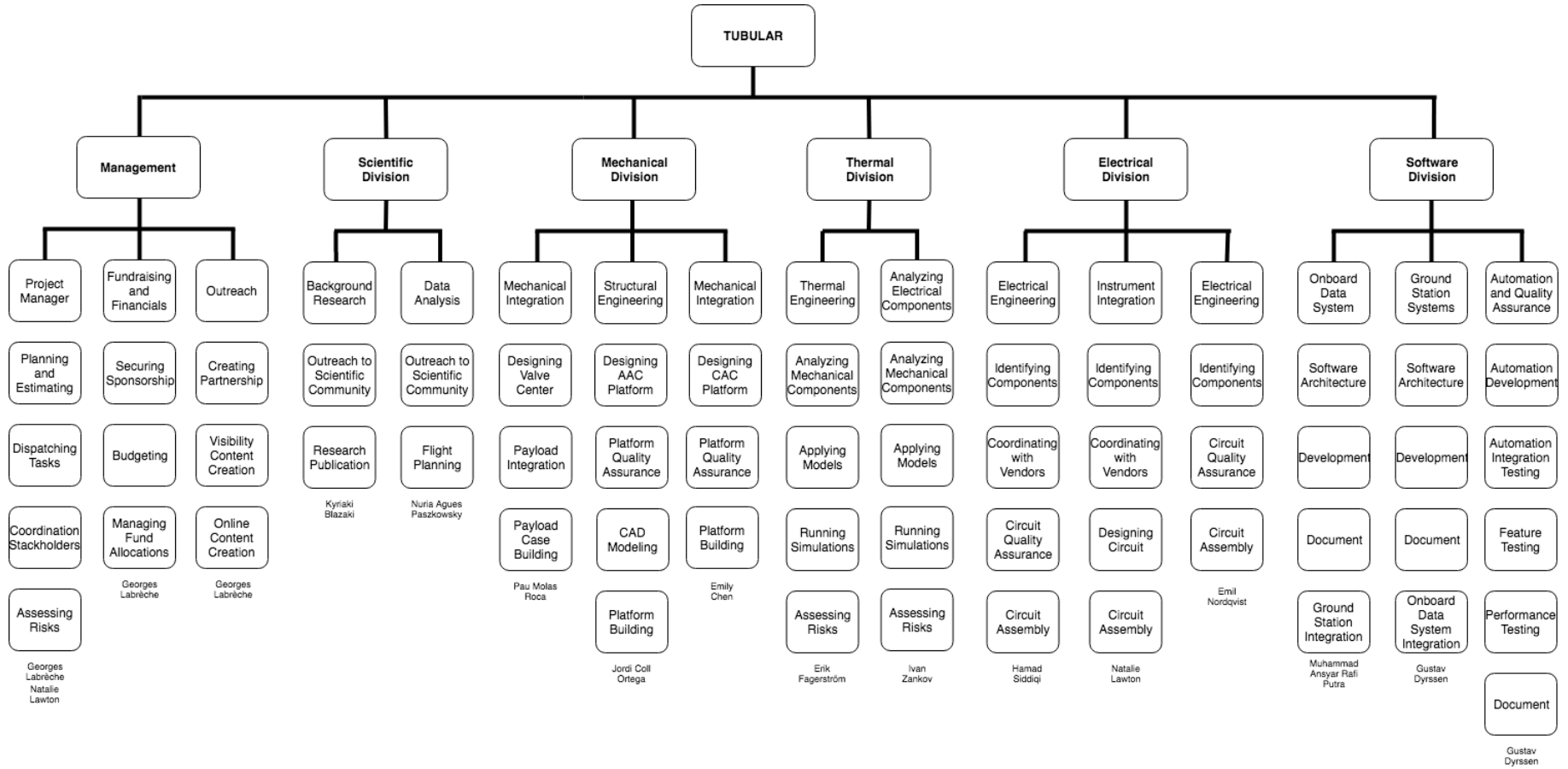
Figure 1: Work Breakdown Structure.

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. It is expected during exam periods the team work output will be lower than usual but project activities will continue, therefore time has been planned accordingly to accommodate this:

Figure 2: Project Schedule Gantt Chart.

Deadlines of the five Student Experiment Documentations (SED) versions have been estimated based on past REXUS/BEXUS Cycles. An expanded version of the Gantt Chart with detailed listing of all sub-tasks not shown in Figure 2 can be found in Appendix F. This expanded Gantt Chart includes all tasks related to the test plan and internal deadlines are set so that a first draft of the documentation is completed one week in advance to allow contents to be checked. Build and test internal deadlines are also placed one week in advance to allow a buffer in case things do not go as expected. The tests are scheduled for as early as possible to allow time for rescheduling if the result is a fail. With some high priority tests, see Section 5.2.1, it is expected these will be very difficult to reschedule therefore extra time is built into the test duration to allow for multiple attempts at the test.

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
Natalie Lawton*	Kyriaki Blazaki*	Pau Molas Roca*	Hamad Siddiqi*	Erik Fragerström*	Muhammad Ansyar Rafi Putra*
Georges L. J. Labrèche	Nuria Agues Paszkowsky	Jordi Coll Ortega	Natalie Lawton	Ivan Zankov	Gustav Dyrssen
		Emily Chen	Emil Nordqvist		

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 L. J. Labrèche	MSc in Spacecraft Design (2nd Year). BSc in Software Engineering.
Nuria Agues Paszkowsky	MSc in Earth Atmosphere and the Solar System (2nd Year). BSc in Aerospace Engineering.
Kyriaki Blazaki	MSc in Earth Atmosphere and the Solar System (2nd Year). BSc in Physics.
Emily Chen	MSc in Space Engineering (4th Year).
Jordi Coll Ortega	MSc in Spacecraft Design (2nd Year). BSc in Aerospace Vehicle Engineering.
Gustav Dyrssen	MSc in Space Engineering (4th Year).
Erik Fagerström	MSc in Space Engineering (4th Year).
Natalie Lawton	MSc in Spacecraft Design (2nd Year). MEng in Aerospace Engineering. Previous experience in UAV avionic systems and emissions measurement techniques.
Muhammad Ansyar Rafi Putra	MSc in Spacecraft Design (2nd Year). BSc in Aerospace Engineering.
Pau Molas Roca	BSc in MSc in Spacecraft Design (2nd Year). Aerospace Technology Engineering, Mechanical experience.
Emil Nordqvist	MSc in Space Engineering (4th Year).
Hamad Siddiqi	MSc Satellite Engineering (4th Year) BSc in Electrical Engineering. Experience in telecommunication industry and electronics.
Ivan Zankov	MSc in Spacecraft Design (2nd Year). BEng in Mechanical Engineering.

Table 4: Project Related Experience of Team Members.

The initial projected effort to be contributed by each team member was averaged at 1.5 hour per person per day corresponding to a team total of 15 hours per day. Since then, 3 new members have been included in the team thus increasing the projected daily effort to 19.5 hours per day. During the period leading up to the launch it is expected that the effort

contributed will be double to 3 hours per person per day. The period of these different effort capacities are listed in Table 5:

From	To	Capacity (hours/day)
08/01/2018	18/03/2018	15
19/03/2018	08/04/2018	16.5
09/04/2018	09/05/2018	18
10/05/2018	15/08/2018	19.5
15/08/2018	22/10/2018	39
23/10/2018	31/01/2019	19.5

Table 5: Projected Daily Team Effort per Period.

Taking into account all team members and the mid-project changes in team size, the efforts/-capacity projected to be allocated to each stages of the project during 2018 are summarized in Table 6:

Stage	Start Date	End Date	Duration (days)	Effort (hours)		
				Capacity	Actual	Diff. (%)
Preliminary Design	08/01	11/02	35	525	708	+29.68
Critical Design	12/02	03/06	112	1680	*2299*	*+36.9*
Experiment Building and Testing	04/06	16/09	105	3072	798*	-74.01*
Final Experiment Preparations	17/09	11/10	25	976	-	-
Launch Campaign	12/10	22/10	10	390	-	-
Data Analysis and Reporting	23/10	30/12	69	1346	-	-
			Total:	**353**	**6282**	*3727**	*-40.67**

Table 6: Project Effort Allocation per Project Stages (Asterisks Denote Still Ongoing 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 LTU during the entire project period. Special attention will have to be made for planning tasks during the summer period where many team members are expected to travel abroad. A timeline of team member availability until January 2019 is available in Appendix E. A significant risk can be observed during the summer months from June to August where most members will only be partially available and some completely unavailable. As such, team member availability and work commitments over the summer have been negotiated across team members in order to guarantee that at least one member per division is present in Kiruna over the Summer with the exception of the Software Division which can work remotely. Furthermore, the Project Manager role will have to be assigned to the Deputy Project Manager due to an extended full time unavailability after the CDR.

As part of their respective Master programmes, most TUBULAR Team members are enrolled in a project course at LTU. The TUBULAR project acts as the course's project for most 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

The project mass and cost budget is summarized in Table 7 for a total project mass of 24 Kg and cost of 31,228 EUR. A complete budget is available in Appendix M and a detailed component mass and cost breakdown is available in Section 4.3 Experiment Components. The component mass and cost breakdown does not include spare components accounted for in the total costs listed in Table 7. A contingency fund of 1,054 EUR is allocated for unseen events such as component failures. Furthermore, an error margin is included in the budget corresponding to 10% of the total costs of components to be purchased. Component loan and donations from sponsors account for 83% of the project's total cost. LTU and SNSB funding accounts for the remaining 17%.

Category	Total Mass [g]	Total Price [EUR]
Structure	11,337.84	619.24
Electronics Box	510.50	1062.74
Cables and Sensors	1,200.62	586.20
CAC	5,539.00	23,114.00
AAC	3,541.00	4,444.71
Tools	–	332.53
Travel	–	500.00
Contingency	–	1053.86
Shipping Costs and Error Margin	2,212.90	568.17
Total	**24,341.85**	**31,227.58**

Table 7: Mass and Cost Budget.

The project benefits from component donations from Restek, SMC Pneumatics, Teknolab Sorbent, and Lagers Masking Consulting as well as component loans from FMI. Furthermore, discounts were offered by Teknolab Sorbent and Bosch Rexroth. Euro value allocation of these sponsorships are presented in Table 8.

Sponsor	Type	Value	Allocated	Unallocated	% Allocation	Status
LTU	Funds	2,500.00	1,880.33	619.67	75	Received
SNSB	Funds	2,909.80	2,475.60	434.20	85	Received
FMI	Component loan	22,500.00	22,500.00	0.00	100	Confirmed
Restek	Component donation	1040.00	1040.00	0.00	100	Received
Teknolab	Component donation	200.00	200.00	0.00	100	Received
SMC	Component donation	860.00	860.00	0.00	100	Confirmed
Lagers Maskin	Component donation	300.00	300.00	0.00	100	Received
Swagelok	Component donation	1971.65	1971.65	0.00	100	Confirmed
	Total	**32,281.44**	**31,227.58**	**1053.86**	**95**	

Table 8: Allocation of Sponsorship Funds and Component Donation Values. Amounts in EUR.

3.3.3 External Support

Partnership with FMI, and IRF will provide the team with technical guidance in implementing the sampling system. FMI's experience in implementing past CAC 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 the 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 result in significant cost savings regarding equipment and component procurement.

Daily access to LTU's Space Campus in Kiruna exposes 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, 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 REXUS/BEXUS programme and its partners will be promoted through the following activities:

- Research paper published in partnership with 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 to summarize the experiment and provide regular updates. Backend web analytics included to gauge interest on the project through number of visitors and their origins (See Appendix B).

- Dedicated Facebook page used as publicly accessible logbook detailing challenges, progress, and status of the project. Open for comments and questions (See Figure 63 in Appendix B).

- 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 64, 65, and 66 in Appendix B).

- GitHub account to host all project software code under free and open source license (See Figure 67 in Appendix B). 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.

- Articles and/or blogposts about the project in team members' alma mater websites.

- 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 REXUS/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.

Whether a risk is acceptable or unacceptable has been assigned according to the SED guidelines. Where mitigation is written for acceptable risks this details the mitigation undertaken in order to reduce the risk to an acceptable level.

ID	Risk (& consequence if)	P	S	P * S	Action
TC10	Software fails to store data	B	2	Very Low	Acceptable Risk: Extensive testing will be done. Using telemetry, all data gathered from sensors will be sent to ground station.
TC20	Failure of several sensors	B	2	Very Low	Acceptable Risk: Thermal test (Test Number 5) to approve the functionality of the experiment.
TC30	Critical component is destroyed in testing	B	1	Very 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	4	Low	Acceptable Risk. D-sub connections will be screwed in place. It will be ensured that there are no loose connections and zip ties will be used to help keep wires in place. Careful soldering and extensive testing will be applied.
TC50	Experiment electronics fail due to long exposure to cold or warm temperatures	B	3	Low	Acceptable 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	Acceptable 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	1	Very 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	2	Very Low	Acceptable Risk: Experiment will be designed to operate autonomously.
TC100	Software fails to control valves autonomously	B	2	Very 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	2	Very 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: A long duration testing (bench test) will be performed to catch the failures early.
TC130	Failure of fast recovery system	B	2	Very Low	Acceptable Risk: Clear and simple instructions will be given to the recovery team. A test will take place before launch to ensure someone unfamiliar with the experiment can remove the CAC box. Test number: 12.
TC140	The gas analyzer isn't correctly calibrated and returns inaccurate results	B	3	Low	Acceptable Risk: Calibrate the gas analyzer before use.
TC150	Partnership with FMI does not materialize, resulting in loss of access to CAC coiled tube.	B	2	Very Low	Acceptable Risk: Signed agreement has been obtained. AAC sample analysis results can be validated against available historical data from past FMI CAC flights.
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: The Brain 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	2	Very Low	Acceptable Risk: no action.
MS60	Balloon power failure	C	2	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	Sampling bags disconnect	C	3	Low	Acceptable Risk: The affected bags could not collect samples. The connection between the spout of the bags and the T-union shall be double checked before flight.

MS71	Sampling bags puncture	B	3	Low	Acceptable Risk: The affected bags could not collect samples. Inner styrofoam walls have been choosen and no sharp edges will be exposed to avoid puncture from external elements.
MS72	Sampling bags' hold time is typically 48h	C	2	Low	Acceptable risk: Validation studies can demonstrate longer stability.
MS80	Pump failure	B	3	Low	Acceptable Risk: A pump was chosen based on a previous similar experiment. The pump has also been tested in a low pressure chamber down to 10hPa and has successfully turned on and filled a sampling bag. The CAC subsystem is not reliant on the pump therefore would still operate even in the event of pump failure.
MS90	Intake pipe blocked by external element	C	3	Low	Acceptable 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.
MS100	Expansion/Contraction of insulation	B	2	Very Low	Acceptable Risk: The insulation selected has flown successfully on similar flights in the past. Test shall be done to see how it reacts in a low pressure environment.
MS110	Sampling bags are over-filled resulting in bursting and loss of collected samples.	B	3	Low	Acceptable Risk: Test will be performed at target ambient pressure levels to identify how long the pump needs to fill the sampling bags. Pressure sensors on board will monitor the in-bag pressure during sampling and no bag will ever be over pressured. In addition an airflow rate sensor will monitor the flow rate and a timer started when a bag valve is opened. The sampling will stop when either the maximum allowed pressure or maximum allowed time is reached.
SF10	Safety risk due to pressurized vessels during recovery.	A	1	Very Low	Acceptable Risk: The volume of air in the AAC decreases during descent because the pressure inside is lower than outside. The CAC is sealed at nearly sea level pressure, therefore there is only a small pressure difference.

SF20	Safety risk due to the use of chemicals such as magnesium perchlorate.	A	4	Very Low	Acceptable Risk: The magnesium perchlorate will be kept in a sealed container or filter at all times. Magnesium perchlorate filters are made of stainless steel which has high durability, and have been used before without any sealing problems.
VE10	SD-card is destroyed at impact	B	2	Very Low	Acceptable Risk: All data will be transmitted to the ground. Most of the data is the gas stored in the AAC and CAC.
VE20	Gondola Fixing Interface	B	4	Low	Acceptable Risk: The experiment box could detach from the gondola's rails and the two boxes could detach one from the other. The experiment will be secured to the gondola and to each other with multiple fixings. These will also be tested.
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: Structural analysis has been done and choosing a wall consisting of an aluminum sheet and Styrofoam to dampen the landing.
VE50	Hard landing damages the AAC equipment	C	3	Low	Acceptable Risk: Structural analysis has been done and choosing a wall consisting of an aluminum sheet and Styrofoam to dampen the landing.
EN10	Vibrations from pump affect samples	C	1	Very Low	Acceptable Risk: Vibrations do not affect the sampled air. No action required.
EN20	The air samples must be protected from direct sunlight and stored above 0 °C to prevent condensation	C	3	Low	Acceptable Risk: Stratospheric air is generally dry and water vapor concentrations are higher closer to the surface. In addition magnesium perchlorate dryers will be used to minimizing the risk of condensation.

PE10	Change in Project Manager after the CDR introduces a gap of knowledge in management responsibilities.	E	1	Low	Acceptable Risk: A Deputy Project Manager is selected at an early stage and is progressively handed over project management tasks and responsibilities until complete handover after the CDR. The previous Project Manager remotely assists the new Project Manager until the end of the project. The Deputy Project Manager is also part of the Electrical Division so a new team member has been included to that division in order compensate for the Deputy Project Manager's reduced bandwidth to work on Electrical Division tasks once she is appointed Project Manager.
PE20	Team members from the same division are unavailable during the same period over the summer.	C	2	Low	Acceptable Risk: Summer travel schedules have been coordinated among team members so that there is at least one member from each division available during the summer.
PE30	No one from management is available to oversee the work for a reasonable period.	B	2	Very Low	Acceptable Risk: Management summer travel schedules have been planned to fit around known deadlines. There will always be at least one member from management available via phone at all times. All team members are made aware of which members will be available at what times so work can be planned accordingly.
PE40	Miscommunication between team members results in work being incomplete or inaccurate	B	2	Very Low	Acceptable Risk: Whatsapp, Asana and Email are used in combination to ensure that all team members are up to date with the most current information.

Table 9: Risk Register.

4 Experiment Design

4.1 Experiment Setup

The experiment consists of the AAC subsystem, with six sampling bags, and the CAC coiled tube subsystem. Shown in Figure 3, the CAC is fitted into the partition on the left, and the AAC into the partition to the right. The principal aim is to validate the AAC sampling method. To do so, it is necessary to sample during Descent Phase in order to compare the results with the ones obtained from the CAC. This is because the CAC collects its air sample passively by pressure differentials in the descent. Flight speeds mentioned in this section have been obtained from the BEXUS manual as well as through analysis of past flights. Figure 4 shows a generic block diagram of the main subsystems interconnection.
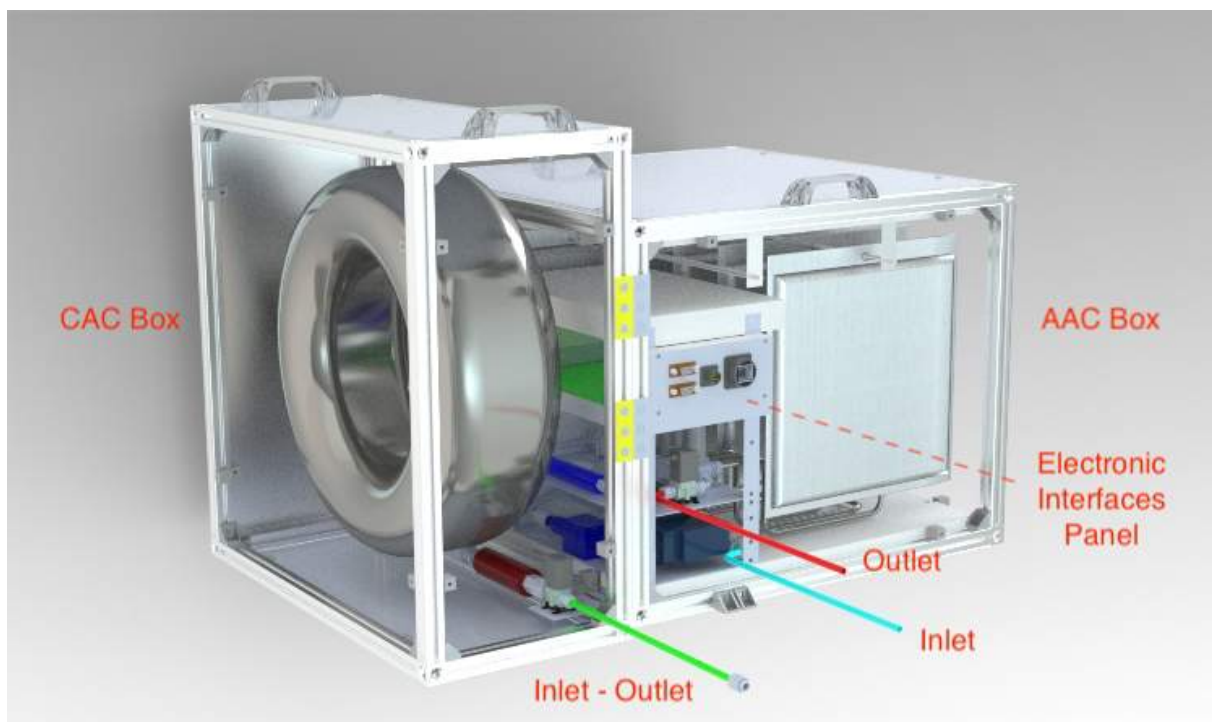
Figure 3: Physical Setup of the Experiment.
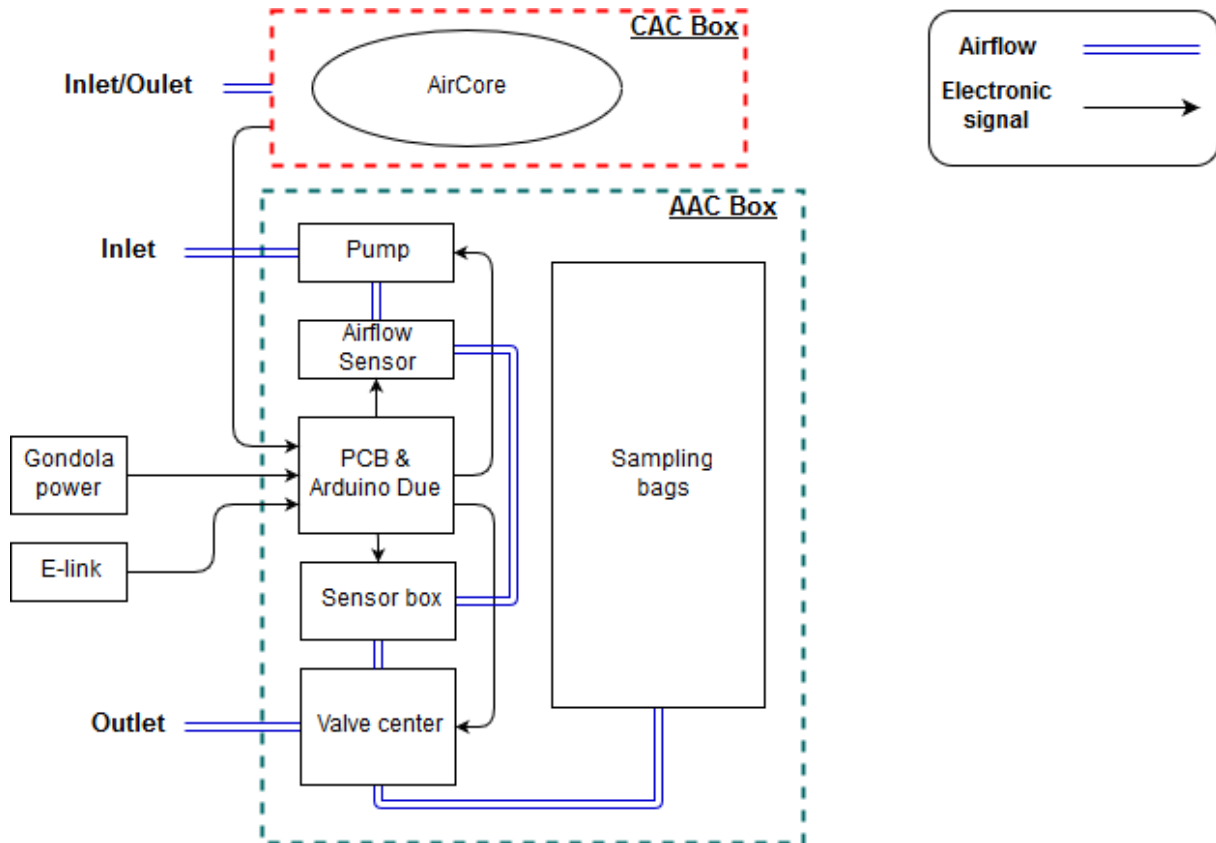
Figure 4: Block Diagram of the Experiment.

The primary concern regarding the AAC air sampling subsystem occurs after the cut-off when the gondola will tumble and fall at an average speed of 50 m/s for approximately two minutes [6]. This descent speed is too large in order to sample air at the desired vertical resolution, capped at 500 m. As such, sampling can only be done after the gondola has stabilized at a descent speed of 8 m/s [6]. The tumbling phase will vertically span for approximately 6 km. Considering a Float Phase altitude of 25 km, sampling during the Descent Phase will commence at approximately 19 km in altitude. However, the primary region of interest in terms of sampling is in the stratosphere, particularly between 19 km and 25 km in altitude. Sampling will thus also occur during the Ascent Phase. Out of the six sampling bags present in the payload, two will be used during the Ascent Phase at 18 km and 21 km and four during the Descent Phase at 17.5 km, 16 km, 14 km and 12 km as seen in Table 10. Details regarding the sampling strategy can be found in Appendix H.

The maximum pressure that the sampling bags can withstand has to be taken into account in order to avoid bursting. Decreasing pressure during the Ascent Phase poses a risk to sampling bags which already contain samples as the gas inside will expand which may cause the bag to burst. In order to avoid this, the sampling bags will not be completely filled. Filling up to a maximum of 80% of the sampling bag's capacity (2 psi/0.14 bar) is recommended by the manufacturers for the Multi-Layer Foil sampling bags that are to be used. Therefore, the maximum expected pressure inside the bags, that will be filled during the Ascent Phase, will be 1.6 psi/0.11 bar. The inverse is also true for the Descent Phase where compression will occur.

As such, the sampling bags should be fully filled during the Descent Phase in order to ensure that enough samples are collected for analysis. During the Descent Phase, the maximum pressure inside the bags is expected to be 1.98 psi/0.13 bar. Past research has revealed that the selected sampling bags can withstand pressure difference of 310 hPa at 30 km of altitude, which is equivalent to 0.31 bar [2]. A series of tests listed in Table 34 will be conducted in order to confirm the maximum allowable pressure for the bags.

The maximum operating pressure for the tubes, according to the manufacturers, is 2.2 psi/0.15 bar. The valve's leakage rate, given by the manufacturers, is 0.001 l/min.

Due to the difference in pressure between sea level and sampling altitudes, the volume of the sample taken will be considerably reduced when it reaches sea level. This shrinking has to be taken into account as the minimum volume that has to be present in the sampling bag at ground level in order to obtain results with the Picarro analyzer. A minimum amount is required for the analyzer to detect concentrations of the targeted trace gases. This minimum amount is 0.18 L at sea level and it has to be specially considered for the samples taken at higher altitudes. The samples taken at lower altitudes will be exposed to smaller changes in pressure, therefore their size will not be critically reduced. Table 10 shows the minimum volume of air that needs to be sampled at different altitudes and the corresponding temperature and pressure conditions, in order the sample volume left at sea level pressure and temperature (288 K) is at least 0.18L.

	Minimum Sampling Volume	Sampling Altitudes	Ambient Pressure	Ambient Temperature
Ascent Phase	1.8 L	18 km	75.0 hPa	216.7 K
	2.4 L	21 km	46.8 hPa	217.6 K
Descent Phase	1.7 L	17.5 km	81.2 hPa	216.7 K
	1.3 L	16 km	102.9 hPa	216.7 K
	1.0 L	14 km	141.0 hPa	216.7 K
	0.7 L	12 km	193.3 hPa	216.7 K

Table 10: Sampling Altitudes as well as the Corresponding Ambient Pressures and Temperatures According to the 1976 US Standard Atmosphere and the Minimum Sampling Volume at Each Altitude to Obtain Enough Air to Perform a Proper Analysis (0.18 L at Sea Level), Appendix H.

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. An air pump with an intake rate of at least 3 L/min will be used to ensure that the vertical resolution of the sampling air remains under 500 m during the Ascent Phase's ascent speed of 5 m/s and the Descent Phase's descent speed of 8 m/s. A flushing valve (see Figure 27, No.23) will be used to flush the AAC system before each bag is filled and make sure that each bag will be filled with fresh air from the corresponding altitude. This filling/flushing procedure occurs twice, the first time during the Ascent Phase for the first two sampling bags and the second time during the Descent Phase for the remaining four sampling bags.

Shortly after the launch, the CAC valve will be opened in order to allow the fill gas that is inside the tube to flush, 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 and it will be emptied by the time it reaches the Float Phase. Filling of the CAC tube also happens passively through the progressive increase in air pressure during the balloon's Descent Phase. The CAC valve will remain open at all time during the Ascent, Float, and Descent phases. The valve will close just before hitting the ground in order to preserve the sample.

The ambient pressure will be measured by three pressure sensors located outside the experiment box. Only one of them is necessary for AAC and CAC, but using three will provide redundancy. To measure the pressure inside the bag that is currently being filled, three more sensors will be allocated inside the sensors box. To measure the ambient temperature in the CAC, three sensors will be allocated in the CAC box (in the Styrofoam). Temperature inside the coil is assumed to quickly adjust to the ambient temperature inside the CAC box, therefore there will not be differentiation in temperature between the air inside the tube and the air surrounding the tube. For the bags three more temperature sensors will be placed in the bags' box (in the Styrofoam). To control the temperature for the Arduino, the pump and the valves in pneumatic subsystem, one temperature sensor will be used for each of them. In total, there will be six pressure sensors and nine temperature sensors.

The sampling of the AAC will be triggered by the pressure reading from the sensors outside the experiment box. When the required pressure is reached, Table 10the valve inside the manifold corresponding to the bag that is to be sampled, 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 [2]. A first estimation of the maximum sampling time has already been made, from Test 18 shown in Table 36, but more tests in the future will determine the maximum pressure condition and confirm the maximum sampling times.

The CAC emptying as well as the AAC and CAC sampling sequence is represented in Figures 5 and 6. It should be kept in mind that the different pressures are what triggers the opening of the valves.

ASCENT
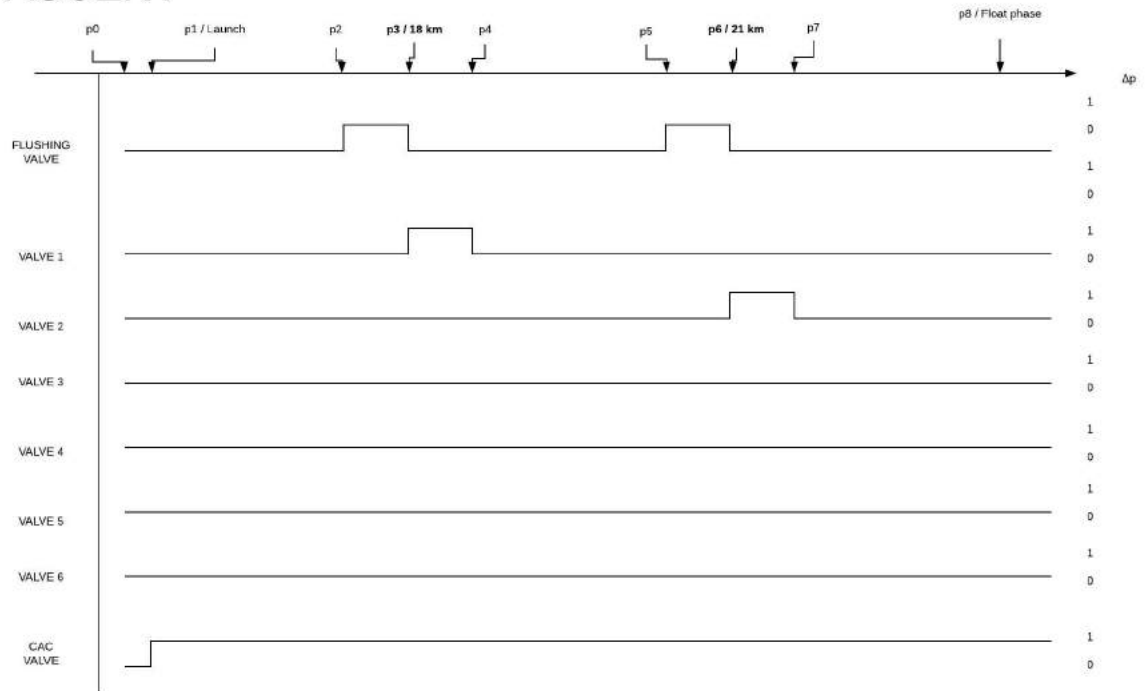
Figure 5: The Emptying and Sampling Sequence-Ascent Phase.
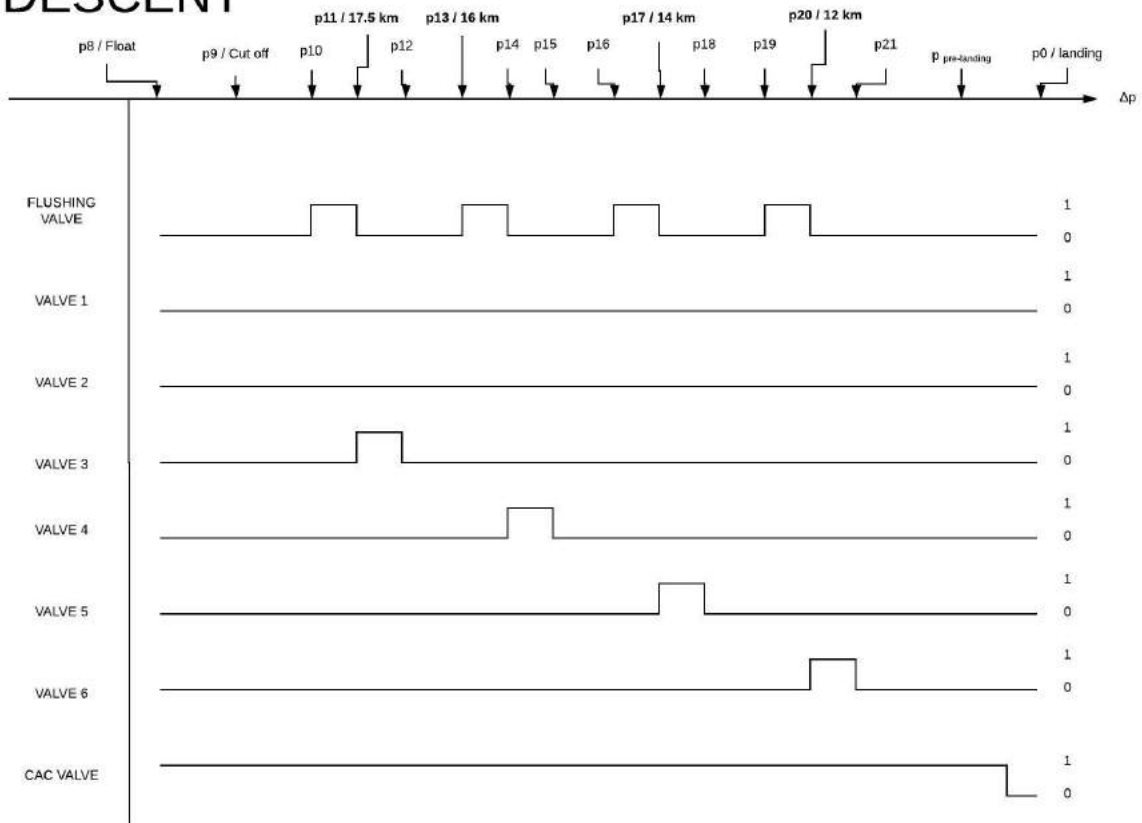
Figure 6: The Emptying and Sampling Sequence-Descent Phase.

In the diagrams, 0 denotes closed/off and 1 denotes opened/on. The horizontal axis denotes the different pressure levels throughout the flight, with p_0 being the sea level pressure and p_8 being the pressure during Float Phase.

The ambient pressure dependent timeline of the experiment is as follow:

Ascent Phase:

$p_0 - p_1$

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

$p_1 - p_2$

- CAC valve shall be opened.
- CAC tube shall start flushing.

$p_2 - p_3$

- AAC flushing valve shall be opened, allowing for the system to flush.

- CAC valve remains open.

$p_3 - p_4$

- AAC flushing valve shall be closed.
- Valve 1 shall be opened, allowing for air to enter the first bag.
- CAC valve remains open.

$p_4 - p_5$

- Valve 1 shall be closed.
- AAC flushing valve shall be closed.
- CAC valve remains open.

$p_5 - p_6$

- AAC flushing valve shall be opened, allowing the system to flush.
- CAC valve remains open.

$p_6 - p_7$

- AAC flushing valve shall be closed.
- Valve 2 shall be opened, allowing for air to enter the second bag.
- CAC valve remains open.

$p_7 - p_8$

- Valve 2 shall be closed.
- AAC flushing valve shall be closed.
- CAC shall finish flushing.

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

Descent Phase:

$p_9 - p_{10}$

- CAC shall start sampling.
- AAC valves shall be closed.

$p_{10} - p_{11}$

- AAC flushing valve shall be opened allowing the system to flush.
- CAC valve remains open.

$p_{11} - p_{12}$

- AAC flushing valve shall be closed.

- Valve 3 shall be opened, allowing for air to enter the third bag.
- CAC valve remains open.

$p_{12} - p_{13}$

- Valve 3 shall be closed.
- AAC flushing valve shall be closed.
- CAC valve remains open.

$p_{13} - p_{14}$

- AAC flushing valve shall be opened allowing the system to flush.
- CAC valve remains open.

$p_{14} - p_{15}$

- AAC flushing valve shall be closed.
- Valve 4 shall be opened, allowing for air to enter the fourth bag.
- CAC valve remains open.

$p_{15} - p_{16}$

- Valve 4 shall be closed.
- AAC flushing valve shall be closed.
- CAC valve remains open.

$p_{16} - p_{17}$

- AAC flushing valve shall be opened, allowing the system to flush.
- CAC remains open.

$p_{17} - p_{18}$

- AAC flushing valve shall be closed.
- Valve 5 shall be opened, allowing for air to enter the fifth bag.
- CAC valve remains open.

$p_{18} - p_{19}$

- Valve 5 shall be closed.
- AAC flushing valve shall be closed.
- CAC valve remains open.

$p_{19} - p_{20}$

- AAC flushing valve shall be opened, allowing the system to flush.
- CAC remains open.

$p_{20} - p_{21}$

- AAC flushing valve shall be closed.

- Valve 6 shall be opened, allowing for air to enter the sixth bag.

$p_{pre-landing}$

- Valve 6 shall be closed.

- AAC flushing valve shall be closed.

- CAC valve shall be opened.

$p_{0-landing}$

- 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

Component	Interface	Amount	Dimensions	Weight/unit	Total weight
Bracket standard 20/20 slot 6/6	AAC-Gondola	8	$20 \times 20 \times 20\ mm$	$5\ g$	$40\ g$
Tolerance holes bracket	CAC-Gondola	2	$20 \times 30 \times 52\ mm$	$20\ g$	$40\ g$
6-hole plate	AAC-CAC	4	$1 \times 60 \times 41\ mm$	$50\ g$	$200\ g$
Rubber bumpers M6	AAC-Gondola, CAC-Gondola	10	$19 \times 19 \times 15\ mm$	$30\ g$	$300\ g$
T-nut slot 6 M4	AAC-CAC, AAC-Gondola, CAC-Gondola	34	$4 \times 5.9 \times 11.5\ mm$	$3\ g$	$102\ g$
T-nut slot 8 M6	AAC-Gondola, CAC-Gondola	10	$6 \times 11 \times 16\ mm$	$6\ g$	$60\ g$
Steel bolt M4	AAC-CAC, AAC-Gondola	34	$8\ mm$ length	$1\ g$	$34\ g$
Steel washer M4	AAC-CAC, AAC-Gondola	24	$ID = 4.3\ mm$ $OD = 9\ mm$	$0.2\ g$	$4.8\ g$
Polyamide bolt M4	Styrofoam-CAC-AAC	8	$20\ mm$ length	$3\ g$	$24\ g$
Polyamide washer M4	Styrofoam-CAC-AAC	8	$ID = 4.3\ mm$ $OD = 25\ mm$	$4\ g$	$32\ g$
Styrofoam bars	AAC-Gondola, CAC-Gondola	4	see Appendix C.6	$-$	$700\ g$
Handles	CAC & AAC	4	$18.6 \times 25.2 \times 112.5\ mm$	$20\ g$	$80\ g$

Table 11: Summary of Gondola-AAC-CAC Interfaces Components.

Gondola - TUBULAR joining

The experiment box will be fixed to the gondola rails by means of 10 brackets interfacing the experiment outside structure with the hammer nuts in the rails. Two different types of brackets are used to be flexible with respect to the gondola rails distances, which can be modified by use after previous BEXUS campaigns. Eight small $20/20$ brackets (Figure 7a) are used to fix the AAC box to specific rails placement, and two other big brackets (Figure 7b) are used to fix the CAC box to the nearest rail. This method is secure as well as fast enough to provide an accessible and easy recovery for later analysis.
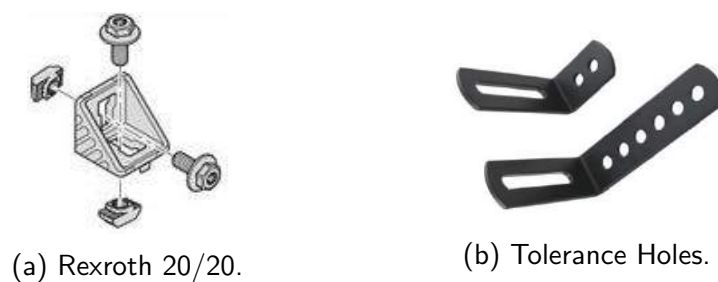

(a) Rexroth 20/20.

(b) Tolerance Holes.

Figure 7: Bracket Components.

CAC - AAC joining

A simple but reliable fixing interface between the two boxes of the experiment has been designed to ensure the fast recovery of the CAC box. The latter requires only unscrewing 12 bolts as well as unplugging a D-Sub connector. Once the CAC box is detached, the AAC

Box will still remain perfectly fixed in the gondola. Table 11 gathers up all the components required to fix the experiment to the gondola.

Handles

Four top handles, as shown in Figure 8 will be mounted to facilitate the experiment box manipulation when moving it in and out of the gondola.
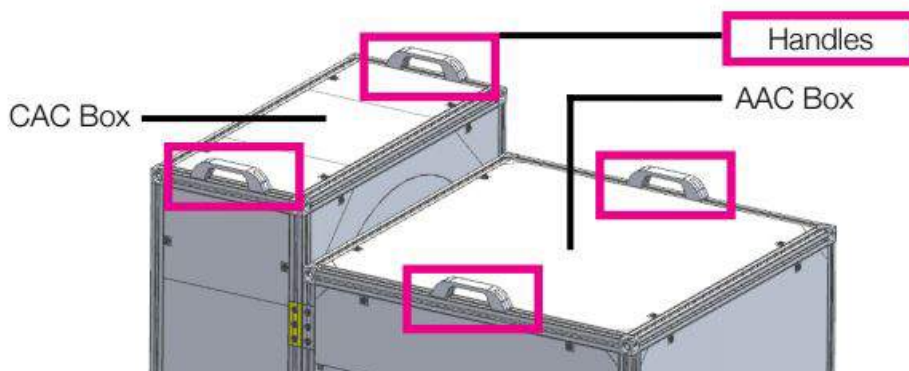
Figure 8: Handling Interfaces.

Inlet/Outlet Pipes

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. As it can be seen in Figure 3, three pipes will extend from the experiment box face: 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.

These pipes are welded/drawn 304 grade stainless steel tubes from RESTEK company, which are specially recommended for chromatography applications and gas delivery systems with low pressures and inert environments. These tubes are sulfinert, which is a required treatment for metal components when analyzing for parts-per-billion levels of organo-sulfur compounds.

The tubes, which are the same that will be used in the pneumatic system of the *Brain* (see Section 4.4.5), have an outer diameter $OD = 6.35\ mm$ (1/4 inches) and an inner diameter $ID = 4.57\ mm$ (0.18 inches).

4.2.2 Thermal Interfaces

Both main structural components and external walls of the two boxes of the experiment are made by aluminum and steel components. For this reason, since these are conductive materials, a direct attachment to the gondola creates many heat paths with the internal space and subsystems of the experiment. Considering that the temperature gradient between the gondola and the operative requirements of the electronic components can be quite high, this conductive connections drastically decrease the efficiency of the thermal insulation. Therefore,

a system based on rubber bumpers and styrofoam bars (see Figure 10) has been designed to add heat bridges and minimize temperature leaks from the inside of the experiment to the outside.

Figure 9 shows a CAD model of the bumper component and how it looks like when attached to the gondola with the brackets explained in the previous section.
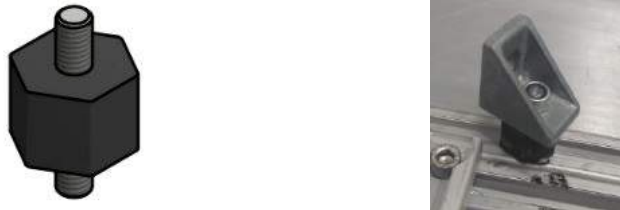
Figure 9: Rubber Bumper.

The styrofoam bars will be attached directly to the rails of the experiment structure by M4 plastic screws and big washers.
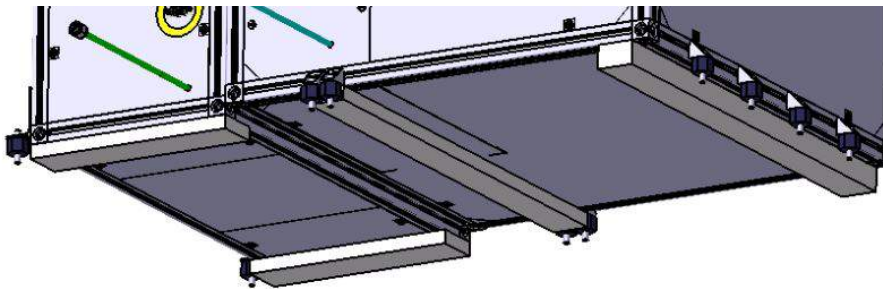
Figure 10: Thermal Interfaces TUBULAR-Gondola.

4.2.3   CAC Interfaces

An uncoupled quick connector, shown in Figure 11, will be attached at each end of the coiled tube to seal the opening. It will remain tightly sealed until the quick connectors are manually coupled.

Figure 11: Swagelok Quick Connector Body.

The interfaces between the other parts in the CAC set up will be joined with specific tube

fittings, listed in Table 12. All the chosen interfaces are from Swagelok. Using products from the same manufacture minimize the risk for leakage or mismatched interfaces in the system.

Component	Interface	Amount	Fitting Size
Quick connector body SS-QC4-B-200	Outlet of coiled tube	1	1/8 in.
Quick connector body SS-QC4-B-400	Inlet of coiled tube	1	1/4 in.
Quick connector stem SS-QC4-D-400	Inlet of coiled tube - Filter	1	1/4 in.
Reducing adapter SS-4-RA-2	Filter - Solenoid valve	1	Female 1/4 in. to male 1/8 in.
Tube screw SS-400-1-2	Solenoid valve - Exit tube	1	1/8 in. to tube OD 1/4 in.

Table 12: Interfaces within CAC Setup.

4.2.4 AAC Interfaces

In the AAC system, the interfaces between various components are a mixture of five different types of tube fittings from Swagelok. The selected types are straight union, T-union, male elbow, female and male connectors with a certain size, shown in Figure 12. Information regarding the fitting's placement in the AAC and fitting sizes are summarized in Table 13.

Figure 12: From Left to Right: Male Connector, Male Elbow, T-union, Straight Union and Female Connector.

Component	Interface	Amount	Fitting Size
Male connector SS-400-1-2	Airflow sensor - Sensor box Tube sensor box - Manifold Manifold - Flushing valve Flushing valve - Outlet tube Solenoid valve - Tube valve	11	Male 1/8 in. to Tube OD 1/4 in. ID 0.21 in.
Male elbow SS-400-2-2	Sensor box - Tube sensor box	1	Male 1/8 in. to Tube OD 1/4 in. ID 5/32 in.
Straight union SS-400-6	Filter - Tube filter Tube filter - Pump Pump - Tube pump	3	Tube OD 1/4 in. ID 5/32 in.
Female connector SS-400-7-4	Inlet tube - Filter Tube pump - Airflow sensor Airflow sensor - Tube airflow sensor	3	Female 1/4 in. to Tube OD 1/4 in. ID 5/32 in.
T-Union SS-400-3	Tube valve - Bag valve	6	Male 1/4 in.

Table 13: Interface Descriptions Inside AAC System.

4.2.5 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) [6]. It will connect to one 28.8 V/1 mA battery pack which consists of eight SAFT LSH20 batteries in series where each has a 5 A fuse[6]. The expected maximum current is 1.1 A.

Figure 13: Connectors.

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[6].

The CAC and AAC will be connected together with a D-SUB 9-pin connector where power, ground and signals for the sensors in the CAC will be connected. A female connector will be located on the AAC wall and a male connector on the CAC wall.

Another female D-SUB 9-pin connector will be located on the wall of the AAC in which the connections for the three ambient pressure sensors will be located. Connectors with different pin configuration are shown in Figure 13.

The expected data rate is 1.58 kbits/s for downlink and 1.08 kbits/s for uplink.

4.3 Experiment Components

Component tables were generated from the project budget spreadsheet in Appendix M using the scripts included in Appendix K. Table headers are letter coded and correspond to the following:

4.3.1 Electrical Components

Table 14 shows all required electrical components with their total mass and price.

ID	Component Name	Manufacturer	Manufacturer Code	Qty	Total Cost [EUR]	Total Mass [g]	Note	Status
E1	Arduino Due	Arduino	A000062	1	36	35	Fast and has many analog, and digital pins	Received
E2	Ethernet Shield	SEEED Studio	SKU 103030021	1	36	30	Can be mounted on top of the board	Received
E3	Miniature diagphram air pump	KNF	NMP 850.1.2 KNDC-B	1	430	350		Received
E4	Pressure sensor	SENSOR SOLUTIONS	MS560702BA03-50	4	5	2.3	High resolution, large measuring range	Received
E5	Sampling Valve (inlet and outlet 1/8"" female)	SMC	VDW22UANXB	1	100	45	Estimated Arrival Date 27/7	Ordered
E6	Airflow sensor	Honeywell	AWM5102VN	1	60	130	0-10 SLPM	Received
E7	Heater	Minco	HK5160R157L12	4	4	95	Easy to mount, compact size	Received
E9	Temperature sensor	Maxim Integrated	DS1631+-ND	8	2	3	I2C digital output interface, temperature range down to -55 °C	Received

E10	DC/DC converter 24 V	Traco Power	S24SP24003PDFA	2	46	49	Provides required output voltage and power, 93% efficiency	Received
E11	Humidity sensor	Texas Instrument	HDC2010	3	5	3	I2C interface, good temperature range, high accuracy	Received
E12	MicroSD	Kingston Technology	SDCIT/16GB	1	0.5	20	Small, good temperature range, sufficient storage	Received
E13	Logic CAT5E Network	Valueline	VLCT85000Y30	1	90	7	For testing and ground station	Received
E14	Resistors (33 Ohm) [3]	n/a	n/a	25	1	0		Received
E15	Capacitors (0.1 uF, 5uF and 10 uF)	n/a	n/a	15	1	0		Received
E16	Mosfet for current control	IR	IRLB8748PBF	11	2	0.7	Cheap, good temperature range	Received
E17	Diodes for DCDC converters	Diotec Semiconductor	1N5059	14	0.4	0.1	Cheap, good temperature range	Received
E18	LED 3.3 V	Wurth Elektronik	151034GS03000	16	0.4	0.52	For monitoring, testing	Received
E19	15-pin D-SUB Female connector with pins	RND Connect	RND 205-00779	2	11	0.75	For connecting distributed components	Received
E20	9-pin D-SUB Female connector with pins	RND Connect	RND 205-00777	3	8.5	0.68	For connecting distributed components	Received
E21	9 pin D-SUB Female connector with soldering cups	RND Connect	RND 205-00704	2	9	0.56	For connecting distributed components	Received

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[3]See schematic in Figure 33 for details on where individual resistors are placed.

E22	9 pin D-SUB Male connector with soldering cups	RND Connect	RND 205-00700	4	9	0.48	For connecting distributed components	Received
E23	15-pin D-SUB Male connector with soldering cups	RND Connect	RND 205-00701	2	11	0.6	For connecting distributed components	Received
E24	9-pin D-SUB backing	Enchitech	MHDTZK-9-BK-K	4	40	2.9	For connecting distributed components	Received
E25	15-pin D-SUB backing	Enchitech	MHDTZK-15-BK-K	2	66	3.1	For connecting distributed components	Received
E26	Wall mounting bolts	RND Connect	RND 205-00786	3	2.5	1	For connecting distributed components	Received
E27	D-SUB cable CAC to AAC	Maxxtro	n/a	1	80	3.8	For connecting distributed components	Received
E28	3.3 V Zener diode	RND Components	RND 1N746A	15	0.5	0.07	Regulate indication LED voltage	Received
E29	Male connector on PCB	Binder	Serie 768	1	5	8.5		Received
E30	Female connector from wall	Binder	Serie 768	1	11	12		Received
E31	Grounding contact	Vogt	DIN 46234	4	0.58	8.6	1 pack of 100 pcs	Received
E32	Logic CAT5 E-link for inside box	Valueline	VLCP85121E015	1	10	1.1	To connect from wall to Arduino shield	Received
E33	Signal wire	Alpha Wire	5854/7 YL005	1	230	34	Roll of 30 m. Half will be used approximately	Received
E34	Flushing valve (inlet and outlet 1/8''' female)	SMC	VDW22UANXB	1	100	45	Estimated Arrival Date 27/7	Ordered
E35	Valves manifold (outlet 1/8''' female)	SMC	VDW23-5G-1-H-Q	6	100	40	Estimated Arrival Date 27/7	Ordered

E36	Power wire - Back	Alpha Wire	5856 BK005	1	370	46	Roll of 30 m. A fifth will be used approximately	Received
E37	Electrical Tape for marking wires - White	Hellerman Tyton	HTAPE-FLEX15WH-15X10	1	34	0.82	Roll of 10 m. A forth will be used approximately	Received
E38	Electrical Tape for marking wires - Black	Hellerman Tyton	HTAPE-FLEX15BK-15X10	1	33	0.82	Roll of 10 m. A forth will be used approximately	Received
E39	Electrical Tape for marking wires - Green	Hellerman Tyton	HTAPE-FLEX15GN-15X10	1	34	0.82	Roll of 10 m. A forth will be used approximately	Received
E40	Electrical Tape for marking wires - Violet	Hellerman Tyton	HTAPE-FLEX15VT-15X10	1	34	0.82	Roll of 10 m. A forth will be used approximately	Received
E41	Electrical Tape for marking wires - Gray	Hellerman Tyton	HTAPE-FLEX15GY-15X10	1	34	0.82	Roll of 10 m. A forth will be used approximately	Received
E42	Electrical Tape for marking wires - Brown	Hellerman Tyton	HTAPE-FLEX15BN-15X10	1	34	0.82	Roll of 10 m. A forth will be used approximately	Received
E43	Electrical Tape for marking wires - Blue	Hellerman Tyton	HTAPE-FLEX15BU-15X10	1	34	1.9	Roll of 10 m. A forth will be used approximately	Received
E48	Power wire - Red	Alpha Wire	5856 RD005	1	370	46	Roll of 30 m. A fifth will be used approximately	Ordered
E49	Potentiometer 1 kOhm	Bourns	M64Y102KB40	4	1	1.8		Received
E50	6-pin male double row header	RND Connect	RND 205-00634	2	1	0.22		Received

E51	8-pin male single row header	RND Connect	RND 205-00629	5	1	0.28		Received
E52	10-pin male single row header	Prostar	SD-2X5-T1-7/3MM	1	1	0.26		Received
E53	36-pin male double row header	Würth Elektronik	61303621121	1	2	1.7		Received
E54	DC/DC converter 12 V	Delta	R-7812-0.5	2	20	34	12V,1.67A, 20W DCDC	Received
E55	Potentiometer 50 kOhm	Bourns	3296Y-1-503LF	4	1	1.8		Received
E56	Static Pressure Sensor	Gems Sensors and Controls	3500S0001A05E000	1	53	140		Waiting for Response
E57	Connector for the Static Pressure Sensor	Schneider Electric	XZCPV1141L2	1	14	14	-25 to 80 celcius, female 4 pin M12 connector with 2 meter wire	Waiting for Response
E58	Main PCB board	Eurocircuits	n/a	2	100	89	Looking for sponsorship and will be custom-made	Waiting for response
E59	Pressure sensor PCB	Eurocircuits	n/a	5	100	14	Looking for sponsorship and will be custom-made	Waiting for response

Table 14: Electrical Components Table

4.3.2 Mechanical Components

Table 15 shows all required mechanical components with their total mass and price.

ID	Component Name	Manufacturer	Manufacturer Code	Qty	Total Cost [EUR]	Total Mass [g]	Note	Status
M1	Strut profile 20x20 M6/M6, length: 460 mm	Bosch - Rexroth	3842993231	16	180	5.8	Railed geometry, Structural element	Received
M2	Strut profile 20x20 M6/M6, length: 360 mm	Bosch - Rexroth	3842993231	4	140	5.5	Railed geometry, Structural element	Received
M3	Strut profile 20x20 M6/M6, length: 190 mm	Bosch - Rexroth	3842993231	4	76	5.1	Railed geometry, Structural element	Received
M4	T-nut N6 M4	Bosch - Rexroth	3842536599	100	3	0.74	Wall, Protective element	Received
M5	Sliding block N6 M4	Bosch - Rexroth	3842523140	100	3	0.72	Wall, Protective element	Received
M6	Bracket standard 20x20 N6/6	Bosch - Rexroth	3842523508	100	5	0.45	Wall, Protective element	Received
M7	Variofix block S N6 20x20	Bosch - Rexroth	3842548836	70	5	0.62	Wall, Protective element	Received
M8	Cubic connector 20/3 N6	Bosch - Rexroth	3842523872	16	10	2		Received
M9	Strap-shaped handle	Bosch - Rexroth	3842518738	4	20	1.9		Received
M10	Retainer ring M4	Bosch - Rexroth	3842542328	100	0.5	0.054		Received

M11	DIN 7984 M4x8 bolts	n/a	n/a	150	1	0		Received
M12	M6x16 bolts	Bossard	79850616	48	5	0.13		Received
M13	ISO 4762 bolts	n/a	n/a	8	2	0		Received
M14	Washers	n/a	n/a	20	0.2	0		Received
M15	Aluminum sheets	-	204599	1	2500	25		Received
M16	Styrofoam 250 SL-A-N	Isover	3542005000	1	1800	97		Received
M17	Fixing bar for the bags	Maskindelen	n/a	2	13	3		Received
M18	Flat plate interface for fixing bar	Alfer	n/a	4	32	2	Will order from Elfa after IPR	To Be Ordered
M19	CAC-AAC interface 6-hole plate	Alfer	n/a	4	50	2	Will order from Elfa after IPR	To Be Ordered
M20	Aluminum sheets	-	204599	1	100	NaN		Received
M21	Steel 304, Equal Angle bar 2,1 m	Alfer	HW1200	1	380	31		Received
M22	DIN 7984 M4x8 bolts	n/a	n/a	26	1	0		Received
M23	DIN 7984 M4x30 bolts	n/a	n/a	16	2	0		Received
M24	Nut M4	n/a	n/a	42	1	0		Received
M25	Flat plate fixing interface	n/a	n/a	2	1	0	Will order from Elfa after IPR	To Be Ordered
M26	15mm M3 Standoff/Spacer for PCB	Keystone Electronics	24339	5	2	0.78	To be ordered with electronics from digikey	Received
M27	Lock nut M3 (DIN985) for PCB	n/a	n/a	5	1	0		Received
M28	M3 Cheese Head Screws 6mm	n/a	n/a	5	0.8	0	In lab	Received
M32	Coiled tube	FMI	n/a	1	5000	22000		To Be Delivered

M33	Interface tube-screw male (OD 1/4" - ID 5/32" to male 1/4")	Swagelok	SS-400-1-4	1	19	10		Received
M34	Interface tube-screw male (OD 1/4" - ID 5/32" to male 1/8")	Swagelok	SS-400-1-2	1	13	10		Received
M35	Interface reducing adapters (female 1/4" NPT to male 1/8" NPT)	Swagelok	SS-4-RA-2	1	35	12		Received
M36	Interface attached to the coiled tube outlet, quick connector	Swagelok	SS-QC4-B-200	1	91	65		Received
M37	Interface attached to the coiled tube inlet, quick connector	Swagelok	SS-QC4-B-400	1	68	50		Received
M38	Interface quick connector stem with valve	Swagelok	SS-QC4-D-400	1	58	40		Received
M39	Testing / Backup seal valve	Parker	4M4F-V6LN-SS	2	1400	150		Received
M40	Magnesium filter with interface	FMI	n/a	1	65	150		Ordered
M41	Testing Valve	Axel Larsson	Lucifer 121K, 122K	1	NaN	100		Received
M43	Gas Sampling Bag, Multi-Layer Foil, 3L, 10"x10", 5pk	Restek	22951	2	25	100	Estimated Arrival Date 27/7	Ordered
M44	Manifold (inlet and outlet 1/8" female)	SMC	VV2DW2-H0601N-F-Q	1	440	140		Received

M45	Interface tube-screw male (OD 1/4" - ID 5/32" to male 1/8")	Swagelok	SS-400-1-2	6	13	14		Received
M46	Interface tube-screw male 90 degree(OD 1/4" - ID 5/32" to male 1/8")	Swagelok	SS-400-2-2	3	13	16		Received
M47	Male 90-degree connector (OD 1/4" - ID 5/32" to male 1/4")	Swagelok	SS-400-2-4	1	16	14		Received
M48	Interface tube-screw female (OD 1/4" - ID 5/32" to female 1/4")	Swagelok	SS-400-7-4	1	28	15		Received
M49	Interface T-Union (male 1/4")	Swagelok	SS-400-3	6	71	33		Received
M50	Nut Ferrule set	Swagelok	SS-400-NFSET	15	41	2.3		Received
M51	Tubing, Sulfinert 304SS Welded/Drawn 50ft (OD 1/4" - ID 0.21")	Restek	29255	1	150	840		Received
M52	Quick Coupling female 1/4"	Swagelok	SS-QC4-B-4PF	6	45	50		Received
M53	90 degree elbow 1/4"	Swagelok	SS-400-9	2	55	19		Received
M54	Interface female 90-degree connector (OD 1/4" - ID 5/32" to female 1/4")	Swagelok	SS-400-8-4	2	62	23		Received
M55	Magnesium filter tube with interface	FMI	-	1	65	150		Ordered

Table 15: Mechanical Components Table

4.3.3 Other Components

Table 16 shows other components which contribute to the mass and/or price.

ID	Component Name	Manufacturer	Manufacturer Code	Qty	Total Cost [EUR]	Total Mass [g]	Note	Status
O1	Hand Tube Bender 1/4 in	Swagelok	MS-HTB-4T	1	n/a	250		Received
O2	Tube Cutter (4 mm to 25 mm)	Swagelok	MS-TC-308	1	n/a	35		Received
O3	Tubing Reamer	Swagelok	MS-TDT-24	1	n/a	26		Received
O4	Travel to FMI for sample bag testing	n/a	n/a	1	n/a	250		Completed
O5	Travel to FMI for integration testing	n/a	n/a	1	n/a	250		Planned
O6	Shipping costs	n/a	n/a	n/a	n/a	n/a		n/a
O7	Error margin	n/a	n/a	n/a	n/a	n/a		n/a
O8	PTFE Tape Thread Sealant, 1/4"	Swagelok	MS-STR-4	1	n/a	1.9		Received
O9	Double-Sided Adhesive Tape	3M	180-89-682	2	n/a	9.8	Will order from Elfa after IPR	To be ordered

Table 16: Other Components Table

4.4 Mechanical Design

The experiment consists of two rectangular boxes, one stacked next to the other, shown in Figure 14. The higher but narrower box (CAC box) allocates the heaviest element, the CAC. The main box (AAC box) contains the AAC system with six sampling bags, as well as the central command unit: The Brain. The Brain contains the general Electronic box (EB) as well as the pneumatic sampling system.

The two-box design will allow ease of access and manipulation of both the CAC and AAC subsystems. In addition, the AAC sampling system is designed to be re-usable for future handover to the FMI, as such, it will be mountable on any standard balloon flight without having to introduce major design changes. If a battery as a power unit where introduced, hence less bags could be carried (around five bags) in this potential future setup, see Figure 15.

Since the CAC will be the heaviest component in the whole experiment its positioning and orientation inside the gondola will directly affect the stress analysis of the structure. In the worst case scenario, without a proper study of the aforesaid interface, shear in the screws could be produced after a violent landing stress or unexpected shaking. The larger the distance to the fixed points, the bigger the momentum produced by the component. Nevertheless, due to fast recovery implementation the CAC box will be securely attached to the AAC box by means of four anchor points, fast recovery fixing interface as seen in yellow in Figure 14. The fast recovery then will only require unscrewing 12 screws and unplugging a D-Sub connector.
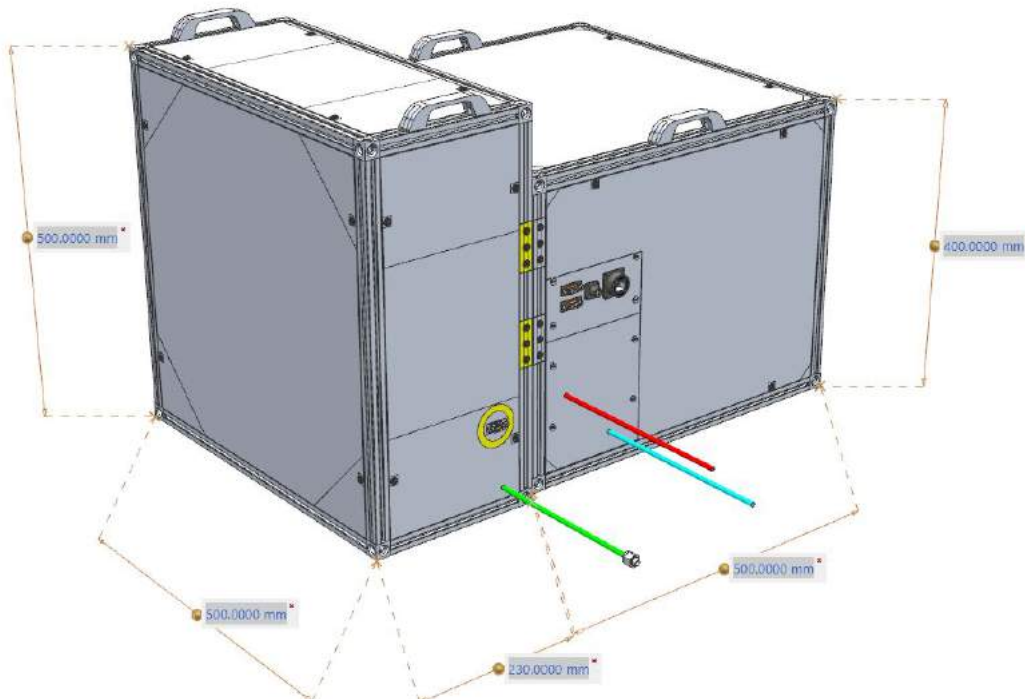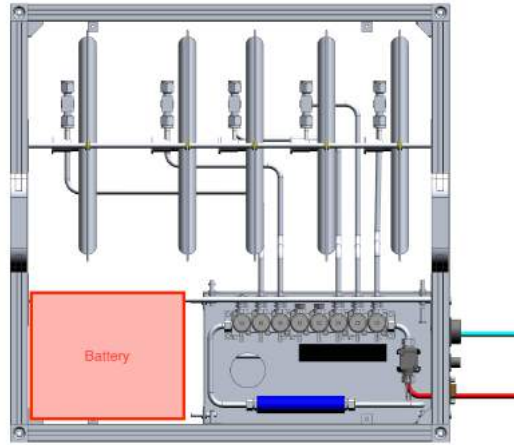

Figure 14: General Dimensions of the Experiment.

Figure 15: Layout Including a Battery (in Red).

The main mechanical characteristics of the experiment are summarized in Table 17, where the values are based on the reference axis shown in Figure 16. The Center Of Gravity for the whole experiment is determined to be located just on base of the third level of The Brain which coincides with the location of the electronics PCB. This outcome is quite advantageous in terms of stability for one of the most sensitive subsystems of the experiment in terms of shakes and loads. It should also be noted that the weights of the table for the boxes and, therefore, the whole experiment, are increased by a safety margin of 10%.

	CAC	AAC	TOTAL
Experiment mass [kg]	12.08	12.37	24.45
Experiment dimensions [m]	$0.23 \times 0.5 \times 0.5$	$0.5 \times 0.5 \times 0.4$	$0.73 \times 0.5 \times 0.5$
Experiment footprint area [m^2]	0.115	0.25	0.365
Experiment volume [m^3]	0.0575	0.1	0.1575
Experiment expected COG position	$X = 23.51\ cm$ $Y = 10\ cm$ $Z = 22.57\ cm$	$X = 29.04\ cm$ $Y = 16.63\ cm$ $Z = 16.2\ cm$	$X = 26.31\ cm$ $Y = 24.99\ cm$ $Z = 19.35\ cm$

Table 17: Experiment Summary Table.
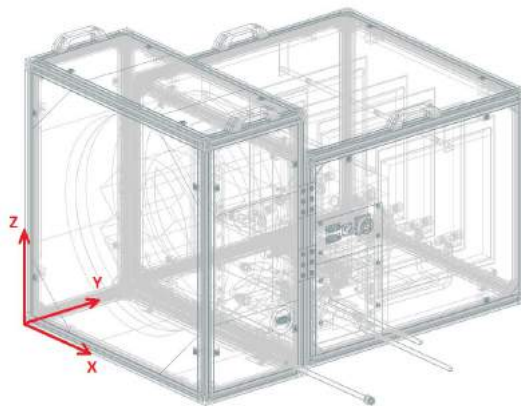
Figure 16: Reference Axis for the Total Center of Gravity.

4.4.1 Structure

The main purpose of an experiment box structure is to provide overall mechanical integrity and maintain the system geometry. It shall be able to carry the loads of all the phases of the flight and ensure that all the components and subsystems can withstand them. Test 9 in Table 30 will help to confirm the frame can withstand these vibrations and updates to the design will be made if necessary.

Moreover, other considerations such as electrical and, especially, thermal conductivity are also be a concern since the experiment will fly up to $25\ km$ in the Polar Circle in October and many critical subsystems have tight operative ranges values.
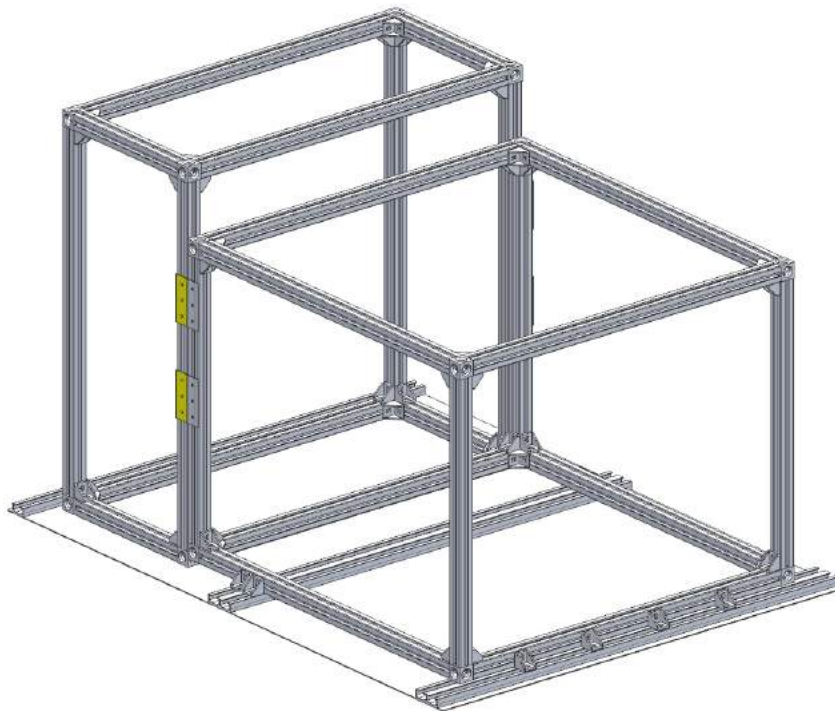
Figure 17: Structure Overview.

For this purpose, two boxes built with straight frames have been chosen as the best option as shown in Figure 17. The frame of these boxes will be strut profiles made of aluminum, with a characteristic cross-section of $20 \times 20\ mm$, and with $M6$ thread at each side. The rails will allow an easy interface between bars and other elements. In turn, these profiles will be joined together in each corner with aluminum cubic connectors of $20 \times 20\ mm$ (see Figure 18b) and $M6 \times 16$ bolts aligned with the bars axis. At the same time, these nodes will be reinforced by three $20/20$ brackets (see Figure 18a) each that will be fixed to the frames with $M4 \times 8$ bolts and the corresponding $M4$ T-nut.
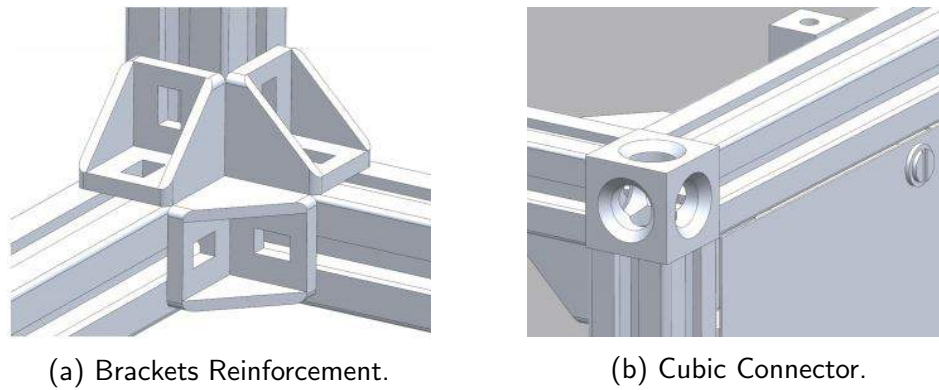
(a) Brackets Reinforcement.

(b) Cubic Connector.

Figure 18: Strut Profiles Connections.

Tables 56 and 18 below show the main mechanical properties of the Bosch Rexroth $20/20$ strut profiles used in the structure.

Section surface	Mass	Moment of Inertia $(I_x = I_y)$	Moment of resistance $(W_x = W_y)$
$1.6\ cm^2$	$0.4\ kg/m$	$0.7\ cm^4$	$0.7\ cm^3$

Table 18: Intrinsic Characteristics of the Strut Profiles.

4.4.2 Walls and Protections

Since the experiment will be placed close to the outside of the gondola, it is very exposed to both external elements impacts and also possible broken parts from other experiments in the gondola due to unexpected rapid movements, and a probable hard landing impact. Therefore, the experiment box will be shielded with removable aluminum walls along with a thick layer of Styrofoam attached to each wall. This thickness varies from two to three centimeters in the AAC box, and five centimiters to protect the AirCore. Besides protection, the thickness of the styrofoam is also motivated by thermal control issues.

To mount the experiment a combination of three different elements will be used, as shown in Figure 19. The walls will be screwed to the Variofix blocks by means of $M4 \times 8$ bolts. In between the aluminum walls and the bolts, a $M4$ retainer ring will be placed to improve the fixation of each spot. Four fixation points for each wall have been considered sufficient to keep the experiment safe from any impact. However, double the amount of fixation points, eight, will be used in the more exposed walls that are facing outside the gondola.

The styrofoam sheets will be attached to the aluminum walls with polyamide washers screwed along both layers.

Tables 57 and 58 show the main properties of the materials used to build the walls of the boxes.
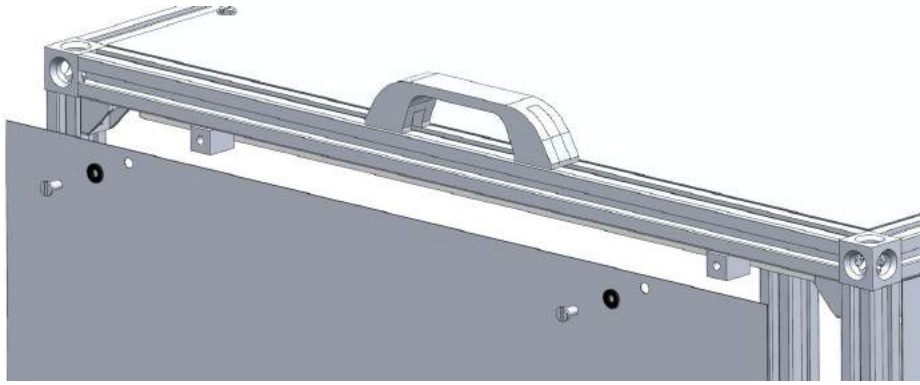
Figure 19: Exploit View of the Attachment of the Walls.

4.4.3 CAC Box

The CAC subsystem is designed to fit a 300 m stainless steel coiled tube, a solenoid valve controlling it, interfaces, an air filter and three temperature sensors. A schematic of this subsystem can be seen in Figure 21. The CAC consists of a combination of a 200 m coiled tube of $1/8$ inches diameter and a 100 m coiled tube of $1/4$ inches diameter. The outlet of the CAC is sealed with a quick connector provided by FMI. The inlet will be sealed the same way but it will be opened by another interface plugged into the quick connector. A filter is placed between this orifice and the solenoid valve. The filter will be custom made by FMI. The set up is a tube containing magnesium perchlorate powder with stone wool at both ends of the tube. It will ensure that no moisture will enter the coil during any testing or sampling. Another tube is attached to the solenoid valve that goes outside the box, thus having a direct outside outlet and inlet for the whole CAC system, as seen in Figure 20.
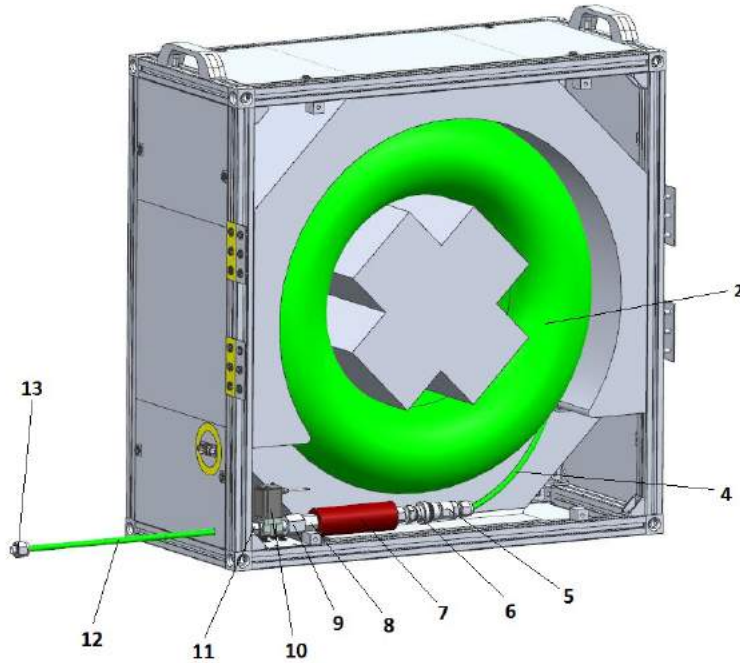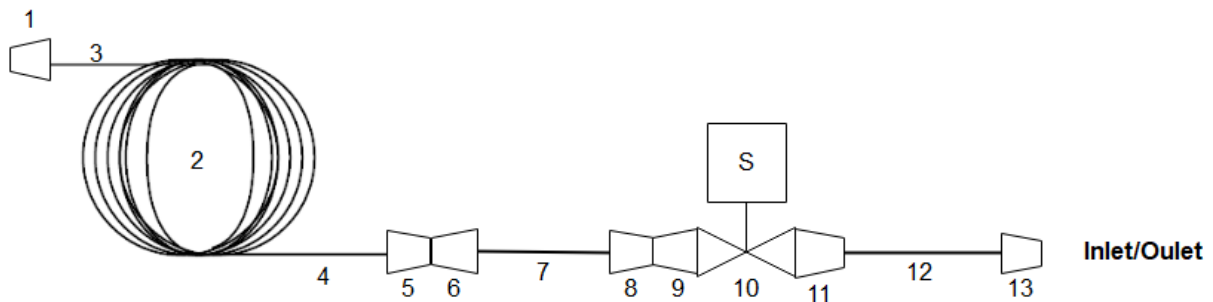
Figure 20: 3D Model of the CAC Box. The Numbers Correspond to the Numbers in Figure. 21.

1. **Interface attached to the AirCore (SS-QC4-B-200):** Q.C body 1/8"
2. **AirCore-HR:** 300m, consist of Tube 1 and Tube 2
3. **Tube 1:** 200m, OD 1/8"
4. **Tube 2:** 100m, OD 1/4"
5. **Interface attached to the AirCore (SS-QC4-B-400):** Q.C body 1/4"
6. **Interface (SS-QC4-D-400):** Q.C stem with valve 1/4"
7. **Magnesium dryer tube:** 7cm, OD 1/4"
8. **Interface male connector:** OD 1/4" to male 1/4" NPT
9. **Interface reducing adapters(SS-4-RA-2):** female 1/4" NPT to male 1/8" NPT
10. **Solenoid valve (VDW22UANXB):** inlet and outlet female 1/8" NPT
11. **Interface male connector (SS-400-1-2):** Tube-screw, male 1/8" NPT to OD 1/4" - ID 0,21"
12. **Tube:** 50cm, OD 1/4" - ID 0,21"
13. **Nut-Ferrule (SS-400-NFSET):** SS OD 1/4"

Figure 21: Schematic of CAC.

The electronic components in the CAC box will be: three temperature sensors and the solenoid

valve. In order to connect these components to the control unit in the AAC box, a D-sub cable will link the respective D-sub connector on each box.

4.4.4 AAC Box

The AAC box has been designed to be as compact as possible. An analysis regarding the variation of the bags dimensions to different sampled volume, has been made and summarized in Appendix C.3. From these results it was shown that the AAC subsystem is able to fit six $3\,L$ sampling bags together The Brain that includes the pneumatic system and the electronic box. 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 hanging from a bar that will be attached to the structure frame by two anchor points on the top. The distribution layout can be seen in Figures 22a and 22b.

(a) Isometric View of the AAC Box.   (b) Lateral View of the AAC Box.
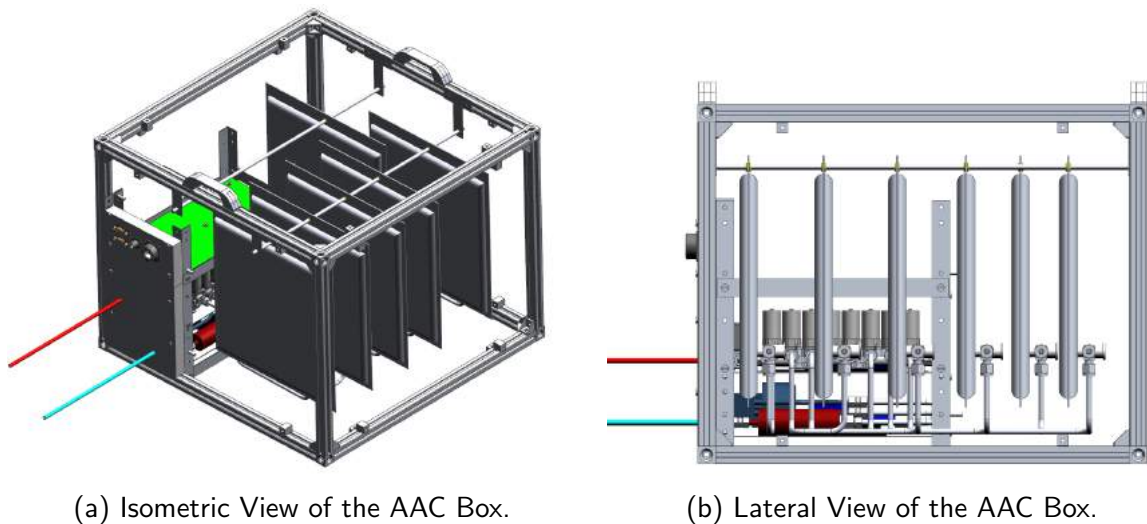
Figure 22: Distribution Inside the AAC Box.

In order to reach to all the bags from the Valve Center, the tubes are brought to the base of the box. More detail on its positioning is included in the following section.

<u>The Brain</u>

The Brain is an essential part of the experiment. It is a three-level structure containing both the pneumatic system and the electronics of the experiment, seen in Figure 23. Its design aimed to make it compact enough to both allow a proper thermal control and to fit into the space left next to the sampling bags. It is placed in a corner of the AAC box. Therefore, The Brain takes advantage of the vertical space inside the AAC box. It has three different levels: Level 1 - Pump, Level 2 - Valve Center and Level 3 - Electronics.
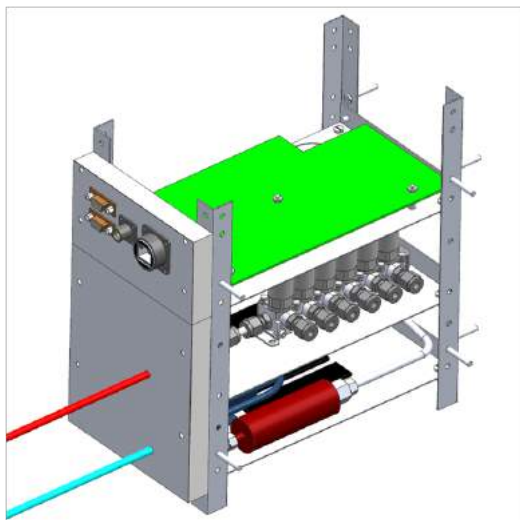
Figure 23: Inside view of The Brain.

Level 1 of The Brain is lying on the base wall styrofoam. It contains the beginning of the pneumatic sampling system. The inlet tube passes through the wall and interfaces with the filter. From here the system continues through the pump, airflow sensor and to Level 2. The reason for having the pump in Level 1 is to have the minimum vibration transmitted to the other components. The pump will have two heaters close by that will be used to regulate its temperature. This can be seen as two black rectangular sheets underneath the pump in Figure 24a.

The second level of The Brain is responsible for the distribution of the air to the selected sampling bag. The manifold with 8 solenoid valves is the main component. From here, the tubes connect with the bags. A T-Union connection is used just before the bag valve. This interface allows the pre-flight flushing of the tubes connecting with the valves as explained previously.

The flushing valve is the responsible to ensure a proper flushing of the system before each sampling period. From the flushing valve, a outlet tube (in red) reaches the outside environment. This can be seen in Figure 24b.

The OBC and its external elements will be allocated in the third level of The Brain. The PCB will be fixed to the aluminum plate by means of 5 standoffs. As shown in Figure 24c, it has a hole, as well as the level plate, to collect all the wires connecting with levels 1 and 2. This level has its own outside wall which contains the electrical interfaces. The latter allows to open the wall without having to remove all the sockets attached with screws and a female in the inside of the wall. The styrofoam shielding of The Brain has a hole at this height to allow the temperature sensors wires to reach the inside of the AAC Box.

A more detailed content of the components for each level is summarized in Appendix C.4.
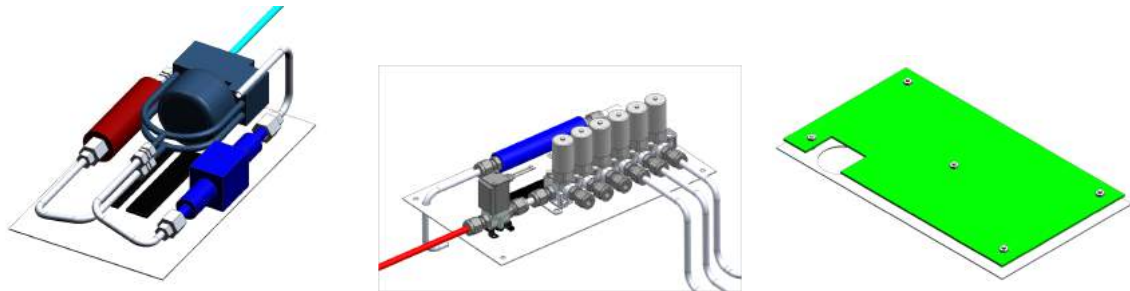
(a) Isometric View of Level 1.   (b) Isometric View of Level 2.   (c) Isometric View of Level 3.

Figure 24: Distribution in Each Level.

This distribution allows easy access to the PCB from the bottom and provides the physical desired separation between electronics and pneumatic circuit.

The structure of The Brain provides versatility in terms of implementation and construction. It is made out of four aluminum 90-degree angle bars placed vertically and six aluminum 90-degree angle bars placed horizontally, 2 on each level. The bars have custom-made holes that allow the possibility to fix all the pieces together and to provide the anchor point for the lateral and top styrofoam shield as well as to fix the whole unit to the box structure bars.

The bulk dimensions of The Brain are 260 mm long, 150mm wide and 290 mm high. If the shielding styrofoam walls are taken into account, the dimensions are 290 mm long, 180 mm wide and 300 mm high. Therefore, accounting for the space the column bars take, each plate has a surface of 258 mm x 158 mm. The distance between levels is variable depending on the components dimensions. Level 1 has a height if 7 cm, Level 2 has a height of 9 cm and Level 3 has 8 cm to the top styrofoam shielding. The Brain with styrofoam shielding can be seen in Figure 25.
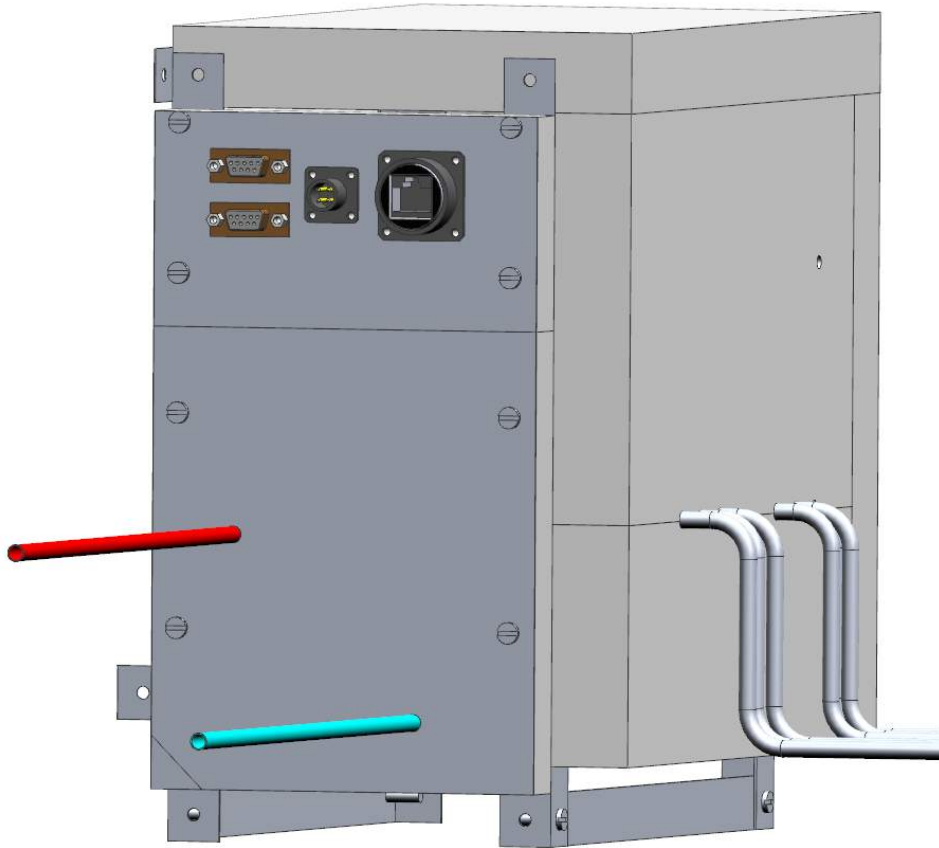
Figure 25: Isometric view of The Brain.

In order to allocate the electrical interfaces required (E-Link, Power Supply and D-Sub Connectors) as well as to allow the tubes of the sampling system to reach the outside environment, the outside facing wall is divided in three pieces. Two small pieces of aluminum sheet are fixed to The Brain structure, as seen in Figure 25. This will make it easy to manipulate when having to open the box wall since the little pieces containing the interfaces and the tubes holes, will remain attached. The bottom piece covers Level 1 and 2 while the other, which contains the electrical connections, protects Level 3. These pieces have the same layout as the main wall. Since the electrical panel is facing to the outside, to avoid any interference with the gondola, the experiment has to be fixed inside it at a certain distance with a safe margin. If the latter is not possible, the whole experiment should then be twisted 180 degrees so the panels would face inwards. Then, the pipes will have to be longer in order to reach the outside of the gondola for clear air samples.

Shielding and anchor points

The most critical components in terms of required thermal control are inside The Brain. These are the pump and the valves. In order to provide a passive thermal shielding, 3 cm thick removable styrofoam walls are placed in the three walls (top and laterals) facing the interior of the AAC box, shown in Figure 25. The lateral walls are fixed by means of four bolts attached to the structure bars that penetrate inside the styrofoam. The top wall is fixed in place taking advantage of the structure columns which penetrate inside it. The larger lateral wall, where

the tubes from the valves are, is divided in two pieces so it can be removed without having to disconnect the tubes.

The Brain is fixed to the structure of the AAC box by means of four anchor points: two flat plates and two 90-degree angles. In order to keep it in its place, the structure bars penetrate 3 cm into the styrofoam base.

4.4.5 Pneumatic Subsystem

In order to be able to collect separated samples of air, a pneumatic subsystem has been developed. The schematics and components of this can be seen in Figure 27. The system is formed by almost 100 components located inside The Brain and the AAC Box.

In between these components, the same Sulfinert-treated stainless steel tubing as the ones used for the Inlet/Outlet pipes explained in Section 4.2.1 have been chosen. According to the datasheet, the minimum suggested bend radius for the chosen diameter tube is $10.2\ cm$. Any bend sharper than this may cause the tubing to stretch, potentially creating active sites as the coating layer density decreases. For this reason, $90°$ elbow interfaces have been used instead of the previously considered straight ones, to perform all the required sharp curves to allocate all the components inside the volume-limited *Brain*.

The schematic for the pneumatic system can be seen in Figure 27. The air is sucked from the outside through the inlet tube (No.1), turquoise in Figure 26, and it goes through the filter (No.3) inside the pump (No.7). From here, it passes through the airflow sensor (No.11), which allows to monitor the flow rate, before changing to Level 2. Thereafter the air passes through the static pressure sensor (No.15) before getting to the six stations manifold (No.19). It is in here where the air is directed to the desired bag (No.31) thanks to its dedicated solenoid valve (No.26).

When flushing the pneumatic system before each sampling period, the flushing valve (No.23) is opened so that the outlet of the system is open and new air runs through the main part of the pneumatic system.
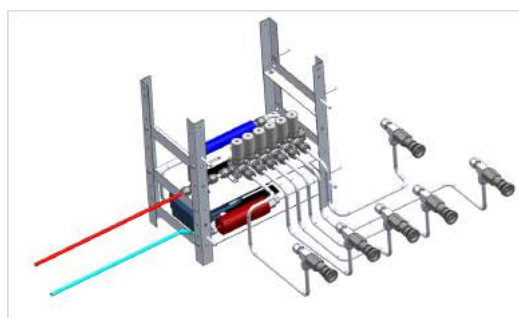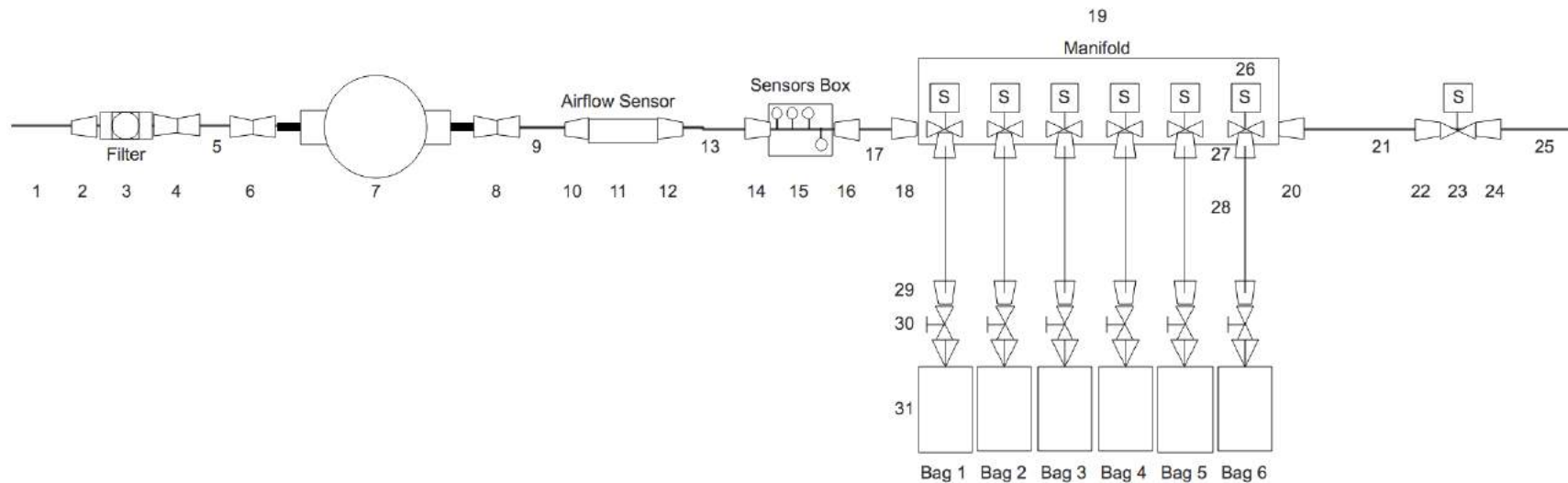

Figure 26: Pneumatic System top view.

Figure 27: AAC Pneumatic System diagram and components.

1. **Inlet tube (29255):** SS OD 1/4" - ID 0,21"
2. **Interface female connector (SS-400-7-4):** OD 1/4" - ID 5/32" to female 1/4"
3. **Magnesium Filter:** male 1/4" to tube
4. **Interface male 90-degree connector (SS-400-2-4):** OD 1/4" - ID 5/32" to male 1/4"
5. **Tube Filter - Pump (29255):** SS OD 1/4" - ID 0,21"
6. **90-degree Union (SS-400-9):** OD 1/4" - ID 5/32"
7. **Pump:** ID4 (ID 5/32")
8. **90-degree Union (SS-400-9):** OD 1/4" - ID 5/32"
9. **Tube Pump - Airflow sensor (29255):** SS OD 1/4" - ID 0,21"
10. **Interface female 90-degree connector (SS-400-8-4):** OD 1/4" - ID 5/32" to female 1/4"
11. **Airflow sensor:** 1/4" male - 1/4" male
12. **Interface female 90-degree connector (SS-400-8-4):** OD 1/4" - ID 5/32" to female 1/4"
13. **Tube Airflow sensor - Sensor Box (29255):** SS OD 1/4" - ID 0,21"
14. **Interface male 90-degree connector (SS-400-2-2):** OD 1/4" - ID 5/32" to male 1/8"
15. **Sensors Box:** 3 pressure sensors,1 humidity sensor, custom-made, inlet and outlet 1/8" female
16. **Interface male 90-degree connector (SS-400-2-2):** OD 1/4" - ID 5/32" to male 1/8"
17. **Tube Sensor Box - Manifold 1 (29255):** SS OD 1/4" - ID 0,21"
18. **Interface male 90-degree connector (SS-400-2-2):** OD 1/4" - ID 5/32" to male 1/8"
19. **Manifold (VV2DW2-H0601N-F-Q):** 6 stations, Inlet and outlet 1/8" female
20. **Interface male connector (SS-400-1-2):** OD 1/4" - ID 5/32" to male 1/8"

21. **Tube Manifold - Flushing Valve (29255):** SS OD 1/4" - ID 0,21"
22. **Interface male connector (SS-400-1-2):** OD 1/4" - ID 5/32" to male 1/8"
23. **Flushing Valve (VDW22UANXB):** inlet and outlet 1/8" female
24. **Interface male connector (SS-400-1-2):** OD 1/4" - ID 5/32" to male 1/8"
25. **Outlet tube (29255):** SS OD 1/4" - ID 0,21"

For 6 bags:

26. **Valve (VDW23-5G-1-H-Q):** female 1/8"
27. **Interface male connector (SS-400-1-2):** OD 1/4" - ID 0,21" to male 1/8"
28. **Tube Valve - T-Union (29255):** SS OD 1/4" - ID 0,21"
29. **T-Union (SS-400-3):** male 1/4"
    2 x Nut-Ferrule (SS-400-NFSET): SS OD 1/4"
    1 x Quick Coupling (SS-QC4-B-4PF): SS female 1/4"
30. **Bag valve:** 1/4"
31. **Bag:** 3L

4.5 Electrical Design

4.5.1 Block Diagram

The electronics design can be seen in Figure 28 which shows the connections, grounding, voltages, and signals.
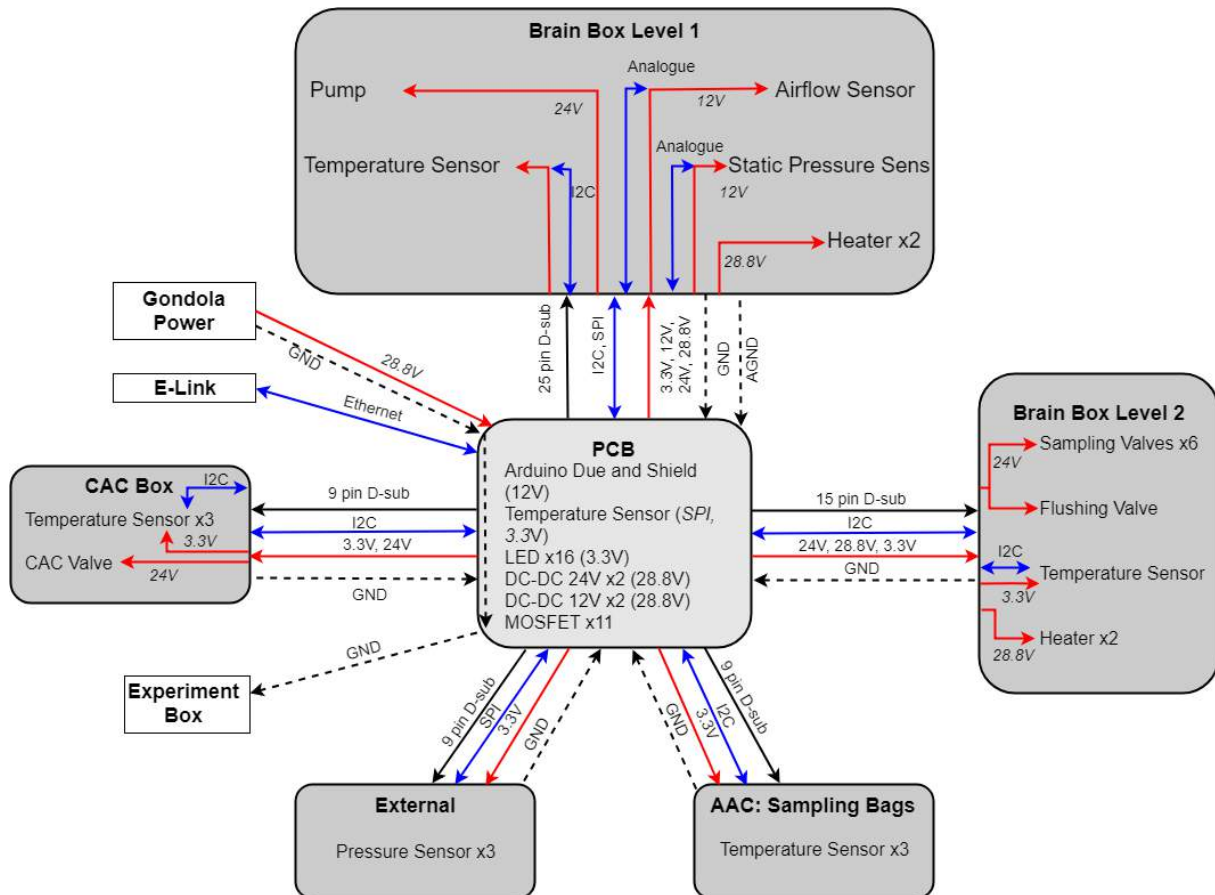

Figure 28: Block Diagram for all Electronic Components Showing the Connection, Signal and Power Connections.

Most of the electronics will be located in the Brain inside the AAC box. However, there will be six distinct areas:

1. The Brain level 3, where the PCB is located with the Arudino and shield, two 24 V DC-DC, two 12 V DC-DC, one temperature sensor, 11 MOSFETs and 16 LEDs.

2. The Brain level 2, where the valve manifolds with six sampling valves, the flushing valve, two heaters and one temperature sensor are located.

3. The Brain level 1, where the pump, two heaters, airflow sensor, one temperature sensor and static pressure sensor are located.

4. The AAC box, where 3 ambient temperature sensors are located.

5. The CAC box, where the CAC valve and 3 ambient temperature sensors are located.

6. Outside of the experiment box, where 3 ambient pressure sensors are located.

From the PCB, on level 3, five D-sub connectors will be used to connect to the other five areas. A 25 pin connector will be used for level 1, 15 pin connector will be used for level 2 and nine pin connectors will be used for the CAC box, AAC box sampling bags area, and the external pressure sensors. In addition there will be a connection to the gondola power and gondola E-link.

All of the power distribution will take place on the PCB using two 24 V DC-DC and two 12 V DC-DC converters in parallel with a forwarding diode.

- $28.8\,V \implies 24\,V$ By DC-DC converters
- $28.8\,V \implies 12\,V$ By DC-DC converters

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

The Arduino will control all of the sensors, valves, heaters and the pump from the PCB. Sensors will be directly connected to the Arduino. The valves, heaters and the pump will be connected via a switching circuit.

The LEDs are used as visual indicators that display whether different parts of the circuit are alive or not. They give indications on the status of the valves, pump, heaters, DC-DC converters and Arduino.

Grounding will be following a distributed single point grounding, with all ground connections meeting at a single star point to ensure there are no floating grounds. As not all components are connected via DC-DC converters the experiment will not be isolated from the gondola power supply therefore there will be a connection between the star point and the gondola ground. The star point will be located on the main PCB board which will then be grounded to the experiment box. The grounding can be seen in Figure 28 where it is indicated by dashed lines labeled GND. The analog sensors that are used on level 1 in the brain use a separate grounding wire(AGND) onto the main PCB where there is a separate trace connecting to the ground pins on the Arduino board. Furthermore the upper and lower level of the main PCB board will make use of one common grounding plane.

4.5.2   Miniature Diaphragm Air Pump

The pump which has been selected is the 850.1.2. KNDC B, Figure 29, 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 where it managed to pump enough air at 25 km altitude to have 180 mL remaining at sea level [2]. However, to ensure the pump will operate as intended, several tests will still be carried out. These tests — 4, 5, 18, 28 and 29, can be seen in Tables 26, 27, 36, 42, and 43. The pump has already passed three of these tests and their results can be seen in Section O.1 for Test 28, Section O.2 for Test 18 and Section O.3 for Test 29.

At sea level conditions the pump was tested and found to have a flow rate of 8.0 L/min and a current draw of 250 mA. The peak current draw was recorded as 600 mA which lasts for less than one second and occurs when the pump is switched on.

From the results of Test 18, in Section O.2, the flow rate is estimated to be 3.0 L/min at the lowest pressure that will be seen in flight. This is in line with requirement D23. The results found in Test 28, in Section O.1, appear to be inline with the information given by the manufacturer, seen in Figure 30. The highest continuous current draw expected from the pump is 185 mA when the experiment is at 12 km altitude and is expected to decrease as we increase in altitude. While it appears the pump increases in current draw at around 6 km there is no plan to sample below 12 km therefore the highest current draw can be taken from 12 km. As the pump has a peak current of 600 mA when it switches on, the mosfet and DC-DC power have been chosen to be able to withstand this demand.

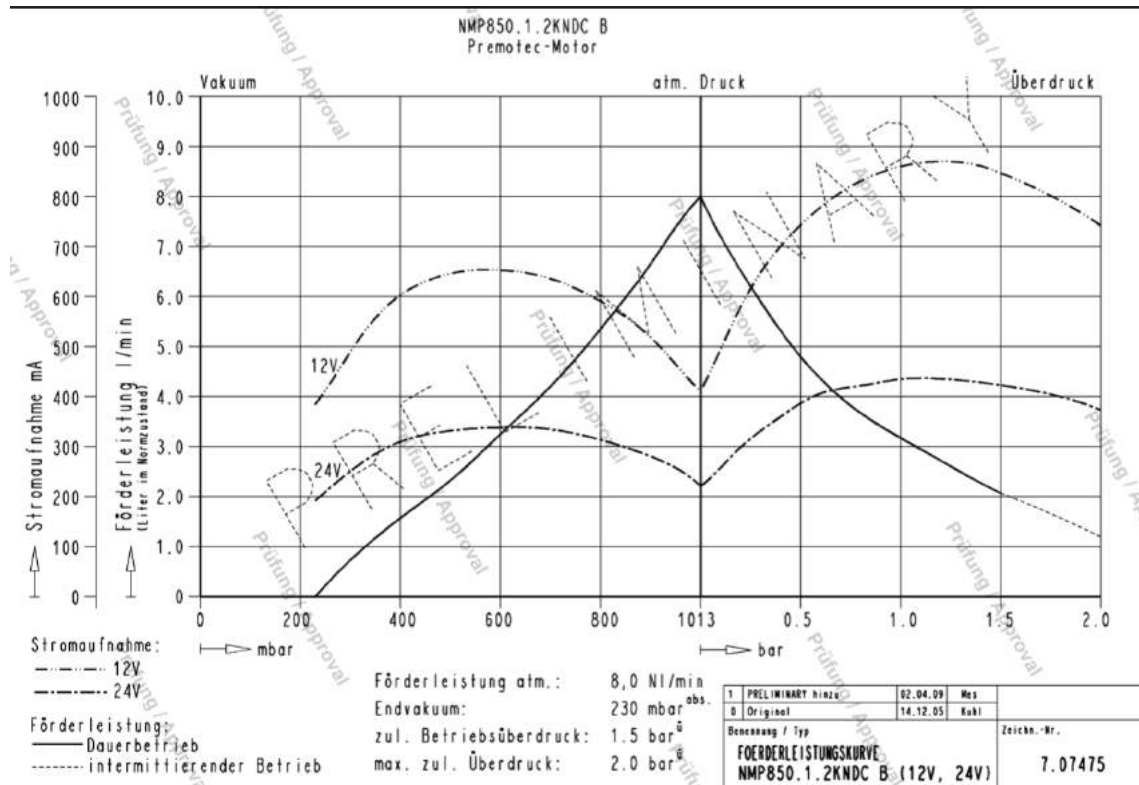Figure 29: KNF 850.1.2. KNDC B Miniature Diaphragm Pump.

Figure 30: KNF 850.1.2. KNDC B Flow Rate and Current Draw to Pressure Graph.

4.5.3 Electromagnetically Controlled Valves

Filling the sampling bags will be controlled by solenoid valves. The solenoid valves which have been selected are model VDW23-5G-1-H-Q, seen in Figure 31, manufactured by SMC. These valves will be normally closed through out the experiment with zero power consumption and will open, when given power, to fill up the sampling bags at specific altitudes. In addition one valve will be on the CAC, in order to seal the coil at the end of the flight and another at the end of the AAC tubing, flushing valve, in order to flush the system. The valves selected for these are model VDW22UANXB, Figure 31. The CAC valve will be opened shortly after take off and remain open the whole flight. This valve will be closed shortly before landing. The flushing valve will be opened before sampling in order to ensure the air in the tubes is from the correct altitude.
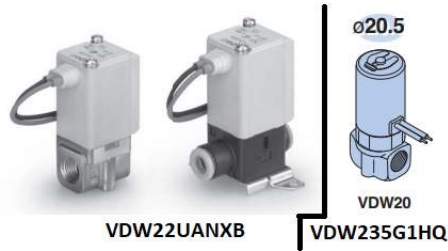
Figure 31: SMC Solenoid Valves, VDW22UANXB on the Left, VDW23-5G-1-H-Q on the Right.

The port size of the valves is 1/8" which is compatible with the gas analyzer. The coil inside can withstand temperatures from -20 to 50 °C which is suitable for flight operations at high altitudes. These valves can operate under a maximum pressure drop of 133 Pa. Valves from the same series have been flown before to the stratosphere and provided successful results [2] however, the valves will be tested at low temperature and pressure to check they still operate as intended. These planned tests can be seen in Test 4, Table 26 and Test 5, Table 27.

4.5.4 Switching Circuits

The valves, pump and heaters will not be powered by the Arduino but they still need to be controlled by it. In order to allow this control a connection will be made for each component to the Arduino with a switching circuit. This switching circuit will use a eleven MOSFETs, model IRLB8748PBF, Figure 32, to control which components are turned on at which time.
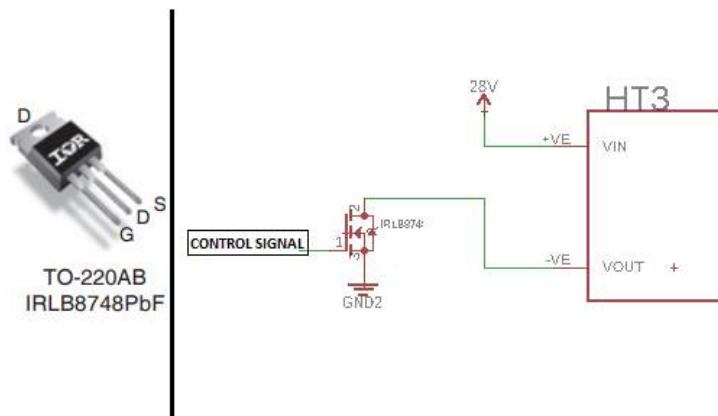

Figure 32: Figure Showing an Image of the 30V,78A,75W MOSFET, Model Number IRLB8748PBF on the Left and the Schematic for the Switching Circuit for One Heater on the Right.

4.5.5 Schematic

The schematics show all the components and how they are connected, the full schematics can be seen in Figure 33. There are four requirements for the the power distribution given below:

- $28.8\,V$ for the heaters.

- $28.8\,V \implies 24\,V$ for the pump and valves.

- $28.8\,V \implies 12\,V$ for the airflow sensor, static pressure sensor and Arduino due.

- $3.3\,V$ for the temperature and pressure sensors.

The voltage available from gondola power is 28.8 V, therefore the heaters have been connected directly to the main power supply. For the rest of the components, two 24 V and two 12 V DC-DCs in parallel has been used to make sure if one of them fails then the other can take over. The circuitry can be seen in Figure 34. All the valves and the pump are then powered through the 24 V DC-DCs. To step down the voltage from 28.8 V to 12 V to power the airflow sensor, static pressure sensor and the Arduino, two 12 V DC-DCs in parallel has been used for the redundancy purposes. Finally, to power the temperature and external pressure sensors, 3.3 V is required which is supplied by the Arduino board.

To meet the requirements of the pneumatic subsystem, a static pressure sensor has been chosen to measure the pressure inside the tubes and bags. This analogue pressure sensor operates on 12 V so can share the same power line as the airflow sensor and Arduino.
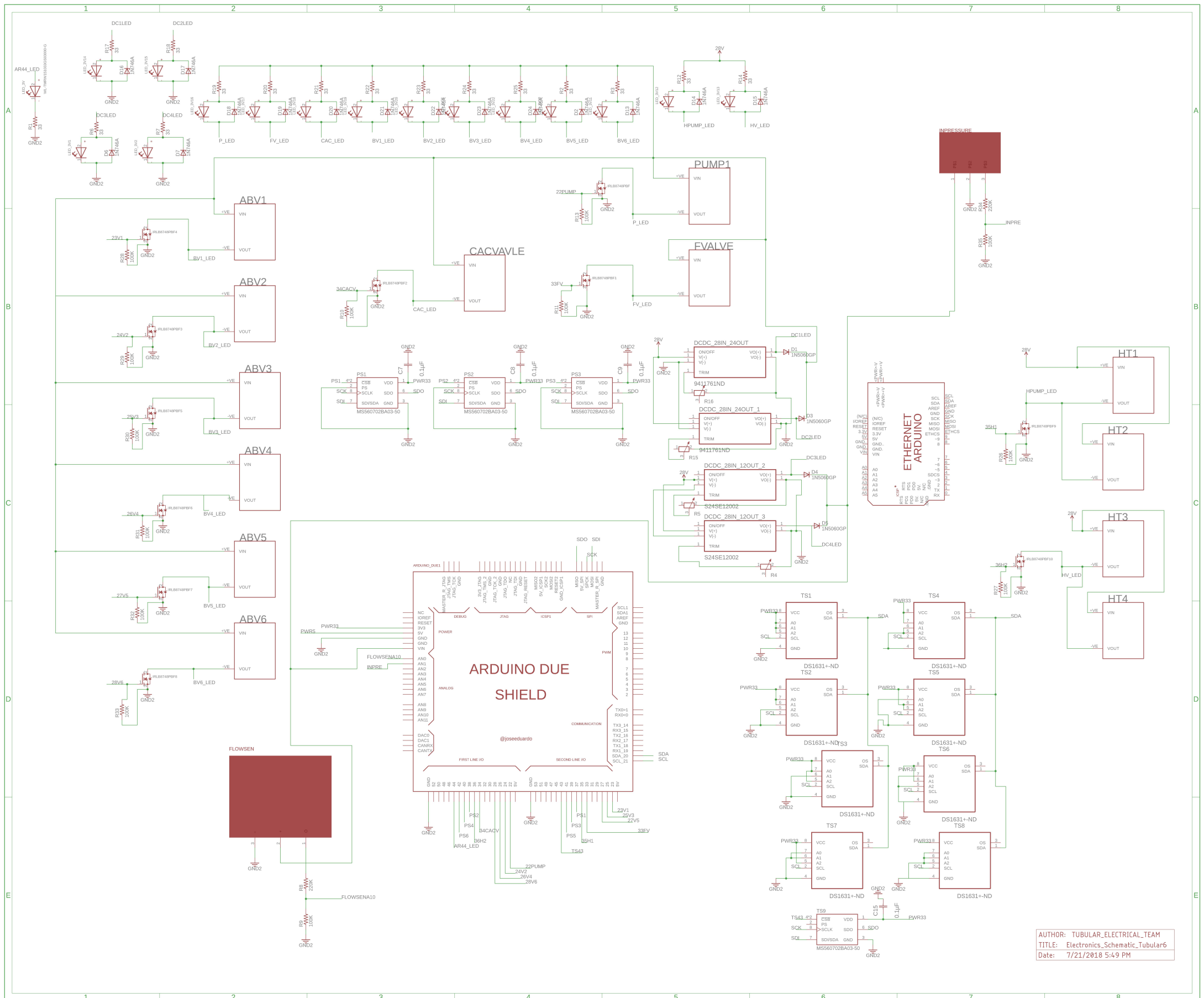
Figure 33: Schematic for All of the Electronics on Board TUBULAR. This can also be Found at https://rexusbexus.github.io/tubular/img/electrical-design-schematics.png
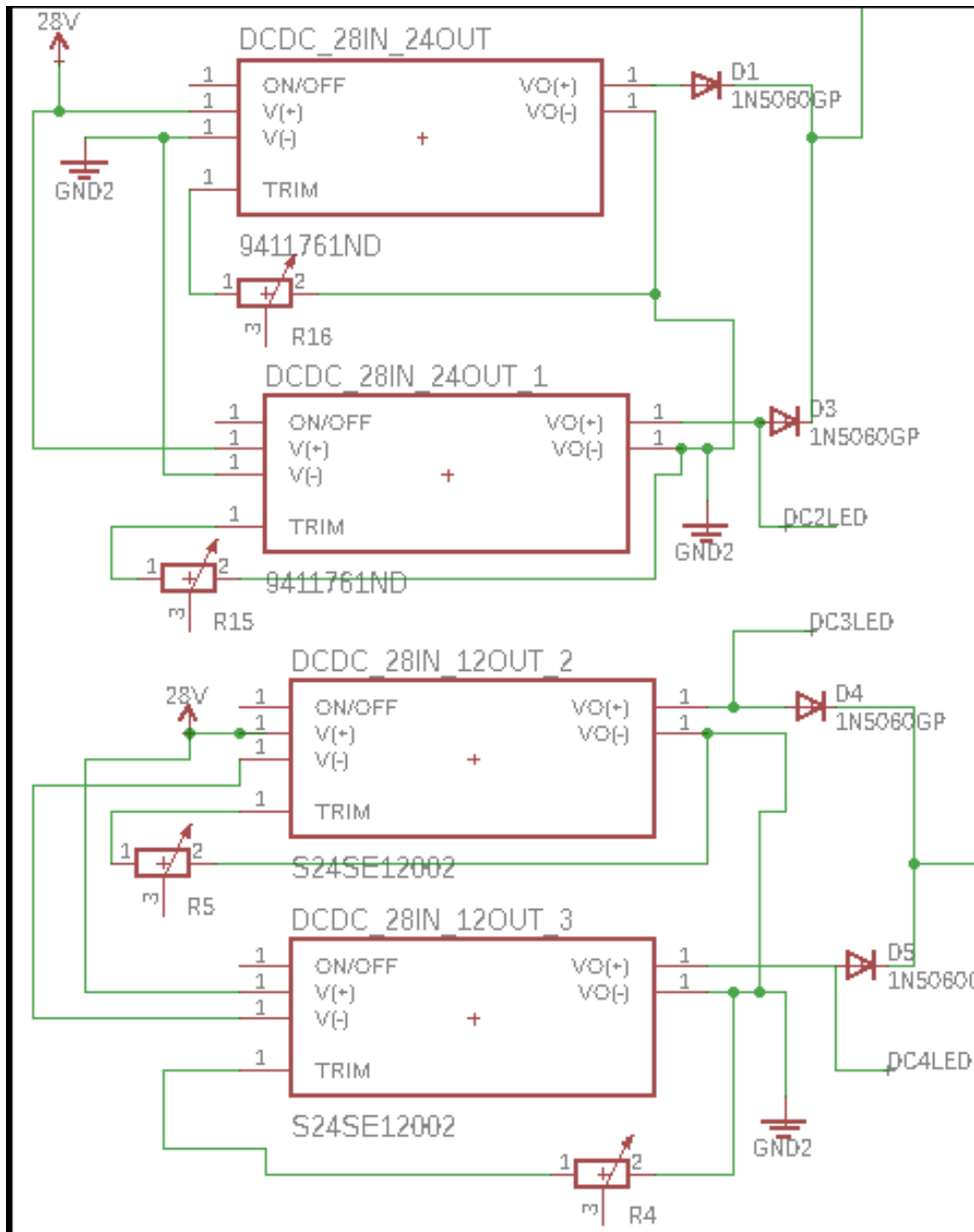
Figure 34: Schematic Showing the DC-DC Redundancy of Both 24 V and the 12 V DC-DC Converters.

4.5.6   PCB Layout

All electronic control circuits will be gathered on a single PCB on level 3 of the Brain. The PCB contains the Arduino due, switching circuits, indication LEDs, a temperature sensor, the power system and all necessary connectors. The connectors have been divided so that each connector's wires goes to the same level of the Brain to improve cable management. To further improve cable management the shared pins for I2C and SPI are connected to a single pin on each respective D-SUB connector and should be split up on the respective level. The PCB Layout can be seen in Figure **??**.

The PCB was made using Eagle software. The traces have a width designed to fit the IPC-2221 standards[11] with extra width added. The PCB layout can be seen in in Section C.11. On the main PCB the traces are 1.4mm wide for the nets containing components that consumes higher amounts of current and the ones with lower current requirements have a trace width of 0.3mm. On the pressure sensor PCB all traces are 0.5mm wide.

4.6   Thermal Design

4.6.1   Thermal Environment

The experiment will experience wide temperature fluctuations during the flight and it must be able to continue to operate despite these changes. As seen in Figure 35 the coldest point of the flight will be between 10 km and 15 km where the air temperature can drop to $-70°$ C outside. Past flights have recorded temperatures on the gondola as low as $-55°$ C during the Ascent and Descent Phases[6]. Sampling with the AAC will begin when the balloon has risen to 18 km during the Ascent Phase and will last until the Float Phase. Sampling will resume when the gondola has fallen to 17.5 km during the Descent Phase. This means the experiment will be above the coldest part of the atmosphere and the critical components will have time to achieve their operating temperature before sampling time commences. In addition, launching from Kiruna in late October means the temperature on the ground could be as low as $-10°$ C. As the component with the highest lower limit operating temperature must be at a minimum of $5°$ C (E3 in Table 19), heating may need to be switched on while the experiment is still on the ground.
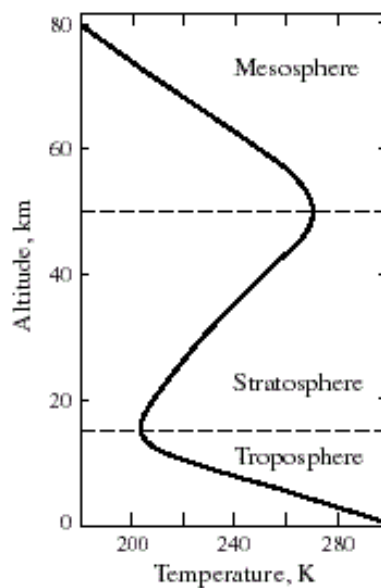

Figure 35: Diagram Showing the Temperature Profile of the Atmosphere [12].

4.6.2   The Critical Stages

The flight will have the following critical stages:

- Launch pad
- Early ascent
- Sampling ascent

- Float

- Descent before sampling

- Sampling descent

- Shut down

- Landed, waiting for recovery

These stages have been accounted for in further calculations and simulations.

4.6.3 Overall Design

To protect the components against the cold, thermal protection will need to be designed. Insulation and internal heating will both come into play in keeping all the components functional throughout the duration of the flight. The two components with the most critical thermal ranges are the pump and the valve manifold system (E3 and E5 in Table 19). Thermal regulation is mainly focused on the AAC however, a thermal analysis of the CAC can be found in Appendix I under Section I.2.8 where the CAC box the valve is identified as the critical component in terms of thermal regulation (refer to component E5 in Table 19). It will have a current through it throughout the flight heating it self up.

The main protection against the cold environment in the stratosphere is a passive thermal design by means of insulating layers added to the walls of the experiment. It will be comprised of two layers: one outer sheet of aluminum and a thicker sheet of Styrofoam. The main insulating factor is Styrofoam which will significantly reduce the heat exchange between the otherwise exposed experiment box, and will also provide shock absorption when the gondola lands after separating from the balloon.
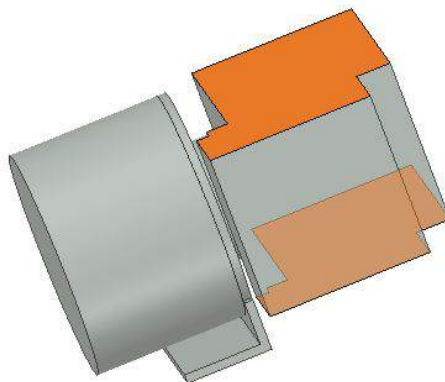

Figure 36: Highlight of the Heater On the Pump.

An active thermal control system will also be included consisting of four heaters. Two heaters will regulate the pump's temperature as seen in Figure 36 and a single heater will regulate the flushing valve temperature and one heater for the manifold. To control these heaters, two

temperature sensors will also be on board in close proximity to the heaters. If the reading from one of the temperature sensors is lower than the predefined threshold, then the heater will turn on to warm up the cooling component. If it is above the higher threshold the heater will turn off.

Simulation in MATLAB (code can be found in Appendix J) where used to determine the uniform heat inside the experiment. The ANSYS thermal modelling platform was used to the simulate the thermal conditions inside the Brain.

Table 19, below, covers the thermal ranges of the components listed in Section 4.3:

ID	Components	Operating (°C)		Survivable (°C)		Expected (°C)	
		Min.	Max.	Min.	Max.	Min.	Max.
E1	Arduino Due	-40	85	-60	150	-30.62	24.01
E2	Ethernet Shield	-40	85	-65	150	-30.62	24.01
E3	Miniature diaphragm air pump	5	40	-10	40	10	34.93
E4	Pressure Sensor	-40	85	-40	125	-19.70	34.93
E5	Sampling Valve (inlet and outlet 1/8'" female)	-20	50	-20[4]	50[4]	-15	20
E6	Airflow sensor AWM43300V	-20	70	-20[4]	70[4]	-8.77	34.93
E7	Heater ($12.7 \times 50.8mm$)	-200	200	-200[4]	200[4]	-20	36
E8	Voltage Regulator	-40	125	-40[4]	125[4]	-30.62	34.93
E9	Temperature Sensor	-55	125	-65	150	-19.70	34.93
E10	DCDC 24 V	-40	85	-55	125	-19.70	34.93
E12	Micro SD	-25	85	-200[4]	200[4]	-19.70	34.93
E16	Mosfet for current control	-55	175	-55	175	-20	-20
E17	Diodes for DCDC converters	-65	175	-65[4]	175[4]	-19.70	34.93
E18	3.3V LED	-40	85	-40[4]	85[4]	-19.70	24.01
E19	15-pin D-SUB Female connector with pins	-55	120	-200[4]	200[4]	-8.77	24.01
E20	9-pin D-SUB Female connector with pins	-55	120	-200[4]	200[4]	-8.77	24.01
E21	9-pin D-SUB Female connector with soldering cups	-55	105	-55[4]	105[4]	-8.77	24.01
E22	9-pin D-SUB Male connector with soldering cups	-55	105	-55[4]	105[4]	-8.77	24.01

[4]If survivable temperatures were not given, operating temperatures were used as survivable limits.

E23	15-pin D-SUB Male connector with soldering cups	-55	105	-55[4]	105[4]	-8.77	24.01
E24	9-pin D-SUB backing	-40	120	-40[4]	120	-8.77	24.01
E25	15-pin D-SUB backing	-40	120	-40[4]	120	-8.77	24.01
E27	D-SUB cable CAC to AAC	-40	85	-55	125	-40	40
E29	Male connector on PCB	-40	85	-40[4]	85	-8.77	24.01
E30	Female connector from wall	-40	85	-40[4]	85	-	-
E32	Logic CAT5 E-link for inside box	-20	75	-20[4]	75[4]	-15	20
E33	Signal Wires	-60	200	-60[4]	200[4]	-	-
E34	Flushing valve (inlet and outlet 1/8''' female)	-10	50	-10[4]	50[4]	-7.36	42.53
E35	Valves manifold (outlet 1/8''' female)	-10	50	-10[4]	50[4]	-6.77	40.504
E36	Power wire black	-60	200	-60[4]	200[4]	-	-
E45	25-pin D-SUB female connector with pins	-10	90	-10[4]	90[4]	-8.77	24.01
E46	25-pin D-SUB male connector with soldering cups	-10	90	-10[4]	90[4]	-8.77	24.01
E47	25-pin D-SUB backing	-10	90	-10[4]	90[4]	-8.77	24.01
E48	Power wire red	-60	200	-60[4]	200 [4]	-	-
E50	6-pin male	-55	105	-55[4]	105[4]	-8.77	24.01
E51	8-pin male single row header	-40	105	-40[4]	105[4]	-8.77	24.01
E52	10-pin male single row header	-55	105	-55[4]	105[4]	-8.77	24.01
E53	36-pin male double row header	-40	105	-40	125	-8.77	24.01
E54	12 V DC/DC converter	-40	85	-55	125	-8.77	24.01
E56	Pressure Sensor	-40	120	-40[4]	120[4]	-8.77	34.93

Table 19: Table of Component Temperature Ranges.

4.6.4   Internal Temperature

As the current experiment model stands, an enclosed partition has been reserved in the lower front left-hand corner of the AAC section of the 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.

The pump has the most critical temperature range as it is a single point of failure component that cannot operate below freezing temperatures. It's data sheet states that it must always operate above $5°$ C, or the EPDM diaphragm may not be able to expand and contract sufficiently to maintain the desired airflow of 8 L/min. However, as this pump has been used successfully on previous high altitude flights, [2], tests will be conducted on the pump to find its true performance at lower temperatures and low vacuum environment. The AAC valves are also crucial to the experiment's function, as they enable each and every sampling bag on board to be used. For this reason, while the valves can operate down to $-20°$ C, it is desirable to be keep them above this limit whenever in use.

As the most temperature-sensitive equipment will all be housed within the Brain, it is important to know what heat will be lost through the different heat transfer mechanisms as this will affect the amount of time the heaters will need to be active. This has been addressed through calculations and simulations to find required insulation. All calculations concerning heat transfer can be found in Appendix I. As a worst-case scenario for heat distribution, it is assumed that *all* of the power dissipated through resistance in the electrical components will reach the marked boundaries of the experiment's walls.

Aluminum sheeting will be used as the outer layer of insulation for the experiment and Styrofoam brand foam will be used as the inner layer. Aluminum may have among the highest of thermal conductivities, but its arrangement around the Styrofoam, creating one large heat bridge with the inner layer, would provide a useful thermoregulatory mechanism [19]. The high ratio between the absorptivity (0.3) and emissivity (0.09) of the material may be used to its advantage [19]. Because the ratio for polished aluminum is higher than 1.0, the element will get hotter as it gets exposed to the radiation from the sun and the power-dissipating components [13]. The low emissivity coefficient for the aluminum cover means it will not get significantly hotter than the surrounding ambient temperature, but its increased temperature may negate some of the heat being lost from the experiment's interior via some of the heat from the aluminum propagating into the experiment, reducing the net heat loss by a small amount. As conservation of power is imperative, the heaters should be used sparingly, and instead methods like the use of aluminum for shielding should be employed as passive heating. The aluminum layer will be 0.5 mm in thickness, while the Styrofoam layer beneath it would span 20 mm in thickness. The Styrofoam, in contrast to the aluminum has a low thermal conductivity even when compared to similar polymer structures [19]. The Styrofoam would handle the bulk of the thermal resistance in keeping the experiment from losing the heat it would have obtained prior to being moved to the launchpad. The aluminum would come into play as the experiment rises into colder altitudes and encounters increased sun exposure. While the warmed aluminum will have little impact on the experiment's heat loss, this also means that the experiment's internal temperatures will be prevented from rising to the upper allowed operating limit of the experiment made possible because of the aluminum's low absorptivity of sunlight. Another heat bridge that is needed is the fastening of the experiment the gondola. The aluminum frame of the gondola will be colder then the experiment and with normal screws

there will be a lot of heat transfer. In this case rubber bumper screw, suggested at CDR will be used to fasten and will reduce the heat transfer between the experiment and the gondola.

4.6.5   Calculations and Simulation Reports

The temperature ranges can vary for the different stages but the most critical moment is during the Ascent Phase. While ascending, the main source of heat to maintain the pump and manifold's operating temperature is the heaters. During the Float and Descent Phases, heat originating from the sun will be enough to maintain these component's operational temperatures. According to the thermal analysis, the heaters would not be required during descent but there is power reserved in the worst case scenario that they need to be run during the Descent Phase. All simulation equations and their details can be seen in Appendix I.

An estimate of the temperature in the Brain at the sampling times during the Ascent Phase is visualized in Figure 37. The higher temperature is in the lower right corner where the pump is located. A cooler area exists around the middle of the left edge where no heaters are applied. The legend in the Figure shows the temperature in Celsius.
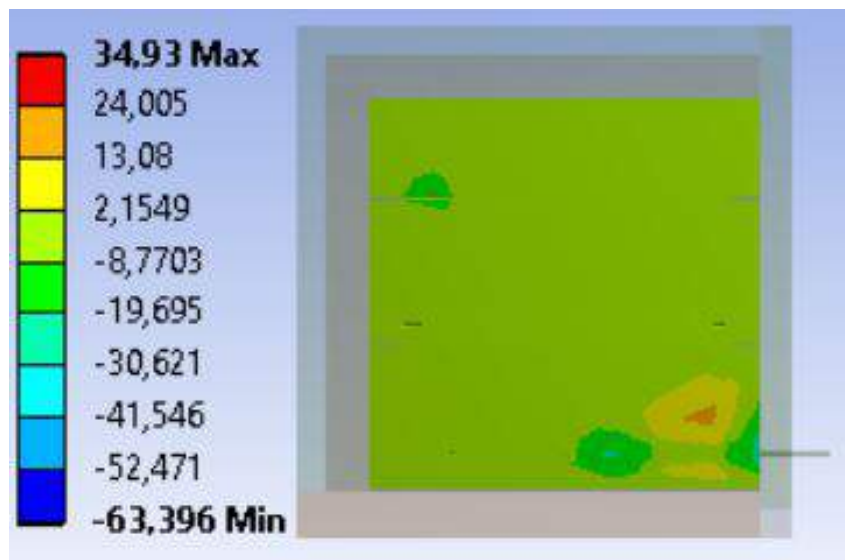

Figure 37: Cross Section of the Air in the Brain at the Time to Start Sample During Ascent.

In Figure 38 the average temperature off the pump with data from ANSYS is presented. One is simulated with no air in the Brain and the other have air with the same density as sea level. In between the vertical dotted line is when the experiment is above 15km. At 4h in the figure the experiment is launched. It can be seen that the pump will have an average temperature over 5 degrees during the flight.
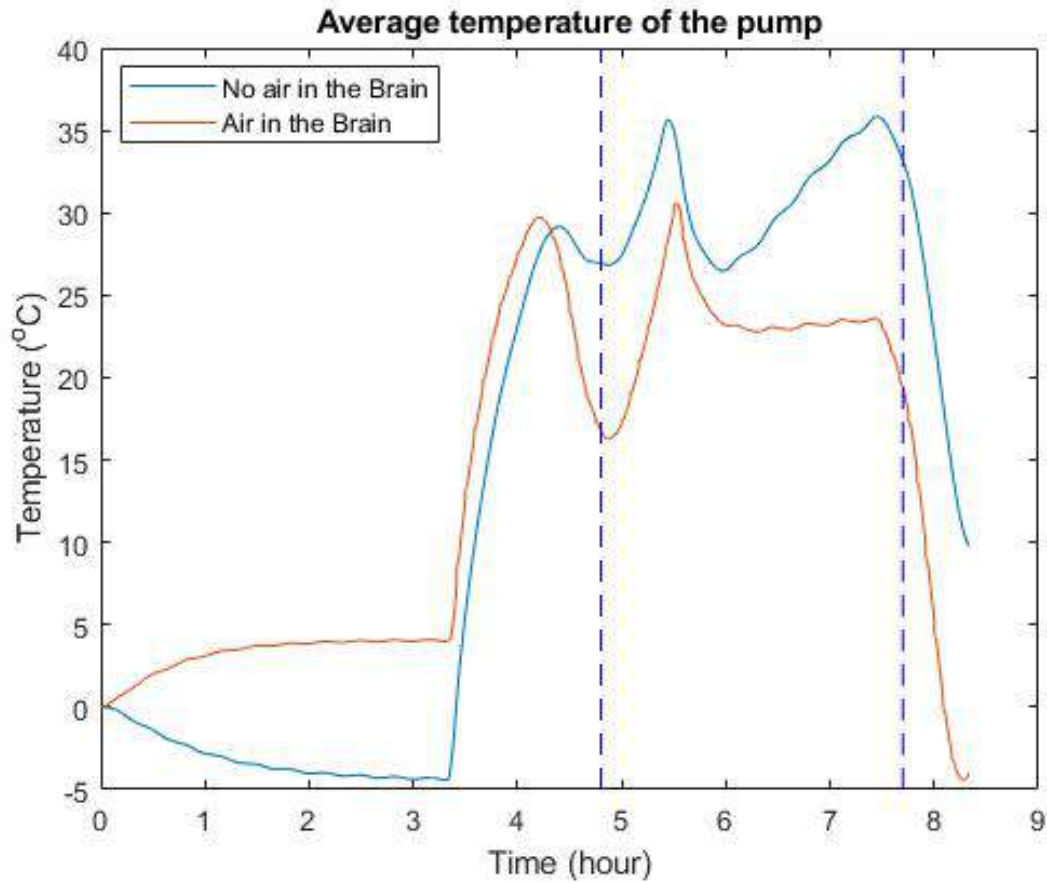
Figure 38: Temperature of the Pump Over a Simulated Flight.

The following two figures in Figure 39 are a visualization of the pump and the manifold at the time in which the AAC sampling begins during ascent.
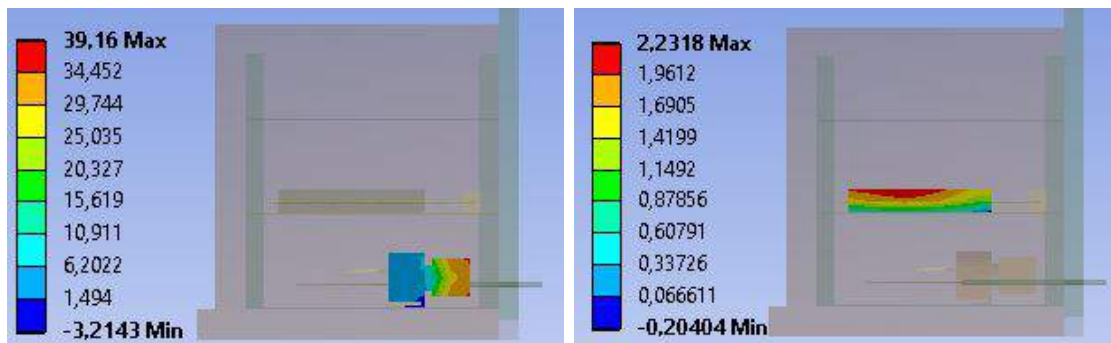

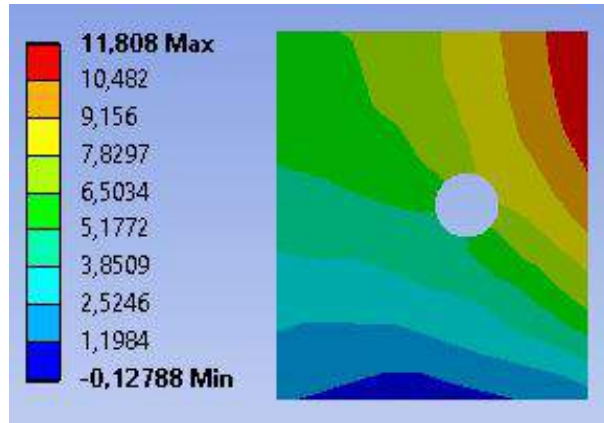Figure 39: Pump and Manifold at Sampling Time During Descent With No Air in the Brain.

Figure 40: Flushing Valve Prior to Sampling Commencing With No Air in the Brain.

During a worst case simulation that is shown in Figure 39 the four heaters were used for 26.66 Wh in total together over the course of the simulation the figures are from. Only the pump heaters might require more time if it is colder outside and there is dedicated 80 Wh in the power budget table, Table 20. So there is a margin to keep the pump heaters on for a longer time if needed.

Based on the calculations and thermal simulations, it can be concluded the thermal designed passive and active thermal control mechanisms detailed in this section will ensure that the AAC's pump and manifold will operate nominally during the entire flight flight. It has been concluded that the CAC has a sufficiently adequate thermal design to operate throughout the whole flight.

4.7 Power System

4.7.1 Power System Requirements

The Gondola provides a 28.8 V, 374 Wh or 13 Ah battery with a recommended maximum current draw of 1.8 A . However, more typical values are 196 Wh or 7 Ah [6].The experiment must run on external power for four hours before launch during the countdown phase and for the entire flight duration, lasting approximately four hours. As a factor of safety, in case of unexpected delays, the experiment should be able to run for an additional two hours. Therefore the experiment must be able to run on external power for a total of 10 hours. For this reason, all the calculations have been done using a 10 hour total time.

ID	Component	Voltage [V]	Current [mA]	Power [W]	Total [Wh]
E1	Arduino Due	12	30	0.36	36
E3	Miniature Diaphragm air Pump	24	200	7.68	7.68
E4	Pressure Sensor	3.3	1.4	0.032	0.32
E5	Solenoid Valves	24	125	24	39
E56	Static Pressure Sensor	12	8	0.1	1
E6	Airflow Sensor	12	8.3	0.1	1
E7	Heaters	28	179	15	80
E54	12 V DC-DC converter	28.8	8 (1670 output)	0.1 (20 output)	1
E9	Temperature sensor	3.3	0.28	0.011	0.11
E10	24 V DC-DC converter	28.8	37 (2500 output)	2 (60 output)	11.69
-	**Total**	-	1100	32	177
-	**Available from gondola**	-	-	-	374

Table 20: Power Design Table.

The estimated total power consumption 177 Wh, Table 20, is within the limits of the available power. Other calculations for the average, peak, and minimum power values are 21 W, 32 W, and 16 W respectively. In addition the different expected current consumption for the average, peak, and minimum values are 0.64 A, 1.1 A, and 0.22 A respectively.

The 24 V DC-DC converters have 2.5 A output current and 60 W output power with the efficiency of 93%. This fulfills the peak requirements for both power and current. Moreover, the dissipated power and current across the DC-DCs are calculated as 12.69 Wh and 45 mA respectively and have been added to the total power budget.

4.8 Software Design

4.8.1 Purpose

The purpose of the software is to automate control of the valves so that they will be opened/-closed at the target altitude. Moreover, the software will store housekeeping data from sensors, pump, and valves states to the on-board memory storage device. Logging sensor data is necessary in order to determine a vertical profile of the analyzed samples:

> In order to determine the vertical profiles of CO_2, CH_4, and CO from the analysis of sampled air, measurements of several atmospheric parameters are needed [...]. The two most important parameters are the ambient pressure and the mean coil temperature. These parameters will be recorded by the AirCore-HR (High Resolution) 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.[5]

Both the ambient pressure and the sampling container temperature are also essential for AAC sampling bags. The temperature data will be collected by the sensors near the sampling bags.

The software shall also transmit data to the ground so that the team can monitor the conditions of the experiment in real time. Telecommand is also needed to overwrite pre-programmed sampling scheduled in case of automation failure or to mitigate unexpected changes in the flight path and reached altitudes. 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 the Arduino reads from the sensors through the analog, I2C, and SPI interfaces. The sensors provides temperature, pressure and airflow data. The acquired data will be time-stamped and stored in the on-board SD card 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 41 visually explain the process flow.
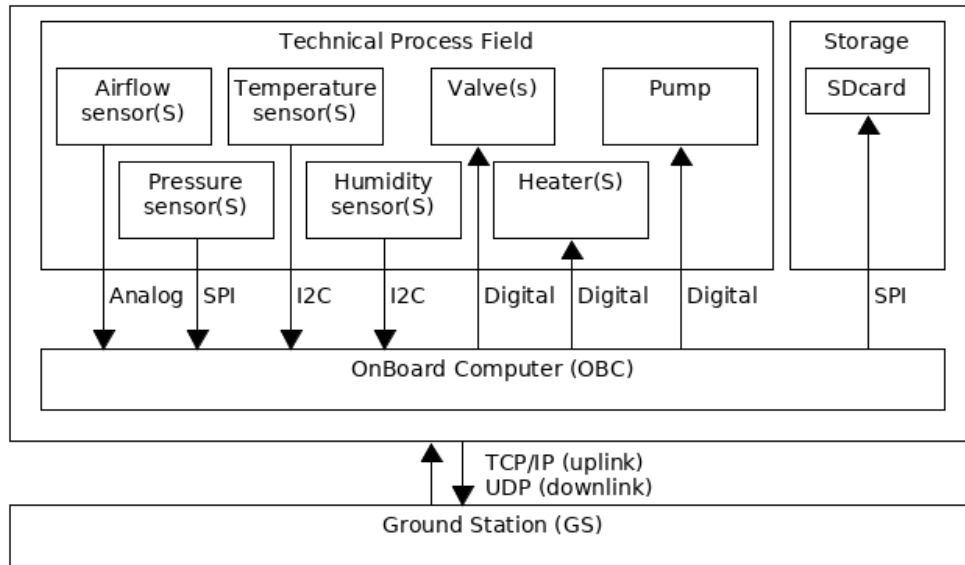
Figure 41: The Process Overview of the Experiment.

(b) General and Safety related concepts

The 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 problem in the software. During normal operations, the software will set flags when done with their task. When all the flags have been set the watchdog gets reset. If any task fails to set the their flag before the watchdog elapses, the system resets, 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 confirmation 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.

(c) Interfaces

Table 21 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	SPI	Arduino SPI and Digital Pins
Temperature sensors-OBC	I2C	Arduino I2C
Airflow sensor-OBC	Analog	Arduino analog pin
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 21: 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 up-linked data packet will have the same structure, with header followed by commands and ended with FCS.

The protocol that has been chosen are UDP for telemetry and TCP for telecommand. The UDP is used to prevent software getting stuck waiting for handshake from the ground if the connection is temporarily lost.

The telecommand contains the following services:

- Changing instrument modes
- Manually control valves, pump, and heaters

Furthermore, telemetry contains the services below:

- Data from temperature, pressure and airflow sensor
- Current instrument modes
- Instrument housekeeping data (valve, pump, and heater states)

(d) Data Acquisition and Storage
Data will be stored on the SD memory card on the Arduino Ethernet Shield using the FAT16 and FAT32 filesystems. To minimize data loss in the event of an reset we will only write to the same file in a set amount of time before closing it and open a new file. It is estimated that for the entire flight, all the sensors will produce less than 5 MB of data. The sampling rate will be fixed at 1 sampling per 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 two times per second and the total telemetry size is less than 4 MB for 10 hours of flight. On the other hand, the telecommand size

will vary based on how many subcommand is sent each time. If all of the subcommand are enabled, the total size is 128 bytes. Considering the telecommand will not be sent more than once per second, the telecommand data rate is 126 bytes/sec.

(e) Process Flow

The process flow can be explained with the mode diagram in Figure 42. The software will start with Standby Mode, in which the software will get samples from all sensors. The on-board memory card contains the default sampling schedule parameters (when the sampling will start and stop), which will be read by the software in Standby Mode. This will allow users to change the sampling schedule without changing the internal code. When the software receives negative increment of pressure changes, it will change to Normal - Ascent mode, where the software will trigger emptying of the CAC's coiled tube by opening the valves. Then, at certain altitudes, air sampling will be conducted during Ascent Phase. During Float Phase, no sampling will be conducted. The software will go to Normal - Descent mode when it detects the increment of pressure is considerably big at which point the software will sample the air by opening the valves for each bag in their designated altitude. Considering that the gondola might not have smooth ascending/descending, the mode changes will only happen if the changes exceed certain threshold. Currently, $-20\,\mathrm{Pa}$ and $20\,\mathrm{Pa}$ are considered as the threshold and might be changed depending on further analysis and testing. The experiment goes to SAFE mode approximately 500 m before the landing, and triggers all the valves to be closed. The manual mode is entered with a telecommand and left with another one. When entering the manual mode the groundstation automatically retransmits the signal for manual mode at a set interval. If the signal is not received by the OBC within a certain amount of time it leaves manual mode and enters into standby mode.
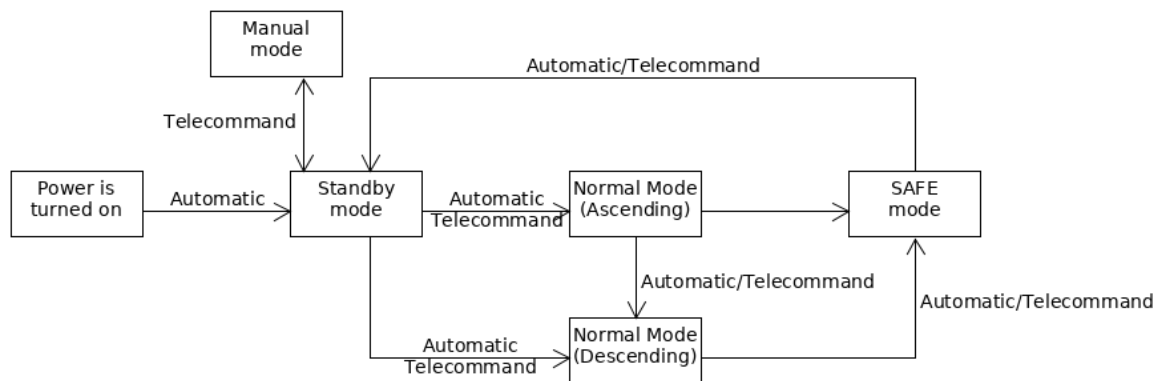

Figure 42: Process Diagram for the Modes.

In the sampling algorithm, it is necessary to keep track of the time because the bag cannot be filled fully (it might burst). A simple library is used to keep track of the time from the start of the experiment.

At the ground station the data is stored sequentially making it possible to order the received data even without a time stamp.

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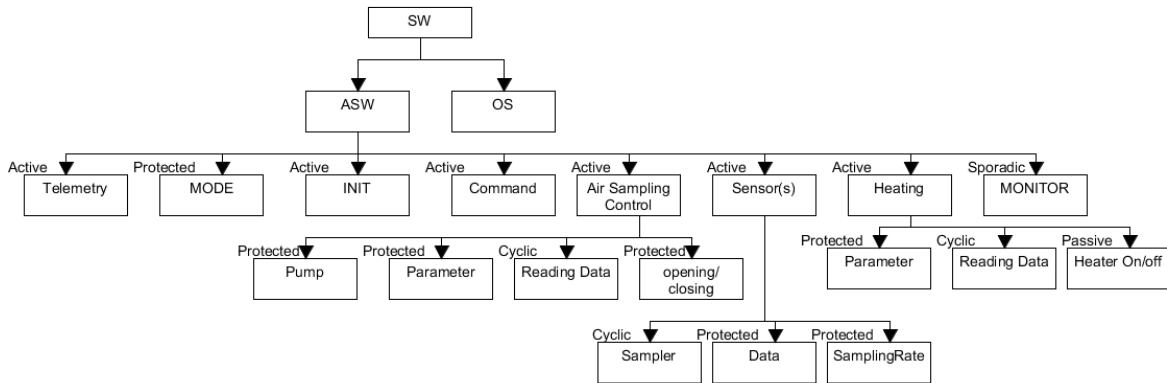## (f) Modularization and Pseudo Code

Figure 43: 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 43.

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.

The MONITOR object utilizes a watchdog timer that causes an interrupt when it reaches 0, underflow. The watchdog does not get fed directly from by the end of the different tasks. Instead the tasks sets a flag, if all the flags are set the watchdog gets reset and the countdown starts from the beginning. If the watchdog times out before all the flags are set the monitor object resets the board.

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 C.7 and C.10.

4.8.3 Implementation

The C/C++ programming language is used when programming the platform. Software's as PlatformIO IDE is used, other software will be used if necessary. The software is functioning autonomously using real-time operating system. FreeRTOS is chosen as the real-time operating system, which provides feature to split functionality into several mutual exclusive tasks. These tasks are

- The Sampler task (periodic)
- The Reading task (periodic)
- heaterTask task (periodic)
- telecommand task (sporadic)

Several libraries that are used:

- FreeRTOS_ARM.h (FreeRTOS specially port for ARM microprocessor like Due)
- ArduinoSTL.h (allows standard C++ functionality)
- RTCDue.h (keeps track of the time from the software start)
- Necessary Arduino libraries.
- Sensors libraries.

4.9 Ground Support Equipment

The purpose of the ground station is to monitor in real-time the experiment and provide manual override capability in case the experiment failed functioning autonomously. The manual override is able to control all the valves, pump, and heaters.

One personal computer will be used to connect to the E-Link through the Ethernet port. A GUI is created to display the sensors data and valves, pump states during the experiment. MATLAB GUIDE is used for the development.

The design of the ground station is responsible for receiving and transmitting data over the provided Ethernet connection. Using GUIDE to create a GUI and respective functions as a skeleton, the necessary functionality to receive, transmit and display are built accordingly. The functions are defined for each GUI element.
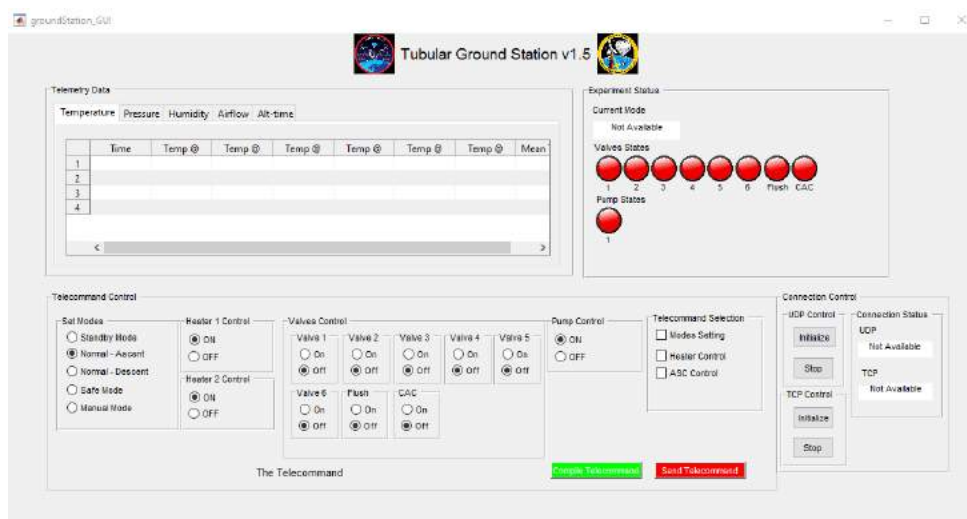
Figure 44: GUI Design for Ground Station Version 1.5.

Figure 44 shows current design of ground station GUI. Telemetry data will be shown in several tables based on the data type. The data shall be recorded and stored on the computer. The experiment status panel represents the real-time status of the experiments, the red indicator will change to green indicator if the pump or valves are open later on. On the bottom side, the telecommand control panel provides command generation for the experiment. On its right side, connection control panel has full control of the connections.

5 Experiment Verification and Testing

5.1 Verification Matrix

The verification matrix is made following the standard of *ECSS-E-10-02A.* [17]. This section does not list obsolete requirements. For a complete list of requirements that include obsolete ones, refer to Appendix N.

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

ID	Written requirement	Verification	Test number	Status
F.2	The experiment *shall* collect air samples by the CAC.	A, R	-	Pass by similarity [8]
F.3	The experiment *shall* collect air samples by the AAC.	A, T	2, 16	Analysis passed, see Section 4.4.4
F.9	The experiment *should* collect data on the air intake flow to the AAC.	A, T	24, 31, 32	Pass by similarity, testing ongoing[5]
F.10	The experiment *shall* collect data on the air pressure.	A, T	24, 31, 32	Pass by similarity, testing ongoing[5]
F.11	The experiment *shall* collect data on the temperature.	A, T	24, 31, 32	Pass by similarity, testing ongoing[5]
P.12	The accuracy of the ambient pressure measurements *shall* be -1.5/+1.5 mbar for 25°.	R	-	Pass from data sheet
P.13	The accuracy of the temperature measurements *shall* be +3.5/-3°C(max) for condition of -55°C to 150°C.	R	-	Pass from data sheet
P.23	The sampling rate of the temperature sensor *shall* be 1 Hz.	A,T	10	Analysis passed, see Section 4.8.2
P.24	The temperature of the Pump *shall* be between 5°C and 40°C.	A, T	5	Analysis passed, see Figure 38
P.25	The minimum volume of air in the sampling bags for analysis *shall* be 0.18 L at ground level.	A, T	16, 17	Pass by similarity [2]. Analysis passed, see Section H

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[5]sensor libraries are available online and used by many users

P.26	The flow rate of the pump *shall* be between 8 to 3 L/min from ground level up to 24 km altitude.	T	18	Test passed, see section 4.5.2
P.27	The accuracy range of the sampling time, or the resolution, *shall* be less than 52.94 s, or 423.53 m.	T	16	To be done
P.28	The sampling rate of the pressure sensor *shall* be 1 Hz.	A,T	10	Analysis passed, see Section 4.8.2
P.29	The sampling rate of the airflow sensor *shall* be 1 Hz.	A,T	10	Analysis passed, see Section 4.8.2
P.30	The accuracy of the pressure measurements inside the tubing and sampling bags *shall* be -0.005/+0.005 bar for 25°C.	R	-	Pass from data sheet
D.1	The experiment *shall* operate in the temperature profile of the BEXUS vehicle flight and launch.[6]	A, T	5	Verification is ongoing.
D.2	The experiment *shall* operate in the vibration profile of the BEXUS vehicle flight and launch.[6]	A, T	9	Analysis passed, see Section 4.4.1
D.3	The experiment *shall* not have sharp edges or loose connections to the gondola that can harm the launch vehicle, other experiments, and people.	R, I	-	
D.4	The experiment's communication system *shall* be compatible with the gondola's E-link system with the RJF21B connector over UDP for down-link and TCP for up-link.	A, T	8	Analysis passed, see Section 4.8.2
D.5	The experiment's power supply *shall* have a 24v, 12v, 5v and 3.3v power output and be able to take 28.8v input through the Amphenol PT02E8-4P connector supplied from the gondola.	A	-	Analysis passed, see Sections 4.2.2 and 4.5.1
D.7	The total DC current draw *should* be below 1.8 A.	A, T	10, 19, 20, 29, 33	Analysis passed, see Table 20, testing ongoing.
D.8	The total power consumption *should* be below 374 Wh.	A	-	Analysis passed, see Table 20
D.16	The experiment *shall* be able to autonomously turn itself off just before landing.	R, T	7, 10, 31, 32	Testing ongoing

D.17	The experiment box *shall* be placed with at least one face exposed to the outside.	R, A	-	Review of design passed, explained in Section 4.2.1
D.18	The experiment *shall* operate in the pressure profile of the BEXUS flight.[6]	A, T	4, 18, 30	Pump Passed Test 18, further testing ongoing
D.19	The experiment *shall* operate in the vertical and horizontal acceleration profile of the BEXUS flight.[6]	A, T	9, 25, 27	Analysis passed, see Section 4.1
D.21	The experiment *shall* be attached to the gondola's rails.	R	-	Review of design passed, explained in Section 4.2.1
D.22	The telecommand data rate *shall* not be over 10 kb/s.	A, R	-	Analysis passed, see Section 4.8.2.
D.23	The air intake rate of the air pump *shall* be 3 L/min at 24 km altitude.	A, T	4, 18	Initial Test passed, Test 4 ongoing.
D.24	The temperature of the Brain *shall* be between -10°C and 25°C.	A, T	5	Analysis passed, see Section 4.6.5
D.26	The AAC air sampling *shall* filter out all water molecules before filling the sampling bags.	A, T	17	Analysis passed, see Section 4.4.5
D.27	The total weight of the experiment *shall* be less than 28 kg.	R, T	3	Review of design passed, explained in Section 3.3.2
D.28	The AAC box *shall* be able to t at least 6 air sampling bags.	R	-	Review of design passed, explained in Section 4.4.5
D.29	The CAC box *shall* take less than 3 minutes to be removed from the gondola without removing the whole experiment.	R, T	12	Review of design passed, explained in Section 4.2.1
D.30	The AAC *shall* be re-usable for future balloon flights.	R, T	7, 16	Review of design passed, explained in Section 4.4
D.31	The altitude from which a sampling bag will start sampling *shall* be programmable.	A,T	10, 14	Analysis passed, see Section 4.8.2

D.32	The altitude from which a sampling bag will stop sampling *shall* be programmable.	A,T	10	Analysis passed, see Section 4.8.2
O.13	The experiment *should* function automatically.	R, T	7, 8, 10	Review of design passed, explained in Section 4.8.3
O.14	The experiment's air sampling mechanisms *shall* have a manual override.	R, T	8, 10	Review of design passed, explained in Section 4.9
C.1	Constraints specified in the BEXUS User Manual.	I	-	Verification is ongoing

Table 22: Verification Matrix.

5.2 Test Plan

5.2.1 Test Priority

As shown in Table 23, tests have been split into three different levels of priority, low, medium and high. The priority given to each test is dependent on several factors including complexity, amount of external help required and time taken.

Priority Level	Test Number	Classification
High	4, 5, 7, 10, 17	- Requires the use of external facilities which must be booked in advance and could have limited availability. - If a re-test is required the wait time could be in the order of weeks or months. - Testing could potentially break a non-spare component with a long re-order time.
Medium	2, 8, 9, 12, 16, 18, 24, 27, 29, 30	- Requires internal cooperation or multiple parts of the experiment completed to a minimum standard. - If a re-test is required the wait time could be in the order of days. - Testing could potentially break a critical component that would require re-ordering or replacing.
Low	3, 13, 14, 15, 19, 20, 25, 28, 31, 32	- Can be performed by a single department. - If a re-test is required the wait time could be in the order of hours. - Have low or no risk of breaking components.

Table 23: Table Showing the Classification of the Tests.

5.2.2 Planned Tests

The planned tests are as follows:

1. ~~Valves test.~~[6]

2. Data collection test in Table 24.

3. Weight verification in Table 25.

4. Low pressure test in Table 26.

5. Thermal test in Table 27.

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[6]Has been combined with Tests 4, 5 and 24.

6. ~~Experiment assembly and disassembly test.~~[7]

7. Bench test in Table 28.

8. E-Link test in Table 29.

9. Vibration test in Table 30.

10. Software operation test in Table 31.

11. ~~Power systems test.~~[8]

12. Experiment removal test in Table 32.

13. ~~Ground station – OBC connection test~~ [8]

14. Ground station - OBC parameters reprogram test in Table 33

15. ~~Ground station invalid commands test~~[7]

16. Sampling test in Table 34.

17. Samples' condensation test in Table 35.

18. Pump low pressure test in Table 36.

19. PCB operations test in Table 37.

20. Switching circuit testing and verification in Table 38.

21. ~~Arduino sensor operation test.~~[9]

22. ~~Arduino, pump and valves operation test.~~[9]

23. ~~Pump thermal test.~~[10]

24. Software and electronics integration testing in Table 39.

25. Mechanical structural testing in Table 40.

26. ~~Insulating foam low pressure test.~~[11]

27. Shock test in Table 41.

28. Pump operation test in Table 42.

29. Pump current in low pressure test in Table 43.

30. Sampling bag bursting test in Table 44.

31. On-board software unit test in Table 45.

32. Software failure test in Table 46.

33. Electrical component test in Table 47

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[7]Unnecessary test.
[8]Has been combined with Test 10.
[9]Has been combined with Test 24.
[10]Has been combined with Test 5.
[11]Has been combined with Test 4.

5.2.3 Test Descriptions

If a non-destructive test is not proceeding as expected *and* it is thought there is a risk to components it will be aborted. If a test is aborted for this reason an investigation must be completed to discover why it did not proceed as expected and the issue resolved before a re-test can occur.

Tests will take place on the flight model due to budget and time restrictions which prevent a test model from being created. However, if a component is broken during testing spares are available. Tests 4 and 5 will not use the entire model due to size restrictions in the chambers. Instead only critical components will be tested.

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

Test Number	2
Test Type	Software
Test Facility	LTU, Kiruna
Tested Item	Arduino, sensors, valves and pump
Test Level/ Procedure and Duration	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	August
Test Completed	NO

Table 24: Test 2: Data Collection Test Description.

Test Number	3
Test Type	Weight Verification
Test Facility	LTU, Kiruna
Tested Item	The entire experiment
Test Level/ Procedure and Duration	Test procedure: Use scales to measure the weight of the entire experiment. Test duration: 1 minute
Test Campaign Duration	1 day
Test Campaign Date	September
Test Completed	NO

Table 25: Test 3: Weight Verification Description.

Test Number	4
Test Type	Vacuum
Test Facility	IRF, Kiruna
Tested Item	Sampling System
Test Level/ Procedure and Duration	Test procedure: Take sampling system down to 20hPa and verify all systems work. If the size of the vacuum chamber is restrictive testing just the pump with the airflow and pressure sensors, one valve and one bag will suffice. Ensure valves and pump still perform as expected by checking the flow rate with the airflow sensor and visually observing the bag inflating. In addition the insulating foam will be checked to ensure it does not deform when exposed to low pressures. Test duration: 5 hours
Test Campaign Duration	1 week
Test Campaign Date	18th July, 20th July and August [12]
Test Completed	TO BE REPEATED

Table 26: Test 4: Low Pressure Test Description.

Test Number	5
Test Type	Thermal
Test Facility	FMI, Finland
Tested Item	The entire experiment
Test Level/ Procedure and Duration	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. Make sure that the Brain stays between -10°C and 25°C. Test duration: 5 hours
Test Campaign Duration	1 week
Test Campaign Date	3rd-7th September
Test Completed	NO

Table 27: Test 5: Thermal Test Description.

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[12]Testing date dependent on valve arrival. A problem arose with the order which we are in contact with the company about.

Test Number	7
Test Type	Verification
Test Facility	LTU, Kiruna
Tested Item	The entire experiment
Test Level/ Procedure and Duration	Test procedure: Assemble entire experiment and ensure all testing points and/or monitors are in place. 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	September
Test Completed	NO

Table 28: Test 7: Bench Test Description.

Test Number	8
Test Type	Verification
Test Facility	Esrange Space Centre TBC
Tested Item	The entire experiment
Test Level/ Procedure and Duration	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: 5 hours
Test Campaign Duration	2 days
Test Campaign Date	October (during launch campaign)
Test Completed	NO

Table 29: Test 8: E-link Test Description.

Test Number	9
Test Type	Vibration
Test Facility	IRF/LTU, Kiruna
Tested Item	Entire experiment
Test Level/ Procedure and Duration	Test procedure: Mount the experiment on the back of a car/trailer in the same way it will be mounted on the gondola and drive over bumpy or rough terrain. Afterwards, check the experiment for functionality and structural integrity. Test duration: 2 hours
Test Campaign Duration	1 week
Test Campaign Date	3rd - 7th September
Test Completed	NO

Table 30: Test 9: Vibration Test Description.

Test Number	10
Test Type	Software and Electronics
Test Facility	LTU, Kiruna
Tested Item	Electronics and sampling systems
Test Level/ Procedure and Duration	Test procedure: First ensure communication between ground station and OBC work. Ensure software and electronics responds well to all possible commands for all phases of the flight. Check the electronic currents, voltages at the different stages. Ensure experiment can be shut down manually. Perform simulated flight using previous BEXUS flight data. Test duration: 10 hours
Test Campaign Duration	2 days (1 day build up, 1 day test)
Test Campaign Date	August
Test Completed	NO

Table 31: Test 10: Software and Electronics Operation Test Description.

Test Number	12
Test Type	Verification
Test Facility	LTU, Kiruna
Tested Item	Entire experiment
Test Level/ Procedure and Duration	Test procedure: Mount the experiment as it would be mounted in the gondola. Using only the instructions that will be given to the recovery team a volunteer from outside of the team will remove the CAC box. A timer will be run to check how long it takes, this time should not exceed three minutes. The procedure should be simple and fast and the instructions clear. Test duration: 5 minutes
Test Campaign Duration	1 hour
Test Campaign Date	September
Test Completed	NO

Table 32: Test 12: Experiment Removal Test Description.

Test Number	14
Test Type	Software
Test Facility	LTU, Kiruna
Tested Item	Ardunio, ground station
Test Level/ Procedure and Duration	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	25th August
Test Completed	NO

Table 33: Test 14: Ground Station-OBC Parameters Reprogram Test Description.

Test Number	16
Test Type	Verification
Test Facility	LTU, Kiruna
Tested Item	Sampling System
Test Level/ Procedure and Duration	Test procedure: Once the sampling system has been connected, including the bags, lay or hang the system out on the bench. The valves will be opened and closed in series and the pump switched on and off using the Arduino to control them. The Arduino should be supplied simulated pressure sensor readings so that the system will run the sampling points as it would during flight. The bags will be monitored to check that they are inflating as expected. Airflow and static pressure readings that give the pressure from inside the bags will be used to verify that sampling is occurring properly. Test duration: 3 hours.
Test Campaign Duration	2 days (1 day build-up, 1 day testing)
Test Campaign Date	August ^{12}
Test Completed	NO

Table 34: Test 16: Sampling System Verification.

Test Number	17
Test Type	Verification
Test Facility	FMI
Tested Item	Sampling bags
Test Level/ Procedure and Duration	Test procedure: All valves, bags and tubes must be connected. Then the entire system needs to be flushed the same way it will be for the flight. After flushing, the bags will then be filled with a gas of known concentration. The bags will then be left outside for 6, 14, 24 and 48 hours. Using 8 bags in total with two bags for each time duration. After each time duration two bags will be removed and analyzed using the Picarro analyzer. The concentration of gases found inside the bags will be compared to the initial concentration of the air placed in the bags. If the concentration changes then the sampling bags must be retrieved and analyzed before that amount of time has elapsed for the samples to be preserved. Test duration: 3 days.
Test Campaign Duration	5 days
Test Campaign Date	7th-9th May AND 3rd-7th September
Test Completed	TO BE REPEATED

Table 35: Test 17: Sampling Bags' Holding Times and Samples' Condensation Verification.

Test Number	18
Test Type	Vacuum
Test Facility	IRF, Kiruna
Tested Item	Pump
Test Level/ Procedure and Duration	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	1st - 2nd May
Test Completed	YES

Table 36: Test 18: Pump Low Pressure Test.

Test Number	19
Test Type	Electronics
Test Facility	LTU, Kiruna
Tested Item	Electronics PCB
Test Level/ Procedure and Duration	Test procedure: As PCB board is soldered check using a multimeter for shorts. Check that the circuit operates as intended by checking the voltages and currents at test points using a multimeter. Test duration: 1 hour
Test Campaign Duration	recurrent
Test Campaign Date	July
Test Completed	NO

Table 37: Test 19: PCB Board Operations Check.

Test Number	20
Test Type	Electronics
Test Facility	LTU, Kiruna
Tested Item	Valves, Arduino, Switching Circuit
Test Level/ Procedure and Duration	Test procedure: Beginning on a bread board the switching circuit will be set up connecting one end to a 3.3 V supply and another to a 24 V supply. It will be checked that turning the 3.3 V supply on and off also turns the valve/heater/pump on and off. The current draws during switching will also be monitored to check that they are in line with what the DC-DC/gondola power that can be provided. Once the circuit is working in this configuration the 3.3V supply will be switched for the Arduino and the 24 V supply to the DC-DC and the test repeated. When the circuit is working on bread board it can then be soldered onto the PCB. As it is soldered onto the PCB each switch should be checked. Finally once all switches are soldered onto the PCB a check should be made on the whole switching system that it turns on and off all components on command. Test duration: Recurrent
Test Campaign Duration	2 months
Test Campaign Date	July and August
Test Completed	ONGOING

Table 38: Test 20: Switching Circuit Testing and Verification.

Test Number	24
Test Type	Verification and integration
Test Facility	LTU, Kiruna
Tested Item	All electronics, ground station and Arduino
Test Level/ Procedure and Duration	Test procedure: Once the electronics is at minimum in a breadboard state it will be tested with the software. This will begin with sensor checks. The Arduino will be connected to the sensors and performance checked. Once the switching circuits have been completed for the valves, pump, and heaters the software which controls how these components turn on and off will be tested. If any of the responses from the electronics are not what was expected from the input from the software then the electronic connections will be checked and the software refined and the test will repeat. These tests will begin on bread board electronics and continue as the electronics are fixed into their final positions. In addition as the software will continue to be developed until 15th September these tests will repeat to ensure that performance continues to be as expected. Test duration: Recurrent
Test Campaign Duration	Until 15th September
Test Campaign Date	Recurrent
Test Completed	ONGOING

Table 39: Test 24: Software and Electronics Integration Testing.

Test Number	25
Test Type	Verification
Test Facility	LTU, Kiruna
Tested Item	Mechanical box structure
Test Level/ Procedure and Duration	Test procedure: The mechanical structure will be tested under different loads to ensure it can withstand the expected stresses and strains during flight regarding different g-loads. This test will consist in a non-destructive static stress test with progressive loads located at the top of the CAC and AAC boxes. Test duration: 2 days
Test Campaign Duration	1 weeks
Test Campaign Date	August
Test Completed	NO

Table 40: Test 25: Structural Test.

Test Number	27
Test Type	Mechanical
Test Facility	LTU, Kiruna
Tested Item	Mechanical interfaces
Test Level/ Procedure and Duration	Test procedure: The mechanical interfaces will be tested under different loads to ensure they can withstand the expected stresses and strains during flight. This is done by dropping the whole box from a certain height were this is a mattress or soft surface underneath it. Maximum height 1 m. Test duration: 2 hours
Test Campaign Duration	2 days
Test Campaign Date	August
Test Completed	NO

Table 41: Test 27: Shock Test.

Test Number	28
Test Type	Electrical
Test Facility	LTU, Kiruna
Tested Item	Pump
Test Level/ Procedure and Duration	Test procedure: The pump will be tested to check its current draw under normal, turn on, entrance covered and exit covered conditions. Test duration: 1 hour
Test Campaign Duration	1 day
Test Campaign Date	24th April
Test Completed	YES

Table 42: Test 28: Pump Operation Test.

Test Number	29
Test Type	Electrical
Test Facility	IRF, Kiruna
Tested Item	Pump
Test Level/ Procedure and Duration	Test procedure: The pump will be tested to check its current draw as the outside air pressure is changed. Test duration: 2 hours
Test Campaign Duration	1 day
Test Campaign Date	4th May
Test Completed	YES

Table 43: Test 29: Pump Current in Low Pressure Test.

Test Number	30
Test Type	Verification
Test Facility	IRF, Kiruna
Tested Item	Sampling Bags
Test Level/ Procedure and Duration	Continuously pump air into the sampling bags until the sampling bags burst. If the tested sampling bag does not burst after 3 minutes of continuous pumping, remove the sampling bag from the pressure chamber and leave at rest to check if it will burst within 48 hours. If bursting occurs in the chamber while the sampling bag is being pump then observe and characterize its impact to assess whether a similar bursting risks damaging the sampling bag's surrounding in the experimental setup. If the bursting occurs during the 48 hours rest period then observe and characterize the damage/rupture on the sampling bag to assess whether a similar bursting risks damaging the sampling bag's surrounding in the experimental setup. Test duration: 3 minutes to 48 hours.
Test Campaign Duration	3 days
Test Campaign Date	1st, 2nd and 4th May
Test Completed	YES

Table 44: Test 30: Sampling Bag Bursting Test Description.

Test Number	31
Test Type	Verification
Test Facility	LTU, Kiruna
Tested Item	On-board software
Test Level/ Procedure and Duration	Test procedure: Unit test cases are build to test the functionality of the software. Test duration: Not Applicable.
Test Campaign Duration	Until software freeze date.
Test Campaign Date	May-September
Test Completed	ONGOING

Table 45: Test 31: On-board Software Unit Test Description.

Test Number	32
Test Type	Software
Test Facility	LTU, Kiruna
Tested Item	On-board software and Arduino
Test Level/ Procedure and Duration	Test procedure: Test failure possibilities in the software. Micro-controller re-sets during auto-mode. Communication loss at inconvenient moments such as when changing mode, when sending a command, when receiving data whilst sampling. Simulate loss of SD card during flight. Test duration: 1 hour
Test Campaign Duration	Recurrent
Test Campaign Date	July and August
Test Completed	ONGOING

Table 46: Test 32: Software Failure Test

Test Number	33
Test Type	Electrical
Test Facility	LTU, Kiruna
Tested Item	Electrical Components
Test Level/ Procedure and Duration	Test procedure: Connect components on breadboard as part of the schematic and test them partwise. Check the resistances required Test duration: 3 hour
Test Campaign Duration	2 weeks
Test Campaign Date	21st-22nd July and 4th-5th August
Test Completed	ONGOING

Table 47: Test 33: Electrical Component Testing.

5.3   Test Results

The results shown here provide the key information obtained from testing. A full report for each test can be found in Appendix O.

5.3.1   Test 28: Pump Operations

It was found that when the power supply was switched on the current went up to 600 mA for less than one second. It then settled to 250 mA. By covering the air intake, simulating air intake from a lower pressure, the current drops to 200 mA. By covering the air output, simulating pushing air into a higher pressure, the current rises to 400 mA.

Therefore the power for each of these conditions is 14.4 W at turn on, 6 W in normal use, 4.8 W when sucking from low pressure, 9.6 W when pushing to high pressure.

5.3.2   Test 18: Pump Low Pressure

The pump was tested at low pressure using a small vacuum chamber down to 10 hPa. Flow rates were recorded from 30 hPa, the expected highest sampling altitude.

The results can also be seen in Table 70 and Figure 138. Note that the results should be considered an approximation due to the lack of equipment such as flow-meters that would have made this test more precise.

Altitude(km)	Pressure Start(hPa)	Pressure End(hPa)	Time(sec)	Flow Rate(L/min)
24	30	23	60	3
17	87	80	53	3.4
11	220	190	37	4.9

Table 48: Table Showing the Time Taken Until the 3 L Bag Stopped Expanding at Various Different Pressures.
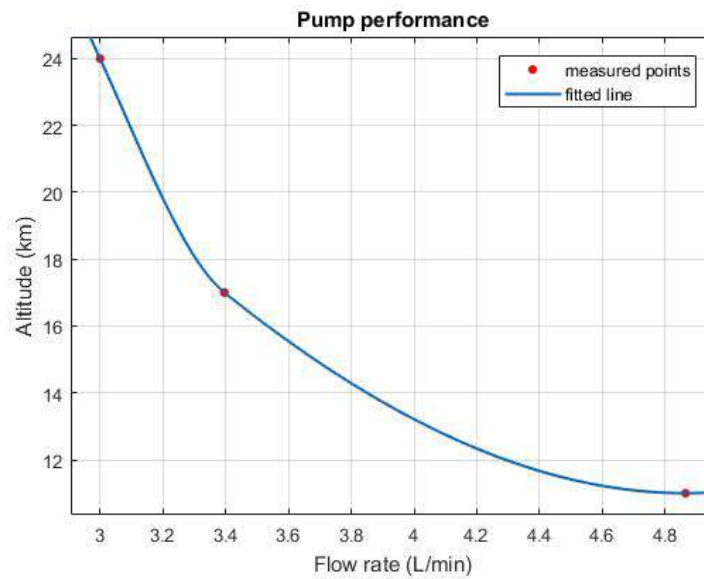
Figure 45: Obtained Pump Performance at Low Pressure.

5.3.3 Test 30: Sampling Bag Bursting

A sampling bag was placed in a small vacuum chamber connected to the pump and the pump was run for 3 minutes with a full bag to see how the bag reacted.

It was found that there are two potential failure modes. The first is a slow leakage caused by damage to the bag seal and the second is a rapid failure of the bag seal leading to total loss of the sample.

It can be concluded that, as long as the bags are well secured to the valves at the bottom and through the metal ring at the top, bag bursting during flight would not cause damage to any other components on board. Even during the more energetic burst that occurs from continuous pumping the bag remained fixed to the valve connection and experienced no fragmentation. The consequences of a single bag burst would be limited to loss of data and a disturbance to audio frequencies.

5.3.4 Test 29: Pump Current under Low Pressure

In general it was found that decreasing the pressure, or increasing the altitude, lead to a decrease in pump current draw. The full results can be seen in Table 71.

Altitude (km)	Pressure (hPa)	Into Bag Current (mA)	Into Seal Current (mA)
20	57	140	138
18	68	150	141
16	100	161	146
12	190	185	175
9	300	-	200
6	500	-	242
0	1013	-	218

Table 49: Table Showing How the Current Draw of the Pump Changed With Outside Air Pressure for Two Different Conditions. The First Pumping Into a Sampling Bag and the Second Pumping Into a Sealed Tube.

From the table it can be seen that the current draw is higher during the bag filling than during the sealed case. As the experiment will sample between 11 km and 24 km it can be concluded that the highest current draw will occur during the 11 km altitude sample and can be expected to be around 200 mA.

5.3.5 Test 17: Sampling bags' holding times and samples' condensation verification

The main objective of this test was to flush eight 1 L sampling bags with nitrogen, the same way it will be done for the flight. After the flushing is done, fill them with a dry gas and leave them outside for 6, 14, 24 and 48 hours. Then analyze two sampling bags after each time duration and see if the concentration of gases inside has changed.

After analyzing the sampling bags the obtained results are presented in Figure 150.
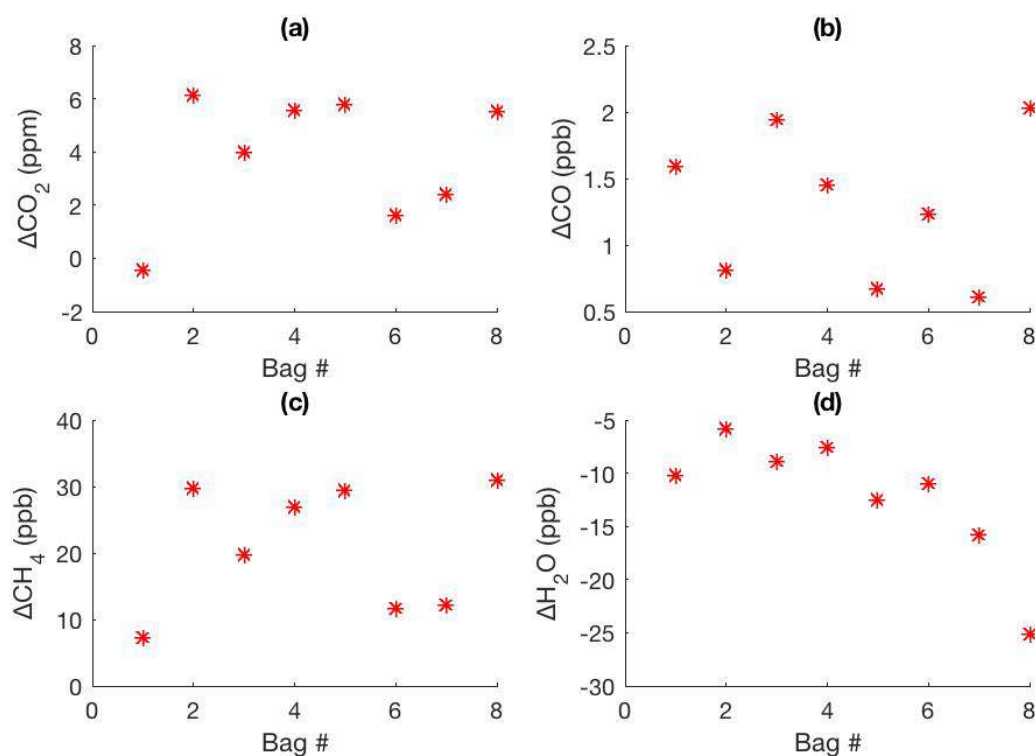
Figure 46: Obtained Variation in Concentration for (a) CO_2 in ppm, (b) CO in ppb, (c) CH_4 in ppb and (d) H_2O in ppb.

It should be mentioned that the results were not at all what was expected. If the sampling bags held the gases for 48 hours, the analyzed concentration should have been the same as the dry gas used to fill them or the variation should have been smaller.

A possible explanation for this results could be that the emptying of the sampling bags was not done rigorously enough and that some air/nitrogen was left inside which diluted in the dry gas and changed the concentrations. This effect is even increased due to the smaller size of the used sampling bags (1 L instead of 3 L). This would also explain why the results don't follow any pattern.

The general outcome of this test is that the team has realized that the flushing of the sampling bags is a very delicate process. This test will be repeated but using the set-up described in Section 4. This test has also been useful to decide that the flushing of the sampling bags should be done with dry gas instead of nitrogen in order to minimize the effects of the nitrogen diluting in the samples.

5.3.6   Test 4: Low Pressure

The same vacuum chamber was used as in Tests 18 and 29. The Styrofoam was measured on each side before it was placed in the chamber. It was then taken down to 5 hPa and held

there for 75 minutes. It was then removed and the sides were measured again. It was found that there was no significant change in dimensions. The results can be seen in Table 72.

Side	Before (cm)	After (cm)
A	9.610	9.580
B	9.555	9.550
C	9.560	9.565
D	9.615	9.610
E	9.615	9.615
F	9.555	9.550
G	9.605	9.605
H	5.020	5.020
I	5.025	5.025
J	5.015	5.015
K	5.020	5.025

Table 50: Styrofoam Size Before and After Vacuum.

As some sides are measured slightly bigger after and some slightly smaller it is thought this is due to the measuring technique and not due to changes in the Styrofoam. It is thought the result from side A could be due to deforming the Styrofoam with calipers or a misread original length.

The pump and the airflow sensor were connected together and tested at 16 different pressures. Due to some issues in the data logging with time stamping it is not possible to verify the pump performance until this issue is resolved. A re-test will be made as soon as possible.

5.3.7 Test 20: Switching Circuit Testing and Verification

This has begun on breadboards with LEDs replacing the valves until the valves arrive. So far DC-DC's have been set up and tested. Sensors have been connected electronically and the next step is to get them to communicate with the Arduino. Mosfets connecting to the pump and the heaters have been tested for switching on and off with good results.

5.3.8 Test 32: Software Failure

So far testing has revealed that losing the SD card does not interrupt ground station data, it just means no data will be written to the SD card. However, if you reconnect the SD after removing it currently it will not connect back to the SD card and it as if the SD card has been permanently lost.

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 51 below is based on the design presented in Section 4.4.

	CAC	AAC	TOTAL
Experiment mass [kg]	12.08	12.37	24.45
Experiment dimensions [m]	0.23 x 0.5 x 0.5	0.5 x 0.5 x 0.4	0.73 x 0.5 x 0.5
Experiment footprint area [m^2]	0.115	0.25	0.365
Experiment volume [m^3]	0.0575	0.1	0.1575
Experiment expected COG position	$X = 23.51\ cm$ $Y = 10\ cm$ $Z = 22.57\ cm$	$X = 29.04\ cm$ $Y = 16.63\ cm$ $Z = 16.2\ cm$	$X = 26.31\ cm$ $Y = 24.99\ cm$ $Z = 19.35\ cm$

Table 51: Experiment Summary Table.

6.1.2 Safety Risks

Table 52 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
Chemical substances	Chemicals could be exposed after a hard landing	Magnesium Perchlorate filter mechanism is sealed and has been used before without any problem. In case of exposure after a hard impact, use protective goggles and gloves to avoid contact with the eyes and skin. The small quantities used for the experiment will not be a threat for the environment. Magnesium Perchlorate alone is not flammable but may cause or intensify fire in case of contact with combustible material. Therefore, the filter is made of stainless steel, which has high durability.

Table 52: Experiment Safety Risks.

6.1.3   Electrical Interfaces

Please refer to Table 53 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	1.58 kbps
	Data rate - Uplink	1.08 kbps
	Interface type (RS232, Ethernet)	Ethernet
Power system: Gondola power required? Yes		
	Peak power (or current) consumption:	32 W
	Average power (or current consumption)	21 W
Power system: Experiment includes batteries? No		

Table 53: Electrical Interface Table.

6.1.4   Launch Site Requirements

The experiment needs some preparations before the flight. For that reason, the team will need a room with a big table to place the Picarro analyzer, with some extra space for all the interfaces between the analyzer and the CAC system, as well as the AAC system. A laptop PC will be used to monitor the experiment. Therefore, a desk and a chair are needed for this station. A total of 16 chairs need to be rented: 13 chairs for all members of the TUBULAR Team and an additional three 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 rectangular 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 details see Section 4.4. The current location of the experiment in Figure 47 is the one arranged with REXUS/BEXUS Coordinators during the Training Week in Esrange.
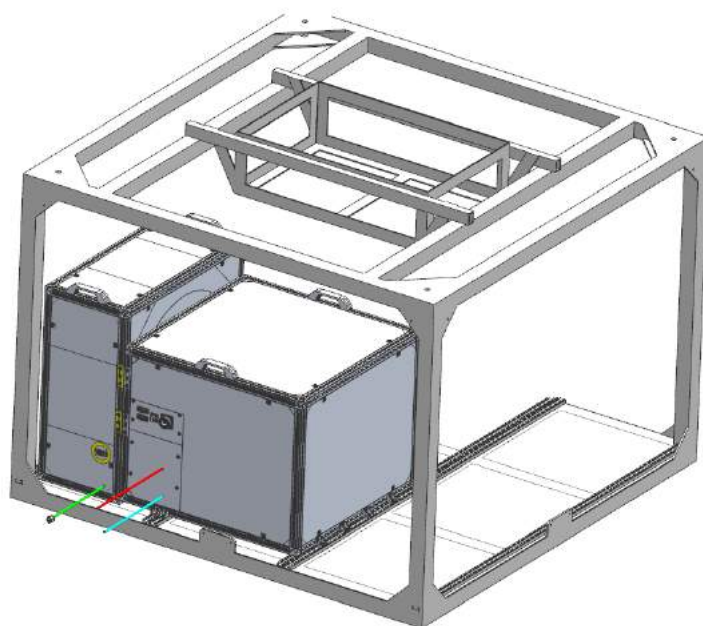
Figure 47: Example of Experiment Box Accommodation Inside the Gondola.

6.2 Preparation and Test Activities at Esrange

The ground station laptop PC will need to be put in place and set up so it is operational. The communication through E-link with the experiment shall be tested. The air sampling schedule on the SD card has to be checked before flight.

In the preparation phase magnesium filters will be prepared. These are short (7 cm) lengths of stainless steel tubing that will be filled with fresh magnesium perchlorate powder [3]. One will be attached to the inlet of the CAC tubing, to ensure that no moisture enters the tubing during testing or sampling. The magnesium perchlorate powder will be loosely packed to make sure that the air flow is not blocked. Stone wool will be placed at both ends of the tube to prevent the powder escaping from the filter.

The same set-up will be used for the AAC. As stratospheric air is dry the risk of moisture entering the system during sampling is very low however, the team decided to use one to reduce the risk of condensation in the samples after landing.

The day before the flight, both CAC and AAC have to go through some preparations. For the CAC, the coiled tube will be flushed and filled with a fill gas. A fill gas is air with a spike of a known gas, for example CO. During the flushing process the coiled tube and solenoid valve and the exit tube will be flushed separately. The magnesium perchlorate filter will not be flushed because it is not necessary. In the flushing process the quick connectors at outlet and inlet will be connected to the fill gas bottle and Picarro analyzer respectively. A fill gas will then flow through the coiled tube all the way to the Picarro. It will be flushed over night at a flow rate of 40 ml/min to ensure unknown gases inside the tube will be removed. Meanwhile on other hand the solenoid valve and the exit tube will be flushed manually. The outlet and inlet will be sealed while the gas is still running through the CAC and therefore the CAC will be filled. Thereafter it will be attached to remaining components such as the magnesium perchlorate filter, solenoid valve and exit tube. At this stage the CAC is ready for the flight.

A pre-launch checklist in Appendix D, was made to assure that the flight preparations will be done thoroughly.

For the AAC all the bags will be cleaned by flushing them with a dry gas the night before the flight. The dry gas is extracted from the fill gas and has slightly different concentrations from the fill gas. The dry gas bottle, the vacuum pump and the AAC system, will all be connected as a system to the central valve. Using the AAC valves and the bags manual valve to control which bags are sealed and which are opened the process will go through each bag individually. The central valve's position will determine whether the dry gas or the vacuum is open. When the valve is open to dry gas the sampling bags are being filled and when it is open to vacuum they are being emptied. The flushing has to be done three times for each bag to ensure the bags are properly cleaned. A flow sensor will be placed close to the central valve, making sure that all bags will be filled with 3 L of dry gas. After the end of this procedure, when the bags are empty again, each bag will be sealed, by closing its valve, while the vacuum pump is open. The pump and the valves of the AAC system will also be cleaned by this procedure. It is anticipated this process will take around 4 hours to complete.

Once the sampling bags have been cleaned and sealed, the system of tubes between the bags and the manifold have to be flushed with the dry gas as well. Again, only one tube will be flushed at a time, using the central valve, the T-union and the solenoid valve that matches the

tube to control which tube is being flushed. The tubes have to be flushed until ten times their volume has passed through, this will be monitored with the air flow sensor. When flushing is complete the dry gas connection will be removed from the T-union and the T-union will be automatically closed (quick connector interface). The corresponding solenoid valve shall be closed at the same time the fill gas is disconnected. The dry gas is then connected to the next tube and the same procedure follows. After the flushing of all the tubes is complete, and the system is sealed, the pump will be started with the flushing valve open, to flush the AAC system. At the end, the pump will be shut off, the flushing valve will be closed, and the AAC will be ready for flight. Note that the manual valves of the sampling bags have to be opened before flight.

The pre-launch checklist in Appendix D will again make sure that all the steps will be done correctly and in the right order.

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.

What is more, the team has decided to clean the rest of the experiment's components, such as the Brain, as well as the structure. Doing so, any unwanted particles released during the experiment's construction, will be removed avoiding these particles to enter the pneumatic system and thus contaminating the collected samples. For that reason, an appropriate device for small and sensitive components, such as a vacuum cleaner or a machine that blows air, will be used. If this is not possible, then the experiment will be cleaned manually with a dust cloth, considering that this cleaning procedure is not of high need as the cleaning of the coil or the bags. What is more, the building of the experiment will take place in a lab, which is a clean environment. Therefore this action will be done once before the flight, and the procedure may change if another, more effective way of cleaning is found. It is yet to be decided whether this procedure will be done the day before the flight or some day earlier.

6.3   Timeline for Countdown and Flight

Table 54 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 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 54 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-3H	0	Experiment is switched on external power
T-3H	0	Experiment goes to Standby mode
T-1H	0	Experiment switches to internal power
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
T+∼1H	∼18 km	Take air samples with AAC until ∼24 km
T+∼1.5H	∼25 km	Float 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 10 km above ground
T+3.5H	∼10 km	Experiment goes to SAFE mode (all valves are closed)

Table 54: Countdown and Flight Estimated Timeline.

6.4 Post Flight Activities

6.4.1 CAC Recovery

It is important that the CAC is recovered as quickly as possible. The experiment has been designed so that the recovery team can easily remove the AirCore in the CAC box from the gondola without having to remove the entire experiment. This is to facilitate possible transportation back to Esrange via helicopter.

This quick recovery is important to minimize the length of time in which mixing of the gas occurs in the collected CAC sample. The sample should be analyzed within five to six hours after the experiment lands. At PDR it was discussed that the CAC box could be brought back to Esrange on the helicopter instead of the truck. This situation would be preferable for TUBULAR Team. The FMI team will arrive at Esrange one or two days before the launch with all the necessary equipment for pre-flight flushing and post-flight analysis. Having the FMI team at Esrange will give additional time for them to install and calibrate their lab equipment and also allow them to proceed faster with the analysis process as soon as the CAC is returned to Esrange.

Detailed instructions are provided on how to remove the CAC box. In addition, instructions are 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.

Recovery Checklist

- Insert the three plastic plugs to the outlet of the three tubes. The plastic plugs will be provided to the recovery team.

- Unplug the gondola power cord from the AAC box. Circled with YELLOW paint.

- Unplug the E-Link connection from the AAC box. Circled with YELLOW paint.

- Unplug the D-Sub connector from the CAC Box. Circled with YELLOW paint.

- Unscrew 6 screws in the outside face of the experiment. Painted in YELLOW.

- Unscrew 6 screws in the inside face of the experiment. Painted in YELLOW.

- Remove the CAC Box from the gondola. Handles located at the top of the box.

6.4.2 Analysis Preparation

To prevent ambient air moisture entering into the analyzer, the Picarro analyzer has to keep working during the flight. After the CAC has been flushed a calibrating gas will be connected to the analyzer and keep running through it until the CAC analysis. The reason this is done is because it is necessary that the readings of calibrating gas stabilize before starting the analysis and the presence of moisture makes this stabilization slower. Having the analyzer running during flight saves precious time as it makes possible to start the analysis as soon as the CAC is recovered.

7 Data Analysis and Results

7.1 Data Analysis Plan

7.1.1 Picarro G2401

The analyzer that will be used is the model Picarro G2401. It uses near-infrared Cavity Ring Down Spectroscopy (CRDS) technology and is capable of measuring four atmospheric trace gases simultaneously and continuously (CO, CO_2, CH_4, H_2O).

The CRDS technique's basic principle is shown in Figure 48. Light from a semiconductor diode laser is used. There is an optical cavity filled with the gas that has to be analyzed and the aim is to determine the decay time of the diode laser light. As it can be seen in Figure 48, the sample gas is introduced in a cavity with three high-reflectivity mirrors. When the laser is shut off, the light that was circulating in the cavity decays with a characteristic time which is measured. If the wavelength of the injected light does not match any absorption feature of any gas in the cavity, the decay time is dominated by mirror loss and it is very long. On the other side, when the wavelength of the injected light is resonant with an absorption feature of a species in the cavity, the decay time is short and decreases as the reciprocal of the species concentration.
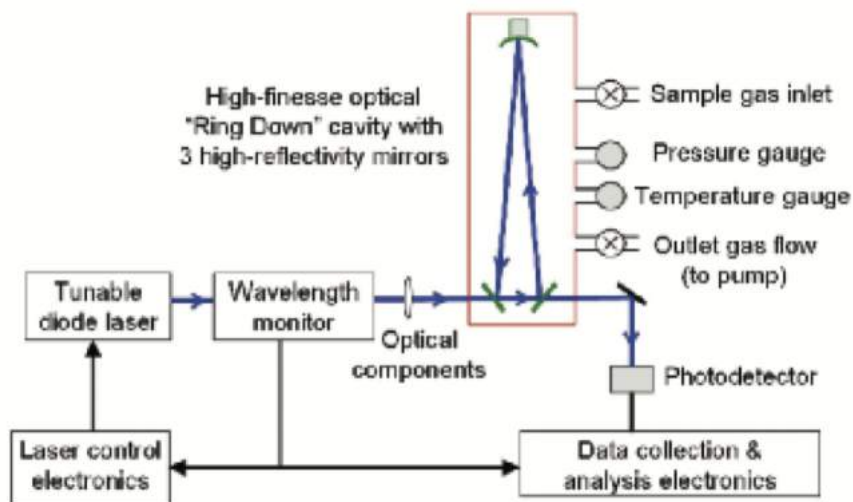
Figure 48: Schematics of CRDS Analyzer Showing Optical Cavity and Sample Gas Flow [15].

Figure 49 shows the back of the analyzer with gas supply, electrical and computer connections. The analyzer can be configured to deliver data in different formats: digital or analogue. When the main power is turned on the analyzer will automatically start, including the Graphical User Interface (GUI).
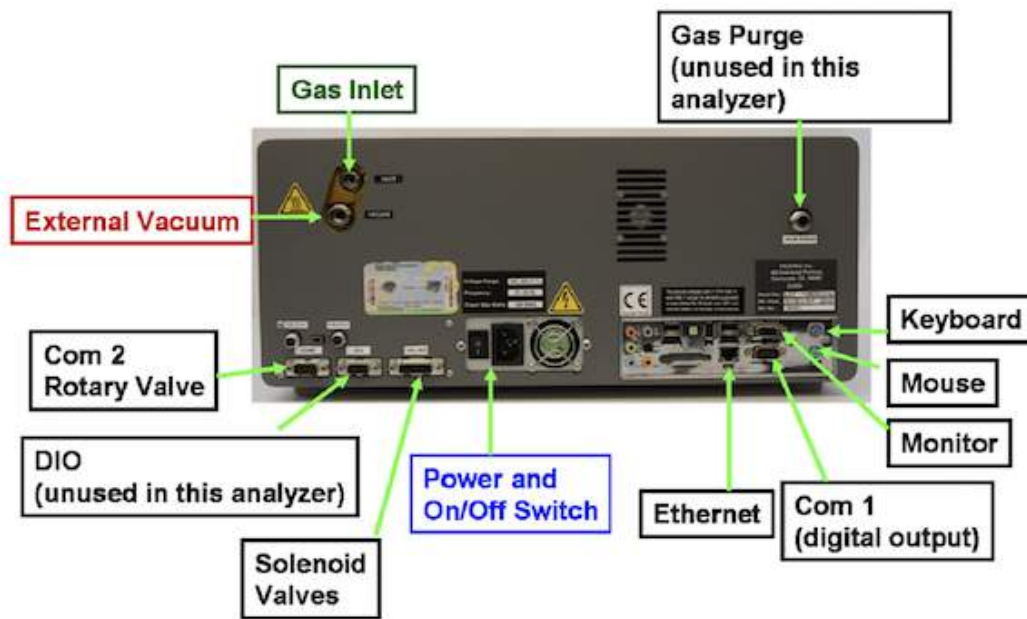
Figure 49: Back of Picarro G2401 Analyzer Showing Gas Supply, Electrical and Computer Connections [9].

Before the Picarro analyzer is ready for analysis, it is necessary to run a calibrating gas through it in order to remove moisture inside and to have stable measurements to compare with. Figure 50 shows the Picarro set up at FMI in Sodankylä. A three way valve controls which is the gas flowing into the analyzer. The tube labelled as "AIRCORE" is the one to be connected to the sample, either sampling bags or CAC. The tube labelled as "PICARRO" is the one that goes to the Picarro's inlet and the third tube, without a label, is connected to the calibrating gas bottle. This set up allows easy changing between the samples, dry gas and fill gas with the calibrating gas without getting moisture inside.
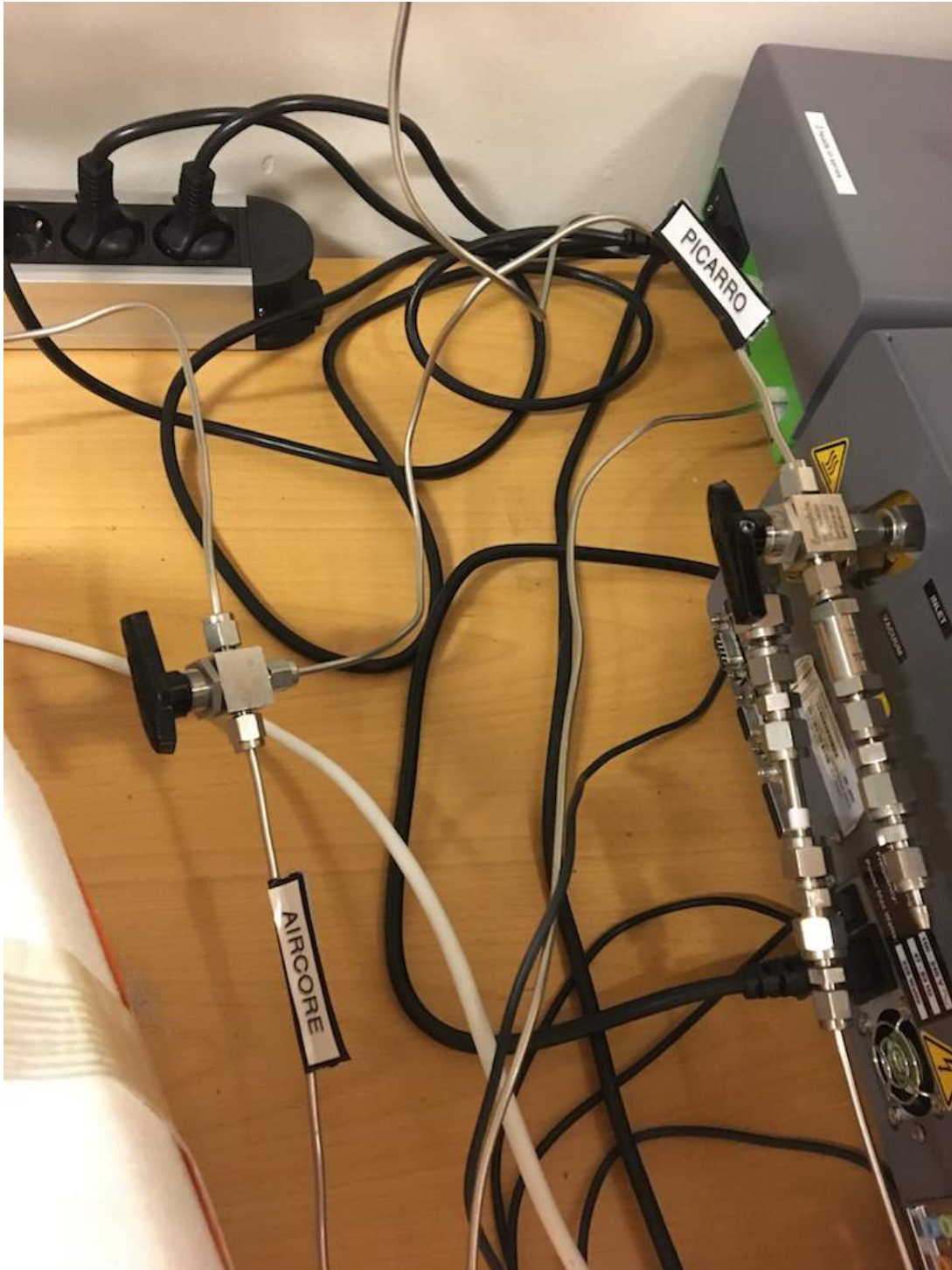
Figure 50: Picarro Set-up Connections at FMI in Sodankylä.

Figure 51 shows the Picarro GUI during analysis. From top to bottom: CO_2 ppm, CO ppm, CH_4 ppm and cavity pressure. These options can be changed during analysis as it only means that those are the ones being displayed. Figure 51 was taken minutes after a change between dry gas-sample had been done so a change in the concentrations of CO_2 and CH_4 can be

easily appreciated. The Picarro analyzer does not only give information about the displayed parameters, all the data is saved in a .dat file to be analyzed afterwards. The most relevant logged parameters are time, date, ambient pressure, cavity pressure, cavity temperature, CO concentration, CO_2, CH_4 and H_2O normal and dry concentration. The dry concentration is a correction done automatically by the Picarro analyzer taking into account the moisture inside the analyzer.
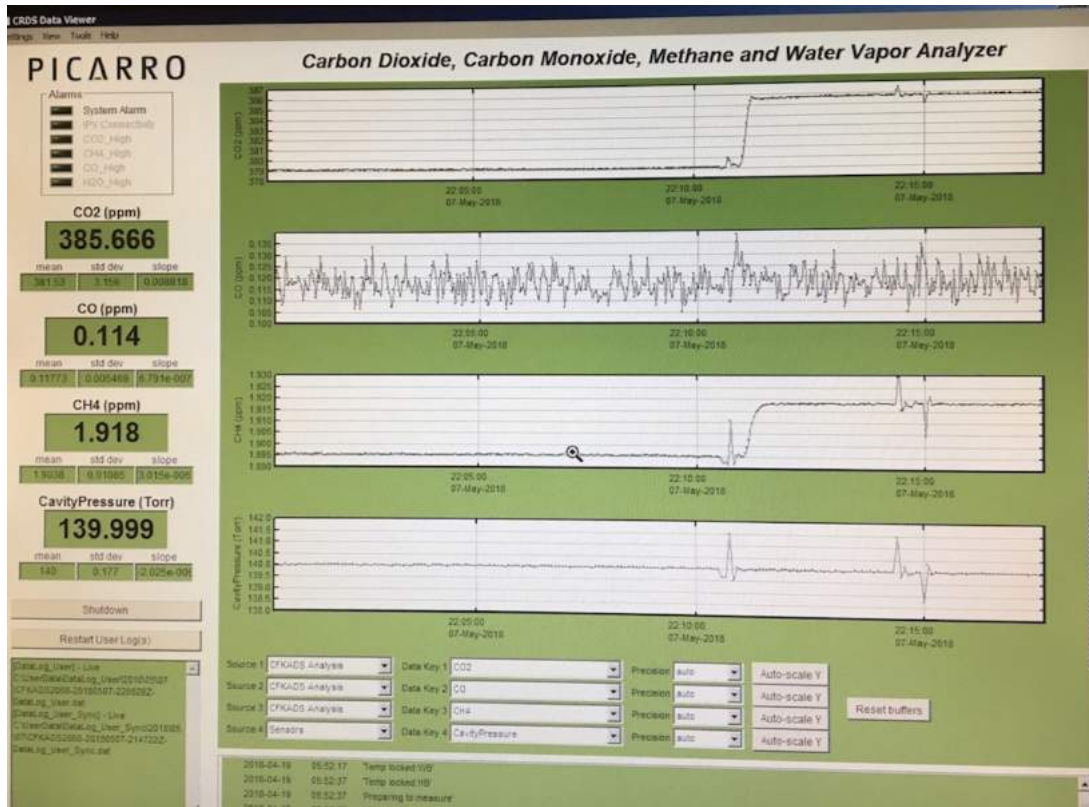
Figure 51: Picarro Graphical User Interface. From Top to Bottom: CO_2 ppm, CO ppm, CH_4 ppm and Cavity Pressure.

7.1.2 Analysis Strategy

As it has been mentioned in the previous section, during the flight, calibrating gas will be flowing through the Picarro G2401. After the flight, the collected samples from the CAC and the AAC will be analyzed. As it is shown in Figure 52, the end of the CAC tube that remains closed during sampling will be connected to the Picarro inlet. The other end of the CAC will be connected to the fill gas that will act as a push gas. As soon as this connection is done, the valve shown in Figure 50 will be switched from calibrating gas to "AIRCORE" position. Then the Picarro GUI will show a sudden drop/increase in concentrations similar to the one shown in Figure 51 due to the difference between the calibrating gas and the sample concentrations. Note that the magnesium perchlorate dryer shown in Figure 52 is removed during analysis.

AirCore analysis system
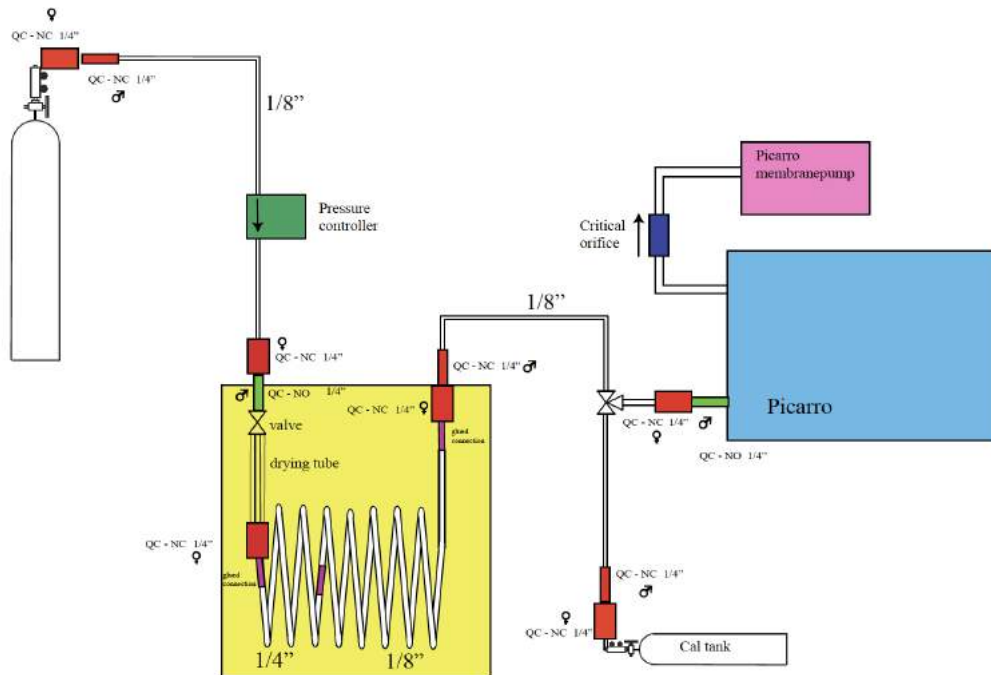
Figure 52: Schematics of CAC Analysis System [8].

The analyzer pump and the push gas help the sample to go through the analyzer. The analysis will be started from the side which contains the samples taken at higher altitudes to avoid losing resolution. The beginning and end of the sample analysis is detected due to changes in concentrations, at the beginning between calibrating gas/sample, and at the end, between sample/fill gas. Once the analysis is done, the sample taken with the CAC is stored in a sampler as seen in Figure 53. This CAC sampler is at FMI and contains fifteen separate sections. All the valves are open when the sample is introduced. Once the analysis is finished and the whole sample is in the sampler, all the valves are closed at the same time, separating the samples for different altitudes and preventing further molecular diffusion.

Figure 53: CAC Sampler with 15 Different Stages.

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,

$$PV = nRT <=> n = \frac{PV}{RT} \qquad (1)$$

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, [5]. 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

$$n_i = n^{max} \frac{t_i}{\Delta t} \qquad (2)$$

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. In the same way as for the CAC, the calibrating gas needs to be flowing through the analyzer until the moisture is minimum and the readings in concentrations are stable. Then a sampling bags system will be connected to the analyzer and a dry gas bottle, in a similar way as it was done in Test 17. The tubes connecting the sampling bags will be flushed with dry gas and when the concentrations given by the Picarro analyzer are stable, the air inside the sampling bags will go through the analyzer followed again by dry gas.

Watching at the Picarro GUI, it is easily recognizable when a sampling bag is being analyzed due to the difference in concentrations between its air and the dry gas.

Again, as for the CAC, equations 1 and 2 are going to be used to relate a specific pressure point with every Picarro measurement of the sample.

The basic working principle used by the chromatographer to obtain the concentrations is as follows:

- Have calibrating gas - sample - calibrating gas flowing through the analyzer. (It could also be the case: calibrating gas - dry gas - sample - dry gas - calibrating gas but the principle is the same).

- Identify in the GUI readings the different gases easily seen by sudden variations in the concentrations.

- Compare the calibrating gas reading with the known real value. Do this before and after the sample. This difference corresponds to the drift given by the Picarro.

- Interpolate the values of drift from before and after the sample to obtain the drift during the sample.

- Correct the readings given by the Picarro analyzer due to drift and that is the real concentration value.

NOTE: A calibrating gas is a gas that has been flowing through the Picarro analyzer multiple times and its concentration is known with accuracy. A calibrating gas has to flow before and after the samples in order to compare the readings given by the analyzer with the real value and obtain a corrected value for the samples.

7.2 Launch Campaign

7.2.1 Flight preparation activities during launch campaign

The flight preparations can be found in Section 6.2.

7.2.2 Flight performance

It is expected to receive a downlink from the gondola. All data received will be stored in the ground station computer. The estimated data across the E-link will be 7.128 MB, while the stored data onboard SD card is estimated to be 6.552 MB.

7.2.3 Recovery

If our request for quick helicopter recovery of the CAC is granted, the retrieval team will be provided a checklist, in Section 6.4.1, so they can pull out the CAC from the gondola while the AAC will be brought back with the rest of the gondola.

7.2.4 Post flight activities

Once the gondola has been brought back, the samples collected by the CAC and AAC will be analyzed.

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, CO_2, and CH_4. The profiles will present a similar pattern to that of Figure 54. The continuous profile (dashed line) belongs to the CAC while the discrete values (black dots) belongs to the AAC ([3]). Both profiles are showing a decrease in concentration of CH_2 and CH_4 with increasing altitude.
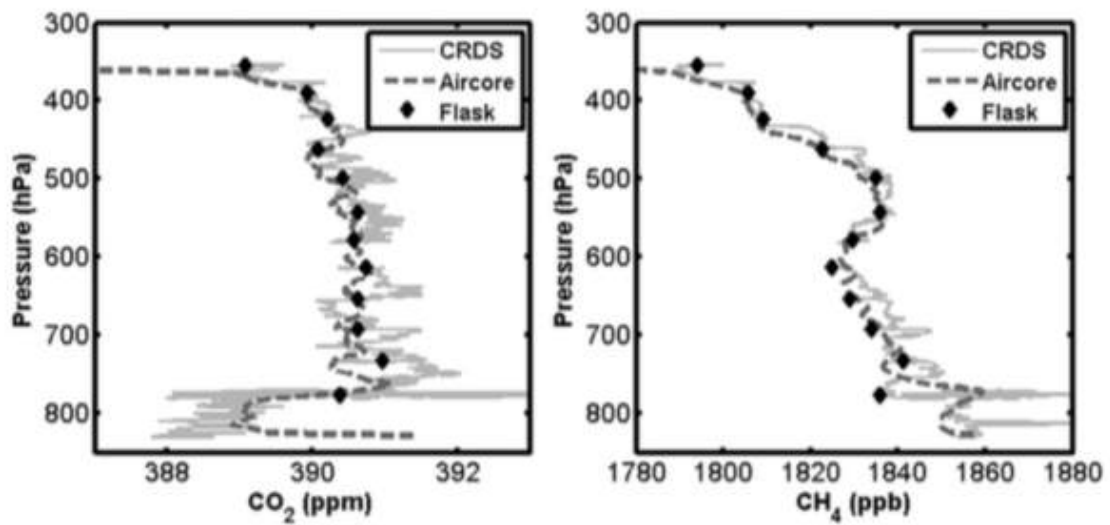
Figure 54: Pressure Profiles for (Left) CO_2 and (Right) CH_4 by Three Different Methods [3].

The experiment's goal is to achieve the highest vertical resolution possible. Since the vertical resolution is determined by the length and the diameter of the tube [5], a 300 m long tube will be used, consisting of 2 smaller tubes. One of 200 m length with 3×10^{-3} m outside diameter and 1.3×10^{-4} m wall thickness, and another one of 100 m 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 55 by Olivier Membrive [5] compares the vertical resolution that can be expected with three different AirCores.
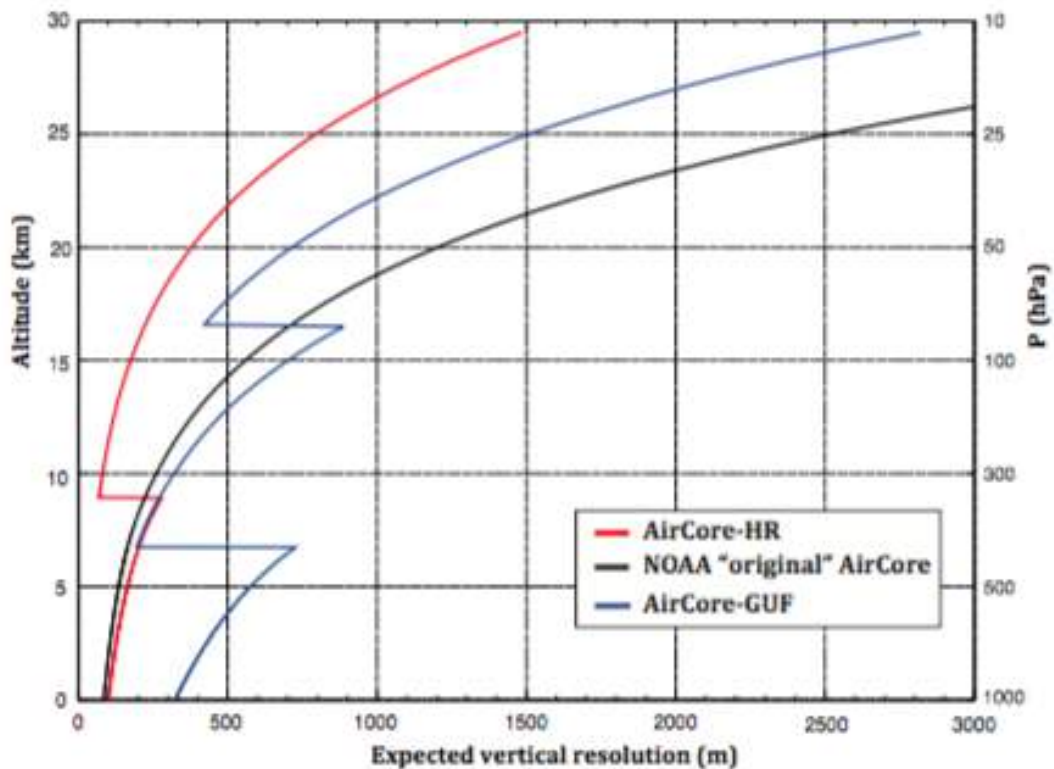
Figure 55: Comparison of the Vertical Resolutions That can be Expected with Different Air-Cores, After 3h Storage Time Before Analysis [5].

The High-Resolution AirCore-HR (red line),[5], is a combination of two tubes. One of 200 m and one of 100 m.

The NOAA 'original' CAC, [3], (black line) is a 152 m long tube and the AirCore-GUF (designed and developed at Goethe University Frankfurt), (blue line) is a combination of three tubes, 100 m 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 CAC, 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 [5]. The first term translates into the longitudinal direction, while the second one is the Taylor dispersion.

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

Finally, storage time, that is the 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 56 shows the effect of time delay between landing and analysis, on the expected vertical resolution.
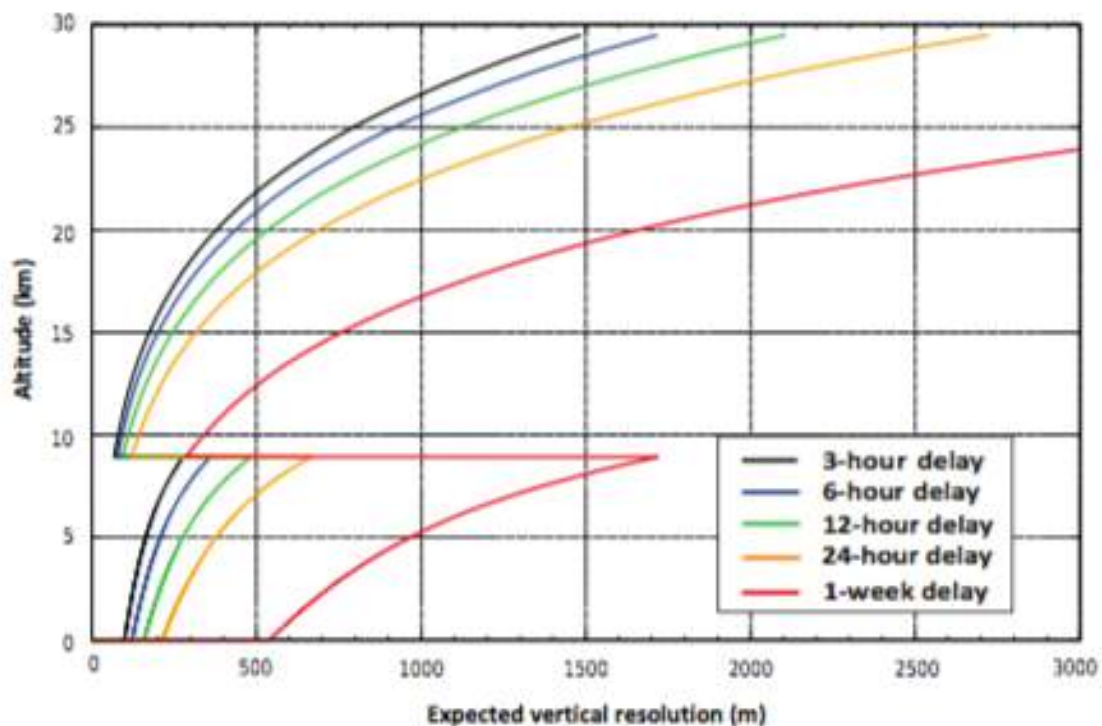
Figure 56: Expected Vertical Resolution of AirCore-HR, for a Storage Time of 3h (Black), 6h (Blue), 12h (Green), 24h (Orange) and 1 Week (Red) [5].

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 20 km the resolution decreases significantly from 300 m to 500 m for 6h and 12h of delay, respectively, [5]. 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 maximum vertical resolution for the AAC is capped at 500 m. This will be achieved assuring the airflow intake rate. For Ascent Phase, a nominal speed of 5 m/s is considered, which means that it will take 100 seconds to fill up a 3 L sampling bag while ascending 500 m, and therefore the airflow intake rate should be of approximately 1.8 L/min. For Descent Phase, the nominal speed is assumed to be 8 m/s. While descending 500 m a 3 L sampling bag will be filled in 62 seconds. However, 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 500 m of vertical displacement, the horizontal resolution of the AAC has been approximated based on past BEXUS flights data obtained from the BEXUS manual [6]. The average horizontal resolution obtained for Ascent Phase is 588m and for Descent Phase is 186.5 m. This means that the square area covered by the sample will be 500 m x 588 m and 500 m x 186.5 m 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 the end of the design phase of the experiment and having already submitted an accepted preliminary design, 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 REXUS/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 Management Division

- Coordination between multiple project stakeholders.

- Task definition, estimation, and management.

- Task integration.

- Conflict management and resolution.

- Communication flows.

- Funding research and outreach.

- Identifying team member strengths as well as weaknesses and assigning responsibilities accordingly without neglecting the opportunities to improve on weaknesses.

- Do not assume cross-division communication will take place without organizing/planning it.

- Reviewing progress of assigned task should be continuous rather than waiting for their due dates.

- Agree on and clearly communicate to the team definition of "Done" when referring to tasks being completed.

- Agree on and clearly communicate to the team the definition of "Final Version" when referring to schematics, diagrams, and component lists.

- The lessons learned section of previous BEXUS SEDs is an invaluable resource that answers many BEXUS related recurring questions.

- If changes in management are required it is important that there is a sufficiently long change over period to allow a transfer of knowledge.

- Tasks that are not completed on time or were simply not worked on during the assigned time will impact projected deadlines and these situations must be planned for and mitigated against. An early red flag for this is if the reported team working hours tend to be lower than expected at which point one can expect to have to make up those hours up before a deadline. These concerns must continuously be communicated to the team.

- The REXUS/BEXUS programme is a significant investment in time and resources from all programme partners and as such the unique opportunity is not limited to participating

students but to component manufacturers and suppliers as well. With this in mind, the team should not shy away from aggressively seeking funds or sponsorships from component manufacturers and suppliers as they stand to benefit from such a partnership to show case the robustness of their products.

7.4.2 Scientific Division

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.

- Knowledge of how to design the scientific requirements in such a way that are in the permitted limits of the budget while the technical requirements are fulfilled.

- How to sufficiently distribute the tasks within the science team and keep good communication with the other departments.

- Experience, that writing down the tasks that need to be done, and keep tracking on them is better rather than having them as goals.

- Knowledge in data analysis procedure and how to extract the desired results from raw data.

7.4.3 Electrical Division

The electrical team has 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.

- Got experience of using the Eagle software and how to find and make the libraries, footprints, and schematics for the required components.

- How to test the components in the vacuum chamber.

- Learned about the different connectors, wires and how to place the components on the PCB so the actual design can fit into the experiment box.

- Discovered the cascading consequences of changing one component.

- Finding how having big sheets with a lot of information can be preferable to several sheets with less specification.

7.4.4 Software Division

- Learned more about version control in the form of Git.

- Learned how to implement RTOS on Arduino.

- Learned how to translate experiment requirements to software design.

- Learned how to split functionality into several testable functions.

- Gained experience on software unit test.

- Learned how to design and create GUI using MATLAB.

- Learned how to use Git, a version control system for tracking changes in computer files and coordinating work on those files among multiple people.

7.4.5 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.

- Adapt the design to components availability and characteristics.

- Select and contact with vendors.

- Implement a real pneumatic system.

- Compute structural analysis.

- Team collaboration with other departments, i.e. Electrical, Science, and Thermal.

- Design is trickier when it comes to implementation.

7.4.6 Thermal Division

- Learned how to do Steady-State and Transient thermal analysis in ANSYS.

- Coordinate between other division to find a solution that works for everyone.

- Do a thermal plan and structure up what needs to be done for a long period of time.

- How to improve and be more efficient when adjusting to sudden changes in design.

8 Abbreviations and References

8.1 Abbreviations

AAC	Alternative to the Air Coil
ASC	Air Sampling Control
ANSYS	ANalysis SYStem
BEXUS	Balloon Experiment for University Students
CAC	Conventional Air Coil
CAD	Computer Aided Design
CDR	Critical Design Review
CFD	Computational Fluid Dynamics
CH_4	Methane
CLK	Serial Clock
CO	Carbon Monoxide CO_2
Carbon Dioxide	
COG	Center of Gravity
CRDS	Cavity Ring Down Spectrometer
DC	Direct Current
DFM	Design for Manufacturability
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EB	Electronic Box
EBASS	Esrange BAlloon Service System
ECTS	European Credit Transfer System
EPDM	Ethylene Propylene Diene Monomer
ESA	European Space Agency
FCS	Frame Check Sequence
FEA	Finite Element Analysis
FMI	Finnish Meteorological Institute
GC	Ground Control Station
GPIO	General Pins Input Output
GPS	Global Positioning System
GUI	Graphical User Interface
H_20	Water
HOOD	Hierarchic Object-Oriented Design
I2C	Inter-Integrated Circuit
IDE	Integrated Software Environment
I/O	Input/Output
IR	Infra-Red
IRF	Institutet för rymdfysik (Swedish Institute for Space Physics)
LED	Light Emitting Diode
LTU	Luleå University of Technology
MATLAB	MATrix LABoratory
MB	Mega Byte
MISO	Master Input Slave Output
MORABA	Mobile Rocket Base

MOSFET	Metal Oxide Semiconductor Field Effect Transistor
	MOSI
Master Output Slave Input	
MSc	Master of Science
NOAA	National Oceanographic and Atmospheric Administration
OBC	Onboard Computer
ppb	parts per billion
ppm	parts per million
PCB	Printed Circuit Board
PDR	Preliminary Design Review
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
STP	Standard Temperature Pressure
TBC	To Be Confirmed
TBD	To Be Determined
TCP	Transmission Control Protocol
TT&C	Telemetry, Tracking, and Command
UDP	User Datagram Protocol
VC	Valve Center
ZARM	Zentrum für angewandte Raumfahrttechnologie und Mikrogravitation

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Appendix A   Experiment Reviews

A.1   Preliminary Design Review (PDR)

REXUS / BEXUS
Experiment Preliminary Design Review

Flight:	BEXUS 26
Payload Manager:	TBC
Experiment:	TUBULAR
Location:	SSC, Esrange Space Center, Sweden **Date:** 6th Feb. 2018

1. Review Board members

Stefan Kramer, SSC (chair)
Veronica Botti (minutes)
Giorgio Parzianello, ESA
Koen Debeule, ESA
Simon Mawn, ZARM
Dieter Bischoff, ZARM

Katharina Schuettauf, DLR MORABA
Maria Holmström, SSC
Klas Nehrman, SSC
Jörgen Blomberg, SSC
Juha Keinström, SSC
Jianning, Li SSC

2. Experiment Team members

Gustav Dyrssen
Jordi Coll Ortega
Natalie Lawton
Nuria Agües Paszkowsky
Hamad Siddiqi
Muhammad Ansyar Rafi Putra
Pau Molas Roca

3. General Comments

- ▪ Presentation
  - The presentation was clear and well done.

- ▪ SED
  - In general, the SED was well done and appreciated by the panel.
  - The team should clarify better the objectives.
  - In general, the team should include more labelled diagrams instead of long pages of text.

4. Panel Comments and Recommendations

- ▪ Requirements and constraints (SED chapter 2)
  - There are too many functional requirements. The team should reduce them.
  - The requirements F16 to F27 do not need to be listed.
  - The team shall add a performance requirement about the volume of air to analyse.
  - The requirements P16 to P22 are all design requirements.
  - For the requirement P16 the team should specify the altitude.
  - The design requirement D8 is fine, but the team should remember that that 374Wh is the capacity of the battery at nominal temperature and with a current draw of 0.1A. A more typical capacity of 7Ah (196 Wh).
  - Regarding the design requirement D13 the team might expect the experiment environment to be below -30C.
  - The constraints listed in the SED are not real constraints.

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- **Mechanics**
  - The team should consider also the locations and accessibility of the external electronic interface.
  - The team should think about a solution to access the experiment without taking it off from the gondola.
  - The set-up of the box needs to be re-discussed.
  - The team should consider a thermal insulation for the experiment since the experiment is drawing cold air from the environment.
  - The team should check the capability of the pump is enough to suck the required amount of air.

- **Electronics and data management** (SED chapter 4.2.2, 4.2.3, 4.5, 4.7, 4.9)
  - A consumption of 1 mA is underestimated.
  - The team should check how to connect the device to the microcontroller and choose a possible interface.
  - To reduce the voltage to that required the team shall use a DC/DC converter.

- **Thermal** (SED chapter 4.2.4 & 4.6)
  - The team should perform a thermal analysis of the experiment, especially considering that the experiment will suck very cold air from the external environment.
  - The team should finish to list the temperature ranges of the components.
  - The team should clarify which temperature they need inside the box.
  - The team should find an alternative solution to access the experiment in order to prevent unwanted openings of the box.

- **Software** (SED chapter 4.8)
  - The software design was well done.
  - The team should consider to perform some manual actions on the experiment. The experiment does not need to be all automatized.
  - If the team wants to keep the triggered watchdog, all the events should be activated from the beginning of the countdown. Maybe it's better to remove the watchdog.

- **Verification and testing** (SED chapter 5)
  - The verification matrix must be reviewed.
  - In general, not everything can be verified by test. Test is often proceeded by an analysis or review.
  - The team should make sure that the test really covers the requirement. M
  - any requirements point to the same test so a detailed test plan will be needed to ensure the test specifically addresses that requirement.
  - In some cases, it might be better to split out separate tests.
  - The team should add a test to verify the functioning of the pumping system.
  - The team should verify that the pump is able to produce the required velocity with such a small delta-p.
  - It's very important for the team to test the opening and closing of the valves.

- **Safety and risk analysis** (SED chapter 3.5)
  - The team, in general, should review the risk register.
  - In general, the risks are underestimated.
  - The team should foresee some managerial risks, such as the risk of someone leaving the team.
  - The team should consider as a major risk the partnership with the Finnish.
  - The team should consider as a major risk also the use of the single pump. This should be ordered early and tested and maybe it would be better to order at least two pumps.

- **Launch and operations** (SED chapter 6)

  - The chapter was well done, however the team should add more information about the recovery, since it is a critical part of the experiment.
  - The team should clarify where did they get the data about balloon descent rate.
  - The team should specify why they cannot flush on the ground.
  - The team should clarify whether the valve operation is linked to time or altitude.

- **Organisation, project planning & outreach** (SED chapters 3.1, 3.2, 3.3 & 3.4)
  - The team should clarify the work packages and specific tasks of each team member in the WBS.
  - The Gantt chart is too basic and should be refined.
  - There is no mapping of team availability over the project period to the work required.
  - The team should clarify whether the project is part of a course.
  - The budget description is too basic. The team should describe all the costs and clarify better what is already covered and what needs to be covered.
  - The outreach plan is good but not implemented yet. The team should create soon a webpage and a page in different social media.

5. Internal Panel Discussion

- Summary of main actions for the experiment team
  - The team should verify that the bags and the pump work properly before the CDR.
  - The team should review the Requirements and Constraints section.
  - The team should further develop and document their electronics design.
  - The team should provide a more defined thermal analysis.
  - The team should improve the management section.

- PDR Result: conditional pass
- Next SED version due: v1-2, 12th March 2018

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A.2 Critical Design Review (CDR)

BEXUS
Experiment Critical Design Review

Flight:	**BEXUS 26**	
Payload Manager: TBC		
Experiment:	**TUBULAR**	
Location:	ESA, ESTEC, Noordwijk, The Netherlands	**Date: 31 May 2018**

1. Review Board members

- Michael Becker (DLR)
- Kristine Dannenberg (SNSB)   - Koen DeBeule (ESA)
- Alexander Kinnaird (ESA)   - Piotr Skrzypek (ESA)
- Veronica Botti (ESA) –Minutes   - Grzegorz Izworski (ESA)
- Stefan Krämer (SSC) – Chair   - Katharina Schüttauf (DLR MORABA)
- Maria Snäll (SSC)   - Dieter Bischoff (ZARM)
-      - Simon Mawn (ZARM)

2. Experiment Team members

- Natalie Lawton
- Erik Fagerström
- Pau Molas Roca
- Gustav Dryssen

3. General Comments

Presentation
– The presentation was very clear and complete and the panel appreciated the approach of the team in analysing and finding a solution to possible issues.

SED
– The team may read the SEDs of BX_COSPA or BX_A5UNIBO for more information about similar pumps and experiment principles.
– The team should be consistent with thousand markers (,) and decimal markers (.) (e.g. in the budget).
– The team should keep the appendices as indicated in the SED Guidelines (in particular A for the review reports and B for outreach) but, in general, there are some excellent additional information.
– The document is going to end up very long. This is not a problem, but the team must try to be succinct using diagrams and summary tables where possible and not including unnecessary 'discussion'.
– The team should keep images compressed without reducing the readability.
– The team should describe what the "Brain" is the first time they mention it in the document.

4. Panel Comments and Recommendations

Requirements and constraints (SED chapter 2)
– Since the team deleted a lot of requirements and the document is getting very big, maybe it would be better to rewrite the updated requirements and put the old ones in the appendix.
– The team should add a note in the introduction and in the objectives to explain the reasons for changing, the type of gas that will be detected during the flight (i.e. from N2O to CO).
– Req. F6-F7: they are software requirements. The team should be aware that it's difficult to justify them in system level functional requirements. If they really want to keep them for verification it's ok,

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but in that case it would be better to put them in the design requirements or re-word them and put them in operational requirements..
- Req. F10 to F12: instead of saying "shall collect data", the team should say "shall measure".
- There are still some performance requirements missing, such as: amount of air, range accuracy and frequency of the flow rate, pressure measurements, temperature measurements and humidity. These requirements should be separate in different performance requirements.
- Req. D3: The requirement "shall not disturb the launch vehicle" should not be deleted but rather reworded such that is unambiguous and verifiable.
- Req. D4: the team should be more specific and define the type of connector, protocol, etc.
- Req. D5: the team should be more specific and define the type of connector, voltage, ripple, grounding, etc.
- Req. D7: the requirement only makes sense with the reference voltage. The team should add it.
- Deleting the duplicated temperature requirements does make sense, but the team shouldn't delete those ranges. The team is advised to put them in the verification plan now.
- When stating "profiles of flight" the team should either state the specifics and/or reference the section manual.

Mechanics (SED chapter 4.2.1 & 4.4)
- The rack built out of strut profiles is a good choice because of flexibility in fixating the components inside and stiffness properties. The team should consider the attachment to the gondola which does not allow tolerances of the rails and which functions as lot of heat bridges.
- The team should consider how to absorb vibrations/shocks of the pumps? ("Bismat" clamps could be a solution).
- The team should specify how they plan to activate the valves. The team should be aware that they will heat up after a while and that there are valves with a high activation power but a lower holding power.
- The team should specify what kind of tubes and connectors are used and consider how to perform a leakage test, how to access any connection and how to seal any connection (it could be easy just raising the torque a little more, but could be difficult as well in case that an O-ring or sealing has to be changed).
- The team should avoid sharp corners, especially at racks with lower space and fulfilled with equipment (such as the "brain".).
- Inline pressure sensor from "FESTO" could be good.
- Mechanical pressure sensors based on pitot tubes may also be an option.
- The team should clarify what is the expected maximum pressure inside the bags and tubes. The team is advised to check the datasheet of the valves regarding leakage rate or perform tests with different pressure on both sides to ensure proper function.
- The team should make sure to define and use the right procedure to clean pumps and valves.

Electronics and data management (SED chapter 4.2.2, 4.2.3, 4.5, 4.7, 4.9)
- The team should consider the connector location carefully. It is very good to have easy access but it's not good to have the cables/connector pointing out of the gondola, because the turn may protrude outside and increase the risk of damage during launch/landing. This issue can be discussed with payload manager during accommodation session.
- In general, the accessibility of the connector panel is pretty good but without any protection. The team should move this panel upwards to the top cover (access from above).

Thermal (SED chapter 4.2.4 & 4.6)
- Regarding the EPS extruded Styrofoam, the team should ensure that this material is suitable for low pressure environment. Many foams expand when the pressure decreases but do not restore completely when back in normal pressure which would cause open gaps of the insulation cover.
- From a thermal point of view the team is suggested to install big heat bridges with this attachment. It would be better to use a flat material or another strut profile fixated with thermal spacers and attached to the gondola with the help of rubber bumpers.
- The team should investigate any hot spots of the setup and try to spread the heat with heat sinks to serve better conditions for the surrounding components.
- In general, there are too many heat bridges in the experiment setup.
- To raise the conditions at the beginning the team could insert chemical heater(s) like hand warmers during late access.
- The team could colour the strut profiles with black paint to count on the effect by heating up by the sun while the setup faces into it.

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- The team should be aware that the expected lowest temperature on a BEXUS launch in October (day flight) is around -55°C.
- The team should specify how will the implementation of the insulation material looks.
- An internal temperature around +5°C is low. The team should consider that the performance decreases at lower temperatures.

Software (SED chapter 4.8)
- The team is suggested to implement hysteresis for automatic mode change and to filter the sensors.
- Regarding the process diagram in figure 44, there is no way out from the manual mode. The team should specify what are they planning to do if the connection to the ground station is lost.
- The team should clarify if/how they are planning to keep track of the time.
- A list of telecommands and supported telemetries is missing. The team should not forget to insert a command to query the storage status, general system status, update automatic timeline, update time and perhaps reinitialise/clean up the storage.
- The team should specify which is the file system used on the SD card. FAT is not recommended.
- The team should clarify the concept of mode switching based on the pressure sensors.
- It's a good choice to use three tasks for Arduino but in the Software design section the identification of these three tasks is missing. The team should add it.

Verification and testing (SED chapter 5)
- Only positive software testing is currently foreseen. The team should explore failure scenarios: resets of the microcontroller (during auto mode), loss of communication at inconvenient times, multiple loss of communication, loss of SD card (unplug, broken filesystem, etc.).
- Req. P12 to P14: the requirement should be verified by Review of Design and not by Inspection (you review a data sheet you inspect a model/build).
- The team should be careful that where items are already verified by analysis, the analysis remains valid if/when the design changes/evolves.
- The team should state within the test plan whether the testing item is flight, prototype or another kind of model; they should also state within the test plan which requirements will be verified and then write the plan to make sure it will clearly verify those requirements.
- The team should insert all these tests in the Gantt Chart and have a global test plan which would lays them out logically.
- The team should consider what happens if a test fails and a change is needed and understand how far to come back in the test plan.
- Doing a vibration test on a shaker is good learning experience for the team, but the team should pay attention to which spectrum(s) are applied to the experiment, as there are none specified for BEXUS.
- There is no need to remove the walls during the test. The team should engage a good test engineer to understand the process.
- The team should include a summary of one or two paragraphs (maybe with figure where relevant) for each test, and then make a separate complete report in the appendix.
- The team should specify for which reasons there are no concerns about bag burst.

Safety and risk analysis (SED chapter 3.5)
- Risk TC40: the severity is too low.
- The team, in general, should avoid the word "proper" when defining an action to mitigate any risks.
- EN10: the team should better clarify which is the risk and which is the foreseen action. "Vibration" does not mean anything.
- The team should consider some management risks, in particular regarding time availability.
- The team should also consider some operational risks.
- The team should check again the severity of some risks. In general, it is too high.
- In general there are many risk with the same code (same probability and severity) that are considered sometimes acceptable and sometimes unacceptable and an action is always foreseen. This is confusing. The team should clarify what is an acceptable risk for them and what is unacceptable and, based on that, they should think of an action or accept the risk.

Launch and operations (SED chapter 6)
- The team should add any safety risks associated with pressurised vessels during recovery.
- It is very good that there is already a checklist. The team should check it with SSC to confirm it is all possible before flight after the final ECTs.
- The team should use this checklist during the systems tests and update them, including photos, and making sure that the person doing the final version is the person who did it before.

- The team should add any launch site requirements, such as a room, a laboratory for preparations or testing on ground.
- The team should add risk connected to the use of chemicals.
- The team should think of what could happen in case of hard landing and exposed gas or liquid.
- The team should insert in the launch and operation chapter (or link to the appendix) the cleaning procedure of the pump and valves.
- The team should use the checklist during the tests.
- The team should be aware that from T -3h to T- 1h the experiment will work on external power.

Organisation, project planning & outreach (SED chapters 3.1, 3.2, 3.3 & 3.4)
- In the Resources section, under Table 6, it is written that all the team members are currently enrolled in LTU master programmes. However, according to the team details, most of the students are bachelor students. The team should clarify.
- The team should be aware that, during the last months they will need to allocate more resources to the experiment.
- In the outreach section is written "a website WILL be launched…". If it has already been done the verb should be at the past, not at the future.
- The team should clarify who is responsible once the subsystems are assembled (i.e. system level AIT and launch/operations).
- The team should try to trace the critical path to know where to focus their efforts.
- The team should better clarify if the exam period is really blocked out.
- It is very good to have some internal deadlines.
- It seems that there is a very little margin at the moment (testing completed at the start of October); the team should not forget to plan some buffer time and, in case of late testing, the team should think about the associated risks and how to mitigate them (e.g. good analysis).
- The team should relate their resource availability to the Gantt chart and clarify how the impact of any delays on the project planning.
- Regarding the budget, the team should specify if they have considered any contingency for unexpected events.
- It would be great to have a dedicated outreach timeline/media plan to see when these events are happening; they could be used to punctuate the project (a nice break or celebration for you) and/or to build excitement around certain events.
- The team should add a picture of the experiment on the website.
- In the "Project" Section, in the website, the first word is "Problem". The team should change it with something like "objective", or something similar.
- The team should add a headline in the website to capture the attention of the reader. Something like "we launch an experiment to the edge of space…." could be a good starting point.
- The team should look again at the relative logo sizing (SNSA is too small) in the website.
- The website loads very slowly, especially large header photos. The team should consider optimising this and check its compatibility for mobile devices.
- In the Facebook page the team should expand the "about" section to include mention of the REXUS/BEXUS programme.

5. Internal Panel Discussion

- **Summary of main actions for the experiment team**
  - Update the mechanical design as per the recommendations.
  - Make the design decision regarding inlet pressure and humidity measurement (contact their mentor for further advice).

- CDR Result: **Pass**

- Next SED version due: **SED_v3-0**, due **3 weeks before IPR. Date TBD**

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Appendix B   Outreach

B.1   Outreach on Project Website

To increase the projects out reach the TUBULAR Team created a project website. On the website there are descriptions of the project, a link to download the latest SED, information on the TUBULAR Team members and sponsors and a contact link. In addition the microblogging carried out by the TUBULAR Team is also displayed on the website.
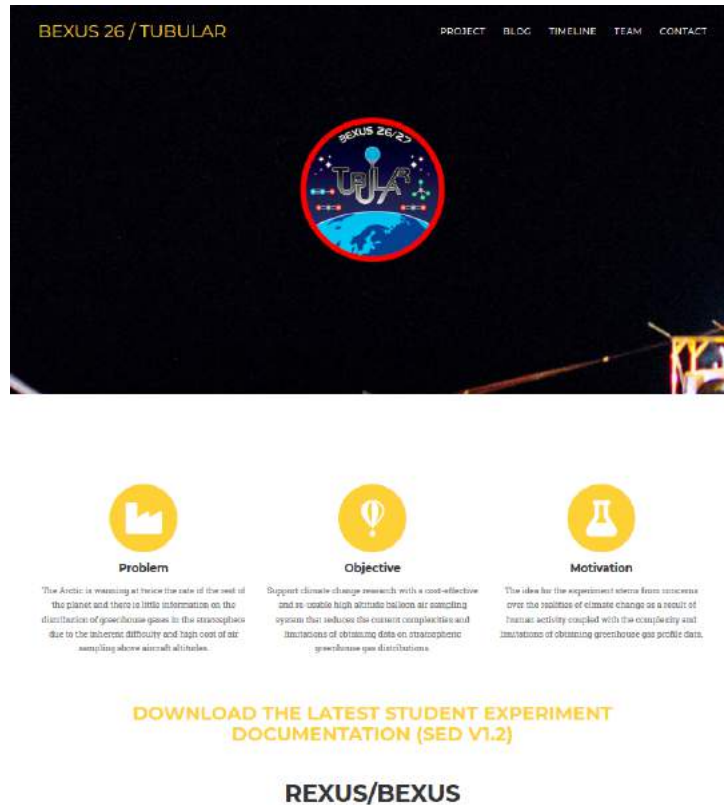
Figure 57: The Home Page of TUBULAR's Website.
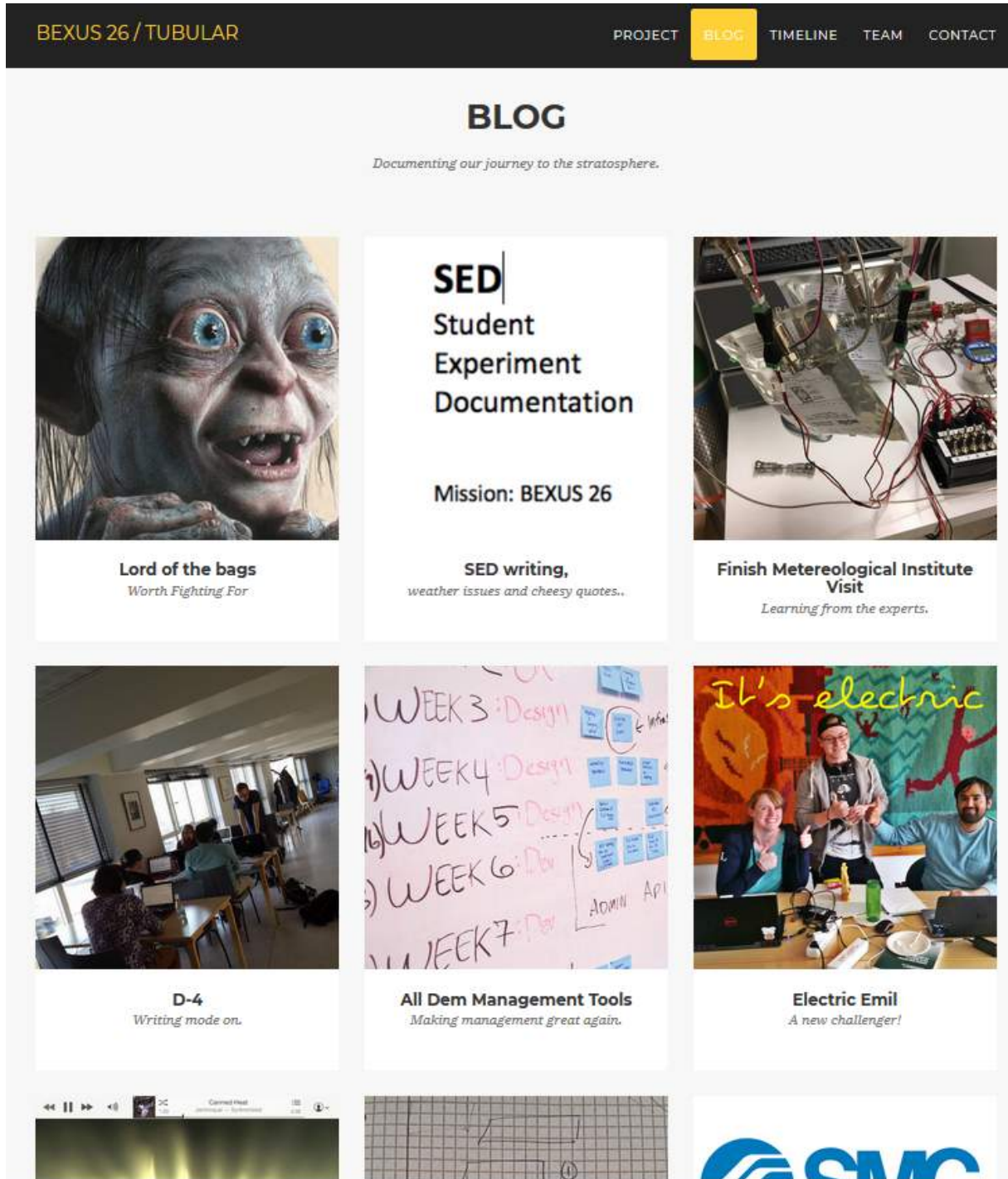
Figure 58: The Daily Microblogging Displayed on the Website.

Figure 59: The Timeline for This Project Available on the Website.

Figure 60: The Information of the Tubular's Team Members Available on the Website.

Figure 61: The Sponsors In This Project Available on the Website.

B.2 Outreach timeline
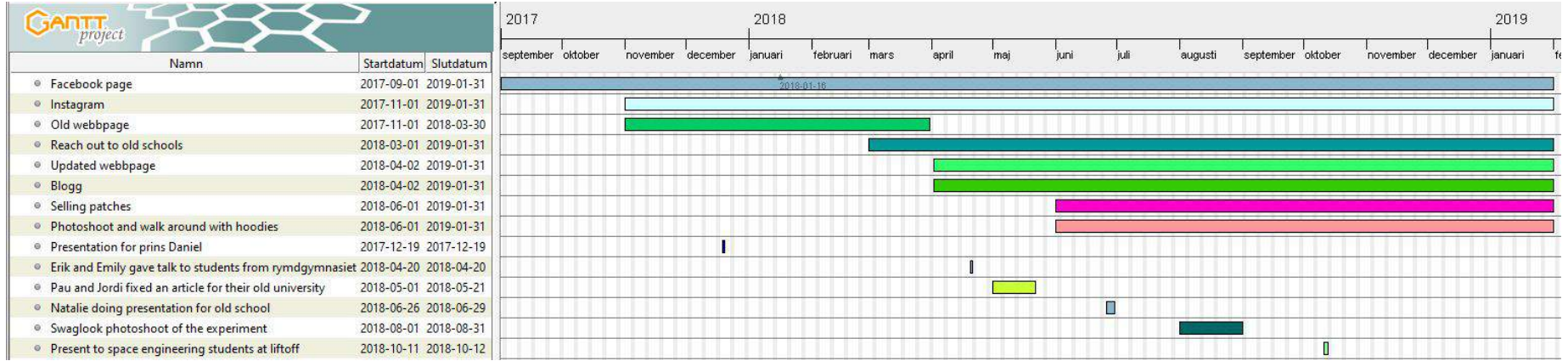
Figure 62: Outreach Timeline for the Whole BEXUS Project.

B.3 Social Media Outreach on Facebook

Another outreach avenue is Facebook. On Facebook the TUBULAR Team posts photos, short text updates and links to our blog posts.
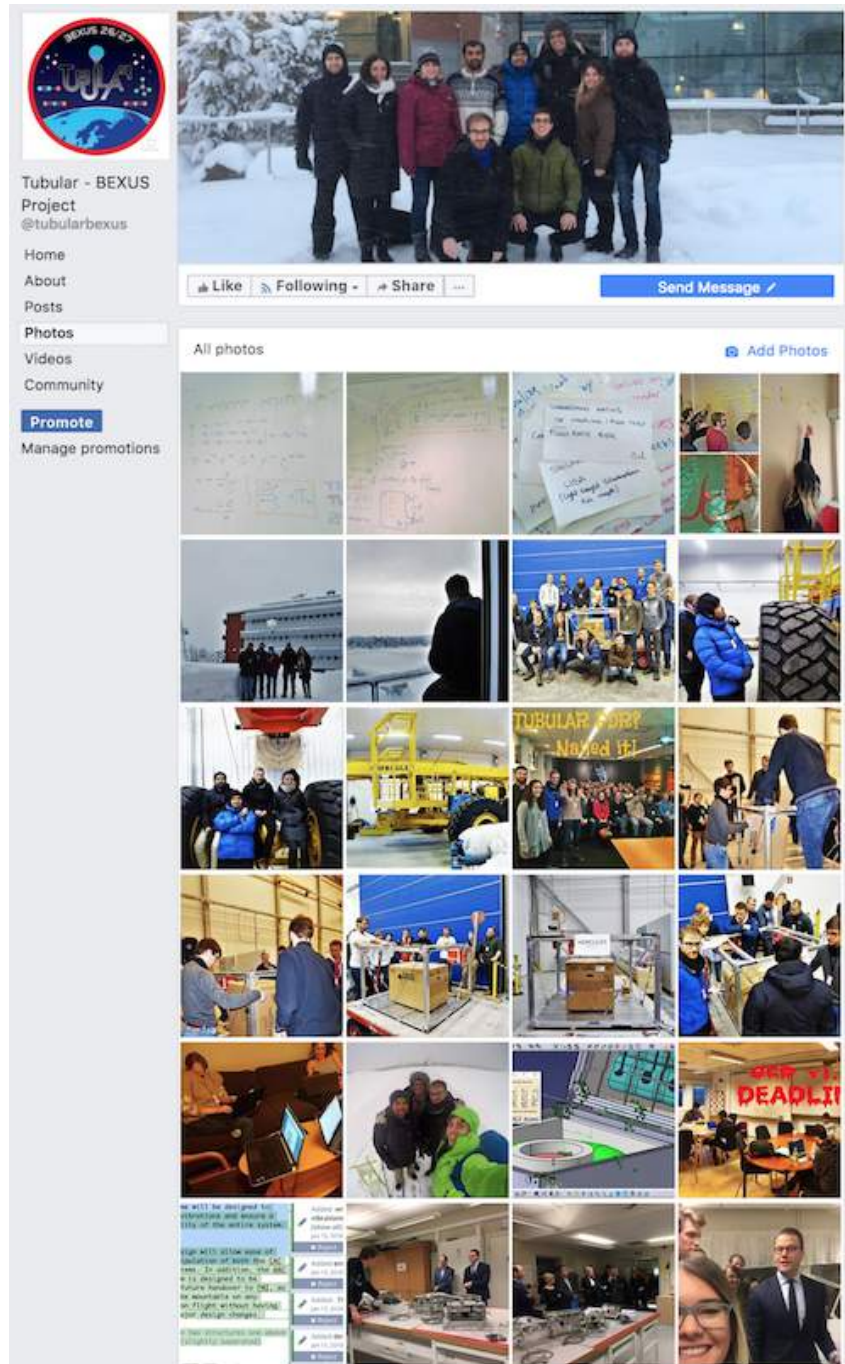
Figure 63: Photos from Social Media Outreach on Facebook.

B.4 Social Media Outreach on Instagram

On Instagram the TUBULAR Team posts regularly with updates on the project progress and what the TUBULAR Team has been up to.
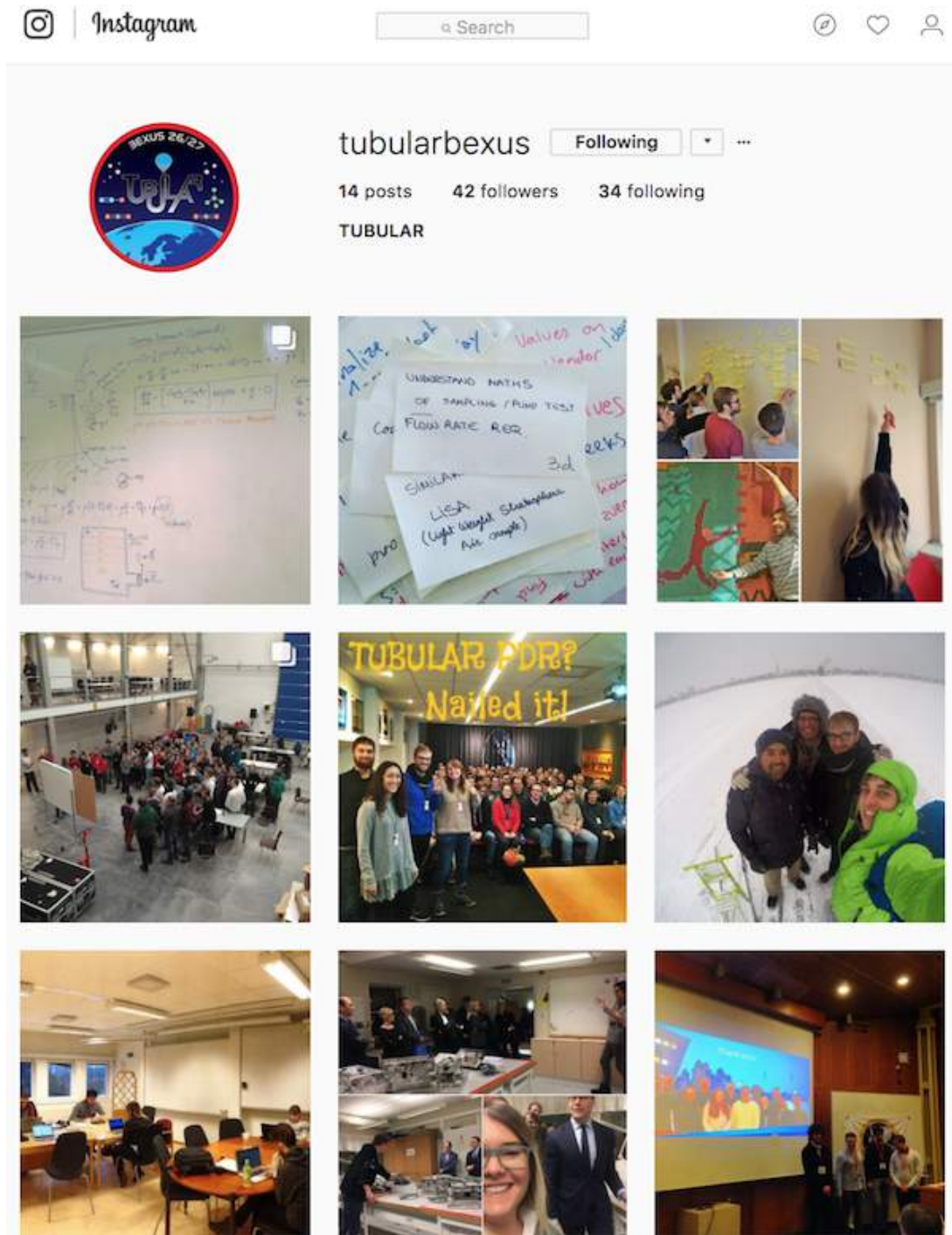
Figure 64: Some of the Social Media Outreach on Instagram.

B.5 Social Media Outreach on Space Instrument Themed Instagram (1/2)
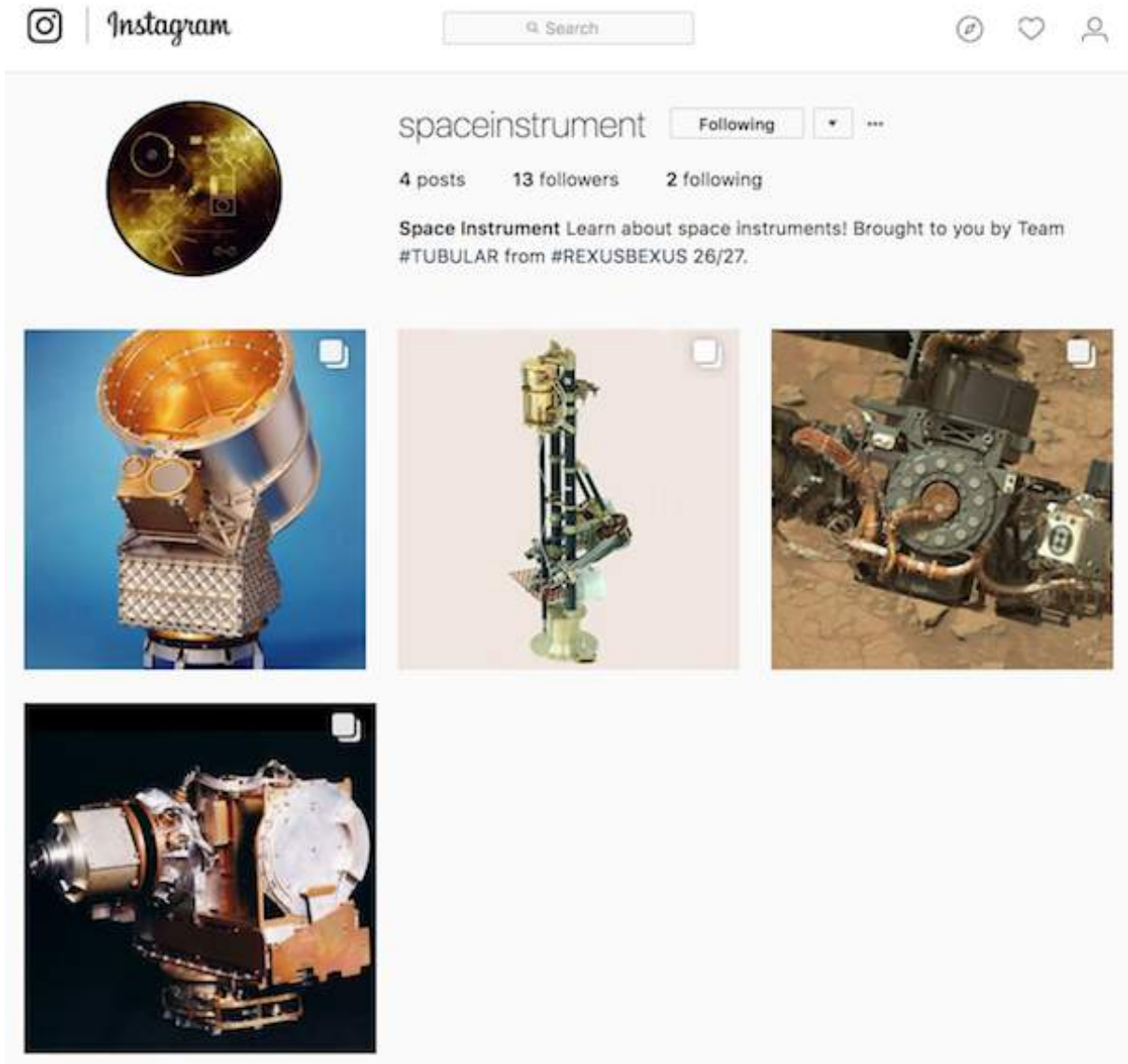
Figure 65: Some of the Social Media Outreach on Space Instrument Themed Instagram.

B.6 Social Media Outreach on Space Instrument Themed Instagram

The Space Instrument Instagram is run by the TUBULAR Team as an educational outreach.
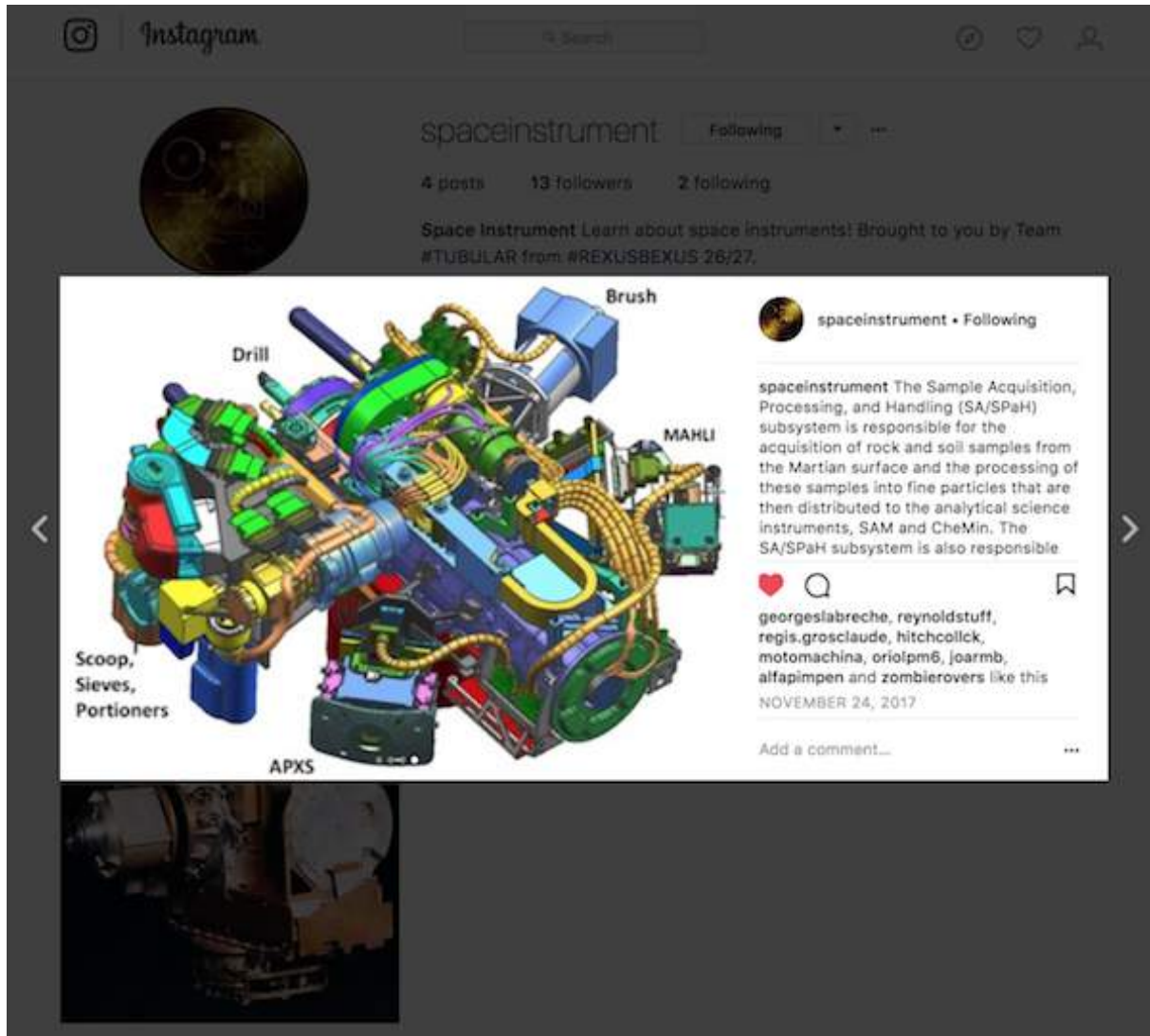
Figure 66: An Example of One of the Posts on the Social Media Outreach on Space Instrument Themed Instagram.

B.7 Outreach with Open Source Code Hosted on a REXUS/BEXUS GitHub Repository

The TUBULAR Team has opened a GitHub Repository to share all the code used in the TUBULAR project. It was created with an open invite to all other REXUS/BEXUS teams to view, use and contribute to.
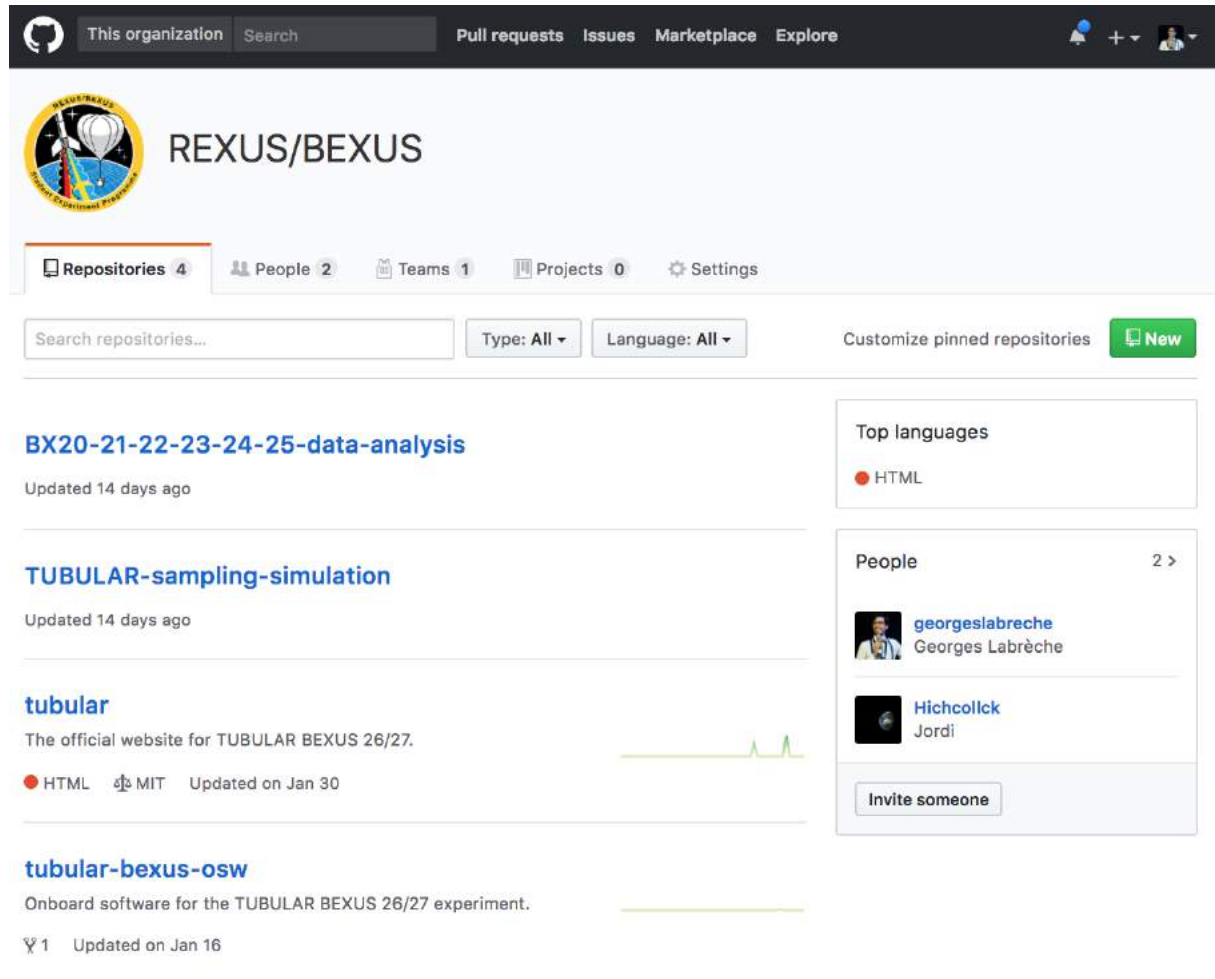
Figure 67: The Open Source Code Hosted on a REXUS/BEXUS GitHub Repository.

B.8   Outreach with Team Patch

The team also had patches made of the TUBULAR logo and 150 patches have been ordered. Around 70 of these have already been bought by the team for themselves and to give to friends and family. It is intended that the remaining 80 will be sold for a small profit at university.

Figure 68: A Photo of the Patch in Production Sent by the Company Making it.

Appendix C   Additional Technical Information

C.1   Materials Properties

Material	Density	Tensile strength	0.2% Proof stress	Ductile yield A_5	Modulus of elasticity	Brinell hardness
EN AW - AlMgSi 6060	2.7 g/cm^3	245 MPa	195 MPa	10%	70GPa	75 HB

Table 56: Mechanical Properties of the Strut Profiles.

Material	Density	Tensile strength	Yield Strength	Modulus of elasticity	Brinell hardness
Aluminum 5754	2.67 g/cm^3	190 MPa	80 MPa	70 GPa	77 HB

Table 57: Mechanical Properties of the Aluminum Panels.

Material	Density	Tensile strength	Maximum Temperature
Styrofoam 250 SL-AN	28 kg/m^3	90 kPa	75 °C

Table 58: Mechanical Properties of the Styrofoam Insulation/Protection.

C.2 Coiled Tube and Sampling Bag Example

C.2.1 CAC Coiled Tube

Figure 69: CAC Coiled Tube.

C.2.2 Air Sampling Bag

Figure 70: Air Sampling Bag.

C.3   Dimensions of the sampling bag

Table 59 shows how the dimensions of the bags change according to the sampled volume. This data has been obtained by testing and has been taken into account in order to determine the maximum number of bags that can be filled inside the box.

Volume	Length (horizontal)	Height (vertical)	Width
Empty	26.4 cm	28 cm	0.5 cm
0.5 L	26.4 cm	27.5 cm	1.5 cm
1 L	26 cm	27.5 cm	2 cm
1.5 L	25.5 cm	26.5 cm	4.5 cm
2 L	25 cm	25 cm	5.5 cm
2.5 L	24.5 cm	23 cm	7.5 cm
3 L	24 cm	22 cm	10.5 cm

Table 59: Dimensions of the Bags When Filled with Different Air Sample Volumes.

C.4   List of components in The Brain

Level 1 - Pump
List of components of Level 1:

    A. 1 Magnesium filter (M48)

    B. 1 Pump (E3)

    C. 1 Airflow sensor (E6)

    D. 1 Temperature sensor (E9)

    E. 2 Heaters (E7)

    F. 4 Tubes (M45)

    G. 3 Straight union interfaces (M41)

    H. 3 Female to tube interfaces (M42)

Level 2 - Valve Center
List of components of Level 2:

    A. 1 Sensor Box (M49)

    B. 3 Pressure sensors (E4)

    C. 1 Temperature sensor (E9)

    D. 1 Heater (E7)

    E. 1 Manifold (M50)

    F. 8 Sampling valves (E36)

    G. 1 Flushing valve (E37)

    H. 12 Male to tube interfaces (M40)

    I. 2 Caps (M47)

    J. 12 Tubes (M45)

Level 3 - Electronics
List of components of Level 3:

    A. 1 PCB

    B. 2 D-Sub female connectors (E23)

    C. 1 E-link socket (E35)

    D. 1 Power socket (E33)

All the electrical components connected to the PCB in Level 3 are summarized in Tables 60 and 61.

CAC		
Area	Electrical component	#
CAC	Solenoid valve	1
	Temperature sensor	3

Table 60: Connections to CAC Box.

AAC		
Area	Electrical component	#
Level 1	Pump	1
	Heater	2
	Airflow sensor	1
	Temperature sensor	1
Level 2	Pressure sensor	3
	Solenoid valves	9
	Heater	1
	Temperature sensor	1
Sampling bags center	Temperature sensor	3

Table 61: Connections to AAC System.

C.5 Pneumatic System Interfaces

C.5.1 Male to tube interface
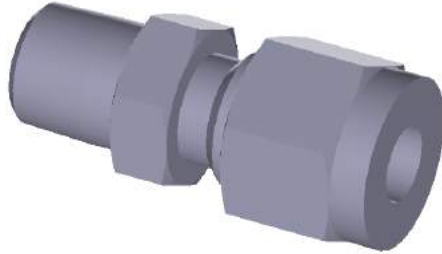
Figure 71: Swagelok Component: SS-400-1-2.

C.5.2 Female to tube interface
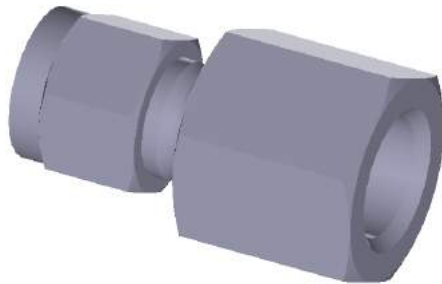
Figure 72: Swagelok Component: SS-400-7-4.

C.5.3 Tube to tube interface
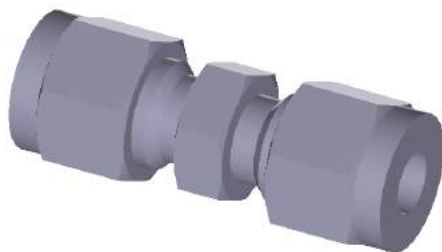
Figure 73: Swagelok Component: SS-400-6.

C.5.4 Male T-Union interface
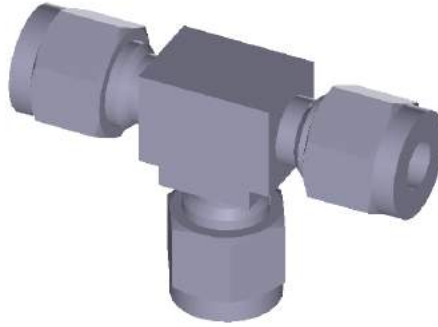
Figure 74: Swagelok Component: SS-400-3.

C.6   Manufacturing Drawings

The following drafts are to be used to manufacture the mechanical components of the experiment.

Detail A
Scale: 1:1

⌀4.8

0.5

9

74

460

360

A

Detail A
Scale: 1:1

⌀4.8

0.5

74

6

460

460

A

Detail A
Scale: 1:1

Ø 4.8

360

0.5

9

74

310

150

108

A

80

0.5

50

10

20

13.35

45

Ø31.3

150

Ø3.2

Ø3

7.36

18.07

Ø11.4

3.51

70

3.76

Ø4.8

10.74

4

14.63

34.63

162

0.5

26

150

47.56

Ø6.35

10

31.5

32

60

95

Detail A
Scale: 1:1

$\emptyset 4.8$

0.5

74

6

460

460

A

Ø4.8

Detail A
Scale: 1:1

0.5

74

6

190

460

A

Detail A
Scale: 1:1

⌀4.8

Detail B
Scale: 1:1

12.91

⌀3.5

14.65

24.99

10.72

⌀4

⌀4

0.5

22.91

98.28

14

B

⌀6.55

A

74

6

24.37

190

460

20

20

12

20

12

68

460

360

30

20

20

12

12

68

460

460

20

20

20

12

12

68

310

150

252

360

80

20

50

20

10

13.35

45

Ø31.3

Ø3

Ø3.2

7.36

18.07

150

Ø11.4

3.51

70

3.76

Ø4.8

10.74

4

14.63

34.63

Ø4.8

Ø6.35

150

10

31.5

60

26

47.56

32

20

95

20

20

162

20

Ø400

Isometric view
Scale 1:15
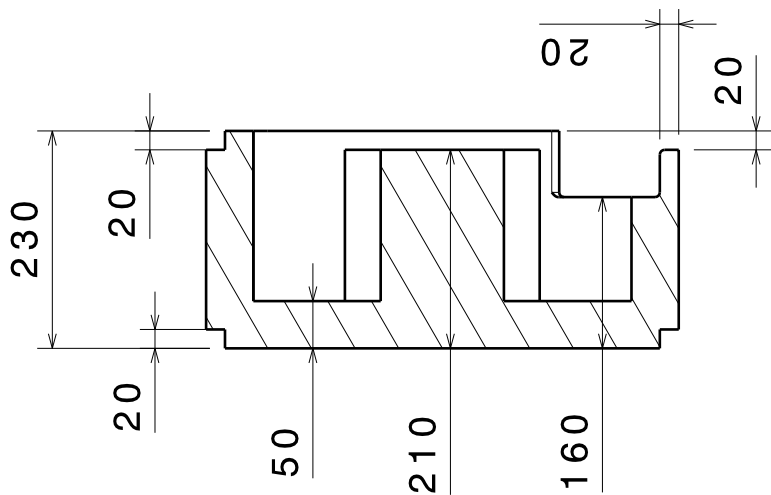
Section view A-A
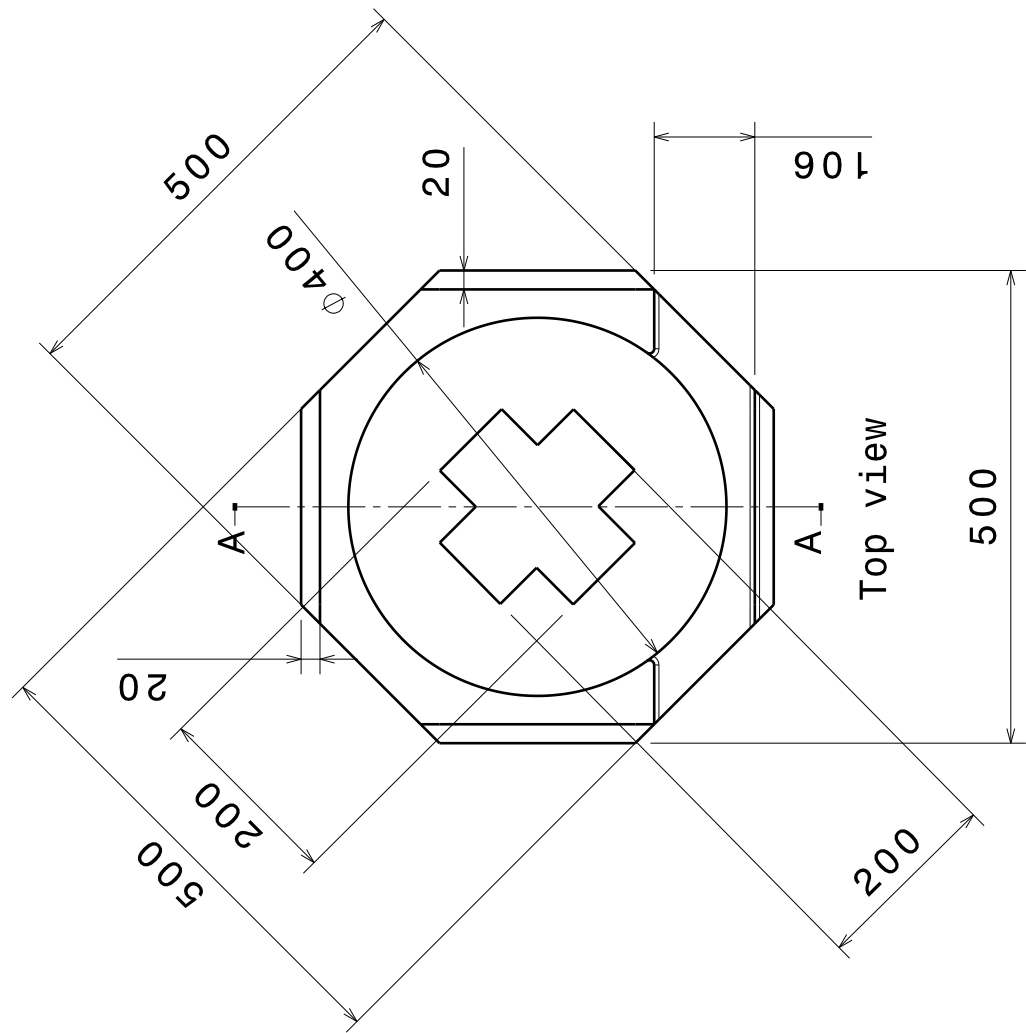
20
20
230
20
20
50
210
160

Top view

500
⌀400
20
106
500
500
200
20
200
200
A
A

Left view   Scale: 1:2

Front view

Scale: 1:2

Scale: 1:2	

TEAM:	TUBULAR - BEXUS 26
UNIVERSITY:	LULEA UNIVERSITY OF TECHNOLOGY
PART NAME:	Foam Lateral Long - The Brain
PART ID:	M16.8	AMOUNT:	1
MATERIAL:	Styrofoam 250 SL-A-N
VERSION:	CRITICAL DESIGN REVIEW - SEDv2.0

DESIGNED BY:	Pau Molas Roca
DATE:	13/05/2018
CHECKED BY:	Jordi Coll Ortega
DATE:	14/05/2018
SIZE	A4	SCALE	1:2

243

30

61

40

Ø4.8

180

10

25

180

19

30

20

20

30

290

20

1

1

1

4.8 ⌀

10
20
20

10
20
40

60

Technical Drawing

148

1

258

Ø40

50

60

148

1

258

20

20

129

74

Ø40

Ø3.6

50

25

TEAM: TUBULAR - BEXUS 26

UNIVERSITY: LULEA UNIVERSITY OF TECHNOLOGY

PART NAME: Structure Column - The Brain

PART ID: M21

MATERIAL: Stainless Steel 304

AMOUNT: 1

VERSION: CRITICAL DESIGN REVIEW - SEDv2.0

DESIGNED BY: Pau Molas Roca
DATE: 13/05/2018

CHECKED BY: Jordi Coll Ortega
DATE: 14/05/2018

SIZE: A4
SCALE: 1:2

20

0.5

40

10

10

Ø4.8

20

1

10

9

258

⌀4.8

20

1

8

10

146

⌀4.8

C.7   Software Sequence Diagram

C.7.1   Air Sampling Control Object Sequence diagrams
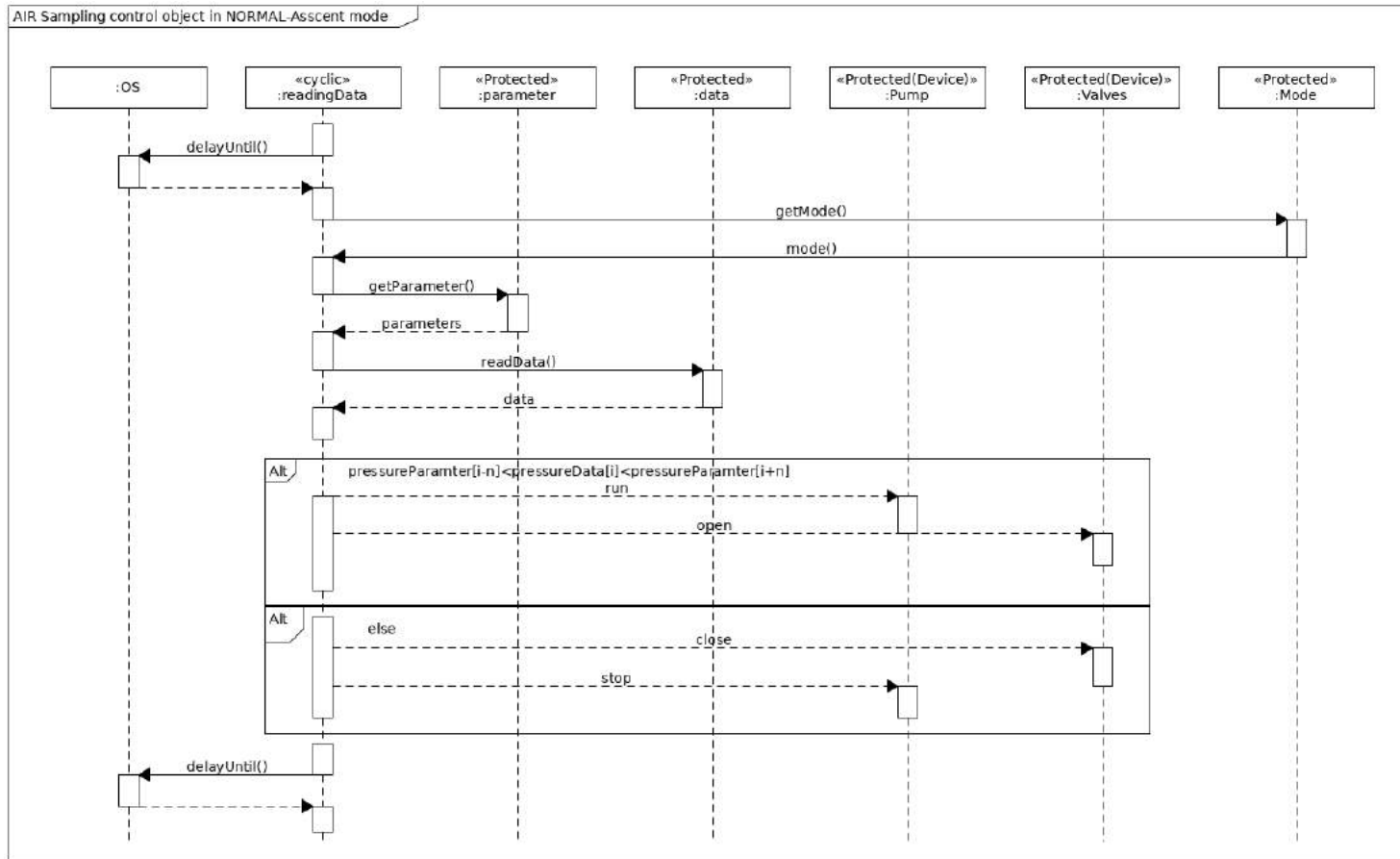
Figure 75: ASC Object in Normal Mode - Ascent.
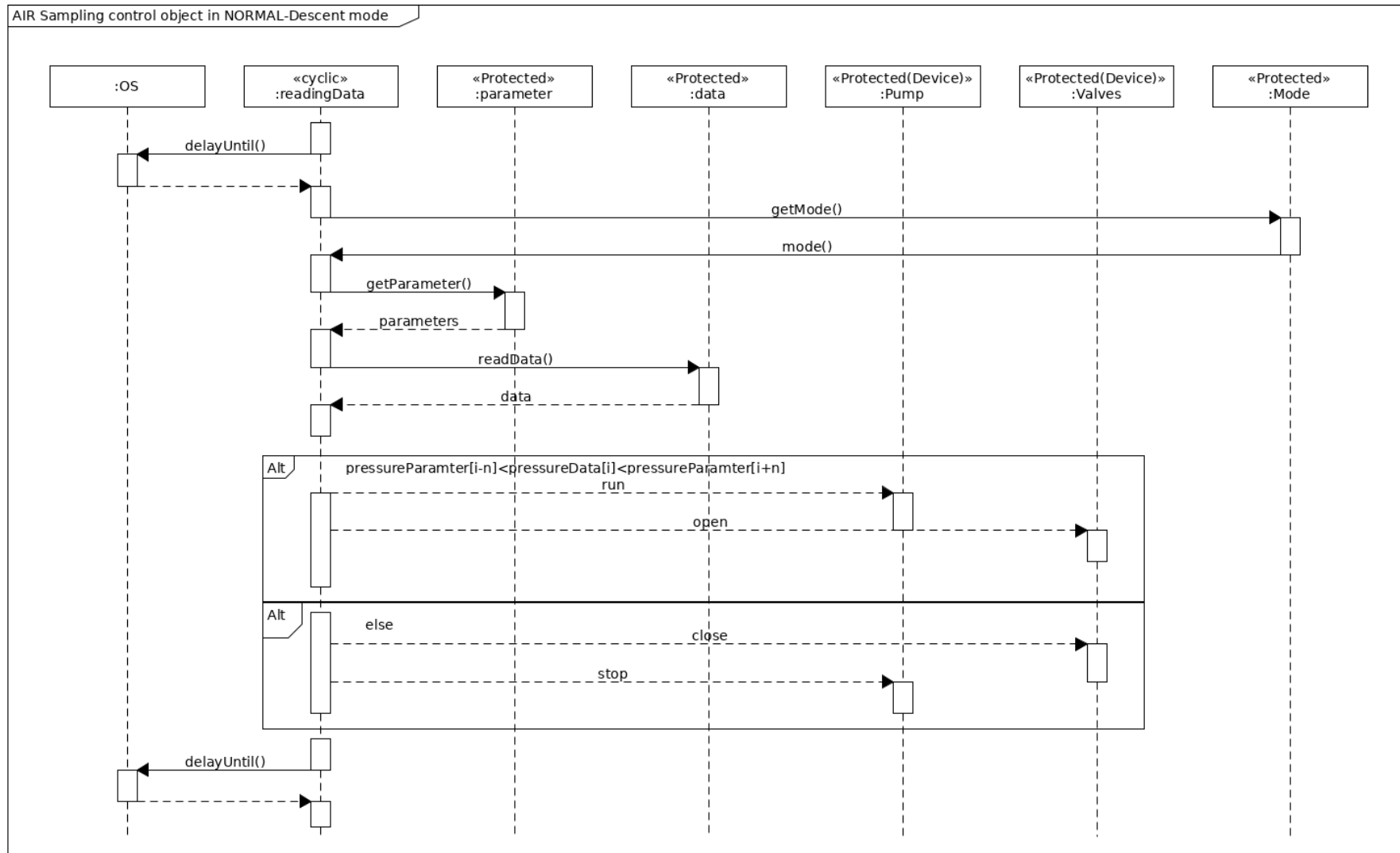
Figure 76: ASC Object in Normal Mode - Descent.
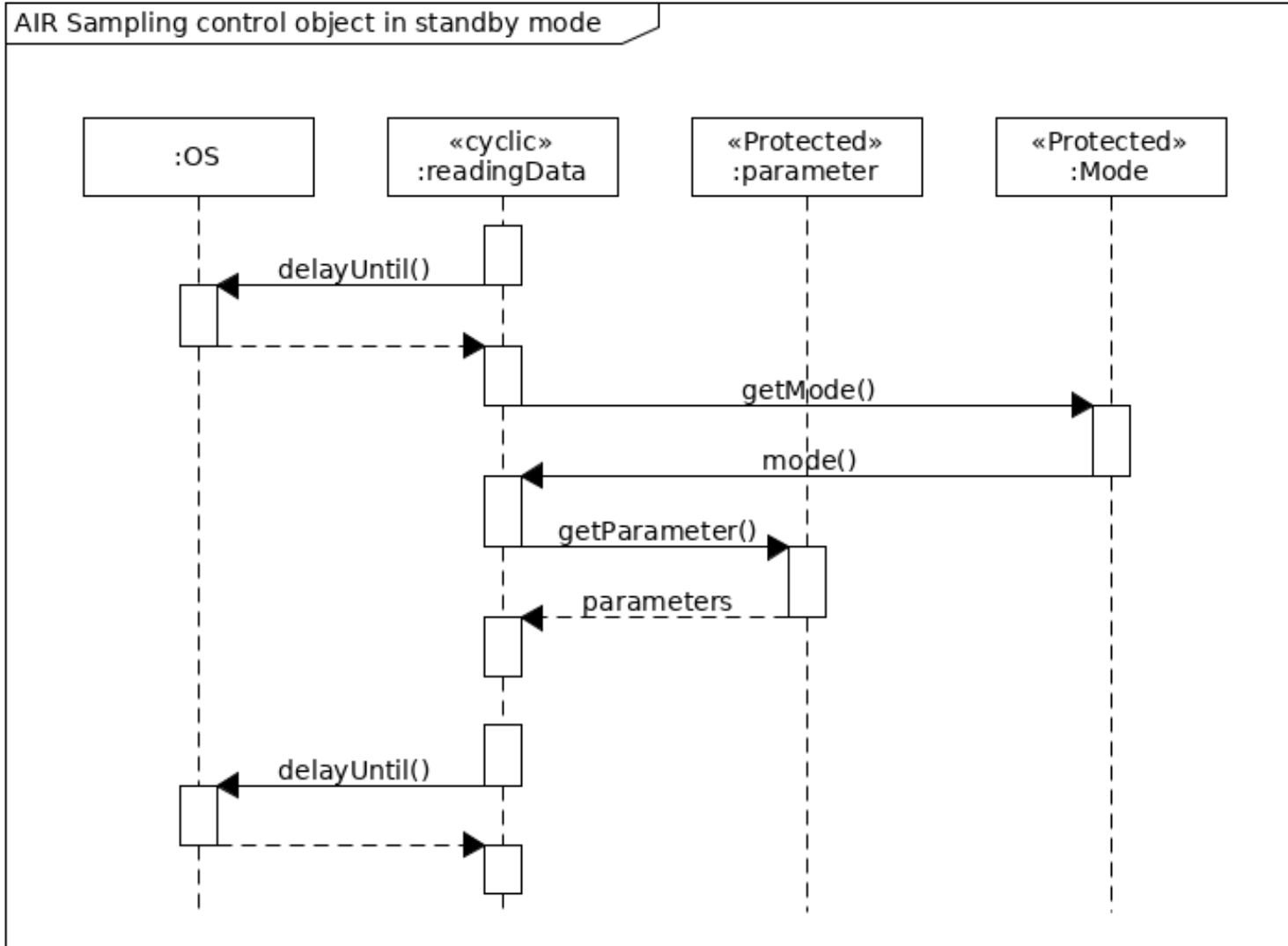
Figure 77: ASC Object in Standby Mode.

C.8 Heating Object Sequence Diagrams
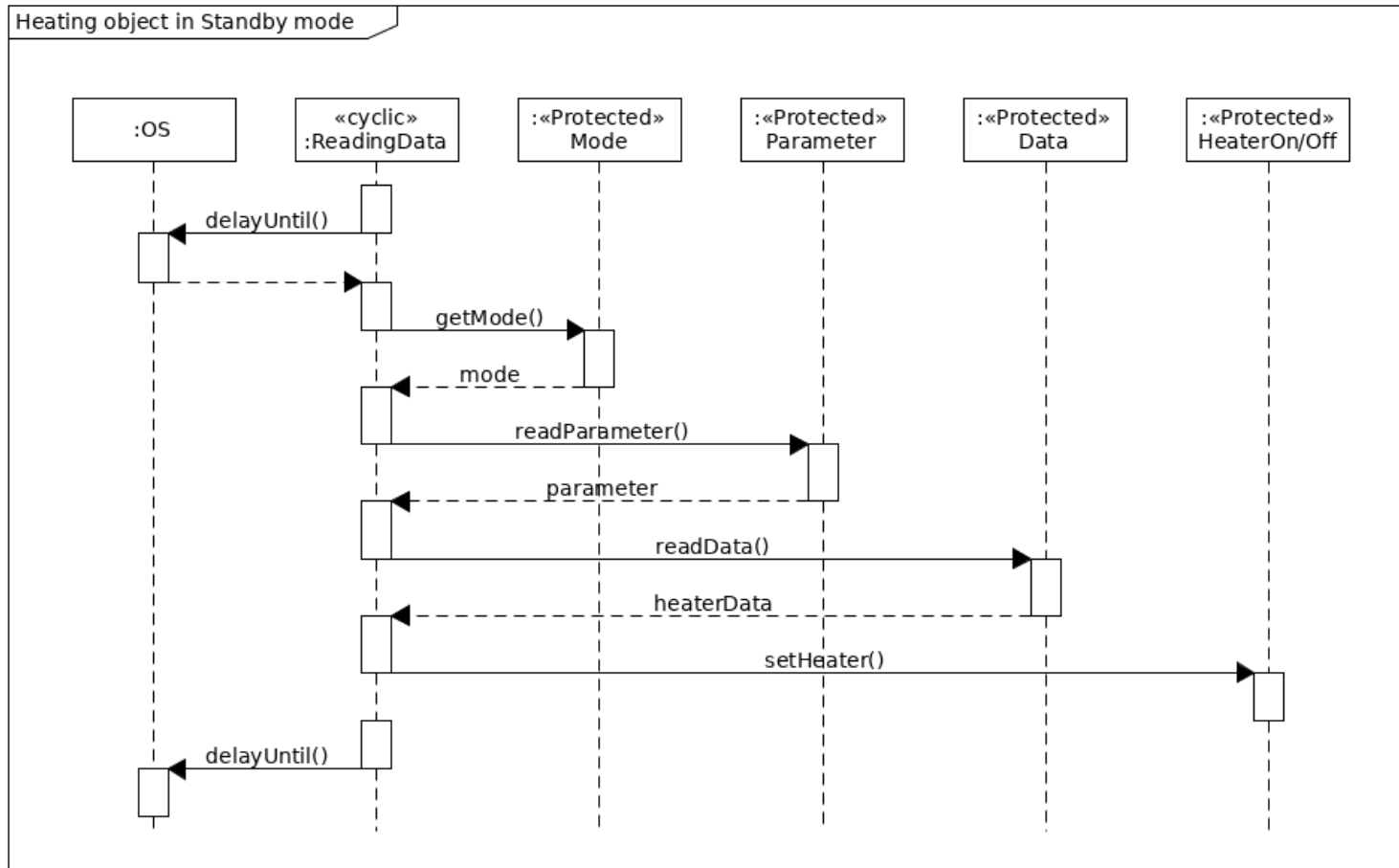
Figure 78: Heating Object in Standby Mode.
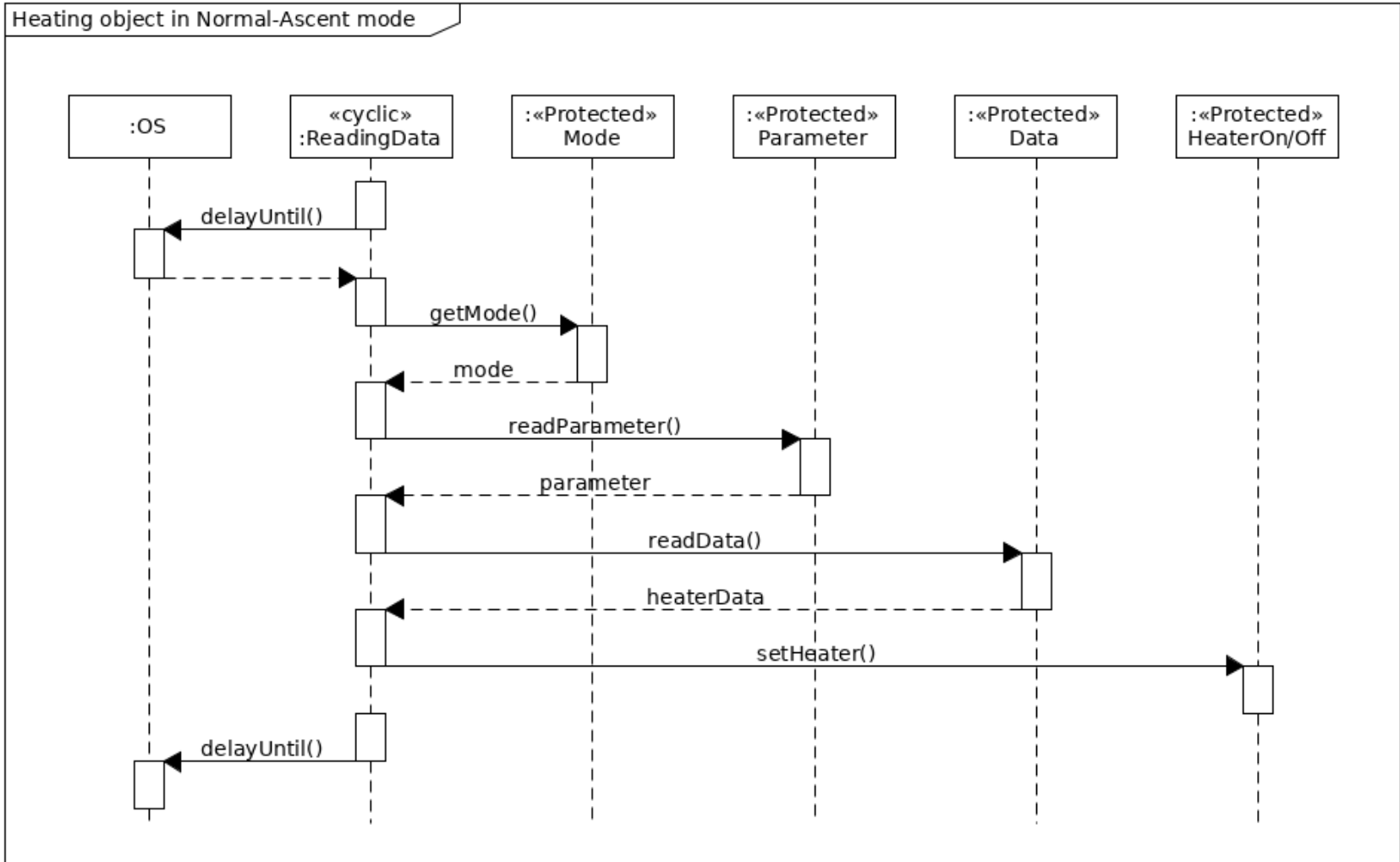
Figure 79: Heating Object in Normal Mode - Ascent.
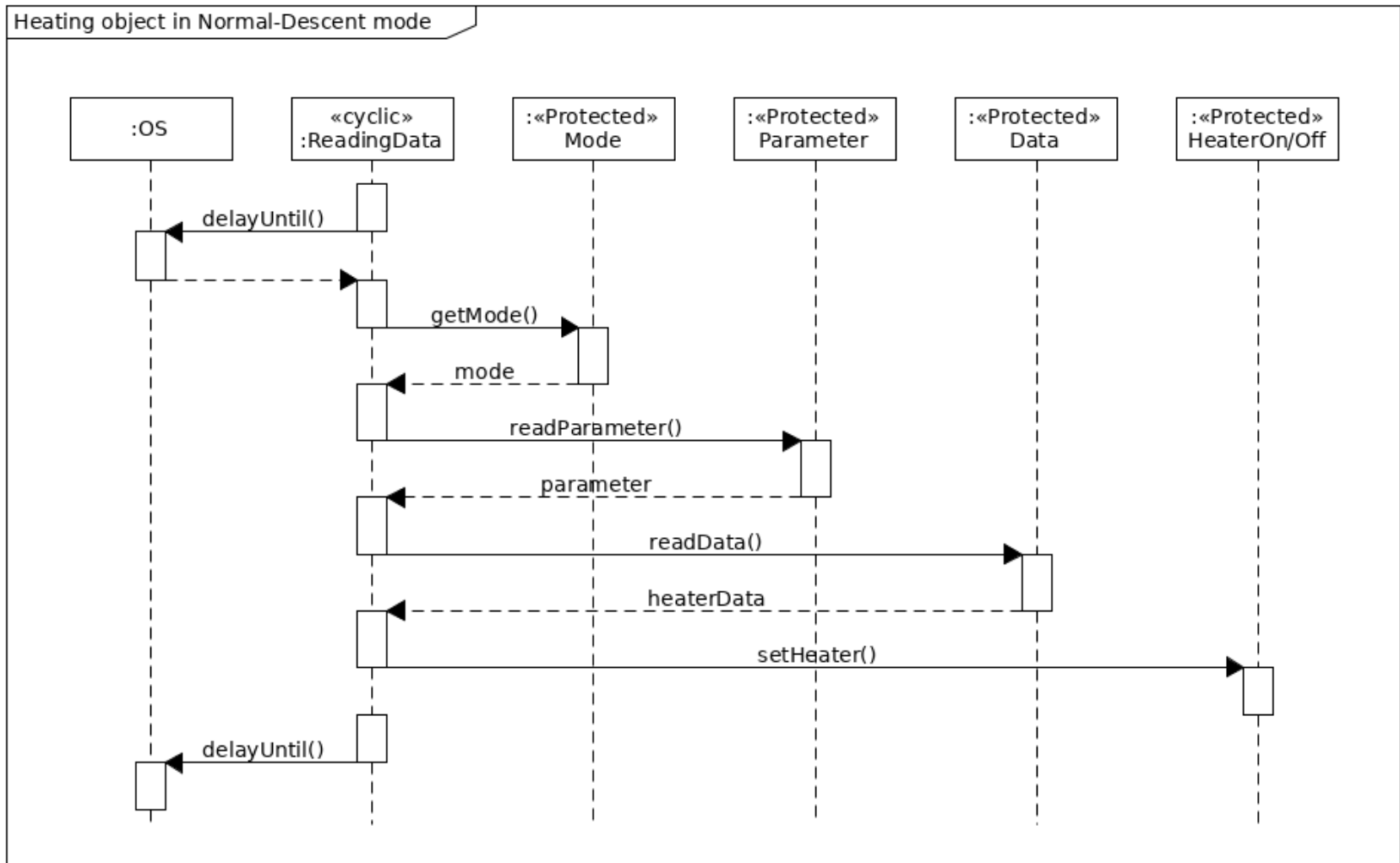
Figure 80: Heating Object in Normal Mode - Descent.

C.9 Sensor Object Sequence Diagrams
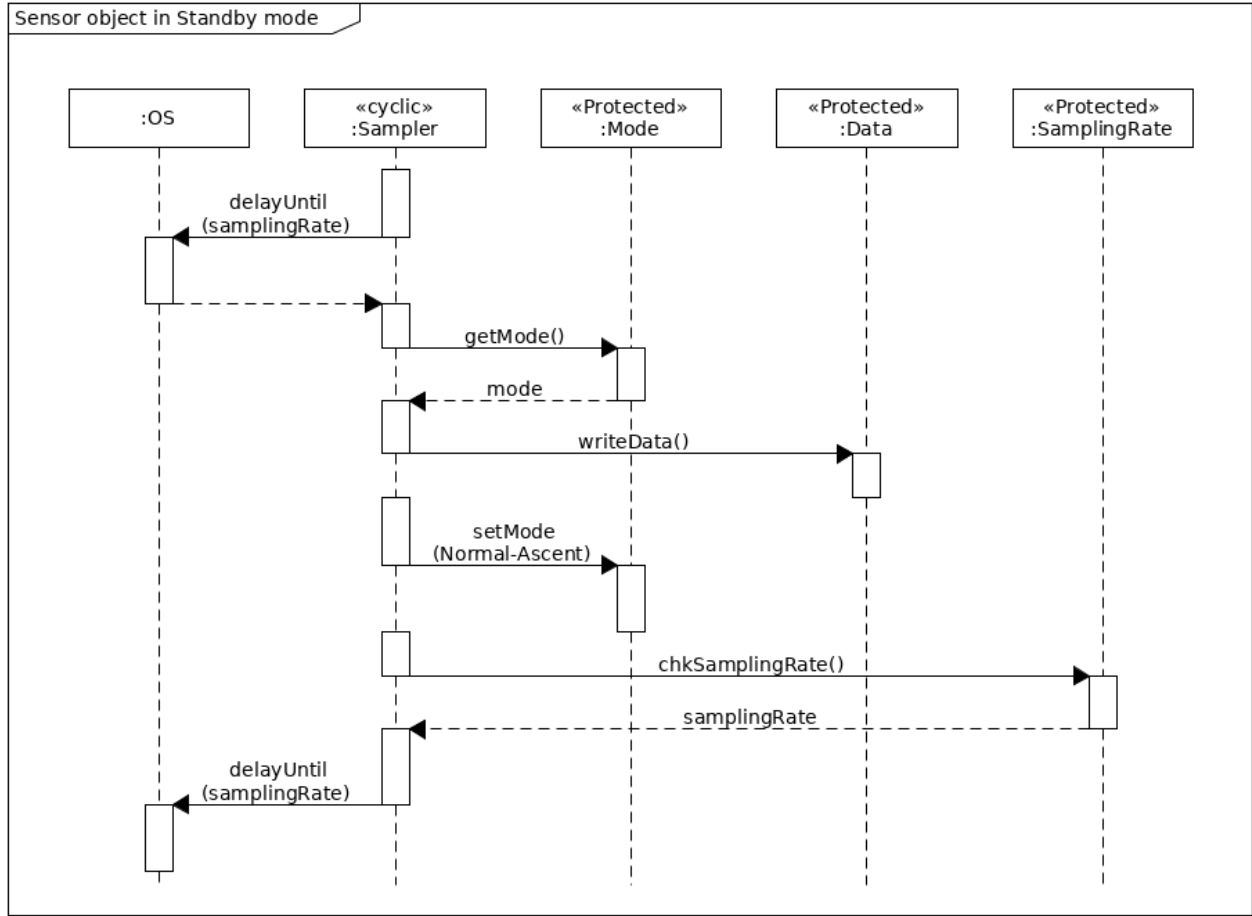
Figure 81: Sensor Object in Standby Mode.
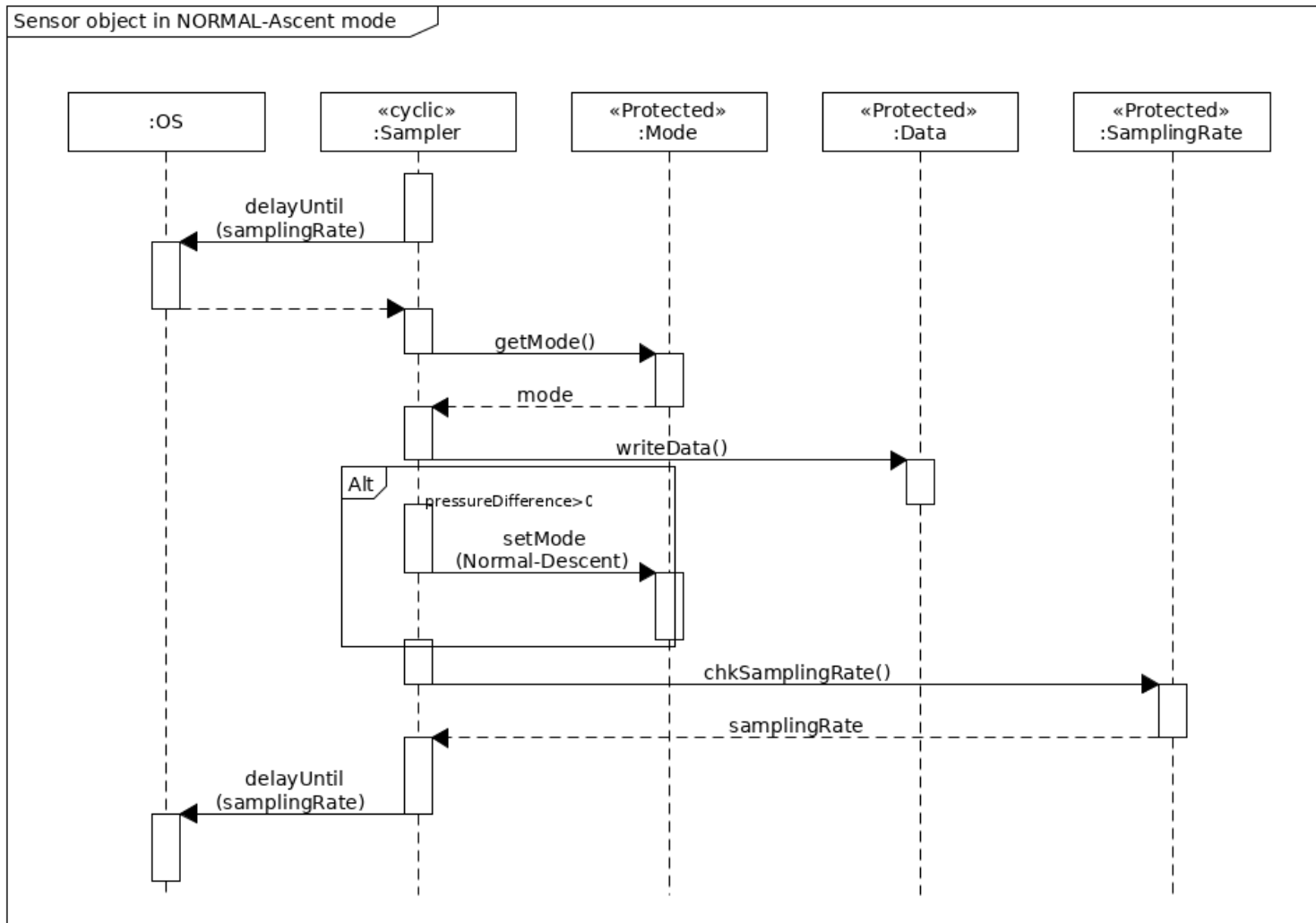
Figure 82: Sensor Object in Normal - Ascent Mode.
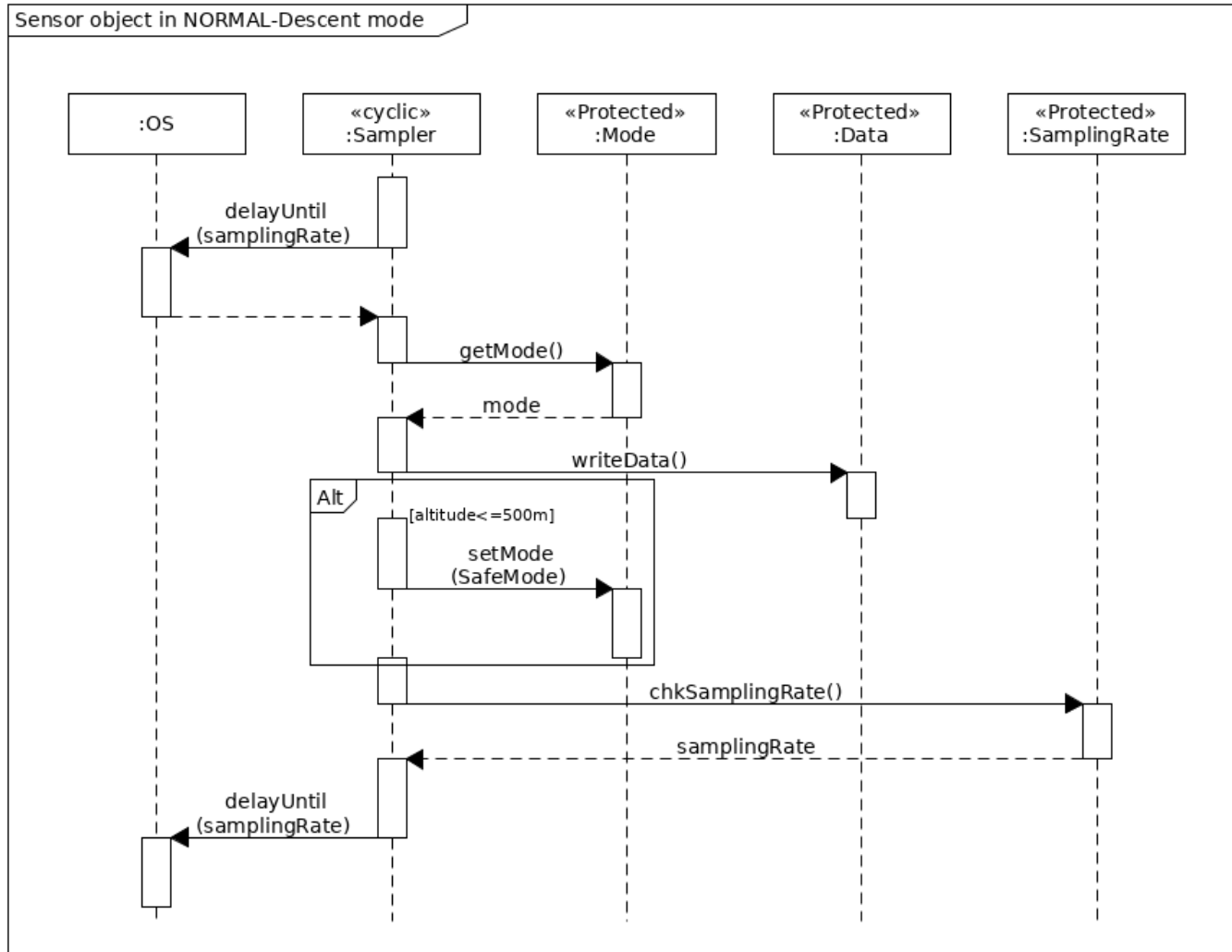
Figure 83: Sensor Object in Normal - Descent Mode.

C.10 Software Interface Diagram

C.10.1 Sensor Object Interface Diagram
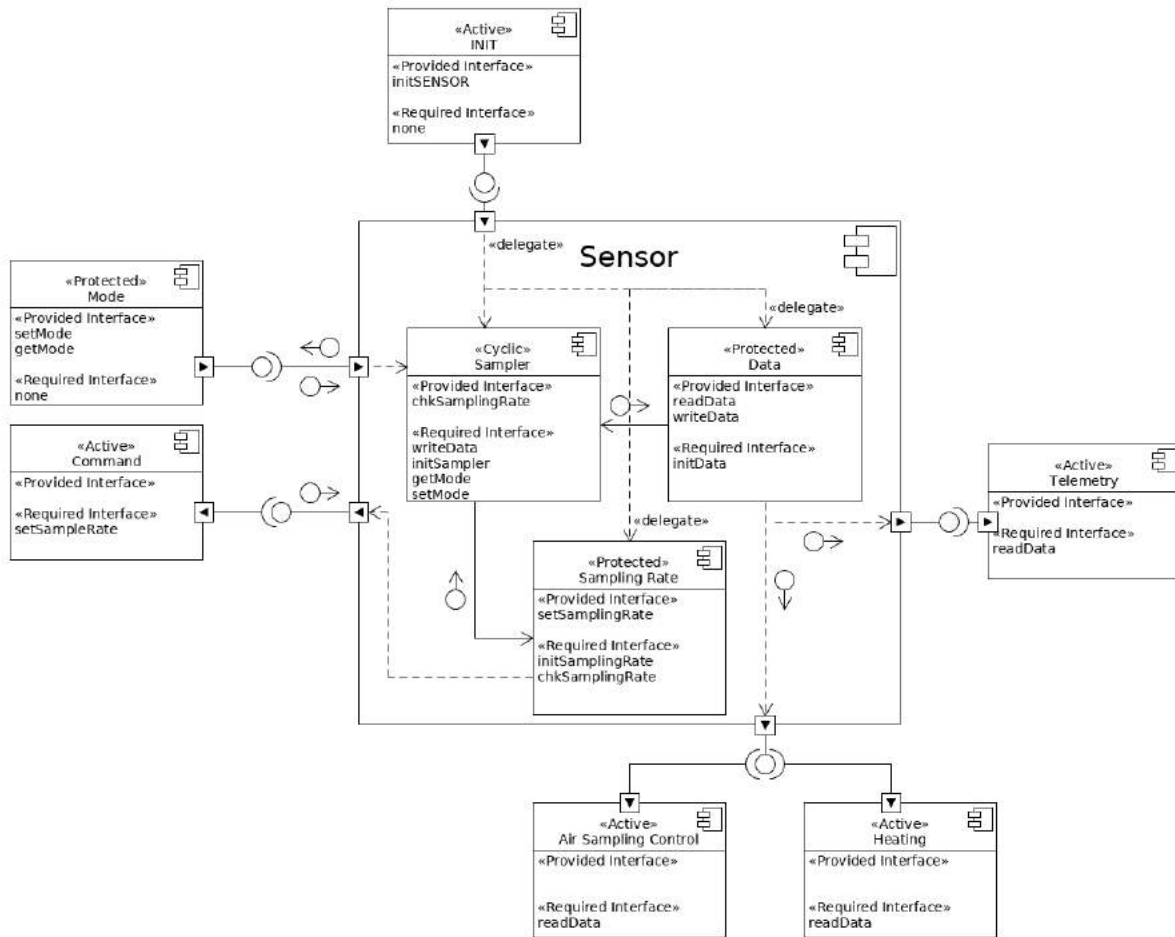
Figure 84: Sensor Object Interface Diagram.

C.10.2   Air Sampling Control Object Interface Diagram
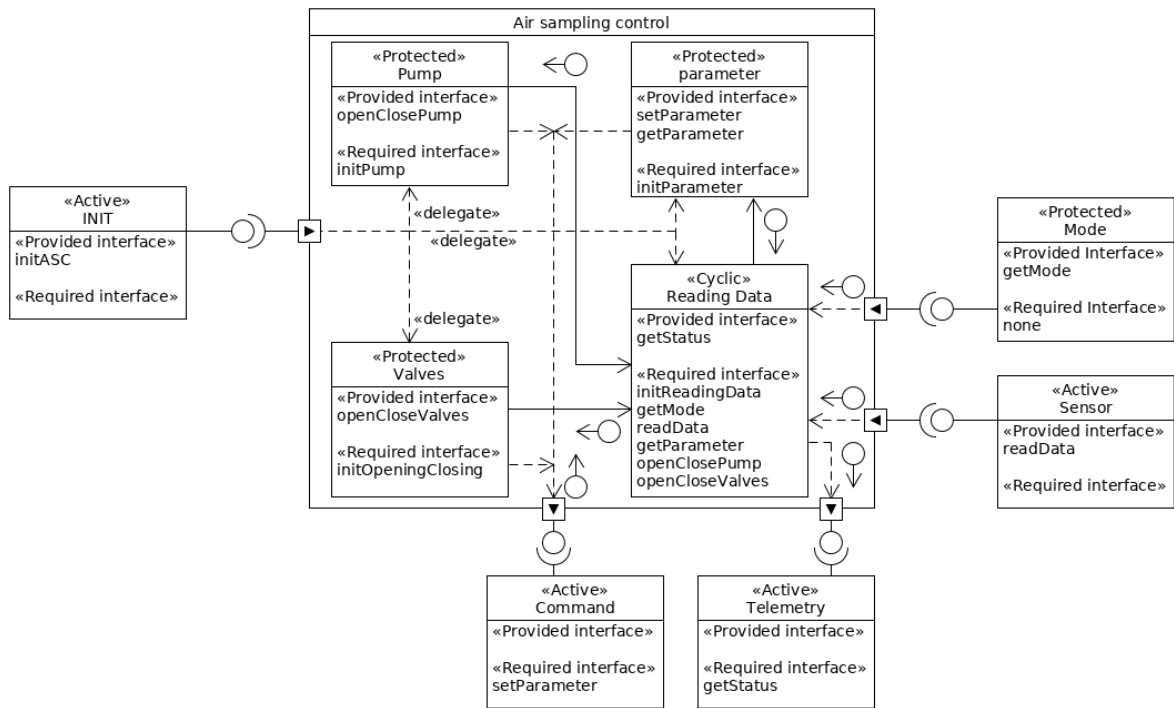
Figure 85: Air Sampling Control Object Interface Diagram.

C.10.3   Heating Object Interface Diagram
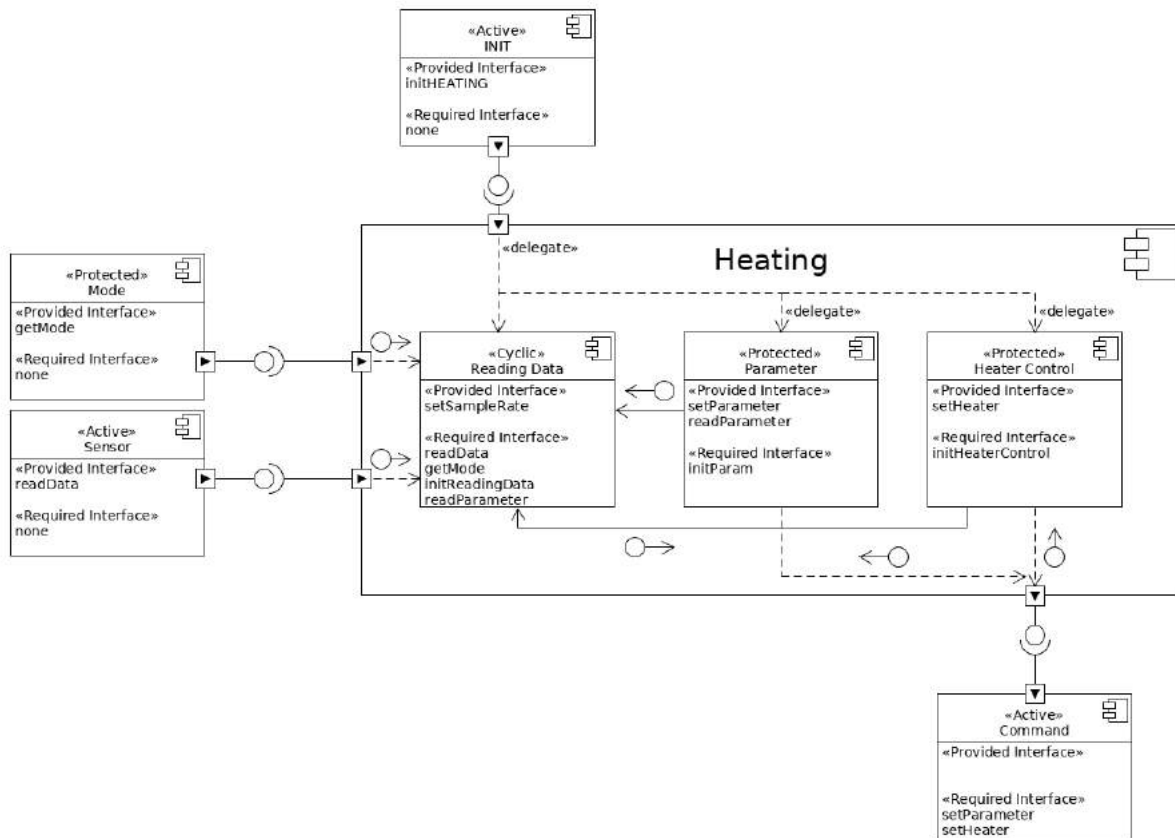
Figure 86: Heating Object Interface Diagram.

C.11 PCB Schematics

Red is traces pulled on the top layer and blue are the traces on the bottom layer.
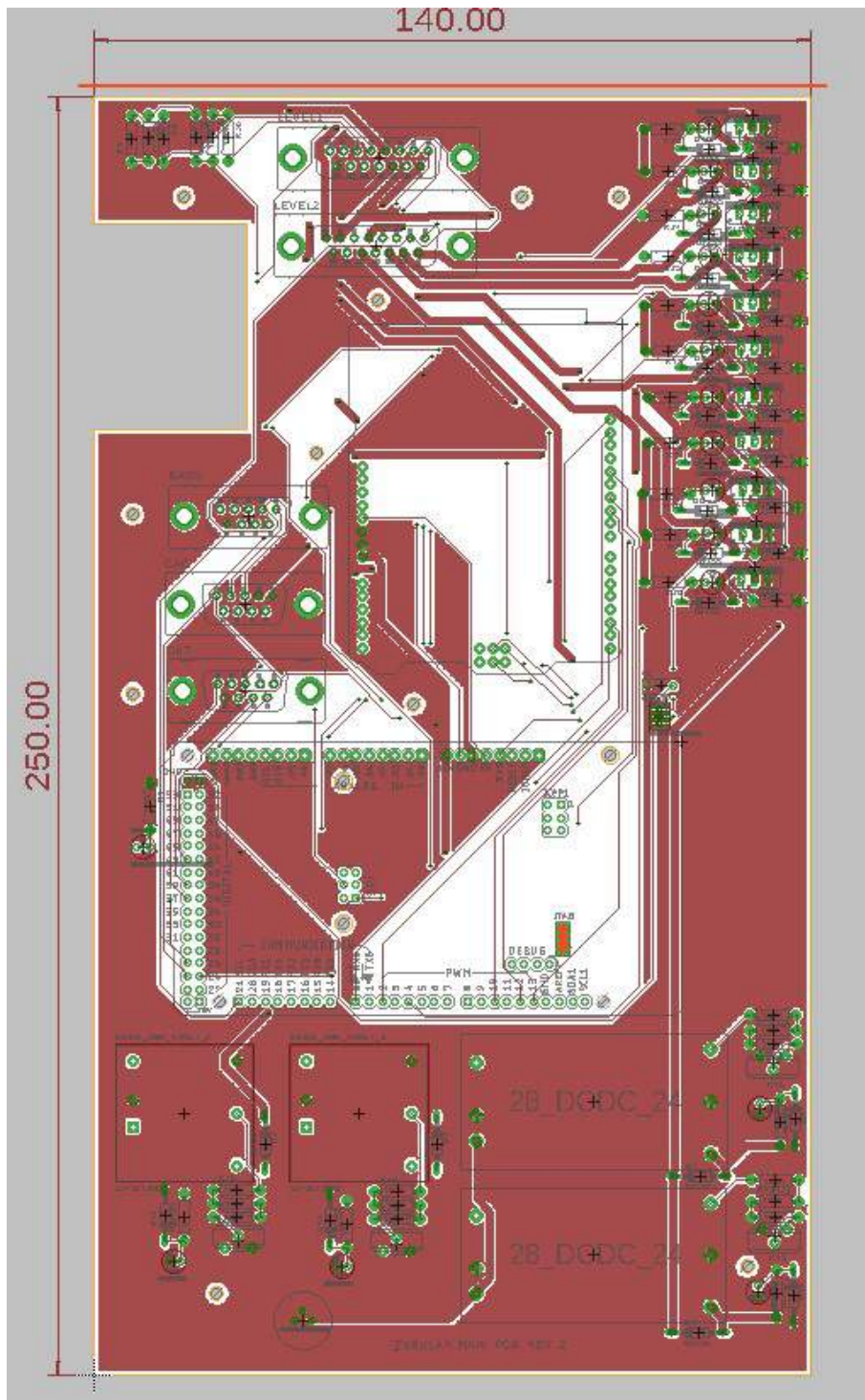
Figure 87: Main PCB Top layer Layout in Eagle.
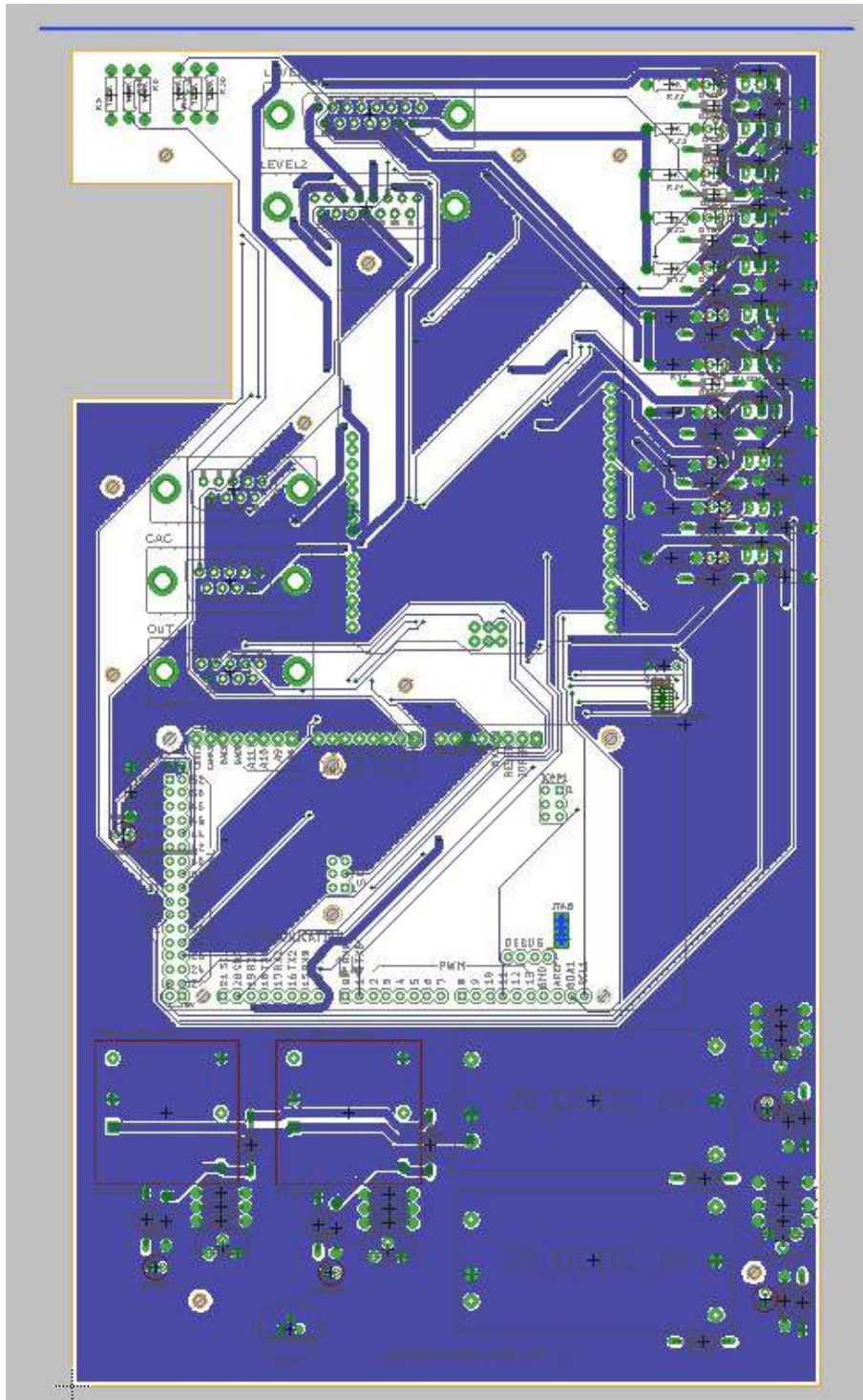
Figure 88: Main PCB bottom layer Layout in Eagle.
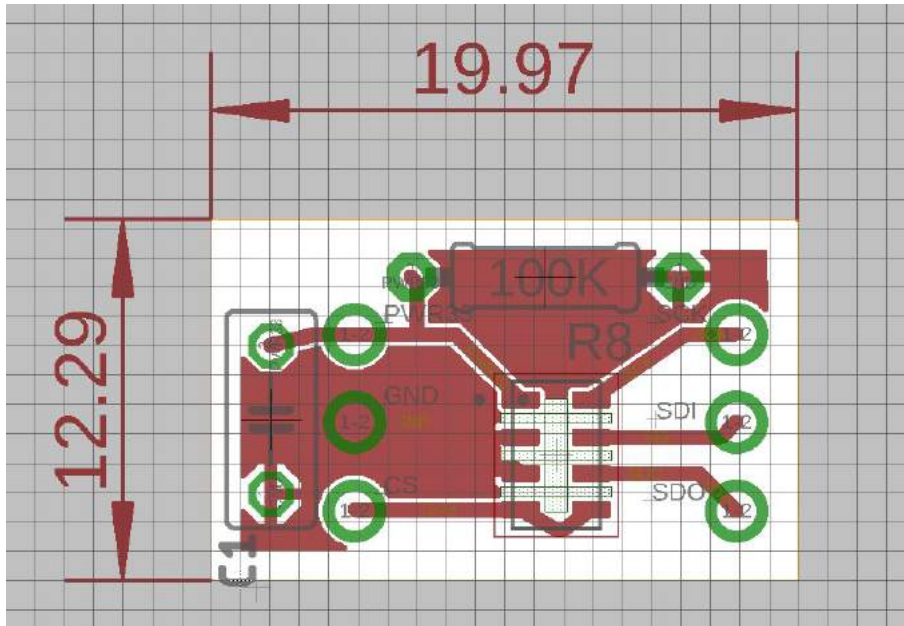
Figure 89: Barometric pressure sensor PCB top layer Layout in Eagle.
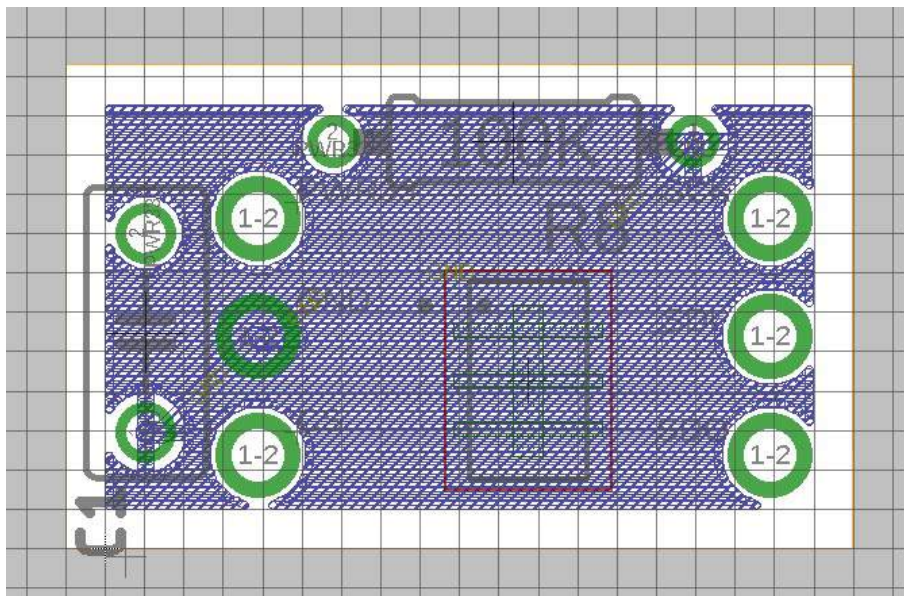
Figure 90: Barometric pressure sensor PCB bottom layer Layout in Eagle.

C.12   Tube

An extra charge is applied for cutting Sulfinert® or Silcosteel®-CR tubing. The charge is calculated from the total number of pieces produced for each line item

Treated Welded/Drawn 304 Grade Stainless Steel Tubing

Our most popular grade of tubing. Recommended for:

- Chromatography applications.
- Gas delivery systems.
- Lower pressures.
- Inert applications.

Maximum temperature of 450 °C in an inert atmosphere.

ID	OD	Wall Thickness	Length 6 Feet cat.#	10 Feet cat.#	15 Feet cat.#	20 Feet cat.#	25 Feet cat.#	50 Feet cat.#	100 Feet cat.#	>100 Feet cat.#*
Sulfinert® Treated (Coiled)										
0.011" (0.28 mm)	0.022" (0.56 mm)		29194	29195	29196	29197	29198	29199	29200	29201
0.021" (0.53 mm)	0.029" (0.74 mm)		29202	29203	29204	29205	29206	29207	29208	29209
0.010" (0.25 mm)	$^1/_{16}$" (1.59 mm)		29210	29211	29212	29213	29214	29215	29216	29217
0.020" (0.51 mm)	$^1/_{16}$" (1.59 mm)		29218	29219	29220	29221	29222	29223	29224	29225
0.030" (0.76 mm)	$^1/_{16}$" (1.59 mm)		29226	29227	29228	29229	29230	29231	29232	29233
0.040" (1.02 mm)	$^1/_{16}$" (1.59 mm)		29234	29235	29236	29237	29238	29239	29240	29241
0.085" (2.16 mm)	$^1/_8$" (3.18 mm)	0.020"	29242	29243	29244	29245	29246	29247	29248	29249
0.210" (5.33 mm)	$^1/_4$" (6.35 mm)	0.020"	29250	29251	29252	29253	29254	29255	29256	29257

*The availability of long lengths is subject to inventory constraints. Lead times may vary depending on the continuous length needed. Please inquire before ordering. Maximum continuous lengths are: 200** ft (cat.# 29201, 29209), 2,000 ft (cat.# 29217, 29225, 29233, 29241), 1,150 ft (cat.# 29249), and 750 ft (cat.# 29257). Pricing for lengths of 101 ft or more is on a per foot basis.
**Contact us if longer length is needed for cat.# 29201 or 29209.

Treated Seamless 316L Grade Stainless Steel Tubing

ordering note

Required length in meters x 3.2808 = length in feet.

High durability tubing. Recommended for:

- Inert applications.
- High temperatures.
- High pressures.
- Corrosive environments.
- Zero bleed.

ID	OD	Wall Thickness	Length 6 Feet cat.#	10 Feet cat.#	15 Feet cat.#	20 Feet cat.#	25 Feet cat.#	50 Feet cat.#	100 Feet cat.#	>100 Feet cat.#*
Silcosteel®-CR Treated (Coiled)										
0.055" (1.40 mm)	$^1/_8$" (3.18 mm)	0.035"	29091	29092	29093	29094	29095	29096	29097	29098
0.180" (4.57 mm)	$^1/_4$" (6.35 mm)	0.035"	29099	29100	29101	29102	29103	29104	29105	29106
0.277" (7.04 mm)	$^3/_8$" (9.52 mm)	0.049"	29107	29108	29109	29110	29111	29112	29113	29114
Sulfinert® Treated (Coiled)										
0.055" (1.40 mm)	$^1/_8$" (3.18 mm)	0.035"	29067	29068	29069	29070	29071	29072	29073	29074
0.180" (4.57 mm)	$^1/_4$" (6.35 mm)	0.035"	29075	29076	29077	29078	29079	29080	29081	29082
0.277" (7.04 mm)	$^3/_8$" (9.52 mm)	0.049"	29083	29084	29085	29086	29087	29088	29089	29090

*The availability of long lengths is subject to inventory constraints. Lead times may vary depending on the continuous length needed. Please inquire before ordering. $^1/_8$" OD: 1,500 ft in one continuous coil; $^1/_4$" OD: 750 ft in one continuous coil; $^3/_8$" OD: 250 ft in one continuous coil. Longer lengths will be more than one coil. Pricing for lengths of 101 ft or more is on a per foot basis.

BX26_TUBULAR_SEDv3-1_22July18

C.13   AAC Manifold Valve

Series *VDW*

For Air Single Unit

Model/Valve Specifications

N.C.

Configuration symbol
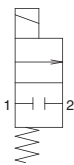
Note) The configuration symbol shows ports 1 and 2 as blocked, but there is actually a limit to the blocking capability when the pressure of port 2 is greater than the pressure of port 1. Please contact SMC when low leakage performance is required.

Normally Closed (N.C.)
Aluminium Body Type

Size	Port size	Orifice diameter [mmø]	Model	Flow-rate characteristics			Maximum operating pressure differential [MPa]	Weight [g]
				C [dm³/(s·bar)]	b	Cv	Pressurized port 1	
2	M5, 1/8	1.6	**VDW20**	0.30	0.45	0.07	0.7	80
		2.3		0.58	0.45	0.18	0.4	
		3.2		1.10	0.38	0.30	0.2	

Resin Body Type (Built-in One-touch Fittings)

Size	Port size	Orifice diameter [mmø]	Model	Flow-rate characteristics			Maximum operating pressure differential [MPa]	Weight [g]
				C [dm³/(s·bar)]	b	Cv	Pressurized port 1	
1	M5 ø3.2 One-touch fitting ø4 One-touch fitting	1.0	**VDW10**	0.14	0.40	0.04	0.9	45
		1.6		0.30	0.25	0.07	0.4	
2	M5 ø4 One-touch fitting ø6 One-touch fitting	1.6	**VDW20**	0.30	0.45	0.07	0.7	80
		2.3		0.58	0.45	0.18	0.4	
		3.2		1.10	0.38	0.30	0.2	

Refer to "Glossary of Terms" on page 11 for details on the maximum operating pressure differential.

Fluid and Ambient Temperature

Fluid temperature [°C]	Ambient temperature [°C]
–10 Note) to 50	–10 to 50

Note) Dew point temperature: –10°C or less

Valve Leakage

Internal Leakage

Seal material	Leakage rate (Air) Note)
NBR	1 cm³/min or less (Aluminium body type)
	15 cm³/min or less (Resin body type)

External Leakage

Seal material	Leakage rate (Air) Note)
NBR	1 cm³/min or less (Aluminium body type)
	15 cm³/min or less (Resin body type)

Note) Leakage is the value at ambient temperature 20°C.

2

SMC

C.14   AAC Flushing Valve and CAC Valve

Compact Direct Operated
2 Port Solenoid Valve For Water and Air *Series VDW10/20/30*

Series VDW10/20/30 2-port type has been remodeled to new compact and lightweight series.
For details about new series, refer to New VDW for VDW10/20 and to Series VX21 for VDW30, respectively.

Dimensions

VDW21-□F

2 x M3 x 5

15

20.5

29.6
14.3
9
0.8

6.7
M3.5 (for grounding)

56

VDW21-*F-

46.2

8

22

M5, 1/8
2 (OUT) port

M5, 1/8
1 (IN) port

27
20
6.35
11.4

27
20

2 x ø3.5
(Bracket mounting hole)

VDW31-□F

2 x M4 x 6

12.8

28

36.5
17.5
9
0.8

10.5
M3.5 (for grounding)

66 (62.5)

VDW31-*F-

55.8

8.5 (6.3)

6

36 (27.6)

1/8, 1/4
2 (OUT) port

1/8, 1/4
1 (IN) port

40
30
6.35
14

34
25

4-ø5
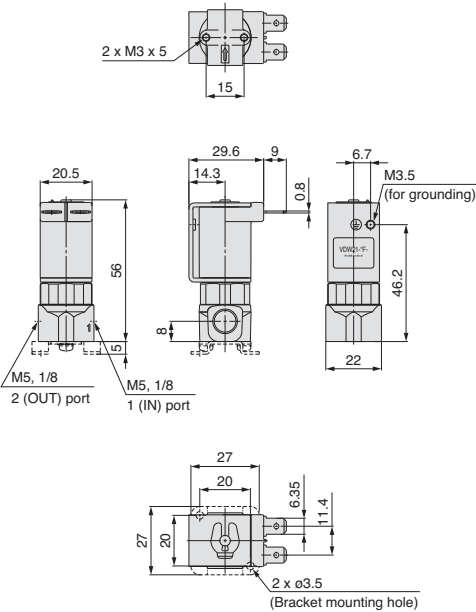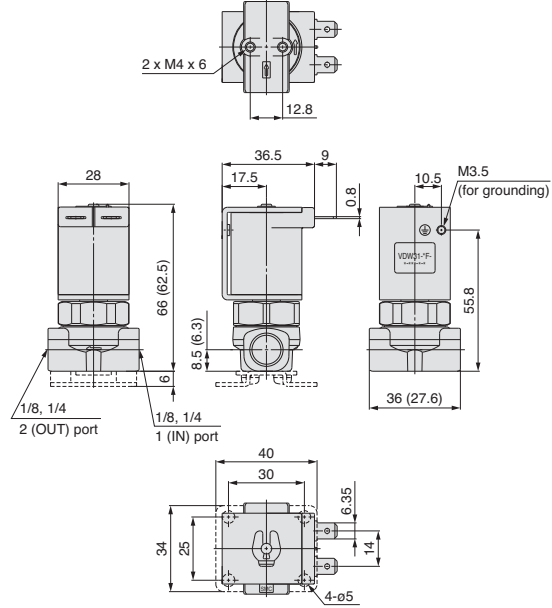
Bracket assembly part no.
・**Series 20**

VDW20−15A−1

・**Series 30**

VCW20−12−01A

BX26_TUBULAR_SEDv3-1_22July18

Series *VDW10/20/30*

How to Order Manifold

VV2DW [2] - [ ] [05] [01] [ ] - [ ] - Q

Series

1	10
2	20
3	30

Material

Symbol	Manifold material	Seal material
-	Brass (C37)	NBR
A		FKM
B		EPDM
G	Stainless steel	NBR
H		FKM
J		EPDM

Stations

02	2 stations
⋮	⋮
10	10 stations

OUT port size

Symbol	Port size	Series		
		10	20	30
M5	M5	○	○	—
01	1/8 (6A)	—	○	○
02	1/4 (8A)	—	—	○

🔍 Note) IN port sizes are as follows.
10: 1/8 (6A)
20: 1/4 (8A)
30: 3/8 (10A)

Thread type

-	Rc
F	G
N	NPT

Option

-	None
F	With bracket

🔍 Note) Series 30 is available with bracket only.

How to Order Manifold Assembly

Enter the mounting valve and option part numbers under the manifold base part number.

<Ordering example>
VV2DW2-0501 ········ 1 set   **Manifold part no.**
∗**VDW23-5G-2** ········ 5 sets   **Valve part no.**
                                      (Stations 1 to 5)

"∗" is the symbol for assembly. Add an "∗" in front of the part numbers to have solenoid valves, etc. mounted on the manifold.

Enter together in order, counting from station 1 on the D side.
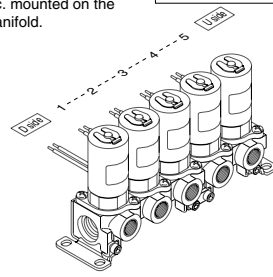
How to Order Valves (For manifold)

VDW [2] [3] - [5] G - [2] - [ ] - Q

Series

1	10
2	20
3	30

Valve type

3	N.C. for manifold

Voltage

Symbol	Voltage	Grommet / Tape winding	Faston™ terminal, Molded	Grommet / Molded
1	100 VAC (50/60 Hz)	●	—	●
2	200 VAC (50/60 Hz)	●	—	●
3	110 VAC (50/60 Hz)	●	—	●
4	220 VAC (50/60 Hz)	●	—	●
5	24 VDC	●	●	●
6	12 VDC	●	●	●
V	6 VDC	●	●	●
S	5 VDC	●	●	●
R	3 VDC	●	●	●

∗ Please consult with SMC regarding other voltages.

Coil type Note)

G	Grommet / Tape winding
F	Faston™ terminal / Molded
W	Grommet / Molded

Note) For series and coil type combinations, refer to page 1.

Material and insulation type

Symbol	Body material	Seal material	Coil insulation
-	Brass (C37)	NBR	Class B
A		FKM	
B		EPDM	
G	Stainless steel	NBR	
H		FKM	
J		EPDM	
L Note)		FKM	

🔍 Note) For deionized water: the armature assembly is a corrosion resistant construction.

Orifice size

Symbol	Orifice diameter (mmø)	Series
1	1	10
2	1.6	
1	1.6	20
2	2.3	
3	3.2	
2	2	30
3	3	
4	4	

Manifold Options

Blanking plate assembly

• Series 10, 20

VVDW [2] 0 - 3A - [ ]

Series

1	10
2	20

Material

Symbol	Plate material	Seal material
G	Stainless steel	NBR
H		FKM
J		EPDM

∗ Plate material is stainless steel only.

• Series 30

VVCW20 - 3A - [ ]

Material

Symbol	Plate material	Seal material
G	Stainless steel	NBR
H		FKM
J		EPDM

SMC

Dimensions

VV2DW1

2 x ∗1/8 (IN port)
(∗: Thread type)

4 x M3
∗ When w/o bracket, M3 threads
at both ends (4 locations) can
be used for other purposes.

| D side | Stations | 1 | 2 | 3 | 4 | 5 | n | U side |

n x M5
(OUT port)
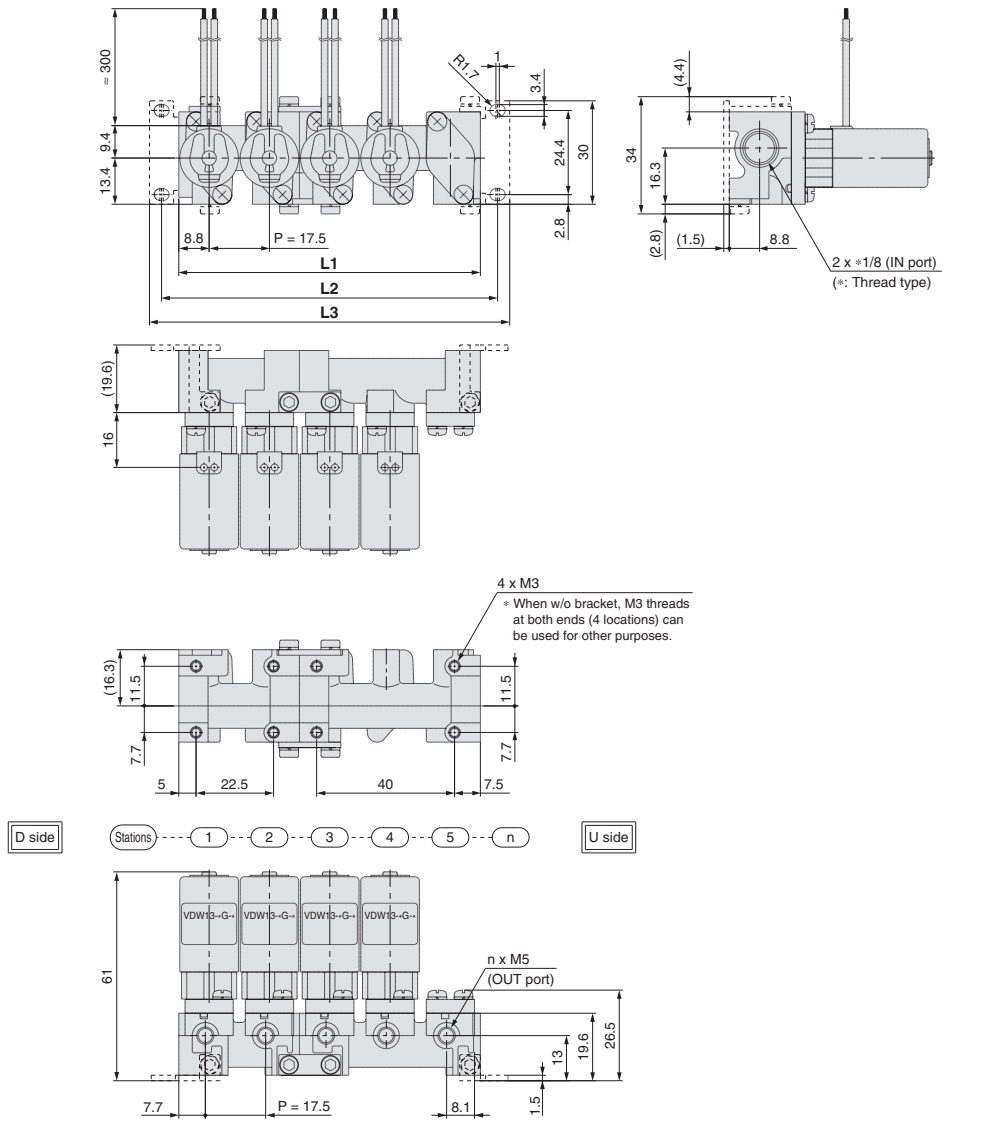
L Dimension
(mm)

Dimension	n (stations)								
	2	3	4	5	6	7	8	9	10
L1	35	52.5	70	87.5	105	122.5	140	157.5	175
L2	45	62.5	80	97.5	115	132.5	150	167.5	185
L3	52	69.5	87	104.5	122	139.5	157	174.5	192
Manifold composition	2 stns. x 1	3 stns. x 1	2 stns. x 2	2 stns. + 3 stns.	3 stns. x 2	2 stns. x 2 + 3 stns.	2 stns. + 3 stns. x 2	3 stns. x 3	2 stns. x 2 + 3 stns. x 2

Note) The manifold base consists of a junction of 2 and 3 station bases.
Refer to page 10 and 11 regarding manifold additions.

C.15   Pump

NMP850K_DC-B

PERFORMANCE DATA

Type	KNF DC motor, brushless (V)	Delivery at atm. pressure (l/min)[1]	Max. operating pressure (bar)	Ultimate vacuum (mbar abs.)
NMP850KPDC-B	12	4.2	1.5	230
NMP850KTDC-B	12	3.5	1.5	300
NMP850KPDC-B	24	4.2	1.5	230
NMP850KTDC-B	24	3.5	1.5	300

[1] Liter at STP

PUMP MATERIAL

Type	Pump head	Diaphragm	Valves
NMP850KPDC-B	PPS	EPDM	EPDM
Chemically resistant version			
NMP850KTDC-B	PPS	PTFE-coated	FFPM
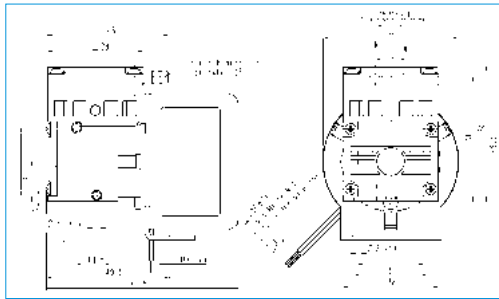
NMP850KPDC-B
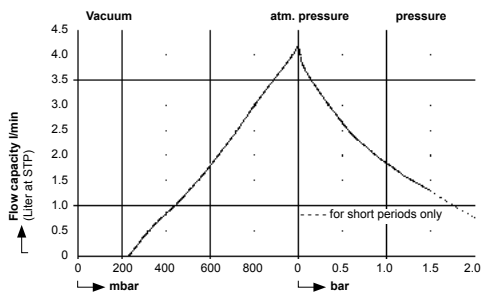
NMP850KTDC-B
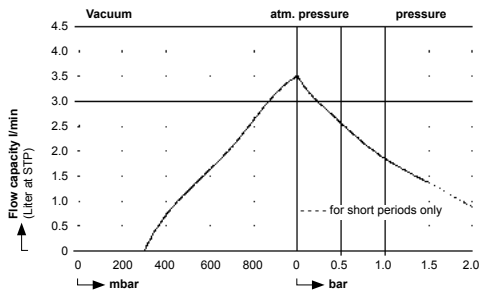
NMP850.1.2KPDC-B

PERFORMANCE DATA

Type	KNF DC motor, brushless (V)	Delivery at atm. pressure (l/min)[1]	Max. operating pressure (bar)	Ultimate vacuum (mbar abs.)
NMP850.1.2KPDC-B	12	8.0	1.5	230
NMP850.1.2KPDC-B	24	8.0	1.5	230

PUMP MATERIAL

Type	Pump head	Diaphragm	Valves
NMP850.1.2KPDC-B	PPS	EPDM	EPDM
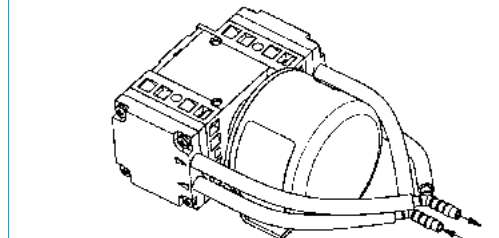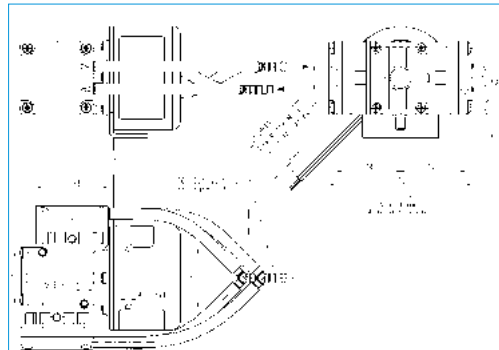
NMP850.1.2KPDC-B
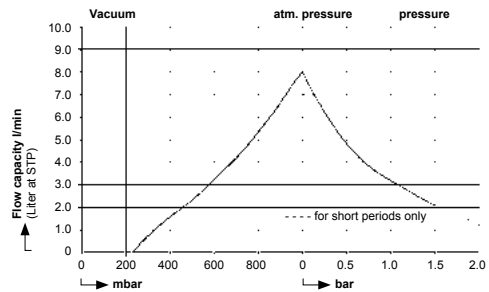
C.16 Airflow Sensor

Airflow Sensors

High Flow Mass Airflow/Amplified

AWM5000 Series

FEATURES
- Linear voltage output
- Venturi design
- Remote mounting capability
- Active laser trimming improves inter-change ability
- Separate gas calibration types:
  - Ar (argon)
  - N_2 (nitrogen) or
  - CO_2 (carbon dioxide)

In-Line Flow Measurement
AWM5000 Series Microbridge Mass Air-flow Sensors feature a venturi type flow housing. They measure flow as high as 20 standard liters per minute (SLPM) while inducing a maximum pressure drop of 2.25″ H_2O. The microbridge chip is in di-rect contact with the flow stream, greatly reducing error possibilities due to orifice or bypass channel clogging.

Rugged, Versatile Package
The rugged plastic package has been designed to withstand common mode pressures up to 50 psi, and the small sensing element allows 100 gs of shock without compromising performance. The included ''AMP'' compatible connector provides reliable connection in demand-ing applications.

On-board Signal Conditioning
Each AWM5000 sensor contains circuitry which performs amplification, lineariza-tion, temperature compensation, and gas calibration. Figure 1 (Heater Control Cir-cuit) and Figure 2 (Sensor Bridge Circuit and Amplification Linearization Circuit) il-lustrate the on-board electrical circuitry for the AWM5000 Series. A 1 to 5 VDC linear output is possible for all listings regardless of flow range (5, 10, 15, or 20 SLPM) or calibration gas (nitrogen, car-bon dioxide, nitrous oxide, or argon). All calibration is performed by active laser trimming.

Figure 1

Heater Control Circuit

Figure 2

Sensor Bridge Circuit and Amplification Linearization Circuit
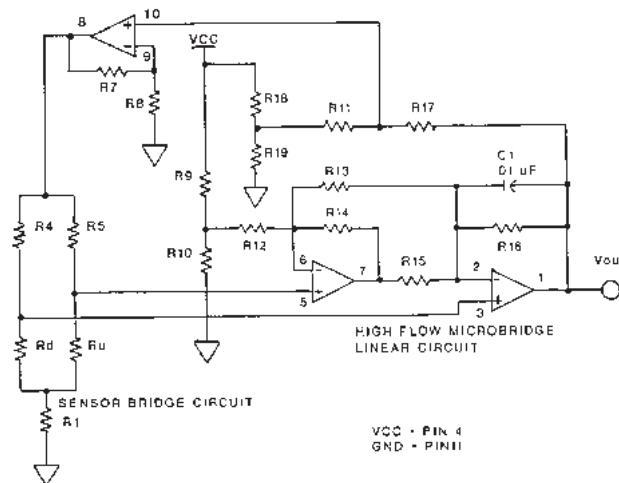
Airflow

BX26_TUBULAR_SEDv3-1_22July18

SPECIFICATIONS (Performance Characteristics @ 10.0 ±0.01 VDC, 25°C)

	AWM5101	AWM5102	AWM5103	AWM5104
Flow Range (Note 3)	0-5 SLPM	0-10 SLPM	0-15 SLPM	0-20 SLPM
Suffix - Calibration gas	**VA** - Argon (Ar)		**VC** - Carbon dioxide (CO_2)	**VN** - Nitrogen (N_2)
	Min.	**Typ.**	**Max.**	
Excitation VDC	8	10±0.01	15	
Power consumption (mW)	—	—	100	
Response time (msec)	—	—	60	
Null output VDC	0.95	1	1.05	
Null output shift −20° to 70°C	—	±0.050 VDC	±.200 VDC	
Common Mode Pressure (psi)	—	—	50	
Temperature range	−20° to +70°C, (−4° to 158°F)			
Weight	60 grams (2.12 oz.)			
Shock ratings	100 g peak, 6 msec half-sine (3 drops, each direction of 3 axes)			
Output @ laser trim point	5 VDC @ Full Scale Flow			
Output voltage shift +20° to −25°C, +20° to 70°C	Suffix VA or VN ±7.0% Reading, Suffix VC ±10.0% Reading			
Linearity error (2)	±3.0% Reading (max.)			
Repeatability & Hysteresis	±0.5% Reading (max.)			
Connector (Included) —Four pin receptacle	MICRO SWITCH (SS12143)/AMP (103956-3)			
Leak rate, max	0.1 psi/min. at static condition, (Note 2)			

Notes:
1. Linearity specification applies from 2 to 100% full scale of gas flow range, and does not apply to null output at 0 SLPM.
2. The AWM5000 series product has a leakage spec of less than 0.1 psi per minute at 50 psi common mode pressure. If during installation, the end adapters are twisted with respect to the flowtube, this may compromise the seal between the o-ring and the flowtube and may cause a temporary leak. This leak might be as high as 1 psi or might remain in specification. It will self-reseal as the o-ring takes a new set. Approximately 85% of the leakage will dissipate in 24 hours. Within 48 hours, complete recovery will take place.
3. SLPM denotes standard liters per minute, which is a flow measurement referenced to standard conditions of 0°C/1 bar (sea level), 50% RH.

NOTICE
AWM5000—Chimney Effect
AWM microbridge mass airflow sensors detect mass airflow caused by heat transfer. The thermally isolated microbridge structure consists of a heater resistor positioned between two temperature sensing resistors.

The heater resistor maintains a constant temperature, 160°C above ambient, during sensor operation. Airflow moving past the chip transfers heat from the heater resistor. This airflow warms the downstream resistor and cools the upstream resistor. The temperature change and the resulting change in resistance of the temperature resistors is proportional to the mass airflow across the sensing element.

When the sensor is mounted in a vertical position, under zero flow conditions, the sensor may produce an output that is the result of thermally induced convection current. This occurrence is measurable in the AWM5000 Series, particularly in the 5 SLPM versions. When designing the sensor into applications where null stability is critical, avoid mounting the sensor in a vertical position.

Airflow Sensors

High Flow Mass Airflow/Amplified

OUTPUT CURVES (Performance Characteristics @ 10.0 ±0.01 VDC, 25°C)
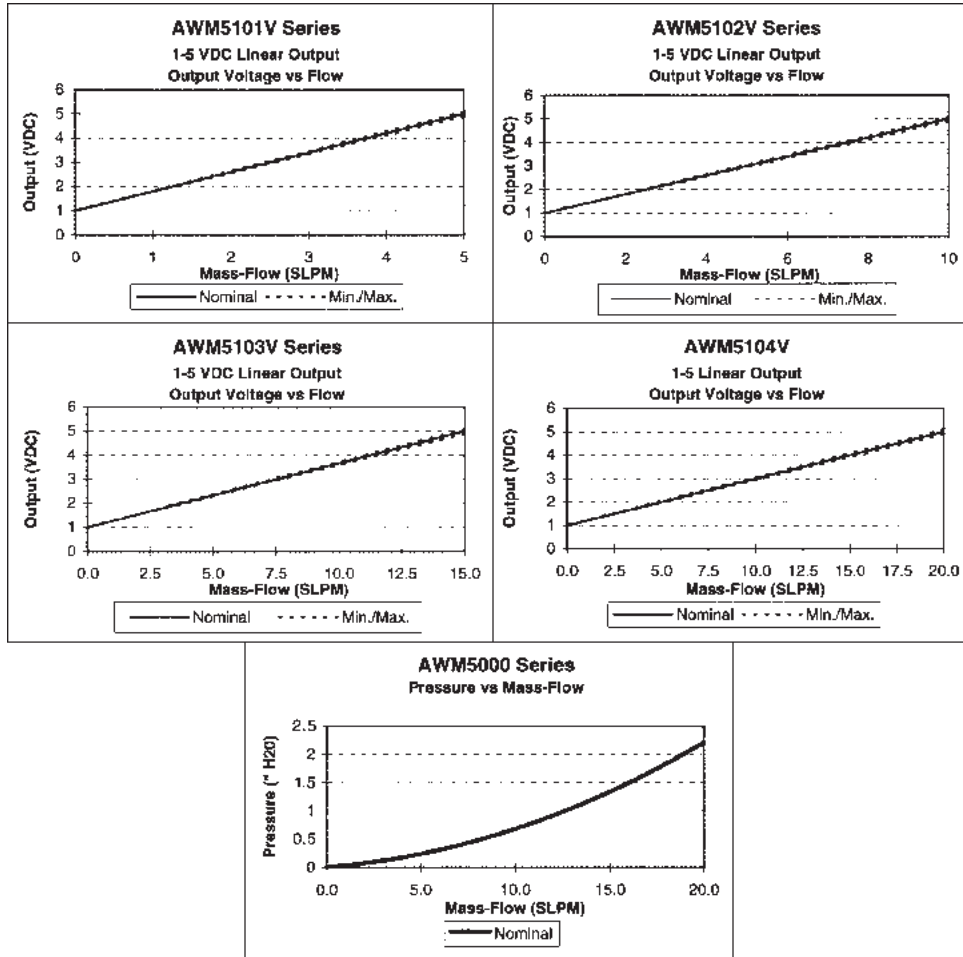
Airflow Sensors

Highflow Mass Airflow/Amplified

AWM5000 Series

AWM5000 ORDER GUIDE

Catalog Listing	Flow Range
AWM5101VA	5 SLPM, Argon calibration
AWM5101VC	5 SLPM, CO_2 calibration (2)
AWM5101VN	5 SLPM, N_2 calibration (1)
AWM5102VA	10 SLPM, Argon calibration
AWM5102VC	10 SLPM, CO_2 calibration (2)
AWM5102VN	10 SLPM, N_2 calibration (1)
AWM5103VA	15 SLPM, Argon calibration
AWM5103VC	15 SLPM, CO_2 calibration (2)
AWM5103VN	15 SLPM, N_2 calibration (1)
AWM5104VA	20 SLPM, Argon calibration
AWM5104VC	20 SLPM, CO_2 calibration (2)
AWM5104VN	20 SLPM, N_2 calibration (1)

CONNECTOR ORDER GUIDE

Catalog Listing	Description
SS12143	Four pin Electrical connector Connectors use Amp 103956-3

Note: All listings have 1 - 5 VDC linear output with 10 VDC supply over given flow range for a specific calibration gas.

1. N_2 calibration is identical to O_2 and air calibration.

2. CO_2 calibration is identical to N_2O calibration.

3. For additional gas correction factors, see Application Note 3.

OUTPUT CONNECTIONS

Pin 1   + Supply voltage
Pin 2   Ground
Pin 3   No connection
Pin 4   Output voltage
Arrow on bottom of housing indicates direction of flow.

MOUNTING DIMENSIONS (for reference only)

82   Honeywell ● Sensing and Control ● 1-800-537-6945 USA ● +1-815-235-6847 International ● 1-800-737-3360 Canada
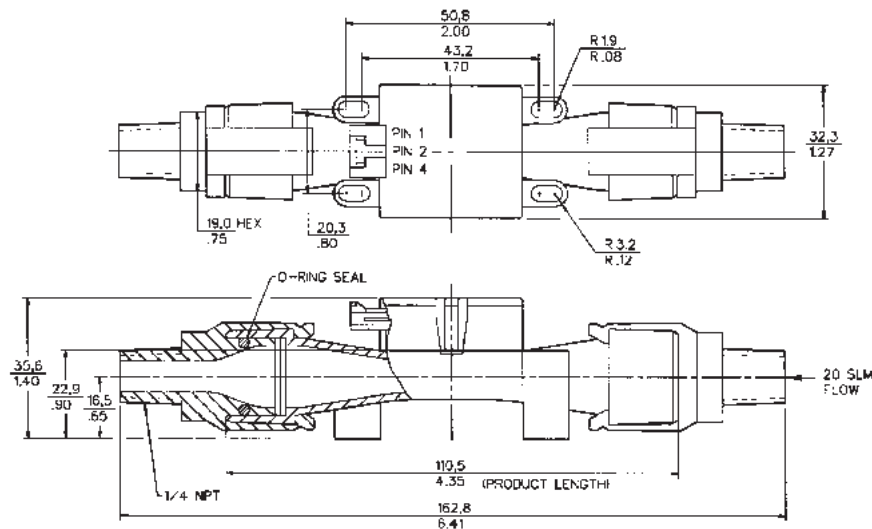
C.17 Inline Pressure Sensor

Gems
Sensors & Controls

3500 Series
Compact Low Pressure OEM Pressure Transmitters

▶ 5 to 600 psi pressure ranges (0.35 to 40 bar)
▶ Choice of outputs, electrical connections and pressure ports
▶ Operating temperature up to 257°F (125°C)

For OEMs that need consistent high levels of performance, reliability and stability the 3500 Series units offer a small package size with all stainless steel wetted parts at an unbeatable price performance ratio. A wide choice of electrical outputs as well as both electrical and pressure connections means the unit is suitable for most applications without modification. The compact construction of the 3500 Series makes it ideal for installation where space is at a premium.

Specifications

Input	
Pressure Range	5-600 psi (0.35-40 bar)
Proof Pressure	2x
Burst Pressure	3X

Performance	
Long Term Drift	<0.2% FS/YR
Accuracy	0.25% FS
Thermal Error, Max.	±1% / 176°F (80°C)
Compensated Temperatures	-4°F to +212°F (-20°C to +100°C)
Operating Temperatures	-40°F to +257°F (-40°C to +125°C)
Zero Tolerance, Max.	±0.5% of span
Span Tolerance, Max.	±0.5% of span
Fatigue Life	Designed for more than 100 M cycles

Mechanical Configuration	
Pressure Port	See under "How to Order," last page
Wetted Parts	316L Stainless Steel
Electrical Connection	See under "How to Order," last page
Enclosure	IP67
Vibration	BSEN 60068-2-6 (FC)
	BSEN 60068-2-64 (FH)
Shock	BSEN 60068-2-27 (Ea)
Approvals	CE, RoHS
Weight	1.23 to 1.9 ounces (35-53 grams). Configuration dependant

EMC Specifications

Emissions Tests: EN61326-1:2006 and EN61326-2-3:2006

EN55011:2009 + A1	Radiated Emissions

Immunity Tests: EN61326-1:2006 and EN61326-2-3:2006

EN61000-4-2:2009	Electrostatic Discharge
EN61000-4-3:2006 + A2	Radiated Immunity
EN61000-4-4:2012	Fast Burst Transients
EN61000-4-6:2009	Conducted RF Immunity

CE RoHS

Individual Specifications

Voltage	
Output	0V min. to 10V max.
	See under "How to Order," last page
Supply Voltage (Vs)	2 Volts above full scale to 30 Vdc
	(24 Vdc, max. above 230°F (110°C) applications)
Source and Sinks	8 mA

Current	
Output	4-20 mA
Supply Voltage (Vs)	10-30 Vdc (24 Vdc, max. above 230°F (110°C) applications)
Maximum Load Resistance	(Supply Voltage -10) x 50ohms

Ratiometric	
Output	0.5 to 4.5V
Supply Voltage (Vs)	5 Vdc ±10%

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Pressure Ports

SAE

	1/8˝-27 NPT	1/4˝-18 NPT	7/16˝-20 UNF with 37° Flare	7/16˝-20 UNF	1/8˝-27 NPTF
Dimensions in Inches	0.52 / 0.39	0.52 / 0.57	0.52 / 0.55	0.52 / 0.5 / 0.43	0.52 / 0.37
Fitting Code	08	02	04	1J	4D
Torque	2-3 TFFT*	2-3 TFFT*	15-16 NM	18-20 NM	2-3 TFFT*

BSP & Metric

	G1/8˝ External	G1/4˝-19 External w/O-Ring	G1/4˝-19 A Integral Face Seal	M12 x 1.5 w/O-Ring
Dimensions in MM	13.1 / 11.0	13.1 / 11.0	13.1 / 12.5 / 11.0	13.1 / 11.0
Fitting Code	OS	01	05	OL
Torque	22-25 NM	30-35 NM	30-35 NM	28-30 NM

* NPT Threads 2-3 turns from finger tight. Wrench tighten 2-3 turns.

General Notes:
1. The diameter of all cans is 19 mm (0.748˝)
2. Hex is 22 mm (0.886˝) Across Flats (A/F) for deep socket mounting

Wiring Diagram

POWER SUPPLY
(-) | (+)   IN (+)   **VOLTAGE OUTPUT** TRANSDUCER
COMMON
(-) | (+)   OUT(+)
READOUT

POWER SUPPLY
(-) | (+)   +   **CURRENT OUTPUT** TRANSDUCER
(-) | (+)   -
READOUT

PRESSURE TRANSDUCERS
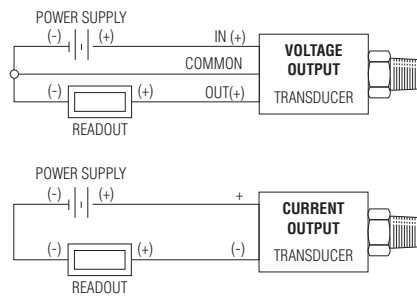
Electrical Connector

	DIN 9.4 mm	M12 x 1P	Deutsch DT04-4P	DIN 43650A	Packard MetriPack

POLARIZING WIDE CONTACT

KEY

Ø0.84 (21.3)

0.07 / 1.9

0.4 (10.1)

0.72 (18.3)

1.5 / 38.1

1.57 (40.0)

0.86 (21.9)

1.52 (38.6)

inch (mm)

Pin #	Code B Voltage Mode	Code B Current Mode	Code K Voltage Mode	Code K Current Mode	Code E Voltage Mode	Code E Current Mode	Code 8 Voltage Mode	Code 8 Current Mode	Code G Voltage Mode	Code G Current Mode	Pin ID	Code 9 Voltage Mode	Code 9 Note
1	V_{out} (pressure)	No Connect	V_{supply}	Supply	V_{supply}	Supply	Ground	Return	V_{supply}	Supply	C	V_{out} (pressure)	
2	V_{supply}	Supply	Ground	Return	V_{out} (pressure)	No Connect	V_{supply}	Supply	Ground	Return	A	Ground	MetriPack connectors may be used with 0.5-4.5V Ratiometric and 4-20 mA only.
3	No Connect	No Connect	V_{out}	No Connect	Ground	Return	No Connect	No Connect	V_{out}	No Connect	B	V_{supply}	
4	Ground	Return	No Connect	No Connect	No Connect	No Connect	V_{out} (pressure)	No Connect	No Connect	No Connect	—	—	

Mating Connectors

Part Number	Description	For Use on Elect. Code #
557230	MINI DIN Connector, Strain Relief (with drive screw & gasket)	B and K
557254	Large DIN 43650A	G
557703-01M0	M12 Cord Set – 1 Meter (Red 1, Green 2, Blue 3, Yellow 4)	E
557703-03M0	M12 Cord Set – 3 Meters (Red 1, Green 2, Blue 3, Yellow 4)	E
557703-04M0	M12 Cord Set – 4 Meters (Red 1, Green 2, Blue 3, Yellow 4)	E
557703-05M0	M12 Cord Set – 5 Meters (Red 1, Green 2, Blue 3, Yellow 4)	E
	Recommended Mating Parts (Deutsch p/n: Housing Plug DT064S-P012; Wedge W4S-P012; Sockets 4X 0462-201-1631)	8
224153	Deutsch Cord Set 3´ Long (18 AWG PVC Cable – Black 1, Red 2, Green 3, White 4)	8
	Recommended Mating Parts (Delphi Packard MetriPack p/n: Body 12065286; Seal 12052893. Consult Delphi for Contacts)	9
218760	Packard Mate Kit	9
223974	Packard Cord Set 3´ Long (24 AWG PVC Cable – White 1, Black 2, Red 3)	9
223975	Packard Cord Set 6´ Long (24 AWG PVC Cable – White 1, Black 2, Red 3)	9
227987	Packard Cord Set 14.75' Long (22 AWG PVC Cable - White 1, Black 2, Red 3)	9
220492	Packard Mate - 12˝ Flying Leads – 3 Conductor PVC 18 AWG	9
222976	Packard Mate - 18˝ Flying Leads – 3 Conductor PVC 18 AWG	9
220797	Packard Mate - 24˝ Flying Leads – 3 Conductor PVC 18 AWG	9

PRESSURE TRANSDUCERS

Appendix D   Pre-Launch Checklist

ID	ITEM	CHECK
SCIENCE		
	CAC	
S1	Connect picarro to quick connector stem at No 6.	
S2	Attach quick connector stem to quick connector body No 1.	
S3	Start flushing the CAC with a fill gas at a flow rate of 40ml/min, the night before the flight.	
S4	Leave it flushing over night.	
S5	Detach the quick connector stem at No 1.	
S6	Detach the quick connector stem at No 6.	
S6	Disconnect the picarro analyser.	
S7	Fill the dryer tube with magnesium perchlorate powder (2gr), YY hr before flight. DO NOT PACK IT TOO DENSE. IT HAS TO BE LOOSELY PACKED.	
S8	Connect the dryer tube (No 7.) to No 6.	
S9	Connect parts 7 to 13.	
S10	Close solenoid valve no 10.	
S11	Connect quick connector stem No 6. to No 5.	
S12	Place the CAC in its box.	
	AAC BAGS	
S15	Connect the vacuum pump, the dry gas bottle, and one bag with a central valve.	
S16	Connect a flow rate sensor close to the central valve. (valve that controls vacuum or filling bags).	
S17	Open bag's manual valve.	
S18	Turn the central valve in the position where the vacuum pump is closed but the dry gas can go through.	
S19	Start filling the bag with 3 L of dry gas with a flow rate lower than 3 L/min (we can start with 1.5 L/min).	
S20	As soon as the bag is full, turn the central valve in the position where the vacuum pump is open (active) and the dry gas is blocked, allowing the bag to empty.	
S21	Turn the central valve in the position where the vacuum pump is closed but the dry gas can go through.	
S22	Increase the flow rate to 3 L/min.	
S23	As soon as the bag is full, turn the central valve in the position where the vacuum pump is open (active) and the dry gas is blocked, allowing the bag to empty.	
S24	Again, turn the central valve in the position where the vacuum pump is closed but the dry gas can go through.	
S25	As soon as the bag is full again, turn the central valve in the position where the vacuum pump is open (active) and the dry gas is blocked, allowing the bag to empty.	
S26	Repeat one more time. Total 3 times.	

S27	Close bag's manual valve.	
S28	Remove bag.	
S29	Connect the second bag.	
S30	Repeat the filling-emptying procedure 3 times, as before.	
S31	Repeat for all bags.	
S32	At the end of this process, all the bags have to be placed inside the AAC box connecting them to the respective T-Union interface by means of a nut ferrule	
S33	The manual valves of the bags shall be opened before the flight	
	AAC TUBES	
S34	Open flushing valve (23).	
S35	Open the 1st tube valve (28) that is connected to the first bag (31).	
S36	Open the respective solenoid valve (26) in manifold (19).	
S37	Connect dry gas bottle at tube valve T-union (29).	
S38	Start flushing. Amount: 10 times the tube's volume for as long as it's necessary (and a little bit longer).	
S39	Disconnect dry gas bottle.	
S40	Close tube valve 1 (28).	
S41	Close solenoid valve (26) in manifold (19).	
S42	Open the 2nd tube valve (28).	
S43	Open the respective solenoid valve (26) in manifold (19).	
S44	Connect dry gas bottle at tube valve T-union (29).	
S45	Start flushing. Amount: 10 times the tube's volume for as long as it's necessary (and a little bit longer).	
S46	Disconnect dry gas bottle.	
S47	Close the 2nd tube valve (28).	
S48	Close the solenoid valve 2 (26) in manifold (19).	
S49	Open tube valve 3 (28).	
S50	Open solenoid valve 3 (26) in manifold (19).	
S51	Connect dry gas bottle at tube valve T-union (29).	
S52	Start flushing. Amount: 10 times the tube's volume for as long as it's necessary (and a little bit longer).	
S53	Disconnect dry gas bottle.	
S54	Close tube valve 3 (28).	
S55	Close solenoid valve 3 (26) in manifold (19).	
S56	Open tube valve 4 (28).	
S57	Open solenoid valve 4 (26) in manifold (19).	
S58	Connect dry gas bottle at tube valve T-union (29).	
S59	Start flushing. Amount: 10 times the tube's volume for as long as it's necessary (and a little bit longer).	
S60	Disconnect dry gas bottle.	
S61	Close tube valve 4 (28).	
S62	Close solenoid valve 4 (26) in manifold (19).	
S63	Open tube valve 5 (28).	
S64	Open solenoid valve 5 (26) in manifold (19).	

S65	Connect dry gas bottle at tube valve T-union (29).	
S66	Start flushing. Amount: 10 times the tube's volume for as long as it's necessary (and a little bit longer).	
S67	Disconnect dry gas bottle.	
S68	Close tube valve 5 (28).	
S69	Close solenoid valve 5 (26) in manifold (19).	
S70	Open tube valve 6 (28).	
S71	Open solenoid valve 6 (28) in manifold (19).	
S72	Connect dry gas bottle at tube valve T-union (29).	
S73	Start flushing. Amount: 10 times the tube's volume for as long as it's necessary (and a little bit longer).	
S74	Disconnect dry gas bottle.	
S75	Close tube valve 6 (28).	
S76	Close solenoid valve 6 (26) in manifold (19).	
S77	Start pump (7) to flush the system for YY time.	
S78	Stop the pump.	
S79	Close flushing valve (23).	
S80	All the valves must be closed.	
S81	Fill the dryer tube (3) with 25 gr of magnesium perchlorate. (DO NOT PACK TOO DENSE. IT HAS TO BE LOOSELY PACKED).	
S82	Connect the dryer as shown in the schematic.	
ELECTRICAL		
E1	Verify all electrical components are working:	
E2	Sensors	
E3	Valves	
E4	Pump	
E5	Heaters	
E6	Check all connections and fix any loose connections (particularly the connection between the boxes.)	
E7	Check LED display is showing all parts are alive	
E8	Check connection with the gondola (e-link and power)	
E9	Check all pcb boards and sensors are secure	
E10	Verify again that components are working and check LED display is still showing all parts are alive	
SOFTWARE		
SW1	The ground station laptop PC will need to be put in place and operational.	
SW2	The correct version of the onboard software have been uploaded to the OBC.	
SW3	The communication through E-link with the experiment shall be tested.	
SW4	The air sampling itinerary is checked.	
MECHANICAL		
M1	Check that all the screws in the frame structure are propely fixed.	
M2	Check that the handles of both boxes are properly fixed.	
	AAC BOX	
M3	Check that The Brain is propely attached ot the structure of the AAC Box.	

M4	Check that all the pneumatic connections are set (interfaces, valves, bags).	
M5	Check that the bags are properly fixed with the circular bar.	
M6	Check that the electronic interfaces panel is properly fixed to The Brain structure.	
M7	Close all the open walls and check that they are all properly fixed and closed.	
	CAC BOX	
M8	Check that the AirCore is properly placed.	
M9	Check that all the pneumatic connections are set (interfaces, valves)	
M10	Close all the open walls and check that they are all properly fixed and closed.	
	GONDOLA	
M11	Introduce both boxes inside the gondola.	
M12	Attach both boxes one to the other.	
M13	Fix the experiment box to the gondola rails.	
M14	Check that the electronic connectors are properly fixed to both electronic panels (D-sub, power, E-link)	

Appendix E Team Availability

E.1 Team availability from February 2018 to July 2018
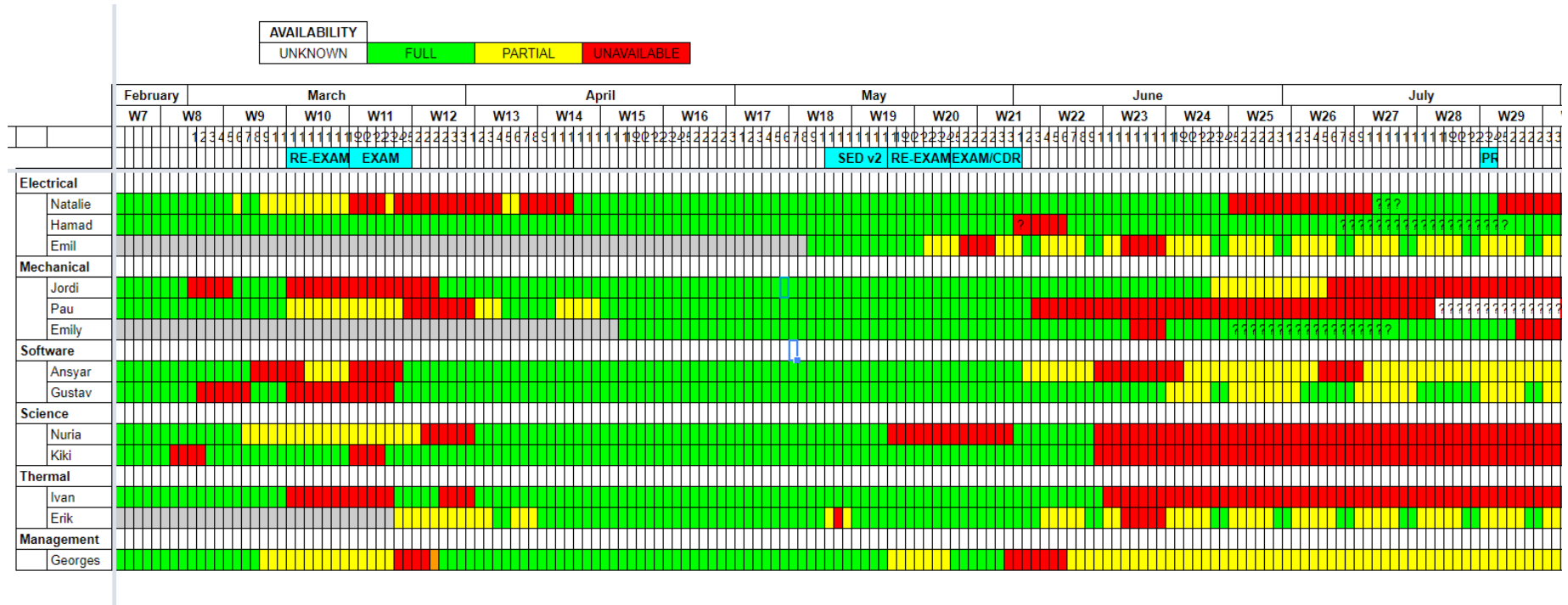
Figure 91: Team Availability From February 2018 to July 2018.

E.2 Team availability from August 2018 to January 2019
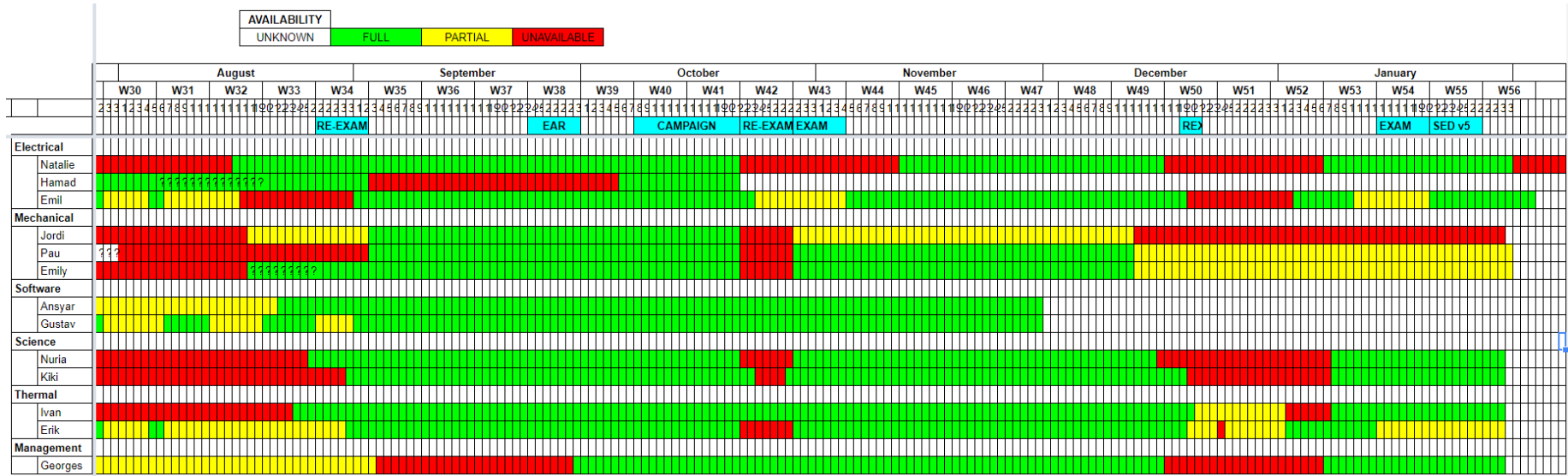
Figure 92: Team Availability From August 2018 to January 2019.

E.3 Graph Showing Team availability Over Summer

Green squares with question marks indicate uncertainty over whether someone will be available in Kiruna at that time.
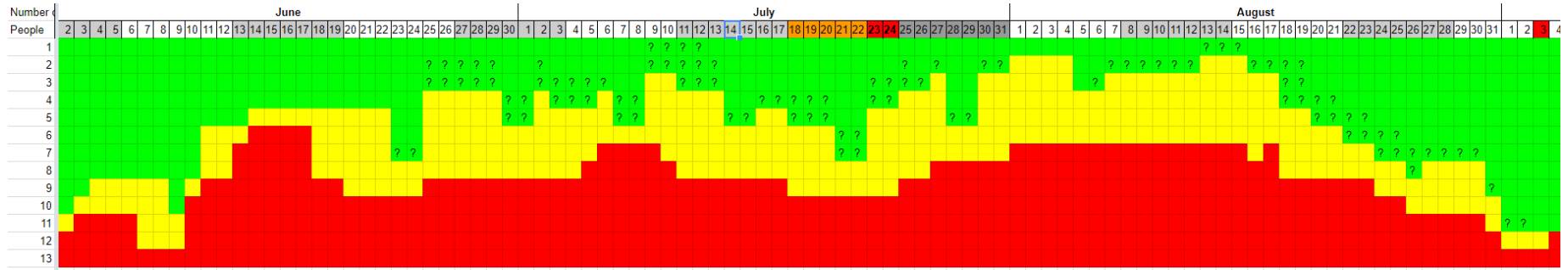
Figure 93: Graph Showing Team Avaliability Over the Summer Period.

Appendix F   Gantt Chart

The current critical path starts with ordering and receiving parts, until this is done building cannot take place. The key components are the pump, valves, tubing, fittings and Arduino. Once orders have been received building can take place and then testing can begin. All remaining tests require some degree of building to be completed. Certain tests such as Test 17 in Table 35 require the entire pneumatic system to be completed and others such as Test 2 in Table 24 require just the electronics and software.

F.1 Gantt Chart (1/2)
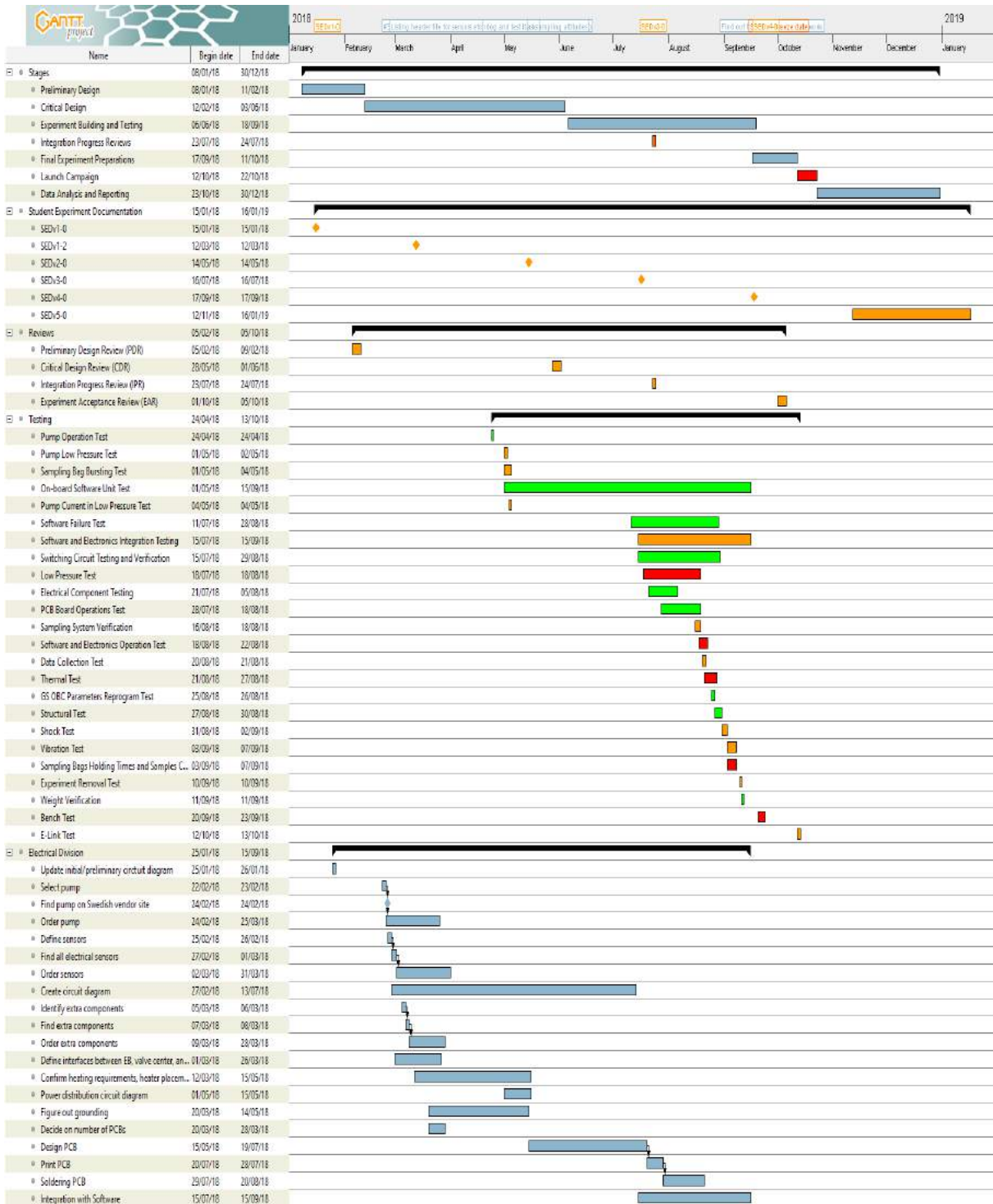
Figure 94: Gantt Chart (1/2).

F.2 Gantt Chart (2/2)
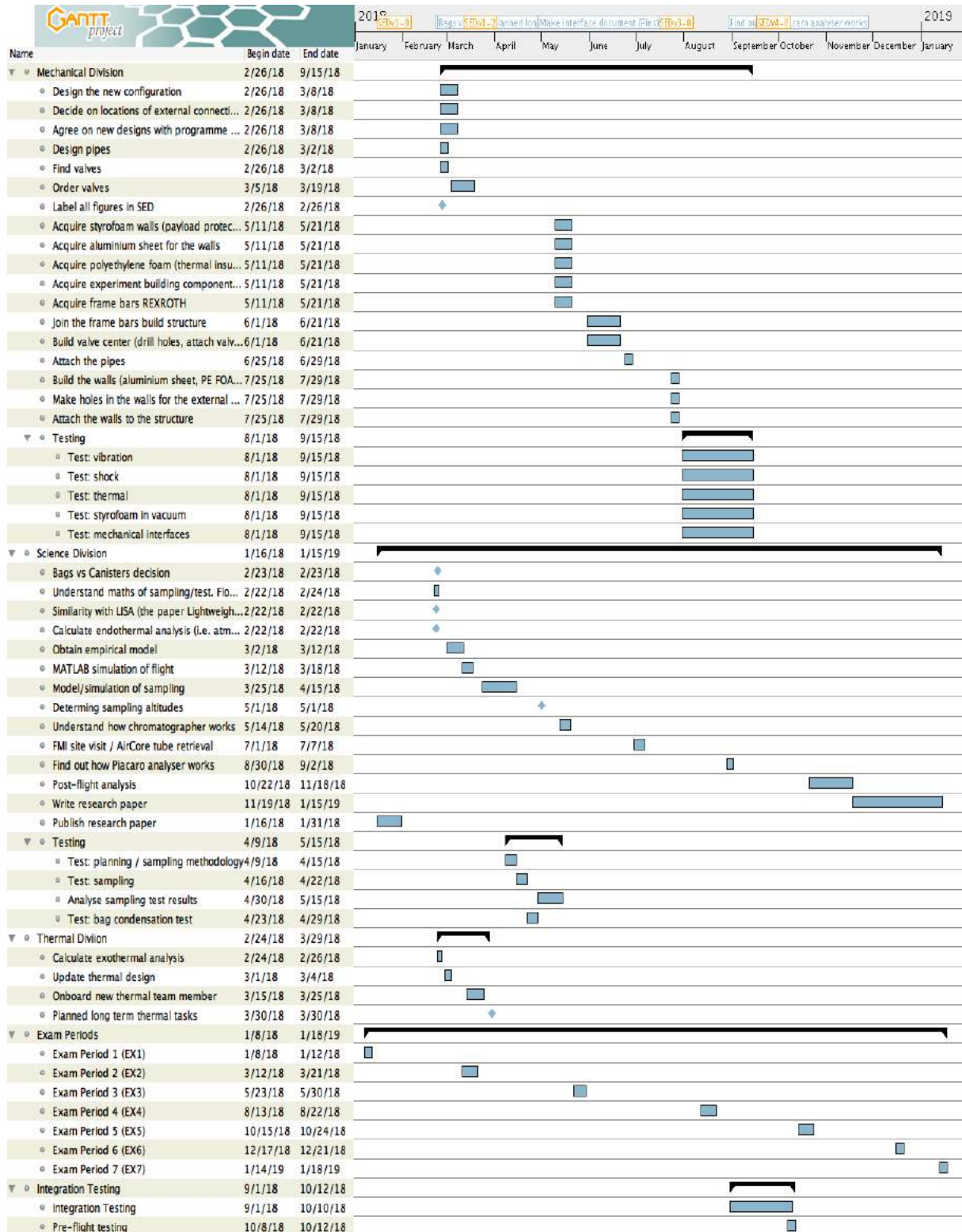
Figure 95: Gantt Chart (2/2).

By comparing the team availability in Appendix E to the Gantt chart it can be seen that across the summer there is lower team availability. In this time frame there are two periods with particularly low team availability; The early summer and early August. The work has been planned so that the critical work will be completed in the periods with higher availability. In the event that the work takes longer than expected the question marks can become green.

Appendix G   Equipment Loan Agreement

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.

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

1

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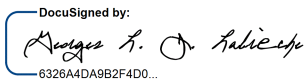
6. *Force Majeure*
   6.1. The Borrower is not responsible to Lender for any loss, damage, or failure to perform if occasioned by fire, flood, explosion, windstorm, riot, war, transportation difficulty, or any other cause beyond the reasonable control of the Borrower.

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　　　　　　**Authorized Lender Representative**

Signature:　　DocuSigned by:　　　　　　　　　　*Signature:*　　Rigel Kivi
　　　　　　Georges L. J. Labrèche
　　　　　　6326A4DA9B2F4D0...

Name: Georges L. J. Labrèche　　　　　　　　*Name:* Dr. Rigel Kivi

Title: Project Manager (Team TUBULAR)　　　　*Title:* Senior Scientist

Date:　　3/12/2018　　　　　　　　　　　　*Date:* March 12, 2018

Appendix H   Air Sampling Model for BEXUS Flight

H.1   Introduction

H.1.1   Objectives

The purpose of this is to theoretically simulate the experiment; its preparation, the sampling methodology, and the expected results.

H.1.2   Justification

This theoretical model will give an estimation of the time needed to fill the bags in order to achieve the best resolution, the required volume of the samples at the different altitudes, to make sure that there is enough sample left for analysis, the sampling altitudes and the number of the bags.

H.1.3   Methodology

For this purpose, a mathematical model was created using MATLAB. In order to make sure that this model is reliable, it is going to be tested for the atmospheric conditions in the Arctic, and then compared with the 1976 US Standard atmosphere model that is used for this region. What is more, the model will be compared with past BEXUS flight data. The goal of the model is to be as close as possible with these past data. After the tests, and making sure that the mathematical model is accurate, it will be adjusted with the TUBULAR's experiment requirements. In this way, the TUBULAR Team will get a general picture of the experiment's layout. Hence, the results of the experiment will be more or less expected, and in the case of complications, the mathematical model will be used as a reference of understanding what went wrong.

H.2   Scientific and Empirical Background

H.2.1   Study of Previous BEXUS Flights

This section has been elaborated based on the flight data files located in the previous BEXUS flights folders in the REXUS/BEXUS teamsite. This data was recorded by the Esrange Balloon Service System (EBASS).

This unit is responsible of the piloting of the balloon is done by Esrange. It provides the communication link between the gondola and the ground station. The EBASS airborne unit, receives the data from the on board sensors, and then it sends them to the EBASS ground unit. It is also responsible for the payload control, providing functions like the altitude control, by valve and ballast release or the flight termination. What is more, EBASS keeps track of the filght trajectory with an on-board GPS system.

Tables 63 and 64 below gather some general information before and after the BEXUS flights. The pre-flight and the post-flight data are more or less in agreement in estimating for example, the ascent/descent time, the cut-off altitude and the float time. Knowing those information and that the estimations are close enough to the real data, will help the TUBULAR Team to define the experiment's parameters with higher accuracy.

It is worth mentioning that the ascent speed in Table 64 is lower than the predicted $5 \sim 6m/s$ which is mentioned in the BEXUS manual. That is because it is the average velocity value of all the data points.

	BEXUS 20	BEXUS 21	BEXUS 22	BEXUS 23	BEXUS 24	BEXUS 25
Main Balloon	Zodiac 12SF	Zodiac 12SF	Zodiac 35SF	Zodiac 35SF	Zodiac 12SF	Zodiac 12SF
Balloon mass [kg]	101.4	101.4	-	-	101.4	101.4
Parachute [m^2]	80	80	80	80	80	80
Vehicle mass - Launch [kg]	256.8	287.8	-	-	300.6	321.15
Vehicle mass - Descent [kg]	155.4	186.4	189.58	181.5	199.2	219.75
Float altitude estimation [km]	28.2	27.5	-	-	27	26.6
Float pressure estimation [mbar]	15.38	17.11	-	-	18.5	19.6
Float temperature estimation [°C]	- 48	- 48	-	-	- 49.5	- 49.9
Estimated ascent time	1h 33min	1h 31min	-	-	1h 29min	1h 27min

Table 63: Pre-flight Information Available in Previous BEXUS Campaigns.

	BEXUS 20	BEXUS 21	BEXUS 22	BEXUS 23	BEXUS 24	BEXUS 25
Ascent time	1h 37min	1h 37min	1h 51min	1h 51min	1h 55min	3h 45min
Average ascent speed [m/s]	4.78	4.59	4.52	4.79	3.79	1.86
Floating altitude [km]	28	27	32	32	26.5	25.8
Floating time	2h 10min	1h 46min	2h 34min	2h 42min	2h 9min	2h 36min
Cut-off altitude [km]	27.7	20.5	28	32	25.7	25.2
Ending altitude [m]	648	723	3380	1630	1050	-
Descent time	36 min	31 min	29 min	31 min	30 min	-

Table 64: Post-flight Information Regarding the Flight Profile for Previous BEXUS Campaings.

In order to find out how many bags it is possible to sample during Ascent and Descent Phase it is important to know the time duration of each phase i.e Ascent, Floating and Descent. For that reason, Figure 96 provides some sights on how previous BEXUS flights perform and what we can expect from BEXUS 26.
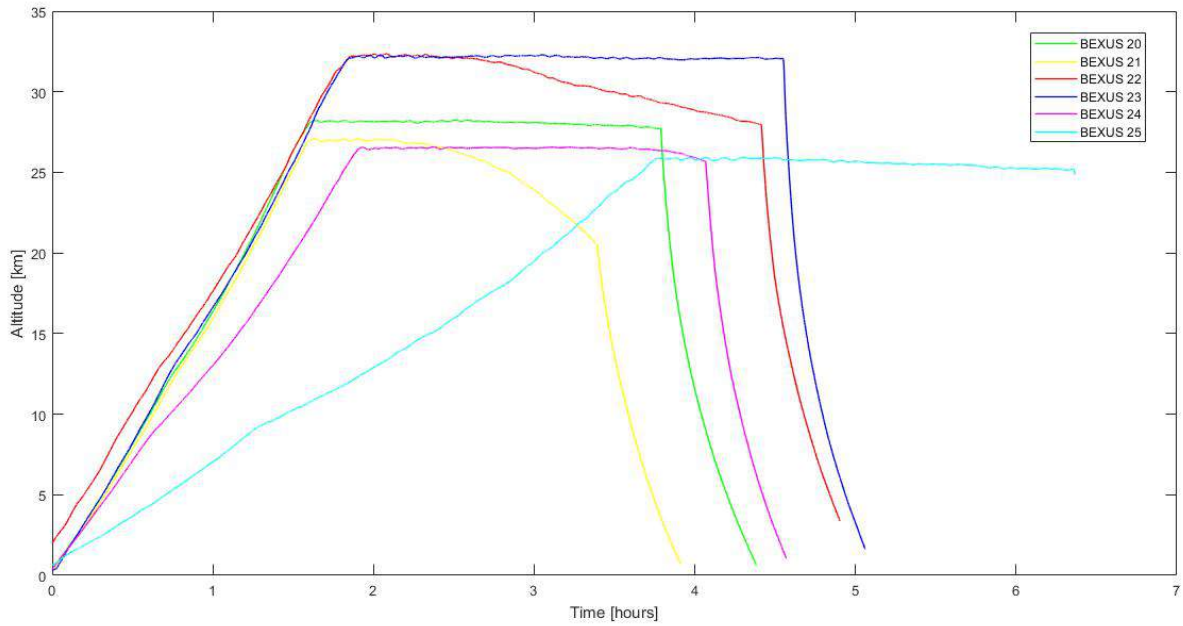
Figure 96: Altitude Over Flight Time for BEXUS Flights 20,21,22,23,24 and 25.

Gondola Dynamics

The velocity of the gondola at each phase can give us information about its dynamics. For example, the data from the BEXUS flight 22 was chosen for analysis in order to get an idea of the velocity values and fluctuations throughout the flight. The obtained diagrams, with some marked points showing the time it takes for the gondola to reach a certain altitude, or the velocity of the gondola at a specific altitude, are shown below.
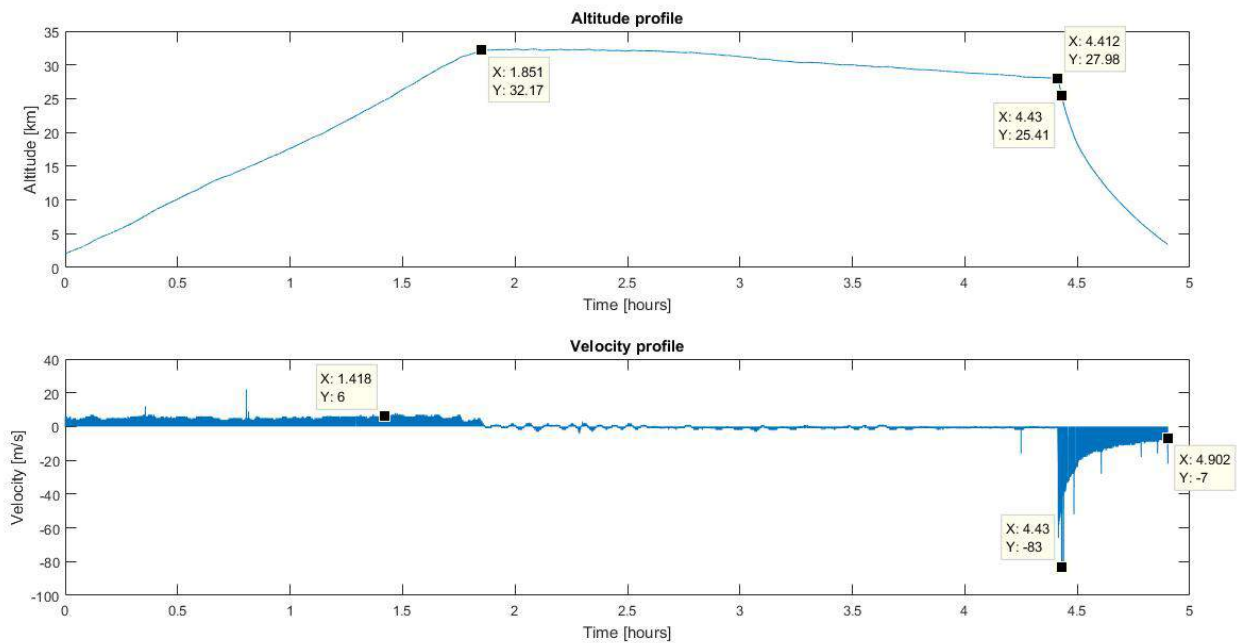
Figure 97: Altitude Profile [Up] and Vertical Velocity Profile [Down] Over the Flight Time During BEXUS 22 Flight.

Figure 98 below, illustrates the velocity changes throughout the different phases. It works like a combination of both graphics form previous Figure 97, however it provides a better representation of the velocity values at each phase. Especially during the Descent Phase, which is the most determinant for the air sampling process.

For each altitude, there are two velocity values, one for the Ascent and one for the Descent Phase. Constant and positive velocities indicate the Ascent Phase. During Ascent Phase the velocity is 6 m/s and almost constant, in agreement with the ascent speed value in the BEXUS manual. A zero velocity value indicates the Float Phase. Then the velocity becomes negative which indicates the Descent Phase. Once again, the velocity value close to the ground is 8 m/s as mentioned in the BEXUS manual[6].
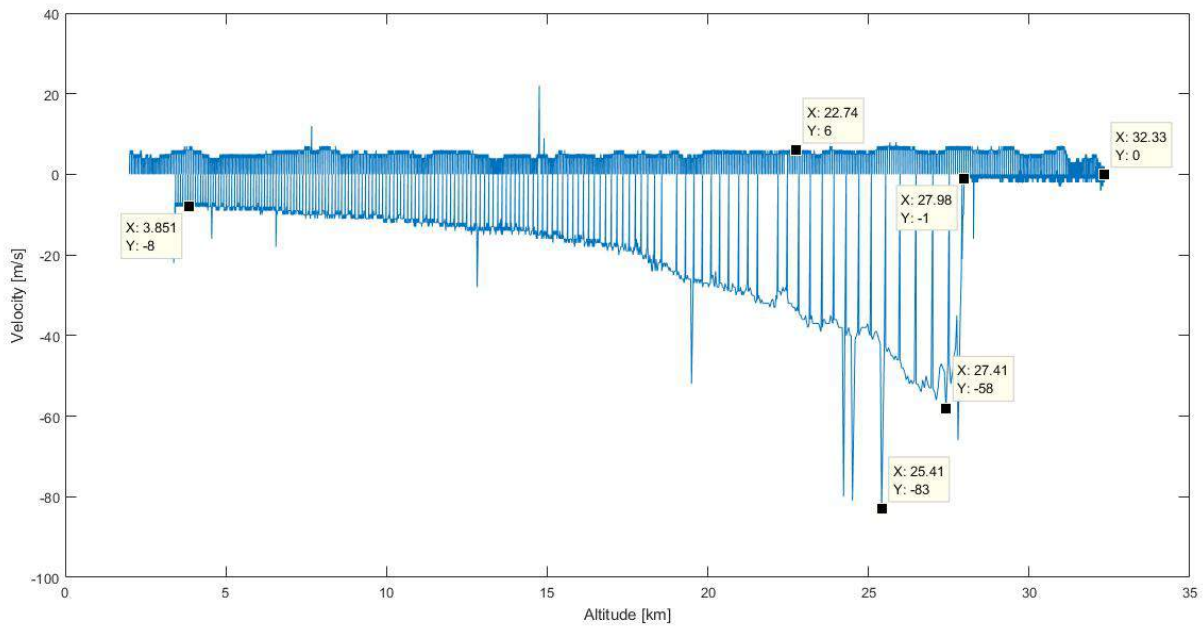
Figure 98: Vertical Velocity of the Gondola Over the Altitude During BEXUS 22 Flight.

Atmospheric Conditions

In order to see how the atmospheric conditions change during a BEXUS flight, the data from the BEXUS flight 22 was chosen for analysis. Figure 99 below shows which kind of information is available for different parameters such as the temperature, the pressure and the air density with altitude.
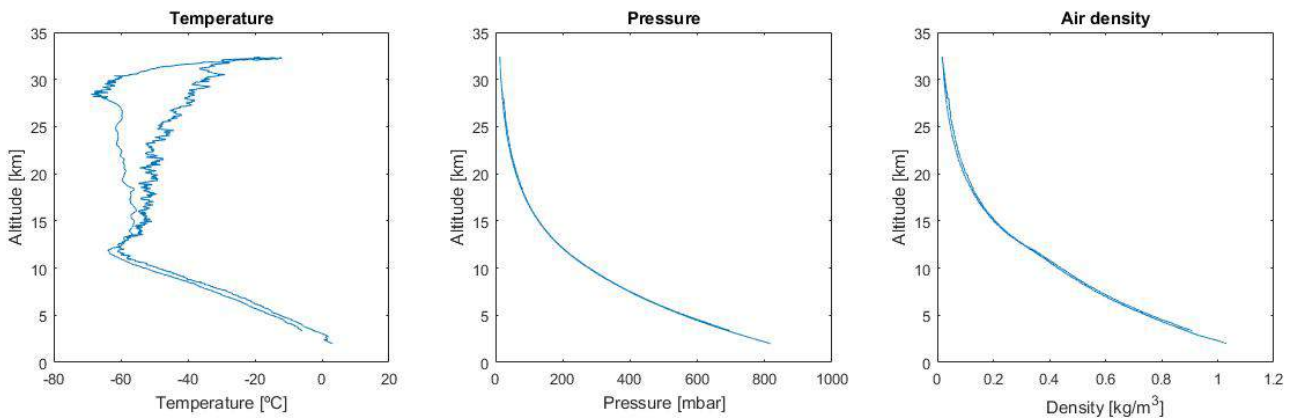
Figure 99: Variations in Temperature, Pressure and Air Density During the Ascent and Descent Phase for BEXUS Flight 22.

H.2.2 Trace Gases Distribution

Atmospheric greenhouse gases are mostly concentrated in the upper troposphere and lower stratosphere. The Arctic region is of significant importance since there is where the maximum concentration of greenhouse gases is found due to meridional circulation (temperature differences) that pushes the gases from the equatorial to higher latitudes. Figures 100 and 101 are showing the concentration over latitude of two of the main greenhouse gases, CO_2 and CH_4 respectively.
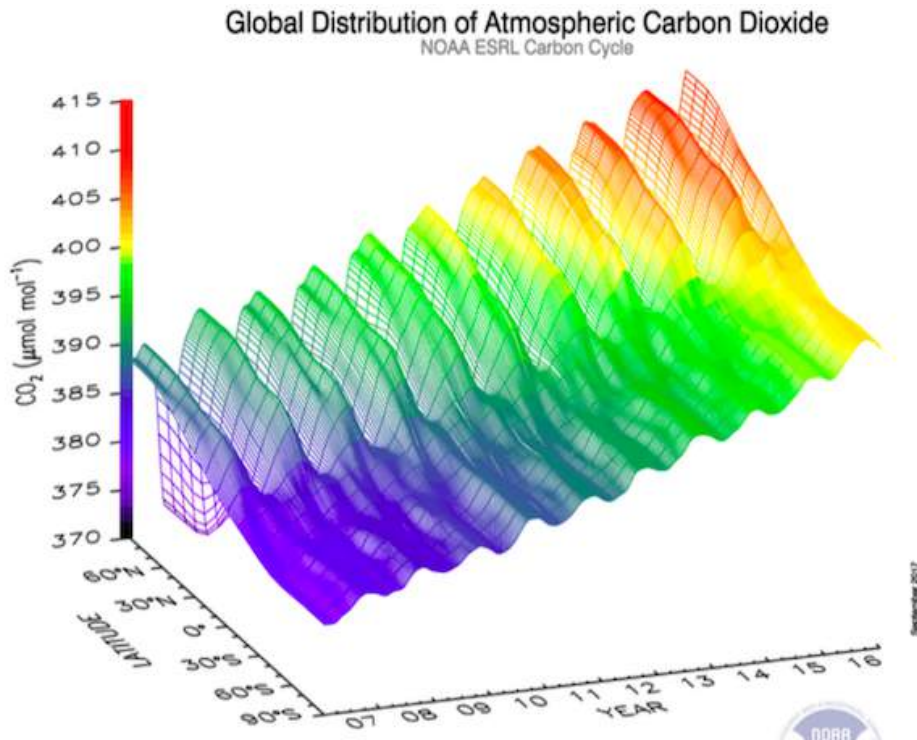
Figure 100: Global Distribution of Atmospheric Carbon Dioxide[14].
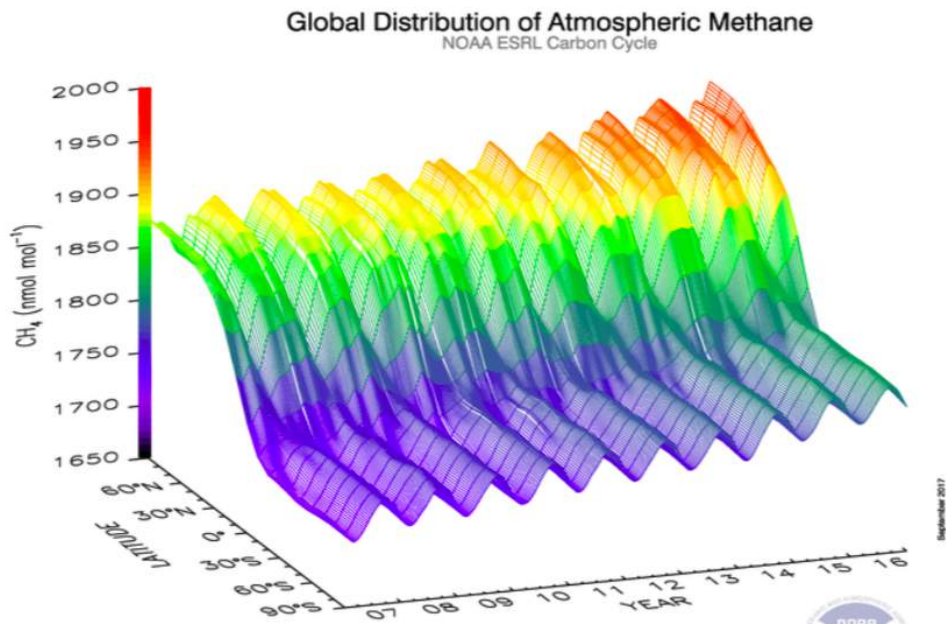
Figure 101: Global Distribution of Atmospheric Methane[14].

The same applies for the vertical distribution of atmospheric greenhouse gases. The favoured altitudes for higher concentrations are the upper troposphere and the lower stratosphere due to gravity waves and the vertical wind, which carry the trace gases at higher altitudes. What is more, CO_2 has longer lifetime in the troposphere and stratosphere, where it has essentially no sources or sinks since it is basically chemically inert in the free troposphere.

Figure 102 shows the global distribution of carbon dioxide in the upper troposphere-stratosphere, at 50-60°N for the time period 2000-2010.

Figure 103 shows the global distribution of the seasonal cycle of the monthly mean CO_2 (in ppmv) in the upper troposphere and the lower stratosphere for the even months of 2010 and the altitude range from 5-45 Km.
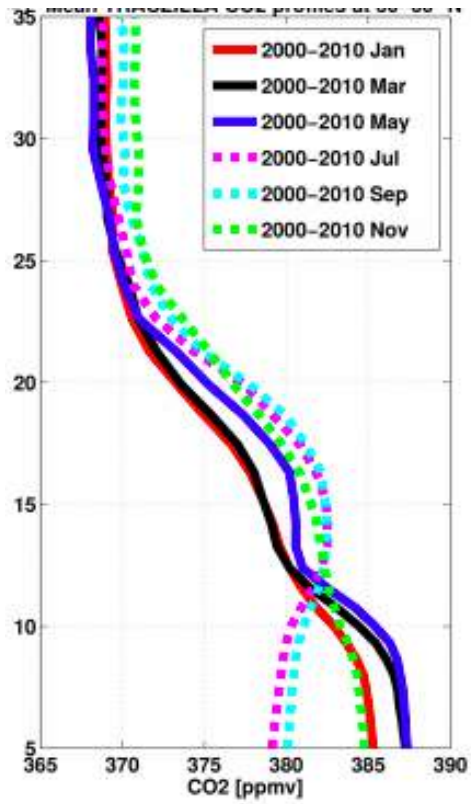
Figure 102: Global Distribution of CO_2 in the Upper Troposphere-Stratosphere[4].
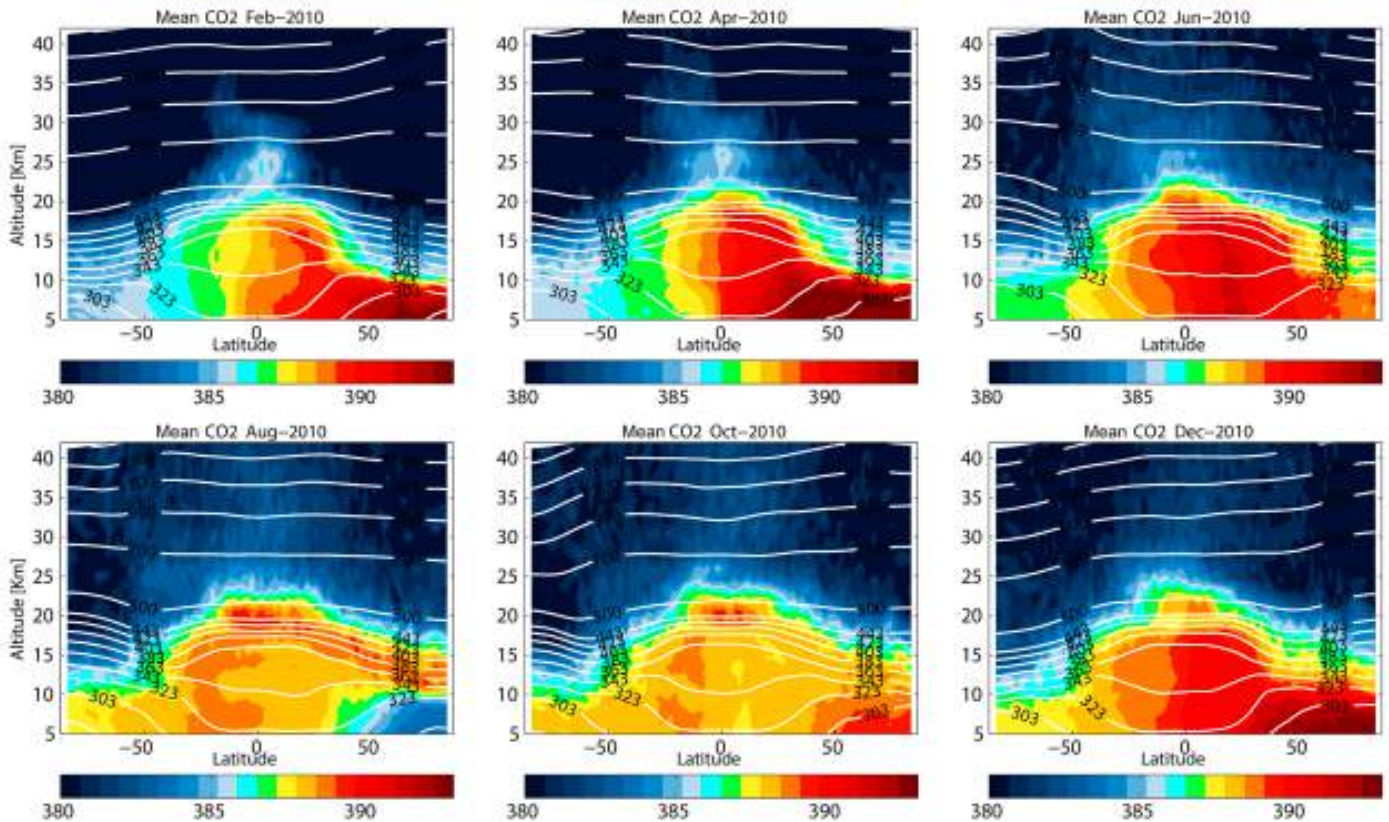
Figure 103: Global Distribution of the Seasonal Cycle of the Monthly Mean CO_2 (in ppm) in the Upper Troposphere and the Lower Stratosphere for the Even Months of 2010[4].

Figures 102, and 103, indicate that the higher CO_2 concentrations are found between 5 and 25 km with peaks around 10 to 15 km (figure 102) and 20 km for October (figure 103).

Figures 104 and 105 focus more on the region near the Arctic Circle. These figures represent vertical profiles distribution of CO, CO_2 and CH_4 extracted from past research papers [2] [5]. The range of altitudes that will be compared is the one between 10 and 25 km. Since Figure 104 vertical axis is in pressure, the equivalent pressures for these altitudes will be from approximately 200 hPa to 20 hPa.

- CH_4 distribution: There is a good agreement between both researches that the concentration around 10 km of altitude is about 1800 ppb and then it starts decreasing gradually with altitude. This decrease seems to be faster above 17 km (70 hPa) which would make this the region of major interest.

- CO_2 distribution: The concentration around 10 km is approximately 390-400 ppm in both researches. The biggest variation in concentration can be found between 10-17 km. The concentration of CO_2 seems to have an increase and then decrease again so this would be the most interesting range to sample.

- CO distribution: Only one research with CO profiles has been presented here so it cannot be compared with other researches. Analysing the only CO profile, it seems that the

largest variation lays on the range 10-15 km, which should be the area of interest.

Based on the vertical distribution profiles obtained from past researches, seems that our experiment should focus on sampling between 10-15 km for CO and CO_2 but above 17 km for CH_4.
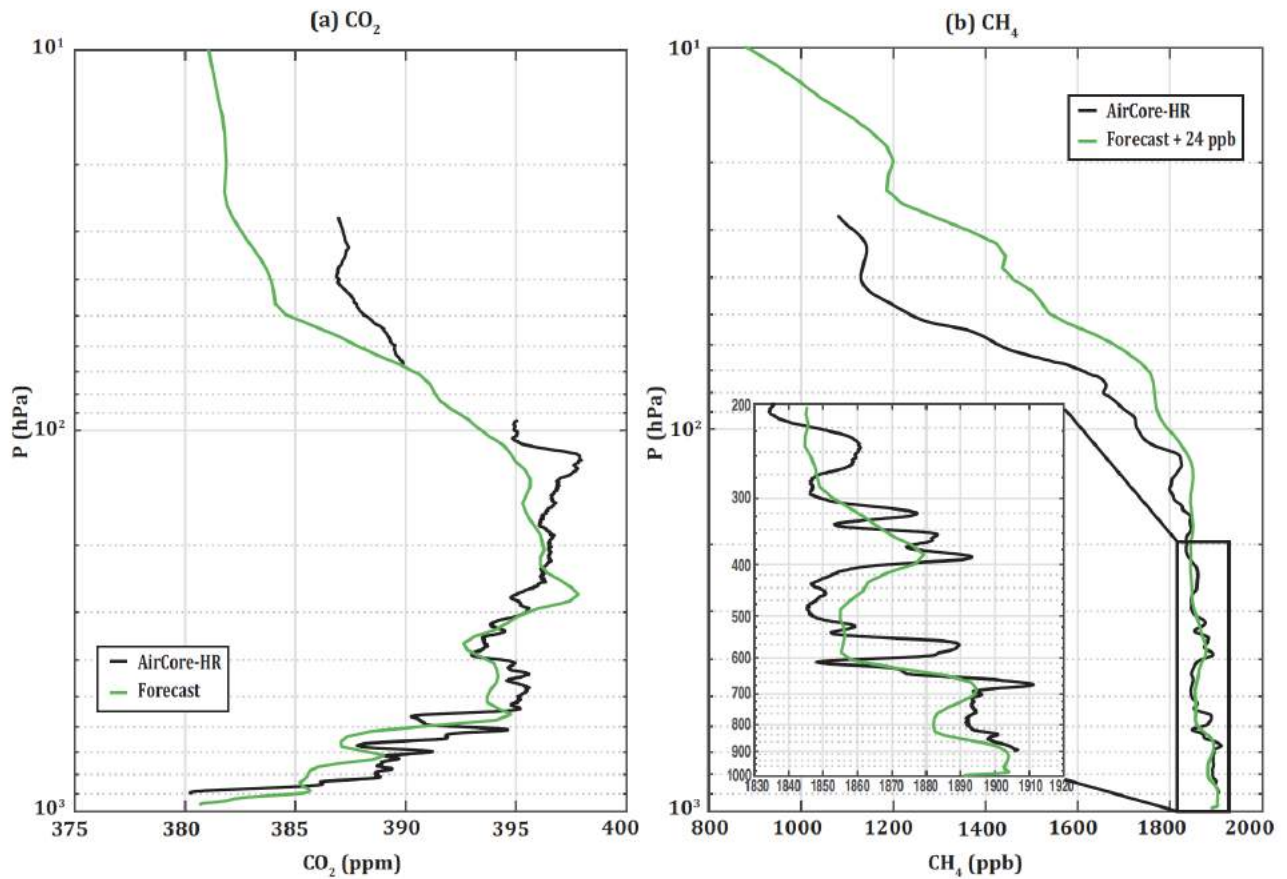
Figure 104: Vertical Profiles in Black for CO_2 and CH_4. The Green Lines are High Resolution Forecasts [5].
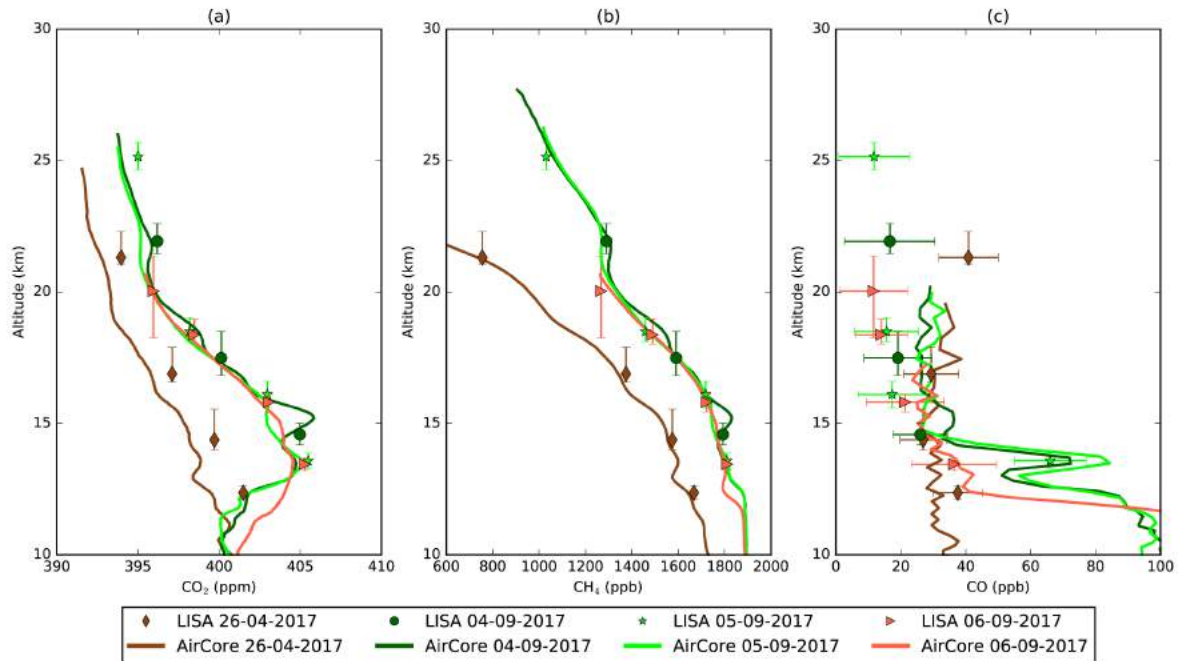
Figure 105: Vertical Profiles Comparison of AirCore and LISA Measurements of CO_2, CH_4 and CO Mole Fractions[2].

H.3 Sampling Flowrate

H.3.1 Pump Efficiency

For the air sampling process, the micro diaphragm gas pum *850 1.2 KNDC B* from KNF company will be used.

By now, the TUBULAR Team has already tested this pump in vacuum conditions in IRF facilities in Kiruna. Since the set of sensors required to obtain extra data such as the air flow rate, the pressure inside the bags and so on is not ready, the corresponding data is missing in Table 65. However, it has been proved that the pump is operative down to $20mbar$.

Altitude	Pressure	Datasheet Flowrate	Datasheet Efficiency	Empirical Flowrate	Empirical Efficiency
0 km	1013 mbar	8 L/min	100 %		
0.5 km	925 mbar	7 L/min	87.5 %		
1.5 km	850 mbar	6 L/min	75 %		
2.3 km	760 mbar	5 L/min	62.5 %		
3.1 km	680 mbar	4 L/min	50 %		
4.6 km	560 mbar	3 L/min	37.5 %		
6.4 km	450 mbar	2 L/min	25 %		
8.3 km	320 mbar	1 L/min	12.5 %		
10.7 km	230 mbar	0 L/min	0 %	4.865 L/min	
12 km	194 mbar	0 L/min	0 %		
17 km	88 mbar	0 L/min	0 %	3.4 L/min	
20 km	55.29 mbar	0 L/min	0 %		
24 km	30 mbar	0 L/min	0 %	3 L/min	
30 km	11.97 mbar	0 L/min	0 %		

Table 65: Pump Flowrate/Efficiency According to the Datasheet and Tests.

H.4   Sampling Strategy Tests

H.4.1   Past Research Sampling Strategy Test

Some of the most important parameters to be determined in this experiment are vertical resolution, sample size, sampling time and sampling flow rate amongst others. The difficulty in determining them lies on the fact that they are all interrelated. For example, the vertical resolution depends on the vertical speed and the effective sampling time. The amount of air samples that can be collected in each sampling bag is a function of the sampling time and the sampling flow rate. This is the reason why testing the pump's performance will be helpful to make a decision.

The test that will be realized is based on previous research [2]. The tested elements will be the pump, one sampling bag, the outlet valve and the electronics necessary to record data (pressure and temperature sensors, datalogger and batteries). The simplified version of the experiment is placed in a vessel where the pressure can be regulated by a vacuum pump in order to simulate the desired atmospheric pressures.

The procedure for the test will be as follows: reach the desired pressure in the chamber and then start sampling air for 153 seconds. Repeat this process for three different pressures: 31.5 hPa, 60.8 hPa and 117.7 hPa. The data for pressure and temperature is logged at 3 Hz. The result of this measurements is represented in Figure 106.
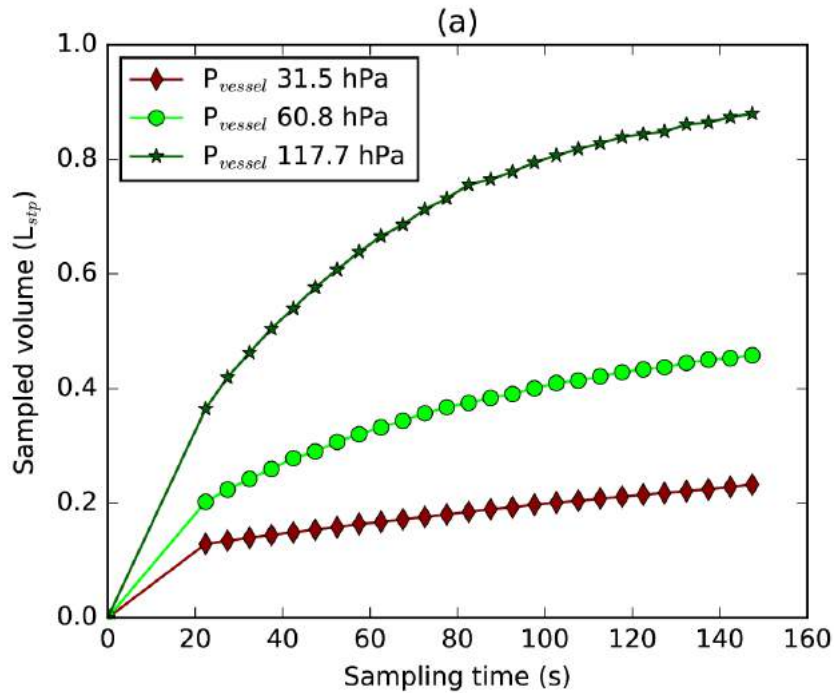
Figure 106: Sampling Time (s) - Sampled Volume (L at STP) [2].

As it can be seen in Figure 106, there is a linear increase of the volume that corresponds to the first twenty seconds when the bag is expanding to its full size. Until then the pressure readings are constant but after that point is reached, the pressure inside the sampling bag starts to increase due to air compression. All the data points are calculated using the data logged from the sensors and the ideal gas law.

The next step is to use a non-linear least squares method to obtain an empirical model of the parameter named a(t) which is relating the volume at STP with the chamber pressure by the equation $V_{STP} = a(t) \cdot p_a$. The model is only valid for $t > 19.7$ seconds which means that the sampling bag has reached total expansion. The fitted values for a(t) are represented in Figure 107. Once a(t) is obtained, Figure 108 can be represented just to see the relationship between the vessel pressure and the sampled volume. Three arbitrary sampling times are chosen for this representation and an horizontal line represents the maximum pressure that the sampling bag can withstand. This implies another procedure during the test: fill the bag until the sealing breaks and calculate the differential pressure that was achieved between the inside and the outside.
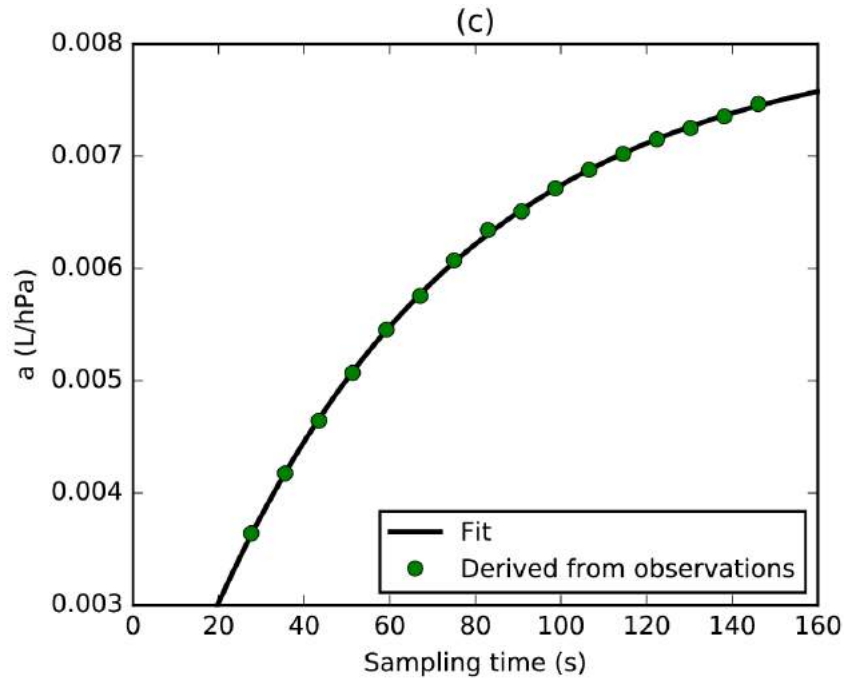
Figure 107: Sampling Time (s) - a (L/hPa) [2].
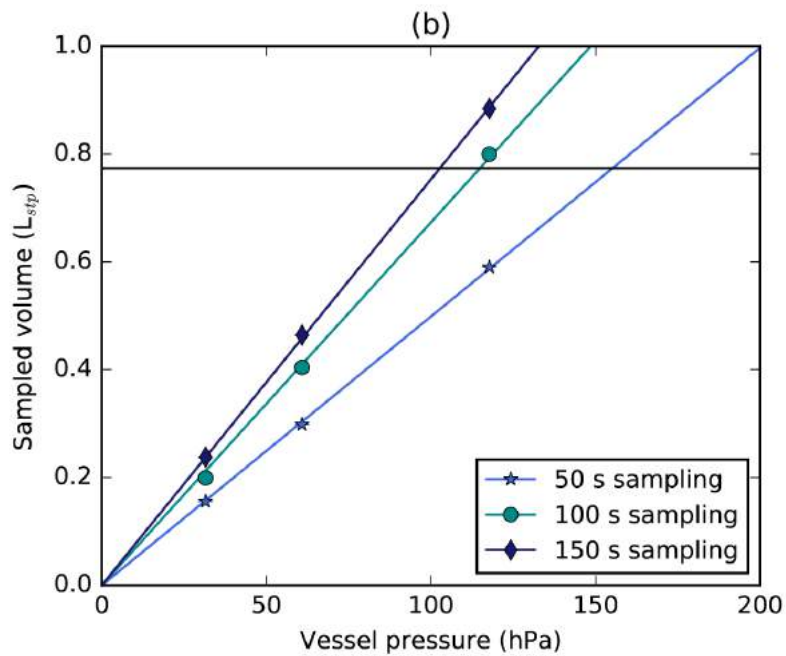
Figure 108: Vessel Pressure (hPa) - Sampled Volume (L at STP)[2].

The objective of the above explained test and the calculations that follow will be to obtain an

empirical model that gives the sampled air volume as a function of time at any pressure level. This will be the tool to calculate vertical resolutions and expected sample size and it should be a graphic looking like the one in Figure 109.
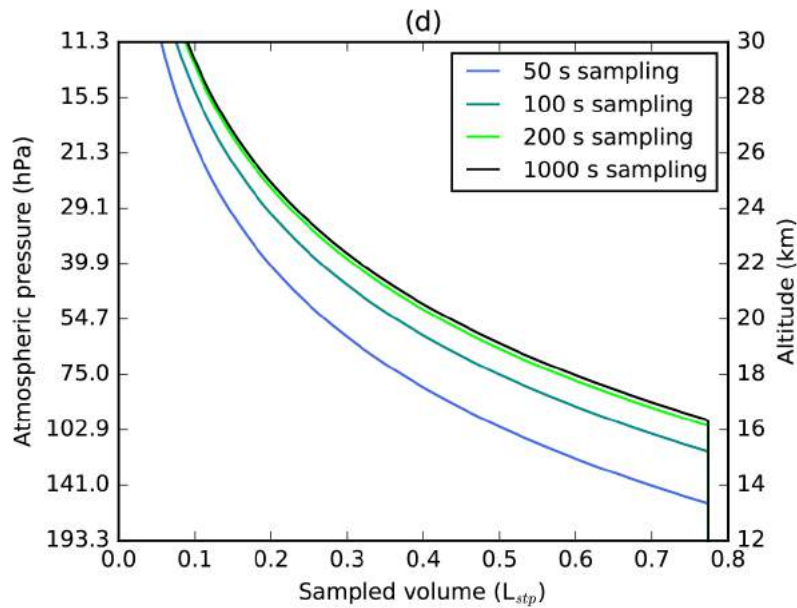
Figure 109: Sampled Volume (L at STP) - Atmospheric Pressure (hPa) [2].

H.4.2 Test Results

The above described test is Test 18 in Table 36 the results of which can be found in Section O.2

H.5 Discussion of the Results

H.5.1 Computational Methods vs. Flight Measurements

Atmospheric Model

In this section, the data from the past BEXUS flights is compared with the 1976 US Standard Atmosphere, for validation reasons. Figure 110 compares the changes in pressure over altitude for the BEXUS flights with the atmospheric model. It can be seen that the flights data-sets are in good agreement with the atmospheric model.
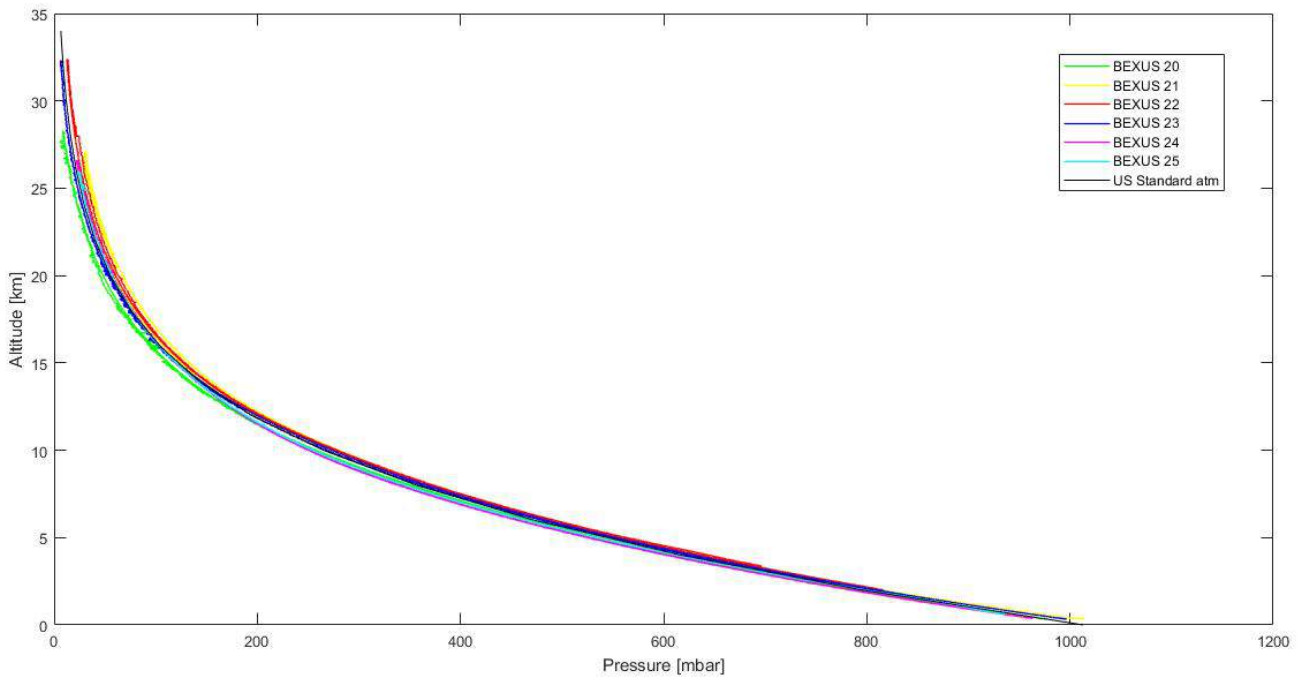
Figure 110: Comparative of Pressure Variation Over the Altitude During Different BEXUS Flights with the US Standard Atmosphere (1976).

Figure 111 below shows the changes in temperature over altitude, for all the BEXUS flights with the atmospheric model. It can be seen that there is a quite large deviation of the temperature above $20 km$ of altitude between the BEXUS flights and the US Standard Atmosphere 1976 model. This is not arbitrary since it appears in all flights. But it is not surprising either, because most of the atmospheric models fail to precisely predict the temperatures at higher altitudes.
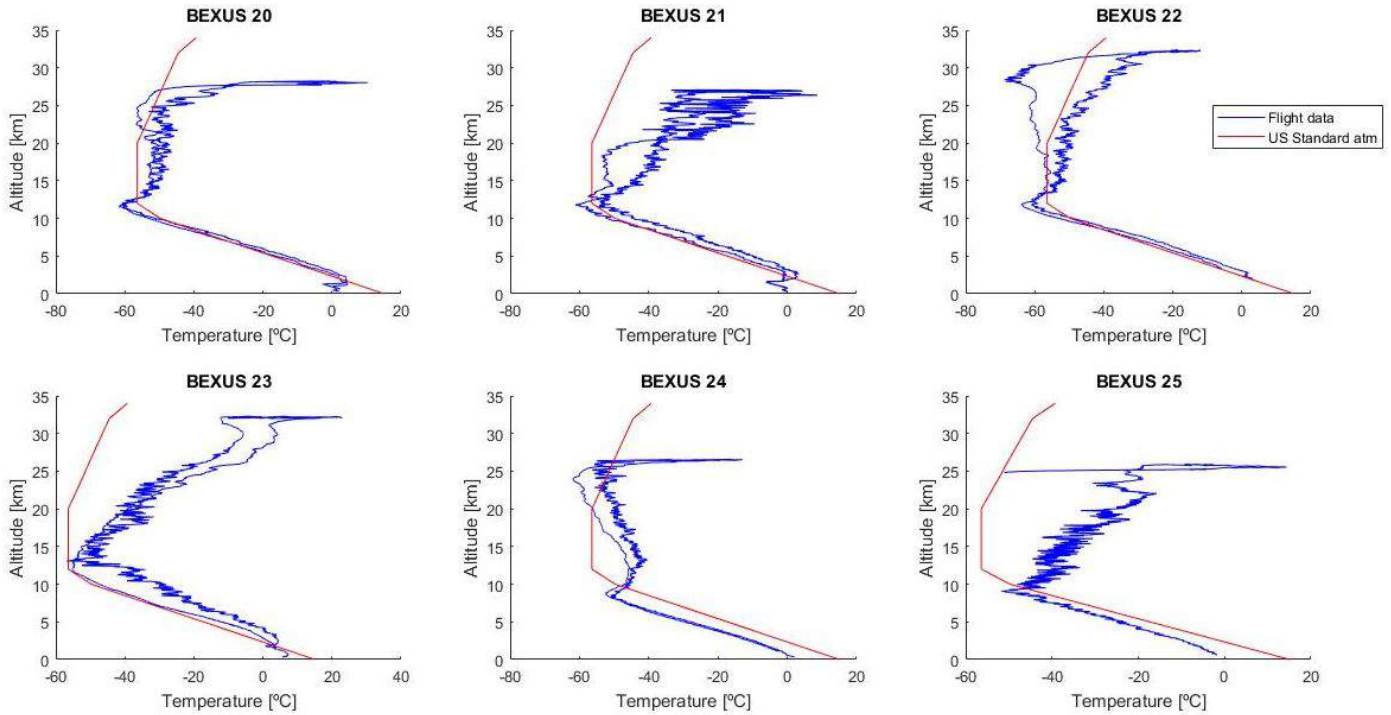
Figure 111: Comparative of Temperature Variation Over the Altitude During Different BEXUS Flights with the US Standard Atmosphere (1976).

Descent Curve

Again, in this section, the trajectories of past BEXUS flights, were compared with the mathematical model for validation reasons as shown in Figure 112. Overall, BEXUS flights 20, 23 and 24 are in good agreement with the mathematical model. Some deviations exist between the mathematical model and the BEXUS flights 21 and 22 mostly in the last $5km$ of the flight.
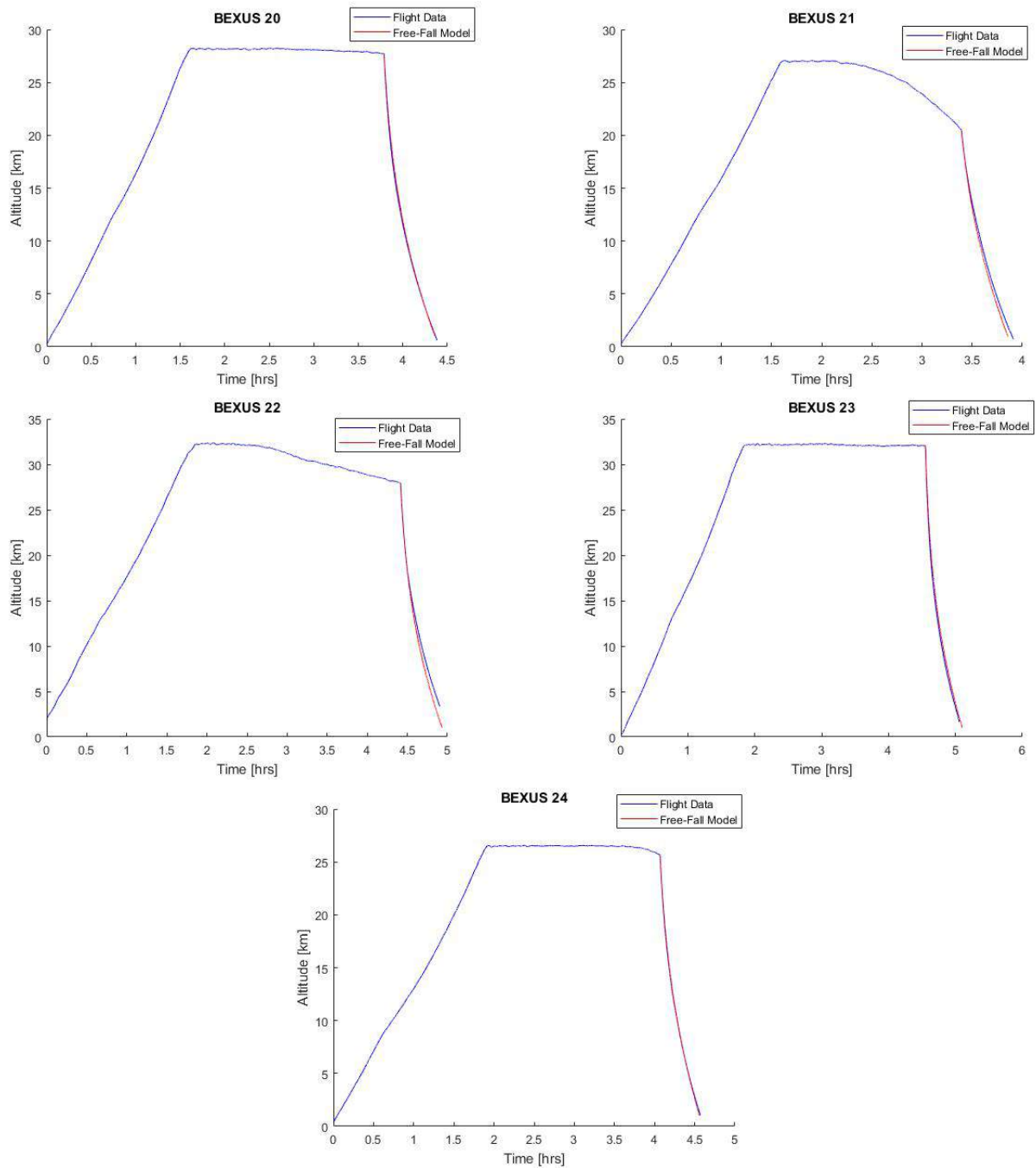
Figure 112: Comparative of the Altitude Over Time During the BEXUS Flights 20, 21, 22, 23, 24 with the Mathematical Model.

Velocity Profile

Here, the mathematical model was compared with the velocity profiles during the flights. It can be seen that the mathematical model in general follows the velocity profile with some minor deviations during Descent Phase, which means that the estimation is quite reliable.
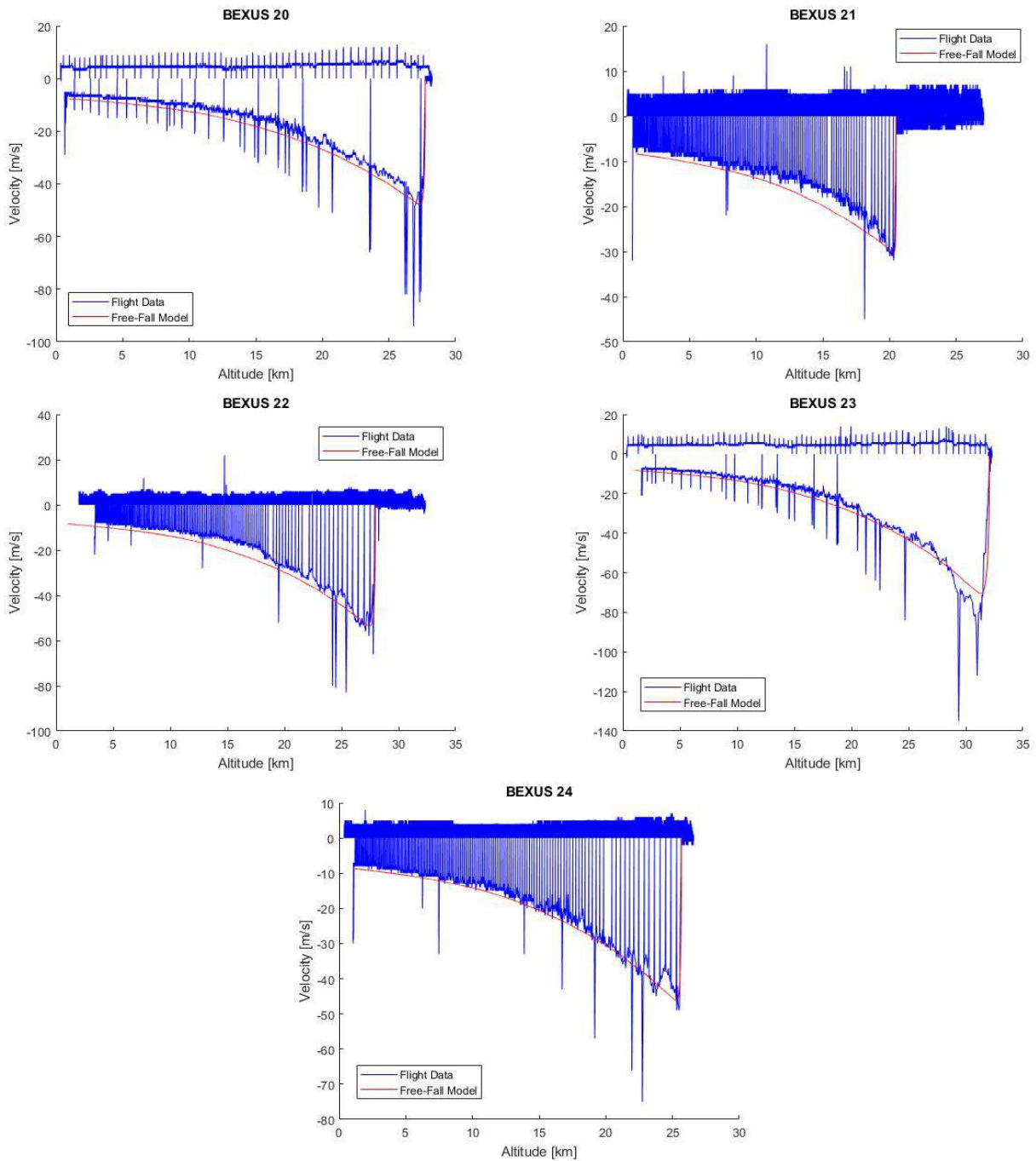
Figure 113: Comparative of the Velocity Over Altitude During the BEXUS Flights 20, 21, 22, 23, 24 with the Mathematical Model.

H.5.2   Mass Effects in the Descent Curve

Figure 114, shows how the descent time changes with different gondola mass values, after the cut-off phase. The heavier the payload, the sooner it will land. For example, if the gondola weights $250kg$, it will land in approximately 25 minutes after the cutoff, while it would take approximately 40 minutes to land if it weights $100kg$.
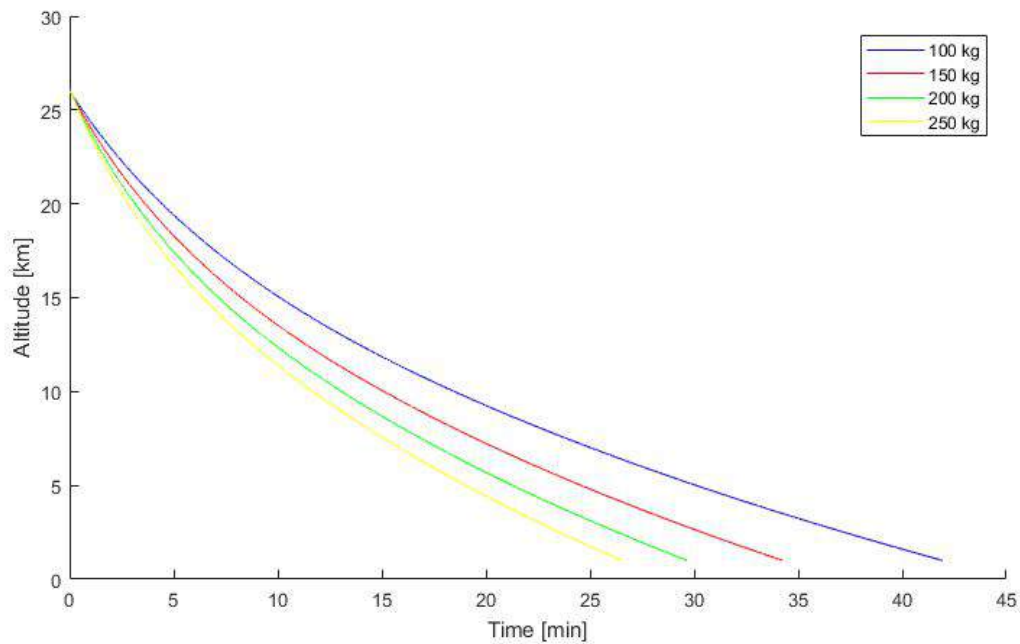
Figure 114: Mass Effects.

H.5.3   Discrete Sampling Volumes

Figure 115 supports the TUBULAR Team's decision to use a pump if sampling at high altitudes is meant, even though there is a single point failure risk. At $20km$ of altitude, the minimum amount of air that would be needed to be sampled, in order to ensure that there is enough left for analysis at ground, would be almost $3L$. Considering the low pressure at this high altitude, and the time it would be needed to fill the bag, it would be impossible to fulfill the experiment's objectives without using a pump. Moreover, without a pump, sampling at altitudes higher than $22km$, and also during Ascent Phase, would be impossible.
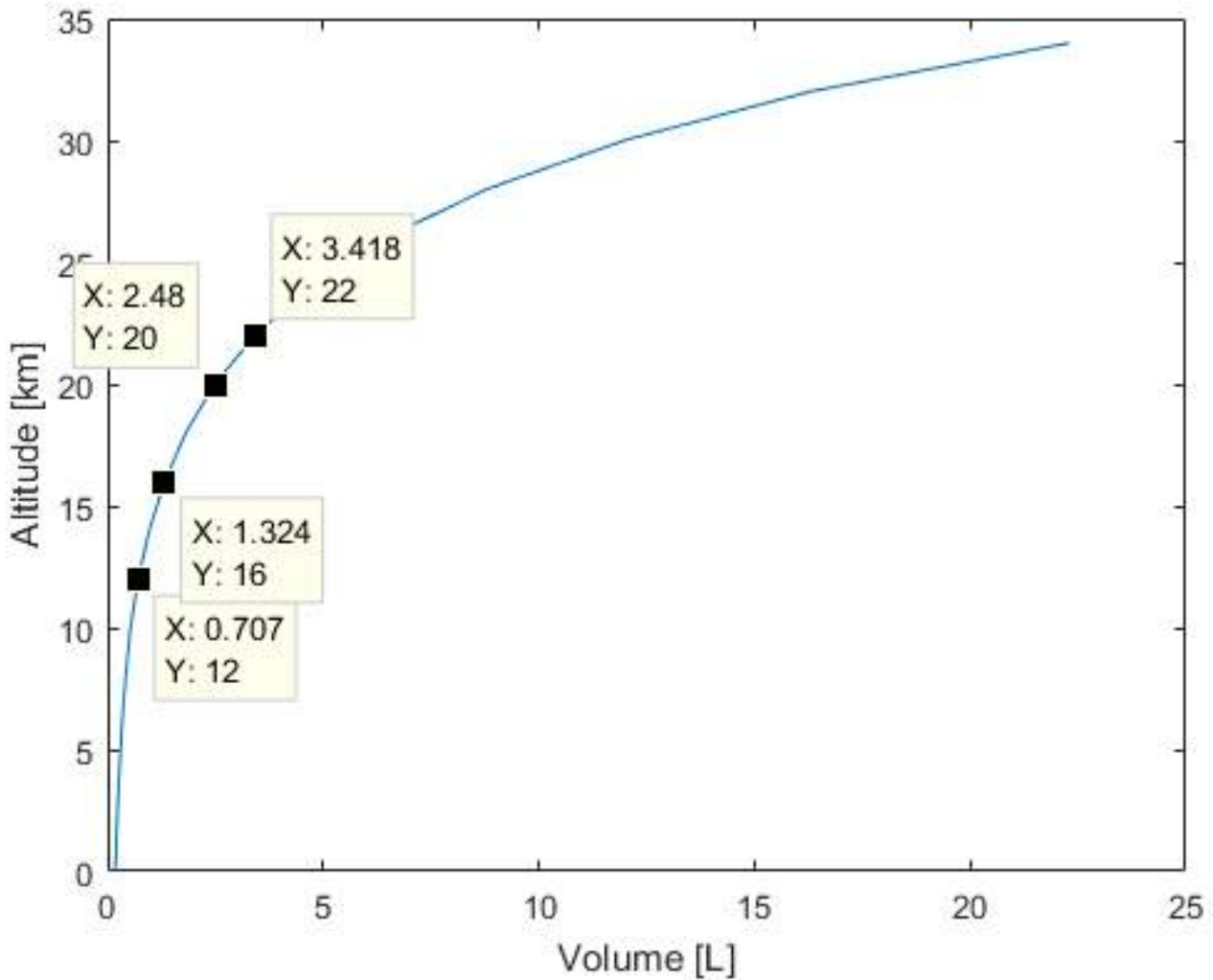
Figure 115: Minimum Sampling Volume at Each Altitude to Obtain Enough Air to Perform a Proper Analysis (180 mL at Sea Level).

H.5.4 Limitations of the Bag Sampling Method

Roof Altitude Effect

Since the pump's flow rate at high altitudes is not known yet, for a hypothetical study case, an ideal and continuous flow rate was used ($1L/min$). The obtained diagrams below, show that even if the sampling starts at $26km$, or at $30km$, or at $40km$, the number of filled bags would still be the same. This happens, due to the low pressure conditions at such altitudes which not allow a faster filling of a bag, and specially the low air density which forces to sample much more volume of air. Of course, the number of bags that can be filled, depends on the pump's efficiency at high altitudes. So, the altitude of the gondola's cut-off over about $26km$ would not affect the experiment's outcome.
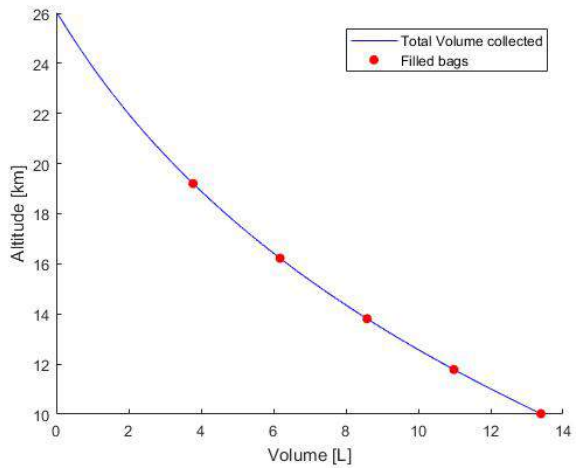
(a) Starting of Sampling at 26 km.
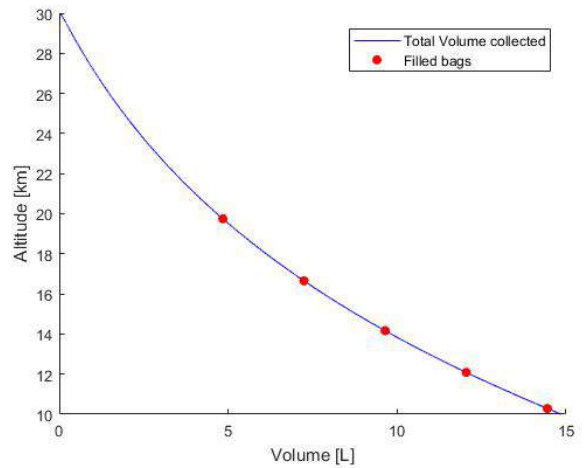
(b) Starting of Sampling at 30 km.
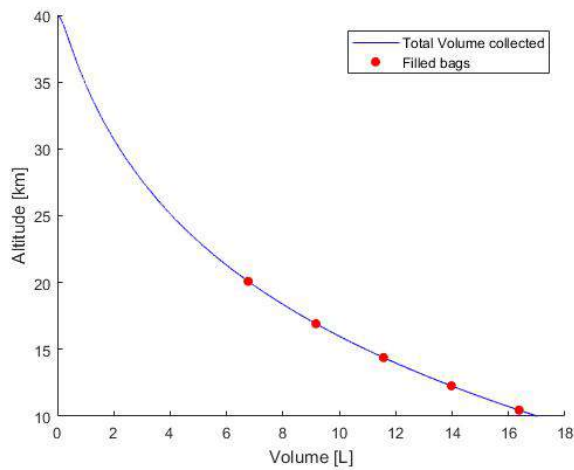
(c) Starting of Sampling at 40 km.

Figure 116: Bag's Sampling System Limitations.

One Single Pump

Since the experiment uses a single pump, it is not possible to sample more than one bags at the same time. For the above hypothetical case, the maximum number of filled bags was five, considering continuous sampling. However, this is not the case when it comes to real life. Before sampling a bag, the system has to be flushed. Then, the sampling of a bag begins. After filling one bag, the system has to be flushed again before starting sampling a second bag. In that case, filling five bags, according to the hypothetical scenario, would be practically impossible.

H.6 Conclusions

H.6.1 Sampling Strategy

After testing the pump at low pressure environment, an overall idea about the performance of the pump at high altitudes is now known and an approximation of the sampling strategy is possible. The total weight of the gondola is not known yet, but the balloon is expected to reach 25-27 km altitude, following the trajectory of the BEXUS 24 flight as shown in figure 112. This serves the objectives of the TUBULAR experiment since, as indicated in Section H.2.2 the altitudes with higher differences in trace gases concentrations, are between 10 and 25 km. These are the altitudes where the sampling will be done. Sampling six bags in total, is enough to fulfil the objectives of the experiment and it is also feasible. Two bags will be sampled during Ascent Phase and four during Descent Phase. The ascent speed of the gondola, as shown in Figure 97, is estimated to be 6 m/s. A velocity of this rate, makes sampling of two bags possible while achieving a good resolution. It is important to mention here that the two bags that will be sampled during Ascent Phase, shall not be fully filled, since their volume will increase with decreasing pressure and may burst. For that reason, only about 80% of their volume will be filled. On the other hand, during Descent Phase the four remaining bags shall be filled with the full 3 L. Since their volume will decrease with increasing pressure it has to be made sure that there will be enough sample left for analysis.

The sampling of the first bag will start at 18 km of altitude. The sampling time is estimated to be 44s with an achieved resolution of 262m. The second bag will be sampled at 21 km of altitude, and it will take 47 s to fill the desired volume of air, with a resolution of 279 m. Before sampling, flushing of the AAC system for 1min is taking into account. During that, the gondola will cover a distance of 360 m.

During Descent Phase, the sampling of the third will start from 17.5 km. The sampling time is estimated to be 52.94 sec with a resolution of 423.53 m. Bag no 4 will be sampled at 16 km for 50.0 s and resolution of 400 m. The fifth bag will be sampled at 14 km for 47.37 s and resolution of 378.95 m. The sample of the last bag will start at 12 km for 40.91 s sampling time and 327.27 m resolution. Again, one minute of flushing is taken into account, in between the sampling of each bag.

The flow rates of the pump, at each sampling altitude were taken from Figure 138.

H.6.2 Discusion of the Results

Overall, the mathematical model is in good agreement with the data from the past BEXUS flights as well as, with the atmospheric model used for the Arctic region. Making this document, helped the TUBULAR Team to cross-check some theoretical values, important for the layout and the planning of the experiment. Tables 63 and 64 show that the estimated data before each flight are pretty close with the real data obtained by the flights which will help the TUBULAR Team to define the experiment's parameters with higher accuracy. In order to make a sampling plan, it is important to know the duration time of each phase. Figure 96, shows the trajectories of the different BEXUS flights, giving the TUBULAR Team a general idea of what the trajectory of the flight can look like and how the duration of each phase changes regarding the maximum altitude that the gondola reaches.

The velocity profile, Figure 98, is of high importance since the velocity during ascent and Descent Phase, will determine the resolution of the samples. In general, the velocity values are in agreement with the BEXUS manual, with an ascent speed of 6 m/s and a descent speed, fluctuating after cutoff, before stabilizing at 8 m/s at the last kilometers of the flight. Another important thing that has to be mentioned here, is the TUBULAR Team's decision to sample during Ascent Phase too and not only during Descent Phase. As seen in figure 98 the gondola is turbulent after the cutoff with velocities up to 83 m/s, and needs more or less 6 km before stabilizing its velocity as figure 97 indicates. Hence, the altitudes that the gondola will be turbulent, will be covered by sampling during Ascent Phase. This will not affect the comparison with the CAC that will be sampled during Descent Phase only, since the horizontal displacement of the gondola is much smaller than the vertical.

Atmospheric conditions play a crucial role for the TUBULAR experiment. The TUBULAR Team should know, the different pressures at each altitude, since the pressure is the parameter that will trigger the sampling of the bags. What is more, the pressure will determine the performance of the pump and it is crucial to know under what pressures the pump needs to be tested depending on the sample altitude. The temperature is of high importance too and the trickier to predict especially at high altitudes. The TUBULAR Team should be able to keep the temperature of the pump within its working temperature range in order to assure that the pump will start working. To do so, the air temperature must be known at each altitude which will help the TUBULAR Team to come up with a good thermal plan.

The sampling altitude range will not be chosen randomly. The idea is to find the altitude range, where the trace gases show the bigger differences in concentration. In Section H.2.2, were presented some theoretical trace gases concentration values as well as, some results from past research papers. According to them, the more interesting area to sample is between 10 and 25 km of altitude. The TUBULAR Team, plans to sample between 17 and 22 km during Ascent Phase and 17 to 10 km during Descent Phase.

Additionally, the sampling software revealed some limitations of the sampling system and also which parameters should be taken into account for the experiment's layout and which not. The weight of the gondola, will affect the maximum altitude that the balloon will reach, and the time needed for the gondola to land, but it doesn't contribute to the decision of how many bags will be used.

The decision of the TUBULAR Team to use a pump was questioned at the beginning, as a single point failure risk. However, this decision is justified by the need of sampling during Ascent Phase, ohterwise the sampling would not be possile. Figure 115, supports the use of a pump because without a pump, sampling at 22 km of altitude, would be impossible considering the low pressure and the time it would take to fill a bag.

Note that even with the pump, some limitations still exist. The sampling of the bags cannot be continuous since the system has to be flushed before sampling a bag. Furthermore, the flow rate of the pump will be lower at high altitudes than it is on the ground, due to pressure differences. Figure 116 points out that even with an ideal flow rate of 1 L/min and sampling continuously, it is not possible to sample more than five bags, because it takes a lot of time to sample a bag at high altitude atmospheric conditions. Additionally, it makes clear why the maximum altitude that the gondola will reach, does not affect the experiment's outcome. As the gondola ascents, the pressure gets lower and takes more time to sample a bag. So, sampling more bags would not be possible even if the balloon reaches a higher altitude. The

same applies for the Descent Phase and the cutoff altitude.

Concluding, whilst at the beginning, the idea was to sample a total of sixteen bags in order to have more samples to compare with the continuous vertical profile obtained by the CAC, this document justifies that this is not feasible. Taking into account all the different parameters, it made clear which of them are important and which are not. Parameters like the gondola's velocity, the pressure at different altitudes, and the pump's flow rate, will determine the outcome of the TUBULAR experiment, the number of the bags that will be used, as well as the sampling altitudes. Parameters like the gondola's weight or the maximum altitude that the balloon will reach, does not affect the experiment's outcome and have a secondary role.

Note that after the pump tests, the sampling altitudes may change.

Appendix I   Experiment Thermal Analysis

I.1   Thermal equations

I.1.1   Variables and Tables

Variable	Description	Unit	Value
α_{Al}	Absorption of aluminum	-	0.3
S	Solar constant	$\frac{W}{m^2}$	1362
A_{Sun}	Area affected by the sun	m^2	0.28
Albedo	Albedo coefficient	-	0.15
A_{Albedo}	Area affected by the albedo	m^2	0.65
ε_{Earth}	Emissivity of Earth	-	0.95
A_{IR}	Area affected by the IR flux	m^2	0.65
IR_{25km}	Earth IR flux at 25 km	$\frac{W}{m^2}$	220
P	Dissipated power from electronics	W	varies
h	Convection heat transfer constant	$\frac{W}{m^2 \cdot K}$	18
K	Scaling factor for convection	-	varies
$A_{Convection}$	Area affected by the convection	m^2	1.3
σ	Stefan-Boltzmann constant	$\frac{W}{m^2 \cdot K^4}$	$5.67051 \cdot 10^{-8}$
$A_{Radiation}$	Radiating area	m^2	1.3
ε_{Al}	Emissivity of aluminum	-	0.09
T_{Out}	Temperature wall outside	K	varies
T_{Inside}	average uniform temperature inside	K	varies
$T_{Ambient}$	Ambient temperature outside	K	varies
T_{Ground}	Temperature of the ground	K	273
k_{Al}	Thermal conductivity of aluminum	$\frac{W}{m \cdot K}$	205
k_{PS}	Thermal conductivity of polystyrene foam	$\frac{W}{m \cdot K}$	0.03
L_{Al}	Thickness of aluminum sheeting	m	0.0005
L_{PS}	Thickness of polystyrene foam	m	varies
P_{Ground}	Pressure at ground	Pa	$101.33 \cdot 10^3$
P_{25km}	Pressure at $25km$	Pa	$2.8 \cdot 10^3$

Table 66: Variables Used in Thermal Calculation.

Wall part	Thickness (m)
Aluminum sheet	0.0005

AAC (Styrofoam)	
Vertical	0.02
Horizontal	0.02
Top/Bottom	0.03

CAC (Styrofoam)	
Horizontal towards AAC	0.02
All other walls	0.05

Table 67: The Different Wall Thicknesses Used for AAC and CAC.

I.2 Thermal calculations in MATLAB

For the MATLAB calculations a few assumptions were made, they are as follows.

- Taking the average of MATLAB calculations for calculations with or without sun.
- Calculate the average temperature on the outside wall of the experiment.
- Assuming the inner temperature at the bags section is uniform.
- The pipes letting cold air in have not been taken into account in MATLAB.
- Assume no interference between the two experiment boxes.
- All conduction is uniform from the inside.
- Assume steady flow through the walls from conduction.
- Assume radiation and convection from/on 6 walls not 5.

I.2.1 Solar flux and Albedo

The albedo is the reflected solar flux from earth so it can be put into the same equation as the solar flux. It is assumed that the sun hit two sides of the experiment at a $45°$ angle at all time over 10 km. In the mid of October at the time for launch the sun will hit the experiment with a maximum inclination of $15°$ from the horizon.

$$Q_{Sun+Albedo} = \alpha_{Al} \cdot S \cdot cos(15) \cdot (A_{Sun} \cdot cos(45) + Albedo \cdot A_{Albedo})$$

I.2.2 Conduction

For calculating the outer walls temperature, the assumption of steady flow through walls is used.

$$Q_{Conduction} = [\text{Steady flow through wall}] = \text{Dissipated power} = P$$

I.2.3 Earth IR flux

The earth IR flux is the flux that comes from earth as a black body radiating. It is calculated from finding the IR flux at the ground then scale it to the altitude the experiment will fly at. The following equations were found from [7].

$$IR_{Ground} = \varepsilon_{earth} \cdot \sigma \cdot T_{ground}^4$$

$$\tau_{atmIR} = 1.716 - 0.5 \cdot \left[e^{-0.65\frac{P_{25km}}{P_{ground}}} + e^{-0.95\frac{P_{25km}}{P_{ground}}} \right]$$

$$IR_{25km} = \tau_{atmIR} \cdot IR_{Ground}$$

After the IR has been calculated for the floating altitude it is put into the following equation.

$$Q_{IR} = \varepsilon_{earth} \cdot A_{IR} \cdot IR_{25km}$$

I.2.4 Radiation

It is assumed that the experiment will experience radiation from all 6 sides. In reality it will experience radiation from 5 sides because the CAC box will be in contact with one of the AAC box's sides. It was decided to leave it at 6 for the calculations in order to compensate for having no holes to let cold air in to the pump.

$$Q_{Radiation} = \sigma \cdot \varepsilon_{Al} \cdot A_{Radiation} \cdot (T_{Out}^4 - T_{Ambient}^4)$$

I.2.5 Convection

At an altitude of 25 km there is far lower air density than at sea level. Therefore, it gives that a scaling factor K has to be taken into account when calculating the convection and K can be seen in Table 68 for different altitudes.

$$Q_{Convection} = h \cdot K \cdot A_{Convection} \cdot (T_{Out} - T_{Ambient})$$

The equation for approximating the heat transfer coefficient for air is outlined as:

$$h = 10.45 - v + 10 \cdot \sqrt{v}$$

Where v is the velocity of the fluid medium.

As the balloon is expected to rise at approximately $5m/s$ for the duration of the Ascent Phase, the starting value for the convective heat transfer coefficient h is expected to be 27.811, assuming negligible wind currents perpendicular to the direction of ascent.

The equations used to obtain the value of K are listed below:

$$F(T_{sea}, T_{alt}) = \left(\frac{k_{alt}}{k_{sea}}\right)^{1-n} \times \left[\left(\frac{\beta_{alt}}{\beta_{sea}}\right) \times \left(\frac{\mu_{sea}}{\mu_{alt}}\right) \times \left(\frac{c_{p-alt}}{c_{p-sea}}\right) \times \left(\frac{\rho(T_{alt})}{\rho(T_{sea})}\right)^2 \right]^n$$

Where:

- n is an exponent value dependent on the turbulence of the fluid medium ($\frac{1}{4}$ for laminar flow and $\frac{1}{3}$ for turbulent flow)

- k is the thermal conductivity of the air

- β is the thermal expansion coefficient for air

- μ is the dynamic viscosity of the air

- c_p is the specific heat capacity of the air at constant pressure

- $\rho(T)$ is the density of the air as a function of only temperature difference (i.e. for constant pressure)

- "sea" denotes the current variable is represented by its value found at sea level

- "alt" denotes the current variable is represented by its value found at a specified altitude

The values for F from this equation were then applied to its respective position in the following equation to determine the ratio between the convective heat transfer coefficient h at sea level (assumed to have negligible differences for Esrange ground level) and the same coefficient at a specified altitude:

$$K = \left(\frac{\rho(P_{alt})}{\rho(P_{sea})}\right)^{2n} \times \left(\frac{\Delta T_{air}}{\Delta T_{sea}}\right)^{n} \times F(T_{sea}, T_{alt})$$

Where:

- $\rho(T)$ is the density of the air as a function of only temperature difference (i.e. for constant pressure)

- δT is the difference between the temperature of the ambient air and the surface in question

Table 68 combines the previously listed convection and radiation formulae integrated into the MATLAB scripts to determine the convective and radiative heat loss in the worst case for (highest) power dissipation during each stage of the experiment. Additional information on the thermodynamics of the atmosphere was obtained from *Engineering Toolbox* [19]

Altitude	Case	T_{amb}	K	h_{alt}	T_{out}	Q_{conv}	Q_{rad}
Hangar (Preparations)	Cold	283	1	10.45	20.3	139.409	6.516
	Expected	288	1	10.45	25.2	139.081	6.844
	Warm	293	1	10.45	30.2	138.743	7.182
Ground (Stationary)	Cold	263	1	18	-0.8	215.705	4.690
	Expected	273	1	18	9.2	215.171	5.222
	Warm	283	1	18	19.2	214.600	5.790
Ground (Launched)	Cold	263	1	28.945	-4.2	217.528	2.884
	Expected	273	1	28.945	5.8	217.195	3.217
	Warm	283	1	28.945	15.8	216.837	3.573
5 km	Cold	228	0.7868	22.774	-37.6	217.979	2.430
	Expected	263	0.8468	24.511	-3.2	216.990	3.417
	Warm	273	0.8507	24.624	6.3	216.615	3.792

10 km	Cold	193	0.4882	14.131	-68.1	217.916	2.480
	Expected	223	0.5286	15.300	-39.1	216.940	3.453
	Warm	238	0.5421	15.691	-24.4	216.336	4.055
15 km	Cold	193	0.3300	9.552	-61.9	224.325	3.961
	Expected	233	0.3680	10.652	-23.9	222.309	5.972
	Warm	253	0.3825	11.071	-4.6	221.050	7.226
20 km	Cold	213	0.2401	6.950	-35.6	220.777	7.430
	Expected	243	0.2563	7.419	-7.4	218.297	9.899
	Warm	268	0.2687	7.778	16.4	215.906	12.282
25 km	Cold	223	0.1683	4.871	-16.0	215.482	12.549
	Expected	253	0.1792	5.187	11.4	211.791	16.226
	Warm	273	0.1847	5.346	30.1	208.893	19.112
Float Phase	Cold	223	0.1683	3.029	-1.7	190.087	19.521
	Expected	253	0.1792	3.226	24.1	185.077	24.530
	Warm	273	0.1847	3.325	41.9	181.196	28.402
25 km	Cold	223	0.1683	5.173	-20.3	199.514	10.633
	Expected	253	0.1792	5.508	7.4	196.295	13.838
	Warm	273	0.1847	5.677	26.3	193.765	16.356
20 km	Cold	213	0.2401	7.379	-36.9	221.276	6.948
	Expected	243	0.2563	7.877	-8.6	218.934	9.280
	Warm	268	0.2687	8.258	15.2	216.672	11.534
15 km	Cold	193	0.3300	10.142	-63.6	216.808	3.561
	Expected	233	0.3680	11.310	-25.4	214.974	5.389
	Warm	253	0.3825	11.756	-6.0	213.829	6.530
10 km	Cold	193	0.4882	15.004	-68.8	218.074	2.326
	Expected	223	0.5286	16.246	-39.7	217.155	3.242
	Warm	238	0.5421	16.661	-25.0	216.586	3.809
5 km	Cold	228	0.7868	24.182	-38.1	218.127	2.284
	Expected	263	0.8468	26.026	-3.6	217.195	3.214
	Warm	273	0.8507	26.145	6.4	216.841	3.567
Ground (Landed)	Cold	263	1	30.734	-4.6	217.700	2.713
	Expected	273	1	30.734	5.4	217.386	3.027
	Warm	283	1	30.734	15.4	217.049	3.363
Ground (Stationary)	Cold	263	1	18	-4.8	207.753	2.586
	Expected	273	1	18	5.2	207.453	2.885
	Warm	283	1	18	15.2	207.132	3.205

Table 68: Table of Predicted Heat Loss.

I.2.6 Thermal equation

If there is no sun on the experiment.

$$Q_{IR} + Q_{Conduction} = Q_{Radiation} + Q_{Convection}$$

$$\updownarrow$$

$$\varepsilon_{earth} \cdot A_{IR} \cdot IR_{25km} + P$$
$$= \sigma \cdot \varepsilon_{Al} \cdot A_{Radiation} \cdot (T_{Out}^4 - T_{Ambient}^4) + h \cdot K \cdot A_{Convection} \cdot (T_{Out} - T_{Ambient})$$

If there is sun on the experiment it is the same but adding $Q_{Sun+Albedo}$.

$$Q_{IR} + Q_{Conduction} + Q_{Sun+Albedo} = Q_{Radiation} + Q_{Convection}$$

$$\updownarrow$$

$$\varepsilon_{earth} \cdot A_{IR} \cdot IR_{25km} + P + \alpha_{Al} \cdot S \cdot cos(15) \cdot (A_{Sun} \cdot cos(45) + Albedo \cdot A_{Albedo})$$
$$= \sigma \cdot \varepsilon_{Al} \cdot A_{Radiation} \cdot (T_{Out}^4 - T_{Ambient}^4) + h \cdot K \cdot A_{Convection} \cdot (T_{Out} - T_{Ambient})$$

From those equations T_{Out} can be calculated and it is the average temperature on the aluminum sheets facing the outside air. After T_{Out} have been found the inner temperature can be calculated by using heat transfer through the wall.

$$P = \frac{T_{Inside} - T_{Outside}}{A \cdot (\frac{L_{Al}}{k_{Al}} + \frac{L_{PS}}{k_{PS}})}$$

$$\updownarrow$$

$$T_{Inside} = P \cdot A \cdot (\frac{L_{Al}}{k_{Al}} + \frac{L_{PS}}{k_{PS}}) + T_{Outside}$$

T_{Inside} is then assumed to be the uniform air temperature in the experiment.

I.2.7 Trial run with BEXUS 25 air temperature data for altitudes

The air temperature data varying over altitude from old BEXUS flight could be found on the REXUS/BEXUS website. To do a simulated test flight for the calculations done in MATLAB, to see how it would be for a real flight it was calculated and plotted in with data from BEXUS 25 flight. Because of there being approx 42000 data points it had to be scaled down and only every 25th data point was used to save time and there was not much detail loss by taking every 25th. In Figure 117 the TUBULAR test flight is the uniform temperature on the inside with a insulation consisting as specified in Table 67.
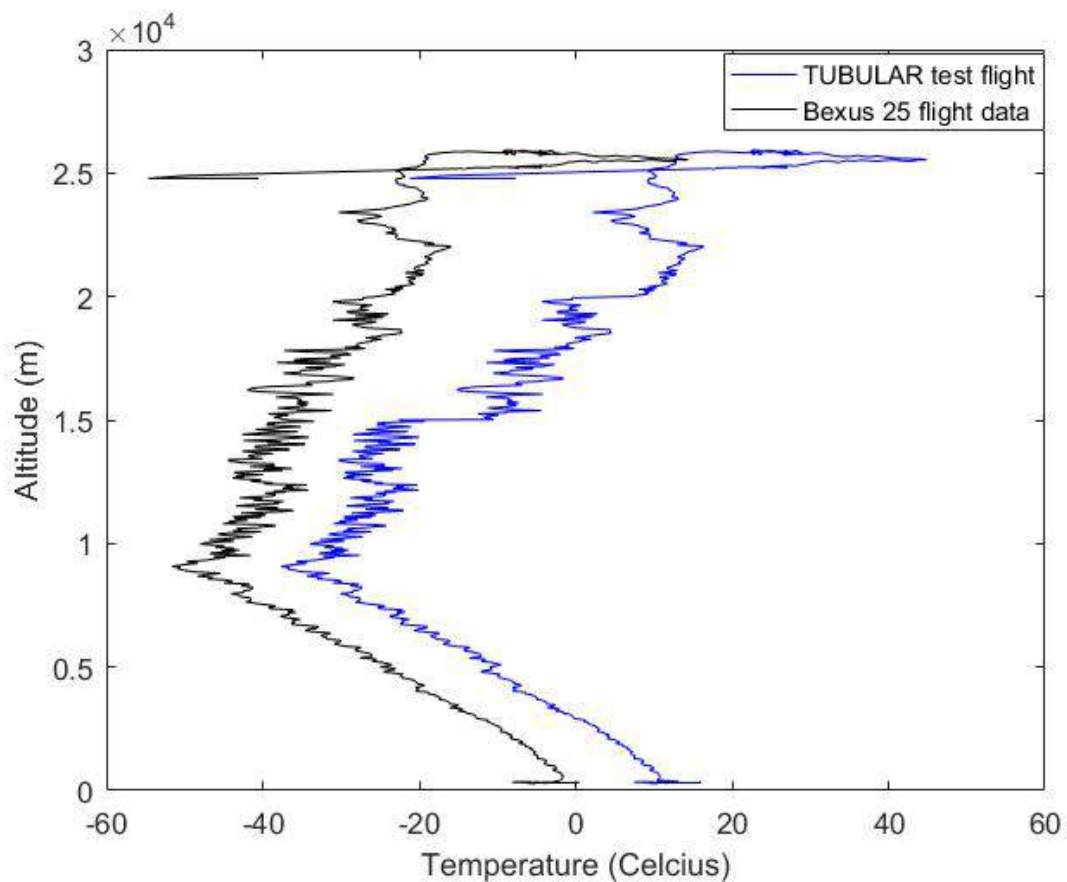
Figure 117: Simulated Test Flight of TUBULAR AAC Box with Data From BEXUS 25.

When the data was found it was checked in ANSYS to determine and add heaters to control the most critical parts of the model.

I.2.8 Trial flight for the CAC

The CAC box does not require as much thermal design as the AAC box. The only part to consider is the valve, which has a lower limit of the operating temperature of $-10°C$. It will not be a problem because the valve will open a little before launch and have a current throughout the whole flight heating it self up. If the thermal analysis is proven wrong by a test, showing that it is not sufficient to use only self heating, a heater can be applied at a later date. The passive thermal design for the CAC box will consist of aluminum sheets and Styrofoam as specified in 67.
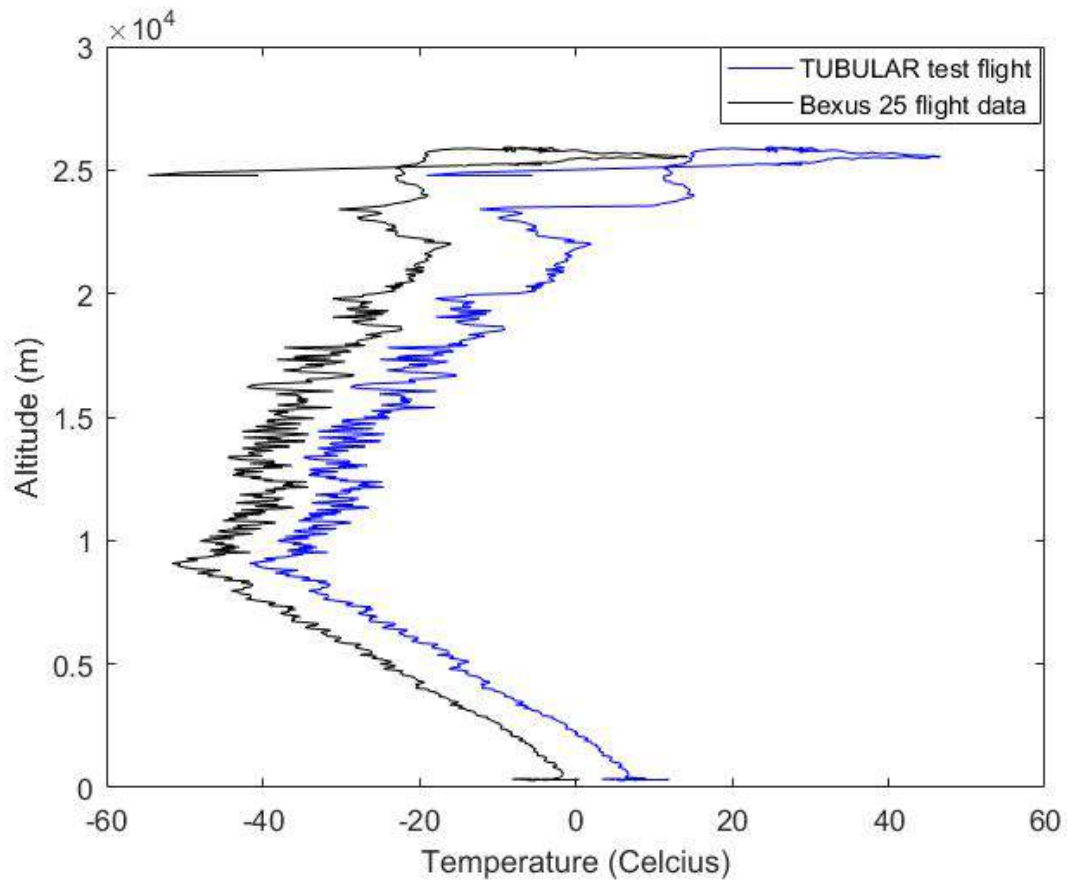
Figure 118: Simulated Test Flight of TUBULAR CAC Box with Data From BEXUS 25.

I.2.9   MATLAB Conclusion

By running the MATLAB script, the hottest and coldest case for $0.02m$ on the wall and $0.03m$ on the top and bottom of the Styrofoam could be found for ascent and descent sampling. The thermal conductivity of Styrofoam is $k = 0.03$. In Table 69 it is shown the hottest and coldest case of temperature on the inside when samples should be taken. The hottest and coldest cases are taken from Figure 117.

	Ascent		Descent	
	Coldest	Hottest	Coldest	Hottest
AAC	-11.39	16.41	-30.28	-4.393
Outer air	-38.22	-15.9	-44.41	-38.18

Table 69: The Sampling Temperature Ranges for Ascent and Descent for the AAC Box.

I.3   Thermal Simulations in ANSYS

In ANSYS, FEA simulations were done using both Steady-State Thermal and Transient Thermal analysis. Because of the limitations in ANSYS student license a simplified model has been used, which can be seen in Figure 120. It is in a lower corner of the experiment showing the Brain and has three walls to the sampling bags and the air is uniform on the inside. The uniform inside air can be taken from the data from the test flight in Figure (117). These simulations were done to see what temperature the pump and manifolds will be as they are the most critical components.
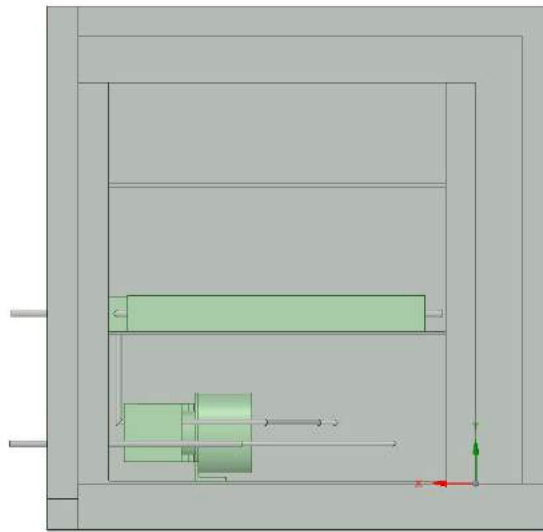
Figure 119: The CAD Model Used for ANSYS Simulations

The CAD model is as seen in the figure 120. The side exterior walls are $0.02m$, the interior walls of the Brain to the bags are $0.03m$ and the top and bottom wall consist of $0.03m$ Styrofoam as well. The outer parts of the pipes are set to stainless steel with a constant temperature (the same as the ambient outside). The tubes closest to the pump and the one going from pump to the manifold were set to air to simulate and be able to vary depending on the temperature outside and the pump heating up from the heater.

A transient thermal analysis was also performed by simulating a test flight with data from BEXUS 25 using results from MATLAB. It was performed so the thickness of the wall could be verified to see if it was good enough and whether adding heaters was required. By being flexible with adding heaters, moving them around, changing their strength and their on time, it is possible to enable the pump and the manifold to operate in their required temperature ranges.

I.4   ANSYS Result

I.4.1   Including Air With Same Density as Sea Level in the Brain
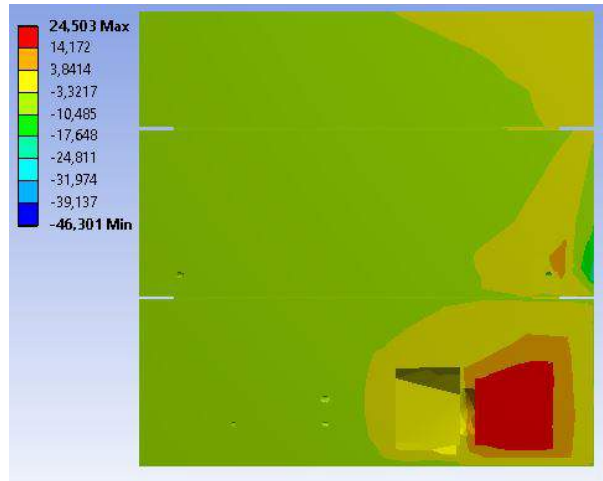
Figure 120: Cross Section of the Air in the Brain at the Time to Sample During Ascent.
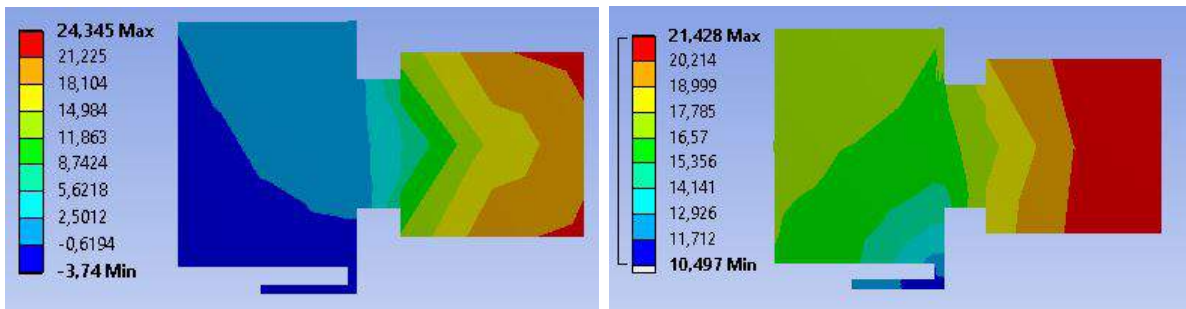
Figure 121: The Pump at the Time to Sample During Ascent (left) and Descent (right).
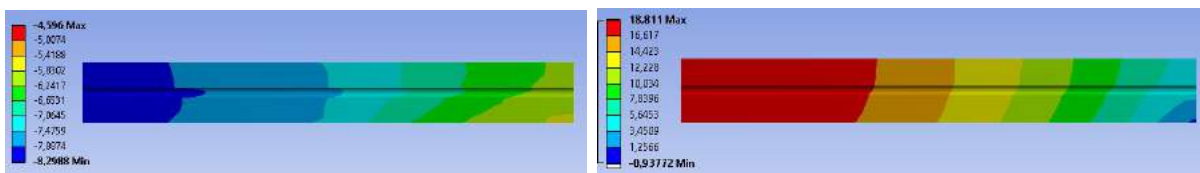
Figure 122: The manifold at the Time to Sample During Ascent (left) and Descent (right).
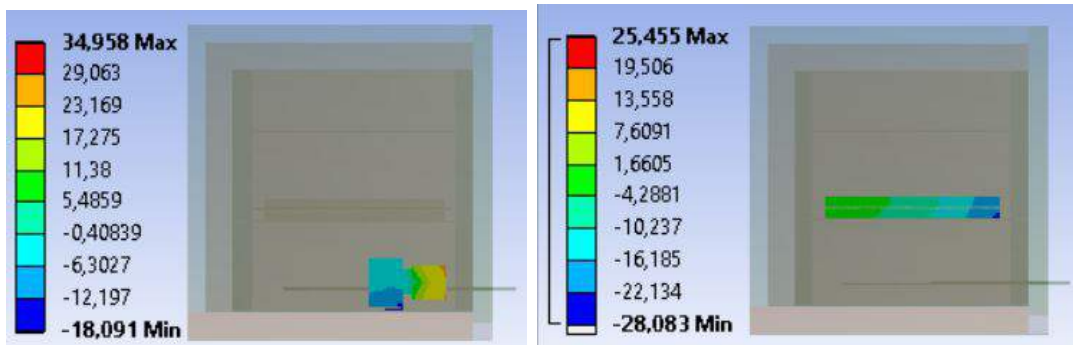
Figure 123: Pump and Manifold at the Coldest Part of Ascent.
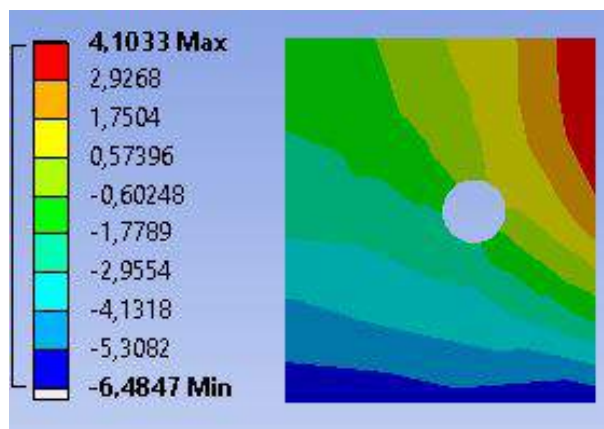
Figure 124: Flushing Valve a Little Before Sampling Shall Start.

I.4.2 No Air in the Brain
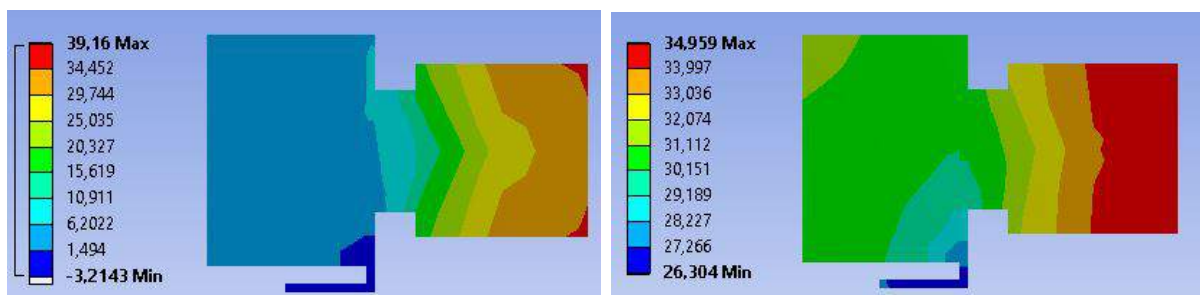
Figure 125: The Pump at the Time to Sample During Ascent (left) and Descent (right).
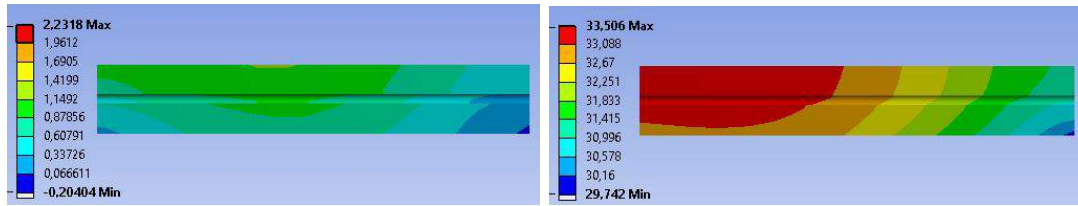
Figure 126: The manifold at the Time to Sample During Ascent (left) and Descent (right).
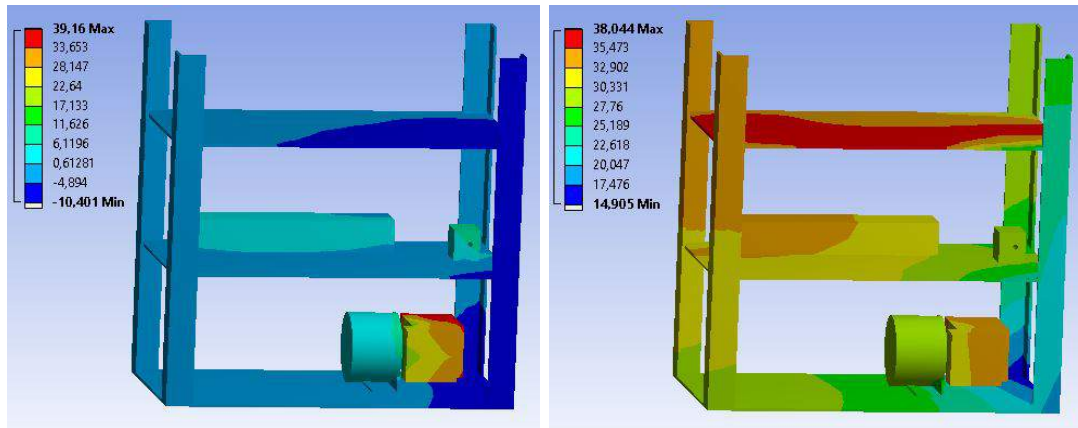
Figure 127: The Structure of the Brain at the Time to Sample During Ascent (left) and Descent (right).
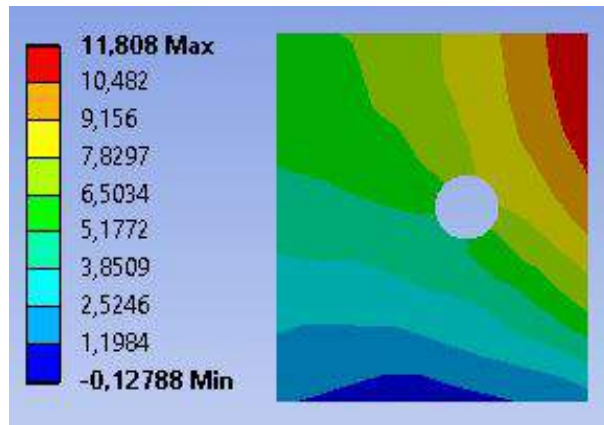
Figure 128: Flushing Valve a Little Before Sampling Shall Start.

I.5   Result

The main objective from performing first the MATLAB calculations and then the ANSYS simulations has been to iterate and find the wall thickness of Styrofoam between the Brain and the inside of the AAC box. The next objective was to iterate the design with adding heaters to find the required amount and find approximately how long they need to run. By

running a transient thermal analysis for the test flight there was the possibility to simulate heaters that will be on and off to determine how strong they need to be.

The results from the ANSYS simulations assumed a worst case scenario. It was to be expected that the results were not fully accurate, and instead were slightly warmer in reality. The worst case is with air inside at normal density. In reality when it is time to sample (at 17km), the air density will be less then 15% of the air density at sea level [18]. It means there will be less heat loss from components to the air inside the brain. Figures 121 and 122 show that the temperature of the pump is above $5°C$ and the manifold is above $-10°C$. It is only during a portion of the Ascent Phase, just prior to the start of sampling that the heater should be on in order for the pump to be above $5°C$, and it shall only be needed to be on during this Phase. By having a heater on the flushing valve and the manifold it is possible to get all the valves to the operating temperature. The flushing tube that goes out to the open air outside will cool down the flushing valve so adding a heater there to compensate is required. When it is time to flush right before sample can be seen in Figure 128. The manifold would still need a heater because it will be affected by the cold outer air and help heat up all the components

The insulation for the AAC will be as specified in Table 67. For the three inner walls between the Brain and the bags there will be a $0.03m$ wall of Styrofoam. By using two $5W$ heaters for the pump, one on top and one on bottom side, a 5 W heater for the flushing valve and one for the manifold. The thermal simulations predict that they will be within the operating limits with a satisfactory margin. For the heater controller, it will be set that if the pump is below $15°C$ it will turn on. As for the flushing valve, the heater will be set to turn on if the flushing valve and manifold is below $-5°C$.

Appendix J   Thermal Analysis MATLAB Code

J.1   Convection MATLAB Code

```matlab
%% Reynolds Number for Forced Convection

Re_v = 6;
Re_D = 0.4;
Re_rho = 1.225;
Re_mu = 1.764e5;

Re = (Re_v * Re_D * Re_rho)/Re_mu;

if Re < 2300
    n = 0.25
else
    n = 0.333333
end


%% Forced Convection

n = 0.25;
rho_sea = 1.225;
rho_alt = 0.0400; %At 25 km
k_alt = 0.02281;
k_sea = 0.02436;
beta_sea = 0.00369;
mu_sea = 1.710e-05;
mu_alt = 1.610e-05;
cp_alt = 1006.0;
cp_sea = 1003.7;
T_sea_cold = 263;
T_sea_exp = 273;
T_sea_hot = 283;
T_5_cold = 228;
T_5_exp = 263;
T_5_hot = 273;
T_10_cold = 193;
T_10_exp = 223;
T_10_hot = 238;
T_15_cold = 193;
T_15_exp = 233;
T_15_hot = 253;
T_20_cold = 213;
T_20_exp = 243;
T_20_hot = 268;
T_alt_cold = 223; % 25 km
T_alt_exp = 253;
T_alt_hot = 273;

F = ((k_alt/k_sea)^(1-n)) * ((beta_alt/beta_sea)*(mu_sea/mu_alt)*(cp_alt/
    cp_sea)*(((T_alt_exp)/(T_sea_exp))^2))^n

P_sea = 101300;
deltaT_sea = 10;
```

```matlab
52 P_alt = 2549; %at 25 km
53 P_5 = 54050;
54 P_10 = 26500;
55 P_15 = 12110;
56 P_20 = 5529;
57 deltaT_alt = 20; % Assumed from surface temperature at 25000 km from
      previous main Thermal script.
58
59 h_ratio = (((P_alt)/(P_sea))^(2*n)) * ((deltaT_alt/deltaT_sea)^n) * F
```

The resulting $h - ratio$ is then applied to the value of K in the main script written below:

J.2   Main Thermal MATLAB Code

```matlab
1 %Erik test earlier version
2 clear all
3
4 %Trial v1.2 ,Erik
5 %Variables:
6 Area_outside=2*0.5*0.4 + 2*0.5*0.5 + 2*0.5*0.4;
7 Area_inside=2*(0.5-0.04)*(0.4-0.04) + 2*(0.5-0.06)*(0.5-0.06) +
     2*(0.5-0.04)*(0.4-0.04);
8 alpha_al = 0.3;                        %Absorbity of aluminium
9 S = 1362*cosd(15);                     %Solar constant
10 A_sun = (0.5*0.4+0.4*0.49)*cosd(45);  %Area affectd by the sun
11 Albedo = 0.15;                        %The albedo coefficient of earth
12 A_albedo = Area_outside/2;            %Area affected by the alebedo
      reflection
13 e_earth = 0.95;                       %Emissivity of earth
14 IR = 220;                             %Earth IR
15 A_IR = Area_outside/2;                %Area affected by the IR
16 P = 11.499;                           %Worst Disapated power
17 P2 = 8.993;                           %Average Disapated power
18 h = 27.811*0.3392;                    %Convection heat transfere constant
19                                       %h=18 ground h=27.811 ascent h
                                            =30.33 descent
20 A_convect = Area_outside;             %Area affected by convection
21 K = 1;                                %Factor which decrease convection
      at high altitude
22 %TO = ;                               %Temperature wall outside
23 %TI = ;                               %Temperature wall inside
24 Ta = 223;                             %Ambient temperature outside
25 sigma = 5.67051*10^-8;                %Stefan-Boltzmann constant
26 A_tot = Area_outside;                 %Whole outer area
27 e_Al = 0.09;                          %Emissivity of aluminium
28
29 %Scaling factors IR flux Tground=10C
30 Qir=e_earth*sigma*273^4;
31 tau=1.716-0.5*(exp(-0.65*(2.8/101.33))+exp(-0.95*(2.8/101.33)));
32 Qir_25k=tau*Qir;
33
34 %Equations that are used:
35 %{
36 Q_sun_Albedo = alpha_al*S*(A_sun+Albedo*A_albedo);
37 Q_conduction = P; %Assumed steady heat flow through wall
38 Q_IR = e_earth*A_IR*IR;
```

```matlab
39  Q_radiation = sigma*e_AL*A_tot*(TO^4 - Ta^4);
40  Q_convection = (h*A_convect*(TO-Ta))/K;
41  %}
42
43  %%%%
44  %For the Worst dissipated power
45  %%%%
46  %Sides with no sun
47  syms x positive
48  outside_temperature = P + e_earth*IR*A_IR == e_Al*sigma*A_tot*((x^4)-(Ta^4)
        ) + (h*A_convect*(x-Ta))/K;
49  solx = solve(outside_temperature, x);
50  T_no_sun = vpa(solx);
51
52  %Solving TO
53  syms x positive
54  outside_temperature = P + e_earth*IR*A_IR + alpha_al*S*(A_sun+Albedo*
        A_albedo) == e_Al*sigma*A_tot*((x^4)-(Ta^4)) + (h*A_convect*(x-Ta))/K;
55  solx = solve(outside_temperature, x);
56  TO = vpa(solx);
57
58  %Solving TI
59  %Assume TI is a uniform temperature inside
60  Lal = 0.002;    %thicknes aluminium
61  Lps = 0.02;     %thicknes polystyrene foam
62  Lpe = 0.00;     %thicknes polyethylene foam
63
64  kal = 205;      %thermal conductivity aluminium
65  kps = 0.03;     %thermal conductivity polystyrene foam
66  kpe = 0.47;     %thermal conductivity polyethylene foam
67
68  TI = P*((Lal/(kal*Area_inside))+(Lps/(kps*Area_inside))+(Lpe/(kpe*
        Area_inside))) + TO;
69  TI_no_sun = P*((Lal/(kal*Area_inside))+(Lps/(kps*Area_inside))+(Lpe/(kpe*
        Area_inside))) + T_no_sun;
70
71  %%%%
72  %For the Average dissipated power
73  %%%%
74  %Sides with no sun
75  syms x positive
76  outside_temperature = P2 + e_earth*IR*A_IR == e_Al*sigma*A_tot*((x^4)-(Ta
        ^4)) + (h*A_convect*(x-Ta))/K;
77  solx = solve(outside_temperature, x);
78  T_no_sun2 = vpa(solx);
79
80  %Solving TO
81  syms x positive
82  outside_temperature = P2 + e_earth*IR*A_IR + alpha_al*S*(A_sun+Albedo*
        A_albedo) == e_Al*sigma*A_tot*((x^4)-(Ta^4)) + (h*A_convect*(x-Ta))/K;
83  solx = solve(outside_temperature, x);
84  TO2 = vpa(solx);
85
86  TI2 = P2*((Lal/(kal*Area_inside))+(Lps/(kps*Area_inside))+(Lpe/(kpe*
        Area_inside))) + TO2;
87  TI_no_sun2 = P2*((Lal/(kal*Area_inside))+(Lps/(kps*Area_inside))+(Lpe/(kpe*
        Area_inside))) + T_no_sun2;
```

```matlab
88
89  %Results
90  TO=TO-273;
91  TI=TI-273;
92  Ta=Ta-273;
93  T_no_sun=T_no_sun-273;
94  TI_no_sun=TI_no_sun-273;
95
96  TO2=TO2-273;
97  TI2=TI2-273;
98  T_no_sun2=T_no_sun2-273;
99  TI_no_sun2=TI_no_sun2-273;
100 %only use if it is Launch pad, Early ascent, shutdown descent, landed
101 T_wall_average2=(T_no_sun2+TO2)/2;
102 T_in_average2=(TI_no_sun2+TI2)/2;
103 T_wall_average=(T_no_sun+TO)/2;
104 T_in_average=(TI_no_sun+TI)/2;
105
106 Results = [Ta T_wall_average T_in_average ; Ta T_wall_average2
        T_in_average2] %TO TI T_no_sun TI_no_sun
107
108 %%%%
109 %The part to run if a test run with BEXUS 25 data wants to be used.
110 %%%%
111 %Testing bexus 25 flight data, Erik
112 Area_inside=2*(0.5-0.04)*(0.4-0.04) + 2*(0.5-0.06)*(0.5-0.06) +
        2*(0.5-0.04)*(0.4-0.04);
113
114 % test CAC
115 %{
116 Area_outside=4*0.5*0.25+2*0.5*0.5;
117 Area_inside=4*(0.5-0.1)*(0.25-0.1)+2*(0.5-0.04)*(0.5-0.1);
118 A_convect = Area_outside;
119 A_sun = (0.5*0.5+0.5*0.25)*cosd(45);
120 A_IR = Area_outside/2;
121 A_albedo=A_IR;
122 %}
123 Allti='Alltitude.txt';
124 Alltitude=csvread(Allti);
125 for i=2:1:length(Alltitude)
126     if Alltitude(i) < 20
127         Alltitude(i)=Alltitude(i-1);
128     elseif Alltitude(i) > 30000
129         Alltitude(i)=Alltitude(i-1);
130     end
131 end
132 Alltitude(41948)=Alltitude(41947);
133 Alltitude(41949)=Alltitude(41947);
134 Alltitude(41950)=Alltitude(41947);
135
136 M='test.txt';
137 T1=csvread(M);
138
139 T1(41948)=T1(41947);
140 T1(41949)=T1(41947);
141 T1(41950)=T1(41947);
142
```

```matlab
143  j=length(T1)/25
144  ty=1;
145  for r=25:25:length(T1)
146      T12(ty)=T1(r);
147      Alltitude2(ty)=Alltitude(r);
148      ty=ty+1;
149  end
150
151  for i=1:1:length(T12)
152      h=18;
153      if Alltitude2(i) < 400
154          h=18*1;
155          P=0.075+10;
156      elseif Alltitude2(i) > 400 && Alltitude2(i) < 5000
157          h=27.811*1;
158          P=0.075+10;
159      elseif Alltitude2(i) > 5000 && Alltitude2(i) < 10000
160          h=27.811*0.7962;
161          P=0.075+10;
162      elseif Alltitude2(i) > 10000 && Alltitude2(i) < 15000
163          h=27.811*0.5134;
164          P=0.075+10;
165      elseif Alltitude2(i) > 15000 && Alltitude2(i) < 20000
166          h=27.811*0.3392;
167          P=7.5+10+5;
168      elseif Alltitude2(i) > 20000 && Alltitude2(i) < 23500
169          h=27.811*0.2292;
170          P=7.5+10+5;
171      elseif Alltitude2(i) > 23500
172          h=18*0.1592;
173          P=0.075;
174      end
175
176
177  %Solving TO
178  syms x positive
179  outside_temperature = P + e_earth*IR*A_IR + alpha_al*S*(A_sun+Albedo*
         A_albedo) == e_Al*sigma*A_tot*((x^4)-(T12(i)^4)) + (h*A_convect*(x-T12(i
         )))/K;
180  solx = solve(outside_temperature, x);
181  TO(i) = vpa(solx);
182
183  %Solving TI
184  %Assume TI is a uniform temperature inside
185  Lal = 0.002; %thicknes aluminium
186  Lps = 0.02; %thicknes polystyrene foam
187  Lpe = 0.00; %thicknes polyethylene foam
188
189  kal = 205; %thermal conductivity aluminium
190  kps = 0.03; %thermal conductivity polystyrene foam
191  kpe = 0.47; %%thermal conductivity polyethylene foam
192
193  TI(i) = P*((Lal/(kal*Area_inside))+(Lps/(kps*Area_inside))+(Lpe/(kpe*
         Area_inside))) + TO(i);
194
195  syms x positive
196  outside_temperature = P + e_earth*IR*A_IR == e_Al*sigma*A_tot*((x^4)-(T12(i
```

```matlab
        )^4)) + (h*A_convect*(x-T12(i)))/K;
197  sol = solve(outside_temperature, x);
198  TO2(i) = vpa(sol);
199
200  TI2(i) = P*((Lal/(kal*Area_inside))+(Lps/(kps*Area_inside))+(Lpe/(kpe*
         Area_inside))) + TO2(i);
201
202  TI(i)=TI(i)-273;
203  T12(i)=T12(i)-273;
204  TI2(i)=TI2(i)-273;
205  if Alltitude2(i) < 10000
206      Tmid(i)=(TI(i)+TI2(i))/2;
207  else
208      Tmid(i)=TI2(i);
209  end
210  i
211  end
212  %{
213  figure(1)
214  plot(TI,Alltitude2,'b',T12,Alltitude2,'k',TI2,Alltitude2,'g')
215  xlabel('Temperature (Kelvin)');
216  ylabel('Altitude (m)')
217  legend('Sun all the way','Bexus 25 flight data','No sun all the way')
218  figure(2)
219  plot(TI,Alltitude2,'b',T12,Alltitude2,'k',TI2,Alltitude2,'g')
220  xlabel('Temperature (Celcius)');
221  ylabel('Altitude (m)')
222  legend('Sun all the way','Bexus 25 flight data','No sun all the way')
223  %}
224  figure(3)
225  plot(Tmid,Alltitude2,'b',T12,Alltitude2,'k')
226  xlabel('Temperature (Celcius)');
227  ylabel('Altitude (m)')
228  legend('TUBULAR test flight','Bexus 25 flight data')
229  %}
```

Appendix K   Budget Allocation and LaTeX Component Table Generator Google Script Code

K.1   Budget Allocation Code

```
1   // Define constants for range and cell locations.
2   var COLUMN_RANGE_SPONSOR = 'K5:K197';
3   var COLUMN_RANGE_COST = 'J5:J197';
4
5   var CELL_SPONSOR_SHIPPING = 'K200';
6   var CELL_SPONSOR_ERROR_MARGIN = 'K201';
7
8   var CELL_SHIPPING_COST_PERCENTAGE = 'F209';
9   var CELL_ERROR_MARGIN_PERCENTAGE = 'F210';
10
11  var CELL_SHIPPING_COST = 'F226';
12  var CELL_ERROR_MARGIN_COST = 'F227';
13
14  // Mapping between sponsors and the total allocated funds cell
15  var SPONSORS_TOTAL_ALLOCATION_CELL_DICT = {
16    'LTU': 'G215',
17    'SNSB': 'G216',
18    'FMI': 'G217',
19    'RESTEK': 'G218',
20    'TEKNOLAB': 'G219',
21    'SMC': 'G220',
22    'PARKER': 'G221'};
23
24  // Sheet and ranges.
25  var sheet = SpreadsheetApp.getActiveSpreadsheet();
26  var rangeSponsor = sheet.getRange(COLUMN_RANGE_SPONSOR);
27  var rangeCost = sheet.getRange(COLUMN_RANGE_COST);
28
29  /**
30   * Iterator through all the item/coponent rows in the budget table
31   * and sum to total cost sponsored by a given sponser.
32   */
33  function calculateSponsorBudgetAllocation_(sponsor) {
34
35    var numRows = rangeSponsor.getNumRows();
36    var totalAmountSponsored = 0;
37
38    for (var i = 1; i <= numRows; i++) {
39      var componentSponsor = rangeSponsor.getCell(i,1).getValue();
40      if(componentSponsor == sponsor){
41        var amountSponsored = rangeCost.getCell(i,1).getValue();
42        totalAmountSponsored = totalAmountSponsored + amountSponsored;
43      }
44    }
45
46    var cell = sheet.getRange(SPONSORS_TOTAL_ALLOCATION_CELL_DICT[sponsor]);
47    cell.setValue(totalAmountSponsored);
48
49    return totalAmountSponsored;
50  }
```

```
51
52
53  /**
54   * Allocate shipping cost to a given sponsor.
55   */
56  function allocateShippingCostToSponsor_(shippingCost, sponsor){
57    var cell = sheet.getRange(CELL_SPONSOR_SHIPPING);
58    cell.setValue(sponsor);
59
60    allocateExtraCostToSponsor_(shippingCost, sponsor)
61  }
62
63  /**
64   * Allocate error margin cost to a given sponsor.
65   */
66  function allocateErrorMarginCostToSponsor_(errorMarginCost, sponsor){
67    var cell = sheet.getRange(CELL_SPONSOR_ERROR_MARGIN);
68    cell.setValue(sponsor);
69
70    allocateExtraCostToSponsor_(errorMarginCost, sponsor)
71  }
72
73  /**
74   * Allocate extra cost to a given sponsor.
75   */
76  function allocateExtraCostToSponsor_(extraCost, sponsor){
77    var costAllocatedToSponsorCell = sheet.getRange(
78        SPONSORS_TOTAL_ALLOCATION_CELL_DICT[sponsor]);
78    costAllocatedToSponsorCell.setValue(costAllocatedToSponsorCell.getValue()
          + extraCost);
79  }
80
81
82  /**
83   * Calculate sponsorship allocation of funds for all sponsors.
84   */
85  function calculateAllSponsorBudgetAllocations(){
86    var amountLTU = calculateSponsorBudgetAllocation_('LTU');
87    var amountSNSB = calculateSponsorBudgetAllocation_('SNSB');
88    var amountFMI = calculateSponsorBudgetAllocation_('FMI');
89    var amountRESTEK = calculateSponsorBudgetAllocation_('RESTEK');
90    var amountTEKNOLAB = calculateSponsorBudgetAllocation_('TEKNOLAB');
91    var amountSMC = calculateSponsorBudgetAllocation_('SMC');
92    var amountPARKER = calculateSponsorBudgetAllocation_('PARKER');
93
94    // Calculate error margin.
95    // Error margin only applies to components purchased with LTU and SNSB
          funds.
96    // This is because other sponsorships are not based on funds but on
          components donated.
97    var errorMarginPercentage = sheet.getRange(CELL_ERROR_MARGIN_PERCENTAGE).
          getValue();
98    var errorMarginCost = errorMarginPercentage * (amountLTU + amountSNSB);
99    var cell = sheet.getRange(CELL_ERROR_MARGIN_COST);
100   cell.setValue(errorMarginCost);
101
102   // Calculate shipping cost.
```

```
103    // Treat the shipping cost the same way as error margin.
104    // only applies to components purchased with LTU and SNSB funds.
105    var shippingCostPercentage = sheet.getRange(CELL_SHIPPING_COST_PERCENTAGE
          ).getValue();
106    var shippingCost = shippingCostPercentage * (amountLTU + amountSNSB);
107    var cell = sheet.getRange(CELL_SHIPPING_COST);
108    cell.setValue(shippingCost);
109
110    // Allocate shipping and error costs to specific sponsor.
111    allocateShippingCostToSponsor_(shippingCost, 'SNSB');
112    allocateErrorMarginCostToSponsor_(errorMarginCost, 'SNSB');
113  }
```

K.2 Latex Component Table Generator

```
1  RANGE_TABLE = 'B5:P202';
2
3  var sheet = SpreadsheetApp.getActiveSpreadsheet();
4  var tableRange = sheet.getRange(RANGE_TABLE);
5
6  /**
7   * Generate all component tables.
8   */
9  function generateAllComponentTables(){
10    generateTable_('M', 'Mechanical Components Table', 'tab:components-table-
        mechanical', 'E300');
11    generateTable_('E', 'Electrical Components Table', 'tab:components-table-
        electrical', 'E301');
12    generateTable_('O', 'Other Components Table', 'tab:component-table-other'
        , 'E302');
13  }
14
15  /**
16   * Generate speficic component table based on provided arguments.
17   */
18  function generateTable_(divisionCode, caption, label, outputCell) {
19
20    var header = '\\ begin{longtable} ' +
21    '{|m{0.05\\ textwidth}|m{0.25\\ textwidth}|m{0.15\\ textwidth}|m{0.2\\
        textwidth}|m{0.05\\ textwidth}|m{0.05\\ textwidth}|m{0.05\\ textwidth
        }|m{0.25\\ textwidth}|m{0.095\\ textwidth}|} ' +
22    '\\ hline ' +
23    '\\ textbf{ID} & \\ textbf{A} & \\ textbf{B} & \\ textbf{C} & \\ textbf{D
        } & \\ textbf{E} & \\ textbf{F}  & \\ textbf{G}  & \\ textbf{H} \\\\
        \\ hline ';
24
25    var footer = '\\ caption{' + caption + '} ' +
26      '\\ label{' + label + '} ' +
27      '\\ end{longtable} ' +
28      '\\ raggedbottom';
29
30    var rowArray = new Array();
31
32    var numRows = tableRange.getNumRows();
33    var numCols = tableRange.getNumColumns();
34
35    for (var i = 1; i <= numRows; i++) {
36      var id = tableRange.getCell(i, 13).getValue();
37
38      if(id.toString().indexOf(divisionCode) == 0){
39
40        var itemNumber = tableRange.getCell(i, 1).getValue();
41        var itemSubNumber = '';
42        var component = tableRange.getCell(i, 2).getValue();
43
44        if(itemNumber == ''){
45          itemSubNumber = tableRange.getCell(i, 2).getValue();
46          component = tableRange.getCell(i, 3).getValue();
47        }
48
```

```
49          var manufacturerCode = tableRange.getCell(i, 4).getValue();
50          var quantity = tableRange.getCell(i, 5).getValue();
51
52          var unitMass = tableRange.getCell(i, 6).getValue();
53          if (unitMass != 'n/a' && totalMass != '' && totalMass != '-'){
54            unitMass = significantFigure_(unitMass, 2);
55          }
56
57          var unitCost = tableRange.getCell(i, 7).getValue();
58          if (unitCost != 'n/a' && unitCost != '' && unitCost != '-'){
59            unitCost = significantFigure_(unitCost, 2);
60          }
61
62          var totalMass = tableRange.getCell(i, 8).getValue();
63          if (totalMass != 'n/a' && totalMass != '' && totalMass != '-'){
64            totalMass = significantFigure_(totalMass, 2);
65          }
66
67          var totalCost = tableRange.getCell(i, 9).getValue();
68          if (totalCost != 'n/a' && totalCost != '' && totalCost != '-'){
69            totalCost = significantFigure_(totalCost, 2);
70          }
71
72          var sponsor = tableRange.getCell(i, 10).getValue();
73          var manufacturer = tableRange.getCell(i, 12).getValue();
74          var status = tableRange.getCell(i, 14).getValue();
75          var note = tableRange.getCell(i, 15).getValue();
76
77          var key = padStart_(id.substr(1), 2, "0")
78          rowArray[key] = '' + id + ' & ' + component + ' & ' + manufacturer +
              ' & ' + manufacturerCode + ' & '  + quantity + ' & ' + unitMass +
              ' & ' + unitCost + ' & ' + note + ' & ' + status + ' \\\\  \\
              hline ';
79
80       }
81
82     }
83
84     // Make sure that rows are sorted by their Component IDs.
85     var rowBuffer = '';
86     var sortedComponentIds = keys_(rowArray, true);
87     for (var i = 0; i < sortedComponentIds.length; i++) {
88       rowBuffer = rowBuffer + rowArray[sortedComponentIds[i]];
89     }
90
91     // Building LaTeX string for the entire component table.
92     var completeTable = header + rowBuffer + footer;
93     completeTable = completeTable.replace(/\\ /g, '\\');
94
95     // Output to spreadsheet so it can be copy and pasted into SED.
96     var cell = sheet.getRange(outputCell);
97     cell.setValue(completeTable);
98
99     return completeTable
100  }
101
102  /**
```

```
103   * Get keys of an array
104   */
105  function keys_(obj, sorted){
106      var keys = [];
107      for(var key in obj){
108          if(obj.hasOwnProperty(key)){
109              keys.push(key);
110          }
111      }
112
113      if(sorted){
114        return keys.sort();
115
116      }else{
117        return keys;
118      }
119  }
120
121  /**
122   * Format numbers
123   */
124  function significantFigure_(n, sig) {
125    var mult = Math.pow(10, sig - Math.floor(Math.log(n) / Math.LN10) - 1);
126    return Math.round(n * mult) / mult;
127  }
128
129  /**
130   * The padStart() method pads the current string with another string (
          repeated, if needed)
131   * so that the resulting string reaches the given length. The padding is
          applied from
132   * the start (left) of the current string.
133   *
134   * Source code taken from here:
135   * https://developer.mozilla.org/en-US/docs/Web/JavaScript/Reference/
          Global_Objects/String/padStart
136   */
137  function padStart_(str, targetLength, padString) {
138    targetLength = targetLength >> 0; // truncate if number or convert non-
          number to 0;
139    padString = String((typeof padString !== 'undefined' ? padString : ' '));
140
141    if (str.length > targetLength){
142      return String(str);
143
144    }else {
145
146      targetLength = targetLength - str.length;
147      if (targetLength > padString.length) {
148        //append to original to ensure we are longer than needed
149        padString += padString.repeat(targetLength/padString.length);
150      }
151
152      return padString.slice(0, targetLength) + String(str);
153    }
154  }
```

Appendix L Center of Gravity Computation

The Center of Gravity of the experiment has been calculated considering all the components' mass listed in Section 4.3.

L.1 Code

```matlab
%%------------------------------------------------------------------------
%   TUBULAR COG (Center Of Gravity)
%%------------------------------------------------------------------------
%   Date: May 2018
%%------------------------------------------------------------------------

clear all
close all
clc

%% Data
m_CAC_valves = 850; %[g]
m_cub = 10; %[g]
m_aircoil = 5049; %[g]
m_profile = 4; %[g/cm]
m_Tunion = 71; %[g]
d_styro = 0.028; %[g/cm3]
d_al = 2.67; %[g/cm3]
m_brain1 = 687; %[g]
m_brain2 = 1522; %[g]
m_brain3 = 285; %[g]

%% CAC
% X-axis
m1_CAC = 2*m_cub+m_profile*19;
m2_CAC = m1_CAC;
m3_CAC = m1_CAC;
m4_CAC = m1_CAC;
m5_CAC = m_profile*46;
m6_CAC = m5_CAC;
m7_CAC = m5_CAC;
m8_CAC = m5_CAC;
m9_CAC = m_aircoil;
m10_CAC = (22*pi*25^2-15*pi*20^2)*d_styro;
m11_CAC = m_CAC_valves;
mT_CAC = m1_CAC+m2_CAC+m3_CAC+m4_CAC+m5_CAC+m6_CAC+m7_CAC+m8_CAC+m9_CAC+
    m10_CAC+m11_CAC;

X1_CAC = 1;
X2_CAC = 49;
X3_CAC = 1;
X4_CAC = 49;
X5_CAC = 25;
X6_CAC = 1;
X7_CAC = 49;
X8_CAC = 25;
X9_CAC = 25;
```

```
47  X10_CAC = 25;
48  X11_CAC = 11.5;
49
50  XG_CAC = (m1_CAC*X1_CAC+m2_CAC*X2_CAC+m3_CAC*X3_CAC+m4_CAC*X4_CAC+m5_CAC*
        X5_CAC+m6_CAC*X6_CAC+m7_CAC*X7_CAC+m8_CAC*X8_CAC+m9_CAC*X9_CAC+m10_CAC*
        X10_CAC+m11_CAC*X11_CAC)/mT_CAC;
51
52  % Y-axis
53  m1_CAC = 2*m_cub+m_profile*46;
54  m2_CAC = m1_CAC;
55  m3_CAC = m1_CAC;
56  m4_CAC = m1_CAC;
57  m5_CAC = m_profile*19;
58  m6_CAC = m5_CAC;
59  m7_CAC = m5_CAC;
60  m8_CAC = m5_CAC;
61  m9_CAC = m_aircoil;
62  m10_CAC = (22*pi*25^2-15*pi*20^2)*d_styro;
63  m11_CAC = m_CAC_valves;
64  mT_CAC = m1_CAC+m2_CAC+m3_CAC+m4_CAC+m5_CAC+m6_CAC+m7_CAC+m8_CAC+m9_CAC+
        m10_CAC+m11_CAC;
65
66  Y1_CAC = 22;
67  Y2_CAC = 1;
68  Y3_CAC = 22;
69  Y4_CAC = 1;
70  Y5_CAC = 11.5;
71  Y6_CAC = 22;
72  Y7_CAC = 1;
73  Y8_CAC = 11.5;
74  Y9_CAC = 9.5;
75  Y10_CAC = 20;
76  Y11_CAC = 3;
77
78  YG_CAC = (m1_CAC*Y1_CAC+m2_CAC*Y2_CAC+m3_CAC*Y3_CAC+m4_CAC*Y4_CAC+m5_CAC*
        Y5_CAC+m6_CAC*Y6_CAC+m7_CAC*Y7_CAC+m8_CAC*Y8_CAC+m9_CAC*Y9_CAC+m10_CAC*
        Y10_CAC+m11_CAC*Y11_CAC)/mT_CAC;
79
80  % % Z-axis
81  m1_CAC = 2*m_cub+m_profile*19;
82  m2_CAC = m1_CAC;
83  m3_CAC = m1_CAC;
84  m4_CAC = m1_CAC;
85  m5_CAC = m_profile*46;
86  m6_CAC = m5_CAC;
87  m7_CAC = m5_CAC;
88  m8_CAC = m5_CAC;
89  m9_CAC = m_aircoil;
90  m10_CAC = (22*pi*25^2-15*pi*20^2)*d_styro;
91  m11_CAC = m_CAC_valves;
92  mT_CAC = m1_CAC+m2_CAC+m3_CAC+m4_CAC+m5_CAC+m6_CAC+m7_CAC+m8_CAC+m9_CAC+
        m10_CAC+m11_CAC;
93
94  Z1_CAC = 49;
95  Z2_CAC = 49;
96  Z3_CAC = 1;
97  Z4_CAC = 1;
```

```
 98   Z5_CAC = 49;
 99   Z6_CAC = 25;
100   Z7_CAC = 25;
101   Z8_CAC = 1;
102   Z9_CAC = 25;
103   Z10_CAC = 25;
104   Z11_CAC = 3;
105
106   ZG_CAC = (m1_CAC*Z1_CAC+m2_CAC*Z2_CAC+m3_CAC*Z3_CAC+m4_CAC*Z4_CAC+m5_CAC*
          Z5_CAC+m6_CAC*Z6_CAC+m7_CAC*Z7_CAC+m8_CAC*Z8_CAC+m9_CAC*Z9_CAC+m10_CAC*
          Z10_CAC+m11_CAC*Z11_CAC)/mT_CAC;
107
108
109   %% AAC
110   % X-axis
111   m1_AAC = 2*m_cub+m_profile*46;
112   m2_AAC = m1_AAC;
113   m3_AAC = m1_AAC;
114   m4_AAC = m1_AAC;
115   m5_AAC = m_profile*46 +3*46*46*d_styro;
116   m6_AAC = m_profile*36 +3*36*46*d_styro;
117   m7_AAC = m6_AAC;
118   m8_AAC = m5_AAC;
119   m9_AAC = m_brain3;
120   m10_AAC = m_brain2;
121   m11_AAC = m_brain1;
122   m12_AAC = m_Tunion;
123   m13_AAC = m12_AAC;
124   m14_AAC = m12_AAC;
125   m15_AAC = m12_AAC;
126   m16_AAC = m12_AAC;
127   m17_AAC = m12_AAC;
128
129   mT_AAC = m1_AAC+m2_AAC+m3_AAC+m4_AAC+m5_AAC+m6_AAC+m7_AAC+m8_AAC+m9_AAC+
          m10_AAC+m11_AAC+m12_AAC+m13_AAC+m14_AAC+m15_AAC+m16_AAC+m17_AAC;
130
131   X1_AAC = 1;
132   X2_AAC = 49;
133   X3_AAC = 1;
134   X4_AAC = 49;
135   X5_AAC = 25;
136   X6_AAC = 1;
137   X7_AAC = 49;
138   X8_AAC = 25;
139   X9_AAC = 33.5;
140   X10_AAC = 33.5;
141   X11_AAC = 33.5;
142   X12_AAC = 41.67;
143   X13_AAC = 12.5;
144   X14_AAC = 33.33;
145   X15_AAC = 25;
146   X16_AAC = 16.67;
147   X17_AAC = 8.33;
148
149   XG_AAC = (m1_AAC*X1_AAC+m2_AAC*X2_AAC+m3_AAC*X3_AAC+m4_AAC*X4_AAC+m5_AAC*
          X5_AAC+m6_AAC*X6_AAC+m7_AAC*X7_AAC+m8_AAC*X8_AAC+m9_AAC*X9_AAC+m10_AAC*
          X10_AAC+m11_AAC*X11_AAC+m12_AAC*X12_AAC+m13_AAC*X13_AAC+m14_AAC*X14_AAC+
```

```
         m15_AAC*X15_AAC+m16_AAC*X16_AAC+m17_AAC*X17_AAC)/mT_AAC;
150
151  % Y-axis
152  m1_AAC = 2*m_cub+m_profile*46;
153  m2_AAC = m1_AAC;
154  m3_AAC = m1_AAC;
155  m4_AAC = m1_AAC;
156  m5_AAC = m_profile*46 +3*46*46*d_styro;
157  m6_AAC = m_profile*36 +3*36*46*d_styro;
158  m7_AAC = m6_AAC;
159  m8_AAC = m5_AAC;
160  m9_AAC = m_brain3;
161  m10_AAC = m_brain2;
162  m11_AAC = m_brain1;
163  m12_AAC = 5*m_Tunion;
164  m13_AAC = m_Tunion;
165
166  mT_AAC = m1_AAC+m2_AAC+m3_AAC+m4_AAC+m5_AAC+m6_AAC+m7_AAC+m8_AAC+m9_AAC+
         m10_AAC+m11_AAC+m12_AAC+m13_AAC;
167
168  Y1_AAC = 1;
169  Y2_AAC = 49;
170  Y3_AAC = 1;
171  Y4_AAC = 49;
172  Y5_AAC = 25;
173  Y6_AAC = 1;
174  Y7_AAC = 49;
175  Y8_AAC = 25;
176  Y9_AAC = 7.5;
177  Y10_AAC = 7.5;
178  Y11_AAC = 7.5;
179  Y12_AAC = 31;
180  Y13_AAC = 17;
181
182  YG_AAC = (m1_AAC*Y1_AAC+m2_AAC*Y2_AAC+m3_AAC*Y3_AAC+m4_AAC*Y4_AAC+m5_AAC*
         Y5_AAC+m6_AAC*Y6_AAC+m7_AAC*Y7_AAC+m8_AAC*Y8_AAC+m9_AAC*Y9_AAC+m10_AAC*
         Y10_AAC+m11_AAC*Y11_AAC+m12_AAC*Y12_AAC+m13_AAC*Y13_AAC)/mT_AAC;
183
184  % Z-axis
185  m1_AAC = 2*m_cub+m_profile*46;
186  m2_AAC = m1_AAC;
187  m3_AAC = m1_AAC;
188  m4_AAC = m1_AAC;
189  m5_AAC = m_profile*46 +3*46*46*d_styro;
190  m6_AAC = m_profile*36 +3*36*46*d_styro;
191  m7_AAC = m6_AAC;
192  m8_AAC = m5_AAC;
193  m9_AAC = m_brain3;
194  m10_AAC = m_brain2;
195  m11_AAC = m_brain1;
196  m12_AAC = 5*m_Tunion;
197  m13_AAC = m_Tunion;
198
199  mT_AAC = m1_AAC+m2_AAC+m3_AAC+m4_AAC+m5_AAC+m6_AAC+m7_AAC+m8_AAC+m9_AAC+
         m10_AAC+m11_AAC+m12_AAC+m13_AAC;
200
201  Z1_AAC = 39;
```

```
202  Z2_AAC = 39;
203  Z3_AAC = 1;
204  Z4_AAC = 1;
205  Z5_AAC = 39;
206  Z6_AAC = 20;
207  Z7_AAC = 20;
208  Z8_AAC = 1;
209  Z9_AAC = 24.5;
210  Z10_AAC = 15.5;
211  Z11_AAC = 6.5;
212  Z12_AAC = 10;
213  Z13_AAC = Z12_AAC;
214
215  ZG_AAC = (m1_AAC*Z1_AAC+m2_AAC*Z2_AAC+m3_AAC*Z3_AAC+m4_AAC*Z4_AAC+m5_AAC*
         Z5_AAC+m6_AAC*Z6_AAC+m7_AAC*Z7_AAC+m8_AAC*Z8_AAC+m9_AAC*Z9_AAC+m10_AAC*
         Z10_AAC+m11_AAC*Z11_AAC+m12_AAC*Z12_AAC+m13_AAC*Z13_AAC)/mT_AAC;
216
217  %% TOTAL
218  m_AAC= 12370;
219  m_CAC= 12080;
220  mT_TOTAL= m_AAC+m_CAC;
221
222  % X-axis
223  XG_TOTAL = (m_AAC*XG_AAC+m_CAC*XG_CAC)/mT_TOTAL;
224  % Y-axis
225  YG_TOTAL = (m_AAC*(YG_AAC+23)+m_CAC*YG_CAC)/mT_TOTAL;
226  % Z-axis
227  ZG_TOTAL = (m_AAC*ZG_AAC+m_CAC*ZG_CAC)/mT_TOTAL;
```

Appendix M   Budget Spreadsheets

M.1   Structure

	Manufacturer Code	Quantity	Mass/Unit [g]	Cost/Unit [€]	Total Mass [g]	Total Cost [€]	Sponsor
1 STRUCTURE					**11,337.84**	**€619.24**	
1.1 Strut profile 20x20 M6/M6, length: 460 mm	3842993231	16	184.00	€5.81	2,944.00	€93.02	SNSB
1.2 Strut profile 20x20 M6/M6, length: 360 mm	3842993231	4	144.00	€5.45	576.00	€21.82	SNSB
1.3 Strut profile 20x20 M6/M6, length: 190 mm	3842993231	4	76.00	€5.14	304.00	€20.54	SNSB
1.4 T-nut N6 M4	3842536599	100	3.00	€0.74	300.00	€74.40	SNSB
1.5 Sliding block N6 M4	3842523140	100	3.00	€0.72	300.00	€72.00	SNSB
1.6 Bracket standard 20x20 N6/6	3842523508	100	5.00	€0.45	500.00	€45.00	SNSB
1.7 Variofix block S N6 20x20	3842548836	70	5.00	€0.62	350.00	€43.26	SNSB
1.8 Cubic connector 20/3 N6	3842523872	16	10.00	€1.97	160.00	€39.36	SNSB
1.9 Strap-shaped handle	3842518738	4	20.00	€1.88	80.00	€18.78	SNSB
1.10 Retainer ring M4	3842542328	100	0.50	€0.05	50.00	€5.40	SNSB
1.11 DIN 7984 M4x8 bolts	n/a	150	1.00	€0.00	150.00	€0.00	LTU LAB
1.12 M6x16 bolts	79850616	48	5.00	€0.13	240.00	€6.24	SNSB
1.13 ISO 4762 bolts	n/a	8	2.00	€0.00	16.00	€0.00	LTU LAB
1.14 Washers	n/a	20	0.20	€0.00	4.00	€0.00	LTU LAB
1.15 Aluminum sheets	204599	1	2,500.00	€24.50	2,500.00	€24.50	SNSB
1.16 Styrofoam 250 SL-A-N	3542005000	1	1,800.00	€96.99	1,800.00	€96.99	SNSB
1.17 Fixing bar for the bags	n/a	2	13.00	€3.00	26.00	€6.00	SNSB
1.18 Flat plate interface for fixing bar	n/a	4	32.00	€2.00	128.00	€8.00	SNSB
1.19 CAC-AAC interface 6-hole plate	n/a	4	50.00	€2.00	200.00	€8.00	SNSB
1.20 The Brain							
1.20.1 Aluminum sheets	204599	1	101.84	10€/kg	101.84	€1.02	SNSB
1.20.2 Steel 304, Equal Angle bar 2,1 m	HW1200	1	375.00	€31.00	375.00	€31.00	SNSB
1.20.3 DIN 7984 M4x8 bolts	n/a	26	1.00	€0.00	26.00	€0.00	LTU LAB
1.20.4 DIN 7984 M4x30 bolts	n/a	16	2.00	€0.00	32.00	€0.00	LTU LAB
1.20.5 Nut M4	n/a	42	1.00	€0.00	42.00	€0.00	LTU LAB
1.20.6 Styrofoam (bulk - 1 piece from 1.16)	3542005000	1	112.00	-	112.00	-	
1.20.7 Flat plate fixing interface	n/a	2	1.00	€0.00	2.00	€0.00	LTU LAB
1.20.8 15mm M3 Standoff/Spacer for PCB	24339	5	2.00	€0.78	10.00	€3.90	SNSB
1.20.9 Lock nut M3 (DIN985) for PCB	n/a	5	1.00	€0.00	5.00	€0.00	LTU LAB
1.20.10 M3 Cheese Head Screws 6mm	n/a	5	0.80	€0.00	4.00	€0.00	LTU LAB

Figure 129: Budget Table for Structure Components.

M.2 Electronics Box

	Manufacturer Code	Quantity	Mass/Unit [g]	Cost/Unit [€]	Total Mass [g]	Total Cost [€]	Sponsor
2 ELECTRONIC BOX					**510.50**	**€1,062.74**	
2.1 Arduino Due	A000062	1	36.00	€35.00	36.00	€35.00	SNSB
2.2 Ethernet Shield	SKU 103030021	1	36.00	€30.00	36.00	€28.00	SNSB
2.3 Heater							
2.3.1 *Heater*	HK5160R157L12	4	4.00	€95.00	16.00	€380.00	SNSB
2.3.2 Testing / Spare		1	4.00	€95.00	-	€95.00	SNSB
2.4 DC/DC converter 24 V							
2.4.1 *DC/DC converter 24 V*	S24SP24003PDFA	2	46.00	€49.00	92.00	€98.00	SNSB
2.4.2 Testing / Spare		1	-	€49.00	-	€49.00	SNSB
2.5 MicroSD	SDCIT/16GB	1	0.50	€20.00	0.50	€20.00	SNSB
2.6 Logic CAT5E Network	VLCT85000Y30	1	90.00	€7.00	90.00	€7.00	SNSB
2.7 DC/DC converter 12 V							
2.7.1 DC/DC converter 12 V	R-7812-0.5	2	20.00	€34.00	40.00	€68.00	SNSB
2.7.2 Testing / Spare		1	-	€34.00	-	€34.00	SNSB
2.8 PCB							
2.8.1 Main PCB board	n/a	2	100.00	€89.10	100.00	€178.20	LTU
2.8.2 Pressure sensor PCB	n/a	5	100.00	€14.11	100.00	€70.54	LTU

Figure 130: Budget Table for Electronics Box Components.

M.3 Cables and Sensors

	Manufacturer Code	Quantity	Mass/Unit [g]	Cost/Unit [€]	Total Mass [g]	Total Cost [€]	Sponsor
3 CABLES AND SENSORS					**1,200.62**	**€586.20**	
3.1 Temperature sensor							
3.1.1 Temperature sensor	DS1631+-ND	8	2.00	€3.00	16.00	€24.00	LTU
3.1.2 Testing / Spare		5	-	€3.00	-	€15.00	SNSB
3.2 Pressure sensor							
3.2.1 Pressure sensor	MS560702BA03-50	4	5.00	€2.30	20.00	€9.20	SNSB
3.2.2 Testing / Spare		2	-	€2.30	-	€4.60	SNSB
3.3 Airflow sensor	AWM5102VN	1	60.00	€132.00	60.00	€132.00	LTU
3.4 Humidity sensor	HDC2010	3	5.00	€3.00	15.00	€9.00	SNSB
3.7 Resistors (33 Ohm) \footnote{See schematic in Figure \ref{fig:Schematic} for ...	n/a	25	1.00	€0.00	25.00	€0.00	LTU Lab
3.8 Capacitors (0.1 uF, 5uF and 10 uF)	n/a	15	1.00	€0.00	15.00	€0.00	LTU Lab
3.10 Mosfets for current control							
3.10.1 Mosfet for current control	IRLB8748PBF	11	2.00	€0.70	22.00	€7.70	SNSB
3.10.2 Testing / Spare		4	-	€0.70	-	€2.80	SNSB
3.11 Diodes for DCDC converters							
3.11.1 Diodes for DCDC converters	1N5059	14	0.40	€0.10	5.60	€1.40	SNSB
3.11.2 Spare / Testing		2	-	€0.10	-	€0.20	SNSB
3.12 LED 3.3 V							
3.12.1 LED 3.3 V	151034GS03000	16	0.40	€0.52	6.40	€8.32	SNSB
3.12.2 Spare/Testing		2	-	€0.52	-	€1.04	SNSB
3.13 D-SUB connectors							
3.13.1 15-pin D-SUB Female connector with pins	RND 205-00779	2	11.00	€0.75	22.00	€1.50	SNSB
3.13.2 9-pin D-SUB Female connector with pins	RND 205-00777	3	8.50	€0.68	25.50	€2.04	SNSB
3.12.3 9 pin D-SUB Female connector with soldering cups	RND 205-00704	2	9.00	€0.56	18.00	€1.12	SNSB
3.12.4 9 pin D-SUB Male connector with soldering cups	RND 205-00700	4	9.00	€0.48	36.00	€1.92	SNSB
3.12.5 15-pin D-SUB Male connector with soldering cups	RND 205-00701	2	11.00	€0.60	22.00	€1.20	SNSB
3.12.6 9-pin D-SUB backing	MHDTZK-9-BK-K	4	40.00	€2.86	160.00	€11.44	SNSB
3.12.7 15-pin D-SUB backing	MHDTZK-15-BK-K	2	66.00	€3.06	132.00	€6.12	SNSB
3.12.8 Wall mounting bolts	RND 205-00786	3	2.50	€1.04	7.50	€3.12	SNSB
3.12.9 D-SUB cable CAC to AAC	n/a	1	80.00	€3.78	80.00	€3.78	SNSB
3.14 3.3 V Zener diode							
3.3 V Zener diode	RND 1N746A	15	0.50	0.07	7.50	€1.05	SNSB
Spare / Testing		4	-	0.07	-	€0.28	SNSB
3.15 Power to PCB							
3.15.1 Male connector on PCB	Serie 768	1	5.00	€8.46	5.00	€8.46	SNSB
3.15.2 Female connector from wall	Serie 768	1	11.00	€11.58	11.00	€11.58	SNSB
3.15.3 Grounding contact	DIN 46234	4	0.58	€8.60	2.32	€8.60	SNSB
3.16 Logic CAT5 E-link for inside box	VLCP85121E015	1	10.00	€1.05	10.00	€1.05	SNSB
3.17 Cables for wiring							
3.17.1 Signal wire	5854/7 YL005	1	230.00	€33.88	115.00	€33.88	SNSB
3.17.2 Power wire - Back	5856 BK005	1	365.00	€46.38	73.00	€46.38	SNSB
3.17.3 Power wire - Red	5856 RD005	1	365.00	€46.38	73.00	€46.38	SNSB
3.18 Electrical Tape for marking wires.							
3.18.1 Electrical Tape for marking wires - White	HTAPE-FLEX15WH-15X10	1	34.00	€0.82	13.60	€0.82	SNSB
3.18.2 Electrical Tape for marking wires - Black	HTAPE-FLEX15BK-15X10	1	33.00	€0.82	13.20	€0.82	SNSB
3.18.3 Electrical Tape for marking wires - Green	HTAPE-FLEX15GN-15X10	1	34.00	€0.82	13.60	€0.82	SNSB
3.18.4 Electrical Tape for marking wires - Violet	HTAPE-FLEX15VT-15X10	1	34.00	€0.82	13.60	€0.82	SNSB
3.18.5 Electrical Tape for marking wires - Gray	HTAPE-FLEX15GY-15X10	1	34.00	€0.82	13.60	€0.82	SNSB
3.18.6 Electrical Tape for marking wires - Brown	HTAPE-FLEX15BN-15X10	1	34.00	€0.82	13.60	€0.82	SNSB
3.18.7 Electrical Tape for marking wires - Blue	HTAPE-FLEX15BU-15X10	1	34.00	€1.85	13.60	€1.85	SNSB
3.19 Potentiometer							
3.19.1 Potentiometer 1 kOhm	M64Y102KB40	4	1.00	€1.83	4.00	€7.32	SNSB
3.19.2 Potentiometer 50 kOhm	3296Y-1-503LF	4	1.00	€1.80	4.00	€7.20	SNSB
3.20 Header pins to solder arduino on PCB							
3.20.1 6-pin male double row header	RND 205-00634	2	1.00	€0.22	2.00	€0.44	SNSB
3.20.2 8-pin male single row header	RND 205-00629	5	1.00	€0.28	5.00	€1.40	SNSB
3.20.3 10-pin male single row header	SD-2X5-T1-7/3MM	1	1.00	€0.26	1.00	€0.26	SNSB
3.20.4 36-pin male double row header	61303621121	1	2.00	€1.65	2.00	€1.65	SNSB
3.21 Static Pressure Sensor	3500S0001A05E000	1	53.00	€142.00	53.00	€142.00	LTU
3.22 Connector for the Static Pressure Sensor	XZCPV1141L2	1	14.00	€14.00	50.00	€14.00	LTU

Figure 131: Budget Table for Cables and Sensors Components.

M.4 CAC

	Manufacturer Code	Quantity	Mass/Unit [g]	Cost/Unit [€]	Total Mass [g]	Total Cost [€]	Sponsor
4 CAC					**5,539.00**	**€23,114.00**	
4.1 Coiled tube	n/a	1	5,049.00	€22,000.00	5,049.00	€22,000.00	FMI
4.2 Sampling Valve (inlet and outlet 1/8" female)							
4.2.1 *Sampling Valve (inlet and outlet 1/8" female)*	VDW22UANXB	1	100.00	€45.00	100.00	€45.00	SMC
4.2.2 Spare		1	-	€45.00	-	€45.00	SMC
4.3 Interface tube-screw male (OD 1/4" - ID 5/32" to male 1/4")							
4.3.1 *Interface tube-screw male (OD 1/4" - ID 5/32" to male 1/4")*	SS-400-1-4	1	19.00	€10.00	19.00	€10.00	SWAGELOK
4.3.2 Spare		1	-	€10.00	-	€10.00	SWAGELOK
4.4 Interface tube-screw male (OD 1/4" - ID 5/32" to male 1/8")							
4.4.1 *Interface tube-screw male (OD 1/4" - ID 5/32" to male 1/8")*	SS-400-1-2	1	13.00	€10.00	13.00	€10.00	SWAGELOK
4.4.2 Spare		1	-	€10.00	-	€10.00	SWAGELOK
4.5 Interface reducing adapters (female 1/4" NPT to male 1/8" NPT)							
4.5.1 *Interface reducing adapters (female 1/4" NPT to male 1/8" NPT)*	SS-4-RA-2	1	35.00	€12.00	35.00	€12.00	SWAGELOK
4.5.2 Spare		1	-	€12.00	-	€12.00	SWAGELOK
4.6 Interface attached to the coiled tube outlet, quick connector							
4.6.1 *Interface attached to the coiled tube outlet, quick connector*	SS-QC4-B-200	1	91.00	€65.00	91.00	€65.00	SWAGELOK
4.6.2 Spare		1	-	€65.00	-	€65.00	SWAGELOK
4.7 Interface attached to the coiled tube inlet, quick connector							
4.7.1 *Interface attached to the coiled tube inlet, quick connector*	SS-QC4-B-400	1	68.00	€50.00	68.00	€50.00	SWAGELOK
4.7.2 Spare		1	-	€50.00	-	€50.00	SWAGELOK
4.8 Interface quick connector stem with valve							
4.8.1 *Interface quick connector stem with valve*	SS-QC4-D-400	1	58.00	€40.00	58.00	€40.00	SWAGELOK
4.8.2 Spare		1	-	€40.00	-	€40.00	SWAGELOK
4.9 Nut Ferrule (1 piece from set order for AAC)	SS-400-NFSET	1	41.00	-	41.00	-	
4.10 Testing / Backup seal valve	4M4F-V6LN-SS	2	1,361.00	€150.00	-	€300.00	PARKER
4.11 Magnesium filter with interface	n/a	1	65.00	€150.00	65.00	€150.00	FMI
4.12 Flushing process (nitrogen or dry calibrated gas)	n/a	1	-	€100.00	-	€100.00	FMI
4.13 Testing Valve	Lucifer 121K, 122K	1	-	€100.00	-	€100.00	LTU

Figure 132: Budget Table for CAC Components.

M.5 AAC

	Manufacturer Code	Quantity	Mass/Unit [g]	Cost/Unit [€]	Total Mass [g]	Total Cost [€]	Sponsor
5 AAC					**3,541.00**	**€4,444.71**	
5.1 Miniature diaphragm air pump							
5.1.1 *Miniature diagphram air pump*	NMP 850.1.2 KNDC-B	1	430.00	€350.00	430.00	€350.00	LTU
5.1.2 Spare		1	-	€350.00	-	€350.00	LTU
5.2 Gas Sampling Bag, Multi-Layer Foil, 3L, 10"x10", 5pk	22951						
5.2.1 *Gas Sampling Bag, Multi-Layer Foil, 3L, 10"x10", 5pk*	22951	2	25.00	€100.00	50.00	€200.00	RESTEK
5.2.2 Testing / Spare		2	-	€100.00	-	€200.00	TEKNOLAB
5.2.3 Testing / Spare		2	-	€100.00	-	€200.00	SNSB
5.3 Flushing valve (inlet and outlet 1/8" female)							
5.3.1 *Flushing valve (inlet and outlet 1/8" female)*	VDW22UANXB	1	100.00	€45.00	100.00	€45.00	SMC
5.3.2 Spare		1	-	€45.00	-	€45.00	SMC
5.4 Manifold (inlet and outlet 1/8" female)							
5.4.1 *Manifold (inlet and outlet 1/8" female)*	VV2DW2-H0601N-F-Q	1	440.00	€140.00	440.00	€140.00	SMC
5.4.2 Spare		1	-	€140.00	-	€140.00	SMC
5.5 Valves manifold (outlet 1/8" female)							
5.5.1 *Valves manifold (outlet 1/8" female)*	VDW23-5G-1-H-Q	6	100.00	€40.00	600.00	€240.00	SMC
5.5.2 Spare		4	-	€40.00	-	€160.00	SMC
5.6 Interface tube-screw male (OD 1/4" - ID 5/32" to male 1/8")							
5.6.1 *Interface tube-screw male (OD 1/4" - ID 5/32" to male 1/8")*	SS-400-1-2	6	13.00	€14.00	78.00	€84.00	SWAGELOK
5.6.2 Spare		6	-	€14.00	-	€84.00	SWAGELOK
5.7 Interface tube-screw male 90 degree (OD 1/4" - ID 5/32" to male 1/8")							
5.6.1 *Interface tube-screw male 90 degree(OD 1/4" - ID 5/32" to male 1/8")*	SS-400-2-2	3	13.00	€16.00	39.00	€48.00	SWAGELOK
5.6.2 Spare		3	-	€16.00	-	€48.00	SWAGELOK
5.8 Interface male 90-degree connector (OD 1/4" - ID 5/32" to male 1/4")							
5.7.1 *Male 90-degree connector (OD 1/4" - ID 5/32" to male 1/4")*	SS-400-2-4	1	16.00	€14.00	16.00	€14.00	SWAGELOK
5.7.2 Spare		1	-	€14.00	-	€14.00	SWAGELOK
5.9 Interface tube-screw female (OD 1/4" - ID 5/32" to female 1/4")							
5.8.1 *Interface tube-screw female (OD 1/4" - ID 5/32" to female 1/4")*	SS-400-7-4	1	28.00	€15.00	28.00	€15.00	SWAGELOK
5.8.2 Spare		1	-	€15.00	-	€15.00	SWAGELOK
5.10 T-Union							
5.10.1 *Interface T-Union (male 1/4")*	SS-400-3	6	71.00	€33.00	426.00	€198.00	SWAGELOK
5.10.2 Spare		3	-	€33.00	-	€99.00	SWAGELOK
5.11 Nut Ferrule set							
5.10.1 *Nut Ferrule set*	SS-400-NFSET	15	41.00	€2.25	615.00	€33.75	SWAGELOK
5.10.2 Spare		5	-	€2.25	-	€11.25	SWAGELOK
5.12 Tubing, Sulfinert 304SS Welded/Drawn 50ft (OD 1/4" - ID 0.21")	29255	1	150.00	€840.00	150.00	€840.00	RESTEK
5.13 Quick Coupling female 1/4"							
5.13.1 *Quick Coupling female 1/4"*	SS-QC4-B-4PF	6	45.00	€50.00	270.00	€300.00	SWAGELOK
5.13.2 Spare		3	-	€50.00	-	€150.00	SWAGELOK
5.14 Interface 90 degree elbow 1/4"							
5.14.1 *90 degree elbow 1/4"*	SS-400-9	2	55.00	€19.40	110.00	€38.80	SWAGELOK
5.14.2 Spare		2	-	€19.40	-	€38.80	SWAGELOK
5.15 Interface female 90-degree connector (OD 1/4" - ID 5/32" to female 1/4")							
5.15.1 Interface female 90-degree connector (OD 1/4" - ID 5/32" to female 1/	SS-400-8-4	2	62.00	€23.28	124.00	€46.56	SWAGELOK
5.15.2 Spare		2	-	€23.28	-	€46.56	SWAGELOK
5.16 Magnesium filter tube with interface	-	1	65.00	€150.00	65.00	€150.00	FMI

M.6 Tools, Travel, and Other

	Manufacturer Code	Quantity	Mass/Unit [g]	Cost/Unit [€]	Total Mass [g]	Total Cost [€]	Sponsor
6 TOOLS						**€332.53**	
6.1 Hand Tube Bender 1/4 in	MS-HTB-4T	1	n/a	€250.00	-	€250.00	SWAGELOK
6.2 Tube Cutter (4 mm to 25 mm)	MS-TC-308	1	n/a	€35.00	-	€35.00	SWAGELOK
6.3 Tubing Reamer	MS-TDT-24	1	n/a	€26.00	-	€26.00	SWAGELOK
6.4 PTFE Tape Thread Sealant, 1/4"	MS-STR-4	1	n/a	€1.94	-	€1.94	SWAGELOK
6.5 Double-Sided Adhesive Tape	180-89-682	2	n/a	€9.80	-	€19.59	LTU
7 TRAVEL					-	**€500.00**	
7.1 Travel to FMI for sample bag testing	n/a	1	n/a	€250.00	-	€250.00	LTU
7.2 Travel to FMI for integration testing	n/a	1	n/a	€250.00	-	€250.00	LTU
8 OTHER					2,212.90	**€568.17**	
8.1 Shipping costs	n/a	n/a	n/a	n/a	-	€378.78	SNSB
8.2 Error margin	n/a	n/a	n/a	n/a	2,212.90	€189.39	SNSB

Figure 134: Budget Table for Tools, Travel, and Other Components.

Appendix N   Full List of Requirements

N.1   Functional Requirements

F.1 ~~The experiment *shall* collect air samples.~~[13]

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.~~[13]

F.5 ~~The experiment's AAC System *shall* be able to collect air samples during the Descent Phase.~~[13]

F.6 ~~The altitude from which a sampling bag will start sampling *shall* be programmable.~~ [14]

F.7 ~~The altitude from which a sampling bag will stop sampling *shall* be programmable.~~[14]

F.8 ~~The experiment *shall* pump air into the AAC Sampling Bags.~~[13]

F.9 The experiment *should* measure the air intake flow to the AAC.

F.10 The experiment *shall* measure the air pressure.

F.11 The experiment *shall* measure the temperature.

F.12 ~~The experiment *shall* collect data on the humidity.~~ [13]

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

F.14 ~~The experiment *should* measure the humidity inside the AAC Valve Box.~~[13]

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

F.16 ~~The experiment *shall* accept telecommand instructions to program AAC sampling altitudes for each sampling bag.~~[13]

F.17 ~~The experiment *shall* accept telecommand instructions to open designated valves.~~[13]

F.18 ~~The experiment *shall* accept telecommand instructions to close designated valves.~~[13]

F.19 ~~The experiment *may* accept telecommand instructions to change the sampling rate of the ambient pressure sensor.~~[13]

F.20 ~~The experiment *may* accept telecommand instructions to change the sampling rate of the ambient temperature sensor.~~[13]

F.21 ~~The experiment *may* accept telecommand instructions to change the sampling rate of the AAC Valve Box temperature sensor.~~[13]

F.22 ~~The experiment *may* accept telecommand instructions to turn on the air pump.~~[13]

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[13]Unnecessary requirement that has been removed.
[14]Moved to design requirements.
[15]Unverifiable requirement that has been removed.

F.23 ~~The experiment *may* accept telecommand instructions to turn off the air pump.~~[13]

F.24 ~~The experiment *may* accept telecommand instructions to turn on the Valve Heater.~~[13]

F.25 ~~The experiment *may* accept telecommand instructions to turn off the Valve Heater.~~[13]

F.26 ~~The experiment *may* accept telecommand instructions to turn on the Electronics Box Heater.~~[13]

F.27 ~~The experiment *may* accept telecommand instructions to turn off the Electronics Box Heater.~~[13]

N.2 Performance Requirements

P.1 ~~The telecommand data rate *shall* be 10 Kb/s.~~[14]

P.2 ~~The default sampling rate of the ambient pressure sensor during Standby mode *shall* be 0.1 Hz.~~[16]

P.3 ~~The default sampling rate of the ambient pressure sensor during Normal operation-ascent mode *shall* be 0.2 Hz.~~[16]

P.4 ~~The default sampling rate of the ambient pressure sensor during Normal operation-descent mode *shall* be 10 Hz.~~[16]

P.5 ~~The default sampling rate of the AAC Valve Box temperature sensor *shall* be 1 Hz.~~[16]

P.6 ~~The programmable sampling rate of the ambient pressure sensor *shall* not be lesser than 0.1 Hz.~~[16]

P.7 ~~The programmable sampling rate of the ambient pressure sensor *shall* not be greater than 100 Hz.~~[16]

P.8 ~~The programmable sampling rate of the Electronics Box temperature sensor *shall* not be lesser than 1 Hz.~~[16]

P.9 ~~The programmable sampling rate of the Electronics Box temperature sensor *shall* not be greater than 7 Hz.~~[16]

P.10 ~~The programmable sampling rate of the AAC Valve Box temperature sensor *shall* not be lesser than 1 Hz.~~[16]

P.11 ~~The programmable sampling rate of the AAC Valve Box temperature sensor *shall* not be greater than 7 Hz.~~[16]

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/-3°C (max) for condition of -55°C to 150°C.

P.14 ~~The accuracy of the ambient humidity measurements *shall* be ±3% .~~ [10][13]

P.15 ~~The accuracy of the AAC Valve Box temperature measurements *shall* be +3.5/-2°C(max).~~[17]

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[16] Replaced by P.23
[17] Combined with P13

P.16 ~~The air intake rate of the air pump *shall* be minimum 3 L/min.~~[14]

P.17 ~~The temperature of the Electronics Box *shall* be between 0°C and 25°C.~~ [14]

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

P.19 ~~The temperature of the AAC Valve Box *shall* be between 0°C and 25°C.~~[14]

P.20 ~~The temperature of the AAC Valve Box *shall* not exceed 25°C.~~[19]

P.21 ~~The air sampling systems *shall* filter out all water molecules before filling the sampling containers.~~ [14]

P.22 ~~The CAC air sampling *shall* filter out all water molecules before filling the tube.~~[20]

P.23 The sensors sampling rate *shall* be 1 Hz.

P.24 The temperature of the Pump *shall* be between 5°C and 40°C.

P.25 The minimum volume of air in the bags for analysis *shall* be 0.18 L at ground level.

N.3   Design Requirements

D.1 The experiment *shall* operate in the temperature profile of the BEXUS flight[6].

D.2 The experiment *shall* operate in the vibration profile of the BEXUS flight[6].

D.3 The experiment *shall* not have sharp edges that can harm the launch vehicle, other experiments, and people.

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.~~[13]

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.~~[21]

D.10 ~~The components of the experiment *shall* operate within their temperature ranges.~~[13]

D.11 ~~The OBC *shall* be able to autonomously control the heaters.~~[13]

D.12 ~~The ground station GC *shall* be able to display some of the received data.~~[13]

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

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[18]Combined with P17 and moved to design requirements.
[19]Combined with P19 and moved to design requirements.
[20]Combined with P21 and moved to design requirements.
[21]Repeated in D18

D.14 ~~The external components that are directly exposed to the outside environment *shall* be able to operate at -70°C.~~[13]

D.15 ~~The watchdog *should* be able to reset the system.~~[13]

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[6].

D.19 The experiment *shall* operate in the vertical and horizontal accelerations profile of the BEXUS flight[6].

D.20 ~~The experiment *shall* operate in the horizontal accelerations profile of the BEXUS flight.~~[6] [22]

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

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

D.23 The air intake rate of the air pump *shall* be minimum 3 L/min at 24 km altitude.

D.24 The temperature of the Brain *shall* be between -10°C and 25°C.

D.25 ~~The temperature of the Brain level 2 *shall* be between 0°C and 25°C.~~ [23]

D.26 The air sampling systems *shall* filter out all water molecules before filling the sampling bags.

D.27 The total weight of the experiment *shall* be less than 28 kg.

D.28 The AAC box *shall* be able to fit at least 6 air sampling bags.

D.29 The CAC box *shall* take less than 3 minutes to be removed from the gondola without removing the whole experiment.

D.30 The AAC *shall* be re-usable for future balloon flights.

D.31 The altitude from which a sampling bag will start sampling *shall* be programmable.

D.32 The altitude from which a sampling bag will stop sampling *shall* be programmable.

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[22]Combined with D19
[23]Combined with D24

N.4   Operational Requirements

O.1 ~~The TUBULAR Team *shall* send telecommands from the ground station to the experiment before and during the flight.~~[13]

O.2 ~~The TUBULAR Team *shall* receive telemetry from the experiment during the flight.~~[13]

O.3 ~~The experiment *shall* change modes autonomously.~~[13]

O.4 ~~The heating mechanism *shall* work autonomously.~~[13]

O.5 ~~The experiment *shall* store data autonomously.~~[13]

O.6 ~~The Air sampling control system *shall* work autonomously.~~[13]

O.7 ~~The valves in air sampling control system *should* be controllable from the ground station.~~[13]

O.8 ~~The experiment *should* be able to handle a timeout or drop in the network connection.~~[13]

O.9 ~~The heaters *should* be controllable from the ground station.~~[13]

O.10 ~~The watchdog[24] *should* be able to reset the system.~~[13]

O.11 ~~The system *should* be able to be reset with a command from the ground station.~~[13]

O.12 ~~The experiment *should* enter different modes with a telecommand from the ground station.~~[13]

O.13 The experiment *should* function automatically.

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

N.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.~~[13]

C.3 ~~Budget limited to TBD.~~[13]

C.4 ~~The dimensions show a minimum print area of 50 x 50 cm and 65 cm height experiment box.~~[13]

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[24]Explained in subsection 4.8. Software Design

Appendix O   Test Results

O.1   Test 28: Pump Operations

The pump was connected via crocodile connections to a power supply set to 24 V. The power supply was then switched on and the current was read off. This set-up can be seen in Figure 135.

It was found that when the power supply was switched on the current went up to 600 mA for less than one second. It then settled to 250 mA. By covering the air intake, simulating air intake from a lower pressure, the current drops to 200 mA. By covering the air output, simulating pushing air into a higher pressure, the current rises to 400 mA.

Therefore the power for each of these conditions is 14.4 W at turn on, 6 W in normal use, 4.8 W when sucking from low pressure, 9.6 W when pushing to high pressure.
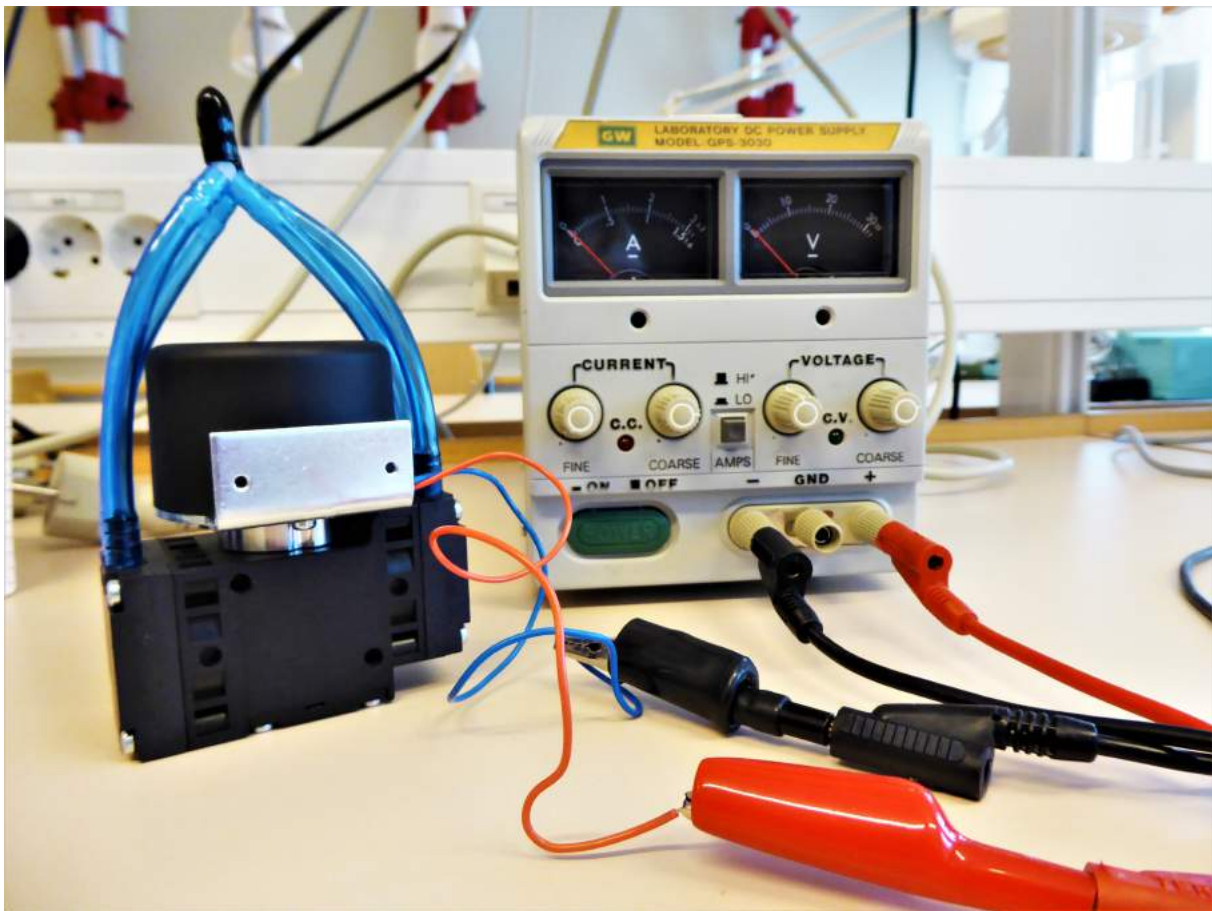

Figure 135: Photo Showing the Set-up for the Pump Testing in the Laboratory.

O.2   Test 18: Pump Low Pressure

The pump was tested at low pressure using a small vacuum chamber that is capable of going down to 1 hPa. For this test the chamber was only taken down to 30 hPa as this is the expected pressure at 24 km, the highest altitude that will be sampled. The experiment set-up can be seen in Figure 136. The pump was connected to the power supply via two cables. It was also screwed into the base plate to prevent it from moving due to its own vibration during the test. A vacuum pump was connected to the chamber wall with a pressure sensor attached to monitor the pressure inside the chamber.

Figure 136: Photo Showing the Set-up of the Vacuum Chamber, Power Supply and Vacuum Pump.

The glass top and cage were then placed on top of the sampling bag and pump and the air slowly removed. Figure 137 shows the test as it was in progress.

As the air was removed from the chamber a new problem became immediately obvious. Air that was inside the bag before the test was expanding as the pressure decreased until the bag reached around 75% of its total volume. The air had been pushed out of the sampling bag before the test but this had not been completed thoroughly enough. Therefore care must be taken to ensure that there is no, or very very small amounts, of air inside the bag before it

enters a low pressure environment. For subsequent tests the pump was used in reverse to suck any remaining air out of the bags.

Figure 137: Photo Showing the Pump and Sampling Bag in the Vacuum Chamber During the Test.

Repeating the test and using the pump to suck out excess air from the bags the chamber was taken to around 30 hPa. Once the chamber was at this pressure the pump was switched on and a stopwatch began. Once the bag stopped inflating the stopwatch was stopped. During this test there was also a drop in pressure to 28 hPa and during a repeat there was a drop to 25 hPa. This also occurred in later tests. This is not seen as a significant problem as during the flight this is exactly what will happen when testing during ascent. In addition the flow rate increases with increasing outside pressure therefore this is showing our worst case flow rate. It was found that the pump was able to successfully switch on and fill the bag at this altitude with a flow rate of approximately 3 L/min.

The test was repeated again at 88 hPa, representing 17 km altitude and 220 hPa, representing 11 km altitude. Here the flow rates were found to be 3.4 L/min and 4.9 L/min respectively. The results can also be seen in Table 70 and Figure 138. Note that the results should be considered an approximation due to the lack of equipment such as flow-meters that would have made this test more precise.

Altitude(km)	Pressure Start(hPa)	Pressure End(hPa)	Time(sec)	Flow Rate(L/min)
24	30	23	60	3
17	87	80	53	3.4
11	220	190	37	4.9

Table 70: Table Showing the Time Taken Until the 3 L Bag Stopped Expanding at Various Different Pressures.
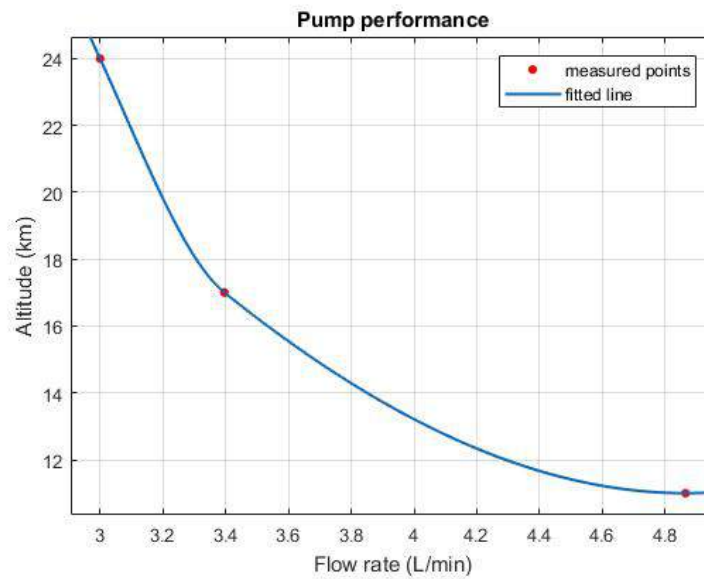
Figure 138: Obtained Pump Performance at Low Pressure.

O.2.1   Test 30: Sampling Bag Bursting

A sampling bag was placed in a small vacuum chamber connected to the pump with the same set up as in Test 18, see Figures 136 and 137. The pump was run for 3 minutes with a full bag to see how the bag reacted. No changes were observed in the bag and no leaks appeared whilst it was in the testing chamber. Upon returning it to atmospheric levels it also appeared to be able to withstand the over pressure. The bag was then left, with the valve closed, on a table where it was handled a little during this time. Approximately 30 minutes after the test the bag made an audible popping noise and air leaked out. The damage that occurred to the bag during the burst can be seen in Figure 139 for the front of the bag and Figure 140 for the back of the bag.

Figure 139: Photo Showing the Extent of Damage on the Front of the Bag Due to Bursting.

Figure 140: Photo Showing the Extent of Damage on the Back of the Bag Due to Bursting.

This kind of bag failure could occur if bags are overfilled, particularly during ascent.

Next the system was set-up in the same way with a new bag. This time the pump was continuously run until failure occurred. This took around 6 minutes. The bag failed along the lower seam close to the valve and also at the valve connection. At the valve connection the bag ripped just above the valve. This time the burst was more energetic with the bottom of the bag moving outwards. Upon inspection the bottom of the bag was completely open and the part of the bag connected to the valve partially ripped open. In addition at the top of the bag small failures similar to those seen in Figure 139 were seen again. It is therefore thought that the bag was starting to fail at both the top and the bottom of the bag and but the bottom failed first.

The damage can be seen in Figures 141 and 142. It should be noted that the white bag valve was pulled off after the test and before photos were taken.

Figure 141: Photo Showing the Damage Sustained to the Bottom of the Bag After Bursting Due to Continuous Pumping.

Figure 142: Photo Showing Where the Bag Ripped Around the Valve.

This kind of bag failure could occur if there is a software error that results in the pump not switching off or a valve not closing, or if there is a malfunction in one of the valves which means it fails to close.

From the damage seen on the bags and from witnessing the burst it can be concluded that, as long as the bags are well secured to the valves at the bottom and through the metal ring at the top, bag bursting during flight would not cause damage to any other components on board. Even during the more energetic burst that occurs from continuous pumping the bag remained fixed to the valve connection and experienced no fragmentation. The consequences of a single bag burst would be limited to loss of data and a disturbance to audio frequencies.

O.3   Test 29: Pump Current under Low Pressure

This test was set up in the same way as above in Test 18, see Figure 136 and 137. The addition to this test was a multimeter to read the current that the pump was drawing. The pump was tested once with the outlet attached to a bag and once with the outlet sealed. This provides the current when the pump is pumping into an ambient pressure and into a higher pressure.

In general it was found for both cases that decreasing the pressure, or increasing the altitude, lead to a decrease in pump current draw. It was noted that there was an increase in current draw in between sea level conditions and 11 km altitude conditions. However as the lowest sampling point it intended to be at 11 km this should not be a problem for the experiment. The full results can be seen in Table 71.

Altitude (km)	Pressure (hPa)	Into Bag Current (mA)	Into Seal Current (mA)
20	57	140	138
18	68	150	141
16	100	161	146
12	190	185	175
9	300	-	200
6	500	-	242
0	1013	-	218

Table 71: Table Showing How the Current Draw of the Pump Changed With Outside Air Pressure for Two Different Conditions. The First Pumping Into a Sampling Bag and the Second Pumping Into a Sealed Tube.

A graphical representation of these results are shown in Figures 143 and 144. From the table and figures it can be seen that the current draw is higher during the bag filling than during the sealed case. As the experiment will sample between 11 km and 24 km it can be concluded that the highest current draw will occur during the 11 km altitude sample and can be expected to be around 200 mA.
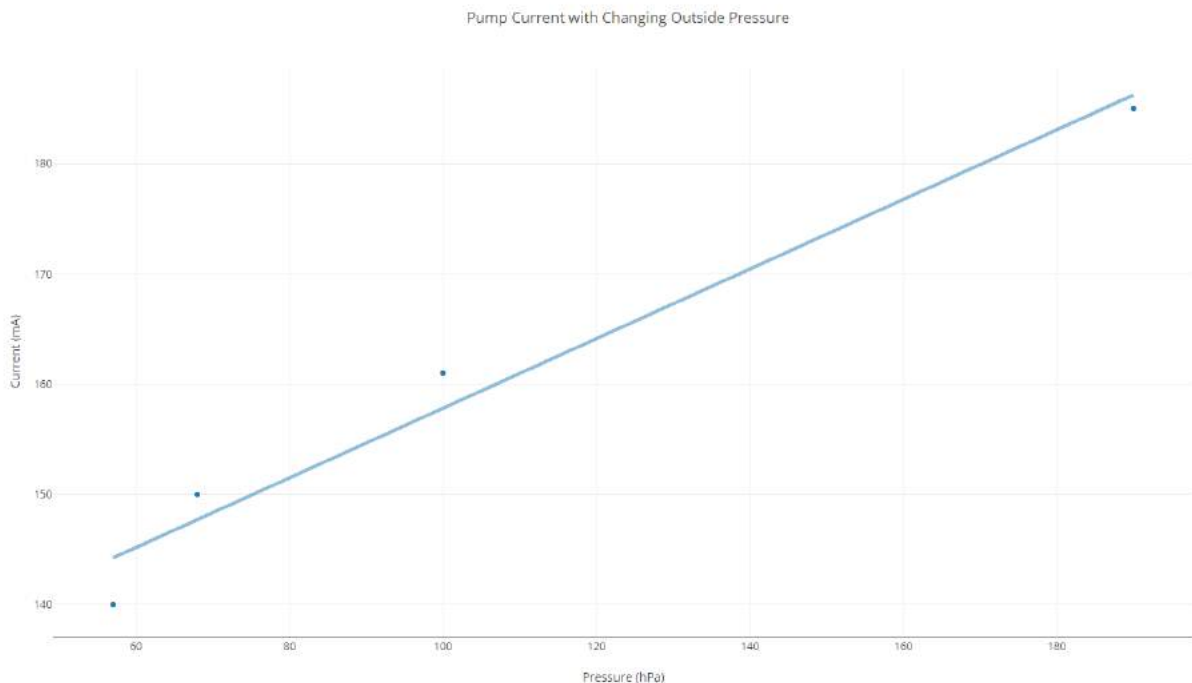

Figure 143: Graph Showing the Expected Current Values When the Pump is Pumping Air Into a Bag Based Upon the Results Obtained.
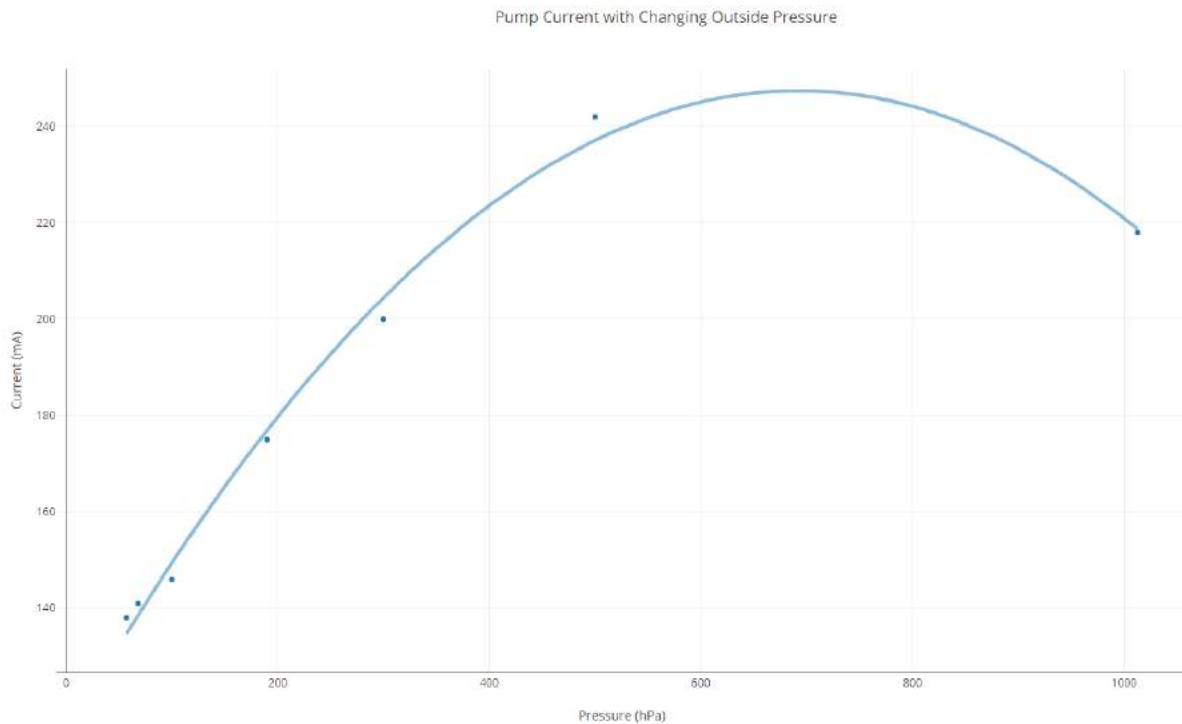
Figure 144: Graph Showing the Expected Current Values When the Pump is Pumping Air Into a Sealed Outlet Based Upon the Results Obtained and the Data Shown In Figure 30.

By looking at the data from both Test 18 and Test 29 a relationship can be seen between the outside air pressure, the flow rate of the pump and the current draw of the pump.

O.4   Test 17: Sampling bags' holding times and samples' condensation verification

The main objective of this test was to flush eight 1 L sampling bags with nitrogen, the same way it will be done for the flight. After the flushing is done, fill them with a dry gas and leave them outside for 6, 14, 24 and 48 hours. Then analyze two sampling bags after each time duration and see if the concentration of gases inside has changed.

A dry gas is a gas of high concentration of CO and low H_2O and its exact concentration can be known by comparison to the calibrating gas in the Picarro analyzer. Therefore, the concentration when sampling the bags is known and it can be compared with the concentration after analysis. If the sampling bags can hold the samples for 48 hours then when analyzing, the concentration of gases should not change. If condensation occurs that will be seen as an increase in water vapour concentration.

Note that the size of the sampling bags was not the same as the size that will be used during the experiment. The reasons were availability of 1 L sampling bags at FMI and a first assumption that the size would not affect the results. The sampling bags were exactly the same model/material.

This test was realized at FMI in Sodankylä. Eight Multi-Layer Foil bags of 1 L volume were connected to SMC valves as shown in Figure 145 and all together connected in series with stainless steel tubes as can be seen in Figure 146.

Figure 145: 1 L Sampling Bag With SMC Valve Attached to It. The Valve is at One of the Ends of the System so a Quick Connector is Connecting it to the Tube That Goes to the Nitrogen Bottle/Vacuum Pump.

Figure 146: Sampling Bags System Connected in Series.

Figure 147 shows a general overview of the experiment set up before the sampling bags were attached to the SMC valves. The picture shows the eight SMC valves hanging on a bar and red and black cables connecting them to the switches. It can also be seen a nitrogen bottle standing at the right side of the table and a vacuum pump under the table. Figure 148 shows the pressure sensor on the table, a flow-metre, a needle valve that adjusts the flow rate and a valve. This valve was used to control the filling and flushing of the sampling bags realized with nitrogen. The position shown in Figure 148 is for vacuuming, the pump is sucking the air from the sampling bags and the nitrogen tube is closed. The valve position for filling is the opposite, opening the nitrogen tube and closing the vacuum. There is also an intermediate position that closes both, nitrogen and vacuum.
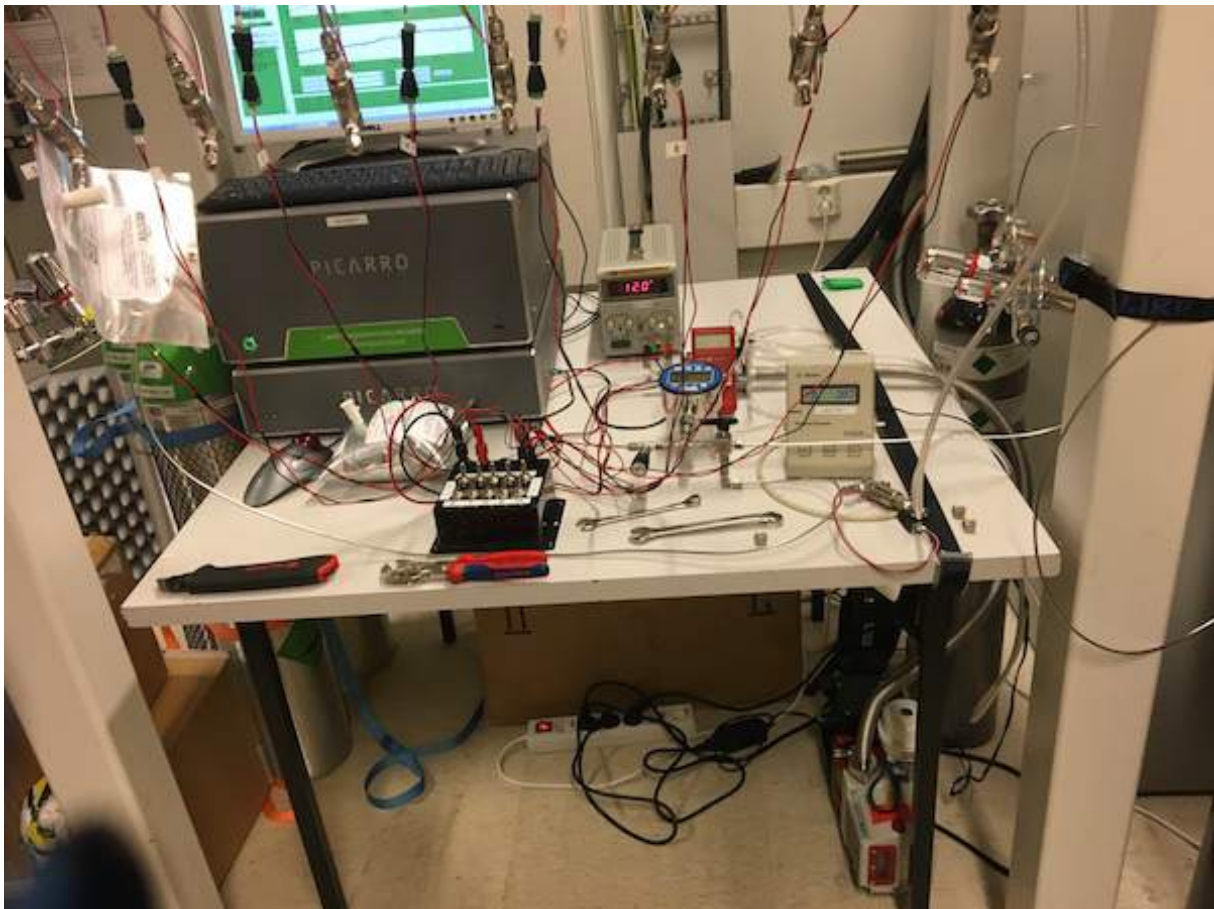

Figure 147: General Overview of the test Set up Before the Sampling Bags Were Attached to the Valves

Figure 148: Valve that Controls Filling/Vacuum in of the Sampling Bags. Pressure Sensor, Flow-metre and Needle Valve.

The procedure during the test was as follows:

- Set up all the connections between pump, nitrogen bottle, valves system in series.

- Attach the sampling bags to the SMC valves.

- Start flushing the tubes with nitrogen. For this all the sampling bags' valves are closed.

- Adjust the flow rate of nitrogen at 500 ml/min.

- Open sampling bags' manual valves (not to be confused with the SMC valves which are still all closed).

- Turn on valve 1. Fill sampling bag number 1 for 2 minutes. Turn off valve 1. Repeat it for the seven sampling bags left.

- Change the valve seen in Figure 148 to vacuum position and empty the bags.

- Flush the tubes after all the sampling bags have been emptied. This is to remove as much air as possible that could be left inside the sampling bags.

- Repeat the flushing for two more times.

- Change the nitrogen bottle for the dry gas bottle.

- Flush the tubes with nitrogen.

- Fill the eight sampling bags one by one.

- Take the sampling bags outside as shown in Figure 149 to simulate the conditions at which they will be exposed after landing.

Figure 149: Sampling Bags Left Outside Waiting to be Analyzed.

After each of the mentioned times, 6, 14, 24 and 48 hours, two sampling bags were taken inside the laboratory to be analyzed. The procedure to analyze was:

- Have the dry gas flowing through the Picarro analyzer for at least one hour before the analysis. This is to avoid having moisture inside the tubes and have stable measurements of concentrations.

- Flush the tubes in between the two sampling bags with dry gas. For that the dry gas has to be disconnected from the analyzer and moisture would get into the Picarro. To avoid this, calibrating gas is flowing through the analyzer while the tubes are being flushed.

- Connect the system formed by two sampling bags with one end to the dry gas bottle and the other to the Picarro inlet.

- Wait for one hour until the readings of dry gas concentrations are stable.

- Open the valve of the first sampling bag.

- Right after the first sampling bag is empty, close its valve and open the valve for the next one.

- Keep the dry gas flowing for one more hour after analysis.

After analyzing the sampling bags the obtained results are presented in Figure 150.
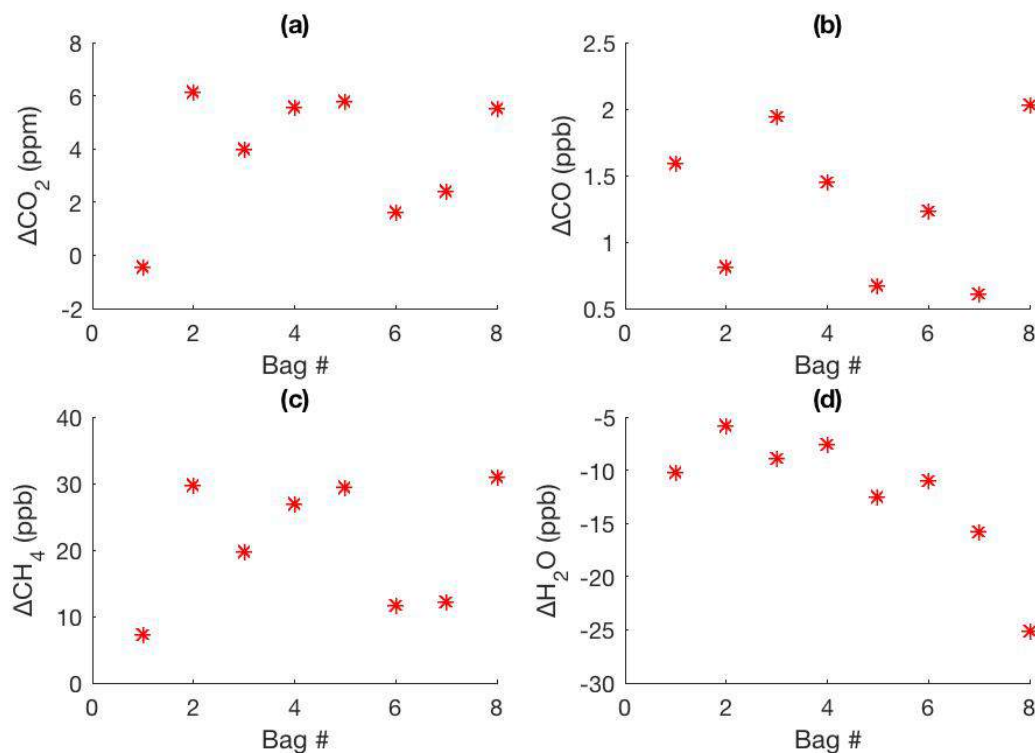

Figure 150: Obtained Variation in Concentration for (a) CO_2 in ppm, (b) CO in ppb, (c) CH_4 in ppb and (d) H_2O in ppb.

It should be mentioned that the results were not at all what was expected. If the sampling bags held the gases for 48 hours, the analyzed concentration should have been the same as

the dry gas used to fill them or the variation should have been smaller.

A possible explanation for this results could be that the emptying of the sampling bags was not done rigorously enough and that some air/nitrogen was left inside which diluted in the dry gas and changed the concentrations. This effect is even increased due to the smaller size of the used sampling bags (1 L instead of 3 L). This would also explain why the results don't follow any pattern.

The general outcome of this test is that the team has realized that the flushing of the sampling bags is a very delicate process. This test will be repeated but using the set-up described in Section 4. This test has also been useful to decide that the flushing of the sampling bags should be done with dry gas instead of nitrogen in order to minimize the effects of the nitrogen diluting in the samples.

O.4.1 Test 4: Low Pressure

The same vacuum chamber was used as in Tests 18 and 29. The Styrofoam was measured on each side before it was placed in the chamber. It was then taken down to 5 hPa and held there for 75 minutes. It was then removed and the sides were measured again. It was found that there was no significant change in dimensions. The results can be seen in Table 72.

Side	Before (cm)	After (cm)
A	9.610	9.580
B	9.555	9.550
C	9.560	9.565
D	9.615	9.610
E	9.615	9.615
F	9.555	9.550
G	9.605	9.605
H	5.020	5.020
I	5.025	5.025
J	5.015	5.015
K	5.020	5.025

Table 72: Styrofoam Size Before and After Vacuum.

As some sides are measured slightly bigger after and some slightly smaller it is thought this is due to the measuring technique and not due to changes in the Styrofoam. It is thought the result from side A could be due to deforming the Styrofoam with calipers or a misread original length.
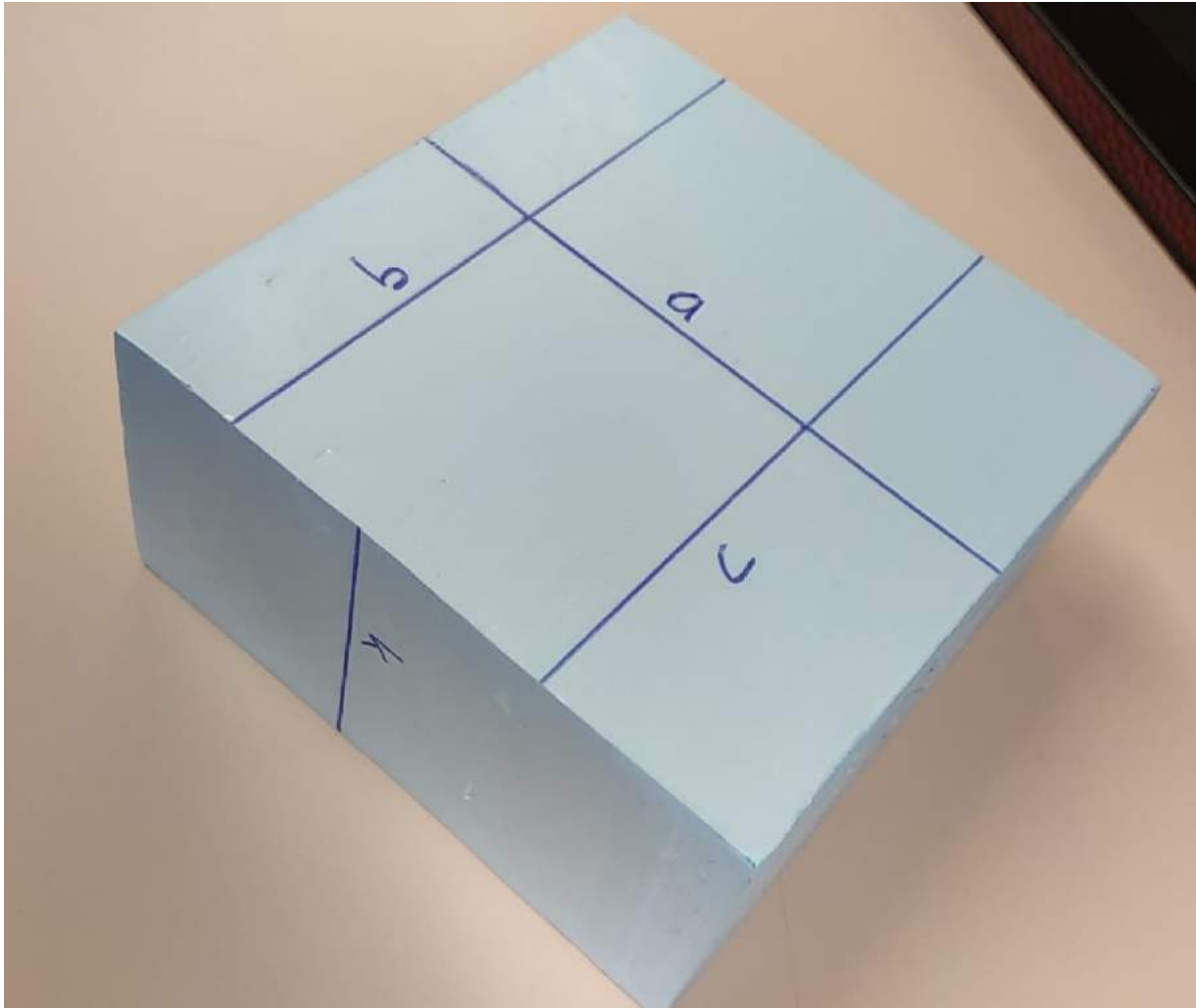
Figure 151: Picture Showing how the Styrofoam was Labeled for the Test.

When testing the airflow sensor and pump these were attached mechanically using a Swagelok fitting between the airflow sensor and the tube and by placing the pump inlet inside the tube and taping it into place. The pump was then connected directly to the 24V power source whilst the Arduino and airflow sensor were connected via two 12V DC-DC converters. The Airflow sensor output was connected to the Arduino to allow data logging.
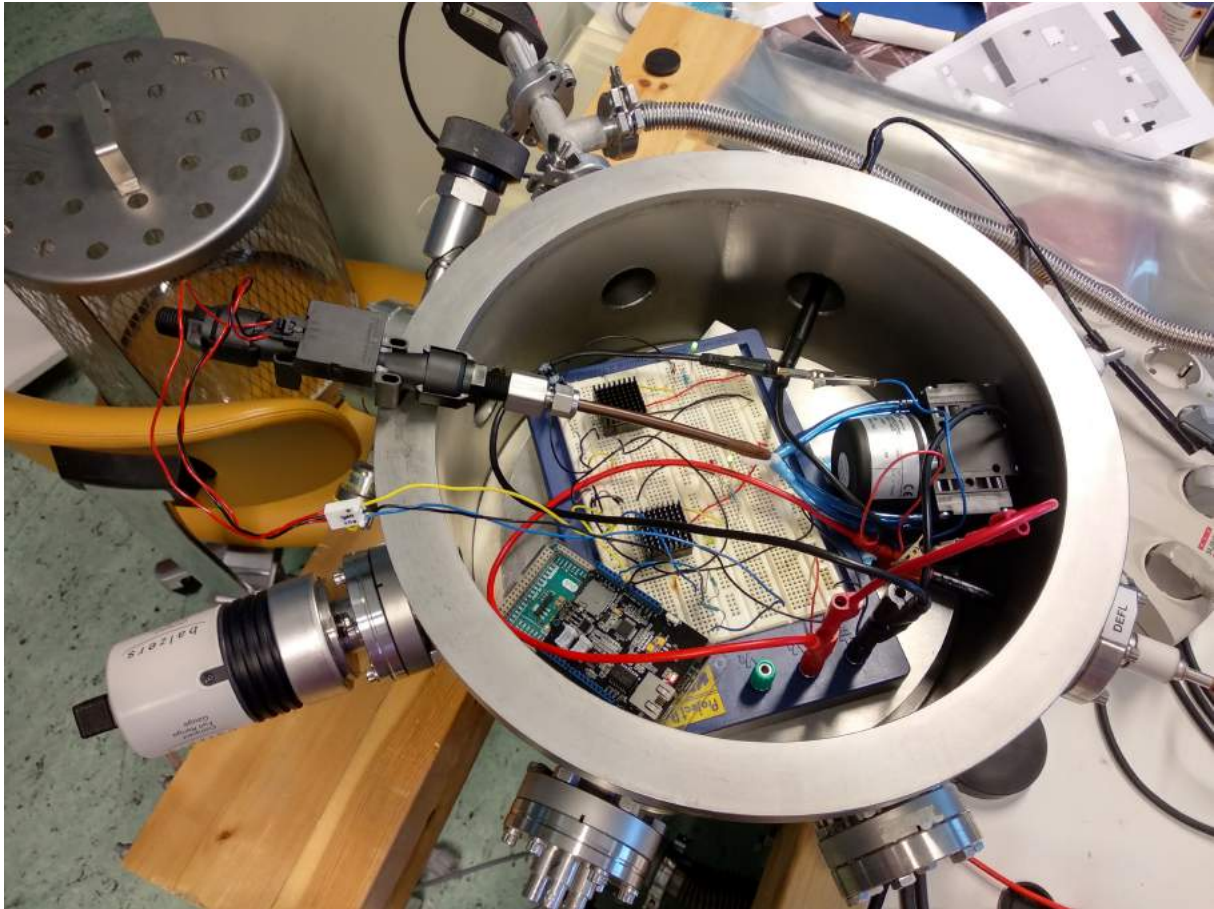
Figure 152: Picture Showing the Test Set-up with the Arduino, Airflow Sensor and Pump.

The vacuum chamber was then taken down to 5, 15, 25, 35, 46, 55, 65, 75, 85, 95, 150, 200, 250, 300, 400 and 500 hPa and the airflow rate logged.

The pump and the airflow sensor were connected together and tested at 16 different pressures. Due to some issues in the data logging with time stamping it is not possible to verify the pump performance until this issue is resolved. A re-test will be made as soon as possible.

O.4.2   Test 20: Switching Circuit Testing and Verification

This has begun on breadboards with LEDs replacing the valves until the valves arrive.

So far DC-DC's have been set up and tested. Sensors have been connected electronically and the next step is to get them to communicate with the Arduino.

Mosfets connecting to the pump and the heaters have been tested for switching on and off with good results.

O.4.3 Test 32: Software Failure

So far testing has revealed that losing the SD card does not interuppt ground station data, it just means no data will be written to the SD card. However, if you reconnect the SD after removing it currently it will not connect back to the SD card and it as if the SD card has been permanently lost.

O.5 Test 33: Electrical Component Testing

Complete	Test #	Test	Description
NO	1	Test Voltage divider (Airflow + Pressure sensor)	Test the airflow sense with voltag
YES	2	Test MOSFET	Test the MOSFETS by applying 3
YES	3	Test LED Configuration	Test the resistance and zener dioc
NO	4	Test Valves with MOSFET	Test to open and close valves thro
YES	5	Test Pump + MOSFET	Same as valves but for pump
YES	6	Test DCDCs in parallel with LED	Test that the parallel configuratio
NO	7	Test interface connections	Test the dsub and power cables th
YES	8	Test Potentiometer trimming for DCDC	Test the DCDC trimming by using
NO	9	Test grounding for analog components	Test the grounding configuration

Table 73: Electrical Component Testing Detailed Procedure and Results