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CHAIRMAN'S CONCLUSIONS

Dear colleagues and friends,

It has been a great pleasure for me to be part of the 24th ESA symposium on European Rocket and Balloon Programmes and Related Research in Essen. It has been a very successful meeting with an intensive exchange of scientific and technological experience and knowledge in a field which is highly challenging both from the experimental and theoretical point of view.

We have seen exciting oral and poster presentations with results from cutting-edge research and technological achievements. The presentations focussed on investigating and using the near space environment for atmospheric, ionospheric, biological, medical, micro-gravity, and astrophysical research, applying sounding rockets and balloons as well as ground based and space borne instrumentation. These applications are challenging and unique.

It has been a particular pleasure to welcome so many young students and post-docs. In general, we can conclude that the topic and format of the symposium is highly attractive. It has been a great pleasure to meet old friends and to share memories and ideas for future activities.

I would like to thank again all members of the symposium programme committee and the organizing committee for their hard work for this event. The success of this symposium is to a significant extent based on this commitment.

Looking forward to welcoming you again in two years in France.

Prof. Franz-Josef Lübken
Symposium Chair

SPACE-RELATED EDUCATION 2

THURSDAY 20 JUNE, MORNING SESSION – PART 2

ROOM 1

CHAIR: S. MAWN

PROJECT TUBULAR: USE OF MULTI-LAYER FOIL SAMPLING BAGS AND A 200 METER AIRCORE FOR GREENHOUSE GAS SAMPLING ON-BOARD THE BEXUS 26 STRATOSPHERIC BALLOON FLIGHT

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ABSTRACT

The TUBULAR experiment launched from Esrange space center in October 2018 as part of the REXUS/BEXUS programme. The experiment aimed to measure carbon dioxide (CO_2) and methane (CH_4). A high altitude balloon flight is the most cost-effective method to obtain a vertical air profile between the upper troposphere and the lower stratosphere. However, recovery time constraints due to gas mixture concerns restrict sampling to locations near existing research centres. The TUBULAR experiment is a technology demonstrator for an air sampling mechanism that minimises the effect of gas mixing within the samples. The experiment includes a secondary sampling mechanism that serves as reference to validate the proposed sampling mechanism. The experiment was a partial success with the secondary sampling mechanism performing nominally and a failure with the primary sampling mechanism. Data from the secondary mechanism was of good quality and accurate atmospheric profiles of CO_2, CH_4 and CO were measured.

Key words: TUBULAR; High Altitude Balloon; AirCore; Climate Change; CH4; CO2; CO; Trace Gases; Greenhouse Gases; Sampling Bags; Space Education; Student Experiment.

1. INTRODUCTION

Climate change is being driven by greenhouse gases in the Earth's atmosphere. While these occur naturally, human activity increases their concentrations thus magnifying the greenhouse effect [1]. Human activity is causing a noticeable rise in the concentrations of carbon dioxide (CO_2) and methane (CH_4), with CO_2 being responsible for 64% and CH_4 for 17% of all man-made global warming [1]. Atmospheric air samples must be collected for analysis in order to better understand the impact that human emissions have on these gas concentrations. However, it is currently difficult to sample atmospheric profiles in more remote locations. This is due to concerns over gas mixing inside the sampler and physical constraints such as ease of transport of the experiment.

Project TUBULAR aimed to provide a more accessible, flexible, and scalable air sampling mechanism to enable sampling in remote regions all while minimizing gas mixing within the collected samples while awaiting recovery [2]. The project was implemented under the REXUS/BEXUS programme which is realised under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Agency (SNSA). The international team behind the project consisted of 13 students from 8 different countries enrolled at LTU's Master Programme in Spacecraft Design as well as the Master Programme in Earths Atmosphere and the Solar System.

The project planned to measure the concentrations of CO_2, CH_4, and carbon monoxide (CO) using two sampling mechanisms: the Conventional AirCore (CAC), based on an established sampling method [3], and the Alternative to AirCore (AAC). The CAC holds an AirCore that is a long and thin stainless steel tube shaped in the form of a coil, which takes advantage of changes in pressure during descent to passively sample the surrounding atmosphere and preserve a continuous vertical profile [4]. However, past research has revealed that degradation in the profile can be seen as soon as eight hours post flight due to the irreversible mixing of gases [4]. The CAC's relatively large mass and high production costs further constrains its deployability. The proposed AAC system is designed to address these limitations.

The AAC sampling system consists of a series of small independent air sampling bags. Each sampling bag was allocated an altitude range, taking discrete samples from the flight's vertical profile. By constraining the sample vertical ranges to no more than 500 m the effect of gas mixing within the collected sample is reduced, thus extending the maximum recovery time up to 48h [5]. The AAC also has a significantly reduced implementation cost with respect to that of the CAC, making it more accessible for replication. Overall the design of the AAC was approached with the idea of miniaturization and cost-effectiveness [2]. A similar experiment, albeit smaller and lighter, was completed with LISA sampler [6]. However, LISA only held four sampling bag and thus generated 50% less data than the ACC's six bag configuration.

2. EXPERIMENT SETUP

The TUBULAR experiment consists of two boxes, as seen in Fig 1, the AirCore is enclosed in the left box and the AAC in the right box.

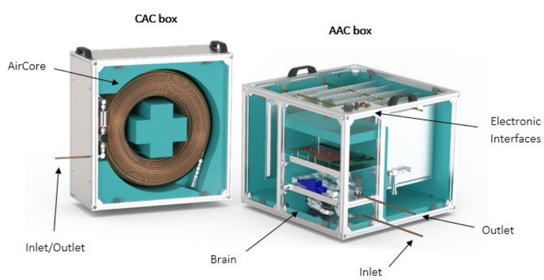

Figure 1: CAD models of the two experiment boxes.

A diagram of the system's components, interconnections, and air flows can be seen in Fig 2.

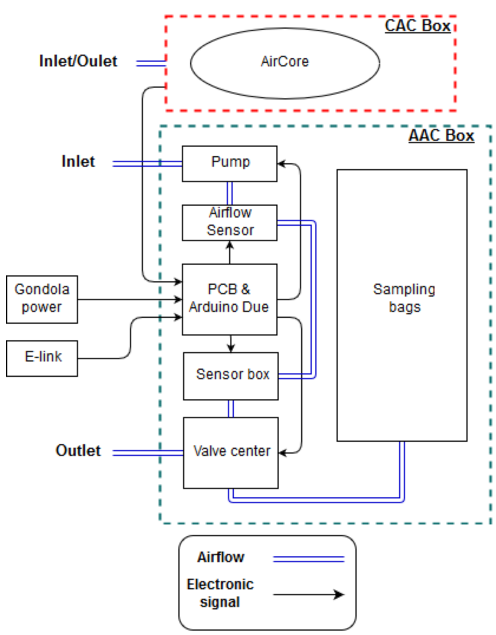

Figure 2: Block diagram experiment configuration.

2.1. Conventional AirCore (CAC)

The AirCore that was flown was 200 m coiled stainless steel tube with a 0.01 inch thick wall. The tube consisted of a 1/8 inch diameter tube with a length of 120 m and a 1/4 inch diameter tube with the length of 80 m and was coated with SilcoNert 2000. The AirCore coil was provided by the Finnish Meteorological Institute (FMI). The coil was placed in a protective box (CAC), as seen in Fig 3, with Styrofoam encasing the tube to provide thermal and impact protection. The Sampling method is entirely passive. A control valve was used to ensure that the system remained clear of contaminants before flight and to seal the sample after flight. The valve opened at an altitude of 1 km during ascent and remained open until shortly before touch down. The valve could also be manually controlled from the ground station if required.

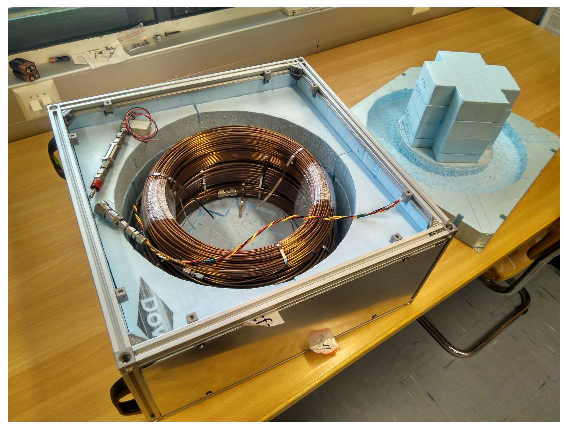

Figure 3: Opened CAC box revealing the AirCore.

2.2. Alternative to AirCore (AAC)

The AAC consisted of six multi-layer foil gas sampling bags (3 L, 10"x10"), provided by RESTEK [5]. Air flow to the sampling bags was enabled via dedicated valves, provided by SMC Pneumatics. As the AAC cannot passively sample, a pump provided by KNF, was used to sample the air. SilcoNert 2000 coated 304SS welded/drawn was used for tubing and provided by SilcoTek. Tubing interfaces, connectors, fittings, and unions were provided by Swagelok. The AAC experiment box also hosts most of the electronics, as seen in Fig 1 with a closeup in Fig 4. Styrofoam walls isolate the electronics from the area allocated to the sampling bags. It was critical to ensure that the electronics were kept within their operational temperature as many components could not withstand the cold temperatures found at high altitudes. For instance, the pump, which had the highest minimum operating temperature of 5°C, was a critical component to keep warm as the outside temperature was expected to drop below -40°C [7].

Figure 4: Electronics distributed across three layers.

The AAC air intake was pumped through a magnesium filter to remove any remaining humidity in the air. The air then went through an air flow sensor used to generate housekeeping data as the flow rate provided evidence on whether or not the pump was operating. The air then reached the valve manifold section from which it was directed to one of the six sampling bags depending on the sample altitude range. A pressure sensor was used to monitor sampling bag pressure levels in order to avoid incidents such as bursting.

3. PROJECT STEPS

The project consisted of several milestones, reflecting standards at ESA. These consisted of the selection workshop, preliminary design review (PDR), critical design review (CDR), integration process review (IPR), and experiment accepted review (EAR). Meeting these milestones ensured that the project progressed at a steady pace. The review panels allowed the organisers, experts, and mentors to highlight problems early during the development of the project and offer adequate guidance and recommendations.

3.1. Design Evolution

The initial idea presented at the selection workshop underwent many design changes based on feedback received from the expert review panel during the PDR and CDR. The design presented for the PDR can be seen in Fig 5, it used a single box for both sampling methods. This approached changed significantly, as can be seen in Fig 1, with a two box approach presented at the CDR where each sampling method was housed separately.

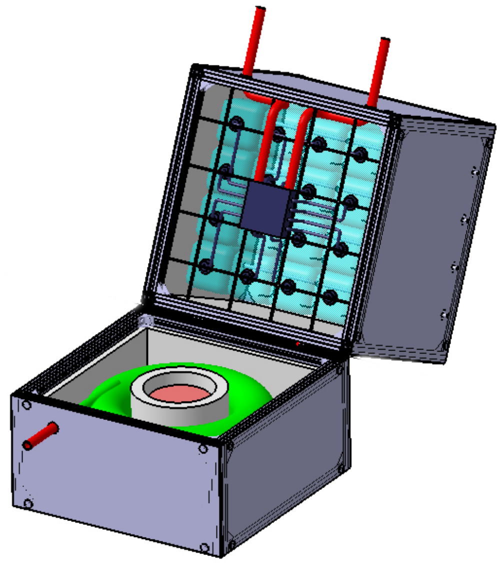

Figure 5: Early CAD model presented at the PDR.

The changes were made to enable the fast recovery of the CAC. A dedicated CAC box ensured that the entire experiment did not need to be brought back thus reducing the size and mass of the payload that needed to be handled by the recovery team. The end result can be seen in Fig 6.

3.2. Building Phase

The next phase of the project was the lead up to the IPR where most of the effort was spent on building the experiment. This experience gave the TUBULAR Team an understanding on how to adequately handle different materials. The boxes were built by first assembling the frames and shaping Styrofoam sheets according to the mechanical drawings produced for the CDR. The resulting CAC box can be seen in in Fig 3. Working with the Styrofoam required some ingenuity as there was a discrepancy between the sizes provided by the manufacturer and the requirements. Furthermore, the available tools were not suitable for handling Styrofoam. Building the experiment as per the mechanical drawings thus required some problem solving, such as creating a customised hot wire cutter.

Working with tubes and metal sheets also presented challenges that required learning how to use some specialist tools. In Fig 4, the different layers of the electronics box are assembled on metal sheets, with the coated tubes going through the layers and from the manifold out to the sampling bags. The completed box is shown in n Fig 6.

A thin layer of aluminum was added to the outside of the Styrofoam walls to protect the Styrofoam from impacts.

Figure 6: Completely built AAC and CAC.

The assembly of the electronic components was completed with support from ESA mentors, a soldering courses, and expert review during the CDR. The components were carefully soldered onto the PCB and cable looms were created. Significant effort was put into routing and labeling cables to make them accessible for repairs and robust against vibration as well as the flight's shock profiles. In Fig 4, the PCB can be seen resting on the top layer with connections to control and power the valves, sensors, and the pump. Issues related to working with different communications buses, due to differences in cable and trace length between sensors, were successfully tackled and served as an invaluable learning experience.

The embedded software for the on board computer was developed in C/C++ using the PlatformIO IDE with an Arduino Due development board and an Atmel SAM3X8E processor. The software provided autonomous and manual control for the sampling system. A ground station was created using MATLAB GUIDE to monitor the sensor housekeeping data received via telemetry and to send telecommands, the interface can be seen in Fig 7.

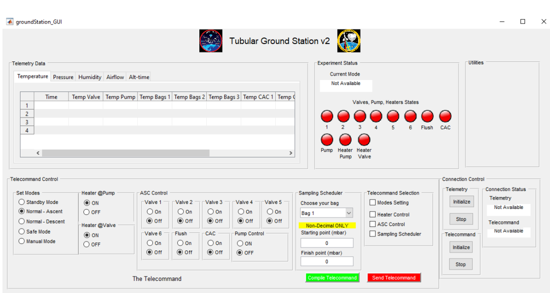

Figure 7: Ground station GUI (version 2).

3.3. Testing

Prior to launch, the experiment had to be thoroughly tested to ensure that it could successfully sample while withstanding the harsh stratospheric environmental conditions it would be exposed to. The tests were based on the guidelines found in the BEXUS user manual [8]. 28% (1,943 hours) of the total project working hours were dedicated to the building and testing phase to ensure test completeness.

3.3.1. Mechanical

Mechanical testing was undertaken to ensure that the experiment structure could withstand the vibrations and impacts which would occur during the mission. Three tests were completed, a structural load test, a drop test, and a vibration test. The structure was tested by placing a load on top of the frame and checking for deformations, the drop test by dropping the experiment from a short height on to a soft surface, and the vibration test by driving it on a gravel road for a 18 kilometers.

3.3.2. Electrical

Electrical testing ensured that all electrical connections were secure and without any short circuits. After verifying that all the components were functioning and their power consumption could be verified, resistive values were determined for trimming the output voltages and for voltage dividers on the analog sensor outputs. The electronics were then tested with software on a breadboard giving the vital information needed to design the main PCB and the smaller PCBs for the barometric sensors. These PCBs were later tested again to ensure functionality and robustness.

3.3.3. Software

Software testing began early in the design process to ensure the code was bug free and that it contained all the required functionality. The ground station was tested rigorously to check that all the sensors gave correct data back and that it could run for 8h collecting and storing data without encountering any errors. The on board software was also tested so that it stored and transmitted data correctly even in the event of communication breaks.

3.3.4. Science and Procedures

At FMI in Sodankylä, Finland, the flushing procedure for the AAC was developed. Furthermore, the bags holding time was tested to verify how long the bags could be left post-flight before gas mixing would become a concern.

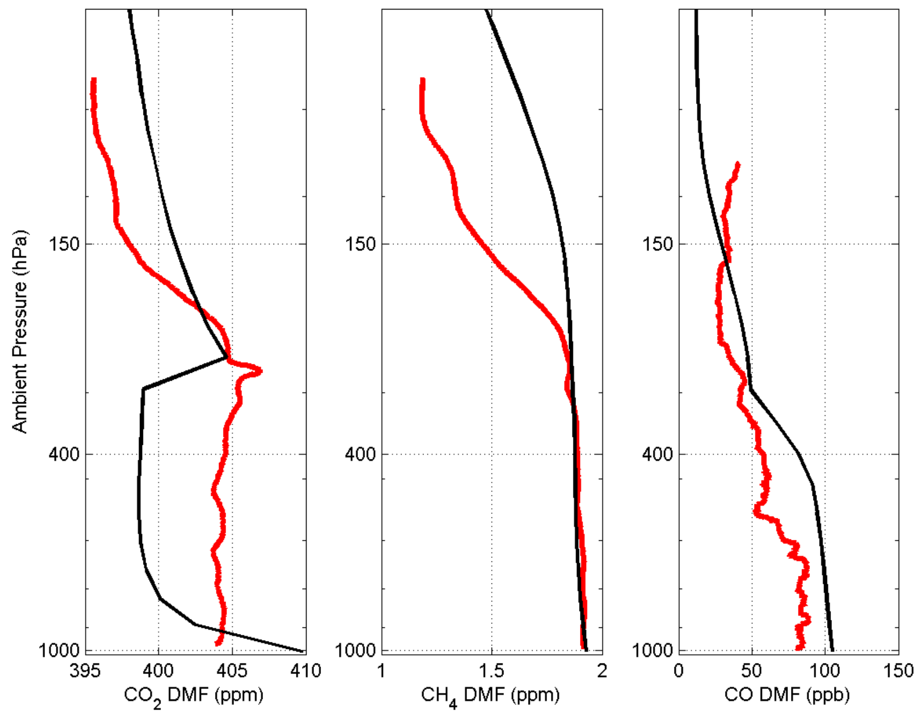

Figure 8: Atmospheric profiles of CO2, CH4 and CO as measured by the AirCore sampler (red lines). For comparison estimated profiles are shown in black.

Holding times tested were for 15h, 24h, and 48h with a 0.5L and a 1L sample of dry gas. The CO_2 had a difference not higher than 2 ppm and the holding time for the sampling bags from RESTEK were considered good for up to 48h.

3.3.5. CAC integration

The AirCore was integrated into the CAC box along with the CAC control valve. As the AirCore was provided by FMI, this testing was done on site at FMI. Prior to this integration test, Styrofoam carving for the AirCore was purposely conservative.

3.3.6. Vacuum

Vacuum tests were carried out in a small chamber provided by the Swedish Institute of Space Physics (IRF). The vacuum chamber tests verified that all components could operate in the low pressure environment expected during the flight. Temperatures of critical components were recorded to ensure they did not overheat in a low pressure environment. The Styrofoam was checked for deformations in the structure before and after being exposed to the low pressure. The expansion of the gas inside the sampling bags was monitored and thresholds were established. Once these tests were complete, the autonomy of the system was also tested to ensure that the valves could open and close and that the pump could turn on and off automatically when predetermined altitudes were reached by checking the pressure readings coming from the pressure sensors.

3.3.7. Thermal

A initial test was performed in Finland at FMI; however, due to sensor error issues further tests were required. The next tests took place in the freezer at LTU going down to -18°C. A final test took place at Esrange Space Center allowing testing below -40°C. These tests verified whether the heaters were turning on at the correct times and whether the temperature inside different areas of the experiment were kept within operation ranges.

4. RESULTS

The results obtained from the experiment are twofold, scientific results and educational results. Scientific results were a partial success. This is due to a current-limiting problem during flight. Whenever the pump attempted to turn on it could not draw enough current from the batteries causing the on board computer to restart. This restart reset all system conditions. As the pump could not start it was not possible to collect any air samples in the AAC system. Post-flight failure analysis confirmed that current limitation was the issue; however, the cause is uncertain. The CAC system operated as intended and resulted in a vertical profile. However, the fault in the AAC system resulted in the CAC control valve closing too early. In order to ensure that the sample was not further compromised a decision was made to keep the CAC control valve closed and to lose the lower altitude sampling opportunity thus resulting in a partial profile. Due to the long recovery time on the CAC, of around 17 hours [2], some leakage was detected at the lower end of the sample. However this leakage allowed surface results to be obtained which have been added to the plot. The vertical profile for CO_2, CH_4, and CO collected by the AirCore can be seen in Fig 8. An estimation forecast had been made using the combination of earlier measurements with a meteorological model based adjustments. AirCore measurements of CO_2 have notable similarities with the predicted forecast, particularly with the concentration spike of 407 ppm around the tropopause. However, the predicted concentrations sharply drop at lower altitudes after the spike whereas the measured concentrations stagnate at around 405 ppm until ground level at 1000 hPA. The measurement of CH_4 at higher altitudes had less ppm than estimated, peaking at around 1.9 ppm at a bit above the tropopause and stagnating until ground level at 1000 hPA. For CO, the measurements followed the estimated trend but with lesser ppb at ambient pressure higher than around 150 hPA, peaking at approximately 90 ppb at 1000 hPA. The CO and CH_4 follows the forecast concentration reasonably well in shape.

While the AAC has been proven to work on ground, in a vacuum chamber, and in a thermal chamber, it has not had a successful validation flight yet. The team has installed a new power system since the BEXUS flight and intends to fly the system again with FMI in the future.

The educational results of the experiment were significant for the team. During the entire design, build, test, flight, and post-flight analysis stages the team was exposed to many challenges in technical and management aspects. By working together and emphasizing communication, the team was able to overcome every problem that appeared before the flight. While the team was unfortunately unable to overcome the problem which occurred with the pump during flight, much could still be learned from the incident. The team learned how to work with outside agencies and how to adhere to the standards expected by those agencies all while following a rigorous industry-level documentation and review standard. This experience with REXUS/BEXUS was an invaluable one that will benefit the whole team as they advance in their careers for years to come.

ACKNOWLEDGMENTS

The TUBULAR Team wishes to acknowledge the invaluable support received by the REXUS/BEXUS organizers: Swedish National Space Agency (SNSA), German Aerospace Center (DLR), European Space Agency (ESA), Swedish Space Corporation (SSC), Center of Applied Space Technology and Microgravity (ZARM), Esrange Space Centre, and ESA Education. In particular, the team's gratitude extends to the following project advisers who showed special interest in our experiment and its success: Dr. Thomas Kuhn (Luleå University of Technology, LTU), Mr. Olle Persson (LTU), Mr. Grzegorz Izworski (ESA), Mr. Koen Debeule (ESA), Dr. Uwe Raffalski (Swedish Institute of Space Physics IRF), and Mr. Vincent Still (LTU Alumni). The TUBULAR Team would also like to acknowledge our gratitude to the following manufactures and suppliers that sponsored the team so the experiment could be built. Restek, SMC Pneumatics, SilcoTek, Swagelok Sweden, Teknolab Sorbent, Lagers Masking Consulting, Bosch Rexroth, KNF, and Eurocircuits.

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