A PROTOTYPE FOR IN-FLIGHT ACQUISITION AND POST-FLIGHT ANALYSIS OF STRATOSPHERIC AEROSOLS

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ABSTRACT

“Stratospheric Census” is a low-cost prototype for in-flight acquisition and post-flight analysis of stratospheric aerosols. The experiment was flown on the BEXUS-7 balloon from ESRANGE, Sweden on 8 October, 2008. A diaphragm vacuum pump generated airflow through a filter catching particles down to 0.4 µm in diameter. Remotely controlled valves ensure that no tropospheric air is sampled. Temperature monitoring and an autonomous failsafe mechanism ensure correct operation in the case of pump overheating or link loss. The experiment demonstrated an economical alternative to large in situ analysis techniques for stratospheric aerosol research. After recovery, advanced analysis methods that are not possible in flight (γ-ray spectroscopy, autoradiography and neutron activation analysis) were used to investigate the particles captured by the filter.

Key words: aerosols, stratosphere, bexus, balloon.

1. INTRODUCTION

Aerosols are microscopic particles of varying composition suspended in the layers of the atmosphere. Their origins are the ashes of volcanic eruptions, earth-borne dust, cosmic dust and human-made atmospheric pollution. Grain size, shape and chemical composition of aerosols vary widely depending on origin.

In the stratosphere, an atmospheric layer between 10 and 50 km altitude, aerosols play a crucial environmental role: Aerosols heat atmospheric layers (through their absorption of sun light), they (back) scatter sun light with a potential cooling effect (sulphuric aerosols), they foster ozone destruction (hydrochloric acid) and they play a role in the formation and characteristics of clouds.

The effects of aerosols on the environment and on global climate make the case for investigations in this field of atmospheric science.

Stratospheric Census is a balloon-based experiment for the investigation of stratospheric aerosol composition. The basic experiment concept consists of in-flight acquisition of aerosols in a filter and analysis of the filter on ground, after flight.

The key objectives of Stratospheric Census are as listed below:

- To develop a simple yet powerful instrument for collecting aerosols in the stratosphere.
- To collect aerosols in situ using a filter and to recover the filter sample.
- To use different techniques of analysis to assess functionality of the prototype and to identify the aerosol composition in the sampled stratospheric region.

These objectives were realised within the REXUS/BEXUS educational initiative [1] and led to a balloon flight onboard BEXUS-7 on the 8 October 2008 from Kiruna in Northern Sweden.

Figure 1. The Stratospheric Census Experiment. In the middle the tubing holding the filter, to its left the control box, to its right the actuators controlling the valves.

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2. BEXUS: BALLOON EXPERIMENTS FOR UNIVERSITY STUDENTS

Balloon flight campaigns such as BEXUS provide a valuable platform for student experiments, not only in the domain of experimental atmospheric science but also for flight-body testing, navigational projects and experiment validation, among many others. BEXUS is part of the REXUS/BEXUS Programme, a joint educational effort by the European Space Agency (ESA) and the Swedish National Space Board (SNSB) together with Deutsches Zentrum für Luft- und Raumfahrt (DLR). Teams of university students are offered the opportunity of planning, designing, testing and implementing their experiment ideas under the supervision of experts in the space field. REXUS/BEXUS balloons and rockets are launched from ESRANGE Space Centre in Kiruna, Sweden by EuroLaunch, a cooperation between the DLR Mobile Rocket Base (MoRaBa) and the Swedish Space Corporation (SSC).

3. SCIENTIFIC BACKGROUND

3.1. Stratospheric aerosols

The stratosphere is a dry and cold environment of major importance to the Earth radiation budget. Most research in stratospheric aerosols is done by in situ analysis or remote sensing. Early research used an Aitken nucleus counter and found a large concentration of sulphur, especially for particles with diameters between 0.1 µm and 1.0 µm [2]. More recent techniques include ground-based optical methods [3]. A large project researched the spatial [4], temporal [5] and size [6] distributions, as well as sources [7] for stratospheric aerosols using a dedicated in-flight detector for aerosols with diameters ≥ 0.3 µm, and found the following size distribution for aerosols between 18 and 20 km:

\[
N_i(r) = \frac{N_0}{\sqrt{2\pi \ln(\sigma_g)}} \int_r^\infty \exp\left[-\left(\frac{\ln(\frac{r'}{r})}{\sqrt{2\ln(\sigma_g)}}\right)^2\right] \frac{1}{r'} dr'
\]

(1)

In equation (1), \(N_0 = 10\, \text{cm}^{-3}\), \(\sigma_g = 1.86\), \(r_g = 0.0725\, \text{µm}\), \(r\) is the diameter.

Volcanic aerosols are common and contain large amount of sulphur [7]. Cosmic aerosols are uncommon and could contain metals such as iron, nickel, calcium, aluminium, titanium, magnesium [8].

3.2. Recent aerosol research missions

As mentioned above, stratospheric aerosol research can be grouped into three different categories: remote sensing of aerosols (from ground or from a satellite), balloon missions with in-flight particle acquisition and in situ measurement of aerosols, balloon missions with in-flight particle acquisition and sample return for analysis on ground. These three methods complement each other and differ in their respective cost, complexity and scientific scope.

An example of recent remote sensing aerosol research are the spectrometer instrument of the Stratospheric Aerosol and Gas Experiment (SAGEIII) [9] or ground-based lidars. Stratospheric Census belongs to the third group of experiments with particle collection in a filter during flight and subsequent laboratory analysis of the filter substrate. In this respect it is highly similar to the DUSTER experiment [10] that also performed a flight in 2008 from the Andøya rocket range.

4. BASIC EXPERIMENT CONCEPT

The basic concept for Stratospheric Census (Fig. 2) consists of a diaphragm vacuum pump generating airflow through a permeable Elmarco nanofilter. Air is taken in through a protruding stainless steel tube, avoiding contamination from the balloon gondola. Contamination from the pump is mitigated by placing it downstream from the filter in the airflow system. Two valves are controlled from the ground via a radio link such that the airflow either passes through the filter or bypasses it. Stratospheric Census gives no spatial resolution (the result is integrated over the trajectory) but is an economic alternative to other techniques for stratospheric aerosol research. Since analysis is performed on ground, it more easily allows advanced and diverse analysis techniques.

4.1. Diaphragm pump

A diaphragm vacuum pump for the medium vacuum range was chosen for Stratospheric Census. The diaphragm avoids contamination from the pump to the airflow system. Also, diaphragm pumps are less susceptible to overheating (as compared to rotary vane pumps for example). However, a cold diaphragm carries the risk of becoming brittle. The diaphragm pump is therefore kept running from experiment launch until the end of the measurement in order to avoid seizure by starting it in stratospheric conditions. Diaphragm pump speed is controlled remotely with the temperature of the components being monitored constantly.

4.2. Nanofilter

The Stratospheric Census experiment allows for the inclusion of any filter with compatible geometry. An Elmarco Nanospider filter was chosen for flight. This type of filter consists of cellulose filtration material treated
with PA6 polymer nanofibers 100 to 500 nm in diameter. During a test (by the manufacturer) the filter was able to catch NaCl particles of 0.2 µm with an efficiency of almost 80% where particles of 1 µm were captured completely [11].

5. TUBING, ACTUATORS AND VALVES

Stainless steel components were chosen for tubing and valves. Based on previous experience from other experimenters [12], special emphasis was placed on avoiding seizure of valves (from negative thermal expansion or freezing) by using globe valves and high-torque actuators. The filter housing was manufactured from aluminium and was designed so that the filter could be inserted and removed gently to avoid contamination and damage of the sample. The threads of all connections were sealed using a combination of thread sealant and intentional deformation of the threads during final assembly. This final assembly was conducted at ESRANGE to minimize risk of accidental contamination of the filter during transport (due to accidental valve switching or unscrewing of the pipe assembly. With this in mind, the modular frame and components were arranged so that the pipe assembly could be inserted safely.

5.1. Prototype mass and volume

The ready experiment, equipped with all components, has dimensions of 350 x 300 x 200 mm and a mass of 7.6 kg, as outlined in Tab. 1.

6. FLIGHT

Stratospheric Census was launched on the BEXUS-7 high-altitude balloon from ESRANGE near Kiruna, Sweden on 8 October 2008. At the time of delivery to ESRANGE, all subsystem components (diaphragm pump, valve actuators, frame/structure, electronics) were fully assembled ready for the insertion of the tubing system and the aerosol nanofilter, which were carefully put together under cleanbench conditions at ESRANGE. Sealing the experiment’s air inlet using a plastic plug until 9 minutes before take-off (last access time) reduced contamination of the collection intake from the launch pad to as large an extent as possible. Aerosol conditions on 8 October 2008 were favorable for a prototype demonstration: According to ESRANGE LIDAR data (Fig. 3), substantial aerosol concentration was present at an altitude between 12-18 km, possibly from an eruption of the Kasatochi volcano\(^1\). BEXUS-7 started at 15:36 CET from ESRANGE and touched down after 19:28 CET near Rovaniemi, Finland, after a flight time of slightly more than 3:52 hours which had brought it up to an altitude of 27 km. Fig. 4 shows the balloon’s flight profile. Contact between ground station and the experiment through the ESRANGE E-Link system could be established before launch and was not lost until after gondola cut-down.

As a result, Stratospheric Census was ground-controlled during the whole flight with telecommand and telemetry working flawlessly. Telemetry data from ESRANGE (geographic location and altitude of the balloon) complemented the experiment’s own data (experiment status, various temperature readings). The control operations that had to be carried out during different phases of the flight in order to start and stop the measurement process were a) setting the diaphragm pump to its full power and b) adjusting the valves to allow/disallow airflow through the nanofilter.

\(^{1}\)On 7 August 2008, an eruption occurred at the Kasatochi volcano of the Andreanof Islands subgroup of the Aleutian Islands, Alaska, USA. LIDAR data measured on-site by K. H. Fricke and collaborators prior to and during the flight measured a high concentration of aerosols at 12-18 km altitude that probably originated from the Kasatochi eruption two months earlier.

<table>
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<tr>
<th>Items</th>
<th>Mass (g)</th>
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<tbody>
<tr>
<td>Frame</td>
<td>1,952.20</td>
</tr>
<tr>
<td>Pump</td>
<td>815.30</td>
</tr>
<tr>
<td>Control box</td>
<td>730.00</td>
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<tr>
<td>Battery box</td>
<td>609.90</td>
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<tr>
<td>Batteries</td>
<td>876.00</td>
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<tr>
<td>Connectors</td>
<td>88.00</td>
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<tr>
<td>Tubing</td>
<td>680.00</td>
</tr>
<tr>
<td>Valves</td>
<td>140.00</td>
</tr>
<tr>
<td>Total</td>
<td>7,600.40</td>
</tr>
</tbody>
</table>
6.1. Flight phases

During most of the ascent phase of the BEXUS-7 balloon, the experiment was kept in 'Stand-by Mode': The diaphragm pump operated at low power so as to avoid starting in stratospheric conditions later on. The nanofilter was kept sealed by the valves. Based on the expected aerosol concentration at an altitude of 12-18 km, the measurements were started ('Sample Mode') when BEXUS-7 passed the 12 km mark at 16:16 CET (at this point, BEXUS-7 had not yet reached floating altitude). The diaphragm pump was remotely switched to full speed and airflow was allowed through the filter. In Fig. 4 the 'Stand-by Mode' occurs at the beginning of the flight before the 'Sample-Mode' during balloon ascent and float.

6.2. Flight performance

The ground station monitored the performance of the actuators and the temperature of the diaphragm pump, the batteries and the microcontroller during the whole flight. Microswitches on the actuators indicated the successful adjusting of the valves when the measurement was started. At the end of the measurement, they showed that the valves had been moved into 'stand-by' position again and the nanofilter was therefore sealed off and ready for landing.

6.3. Recovery and post-flight filter handling

After landing of BEXUS-7, it was recovered by ES-RANGE personnel. Visual inspection of Stratospheric Census showed that the nanofilter had been sealed successfully after the particle capture. No major signs of wear on the structure and components could be observed. After removal of the tubing holding the nanofilter, a post-flight system test showed that the diaphragm pump and the actuators were functioning normally.

After flight, the filter sample was extracted in a clean environment and transported in double-sided polyethylene bags cleaned with demiwater.

7. FILTER ANALYSIS AND RESULTS

The key advantage of a sample return concept is the vast choice of methods for laboratory analysis of the aerosols collected in the filter. Autoradiography and X-ray fluorescence analysis were employed successfully for the Stratospheric Census flight filter and Nuclear Activation Analysis was also investigated as an analysis method. The various analysis methods were applied to one flight sample and nine control samples.

High Purity Germanium gamma spectrometry measured spectra of natural emitters in the sample. An acquisition time of 24 h ensured good statistics. Four-fold energetic calibration was performed with the spectra of $^{152}$Eu, $^{22}$Na, $^{60}$Co and the 511 keV background annihilation peak.

Gamma spectrometry identified $^{57}$Co, $^{111}$In, $^{125}$I, $^{133}$Xe, $^{137}$Cs and $^{192}$Ir as natural emitters in the flight sample. None of these could be shown for the control samples.

Strong X-ray emitters ($^{241}$Am of 740 MBq) were used to excite the samples and to provide characteristic radiation of captured elements (due to the emitter used, the energy limit of this method is at 60 keV). Calibration was performed with Co, Cd and Au. After a measurement time
of 14 h, spectral lines corresponding to the elements detected in the Autoradiography before could be identified, albeit with lower significance.

8. CONCLUSION

A prototype for in-flight acquisition and post-flight analysis of stratospheric aerosols has been realised by Stratospheric Census. The instrument was flown successfully on the BEXUS-7 balloon mission. Remote feedback from the system suggests that all monitored systems performed as expected. No provisions for measuring the airflow through the system had been made; the analysis results of the filter is the indicators of successful performance.

Future enhancements of the system could include, but are not limited to, measurement of the airflow or the use of multiple filters.

Details on Stratospheric Census, pictures, the design and a full final report can be found on the team’s homepage at http://www.stratospheric-census.org.

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REFERENCES