POLECATS - A PLASMA INSTRUMENTATION TECHNOLOGY DEMONSTRATION FOR REXUS-14

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ABSTRACT

PoleCATS - the Polar test of the Conceptual And Tiny Spectrometer - is a technology demonstration in the lower ionosphere of a new concept in space plasma instrumentation. The experiment uses CATS (the Conceptual And Tiny Spectrometer), which is a novel highly miniaturised plasma analyser head, together with an unconventional detector for low energy electrons: a CCD (charged-coupled device). CATS offers the unique ability to study simultaneously multiple energies of electrons and ions using extremely compact electrostatic optics, allowing for very rapid sampling of plasma energy distributions. Specially processed CCD detectors offer a sensor that can potentially detect both electrons and ions simultaneously and without the high voltage and high vacuum requirements of the detectors conventionally used in low energy plasma instruments. PoleCATS used these components to produce an instrument capable of analysing the fluxes and energies of electrons above 75 km altitude.

Instrumentation based on this combination of CATS and the CCD provides an attractive low-resource solution for a range of space plasma applications, and the technology developed for the PoleCATS project has the potential to drastically improve upon the current generation of space plasma instruments. The likely performance increases and the highly miniaturised design would allow them to be flown on very small-scale missions such as nano- and picosatellites.

Here, we present the results and information gained from the flight in May 2013, including the performance of the analyser, sensor, electronics and mechanical design and lessons to be learned about the design of a future instrument based on our recorded data.

Key words: REXUS; PoleCATS; detectors.

1. INTRODUCTION

The REXUS (Rocket EXperiments for University Students) programme allows teams of students from across Europe payload space on a dedicated sounding rocket. The experiments are launched on an unguided, spin-stabilised rocket powered by an Improved Orion Motor with $290\,\mathrm{kg}$ of solid propellant. It is capable of taking $40\,\mathrm{kg}$ of student experiment modules to an altitude of approximately $90\,\mathrm{km}$. The vehicle has a length of approximately $5.6\,\mathrm{m}$ and a body diameter of $35.6\,\mathrm{cm}$.

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

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

REXUS and BEXUS are launched from SSC, Esrange Space Center in northern Sweden.

The PoleCATS experiment was designed and built by a team of science and engineering students based at multiple institutes, mainly within the UK. The hardware was developed at the Mullard Space Science Laboratory of University College London. Since the population of energetic electrons at the altitude of REXUS 14 was highly unlikely to be sufficient, the development for the experiment was carried out as part of the development for a potential future plasma measurement mission.

2. CATS

The Conceptual And Tiny Spectrometer was developed at the Mullard Space Science Laboratory as a PhD project to develop a novel plasma analyser for small satellite applications [1]. Athough it is based on a conventional cylindrical electrostatic geometry, the instrument is only approximately $2 \times 2 \times 1$ cm in size. Narrow channels mean it is capable of selecting energetic electrons and ions in narrow energy, azimuth and elevation bins, and also that its geometric factor is low. Its small size was motivated by the need for miniaturised instrumentation for CubeSats and other small spacecraft, and the need for low-resource plasma analysers.

Currently only one prototype model of CATS has been built. It has been used for all calibration and testing pre-flight [2]. During the instrument development it was discovered that there were some manufacturing defects within this model; since calibration was only valid for this version, and because of the expense and robustness of the device, manufacturing another was not considered.

In the operation mode used in PoleCATS, a scale of voltages would be put across CATS in succession so that the full range of electron energies from $1\,\mathrm{keV}$ to $8\,\mathrm{keV}$ could be sampled in 40 energy bins.

3. THE CCD

While in a satellite instrument, the choice of detector to use with CATS would be more likely to be an MCP or similar, this would create several difficulties in a rocket environment. Far higher voltages and cleanliness would be required, and in the low-altitude, short flight-time of REXUS, the risk of arcing would be too severe. Instead a specialised position-sesitive, solid state detector was used, which has previously been used for testing and calibration of the CATS setup.

The CCD (Charge-Coupled Device) used in the PoleCATS instrument is an e2v CCD64-00 x-ray CCD sensor, a spare special-order CCD from the SXI instrument for the GOES programme [3]. The back-illuminated version was tested with CATS and has been shown to be capable of detecting electrons down to energies of $500\,\mathrm{eV}$. Although the CCD would not be capable of detecting ions at these energies, the population of ions was expected to be far lower than that of electrons, and the ion channels would be used purely for light-level calibration.

4. PREVIOUS CALIBRATION AND TESTING

CATS has been tested first using an MCP and later calibrated more accurately with a CCD, where the particle source was an electron gun.

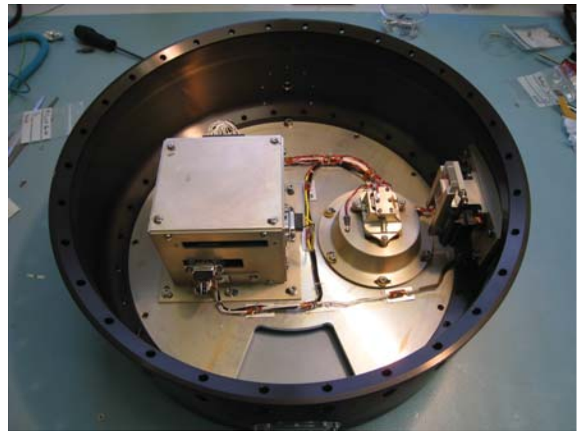

Figure 1. The experiment in the module prior to flight.

The setup used a back-illuminated CCD64, together with the engineering model readout electronics from the INTEGRAL-OMC instrument. The combination of CCD and CATS mounted together was tested in a vacuum chamber with a basic nitrogen cooling system and an electron gun producing particles of up to a few keV. The response of the CATS and CCD setup was measured for a range of azimuth and elevation for impinging particles; these results were used in designing the mechanical setup as well as data analysis in PoleCATS.

5. FLIGHT INSTRUMENT DESIGN

Since all subsystems from the laboratory-based setup were bulky and relatively high-resource, the challenge for the design was the miniaturisation and flight-readiness of each component: CCD control and readout; HV production and control; power supply; data flow and storage; interface to the service module; hatch control; and thermal control. All these systems together ready for flight are shown in Fig. 1.

The high voltage part of the experiment was only to be switched on at over $75\,\mathrm{km}$ altitude, to reduce as far as possible the risk of arcing across the CATS channels. In addition, the hatch system was designed to protect the instrument from hot air at launch and re-entry, and was only opened when the instrument was operating in 'electron detecting' mode. However, the CCD was on and recording data from the experiment switch on at T-600s until experiment switch off at re-entry.

5.1. CATS operations

The voltages across CATS were between 0 and $450\,\mathrm{V}$, with one CCD frame readout at each voltage level.

A slow readout plan for the CCD was used; similar to TDI (Time Delay and Imaging), where the CCD was read out line-by-line over the time period of the readout. Each line was readout, placed in data storage and other tasks were performed before the next line was addressed. This allowed a linear increase in integration time over the height of the CCD, and would allow a separation of time-based and electronics-based noise sources.

Since the channels of CATS cover only a small area of the CCD, only the relevant region and a surround calibration area was read out and stored; a total area of 200×300 pixels. Although it was planned that the rate of image readout should be 1 to 10 frames per second, in the flight readout of each frame took up to $2.4\,\mathrm{s}$.

5.2. Electronics design

The format of the electronics box was similar to that of 1U of a CubeSat, using the PC104 form factor for the boards. Four boards were used, including one for low voltage supply; one for HV generation, using PWM (pulse width modulation) control; one for interfacing with with the service module and telemetry; and one for control and data handling.

A PIC24 was used as controller to run the driver for the CCD and other subsystems, and data storage was planned to use two SD cards - although only one was flown. Only housekeeping data was downlinked during flight and the rest recovered on the return of the module to Esrange.

5.3. Thermal control

The setup in the vacuum chamber used a steady nitogen supply to cool the sensor from the back of its mounting. This was both inefficient and impractical for the REXUS platform. While an optimal setup might have included a nitrogen-based cooling system for a heatsink on the launchpad, this would not have been feasible within REXUS, and a thermoelectric cooler-based sytem was designed.

Two Peltier coolers were used, for redundancy, between the bottom of the CCD mounting and a heatsink which was insulated from the bulkhead of the module. In the original plan, the heaters would be turned on when the temperature of the CCD rose above $10°\mathrm{C}$ during flight, but the power required for this system caused the low voltage supply board to rapidly heat when the Peltier was on. Therefore, in the flight scheme, the Peltier control was set to switch them off when the supply board reading grew to above $50°\mathrm{C}$, and the requirement for the sensor to remain below $10°\mathrm{C}$ during the data-collecting part of the flight was relaxed.

5.4. Hatch system

Since hot gases at launch and re-entry might have damaged some parts of the instrumentation, and because uncovered openings in the rocket skin might have caused problems during the flight, it was decided to include an actuated hatch in the design of the experiment. Since it is transparent, light but not electrons would be able to penetrate and reach the sensor, allowing further calibration and image data while the experiment is not in ’electron detecting’ mode.

6. FLIGHT PERFORMANCE

During the flight all subsystems behaved nominally; the hatch opened and HV cycles ran at the planned points on the timeline. However an issue with the ground station prevented some signals and downlinked data from being viewed during flight; however, since no commmands were planned to be uplinked, this caused no problem with operations. The downlinked data was successfully stored for later viewing and the data from on-board storage was recovered soon after the flight.

7. DATA ANALYSIS

The frame data recovered from the SD card in the module contained all that was expected pre-flight, but not all as planned in the as-designed experiment. The CCD data are 12-bit, but corruption occurred during data readout or storage. The three least significant bits appeared to have been replaced by a regular series of ones and zeros and were discarded from the CCD data. The one most significant bit was also missing, being always zero, and an attempt was made to estimate this bit.

In addition housekeeping data was recovered in the form of temperature data from each of the electronics boards. An attempt had been made to take four thermal readings on and around the CCD, but during integration these were found to be faulty, and this was not possible to repair before launch. However, the low voltage supply board temperatures rose and fall during the Peltier cycles, showing that the coolers worked correctly during flight.

7.1. Frame processing

The three least significant bits were discarded as being relatively unimportant, but estimating the missing most significant bit was vital for futher analysis. A simple filtering system proved to be the most successful. Each line on the CCD would be addressed in turn: each pixel on it was compared to the three closest pixels in the row below and the value of the most significant bit was decided based on which value would bring the pixel closer to its neighbours. Since the lower rows in the frame were usually correct in having a null first bit and there were not expected to be very sharp edges in the data, by propagating up the frame in this way a good estimate to the correct data could be made.

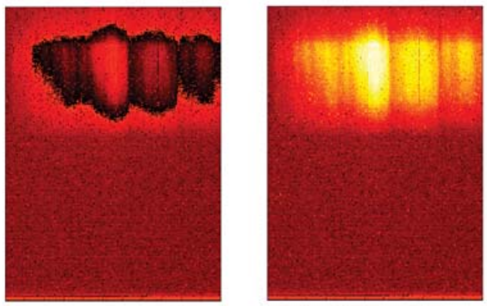

Figure 2. Example of a recovered frame, both pre- and post-processing.

By eye, this method, appeared to be very successful; only three frames did not respond well, and these were heavily saturated and could be either removed from further analysis or the beginning of the processing tweaked such that small errors at the start would not propagrate through the whole frame. An example of a frame processed this way is shown in Fig. 2.

However, it must be noted that the noise levels in many frames of the data were great enough, that some uncertainty must still remain on the best value of each pixel.

7.2. Qualitative analysis

It is clear from the obtained frames that the most significant contributors to the pixel signals are light and thermal noise. In this mission the light signal could provide information about the light reflectance through the instrument and the sensitivity of the CCD to photons, while at the times the instrument pointed away from any light source, the view was equivalent to that which would have been seen with near-perfect blacking.

Saturation of the image frame also occurred at certain points during the flight, in particular around lift off, where light conditions, and possibly fields were at their strongest. Noise levels could be seen to increase slightly around these times; it is known that the data line from the CCD would have been particularly susceptible to fields created both inside and outside the PoleCATS experiment.

7.3. Rotational behaviour

It can be seen from the changing light levels throughout the flight that the rotation of the rocket had a large effect on the light levels recorded in the images. The time between light pattern minima varies from around $14\,\mathrm{s}$ to $17\,\mathrm{s}$ during the flight, which can be compared to the rotational speed recorded by the REXUS service module of $16\,\mathrm{s/revolution}$ to $18\,\mathrm{s/revolution}$. These behaviours demonstrate the link between the flight trajectory and the experiment data.

8. LESSONS LEARNED AND CONCLUSIONS

From the recovered data, it is possible to list the major modifications that would be required to turn PoleCATS into a scientific instrument for example in a higher-altitude sounding rocket:

1. Careful choice of environment. An altitude of $50\,\mathrm{km}$ to $150\,\mathrm{km}$ higher would place the apogee in the auroral region, and the choice of a launch time with high solar activity, would allow a significant number of particles to be detected.
2. Further development is needed on surpressing light reflactions through the instrument. This would initially be attempted through a blacking process over the aluminium surface.
3. The cooling system must be redesigned to meet a harder CCD temperature requirement. The form this would take would depend heavily on the platform.
4. Analysis of CCD readout problems. The missing bits should be restored, and electronic noise should be reduced, with shorter cabling and inproved routing. A new CCD control may need to be implemented to increase the frame rate significantly.

Each of these items would fit within another development cycle of the instrument, and with a flight opportunity and interested development team, another experiment based on CATS and this, or a similar, CCD would be a feasible and worthwhile instrument for rapid, high-resolution measurements of dense, energetic space plasma.

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