DEPLOYMENT AND CHARACTERISATION OF A TELESCOPIC BOOM FOR SOUNDING ROCKETS

Johnalan Keegan\(^{(1)}\), Mark Wylie\(^{(2)}\), Stephen Curran\(^{(2)}\), Dinesh Vather\(^{(2)}\), Paul Duffy\(^{(2)}\)

\(^{(1)}\) Dublin Institute of Technology, Kevin Street, Dublin 8, Ireland, Email: spaceresearch@dit.ie
\(^{(2)}\) Dublin Institute of Technology, Bolton Street, Dublin 1, Ireland, Email: spaceresearch@dit.ie

1. ABSTRACT

In any sounding rocket, volume and mass are at a premium. Payload designers strive towards smaller, lighter and cheaper mechanisms which can achieve the same goals. This project aims to reduce the mass and volume for probe deployment booms and their deployment mechanisms. An experiment (Telescobe) to test a low cost novel method of boom deployment using telescopic carbon fibre poles was developed.

A custom camera measurement system was also developed to measure boom length and harmonic deflection. This experiment was flown onboard the REXUS 9 sounding rocket \([1]\) in February 2011 from Esrange space centre, Sweden. The experiment functioned as expected in all pre-flight tests. However, an unexpected malfunction in the experiment hatch door was experienced during flight which prevented the boom from being extended through the hatch. Despite this, it was found that the carbon fibre sections, all mechanisms and hardware, survived the flight and functioned as expected as far as possible. It is hoped that with a redesigned hatch, the experiment can be re-launched onboard a future REXUS rocket.

2. INTRODUCTION

Telescobe is an experiment, developed by postgraduate and undergraduate engineering students from the Dublin Institute of Technology (DIT), Ireland. The aim of the Telescobe project was to design, build and fly a telescopic boom system capable of being used to deploy E-Field and Langmuir probes for use in upper atmospheric research. A telescopic boom system potentially makes more efficient use of the available space and mass onboard a sounding rocket when compared with other boom systems.

The Telescobe experiment was developed as part of the REXUS/BEXUS programme. The REXUS/BEXUS programme is realised under a bilateral Agency Agreement between the German Aerospace Centre (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 collaboration with the European Space Agency (ESA). Funding for the project was provided by the Dublin Institute of Technology, Enterprise Ireland and Acra Control Ltd. The campaign began in January 2010 and ran until the launch in February 2011.

3. SCIENTIFIC BACKGROUND

Measurements of the Earth’s magnetic field and the atmospheric plasma electron density are typically taken using E-Field and Langmuir probes respectively. To take accurate measurements, these probes are extended out from the spacecraft so that they are clear of any wake turbulence or electromagnetic fields created by the rocket. They can be used in single probe and multiple probe configurations. When used in a multiple probe configuration the relative positions of all the probes must be known for accurate measurements to be taken.

There are a number of different systems available to deploy these probes. Probes extended from spacecraft by wires are compact and light weight. However the spacecraft must be spinning as centrifugal force is utilised for deployment. These probes are also prone to oscillation as they extend. Single rigid booms extended from spacecraft can support larger probes and are less prone to oscillation. However, this design does not lend itself to efficient use of the payload volume available. Folded booms are another option. However, they can also require a significant amount of storage space and the addition of hinges and motors also adds further mass and volume. A typical configuration using folded booms is shown in Fig. 1.

Figure 1: Typical folded boom sections for E-Field probes \([2]\).
An effective telescopic boom system offers a more efficient use of the storage space and potentially a reduction in the overall mass. It can also take advantage of the centrifugal force generated by a spinning spacecraft to deploy, but it does not solely rely on this for deployment. By using a spring loaded configuration, the deployment time of such boom configurations is greatly reduced. This is ideal for short flight sounding rockets.

4. PROJECT AIMS

The primary objectives of the Telescobe project were:

- To design and build a telescopic boom, boom deployment and boom jettison system.
- To safely test this system on a near-space flight aboard the REXUS 9 sounding rocket [1].
- To monitor and record boom deployment length, boom vibration characteristics and boom jettison.
- To collate, analyse and disseminate experiment data via presentations and publications.
- To promote the activities of the Telescobe team, DIT and the REXUS/BEXUS program through an outreach program.

Performing electric field measurements did not fall within the scope of the experiment. Instead a mock probe, housing an accelerometer and six LEDs, was fitted to the end of the telescopic boom. This probe was used as the datum point for measurement.

5. EXPERIMENT OVERVIEW

The Telescobe module, shown in Fig. 2, is 220 mm in height and has an internal diameter of 348 mm. An exploded view of the experiment can be seen in Fig. 3. The boom is made from tapered carbon fibre sections and, during the flight it is stored in a PEEK housing inside the experiment. A foam cap is used to prevent the boom from being damaged by excessive vibrations during lift-off.

At a designated time during the flight, a hatch in the skin of the rocket opens. Three seconds later, a pyrotechnic guillotine fires, cutting a nylon cable that retains the boom in its stored position. Two tension springs on either side of the boom housing then deploy the boom out through the hatch. The foam cap is pushed out with the boom and then falls away from it as it is in three sections.

When the boom is deployed, cameras are used to measure its length and an accelerometer is used to quantify any vibrations. After the payload has gone past the flight apogee, a second pyrotechnic guillotine fires, cutting a nylon cable that secures the base of the boom to the experiment. The remaining tension in the two springs then jettisons the boom from the experiment.

The boom falls to ground and the hatch closes, preventing hot air from entering the module during re-entry. The timeline for the experiment during the flight is shown in Tab. 1.

![Figure 2: The complete experiment module](image)

![Figure 2: An exploded view of the experiment module with important parts labelled](image)

<table>
<thead>
<tr>
<th>#</th>
<th>Event</th>
<th>Time (s)</th>
<th>Altitude (km)</th>
<th>Approx.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lift-off</td>
<td>0.0</td>
<td>0.332</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Motor Separation</td>
<td>77.0</td>
<td>~ 64.7</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Hatch Opens</td>
<td>80.0</td>
<td>~ 67.0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Boom Deploys</td>
<td>84.0</td>
<td>~ 69.0</td>
<td></td>
</tr>
</tbody>
</table>
6. EXPERIMENT DESIGN

6.1. Boom

The boom is manufactured from tapered carbon fibre sections. The sections are stored one inside the other when the boom is in its stowed position. The largest section has a maximum outer diameter of 55 mm and an average wall thickness of 1.5 mm. The smallest section has a maximum outer diameter of 20 mm and an average wall thickness of 0.5 mm. When extended, the boom locks out with a 20 mm interference fit between each section. The largest boom section is bonded into a cylindrical aluminium sleeve which slides in the boom housing, shown in Fig. 4. Pre-flight, all of the boom sections are collapsed and retained in the boom housing.

![Boom Housing Diagram](image)

**Figure 3: Boom housing with pyrotechnic guillotines**

6.2. Boom deployment and jettison mechanism

Two pyrotechnic guillotines are used to initiate boom deployment and boom jettisoning. When they are subjected to an electrical current of greater than 0.85 A for longer than 15 ms the pyrotechnic charge inside the devices detonates. The rapidly expanding gases then push the guillotine which cuts through a nylon cord (Cypress parachute cord).

Two tension springs, shown in Fig. 4, attach to the pushing cup shown in Fig. 5A. When the boom is loaded it is held in position by a nylon cord as shown in Fig. 5A. This cord passes through a pyrotechnic guillotine and is anchored to the boom housing.

When the first pyrotechnic guillotine is activated it cuts this nylon cord. The boom sleeve and boom sections are then accelerated forward by the springs. After they have travelled 100 mm, the slack in a second nylon cord is taken up and the boom sleeve and largest boom section come to a dead stop. However, all of the other boom sections keep moving and lock out into one another, fully extending the boom. This is shown in Fig. 5B.

To jettison the boom, the second guillotine is activated. This cuts the second nylon cord. The remaining tension in the springs then jettisons the boom from the experiment module as shown in Fig. 5C. Four, highly flexible cables also pass up through the boom. They are connected with rest of the experiment module through a Winchester plug at the back of the boom housing. When the boom is jettisoned, this disconnects so that the cables are jettisoned along with the boom and there is no risk of any short circuits occurring inside the experiment.

6.3. Probe

A three axis accelerometer (Analog Devices ADXL345) and an array of six LEDs are mounted on a printed circuit board (PCB) that is placed in the probe fitted to the distal end of the boom. It measures the acceleration profile of the boom during deployment and is used to determine the frequency of vibration of the boom when it is deployed. The LEDs (Thorlabs LED661L) emit...
light at a wavelength of 655 nm and are lensed to direct this light towards the measurement cameras. Four flexible single core cables pass through the boom. Two of which carry 3.3 V and the ground signal connections for the LEDs and accelerometer. The other two facilitate the transmission of the clock and data signals for an I2C bus.

6.4. Cameras

Three cameras are used in the experiment. They are mounted on custom designed camera brackets. The camera brackets mount directly to the inside skin of the module. A float glass window with an extended temperature range is mounted in the camera bracket parallel to the camera lens. This allows the camera to gather light from outside the rocket while preventing hot air from entering the module through the hole in the skin. This assembly can be seen in Fig. 6.

Figure 6: Camera and camera bracket

Two of the cameras are measurement cameras (SONY XC-ES50) and are used to precisely measure the length of the boom when it is fully deployed, as well as the magnitude of any boom deflection. They are both fitted with a compact fixed focal length lens. A narrow band pass filter is fitted to each lens. The filters will only allow light with a wavelength of 655 nm to pass through it. Filtering out most of the superfluous light allows for better frame compression and makes it easier to acquire relevant information from the video frames during post-flight analysis. An image of the probe captured by one of the measurement cameras is shown in Fig. 7.

Figure 7: The LEDs in the probe, as seen by one of the measurement cameras

6.5. Hatch

The experiment has been fitted with a hatch to allow the boom deploy through the skin of the rocket and prevent hot air from entering the experiment during ascent and re-entry. The hatch consists of guide rails, a door and a spring return rotary solenoid. The solenoid is connected to the door using a link arm. The hatch is powered from the same power source as the pyrotechnic guillotines. A pulse width modulation (pwm) solenoid driver is used to control the flow of electrical current to the solenoid. When power to the solenoid is switched on, 2.2 A flows into it, opening the hatch. Because of power consumption limitations, after 1 second, pwm mode begins and the current flowing into the solenoid is reduced to a 350 mA “holding” current.

6.6. Flight computer and frame grabber

The flight computer is a PC/104-plus CPU module (Eurotech ISIS XT). It is a fanless design that instead incorporates a large heatsink which is in contact with the aluminium skin of its enclosure. This dissipates the waste heat generated. The computers operating system, all the flight telemetry and images acquired from the two measurement cameras are stored in the internal 2 GB memory. For additional security, the flight telemetry and camera images are also stored on a 2 GB industrial grade SD card. The ISIS-XT has an I2C bus interface which is used for interaction with the accelerometer. The built in RS422 port is used during flight to transmit selected telemetry information, through the rocket service module’s telemetry system, to a ground station. It also has digital I/O ports available which are used to read the status of control signals from the rocket service system.

The framegrabber is a PC/104-Plus type MPEG encoder module (Eurotech CTR1475). It connects directly into the PC/104-Plus bus of the flight computer from which it draws its power. The frame grabber has the ability to take images from up to four analogue cameras, digitise them, and compress them into MPEG4 format.
6.7. Power management and distribution

Power is supplied to the experiment at 24-36 V from the Rocket Service module. However, the various experiment sub-systems require power to be provided at 12 V, 5 V or 3.3 V. To achieve this, a power management board is used (Eurotech ACS5151). Power is supplied at 12 V, 5 V and 3.3 V to the power distribution and switching PCB for use by the other experiment sub-systems.

Power for the pyrotechnic guillotines, as well as the hatch, is supplied from an independent rocket service module interface to that of the rest of the experiment. This power is only switched on at a designated time during the flight. The experiment receives three control signals from the rocket service module. The first of these is received at lift-off. If the LO signal is not received, guillotines cannot fire. The other two control signals, (SODS and SOE), are switched on at pre-programmed times during the flight. Each of these control signals is linked to one of the pyro guillotines and is used as the final trigger for initiating boom deployment or jettison.

6.8. Experiment Control Software

The flight computer runs Windows Embedded as its base operating system. The experiment controller application was written in Python 2.6. The experiment controller is implemented as a modified state machine with states for initialization, start, ascent, deployment, jettison and finalisation. A graphical representation can be seen in Fig. 8.

![Experiment controller state machine diagram](image)

Figure 5: Experiment controller state machine

A summary of the states is given below:

- **INIT**
  This is first set of commands executed by the experiment controller on system boot. All initialisation is done in this state including memory storage, data acquisition parameters and communication protocols. Once all parameters and subsystems are set up correctly the system immediately transitions to the **START** state.

- **START**
  This is a waiting state. The system is ready for launch. Telemetry and logging are active throughout this state. On receipt of the lift-off signal from the rocket service module the system transitions to the **ASCENT** state.

- **ASCENT**
  In this state a control timer is started to control transition into the next state in which the camera frames are recorded. The timer is set to trigger state transition at T+74 seconds, 10 seconds before boom deployment. As a failsafe the SODS signal from the rocket service module, which triggers boom deployment at T+84s, is also monitored. On receipt of either the timer signal or SODS signal, the system transitions into the **DEPLOY** state.

- **DEPLOY**
  On entry to the **DEPLOY** state a camera timer is started and both onboard measurement cameras start recording frames to onboard storage. This data is subsequently used to determine the deployed length of the boom. Frames continue to be recorded from both measurement cameras until detection of the SOE signal from the rocket service module at T+210s. At this point the system transitions into the **JETTISON** state.

- **JETTISON**
  On entry into this state both cameras and accelerometer acquisition is switched off. Once this is complete the system immediately transitions into the **FINALISE** state.

- **FINALISE**
  In the **FINALISE** state the final log entries are made and all log files are closed. At this point all data files are backed up to the SD card as a safety precaution in the event that the internal memory of the CPU is damaged on landing. Once this is complete the state machine exits the main loop and sends a ‘Goodbye’ signal to the ground station before execution is stopped.

6.9. Telemetry

The telemetry is sent to the ground station via the rocket service module through an on-board RS422 connection. Throughout the experiment, four types of telemetry messages are sent in the packets to the ground station. The **Session** packet contains a 6 byte code to signify a unique session string for each run of the experiment. This is used to correlate different sets of data files with those received at the ground station during pre-flight tests and the actual flight. The **Housekeeping** packet holds the status information for the entire experiment. It
wraps a message consisting of two bytes of data which encode the states and status information of the experiment controller and related sub-systems. The **Accelerometer** packet wraps a 6 byte representation of the current sample from each of the x, y and z axes registers. The **Goodbye** packet contains a 6 byte message to signify that the experiment controller and all sub systems have reached their finalised state successfully and are ready to shut down. This is the last message sent to the ground station and is used to indicate that the telemetry is about to stop.

**6.10. Ground Station:**

The ground station software is again written in Python 2.6. The job of the ground station is to parse the telemetry stream received from the rocket and display the current status of the experiment as well as a realtime display of the accelerometer samples.

**7. THE FLIGHT**

The Telescobe experiment was launched on 22nd February 2011, on the REXUS 9 sounding rocket. All experiment systems passed pre-flight checks and were deemed operational pre-launch. However, an unforeseen event occurred during the ascent phase of the flight which caused one of the experiments components (i.e. the hatch) to malfunction. This prevented the telescopic boom from deploying. During the flight, all of the experiments software and electronic systems functioned as expected and telemetry data was received at the experiment ground station. Data was obtained from the accelerometer and images from the two experiment measurement cameras were recorded. Mechanically, the boom deployment system worked, as in, the pyrotechnic guillotines fired, cutting the deployment cable and firing the boom forward. This was also true for the jettison. When the payload was retrieved after landing, the experiment was still operational and data was obtained from the onboard SD card. Ultimately the hatch failure was deemed responsible for the experiments failure.

**8. POST-FLIGHT ANALYSIS**

**8.1. Hatch failure**

A foam cap supported one end of the telescopic boom to prevent it from being damaged by vibrations during the launch. Friction held it in position. During the ascent stage of the flight, the centrifugal forces generated by the spinning rocket caused the cap to move towards the hatch door. After rocket was de-spun, the foam cap was still in contact with the hatch. Then, when power was switched on to open the hatch, the hatch door only half opened, jammed by the foam cap. When the signal for deploying the boom was subsequently received the boom deployed against the hatch door. This problem may have been prevented if the foam cap was retained more robustly but this issue was not anticipated before the flight. Most crucially, the late design and assembly of the hatch meant that the experiment was not spin tested with a loaded boom and a fully assembled hatch.

Other issues may also have contributed to the malfunction. The electronics for controlling the hatch were short-circuited before the launch by an incorrect cable. The experiment was partially disassembled to repair this. This caused the plastic foam cap to move 2-3mm from its normal position towards the hatch door. This was never seen before but was deemed acceptable by the team at the time. Also, an issue during the countdown meant that the rocket was unexpectedly elevated outside for approximately two hours. This caused the temperature inside the rocket to drop well below 0°C. While many parts of the experiment were tested in a sub zero environment, the hatch and foam cap were never tested at these temperatures and the effect that this might have had on it is unknown. Finally, during post-flight tests it was discovered that cycling the power to the hatch so that it would receive more than one initial current spike would most likely have fully opened the hatch. Therefore, putting in a sensor to detect if the hatch was fully opened and, if not, to cycle the power to the hatch, may also have avoided the failure.

**8.2. Analysing camera images**

Images recorded by the experiments measurement cameras, such as that shown in Fig. 7, are read into Matlab to be analysed. They are then filtered and eroded to give an image similar to that shown in Fig. 9. The position of the centroid of each of the white areas is then found and, from this, the co-ordinates of the centre point of the probe are found. This can then be compared with a set of calibration data to give the co-ordinates of the centre point of the probe relative to the rockets co-ordinate system. However, as the boom did not deploy during the flight there were no images to perform useful post-flight analysis on.

*Figure 6: A filtered and eroded image obtained from one of the measurement cameras*
8.3. Other post-flight analysis

Both the onboard flight log and ground station event log can be inspected visually as they are recorded in plain text format. For analysis of the accelerometer data the python Scipy and MatPlotLib libraries are utilised. The telemetry byte log is parsed using Python.

9. RESULTS

Although the boom did not deploy fully as expected, examination of the accelerometer data shows that, had the hatch not obstructed the boom deployment, it would have deployed as expected. Fig. 10 shows the acceleration profile of the probe during the flight.

![Probe Accelerometer Profile](image)

*Figure 7: Probe Accelerometer Data from T-5s to T+210s*

A magnified view of the accelerometer data from T+65s to T+88s is shown in Fig. 11. It can be seen that there are acceleration spikes at T+69.8s, T+80.15 and T+84s. These times correspond to nosecone ejection, hatch opening and boom deployment respectively.

![Probe Accelerometer Profile](image)

*Figure 8: Section of Probe Accelerometer Profile from T+65s to T+88s*

The fact that there is an acceleration spike at hatch opening verifies that the probe must have been in contact with the hatch door at this time. Acceleration spikes at boom deployment and boom jettison verify that the boom pusher cup was still held in the required positions prior to the firing of the pyros and moving forward each time each of the pyros were activated.

10. CONCLUSION

The hatch on the experiment module failed to open fully during the flight. This was ultimately responsible for the failure of the boom to deploy. A thorough and careful post flight analysis was carried out to determine the cause of this failure. The conclusion was that foam cap that protected the probe during lift-off moved against the hatch door during the flight and caused it to jam. This could have been avoided by better retaining the foam cap or by incorporating active feedback into the hatch that would detect if it was not fully open and then take corrective action such as cycling the power supply to it.

All of the other experiment systems functioned as expected, as far as possible, during the flight. Accelerometer and telemetry data was retrieved from the experiment and, from this data, it is believed that the experiment would have performed as expected had the hatch failure not occurred.

The experiment was retrieved completely intact after the flight. As such, it is intended to apply for a re-flight onboard a future REXUS sounding rocket with a modified hatch.

11. REFERENCES
