In-Orbit Performance of AstroTube™: AlSat Nano’s Low Mass Deployable Composite Boom Payload

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ABSTRACT
This paper reports on the in-orbit performance of the longest retractable boom (OSS’ AstroTube) that has ever been deployed and retracted from a 3U Cubesat. AstroTube is hosted by AlSat-1N, a 3U technology demonstrator CubeSat collaboration between the space agencies of the UK and Algeria. Agile development of the boom payload saw it progressed to TRL6 in less than 20 months; further platform-level integration and testing through to launch were completed within 30 months. AstroTube combines novel, proprietary materials and proven actuation principles to deploy a low mass 1.5m-long 1-DOF motion structure. It incorporates a novel deployment mechanism for actuation and a flexible composite structure for the boom element. The boom element possesses very low length-density with tuneable bending and torsional stiffness characteristics. The boom payload is housed within a 1U volume and has a total mass of 0.61kg. A brief description of the payload and the test campaign is provided together with relevant results from this project phase. The AlSat-1N platform carries high definition cameras (supplied by the Open University in UK) which enabled visual confirmation of successful boom commissioning and deployment. Relevant data and high definition in-orbit images are also provided in this paper.

INTRODUCTION
Space missions often require a payload to be positioned and supported away from the main body of a spacecraft; obvious examples being that of a magnetometer or to deploy and support helical antenna systems. However, the challenges presented by the cubesat form factor means that deployable elements, although highly desired, are often compromised by the stowage volume available. This paper covers the development and on-orbit evaluation of AstroTube, a highly stowage efficient, scalable and retractable boom system that could be used in a variety of deployable payload applications and in so doing so, unlock the potential of smaller form factor spacecraft.

ASTROTUBE DESIGN DESCRIPTION
The boom payload of the AlSat-1N 3U platform comprises the following sub-systems:

- 1.5m long extendible rolled composite boom, boom mechanism, and associated controller PCB.
- Magnetometer and associated electronic circuit
- 2x RADFET (Radiation-Sensing Field-Effect Transistor) and associated electronic circuit

The extendible element of the boom is a 20mm diameter open-section flexible composite member with a 224° subtended angle and 0.3mm thickness. Epoxy-based plain weave carbon fibre prepreg has been used in the manufacturing of the boom due to its low outgassing characteristics and relatively high radiation tolerance, consistent with space environment requirements. The boom element can be fully deployed or only partially deployed; it can be retracted from any of these two states with a rotary encoder providing an indication of deployed length: this makes it the first retractable boom ever to be deployed from a Cubesat.

Figure 1: Flexible Composite Member similar to that used by AlSat-1N’s AstroTube
The magnetometer sub-payload is based on fluxgate magnetometer with driving analogue circuits and high precision/high speed 20 bit ADC.
The RADFETs (Radiation-Sensing Field-Effect Transistor) are microminiature silicon pMOSFET transistors which act as an integrating dosimeter, measuring dose in rad or Gy(Si) by virtue of the field effect caused by space charge trapped in an inorganic insulator (SiO$_2$). The radiation-induced charge remains stored for many years.

The boom payload and sub-payloads fit within a standard 1U Cubesat platform volume and its weighed total mass is 0.61kg.

**Mechanical Design**

The mechanical components are manufactured using Alumoweld aluminium 6082T6. Delrin-acetal was used in all components interfacing with the composite boom due to the low and repeatable friction characteristics of this interface as a low contact friction alternative. The payload consists of two 1.6mm thickness FR4 PCBs. The controller PCB drives the operation of the boom mechanism and the upper PCB regulates the operation of the magnetometer and the RADFETs. The main structural components of the boom payload are the front plate and the mechanism retention plate. A stiffener bracket connecting the front and back plates has been included to ensure the distance between these two components is preserved under transient mechanical loading. This bracket also increases the stiffness of the assembly considerably. Separation between the PCBs and between the controller PCB and the interface bracket is achieved via GRP stand-offs.

In the current mission, the boom is deployed along the Nadir pointing +Z axis. Figure 2 shows the payload and its axis definition.

![Figure 2: Boom payload geometry and axis definition](image)

From its stowed configuration the boom deploys through the retention cone: a conical-surfaced acetal component that houses the boom end plate during launch and during fully-stowed modes. Two boom trim plates are located in the retention cone as depicted in Figure 3. These trim plates allow adjustments to the orientation of the boom to ensure deployment occurs perpendicular to the XY plane. Inevitably some friction will be experienced between the boom and the trim plates and for this reason acetal has been selected for their construction.

![Figure 3: Boom retention feature and trim plates](image)

**Electronics Design**

The boom payload PCBs consist of a primary system & a redundant secondary system with independent sensing circuits, data storage and power supplies. The 1C spacecraft interface is the primary link with the OBC for both primary and sub-payloads.

The primary system consists of a STM32F429 series microcontroller running at a maximum clock rate of 180 MHz, a 64 MB NAND flash, an 8 MB SD RAM, the primary motor control, three 20 bit ADCs running at a maximum rate of 1 MSPS, and switches to control the sub-payloads. The 5V rail from the spacecraft interface powers the motor control circuits and the 20 bit ADCs, while the rest of the systems are powered by 3.3V rail. The primary system is switched on by the spacecraft switch 1. The MCU has 12 bit ADCs, 16 channels programmed to run at 200 ksps which is used for internal current monitors, temperature monitors, calibrations and performance monitoring. The clock speed of the MCU can be changed according to the current task. The MCU and RAM combination will perform FFTs and different types of data compression, based on the type of data collected. A high precision rotary encoder monitors the position of the boom. The encoder is self-calibrated with 2 end stops at the stowed position.
and deployed position of the boom. The controller PCB can also connect to an external GPS if available.

**Figure 4: Boom Payload PCB**

The redundant system consists of a STM32L151 series microcontroller running at a max clock speed of 32 MHz, 64 MB NAND flash, redundant boom motor control and power switches to control various sub payloads. The battery rail from the spacecraft interface powers all the systems through a switch mode regulator. The redundant system is switched on by the spacecraft switch 2. The MCU has 12 bit ADCs, 16 channels programmed to run at 50 ksp which is used for internal current monitoring, temperature monitoring, calibrations and performance monitoring. The clock speed of the MCU is changed according to the current task to minimise power drain on the spacecraft bus. The MCU can perform a limited data compression.

**Mechanism Design**

The boom mechanism is a positive drive system which guarantees deployment of the flexible composite member by engaging a multi-peg cog into the composite boom holes. The expected peak deployment torque is approximately 130Nmm and the expected peak retraction torque has been estimated at 200Nmm. With the current worm and transmission design this leads to a minimum required operational output torque of approximately 26Nmm for stowage and 17Nmm for deployment. With the current 5V drive system, a stall torque of approximately 60Nmm is expected. This provides a margin of 3.5 during deployment and 2.3 for stowage.

**Accommodation**

The boom and sub-payloads fit within a 1U volume and interfaces mechanically with the platform via two Al6061T6 brackets consistent with the current Cubesat standard. Access to the mounting holes of the payload is available by virtue of the PCB standoffs and the separation between the controller PCB (lower) and the bottom mounting bracket. The integration of the payload to the platform is achieved via eight M3 screws that secure the unit to the platform structural frame. The payload itself is supplied as a standalone unit bounded by two Al6061T6 brackets. The main structural components (e.g. the back plate and the front plate) are attached to these brackets via another eight corner M3 screws which do not interface with the rest of the platform. The torque levels ensure there is no slipping or gapping between the unit and the mechanical interface during launch.

**QUALIFICATION TEST CAMPAIGN**

In order to meet stringent budget and project time constraints consistent with a Cubesat development, AstroTube underwent only functional testing prior to platform integration and formal qualification testing.
Platform integration and qualification testing took place at Surrey Space Centre in the UK.

From a boom perspective, the tests relevant to the boom consisted primarily of the following:

- Platform functional testing prior to environmental testing
- Thermal cycling testing
- Deployment and retraction testing at expected in-orbit operational temperatures
- Vibration test campaign

After every environmental test, a functional test consisting of boom deployment, retraction and monitoring of actuation and encoder currents was conducted. Drawn current was recorded during pre and post environmental testing as well as deployment and retraction times. These parameters were used as health monitoring and check of the payload at every stage of the qualification campaign.

The complete set of qualification tests went far beyond what has been described herein and was in line with a “New Space” project development approach. A successful launch and subsequent in-orbit operations demonstrates the robustness and effectiveness of the qualification campaign devised for this low-cost project.

**On-Ground Testing**

The AstroTube boom Engineering Qualification Model was subjected to repeated deployment and retraction bench tests to ensure the current values of the encoder and deployment motor were consistent from one cycle to the next (Figure 7). Calibration tasks and current limits (to account for torque margins) and other settings (such as command time-outs) were also established during this stage of development. The boom can be commanded to initiate and stop deployment at a predefined length and retract at any point during boom operations. Alternatively, the boom can be commanded to deploy fully in steps or through a single command operation. Knowledge of boom position is maintained via the rotary encoder. Should the rotary encoder fail, or knowledge of boom position be lost, a mechanical stopper attached to the end of the boom within the actuation mechanism overloads the motor and triggers its stall current thereby enforcing termination of deployment command and preventing damage to the boom and its dispensing mechanism.

![Figure 7: Full deployment (1.5m) bench test of the AstroTube FM](image)

After ten deployment and retraction cycles, AstroTube showed consistent current demands in the 5V line and consistent deployment and retraction times. These are provided in Table 1 for a test temperature of 22°C. Time histories of current drawn during boom deployment and retraction in laboratory conditions are shown in Figure 8 and Figure 9 respectively.

![Figure 8: Current demand during deployment in laboratory conditions (approximately 22°C)](image)
Figure 9: Current demand during retraction in laboratory conditions (approximately 22°C)

Table 1: AlSat-1N’s AstroTube boom on-ground deployment test results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Deployment</th>
<th>Retraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave. current [mA]</td>
<td>151</td>
<td>193</td>
</tr>
<tr>
<td>Ave. duration [s]</td>
<td>176</td>
<td>198</td>
</tr>
</tbody>
</table>

Results from Platform Thermal Cycling

Thermal cycling of the EQM was conducted at platform level for five different environmental temperatures ranging from -20°C to +48°C in five steps (including these limits). Boom deployment and retraction operations were performed at each temperature which enabled verification of the torque margins applied during bench tests and provided an indication of payload performance as a function of temperature. As expected, the power consumption of the boom increased during retraction and deployment at lower temperatures. Further experimental work revealed that the origin of this behavior was the viscous property of the lubricant in the drive two-stage gearhead. The current drawn from the 5V line is inversely proportional to temperature, as depicted in Figure 10.

Platform Vibration Test

The AlSat-1N AstroTube underwent vibration test qualification at platform level as per Reference 1 vibration levels for Cubesat-like mechanical platforms. Vibration analysis conducted during the early stages of development predicted a dynamic response of the payload which was within the design envelope of AstroTube. Some results were presented in Reference 2 which demonstrated the suitability of the payload to withstand the transient mechanical loading conditions expected during launch. This was further corroborated during EQM qualification testing at SSC. Images illustrating the location of three unidirectional accelerometers are provide in Figure 11 and Figure 12. Unfortunately, a full analytical-to-experimental correlation is not possible due to the analysis being conducted at payload level and the test results are only available at platform level. Although this entailed some known risks, (consistent with “New Space” projects) the benefits on cost and schedule far outweighed the calculated probability of payload on-ground malfunction.

Figure 11: Unidirectional accelerometer (R) attached to the end plate of the boom

Figure 12: Unidirectional accelerometer bonded to the structure in the AstroTube boom payload area
Prior to the vibration test taking place, a reduced functional test (e.g. three deployment and retraction operations) was conducted and the current drawn from the 5V line was recorded. Average deployment and retraction current values before and after the vibration tests were obtained and compared, Figure 13. This reduced functional check provided an indirect indication of the health of the system throughout the test campaign.

**Figure 13: Pre and post vibration test deployment and retraction current demands**

**IN-ORBIT OPERATIONS AND PERFORMANCE**

AlSat-1N was launched from Sriharikota in a PSLV-C35 rocket carrying several other satellites. The satellite was launched on September 26th, 2016 into a 670-kilometre altitude polar orbit. The primary payload was SCATSAT 1, which was launched into a Polar Sun Synchronous Orbit. This was the first time PSLV launched satellites into different orbits.

**AstroTube Commissioning**

Upon reaching orbit, the AlSat-1N team in the UK and Algeria started the sequential commissioning of different systems within the spacecraft. The commissioning of AstroTube was completed approximately three months after launch. This consisted of partial deployment and retraction (~0.40m) of the boom under the highest achievable in-orbit temperature (as recorded by the temperature reference point in the control PCB).

Visual confirmation was possible due to the Open University’s high-resolution camera being fully operational by the time commissioning of the boom was underway. A high-resolution image of the boom during in-orbit commissioning (from the satellite’s perspective) is shown in Figure 14.

**Figure 14: Boom commissioning; AlSat-1N’s boom has deployed to and retracted from a 0.4m length**

**AstroTube In-Orbit Operation**

In-orbit operations of the boom followed from a successful commissioning phase. Initially, boom deployment was conducted in stages to ensure power supply maintained safe levels during this operation. Only partial data for current demand under full deployment is available at this point in time, depicted in Figure 15. In this figure, Stage 1 lasts for approximately 50s. This operation deploys the boom to a length of approximately 0.4m. Stage 2 deployment sees the boom going from a partial deployment to a fully deployed configuration (1.5m). However, this operation failed to be captured and only partial data is available. Nevertheless, visual confirmation of deployment is provided by the sequential deployment images captured in Figure 17 through to Figure 19.
Figure 16: Current demand recorded from the 5V line during a 4-stage sequential retraction

Figure 17: The boom has been deployed to 0.6m during the first stage of deployment operations

Figure 18: In this image AstroTube has been deployed to 0.9m

Figure 19: Image showing AstroTube deployed to 1.2m from the spacecraft

The current demands provided in Figure 15 and Figure 16 are for a temperature reference reading of approximately -3°C. Compared to the on-ground thermal cycling results it can be claimed that AstroTube has displayed similar behaviour to that shown during the qualification campaign.

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References