**CubeSat report rough**

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**Introduction**

-Growth of space industry

https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/space-the-1-point-8-trillion-dollar-opportunity-for-global-economic-growth

-Space Debris problem

-Interest in Demise

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-What will be covered in the report

The space industry plays a key role in modern society, driving technological innovation, supporting global communications and addressing challenges such as climate monitoring and disaster management. Satellites in orbit enable GPS navigation, weather forecasting and internet connectivity, all of which are deeply ingrained in daily life. Looking ahead, the industry is expected to grow rapidly, with projections estimating the market to reach nearly $2 trillion USD by 2035. Much of this growth is being fuelled by increasing involvement from the private sector and new markets in areas such as space tourism and asteroid mining. We’ve already seen some of this growth come to fruition, with SpaceX having launched over 4,000 satellites in the past five years for their Starlink Satellite constellation. Furthermore, we’re expecting to see the worlds first Space Hotel in the not-too-distant future – Voyager station is expected to open in 2027. With all this new interest Earth’s Orbit is going to become a much busier place.

However, this comes with its own set of issues. Global space agencies are already tracking over 25,000 objects in low earth orbit, with over half of it being classed as debris or rocket bodies. However not all objects are being tracked, with the European space agency estimating there could be 130 million space debris objects larger than 1mm in diameter. The source of this debris is often collisions or explosions of defunct satellites or rocket bodies left in orbit. Given this level of debris is only from 70 years of the developing space industry, it’s clear that the issue could compound uncontrollably if ignored– as described by the Kessler effect, where a chain reaction of colliding space debris leads to the accumulation of debris, eventually rendering low Earth orbits unusable for space missions due to the high risk of collisions with debris. This has led to an increased interest in re-entry dynamics as de-orbiting spent satellites or using reusable vessels has become more of a priority. Being able to predict how an object will interact with the atmosphere during re-entry is key to designing vessels with efficient demise, or that will survive re-entry for reuse or recovery. In the long term, this understanding could also be crucial to protecting the environment from potentially harmful materials that are released during re-entry.

The current understanding of how any specific material or geometry behaves in the hypersonic environment of re-entry is limited, as ground testing facilities can’t effectively replicate the high enthalpies and high speeds in conjunction with each other. Furthermore, facilities that are capable of high enthalpies are limited to short test times, meaning test models are limited to small sizes. The fixed nature of these tests does not allow for much or any change in orientation, so fails to accurately replicate tumbling that would be present during re-entry of a satellite of certain geometries.

This is the problem this project aims to address, by developing a commercially available CubeSat platform that allows for the standardised testing of heatshield materials in the hypersonic conditions of re-entry. In addition, the environmental impact of the material on the ionosphere will also be examined.

CubeSats are a modern standardised classification of microsatellites that make small space missions more cost effective through the use of standardised commercially available parts and services. Launch providers offer rideshare opportunities for different CubeSat geometries for a reasonable price, allowing many to be deployed in a single launch, often alongside the primary load. A CubeSats geometry is often described by its volume in the “U” unit, which roughly describes a 100mmx100mm cube, these units are then arranged in a variety of geometries, from the simplest 1U to the largest standard configuration, 12U.

For the purposes of this project, an 8U configuration in a 2x2x2 configuration is being proposed, as it provides a sufficient volume for the required hardware and heatshield materials whilst being symmetrical in 3 dimensions. This allows a tumbling condition to be assumed as there’s no equilibrium point, allowing for even exposure of all faces of the CubeSat to the freestream. Even exposure degrades all sides evenly, keeping the internals within their operating region for as long as possible while allowing multiple materials to be tested simultaneously.

Recession sensors placed within the test material will be used to measure the degradation of the ablatives during re-entry alongside a set of thermocouples to track temperatures on the inside faces of the heatshield. The Environmental impact of the materials will be examined by an optical spectrometer which will observe the emission spectra of the demising species within the hypersonic shock layer to quantify the contamination of different species in the ionosphere. This data will be transmitted back to Earth via the Iridium Satellite network, using Constructive interference from multiple antennae to direct a strong signal through the thin plasma layer formed at the back of the CubeSat.

The proposed launch date is December 2026, when space weather is predicted to be ideal for our mission and conforms with RocketLab’s - our chosen launch provider – timeline. The expected mission length is 20 days. The CubeSat will be deployed at around 400km altitude where it will perform a deorbit burn of its cold gas thrusters. At 200km measurements will start to be taken and transmitted via Iridium which will continue until demise or complete power drain. To ensure demise and eliminate the risk of dangerous ground impact, the CubeSat is fitted with a set of carefully placed thermite charges. They will self-ignite at a certain design temperature independently of any other system, destroying the internal structure apart, allowing individual parts to demise on their own. Thermite ignition is expected at around 40km altitude.

This report will begin with a comparison and justification for our choice of Launch provider. Next our Trajectory section will describe how our mission timeline was modelled with an analysis of space weather, atmospheric models and thrusters to calculate our expected mission time and ideal launch window. The Mechanical and Structural design section will use an analysis of the Launch Environment to design the CubeSat frame to survive the harsh forces and vibrations during launch, as well as internal component placement. The electronics section will explain how data will be processed and successfully transmitted through the iridium network, before describing the how the power budget is being managed. Following that, the instrumentation section will describe the various design choices that went into selecting components and sensors, before describing their use. Most importantly, this section describes the altitude tracking system, attitude control system, and atmospheric composition analysis. Next the Aerothermal section describes the expected environment during orbital and re-entry periods through several simulations and calculations, informing the expected demise window and maintaining the internals in their operational temperature window. Finally, the estimated costs and expected risks of the project will be summarised briefly, before concluding statements are made.

Reaction wheels

Reaction wheels are essential components within space vehicles and satellites during their orbital life. They use a spinning flywheel and the conservation of angular momentum to allow for the control of a vehicles attitude, which can be necessary for angling the vehicle for directional communications or thrusters. They are simple devices. In principle, a flywheel spins in one direction with a certain torque. To satisfy conservation laws, the rest of the CubeSat rotates in the opposite direction, but with the same magnitude of torque. The relative speeds of these rotations depend on the ratio of the moment of inertia between the flywheel, and the rest of the CubeSat.

In this project, reaction wheels serve two purposes. The first is attitude control of the CubeSat to allow for a successful de-orbit burn and efficient re-entry, requiring a reaction wheel ready on 3 separate axes. The second is as spin up manoevre to encourage the CubeSat to tumble through the atmosphere rather than stagnate, ensuring that the heatshield material is tested evenly on all faces.

When selecting a reaction wheel, several factors were considered. Size was the most crucial aspect, as they needed to be small enough to reasonably fit three reaction wheels within the CubeSat. Ideally, the length, width and heights will be similar values as a singular significantly larger dimension makes internal component placement more difficult. A high maximum momentum is desirable to make manoeuvres in a shorter time frame, as well as giving the CubeSat a higher maximum spin rate during the spin up during the re-entry phase. A low mass was looked upon favourably but wasn’t a critical factor in decision making.

*An abridged table comparing potential CubeSat options*

Maximum angular velocities were estimated by assuming the CubeSat has a mass of 12kg (1.5kg per U) and that mass is evenly distributed. This yields an inertia of 1kgm2. Maximum angular velocity can then be calculated directly from the equation below.

The Granstal GS-RW10 was the clear choice with the lowest mass, and the highest resulting CubeSat angular velocity whilst having reasonable dimensions.

A black round object with a metal connector

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Magnetometer

A magnetometer is a device that measures magnetic fields. The simplest case of a magnetometer is a compass, which was first invented in 206 BC China and initially used for geomancy and divination. It took over a millennium after this for the development and use of a navigational compass. As we know, they measure the directionality of the earths magnetic field to give the user their orientation, which can be used in conjunction with known geographical data (maps) to allow for navigation. Magnetometers used in satellites work similarly. Field direction and magnitude are both measured but are then instead compared to known magnetic field data to help determine position and orientation – for example the World Magnetic Model.

The World Magnetic Model (WMM) is the standard model for navigation systems which use the geomagnetic field. Its developed jointly by the British Geological survey and the National Centers for Environmental Information, of the US. The model is accurate up to 850km in altitude and track’s location using seven geomagnetic readings, which can be thoroughly decoded at a ground station once the readings have been received. Onboard, the measured magnitude of the magnetic field can be compared to an uploaded sample of the WMM to aid in altitude estimation. The measured magnetic field direction can be used to help determine CubeSat orientation, which is critical for performing a successful deorbit burn

Use of a magnetometer has limitations. During re-entry, the plasma layer formed can affect local magnetic fields due to the high density of charged particles within it. This disruption interferes with all readings taken by the magnetometer, limiting its use to earlier stages of the mission. Furthermore, the WMM can be affected by solar wind at higher altitudes, which needs to be accounted for prior to launch to prevent inaccuracies in altitude estimation. Blackout zones exist around the poles where the WMM shouldn’t be relied upon, and the orientation measured from the magnetometer will be significantly different to anywhere else in orbit. Therefore, polar orbits will be avoided.

The MM200 magnetometer from AAC Clyde Space was chosen for our CubeSat. It is extremely light weight and low volume, making it ideal for a CubeSat mission. Its high precision of 1.18nT/(Hz)^0.5 and sampling rate of up to 500Hz allows for high accuracy measurements to be made, aiding in altitude and orientation estimation. The measurement range of +/- 800microT far exceeds the expected magnetic field intensities of up to 28 microT, courtesy of the WMM.



Design Goals

This iteration of the physical CubeSat was designed with several goals in mind. These goals are as follows:

-Geometrically centralised centre of mass (COM)

-Geometry that won’t form a stable equilibrium point during re-entry

-Critical electronics centralised

-Reaction wheel centred on each major axis

-All critical components included

-On Board computer (OBC)

-Communications array

-Power source

-Reaction wheels

-Thrusters

-Sensors

-Heatshield

-Sufficient volume left for secondary components

Both the geometrical central COM and no stable equilibrium conditions are necessary to assume the tumbling condition which gives even exposure to all faces. This is advantageous in two ways. Firstly, distributing the ablation across the entire CubeSat surface protects the internals for as long as possible, letting us collect more data. Secondly, the even distribution gives a more standardised test, making the experiment more repeatable, which is ideal given an overall goal is to provide a test that becomes industry standard. The centralisation of critical electronics keeps the communications system within it’s thermal operation limit for as long as possible, again allowing the collection of more data. Centring a reaction wheel on each major axis is necessary for the control of attitude. This first iteration of the design is not fully complete, so its in our best interests to leave excess volume for unconsidered minor components, and the proper design of internal structure, rather than just internal component placement. Examples of secondary components include wiring and its routing, internal support structures, internal thermal control materials and minor circuit boards.

CubeSat Geometry

One of the major limitations of designing a CubeSat is the few geometries available to be chosen. To satisfy design goal B only two geometries were available, 1U and 8U (2\*2\*2 configuration) as they are the only reasonably sized options that form a cube.

Ultimately an 8U design was decided on due to its significantly higher volume. Although a working 1U design would be superior in the long run due to much lower launch costs and more launch options, an early design was shown to be unfeasible due to a lack of volume. This is largely because most CubeSat components on the market seemed to be designed with the extreme dimensions of a 1U CubeSat in mind. For example, our chosen OBC has dimensions 96mm\*96mm\*25mm, would just tuck into a 1U CubeSat, but doesn’t leave enough room at the edges for a significant heatshield to test. Figure X shows an earlier design of a 1U CubeSat containing only two reaction wheels, a battery and an OBC. This design determined the unfeasibility of a 1U design due to the lack of available volume for other key components e.g. a communications array, thrusters or a third reaction wheel.

A 3d model of a machine

Description automatically generated

Figure - An early 1U CubeSat design showing

Furthermore, the excess volume of the 8U CubeSat allows the inclusion of a Spectrometer so that our secondary objective – observation of environmental impact on the atmosphere – can be completed.

Internal Design

The current design iteration is an 8U design containing the components listed in the table below, including an example heatshield and custom designed frame. The initial designs mass comes to ~7kg, which is significantly lower than the estimated 12kg used for analysis throughout this report. However, secondary components and internal structures were not considered on this iteration of the design, which is a significant omission that should make up close to the difference. Furthermore, the total mass is inherently variable as the heatshield material will vary with every mission.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Component** | **Count** | **L(mm)** | **W(mm)** | **H(mm)** | **Mass(g)** | **Total Mass(g)** |
| GS-RW10 Reaction wheel | 3 | 50 | 50 | 60 | 250 | 750 |
| Vacco Cold Gas Thruster | 3 | 100 | 100 | 30 | 542 | 1626 |
| AvaSpec-Mini2048CL Spectrometer | 1 | 95 | 68 | 20 | 175 | 175 |
| ICEPS Spacecraft System Core All-In-One: EPS/OBC/Radio | 1 | 96 | 96 | 25 | 100 | 100 |
| CC-UV/VIS/NIR-8MM  Cosine Corrector | 6 | 12(diameter) |  | 29 | Unknown |  |
| BA06 A/S Battery | 1 | 90 | 96 | 9 | 209.45 | 209.45 |
| HXDC16010 SA00 Iridium SBD | 4 | 14(diameter) |  | 41.5 | 22 | 88 |
| EPB-25PS-C20004 Pressure Transducer | 6 | 6.98(diameter) |  | 5.84 | Unknown |  |
| MEAS 410 Thermocouple | 6 | Negligible | Negligible | Negligible | Negligible |  |
| MM 200 magnetometer | 1 | 33 | 20 | 11.3 | 12 | 12 |
| Thermite Charges | 8 | Arbritrary | Arbritrary | Arbritrary | unknown |  |
| Frame | 1 | 180 | 180 | 180 | 361.63 | 361.63 |
| Central plate | 2 | 112 | 112 | 2 | 70.16 | 140.32 |
| Example Heatshield of GE-223 Carbon ablator | 1 | 200 | 200 | 200 | 3664.12 | 3664.12 |
|  |  |  |  |  |  | 7000.47 |

**A diagram of a cube with different colored objects

AI-generated content may be incorrect.**

Figure – CAD abstraction with heatshield hidden

The current CAD model is an abstraction of what the final design might look like, using rough volumes of components to show how the packing problem can be solved whilst fitting components into ideal places with regard to the design goals. The sensors that seem to be floating are embedded partially within the heatshield on each face.

Thrusters are placed as such to minimise the routing required for propellant. Also, as their critical role is to perform a deorbit burn near the start of the mission, their increased thermal exposure during re-entry due to proximity to the CubeSat edge is no problem. The communications array and OBC are placed as centrally as possible as they make up the critical electronic components, achieving the design goal to protect them as much as possible from the extreme thermal environment of re-entry. The antennae array is made up of four antennae placed in a two-by-two grid, 92mm apart. This is necessary to allow beamforming and therefore communication as described in section 6.1.3. The COM is successfully designed to be near the geometric centre and there’s a reaction wheel centred on each central axis, again satisfying the design goals.

A blue square with different colored squares

AI-generated content may be incorrect.A colorful rectangular object with different colored objects

AI-generated content may be incorrect.

A colorful square object with different shapes

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Frame Design

**Material**

Material selection is of high importance when designing a space frame. The material must satisfy physical, mechanical and thermal properties to be determined an appropriate fit. Often, the strength to weight ratio is the key factor when determining what material to use, as it’s ideal to minimise payload mass for a cheaper launch, whilst maintaining the strength of the structure. Our case is no different.

Aluminium alloys have some of the best strength to weight ratios of any readily available material, are highly machinable and have high corrosion resistance, making them an ideal material for a spaceframe. A qualitative analysis on common aluminium alloys was conducted, with an emphasis on ease of manufacture, strength and low thermal conductivity. Low thermal conductivity is important to slow conduction through the CubeSat and keep the critical electronic systems within their operational window.



Ultimately, Al 2014 was the clear choice of frame material for our CubeSat. It had one of the highest Tensile and Proof stresses, one of the lowest thermal conductivities and remains easy to manufacture as it can be cold arc welded as well as machined easily. It’s comparatively low melting point means it will demise easily from the thermite ignition, which is planned for when the internal temperature reaches 650K at approximately 40km altitude. It’s one drawback is that it’s the densest of the considered options, however at this stage in the design process we are happy with our current mass estimate, so this isn’t a problem.

**Physical frame design – diagram and cross section, discuss manufacture?**

**Launch Environment analysis**

While the thermal attributes of the CubeSat were designed to survive the harsh environment of space, it was necessary to design the mechanical aspects of the CubeSat to survive the launch phase. Two major causes of failure were considered. The first was resonance, which considers the random vibrations during launch and ensures they do not induce large enough vibrations in the CubeSat such that the frame fails. The second was acceleration loading, which considers the load through the CubeSat during launch due to its self-weight at the high g-forces it would experience during launch.

**Vibrational analysis**

Modelling

Figure 2 shows how the CubeSat was modelled for vibrational analysis, a frame with n frames and m columns, whilst being symmetrical in the x and y axis. The bottom floor is fixed to the baseplate, where the vibrations enter the system. Each floor is assumed to hold an equal portion of the total CubeSat mass. It followed to model this as a horizontal mass-spring system, with the bending of the supports producing spring-like action. The spring constant was calculated from the support height, second moment of area and the Youngs modulus of material, as shown in Figure 2 and below. This analysis only considered horizontal vibrations as vertical vibrations are prevented by the fixed baseplate, and any elastic behaviour along the length of a strut is considered negligible when compared to the horizontal displacements of the floors.

A line on a graph paper

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Figure – HLT page 130

The analysis point of figure 1 was taken as the midpoint between each floor such that and where h is floor height and is the horizontal floor displacement. Substituting and rearranging into the form to find the spring constant gave the following.

A diagram of a floor

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Figure 2

The equations of motion of the modelled system can be expressed in matrix form as:

Where is a vector of horizontal floor displacements and is the floor mass. The comes from summing the spring constants of all supports within the square shape.

Assuming a sinusoidal solution for with natural frequency gives:

Solving for gives us the natural frequencies of the system. Ideally, we design these frequencies to be in the low power areas of the vibrational power spectral density – shown in figure 3. It is important to note that this analysis assumes no damping, which means that the real system would have resonant peaks at slightly different frequencies to those calculated by this method.

Vibrational PSD for RocketLab Electron launch


Figure 3 – Following the CubeSat plot. From Electron User Payload Guide

Simulation

Figure 3 shows the power spectral density (PSD) of random vibrations the CubeSat would experience during launch. Using MATLAB, the PSD was used to generate a set of sample signals to simulate the system vibrations. Summing these signals into the time domain produces a single signal. The flowcharts in Figures 4,5 and 6 describe the entire process.

A diagram of a flowchart

AI-generated content may be incorrect.

Figure 4 – Overall flow chart of vibrational analysis program

With the PSD’s maximum frequency being 2000Hz, to avoid aliasing the signals, a dt of seconds was chosen, for a sampling rate of 4000Hz, satisfying the Nyquist frequency limit.

The natural frequencies are calculated using the process described in the modelling section prior.

A diagram of a machine

AI-generated content may be incorrect.A diagram of a flowchart

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Figure 5 – Simulate in Time block Figure 6 – Generation of base acceleration signal

Validation

Due to the relatively simple modelling approach, validation of this simulation was achieved by comparison of a solved base case – the single mass-spring system with a sinusoidal forcing function, for which the equation of motion for is:

This has two different solutions depending on the value of . The first is where giving;

Which is simply a sum of coherent sinusoidal functions, which produces a single output sinusoid.

The second case is where ; which has the solution:

Which produces a sinusoid which has a growing oscillatory response, bounded by the line , showing resonance.

To test this base case, a two-floor model was used, with a single, manually generated sinusoidal input. The two-floor model matches the single spring -damper model due to the single set of supports between the base and the only unfixed floor. Firstly, the case was tested in a 1 second simulation, as shown in figure 7.

A screen shot of a graph

Description automatically generated

Figure 7

Floor 1 is the fixed floor, which showed some movement as the displacements are all taken relative to the n-1 displacement of the fixed base. Otherwise, the second floor behaved as expected, following a sinusoid of fixed amplitude

The same parameters were tested again, using an input signal at to the systems natural frequency. This showed resonance as expected, with a sinuiod bounded by an x = at curve reaching magnitude orders of magnitude above the non-resonant case.A screenshot of a graph

Description automatically generated

Figure 8

In the case where ; and the simulation time is extended; a beating effect can be observed, which is again, expected in a real system.

A green lines on a white background

Description automatically generated

Figure

Results

Simulations using this model on various frame geometries were ran to inform on which geometry showed the most promise for surviving launch. Standard runs were completed on varying numbers of floors, with the same randomly generated signal and the parameters described as follows:

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| CubeSat Mass (kg) | Strut count | Strut second moment of area (m4) | Frame material | Material Youngs modulus (GPa) | Simulation time (s) | Number of Sampled Signals | Frame Length (mm) |
| 12 | 4 | 3.385 \*10-11 | Aluminium | 70 | 50 | 1000 | 200 |

A graph showing a blue and red line

AI-generated content may be incorrect.

Whilst the simulation results may be pretty, there’s limited useful data we can draw from them due to the absence of damping in the simulation. They serve as an upper bound for the potential of the vibrations in the extreme case of low damping. Therefore, we can only usefully use the maximum displacements of each simulation for a comparison. The table below shows the mean maximum displacement of each CubeSat over 10 trials, with each geometry being tested with the same input signal.

|  |  |
| --- | --- |
| **Number of floors** | **Max Displacement magnitude (mm)** |
| 2 | 1.04650788 |
| 3 | 2.188738 |
| 4 | 0.392875 |
| 5 | 0.925319 |
| 6 | 0.323091 |

It can be observed that both the 4 and 6 floor geometries show the lowest mean maximum displacement over the set of trials, indicating that they might be the better suited to survive the harsh vibrational environment at launch.

**Finish with simulation of actual frame**

Acceleration environment

During launch the CubeSat will be subject to large g-forces due to the rocket accelerating. The figure below shows the typical envelope for which the electron accelerations lie. Lateral acceleration forces would be caused by manoeuvres whilst axial acceleration would be caused by thrust or drag.

A graph of a graph

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To ensure the frame doesn’t fail under these g-forces, the design was analysed using Finite element analysis (FEA) within SolidWorks to simulate the extreme load cases.

FEA is a numerical analysis technique that works by dividing an object up into a mesh of small elements, before a governing equation is applied across the mesh to simulate what might happen under different boundary and initial conditions. **Ask Fizza to clarify equations and elaborate on fea.**

The frame was analysed with the estimated CubeSat mass of 12kg distributed across its top surface whilst the bottom face was fixed, under all the load pairs on the vertices of the Acceleration MPE. Distributing the mass across the top surface simplifies the boundary conditions and provides slightly harsher conditions than shown by the MPE, as it overestimates the weight each top cross beam has to support. This upper bound simplification is valid as it only builds more confidence in the frame design.

-1.5g, 7.5g with lateral acceleration perpendicular to face

A blue and green wireframe with a red arrow

AI-generated content may be incorrect.A blue and green metal frame

AI-generated content may be incorrect.

Stress Displacement

-1.5g,7.5g with lateral acceleration 45 deg to face

A blue and green wireframe with a red dot

AI-generated content may be incorrect.A blueprint of a metal frame

AI-generated content may be incorrect.

Stress Displacement

As we can’t assume the angle which the CubeSat will be at whilst the rocket makes lateral manoeuvres, it’s necessary to simulate them at the two most extreme angles; perpendicular to and at 45o to a flat face.

Results: In no case is the highest stress within the order of magnitude as the yield stress of the frame, and the highest observed displacement across all cases was 0.606mm, which is observed in one of the top supporting beams that are taking several times the load they’re expected to carry. Overall, this analysis shows that the frame is more than capable of surviving the g forces present during launch.