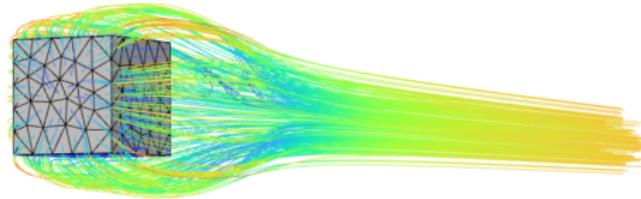


Materials Testing for Heatshield Applications during CubeSat Re-entry with Passive Demise

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March 11, 2025



0. Outline

- 1 Introduction
- 2 CubeSat Design
- 3 Mission
 - Deployment
 - De-Orbit Burn
 - Spin-Up Manoeuvre
 - Data Acquisition & Transmission
 - Thermite Ignition
- 4 Conclusion

Primary Objectives

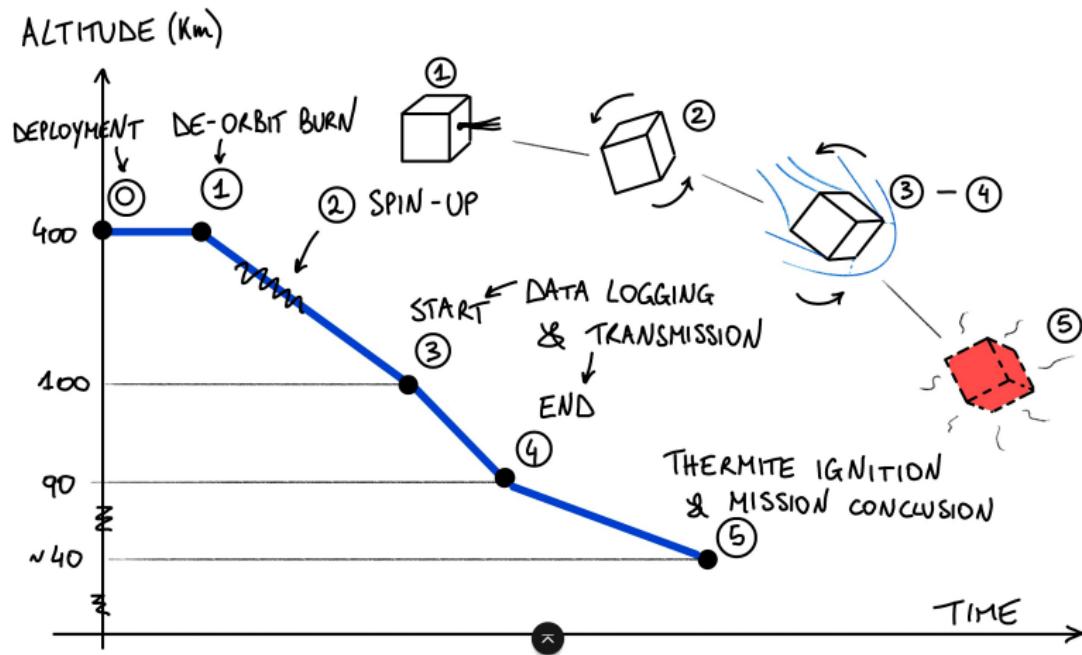
- Commercial platform for testing CubeSat heatshield materials through hypersonic re-entry with reproducible design
- Successful data acquisition and indirect transmission to a ground station
- Passive ignition of onboard thermite mass for low altitude demise

Secondary Objectives

- Successful spin-up manoeuvre for induced tumbling during re-entry
- Monitoring atmospheric composition changes from demise material trail

1.1. Introduction: Mission Profile

Brief Mission Overview:

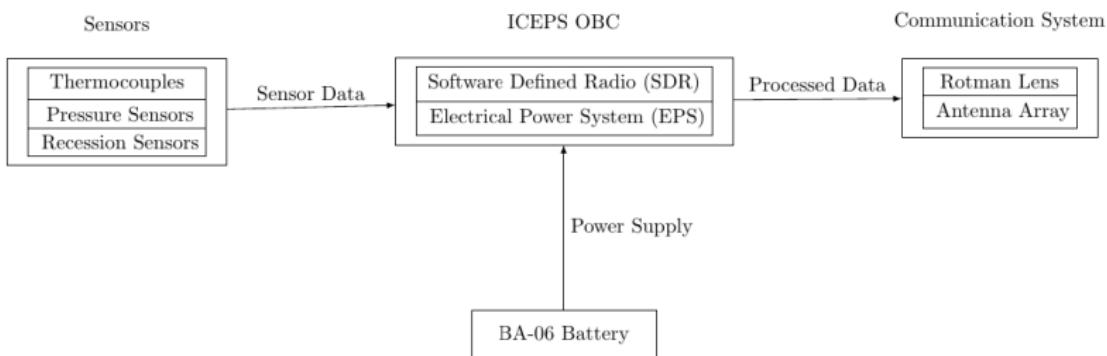


2.0. CubeSat Design

- 8U CubeSat - 200mm x 200mm x 200mm
- Aluminium alloy frame
- Multilayer sandwich ablative structure tested on each face
- Expected mass of 12kg
- Centre of mass = geometric centre (ballast used)
- Reaction wheels on 3 Major Axes
- Critical Electronics to be centralised

2.1 CubeSat Electronics

- The ICEPS Spacecraft System Core OBC has an EPS system, I2C rails and an on-board software-defined radio
- The BA-06 battery has a 9mm height and compatible interfacing for the OBC, along with Carbon Nanotubes Thermal Transfer Bus (CN/TTB) shield for temperature control



3.0. Orbit Deployment



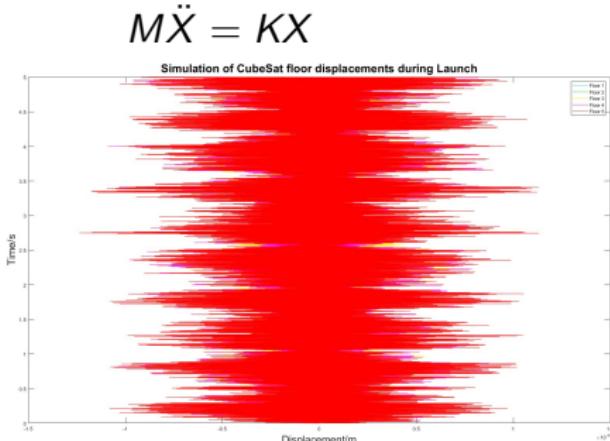
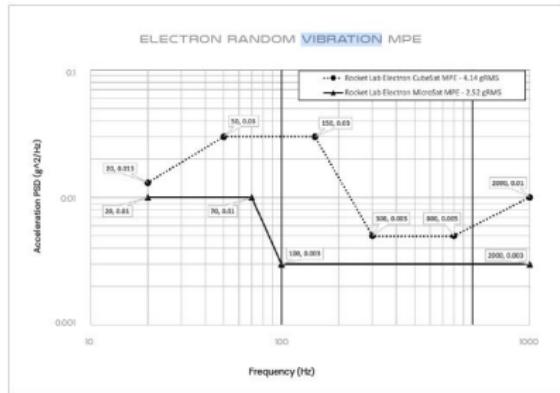
3.0.1 Deployment: Launch



- Deployment as low as 400km
- Multiple altitude deployments in single Launch ¹

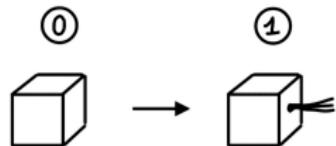
¹ "Electron-Payload-User-Guide-7.0 - Rocket lab". In: (). URL: <https://www.rocketlabusa.com/assets/Uploads/Electron-Payload-User-Guide-7.0.pdf>

3.0.2 Deployment: Launch vibrations

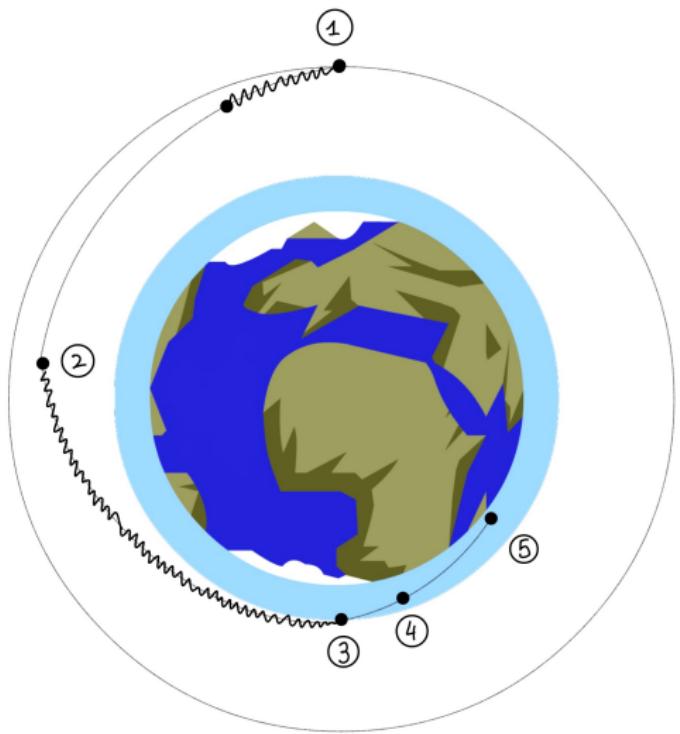


3.1. Orbit Lowering

3.1. De-Orbit Burn



3.1.1 Trajectory Overview



- ① Orbit Insertion
- ② Spin-Up
Manoeuvre
- ③ Data Logging:
Start
- ④ Data Logging:
End
- ⑤ Thermite
Ignition

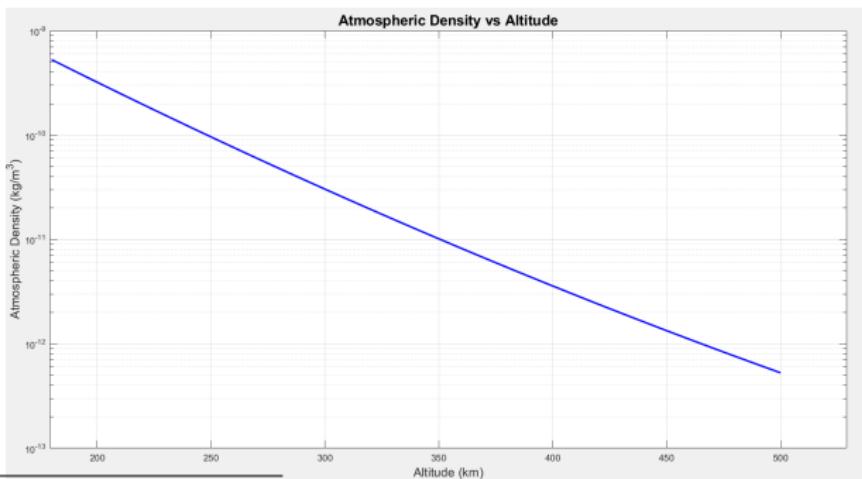
3.1.2 Atmospheric Drag Model

- Drag Force:

$$F_{\text{drag}} = \frac{1}{2} C_d \rho A v^2$$

- Atmospheric density model²:

$$\rho = 6 \times 10^{-10} \exp \left(-\frac{(h - 175) \cdot (27 - 0.012(h - 200))}{900 + 2.5(F_{10.7} - 70) + 1.5A_p} \right)$$



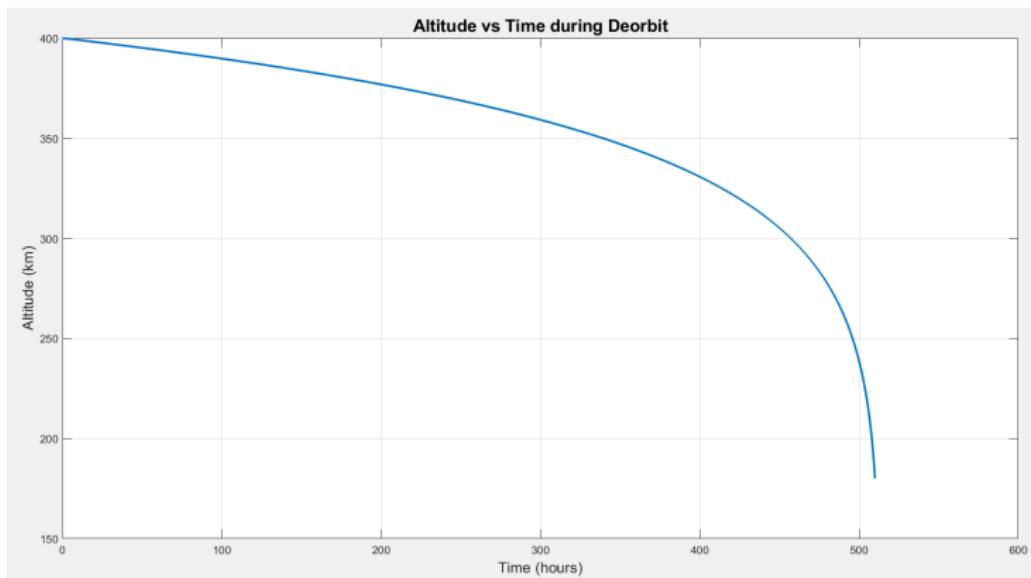
² Australian Space Weather Agency. "Satellite Orbital and Decay Calculations". In: (). URL: www.ips.gov.au

3.1.3 Numerical Methods in Simulation

- The equations that govern orbital motion and atmospheric drag are non-linear and can't be solved analytically.
- RK4 is manually implemented to simulate trajectory dynamics.
- RK4 is a fixed-step, fourth-order Runge-Kutta method that provides a balance between accuracy and computational efficiency for solving orbital dynamics.
- Equation of motion:

$$\dot{h} = -\frac{C_D A \sqrt{\mu}}{m} \sqrt{R_E + h} \rho(h)$$

3.1.4 MATLAB simulation results

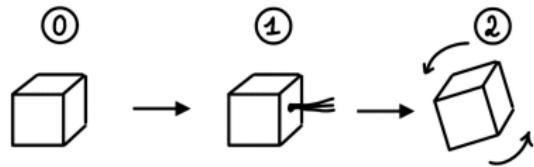


- The main limitation of the simulation is that it assumes the chance of collision with other objects is negligible
- Probability of collision can be calculated using a Poisson distribution

$$P_{\text{collision}} = 1 - e^{A\lambda vt}$$

3.2. Spin-Up

3.2. Spin-Up Manoeuvre

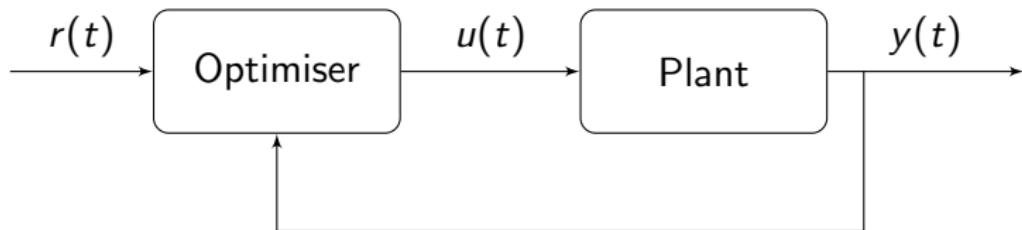


3.2.1. Control System

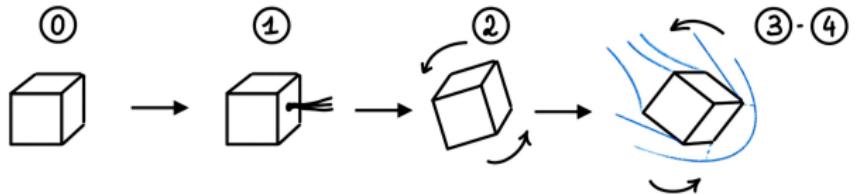
- Attitude controller is a MIMO Model Predictive Control (MPC) implementation of a system with kinematics and dynamics, respectively (using quaternion representation):

$$\dot{q} = \frac{1}{2}\Omega(\omega)q; \quad J\dot{\omega} = -\omega \times (J\omega) + \tau$$

- Knowledge of attitude state $y(t) \leftarrow q(t)$ is coupled with an Open-Loop altitude controller (cold gas thruster valve)

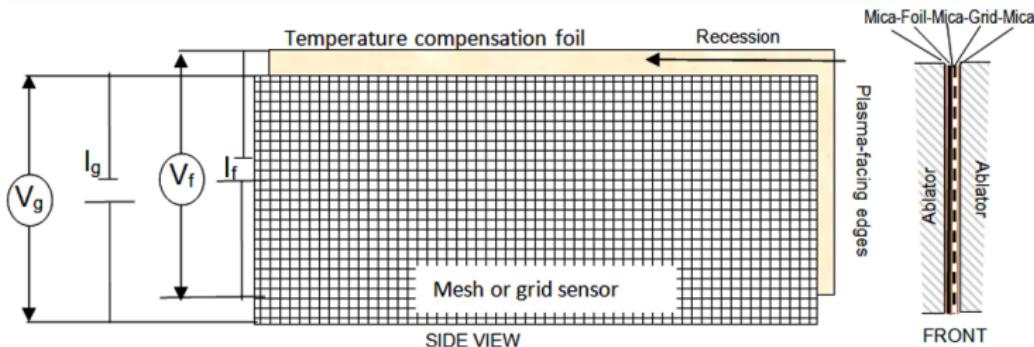


3.3. Data Acquisition & Transmission: Start



3.3.1. Data Acquisition

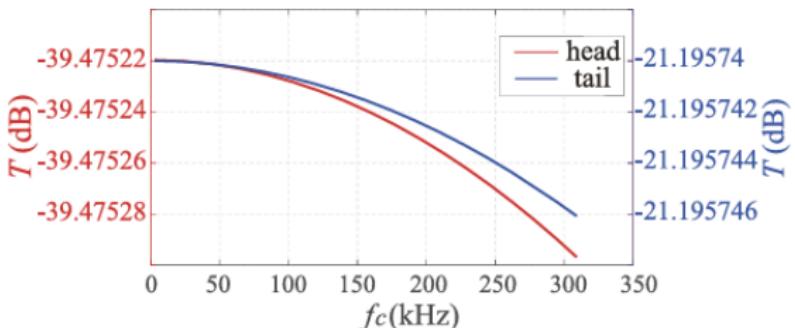
- Six sheets of test material are placed on the outer surface, each with its own sensor array measuring temperature and pressure
- A ReWiG recession sensor³ is additionally integrated into each test material face



³George Vekinis. "ReWiG" "A Resistive Wire Mesh TPS recession sensor".

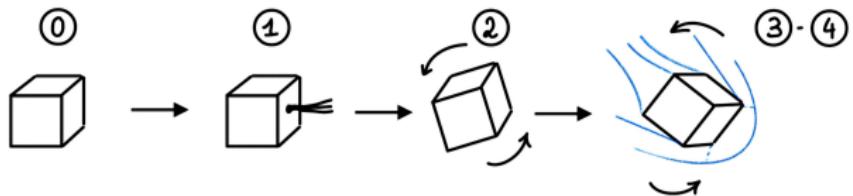
3.3.2. Data Transmission

- CubeSat will spin during reentry for uniform material testing, encountering a plasma sheath absorbing transmission⁴
- Beamforming via a phased antenna array mitigates this issue, directing signals backward to the Iridium network
- Data is collected and then modulated with the software-defined radio on the OBC before transmission



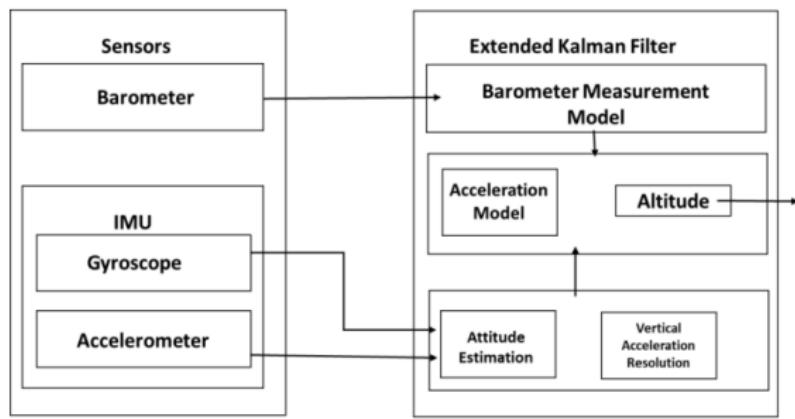
⁴ Mingyang Mao et al. "The propagation characteristics of low frequency radio waves in magnetized hypersonic plasma sheaths". In: *AIP Advances* 13 (2023)

3.4. Data Acquisition & Transmission: End



3.4.1. Secondary objective instrumentation

- **Spectrometer:** AvaSpec-Mini2048CL⁵ Small and Powerful OEM Spectrometer, 200-1100nm
- **Calibration lamp:** AvaLight-CAL (-Mini) ⁶
- **Inertial Measurement Unit and Barometer**
 - Altitude tracking accuracy will be improved by applying a Kalman filter with sensor fusion



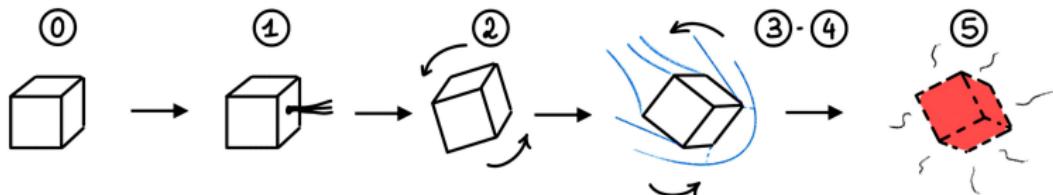
⁵ AvaSpec-Mini - Avantes. URL:

<https://www.avantes.com/products/spectrometers/compactline/avantes-spectrometer-mini-2048cl-2/>

⁶ AvaLight-CAL (-Mini) - Avantes. URL:

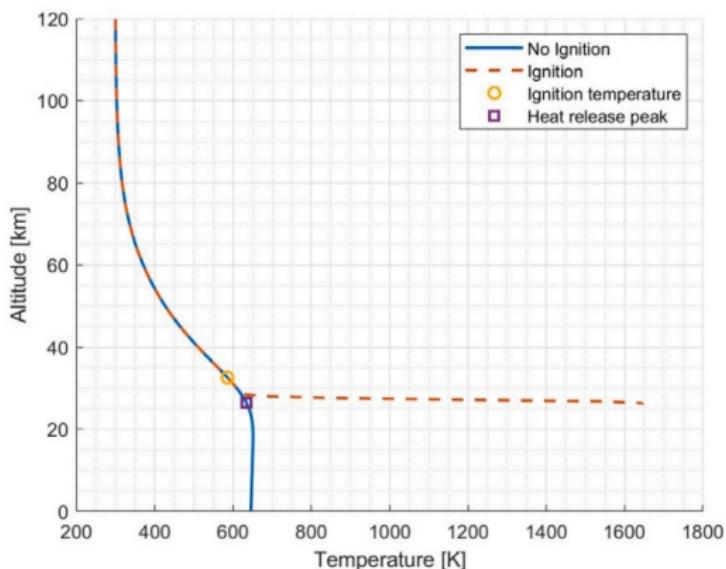
<https://www.avantes.com/products/light-sources/calibration-light-sources/avalight-cal-mini/>

3.5. Thermite Ignition



3.5.1 Thermite for Demise

- Thermites (e.g. Al + Fe₂O₃) offer a safe and reliable mechanism for passive Demise (T4D⁷)
- Tailored ignition temperatures and reaction characteristics can be achieved through **mechanical activation**

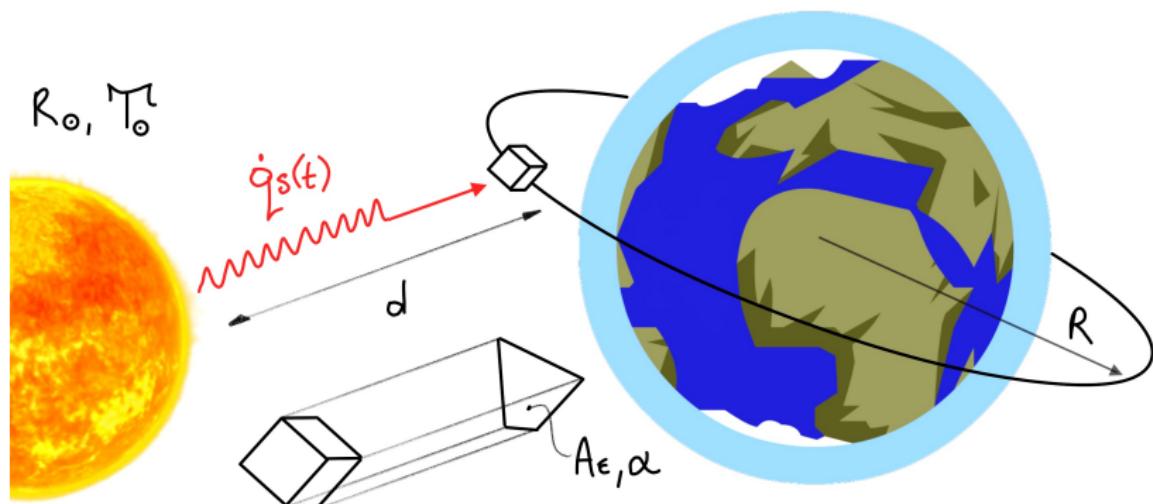


⁷A. Finazzi et al. "Thermite-for-Demise (T4D): Experimental analysis of heat transfer principles and preliminary sizing of an application". In: *International Journal*

3.5.2. Aerothermal Modelling - Orbit

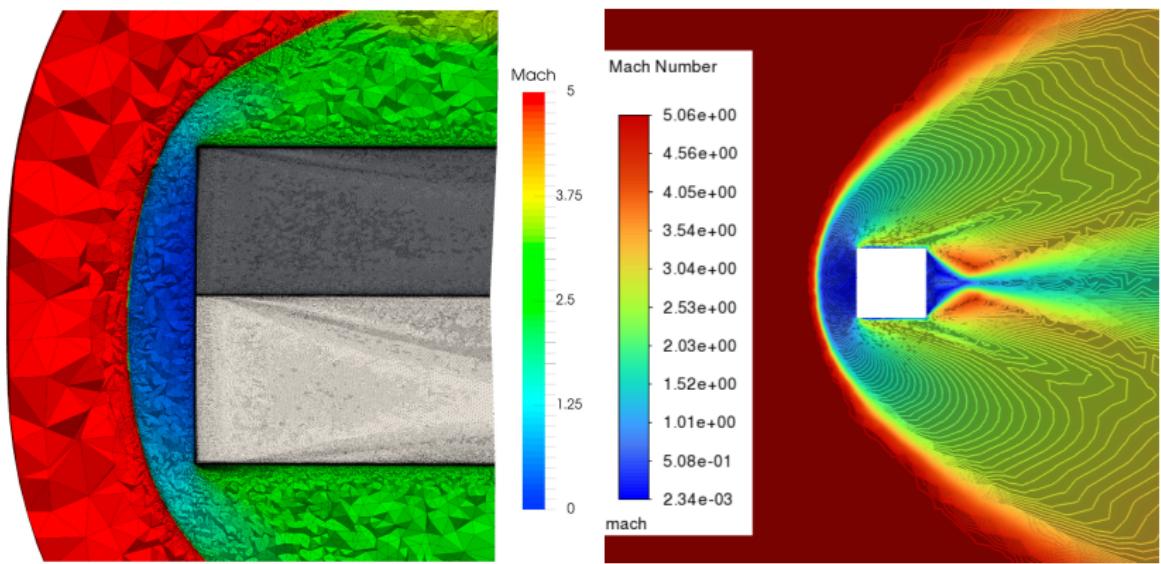
Design objective: Ensure inner CubeSat temperatures remain within the electronics' operational range during:

- ① Orbital regime: $T_i > T_{min}$ with $T_o = \frac{T_\odot}{\sqrt[4]{A_E}} \sqrt{\frac{R_\odot}{d}} \simeq 120.6^\circ\text{C}$
- Given uniform temperature distribution, constructed 1D inverse heat conduction problem (IHCP) solver based on forward-time central-space (FTCS) finite differencing scheme



3.5.3. Aerothermal Modelling - Re-Entry

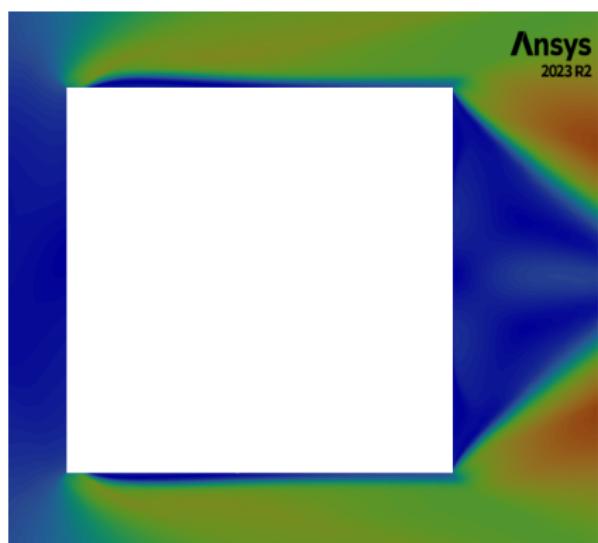
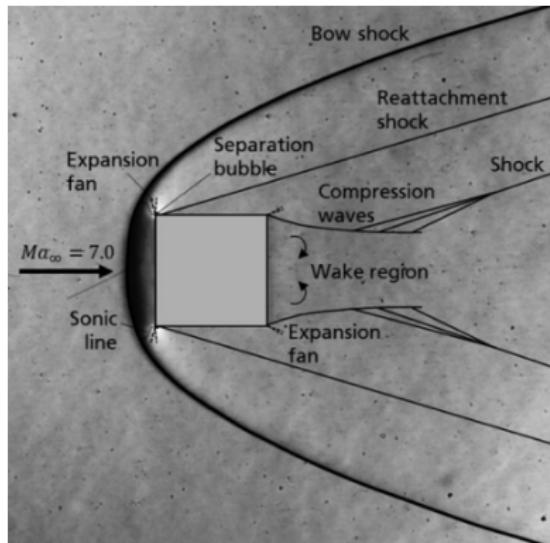
- ② Re-entry data logging phase: $T_i < T_{max}$
- Due to low Strouhal numbers ($St = \frac{\Omega L}{V} \approx 10^{-5}$), quasi-steady state is assumed for flow around our 2U CubeSat
- 2D CFD Results show close agreement with Rees⁸ experimental data. Here: $M = 5$ and zero incidence



⁸ Thomas W. Rees et al. "Numerical and experimental studies of the hypersonic flow around a cube at incidence". In: *Acta Astronautica* 183 (June 2021), pp. 75–88. ISSN: 00945765. DOI: 10.1016/j.actaastro.2021.04.016

3.5.4. Aerothermal Modelling - CFD Validation

- We employed AMR, large nodal mesh counts, prismatic inflation layers, $k - \omega$ SST turbulence in Fluent simulations
- Results were also qualitatively validated against Seltner⁹



⁹

Patrick M. Seltner, Sebastian Willems, and Ali Gühan. "Aerodynamic coefficients of free-flying cubes in hypersonic flowfield". In: *Journal of Spacecraft and Rockets* 56 (6 2019), pp. 1725–1734. ISSN: 15336794. DOI: 10.2514/1.A34345

4.1. Conclusion: Project Risks & Budget

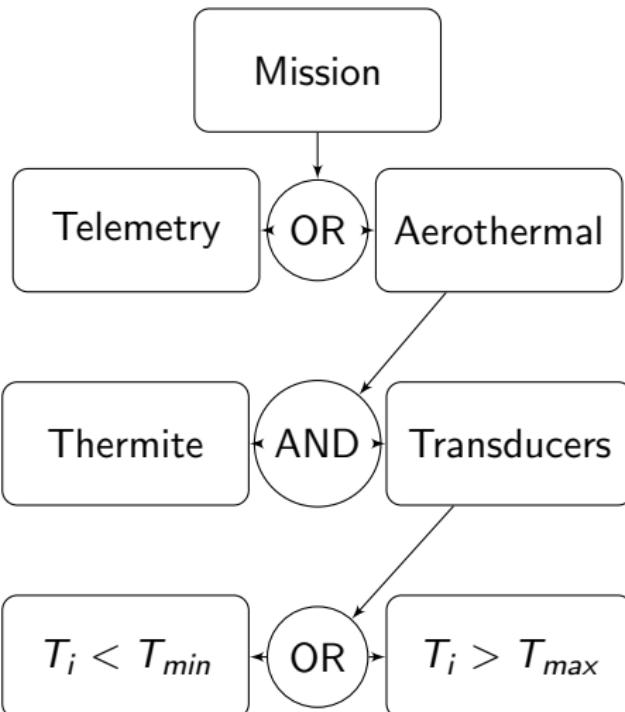
Project Risks

- Fault tree analysis with highest risks shown
- FTA is dominated by telemetry failure

Estimated Mission Cost

- Mission £318,000 ^a
- Components a broad estimate of £100,000 Based on a few known component costs

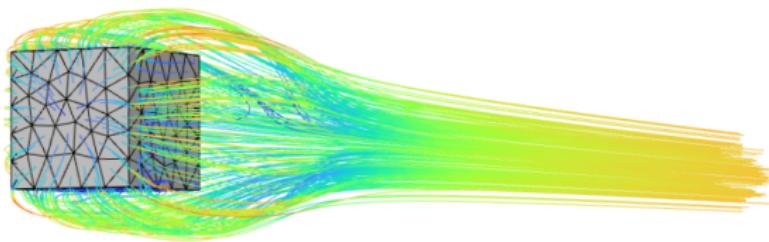
^a Just for mission itself. Calculated by <https://www.endurosat.com/configurator/> using most broad parameters - likely a lower bound



4.2. Conclusion: Future Work

- Mechanical
 - Build a CAD Mock-up to finalise component placement
 - Design Frame to match component placement and survive launch
- Trajectory
 - Consider the collision analysis in more depth
 - Simulate the trajectory below 180km
 - Validation cases for the trajectory code
- Electronics
 - Internal heating considerations
 - Simulation of telemetry
 - Connection and wiring needs planning
- Aerothermal
 - Refine and validate 3D CFD Ansys simulations
 - Enhance dimension of FTCS solver to 3D
- Project
 - Refine budget estimate

Thank you for your attention.
Any questions?



Appendix A.1: Quaternions

Attitude controller is a MIMO Model Predictive Control (MPC) implementation of a system with kinematics and dynamics:

$$\dot{\mathbf{q}} = \frac{1}{2} \boldsymbol{\Omega}(\omega) \mathbf{q}; \quad \mathbf{J}\dot{\boldsymbol{\omega}} = -\boldsymbol{\omega} \times (\mathbf{J}\boldsymbol{\omega}) + \boldsymbol{\tau}$$

- $\boldsymbol{\omega} \in \mathbb{R}^3$ is the angular velocity vector of the CubeSat wrt an inertial frame, expressed in the CubeSat's frame of reference
- $\mathbf{q} \in \mathbb{R}^4$ is the quaternion attitude: $\mathbf{q} := \begin{bmatrix} \eta \\ \boldsymbol{\epsilon} \end{bmatrix} : \eta^2 + \|\boldsymbol{\epsilon}\|^2 = 1$
- $\boldsymbol{\Omega}(\omega) \in \mathbb{R}^{4 \times 4}$ is the skew-symmetric quaternion representation

of angular velocity: $\boldsymbol{\Omega} := \begin{bmatrix} 0 & -\omega_i & -\omega_j & -\omega_k \\ \omega_i & 0 & \omega_k & -\omega_j \\ \omega_j & -\omega_k & 0 & \omega_i \\ \omega_k & \omega_j & -\omega_i & 0 \end{bmatrix}$

- $\mathbf{J} \in \mathbb{R}^{3 \times 3}$ is the moment of inertia matrix,
- $\boldsymbol{\tau} \in \mathbb{R}^3$ is the applied torque: $\boldsymbol{\tau} = \boldsymbol{\tau}_a + \boldsymbol{\tau}_d$ where $\boldsymbol{\tau}_a$ is the actuator torque and $\boldsymbol{\tau}_d$ is the disturbance torque.

Appendix A.2: Quaternions

Given unit quaternion:

$$\mathbf{q} = \eta + \epsilon_i \mathbf{i} + \epsilon_j \mathbf{j} + \epsilon_k \mathbf{k} \equiv \cos(\eta) + \sin(\eta) (\epsilon_i \mathbf{i} + \epsilon_j \mathbf{j} + \epsilon_k \mathbf{k})$$

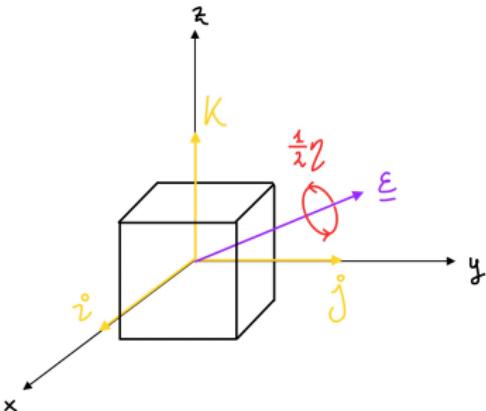
Any rigid body rotation can be represented as:

$$\mathbf{p}' = \mathbf{q} \mathbf{p} \bar{\mathbf{q}}$$

where η is the half-angle of rotation, and ϵ defines the rotation axis.

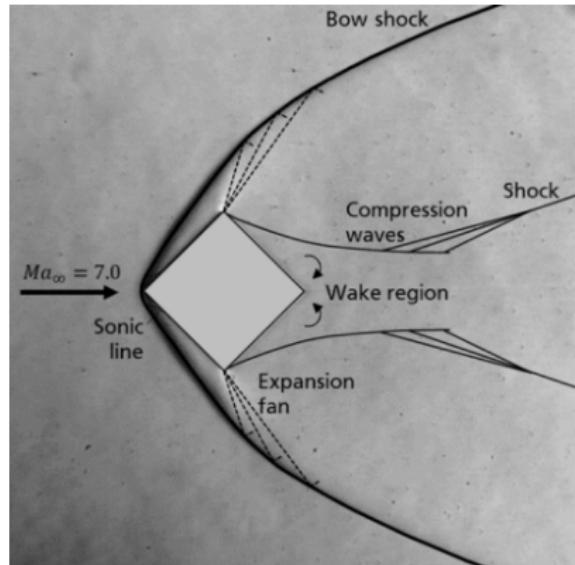
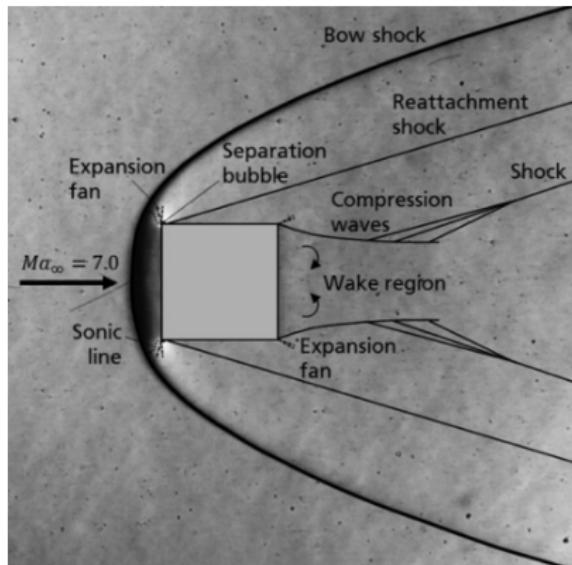
For constant angular velocity $\omega(t) = \omega_0$, the state update simplifies to:

$$\mathbf{q}(t) = \exp \left[\frac{1}{2} \boldsymbol{\Omega}(\omega_0) t \right] \mathbf{q}(0)$$



Appendix B.1: Critical Flow Configurations

Experiments and simulations have been carried out on cube geometries¹⁰. Critical 2D configurations as shown:



¹⁰ Patrick M. Seltner, Sebastian Willems, and Ali Gühan. "Aerodynamic coefficients of free-flying cubes in hypersonic flowfield". In: *Journal of Spacecraft and Rockets* 56 (6 2019), pp. 1725–1734. ISSN: 15336794. DOI: 10.2514/1.A34345

Appendix B.2: Pressure Distribution and Mesh

