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

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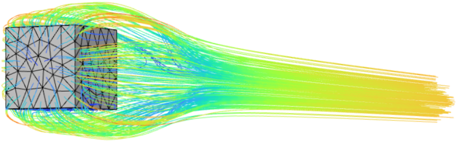


0. Outline

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

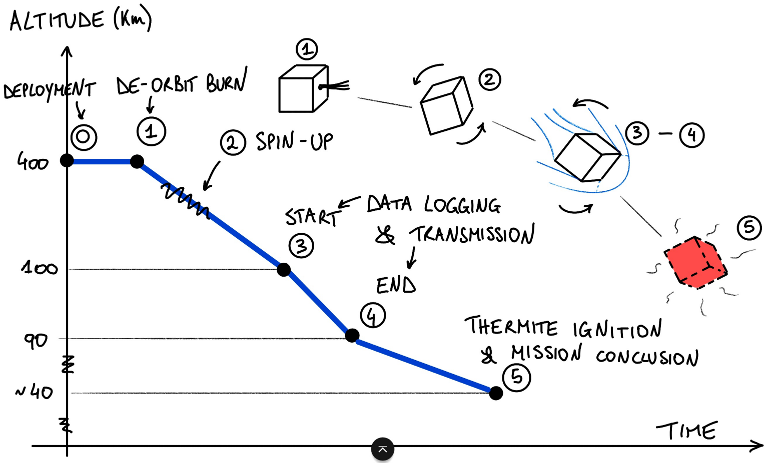
Primary Objectives

- 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

Brief Mission Overview:

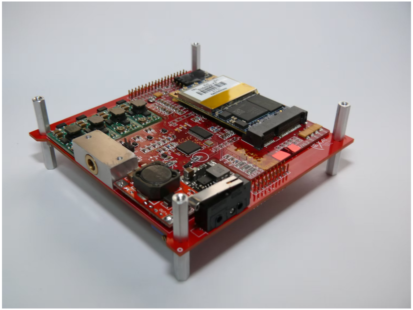


2.0. CubeSat Design

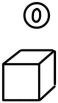
- 8U 200mmx200mmx200mm cube
- Expected mass 12kg
- Central COM
- Minimise moment of inertia to maximise spinrate
- Reaction wheels on 2 Major Axis
- Critical components - comms array and OBC to be centralised

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



3.1. Deployment: Launch

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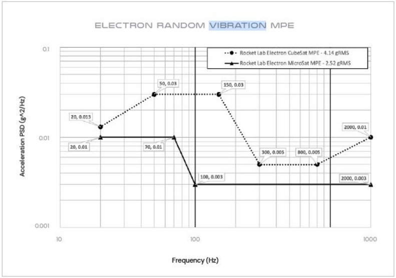
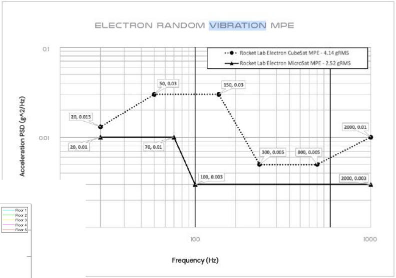
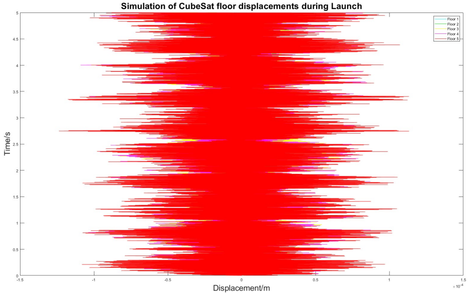
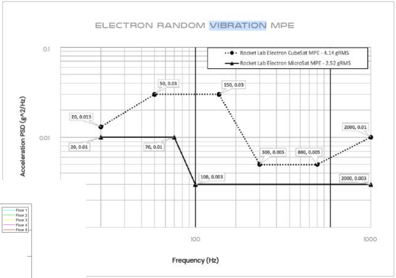


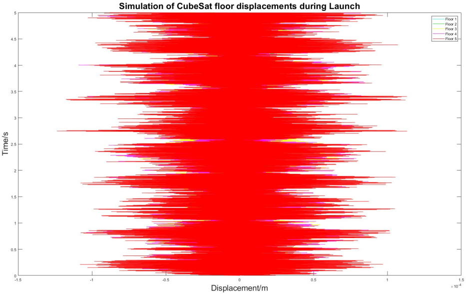
3.1. Deployment: Launch

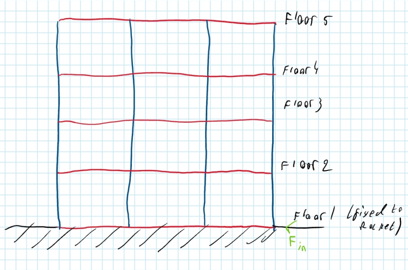
ROCKETLAB



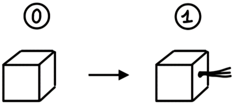



ELECTRON RANDOM VIBRATION MPE
Rocket Lab Electron CubeSat MPE - 4.14 gRMS
Rocket Lab Electron MicroSat MPE - 2.52 gRMS
20, 0.013
50, 0.03
150, 0.03
20, 0.01
70, 0.01
100, 0.003
300, 0.005
800, 0.005
2000, 0.01
2000, 0.003
Acceleration PSD (g^2/Hz)
Frequency (Hz)

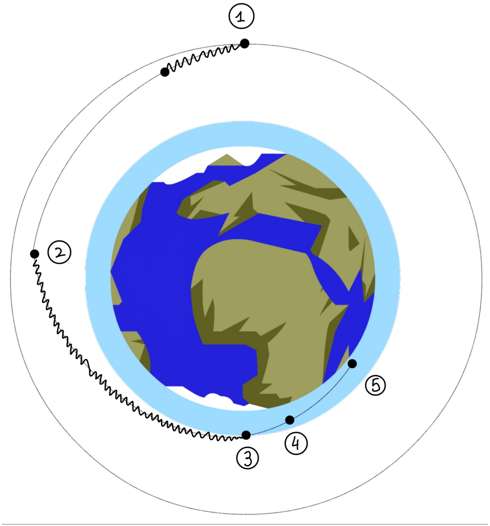

Simulation of CubeSat floor displacements during Launch
Floor 1
Floor 2
Floor 3
Floor 4
Floor 5
Time/s
Displacement/m


Floor 5
Floor 4
Floor 3
Floor 2
Floor 1 (fixed to Rocket)
F_{in}

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

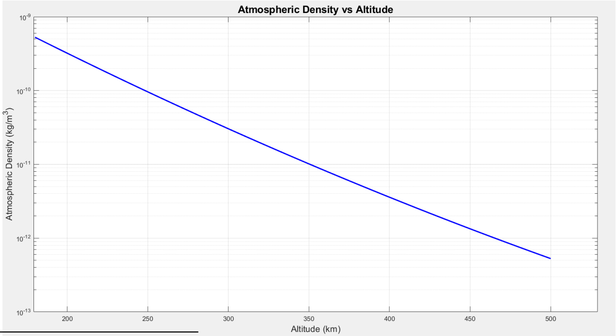
3.1.2 Atmospheric Drag Model

- Drag Force:

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

- Atmospheric density model[1]:

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



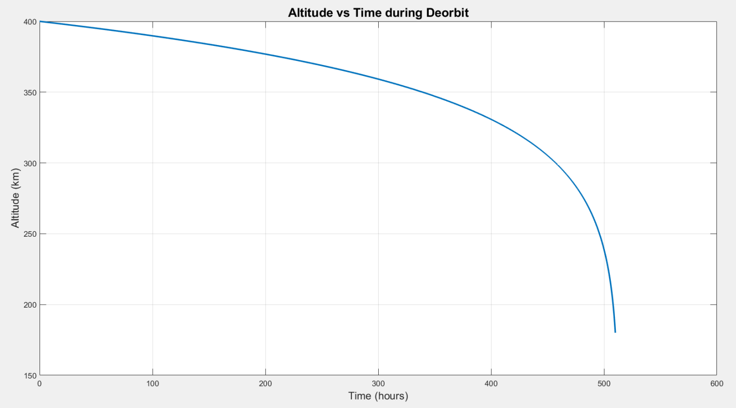
[1] Australian Space Weather Agency. "Satellite Orbital and Decay Calculations". In: (). URL: www.ips.gov.au

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:

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

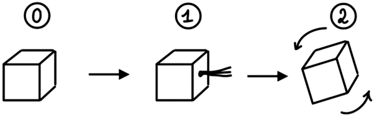
3.1.4 MATLAB simulation results



- 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 Manoeuvre

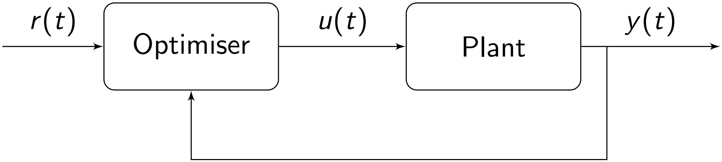


3.2.1. Control System

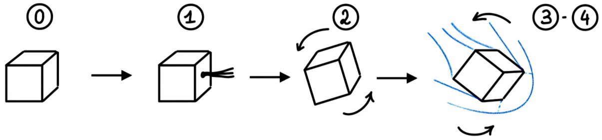
- Attitude controller is a MIMO Model Predictive Control (MPC) implementation of a system with kinematics and dynamics, respectively (using quaternion representation):

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

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

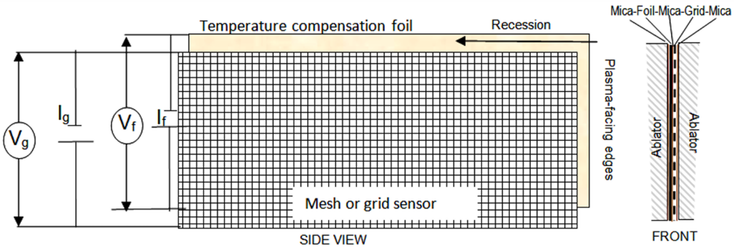


3.3. Data Acquisition & Transmission: Start



3.3.1. Data Acquisition

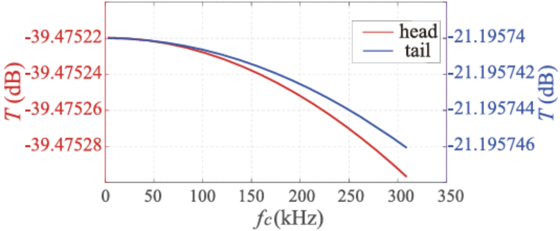
- Six sheets of test material are placed on the outer surface, each with its own sensor array measuring temperature and pressure
- A ReWiG recession sensor[2] is additionally integrated into each test material face



[2] George Vekinis. *"ReWiG" "A Resistive Wire Mesh TPS recession sensor"*. 2014

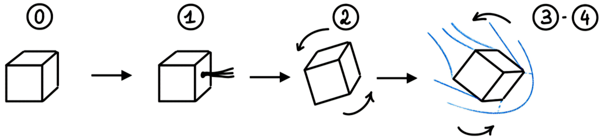
3.3.2. Data Transmission

- CubeSat will spin during reentry for uniform material testing, encountering a plasma sheath absorbing transmission[3]
- 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



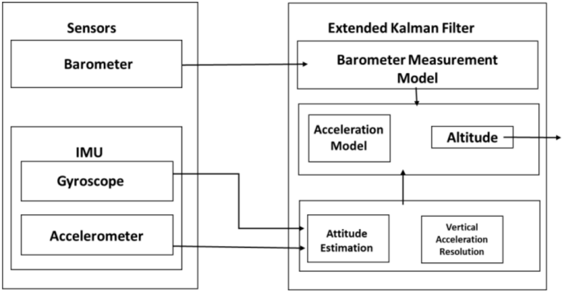
[3] Mingyang Mao et al. "The propagation characteristics of low frequency radio waves in magnetized hypersonic plasma sheaths". In: *AIP Advances 13* (2023)

3.4. Data Acquisition & Transmission: End



3.4.1. Secondary objective instrumentation

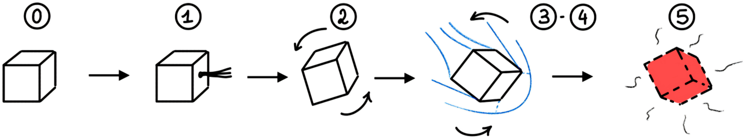
- **Spectrometer:** AvaSpec-Mini2048CL[4] Small and Powerful OEM Spectrometer, 200-1100nm
- **Calibration lamp:** AvaLight-CAL (-Mini) [5]
- **Inertial Measurement Unit and Barometer**
  - Altitude tracking accuracy will be improved by applying a Kalman filter with sensor fusion



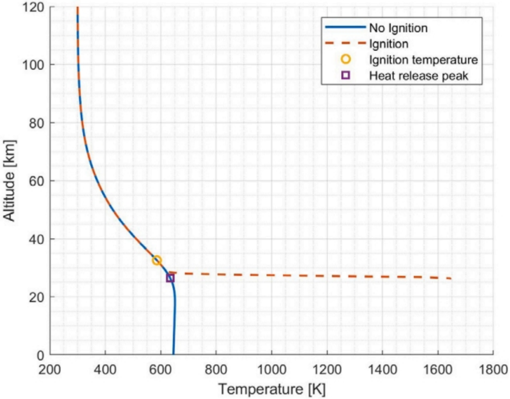
[4] *AvaSpec-Mini - Avantes.* URL: https://www.avantes.com/products/spectrometers/compactline/avantes-spectrometer-mini-2048cl-2/

[5] *AvaLight-CAL (-Mini) - Avantes.* URL: https://www.avantes.com/products/light-sources/calibration-light-sources/avalight-cal-mini/

3.5. Thermite Ignition



- Thermites (e.g. $\mathrm{Al} + \mathrm{Fe_2O_3}$) offer a safe and reliable mechanism for passive Demise (T4D[6])
- Tailored ignition temperatures and reaction characteristics can be achieved through **mechanical activation**

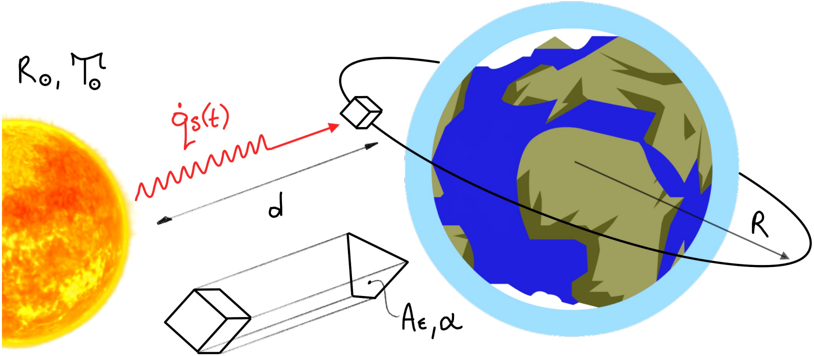


[6] A. Finazzi et al. “Thermite-for-Demise (T4D): Experimental analysis of heat transfer principles and preliminary sizing of an application”. In: *International Journal*

3.5.2. Aerothermal Modelling - Orbit

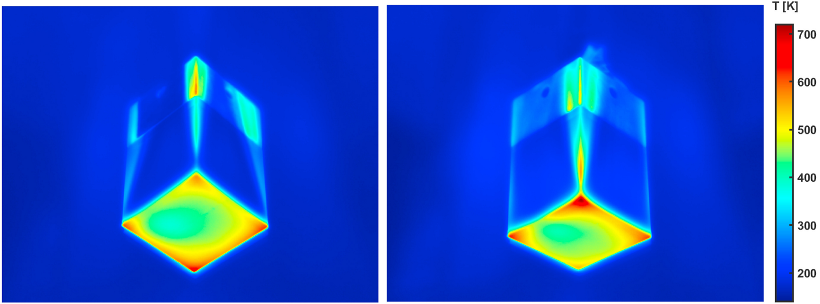
Design objective: Ensure inner CubeSat temperatures remain within the electronics' operational range during:

1. Orbital regime: $T_i > T_{min}$ with $T_o = \frac{T_\odot}{\sqrt[4]{A_E}}\sqrt{\frac{R_\odot}{d}} \simeq 120.6\,°C$



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

1. Orbital regime: $T_i > T_{min}$
2. Re-entry data logging phase[7]: $T_i < T_{max}$
   - 2D conduction model based on planar temperature distribution



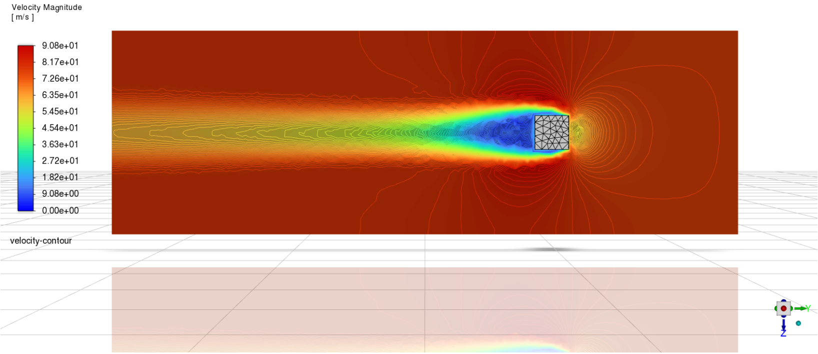
(a) $+5°$ experiment (leeward side)

(b) $-5°$ experiment (windward side)

[7] 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:

3.5.4. Aerothermal Modelling - CFD

- Due to low Strouhal numbers ($St = \frac{\Omega L}{V} \approx 10^{-5}$), quasi-steady state is assumed for flow around our CubeSat
- CFD results show agreement with experimental data for subsonic flow regimes
- Adaptive Mesh Refinement (AMR), and large mesh polyhedral counts are used in supersonic simulations to capture shocks and boundary layers



4.1. Conclusion: Project Risks & Budget

- Project Risks
  - Collisions with other satellites - low risk due to short mission time
  - Poor data quantity - Electronics/Sensors breaking too early - high risk
  - Earth Impact - very low due to Thermite

[8] Just for mission itself. Calculated by https://www.endurosat.com/configurator/ using most broad parameters - likely a lower bound

4.1. Conclusion: Project Risks & Budget

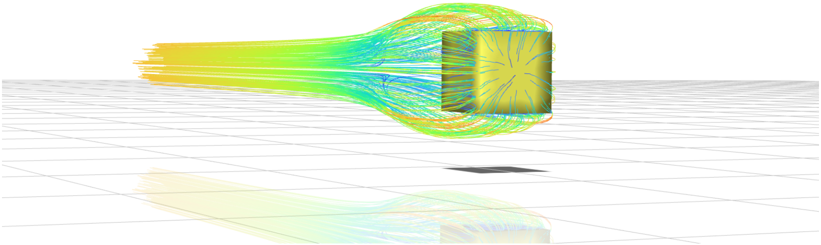
- Project Risks
  - Collisions with other satellites - low risk due to short mission time
  - Poor data quantity - Electronics/Sensors breaking too early - high risk
  - Earth Impact - very low due to Thermite
- Estimated Costs
  - Mission £318,000 [8]
  - Components £100,000 Based on a few known component costs

[8] 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 consideraions
  - Simulation of telemetry
  - Connection and wiring needs planning
- Aerothermal
  - Refine CFD meshes for hypersonic simulations
  - Validate simulations against hypersonic experimental results

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:

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

- $\boldsymbol{\omega} \in \mathbb{R}^3$ is the angular velocity vector of the CubeSat wrt an inertial frame, expressed in the CubeSat's frame of reference
- $\boldsymbol{q} \in \mathbb{R}^4$ is the quaternion attitude: $\boldsymbol{q} := \begin{bmatrix} \eta \\ \boldsymbol{\epsilon} \end{bmatrix} : \eta^2 + \|\boldsymbol{\epsilon}\|^2 = 1$
- $\boldsymbol{\Omega}(\boldsymbol{\omega}) \in \mathbb{R}^{4\times 4}$ is the skew-symmetric quaternion representation of angular velocity: $\boldsymbol{\Omega} := \begin{bmatrix} 0 & -\omega_i & -\omega_j & -\omega_k \\ \omega_i & 0 & \omega_k & -\omega_j \\ \omega_j & -\omega_k & 0 & \omega_i \\ \omega_k & \omega_j & -\omega_i & 0 \end{bmatrix}$
- $\boldsymbol{J} \in \mathbb{R}^{3\times 3}$ 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:

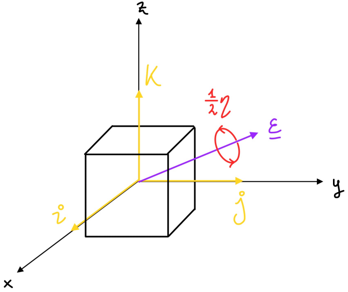
$$\boldsymbol{q} = \eta + \epsilon_i \boldsymbol{i} + \epsilon_j \boldsymbol{j} + \epsilon_k \boldsymbol{k} \equiv \cos(\eta) + \sin(\eta)(\epsilon_i \boldsymbol{i} + \epsilon_j \boldsymbol{j} + \epsilon_k \boldsymbol{k})$$

Any rigid body rotation can be represented as:

$$\boldsymbol{p}' = \boldsymbol{q}\boldsymbol{p}\overline{\boldsymbol{q}}$$

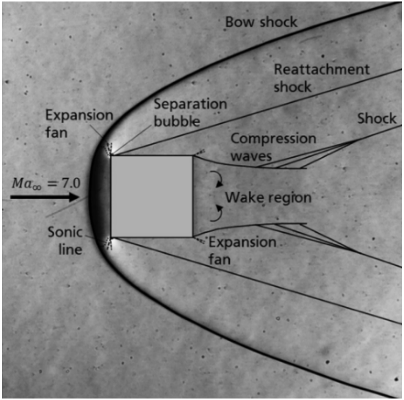
where η is the half-angle of rotation, and $\boldsymbol{\epsilon}$ defines the rotation axis.
For constant angular velocity $\boldsymbol{\omega}(t) = \boldsymbol{\omega}_0$, the state update simplifies to:

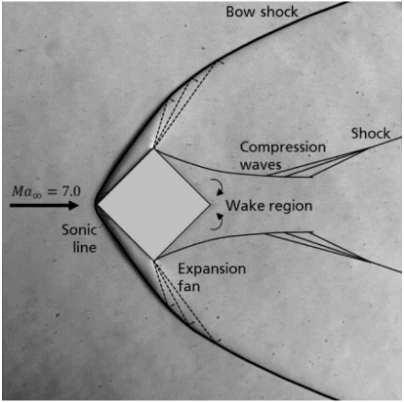
$$\boldsymbol{q}(t) = \exp\left[\frac{1}{2}\boldsymbol{\Omega}(\boldsymbol{\omega_0})t\right]\boldsymbol{q}(0)$$



Appendix B: Critical Flow Configurations

Experiments and simulations have been carried out on cube geometries [9]. Critical 2D configurations as shown:





[9] Patrick M. Seltner, Sebastian Willems, and Ali Gülhan. "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