

# Aerodynamics of CubeSat Geometries in High-Speed Flow

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CubeSats are a popular form of miniature spacecraft capable of quality science experiments, so it was of interest to study their behavior in high-speed flow. The aerodynamic coefficients of CubeSat geometries were studied in a hypersonic wind tunnel located at the University of Maryland using free-flight techniques. A high-speed visualization device was used to capture the body's motion during the testing period. Combining a function for the cube outline with a pixel edge tracking routine allowed for the calculation of the aerodynamic coefficients. It was observed that the three rotation angles had a significant impact on the aerodynamic properties.

## Nomenclature

$\alpha$	=	angular acceleration
$a$	=	linear acceleration
AoA	=	rotation about the x-axis
$C_L$	=	lift coefficient
$C_D$	=	drag coefficient
$C_M$	=	moment coefficient
$c$	=	chord
$dt$	=	time step between frames
$F_x$	=	X component of the force on the cube
$F_y$	=	Y component of the force on the cube
$I$	=	moment of inertia
$S$	=	reference area
$K$	=	Kelvin
$m$	=	cube mass
$a$	=	cube acceleration
$x_0$	=	cube center of mass x position
$y_0$	=	cube center of mass y position

## I. Introduction

In the current age, many satellites operate in Low Earth Orbit (LEO). As new spacecraft are launched into space, the old ones are deorbited and free-fall back towards the Earth's surface. In addition, small meteoroids and other spacecraft debris will reenter the atmosphere. These objects have the potential to be dangerous towards people and items on the surface. Thus, it is important to understand how the debris responds to atmospheric forces, enabling scientists and engineers to predict their trajectories as they travel towards the ground at hypersonic speeds. One popular satellite geometry is CubeSats, which will be the target of this study.

Previous research performed in Germany observed the pitch-angle-dependent aerodynamic of cubes in hypersonic flow [1]. It was found that the aerodynamic coefficients were strongly affected by the orientation of the cube in the flow field and equilibrium was achieved at two specific orientations.

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This study seeks to determine and corroborate the effect of orientation angles on the aerodynamic properties of cube geometries in hypersonic flow. The free-flight technique in tandem with a hypersonic wind tunnel was used to replicate the conditions of atmospheric reentry. The following section will discuss in more detail the methodology used to perform the tests and derive the forces/moments. After this, the results will be presented and analyzed.

## II. Methodology

### A. Wind Tunnel Tests

The experiment was conducted at the University of Maryland's HyperTERP wind tunnel. HyperTERP is capable of Mach 6 flow and reservoir temperatures and pressures of 1500 K and 25 atmospheres. With a frame rate of 20,000 frames per second, the test was done over a span of milliseconds. Initially, the cube was suspended in the testing chamber with masking tape, so upon contact with the flow it would fall freely into the chamber to undergo aerodynamic loading. Simultaneously, a telecentric illuminator allowed the exact silhouette of the cube to be displayed. To observe the cube's motion over such a short period of time, the tunnel is equipped with a high-speed camera that captures the cube's isolated silhouette over 1000 frames. Figure 1 shows one of thousands of frames captured during the test, which will subsequently be processed using a variety of MATLAB scripts to obtain the aerodynamic coefficients.

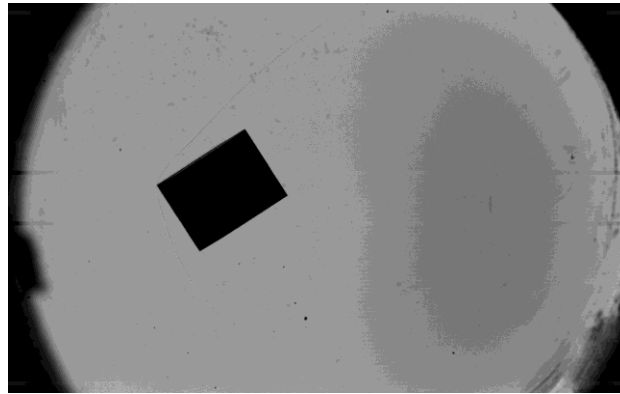


Fig 1. Frame of the cube during testing

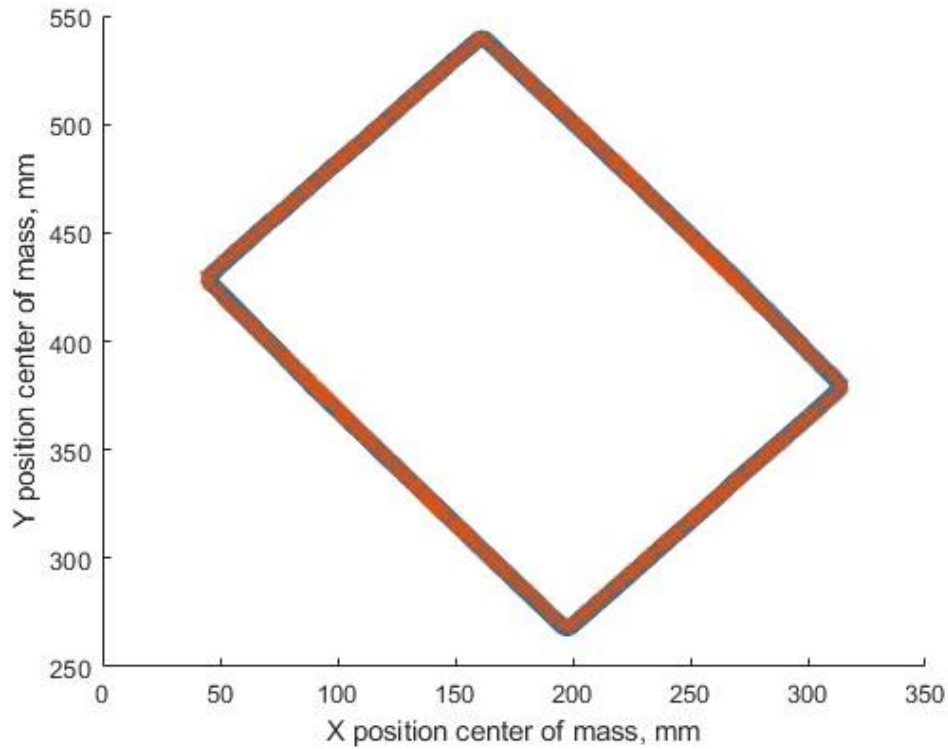
For this experiment, the freestream velocity was 677.771 meters per second, and the density was 0.0367 kilograms per cubic meter. The cubesat had dimensions of 20 mm x 20 mm x 34 mm and a mass of 0.0169 kilograms. This model is much smaller and less massive than the one used in Germany, which had an edge length of  $50.30 \pm 0.06$  mm and a mass of  $981.33 \pm 0.03$  grams [1].

### B. Calculating Coefficients

After the wind tunnel tests, hundreds of frames were processed using a variety of MATLAB scripts. First, an edge detection routine was used to obtain x and y coordinates of the cube's outline in each frame. This algorithm has been used in a similar study examining the aerodynamic coefficients of cylinders [2]. Two other scripts were used with the edge tracking script: a script that produced the radius from the center of the outline and an optimization program that determined the pose parameters of each frame over time.

The first program used cartesian to polar coordinate formulas to produce the radius from the center given a theta value around the outline. Other inputs included a scale factor and the three orientation angles, as these parameters allowed for an edge to be generated. The outline detection was performed using MATLAB's built-in convex hull function. The radius output was used within the optimization script, based on the cylindrical algorithm used by Duchene and Laurence [2]. The first set of points from the edge detection routine was loaded in, and then initial guesses of the six parameters were inputted (scale, angle of attack, yaw, roll,  $x_0$ ,  $y_0$ ). Using the radius script, the difference between the actual outline and the guess outline was minimized using nonlinear least squares. Upon successful convergence, the parameters for that frame were produced. To get the parameters for the successive frame, the previous frame's final values were used as the initial guess for the next frame due to the minimal motion that the cube experienced between the two points in time. As shown in Fig 2 below, there is great agreement between the

actual and optimized outline, ensuring that the following frames will have accurate pose parameters.

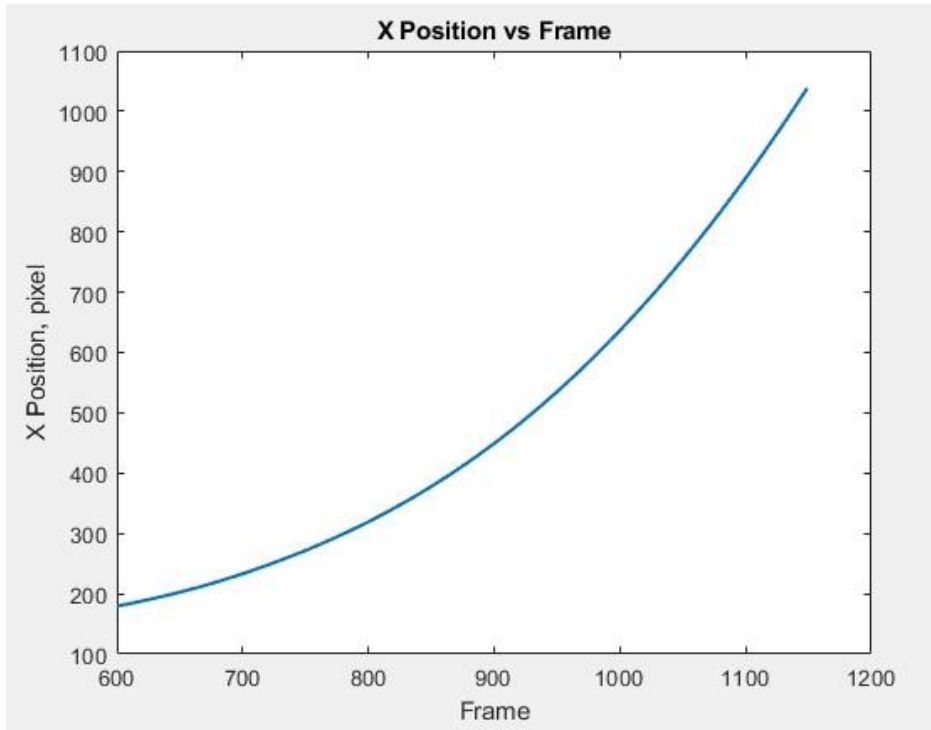


**Fig 2. Actual outline (blue) vs. Optimized outline (orange)**

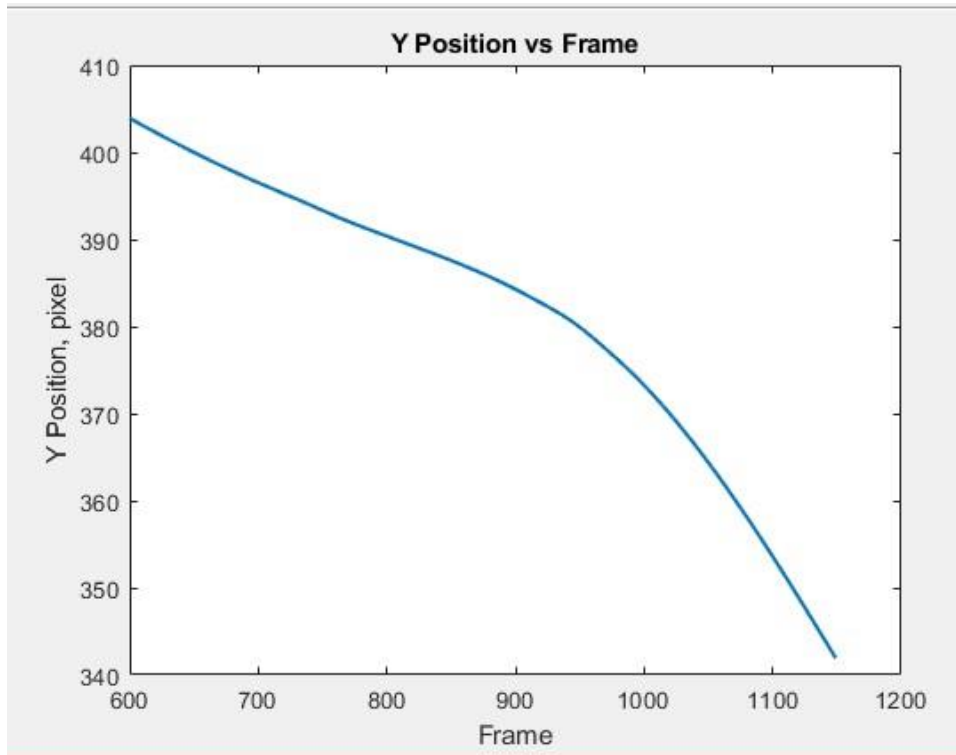
To calculate the forces and moments on the cube, central difference was performed twice on the center of mass position and each rotation angle to obtain the corresponding accelerations; MATLAB's `gradient()` function was used for this task. With the modal mass and accelerations in the x and y direction, the forces in those directions were found using Newton's 2nd Law ( $F=m*a$ ). A conversion factor of 8.5 pixels per mm ( $1.174 * 10^{-4}$  m per pixel) was applied to convert the (x,y) coordinates to the proper units of meters to obtain the forces. Using the rotational analog of the formula, the moment of inertias and angular accelerations in the x, y, and z directions were multiplied to get the moments ( $M = I*\alpha$ ). From there, calculating the lift and drag coefficients was done by dividing the forces by  $q*S$ . Similarly, the moment coefficients were computed by dividing the moments by  $q*S*c$ .

### III. Results

After processing the images, the x and y position and the three rotation angles of the cube were plotted over the frames to observe the behavior over time. To remove the noise from the plots, a Savitsky-Golay filter was applied three times to the data: first to the pose parameters, second to the velocities, and finally to the accelerations. It allowed the trends in the aerodynamics coefficients to be seen over time and as a function of the angles.

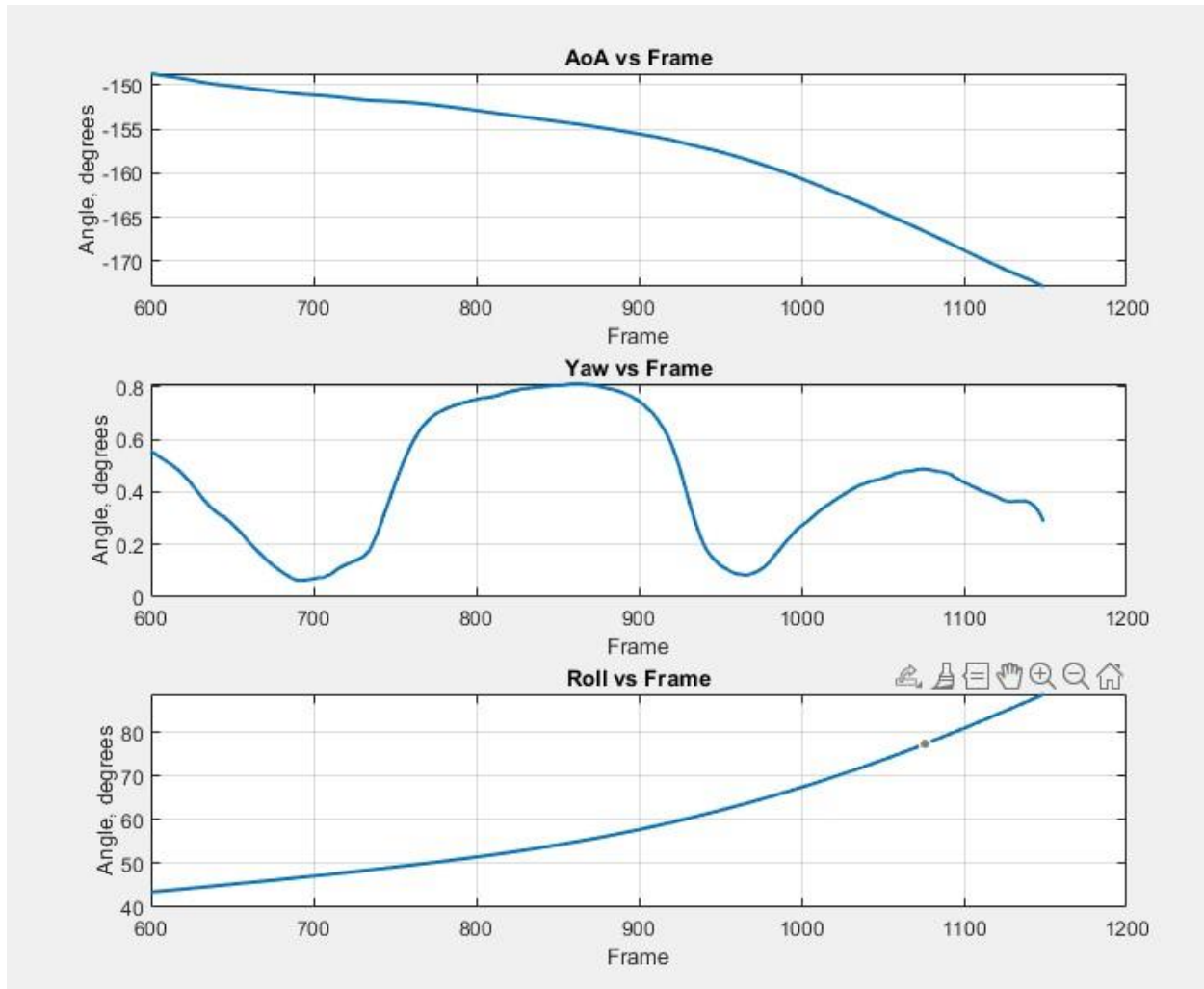


**Fig 3. X Position versus Frame**



**Fig 4. Y Position versus Frame**

The two figures above show smooth motion of the cube's position over time; these values were twice differentiated to calculate forces and subsequently lift and drag coefficients.

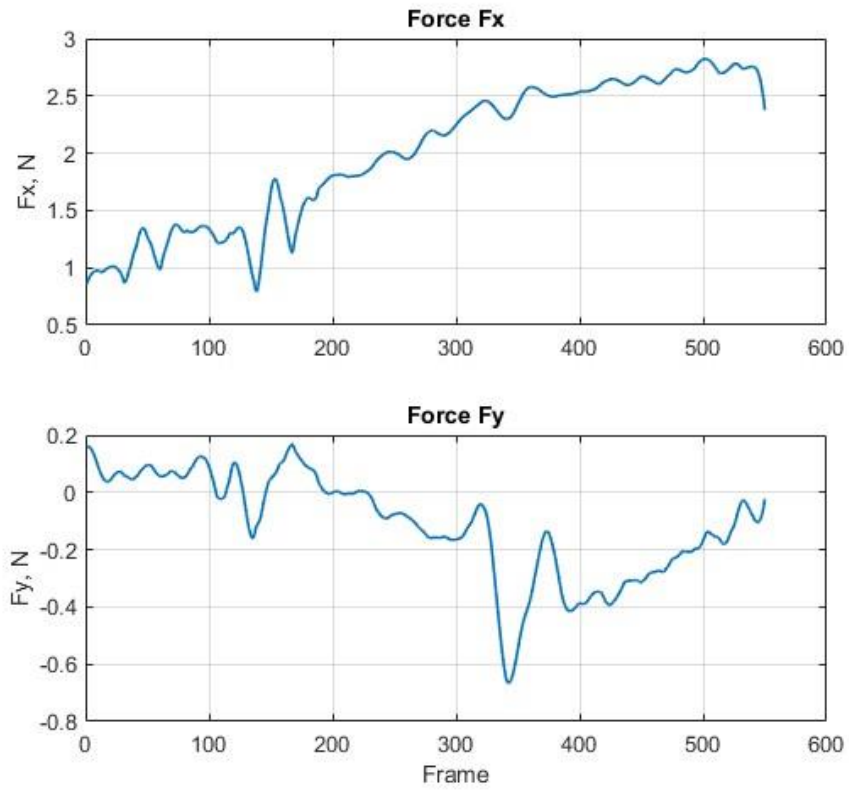


**Fig 5. Orientation Angles versus Frames**

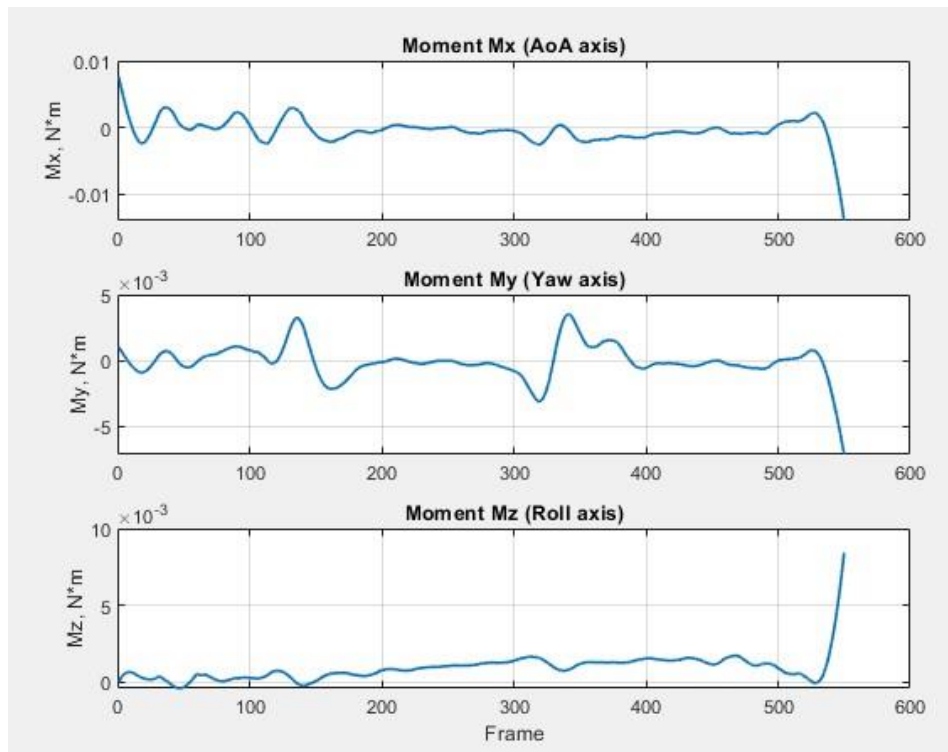
As shown in Fig 5, the angle of attack, i.e. rotation about the x-axis, decreased over the duration of the test, and the roll increased in a polynomial-like shape. On the other hand, the yaw oscillated about a mean value of approximately 0.4 degrees with an amplitude of 0.3 degrees, so it remained very small throughout the experiment. These parameters provide the angular accelerations in each direction, which allow for the calculation of moments. In Fig 6 below, one can observe that  $F_x$ , or the drag force, increased in magnitude while  $F_y$ , or the lift force, did not seem to change very much, ultimately settling near zero newtons by the end of the test. Finally, the moments in all three directions were close to zero during the entire duration as well.

To gauge the effect of orientation on the aerodynamic behavior of the cube, it is more interesting to plot the forces versus the true angle of attack which is calculated using equation (1).

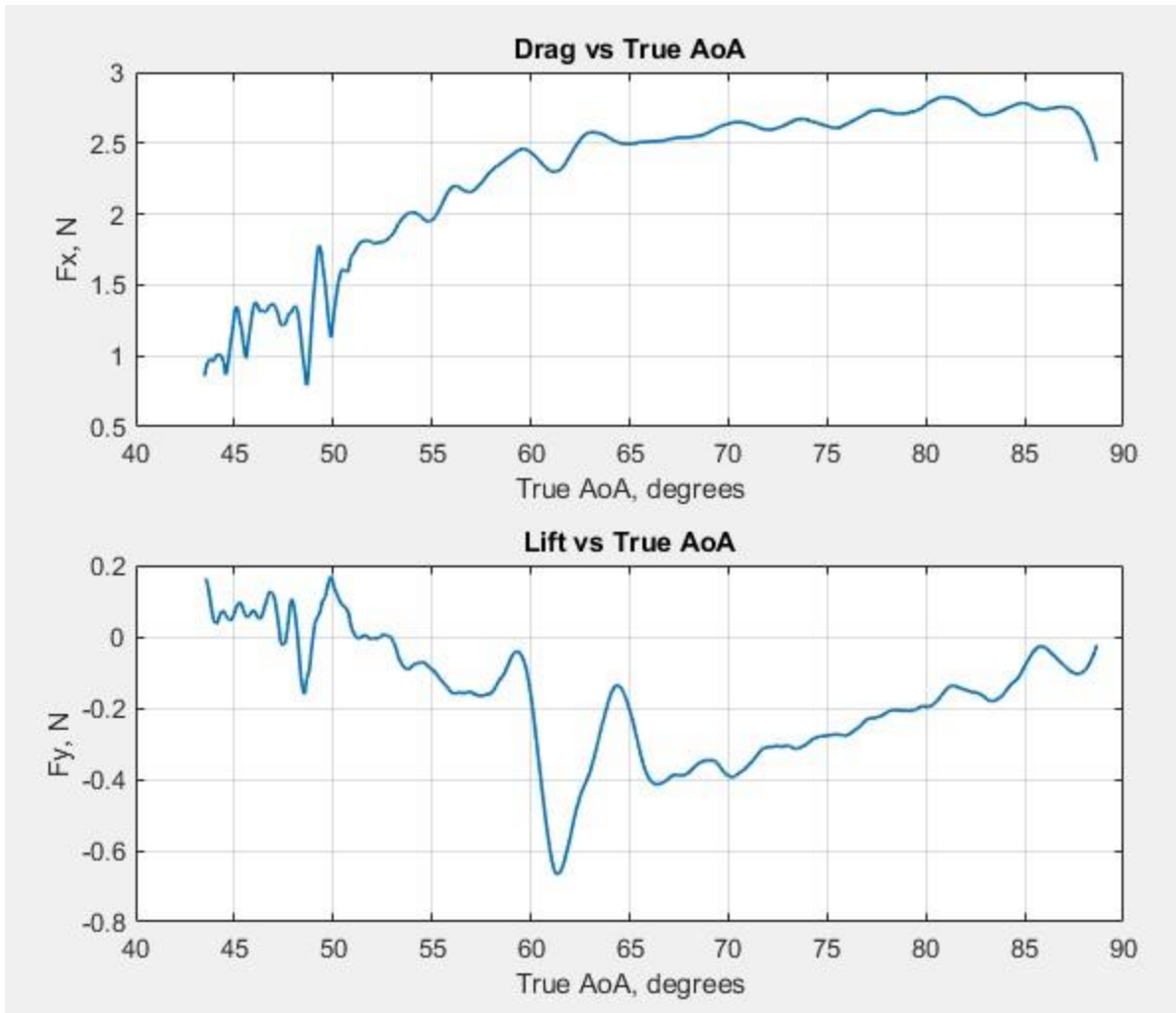
$$\arccos(\cos(yaw) \cdot \cos(roll)) \quad (1)$$



**Fig 6. Forces versus Frame**



**Fig 7. Moments versus Frames**



**Fig 8. Lift and Drag versus True Angle of Attack**

Figure 8 shows a clear relationship between drag and the true angle of attack. As the angle increased, drag also increased before stabilizing a value of  $\sim 2.5$  newtons. For lift, the relationship is not as evident. Between angles of 40 and 65 degrees, the lift decreased before increasing towards zero newtons at angles greater than 65 degrees. These findings generally agree with those of the German experiment, which found that “the aerodynamic coefficients depend on the flight attitude” [1]. In this experiment, as the cube undergoes the flow field, the drag force on the object increases as the angle of the cube with respect to the flow changes.

#### **IV. Conclusion/Further Work**

The HyperTERP wind tunnel at the University of Maryland was used to study the behavior of a CubeSat geometry in hypersonic flow with free-flight techniques. With the goal of predicting reentry trajectory, an advanced camera system was used to capture the cube’s silhouettes as it experienced the flow. Calculating the lift and drag and plotting them as functions of the true angle of attack, there was evidence to suggest that the drag force is influenced by the orientation of the cube with the flow.

In the future, it would be beneficial to study other CubeSat geometries, such as 2U and 3U, which are multiple cubes stacked on top of one another. Since many objects in Low Earth Orbit are not necessarily cube-shaped, this would allow us to understand how different types of objects respond to hypersonic flows. and hopefully predict their trajectories as they reenter the Earth’s atmosphere.

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### **References**

[1] Seltner, P. M., Willems, S., and Gulhan A., "Aerodynamic Coefficients of Free-Flying Cubes in Hypersonic Flowfield," *Journal of Spacecraft and Rockets*, Vol. 56, No. 6, 2019, pp. 1725–1734.  
doi: 10.2514/1.A34345

[2] Duchene, T. A., and Laurence, S. J., "The Aerodynamics of Free-Flying Cylinders in High Supersonic Flow," *AIAA Aviation Forum and ASCEND 2024*, Las Vegas, NV, 29 July–2 Aug. 2024.  
doi: 10.2514/6.2024-3923