CFD Analysis of a Passive Deorbit Device

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San Jose State University

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Master of Science in Aerospace Engineering

By

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approved by

Dr. ___________
Faculty Advisor

San José State
UNIVERSITY

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Summary

CBAERO will be used to simulate the flow about a passive deorbit device (Exo-Brake) as it deorbits from Low Earth Orbit. These results will be compared to high fidelity solvers implementing DSMC code and other lower fidelity models such as DACFREE. The comparison will show that CBAERO is a good starting point for iterative design where a fast solution is desired.

Background

Small satellites have changed the way experiments are conducted in space. A typical commercial satellite weighs hundreds of pounds, is the size of a small car, and can cost billions of dollars to design, build, launch, and maintain. A nanosat weighs between 2.2 and 22.0 pounds, can range in size from 1U to 6U (1U = 10cm x 10cm x 10cm by CalPoly standards), and are budgeted under $4 billion; many are created for hundreds of thousands of dollars. Nanosats have a typical lifespan of about one year if deployed in Low Earth Orbit (LEO), but this lifespan can be lengthened or shortened depending on whether the nanosat has a propulsion or drag system. Measurement, communication, and other electronic hardware have become so small, low powered, and accessible that it has allowed game changing technologies and scientific experimentation to be conducted in a small volume. The small scale of a nanosat mission allows for research to be performed in incremental steps with a higher frequency of experimental data return.

Introduction

TechEdSat-X (TES) is a series of nanosats that have been designed, built, and tested at NASA Ames Research Center with collaboration from San Jose State University (SJSU) and the University of Idaho (UofI). The objective of TES is to be able to quickly and precisely land a payload on the surface of a planet from orbit. The first stage of the mission involves deorbiting the nanosat using a passive deorbiting system known as an Exo-Brake. The Exo-Brake is a cross-parachute that is deployed from the nanosat and increases the nanosat’s drag and decreases its ballistic coefficient. The first experimental flight of the Exo-Brake was onboard TechEdSat-3p (TES-3p) and was deployed from the ISS in November of 2013. TES-3p was a 3U nanosat with a calculated lifespan of about eight months. Two-line elements (TLEs) collected from USSTRATCOM show that TES-3p spent about 28 days in orbit before it reentered the Earth’s atmosphere. Deploying an Exo-Brake with a front cross-sectional are of about one meter squared, it reduced the typical time in space by about seven months. The deorbit duration of TES-3p proved the technology demonstration.

Future missions require that the on-orbit duration be less than two days, therefore it will be necessary to increase the size of the Exo-Brake but also provide a range of areas in order to increase or decrease orbit duration by modulation of the Exo-Brake. In order to provide this range of areas a more accurate analysis of the Exo-Brake's orbit trajectory is required, therefore CFD tools like CBAERO, esi, and DAC will be utilized to create a flow case study.

Environmental Considerations

The Exo-Brake will be traveling at hypersonic speeds and at very high altitudes. At very high altitudes the flow through which the Exo-Bake travels has very little molecular density but it increases as altitude decreases (Figure 1). The first flow regime encountered by the Exo-Brake is free-molecular flow and is characterized by a Knudsen number greater than 10. The Knudsen number is a dimensionless number that defines the ratio of the average distance travelled by a molecule in between collisions and a representative length. A large Knudsen number represents a flow where there is a large amount of space between molecules causing fewer collisions (low energy). The second regime is transitional flow which is characterized by a Knudsen number that is less than 10 but greater than 0.1. The third regime is slip flow and is characterized by a Knudsen number that is less than 0.1 and greater than 0.01. Eventually the Exo-Brake enters the continuum flow regime where the Knudsen number is less than 0.01.

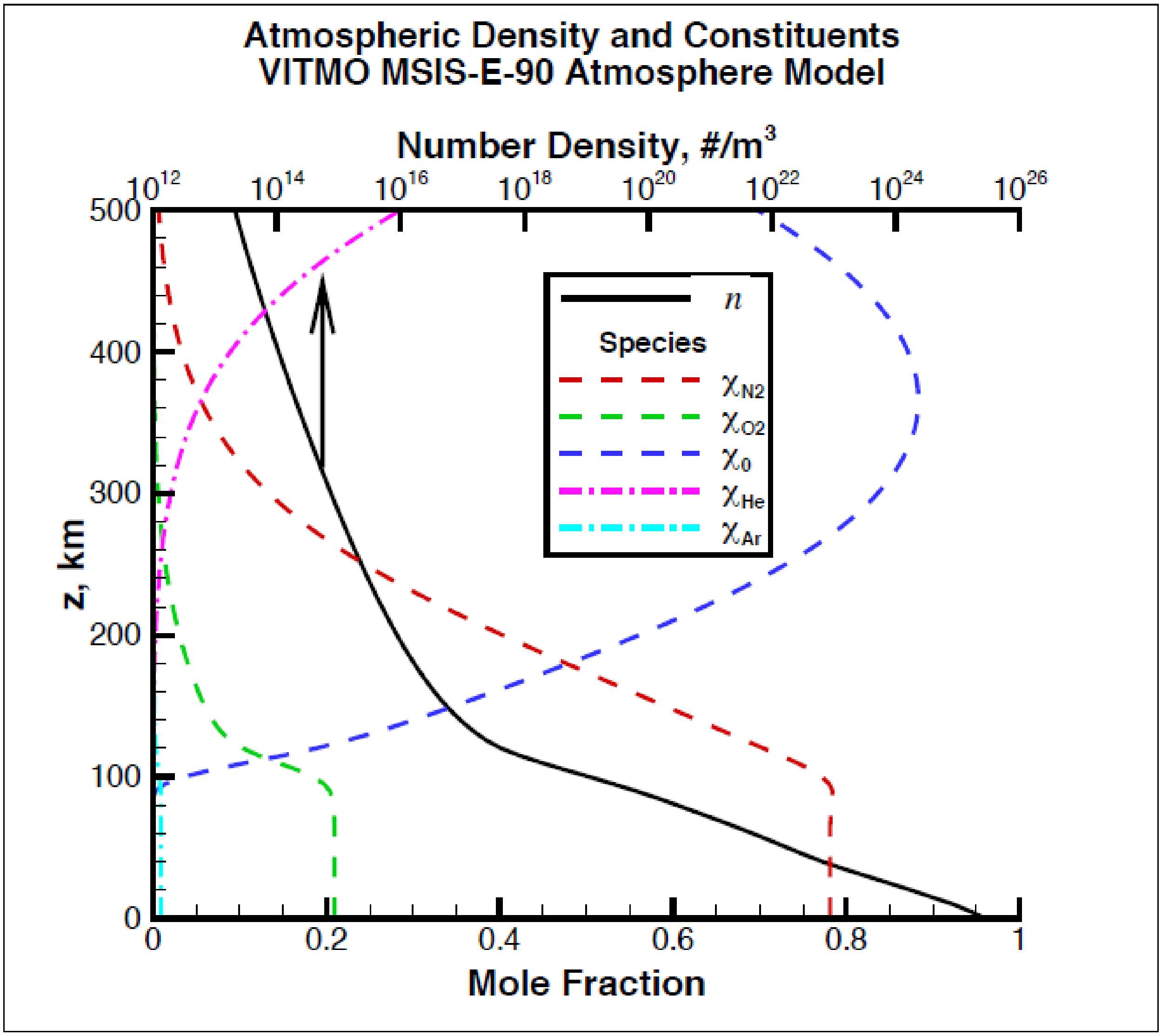


Figure 1: Atmospheric Density and Constituents, obtained from http://omniweb.gsfc.nasa.gov/vitmo/msis_vitmo.html

As the satellite decreases in altitude and travels through theses regimes, the density of the atmosphere will dramatically increase, which will decrease the satellite's speed exponentially. Analysis of the Exo-Brake requires a statistical mechanics approach where the flow has a Knudsen number of greater than one.

Tools

In order to complete a thorough analysis of the Exo-Brake a few selected computer modeling programs will be utilized.

SolidWorks

- Geometry
- 2D Grids

ESI Suite

CFD-GEOM

- Surface meshes
- Cartesian meshes

CFD-VisCART

- Fix discontinuities in the geometry

CFD-FASTRAN

- Hypersonic continuum flow simulation

CFD-VIEW

- ESI flow analysis

Pointwise

- Mesh

CBAERO

- Engineering level hypersonic flow analysis
- DAC data anchoring
- Exo-Brake optimization

DAC

- High fidelity hypersonic flow analysis
- DAC-Free for free-molecular flow regime

Methodology

The analysis of the Exo-Brake will be broken down into segments and evaluated at each stage in order to obtain a correlation of data as the simulations become more complex.

Geometry

The geometry of the Exo-Brake will evolve as follows: Flat Plate (2D), Flat Cross-Parachute (2D), Quarter Circle (2D), Half Dome (3D), Exo-Brake (3D), and TES-3p (3D). All geometries have been created in SolidWorks 2014 as .STL files.

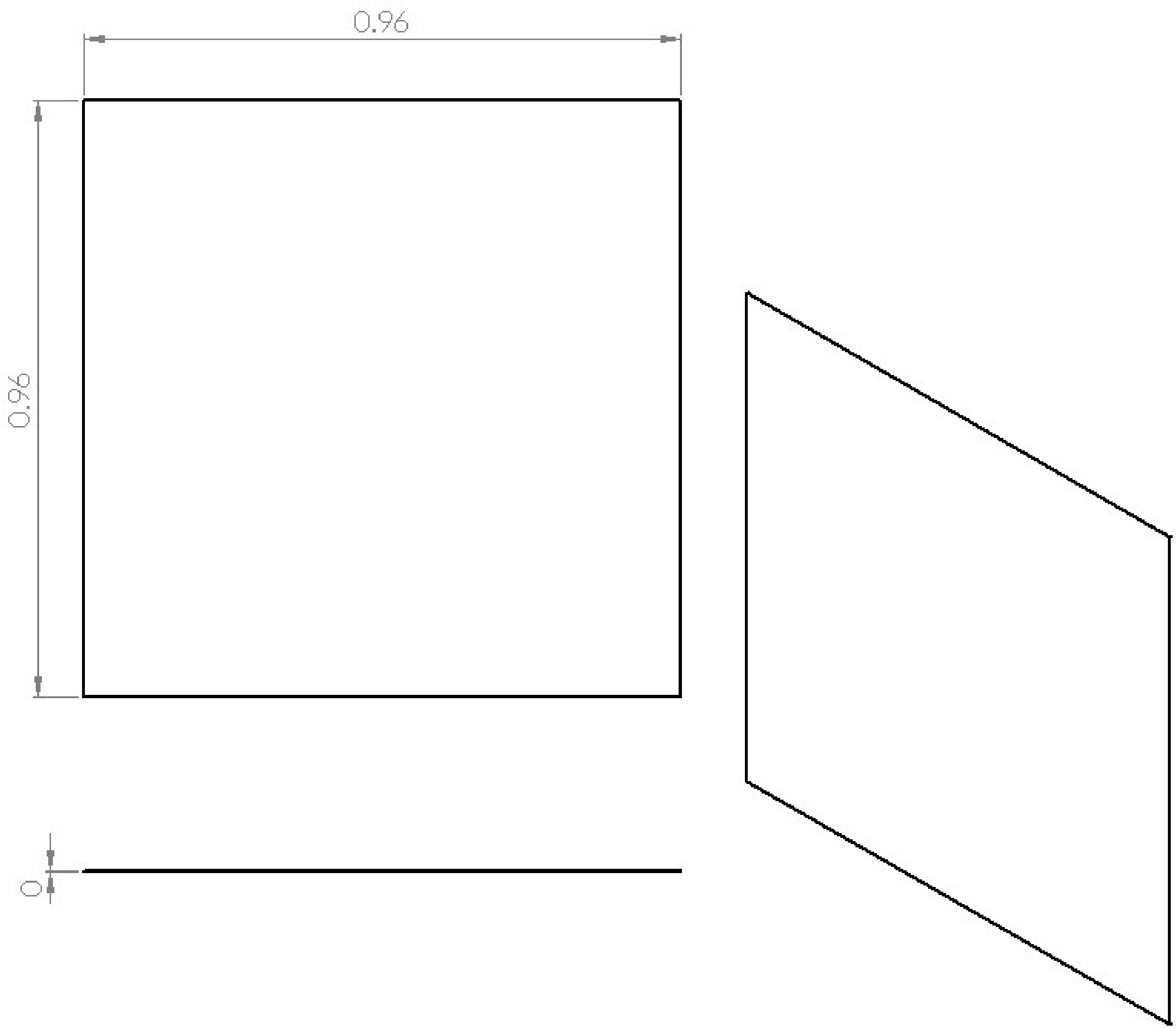


Figure 2: Flat Plate Geometry

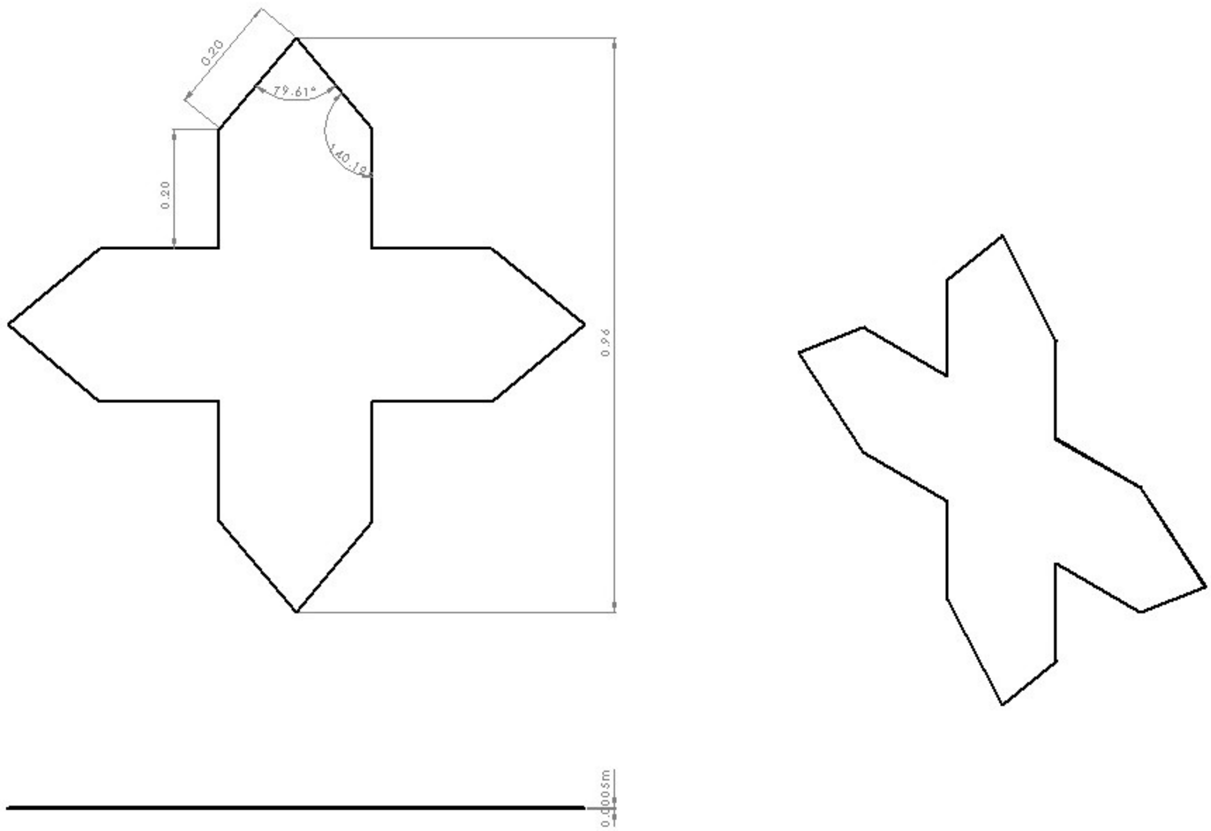


Figure 3: Flat Cross-Parachute Geometry

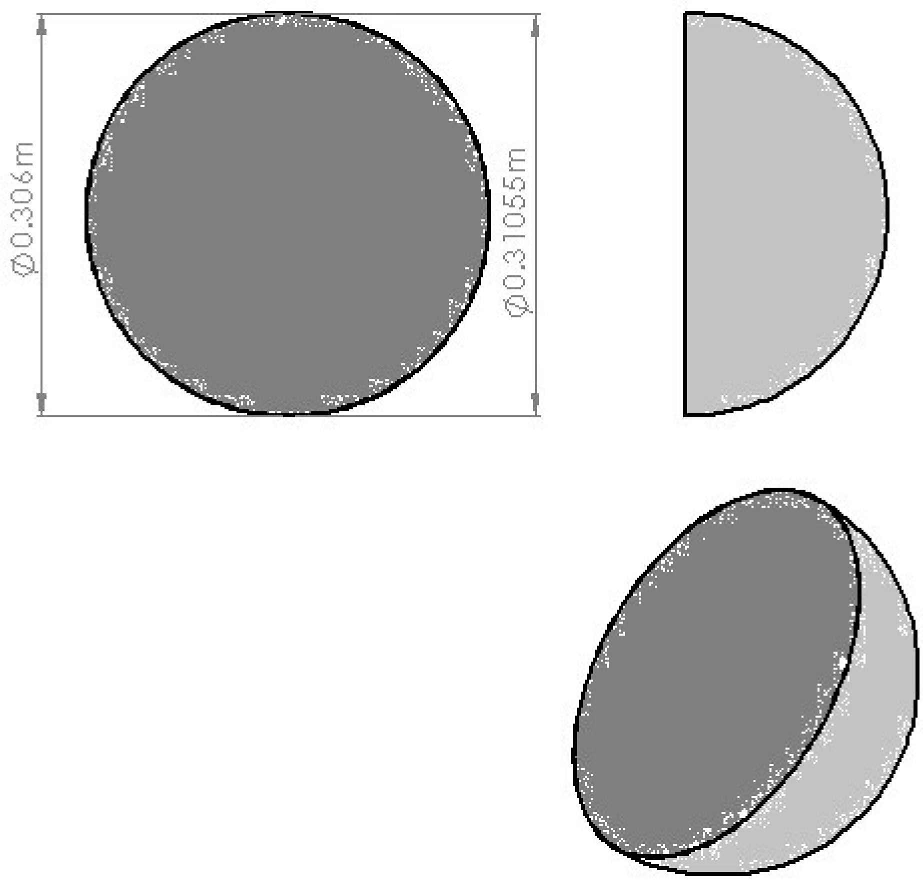


Figure 4: Dome Geometry

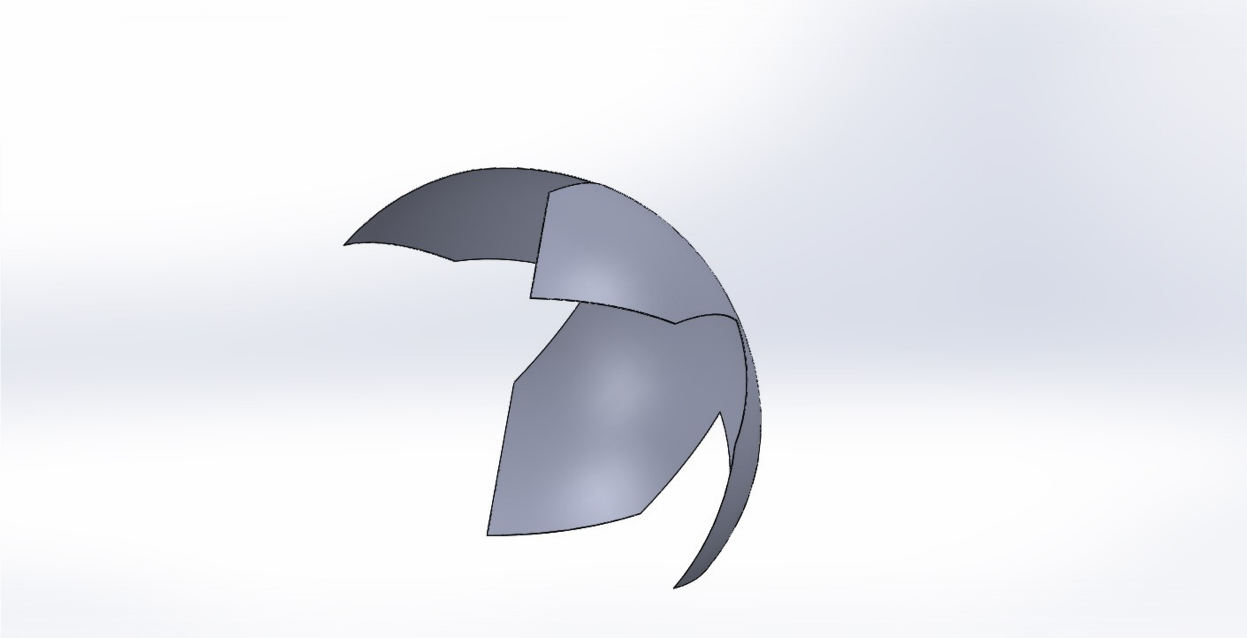


Figure 5: Exo-Brake Geometry

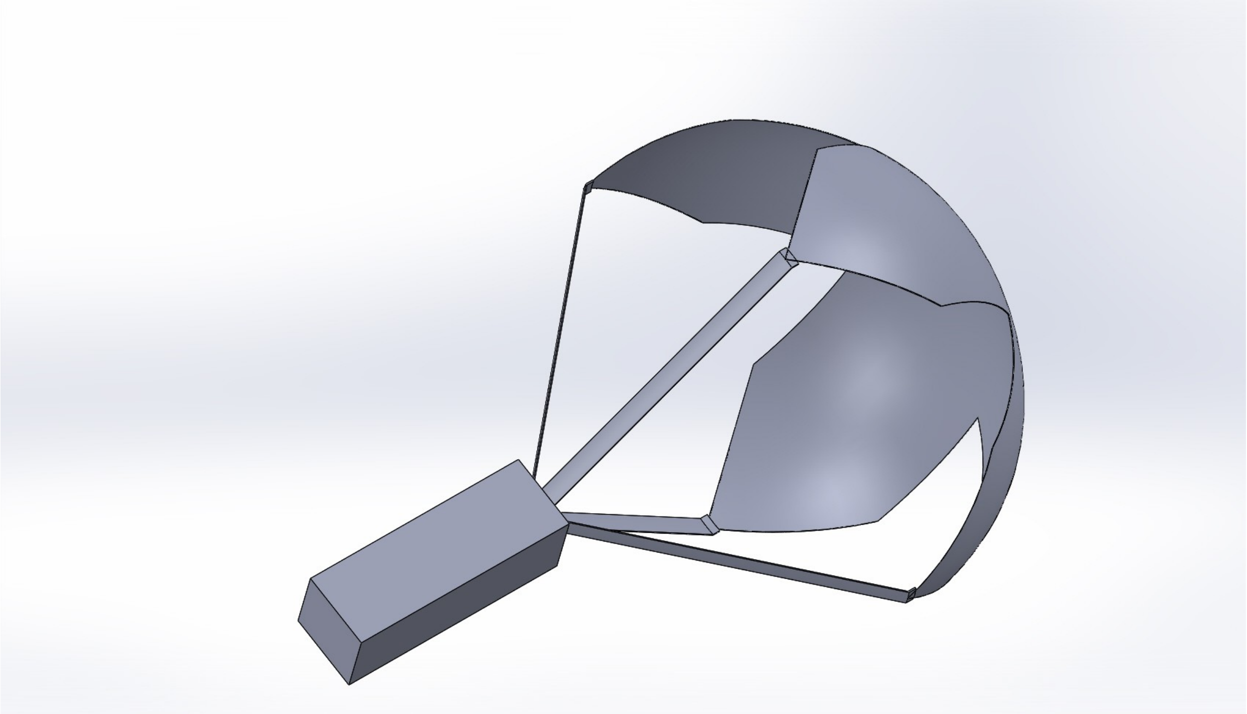


Figure 6: TES-3p Geometry

Grids/Meshes

All two-dimensional geometries will have grids created in SolidWorks 2014 (.STL) and surface meshes created in esi's CFD-GEOM as .msh files. Three-dimensional geometries will have Cartesian meshes created in esi's CFD-GEOM as .DTF files.

These .DTF files will be converted to the CBAERO .msh using a Python script written by Dr. Periklis Papadopoulos.

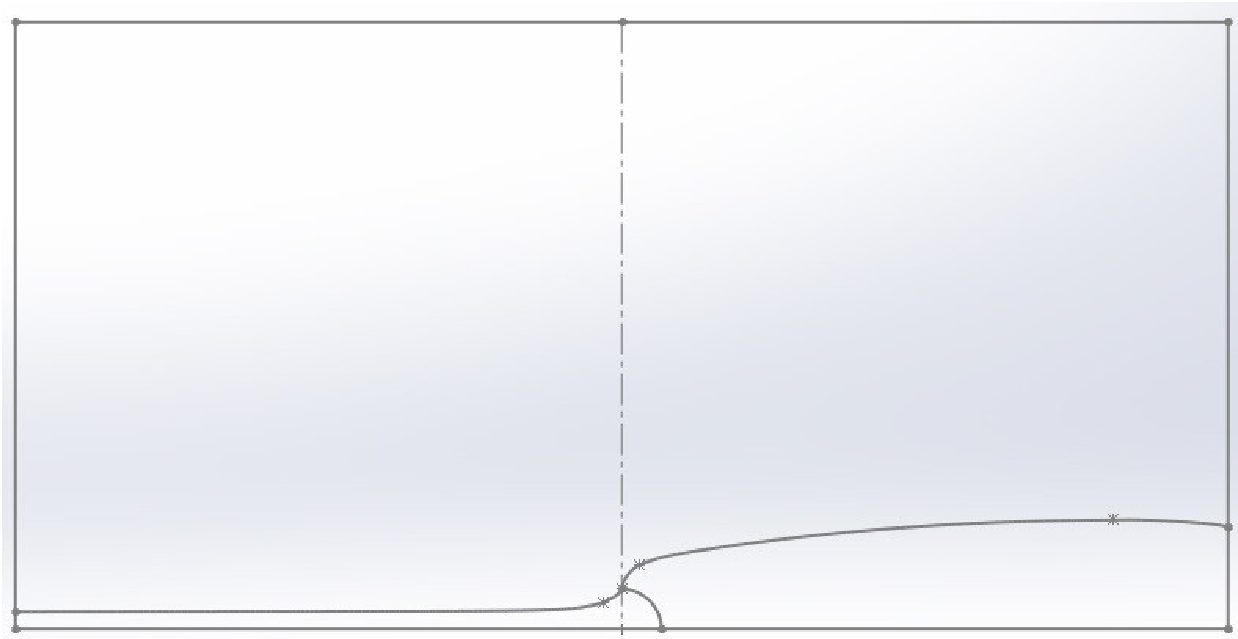


Figure 7: Quarter Circle Grid

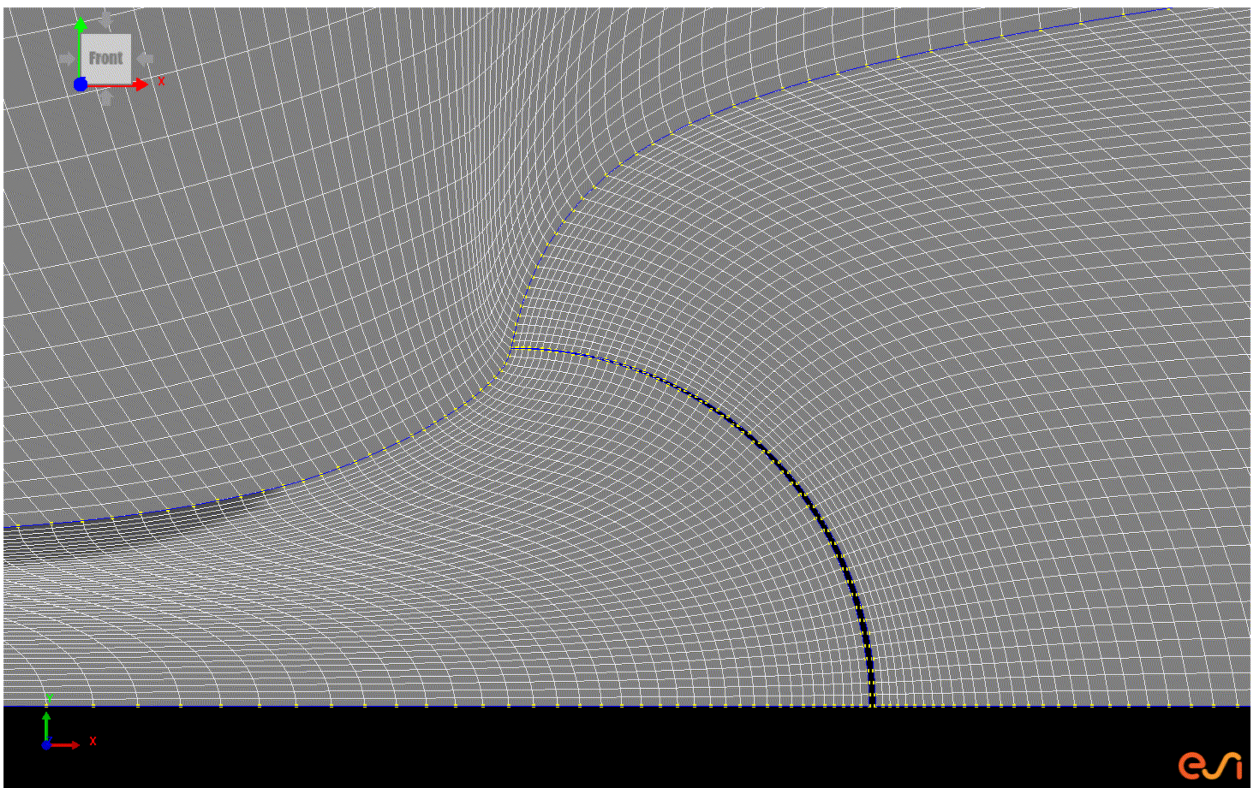


Figure 8: Quarter Circle Surface Mesh

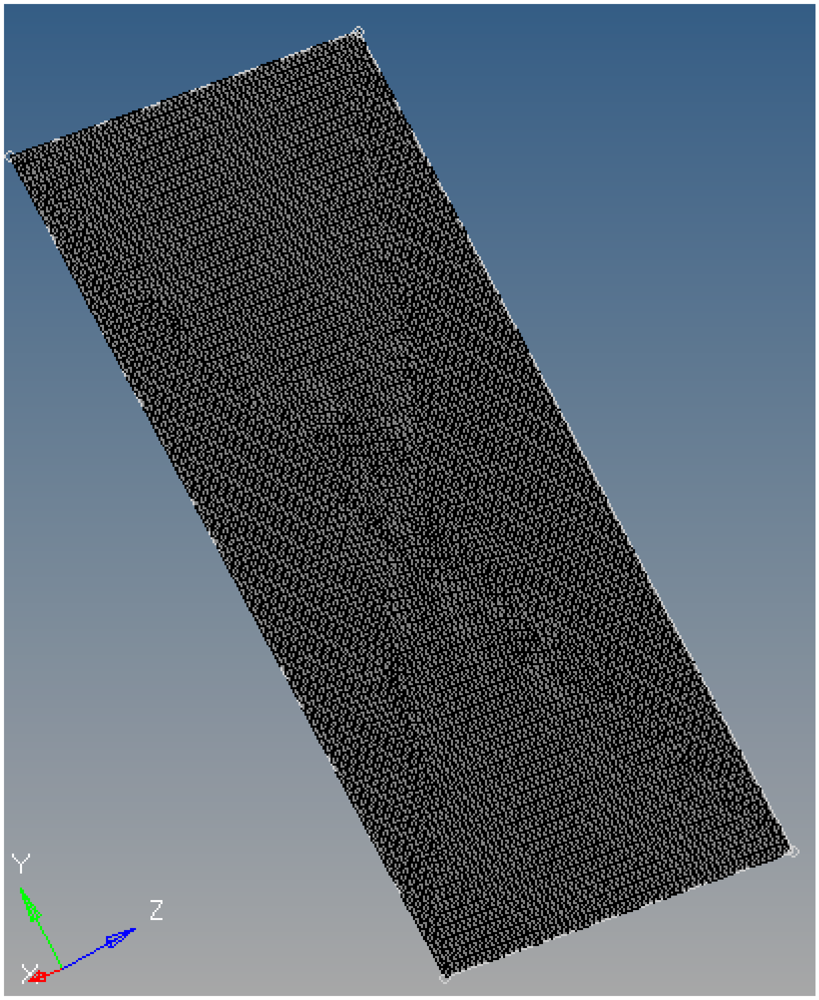


Figure 9: Flat Plate Surface Mesh

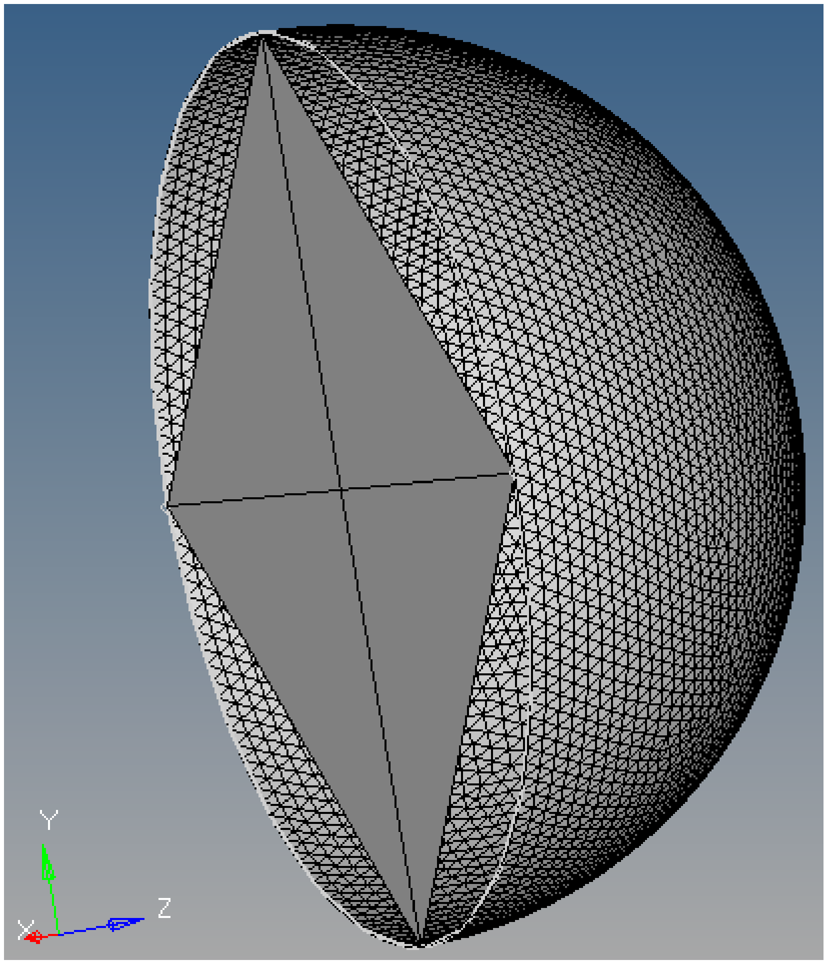


Figure 10: Half Dome Surface Mesh

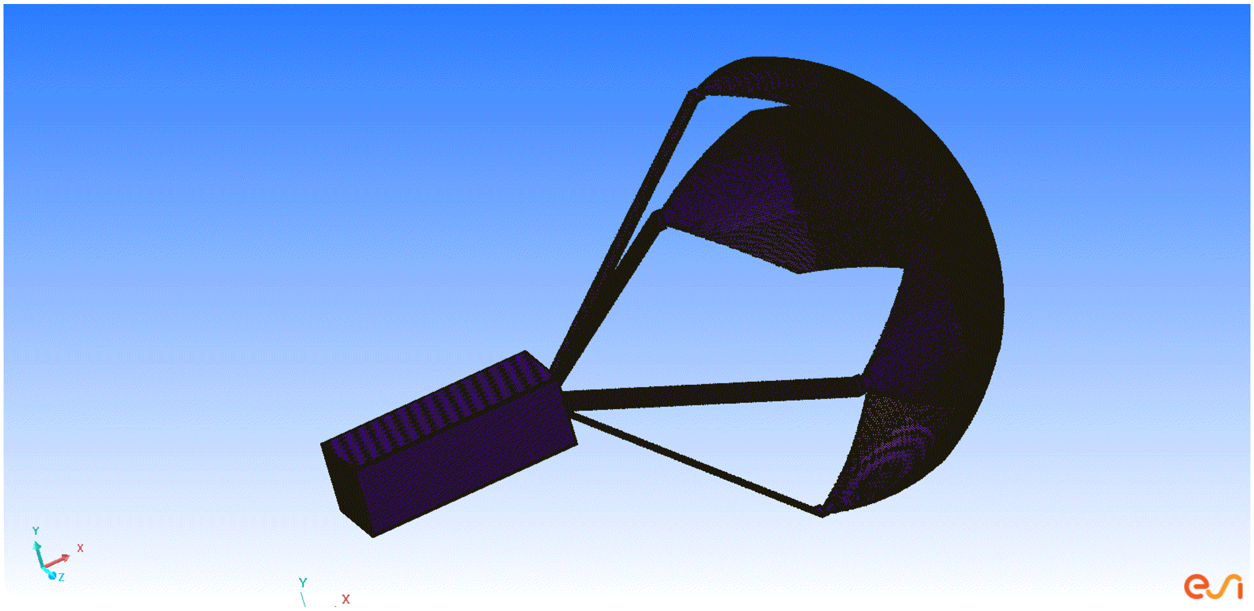


Figure 11: TES-3p Cartesian Mesh

Flow Simulations

Flow simulations will initially be loaded into CBAERO and esi for engineering level analysis and later run in DAC to obtain high fidelity results. The results from DAC will then be loaded into CBAERO and anchored to the simulation to provide a better approximation of the results.

Flow Visualization

For results obtained from esi’s CFD-FASTRAN, CFD-VIEW will be used to visualize the results as can be seen in Figure 12. CBAERO has a similar functionality that will allow visualization within the program.

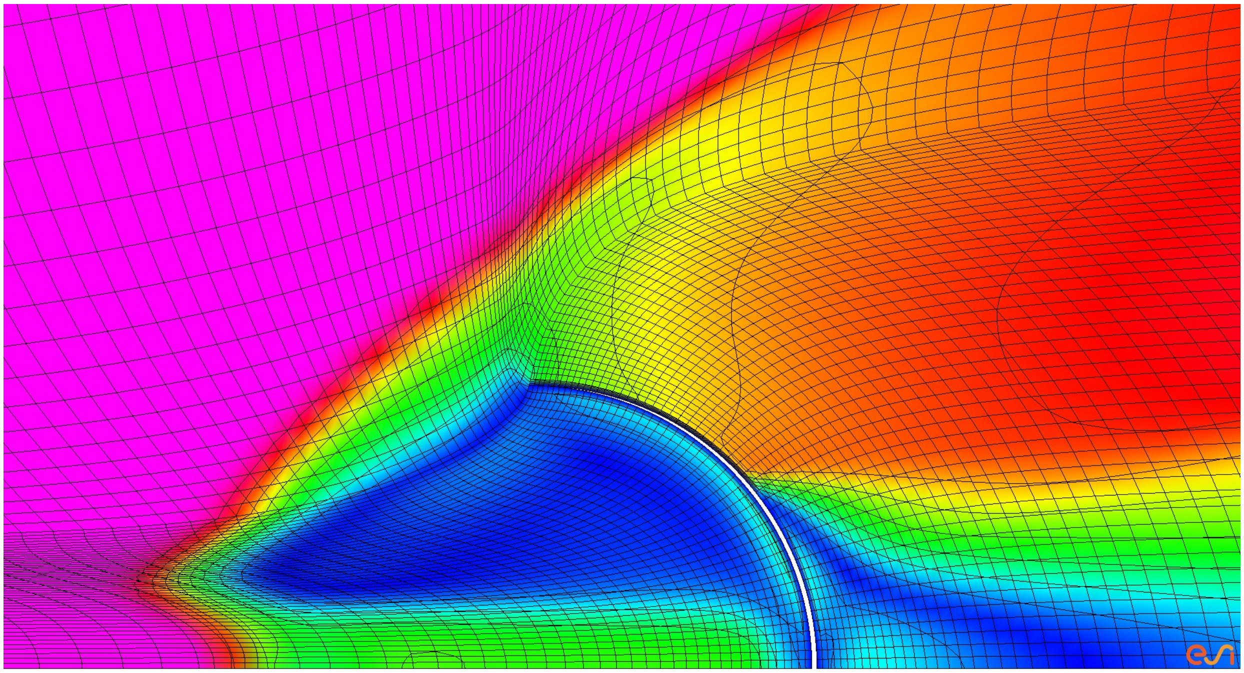


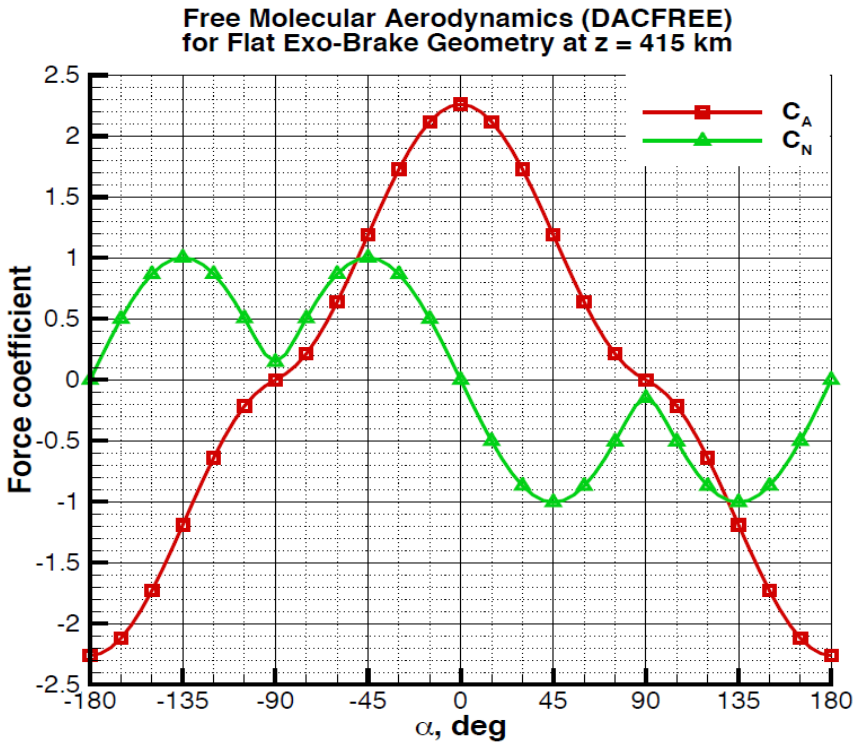
Figure 12: Quarter Circle Hypersonic Continuum Flow

Results

DSMC Analysis Code (DAC), and DACFREE

Simple Geometries

The geometries above were given to a team at NASA Langley Research Center lead by Christopher Glass, to be analyzed using Direct Simulation Monte Carlo (DSMC). From the geometries in Figure 2, Figure 3, and Figure 4, unstructured grids were created and analyzed in DACFREE. The analysis returned the coefficients for axial and normal forces versus angle of attack at an altitude of 415 km.


Free Molecular Aerodynamics (DACFREE)
for Flat Exo-Brake Geometry at z = 415 km
C_A
C_N
Force coefficient
α, deg
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-180
-135
-90
-45
0
45
90
135
180

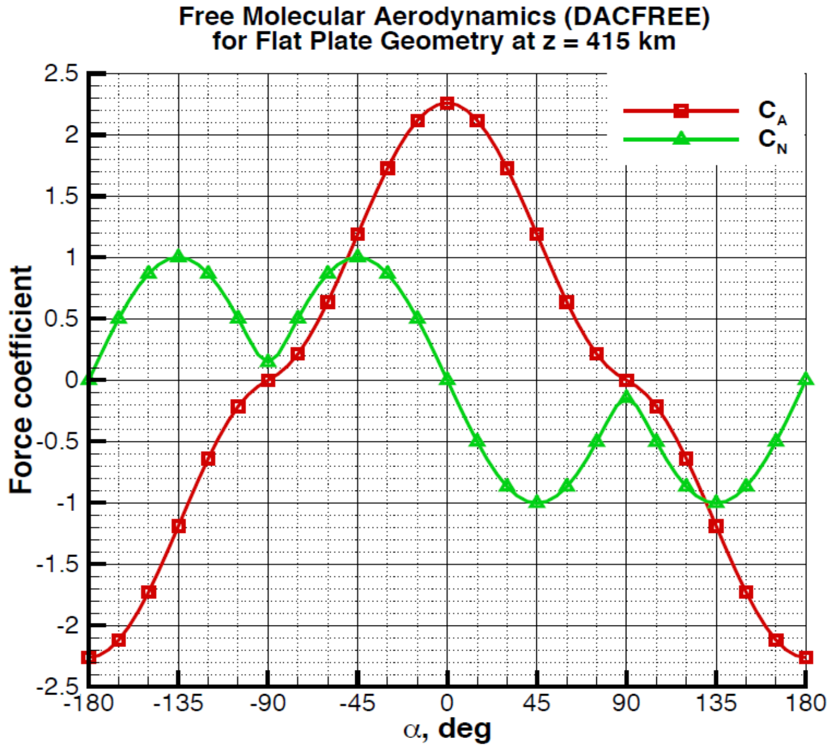


Figure 13 DACFREE for Flat Plate

Figure 14 DACFREE for Flat Exo-Brake

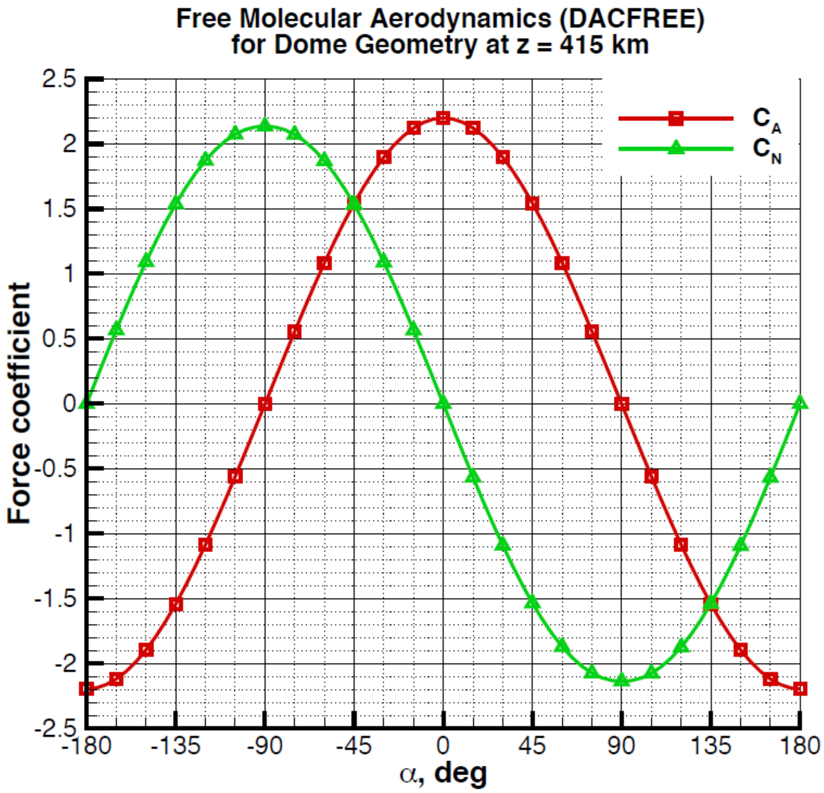


Figure 15 DACFREE for Dome

Because there is little difference between a flat square plate and a flat Exo-Brake of this size, the graphs in Figure 13 and Figure 14 are practically identical. There is a maximum axial force of about 2.25 at 0 degrees angle of attack and maximum normal force of 1.00 at 45 degrees angle of attack. The dome geometry in Figure 15 has a slightly lower maximum axial force of 2.20 at 0 degrees angle of attack due in part to its decreased surface area. Its maximum normal force is 2.13 at 90 degrees angle of attack.

The Dome geometry from Figure 4 was then used to calculate the coefficients of axial force, normal force, and pitching moments versus angle of attack, at various altitudes using both DSMC and DACFREE. Figure 16, Figure 17, and Figure 18 show the force coefficients versus alpha for 250 km, 200km, and 150 km respectively. The results indicate that the force coefficients do not change in that altitude range. These results also indicate the coefficient of pitching moment has a maximum of about 1 at an angle of attack of 90 degrees.

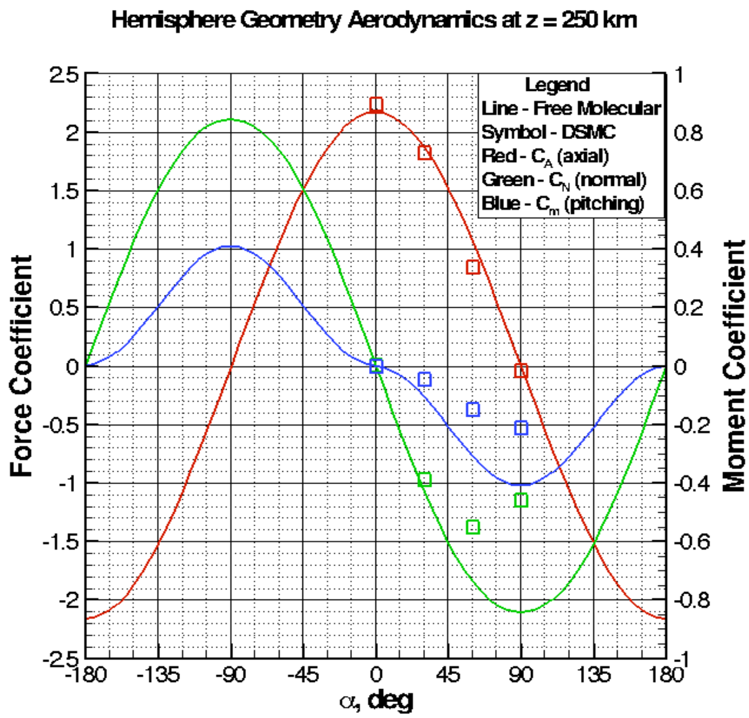


Figure 16 Dome Aerodynamics at 250km

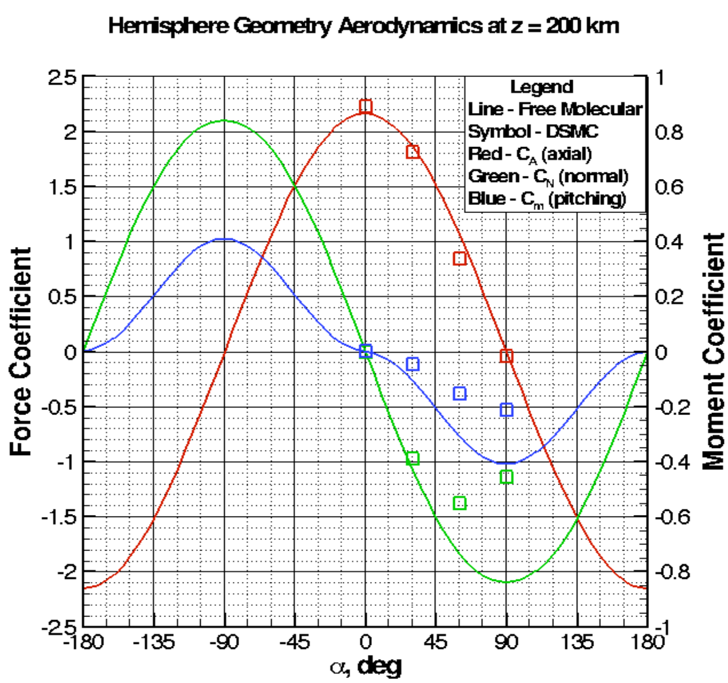


Figure 17 Dome Aerodynamics at 200km

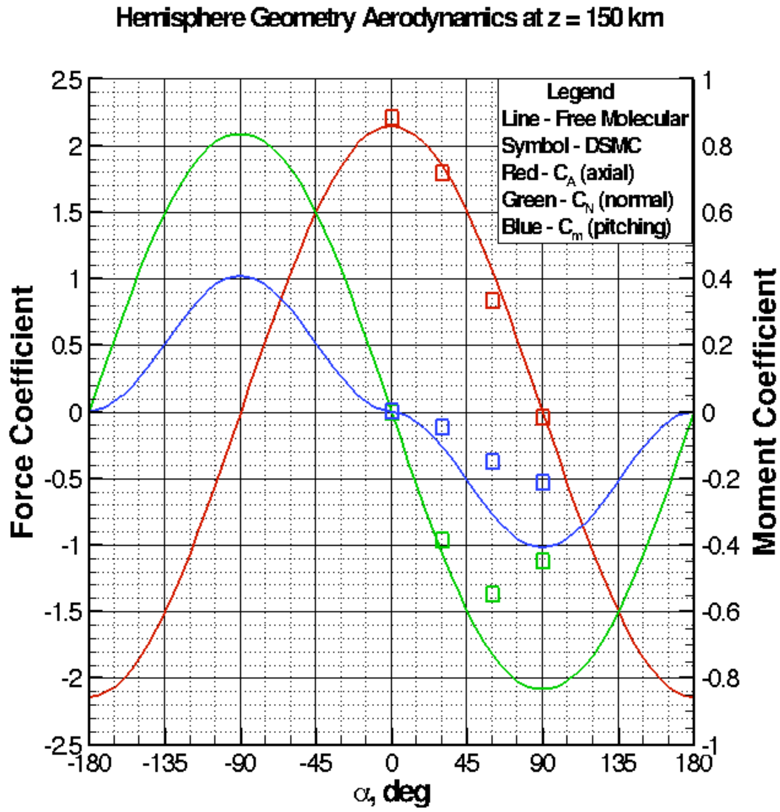


Figure 18 Dome Aerodynamics at 150km

The next iteration of analysis uses the full Exo-Brake (Cross-Curved) geometry from Figure 5 and compares it to the dome geometry. It compares the coefficient of drag, lift, and pitching moment versus angle of attack and uses both the DSMC and Free molecular flow models. Both the dome and Exo-Brake geometries are shown side by side for comparison. Each set is taken at three different altitudes: 200 km, 150 km, and 100 km.

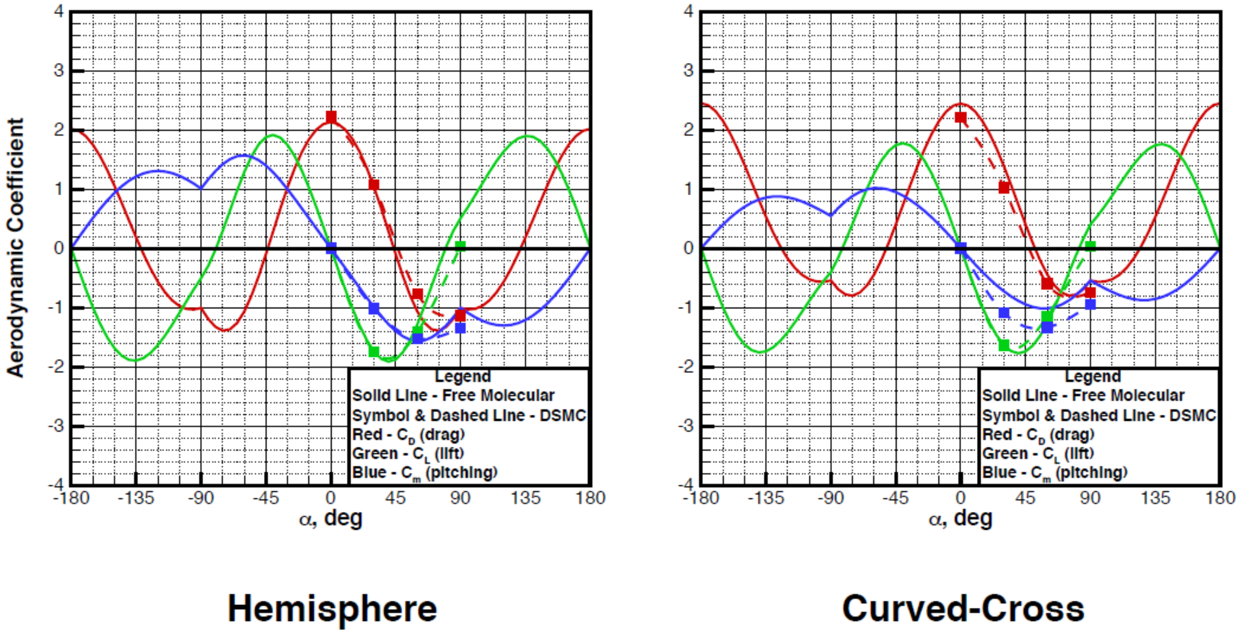


Figure 19 Aerodynamics at 200 km

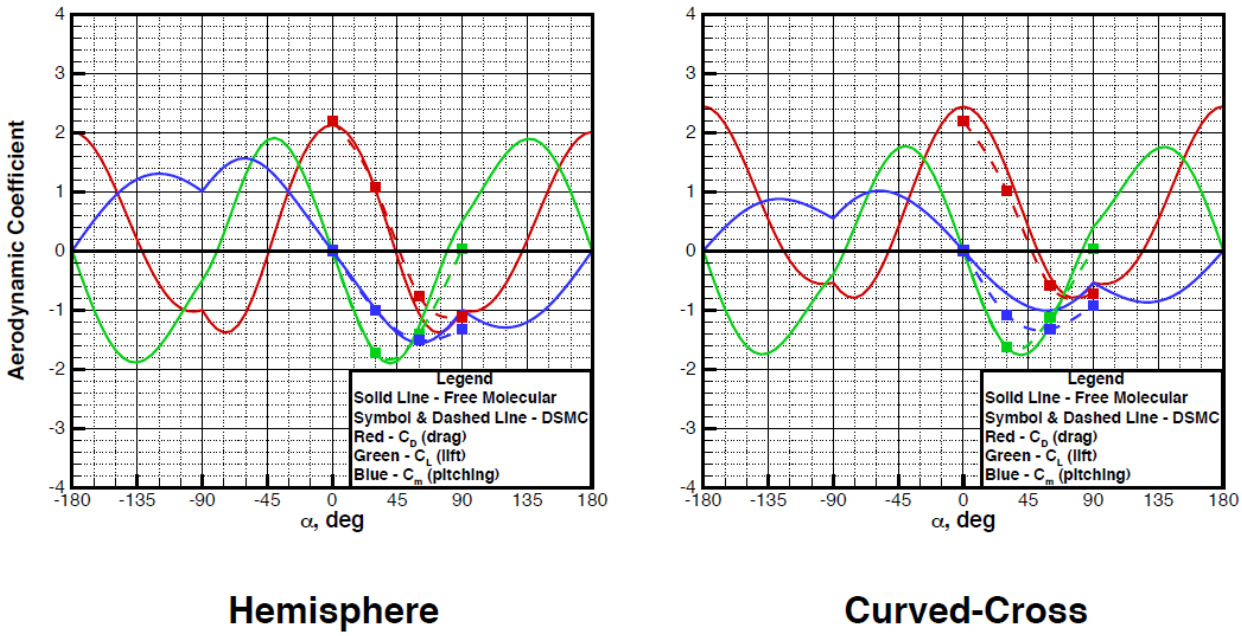


Figure 20 Aerodynamics at 150 km

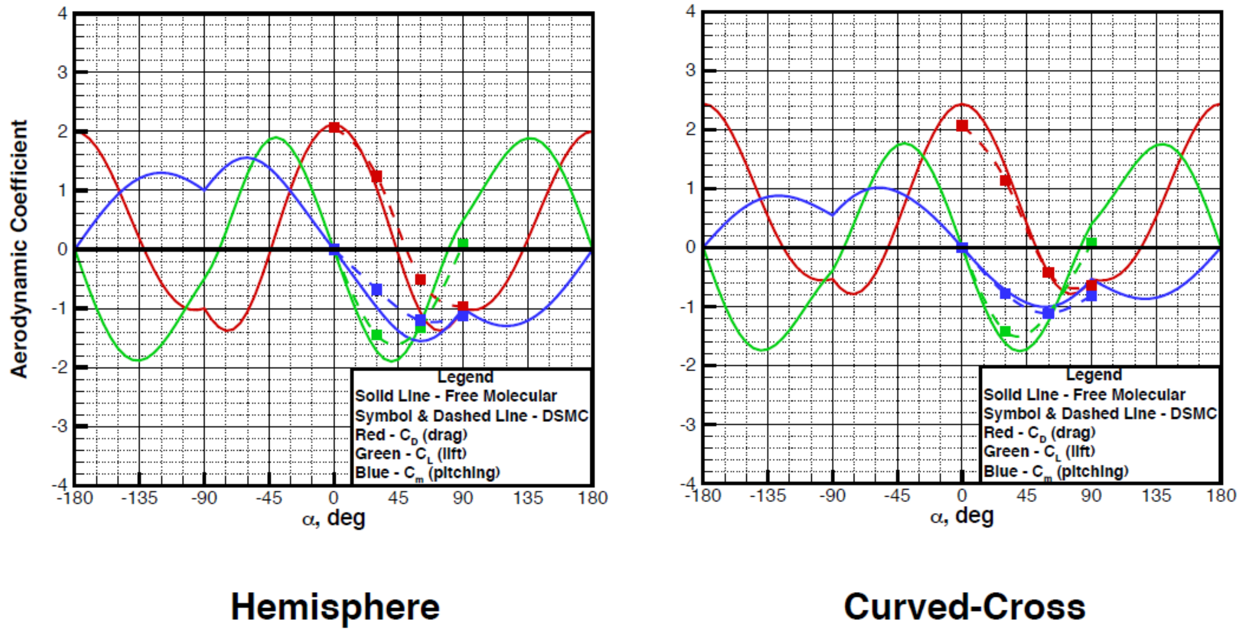


Figure 21 Aerodynamics at 100 km

These results show a clear agreement between the DSMC model and the DACFREE model for altitudes of 150 km and 200 km. The maximum coefficient of drag for the Exo-Brake geometry is 2.2 at 0 degrees angle of attack using DACFREE. The maximum coefficient of lift for the Exo-Brake geometry is 1.8 at 45 degrees angle of attack using DACFREE. The maximum coefficient of pitching moment for the Exo-Brake geometry is 1 at 60 degrees angle of attack using DACFREE.

At 100 km where the molecular composition is moving into the transitional flow regime, the aerodynamic coefficients do not agree between DSMC and DACFREE. At 100 km the DSMC model shows slightly lower maximum values for each of the coefficients. The maximum coefficient of drag for the Exo-Brake geometry is 2.0 at 0 degrees angle of attack using DACFREE. The maximum coefficient of lift for the Exo-Brake geometry is 1.4 at 40 degrees angle of attack using DACFREE. The maximum coefficient of pitching moment for the Exo-Brake geometry is 1.2 at 60 degrees angle of attack from DACFREE. Here, the more complex Curved-Cross geometry creates geometry shadowing when the flow is obstructed by other parts of the geometry. As the Angle of Attack increases, the corners of the Exo-Brake cast a shadow on the inner surface of the Exo-Brake.

Full TES-3p Geometry

The geometry in Figure 6 and the mesh shown in Figure 22 were used to conduct the following analysis using the DAC code.

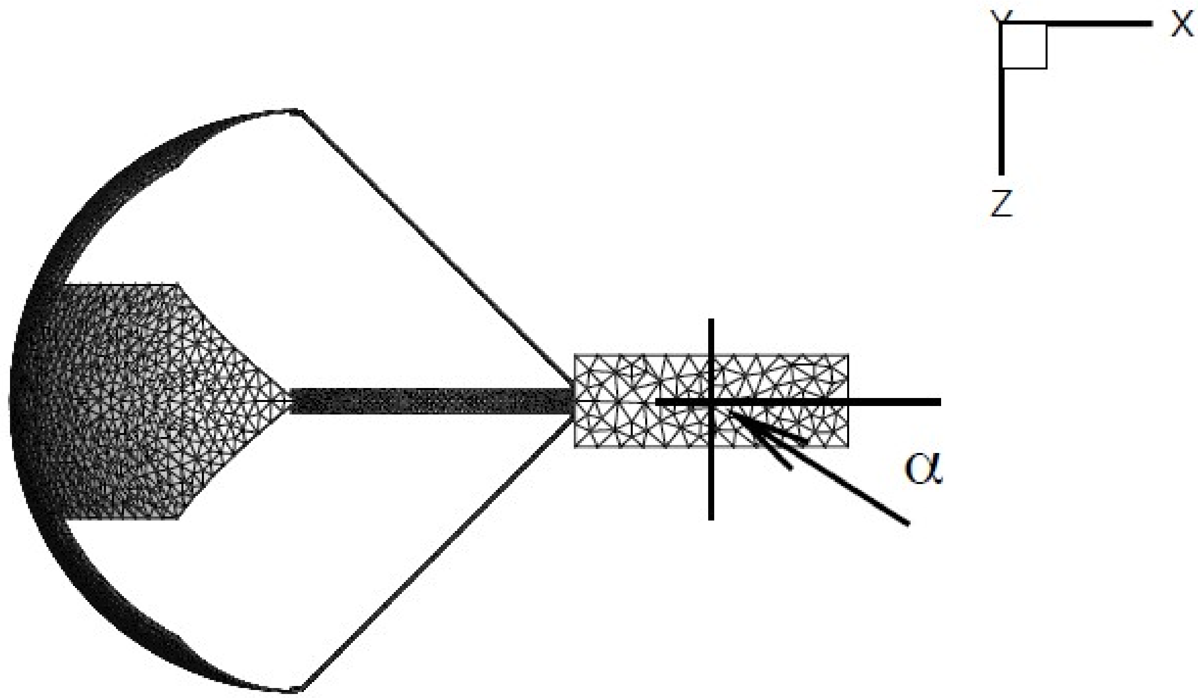


Figure 22 TES-3p Mesh Generated by NASA Langley

The conditions computed were as follows and the results are displayed below.

1. Triangulated Geometry
2. Velocity of 7660 [m/s]
3. Altitude: 334, 236, 166, 126, 109, 96 [km]
4. Knudsen: 0.1, 1, 10, 100, 1,000, 10,000
5. Angle of Attack: 0-90 [degrees]

Mapping	Value
1: z, km	96.1396
2: T, K	187.434
3: r,kg/m3	1.1061E-06
4: n, #/m3	2.31217E+19
5: c,O2	0.194305
6: c,N2	0.778194
7: c,O	0.0191826
8: c,N	0
9: c,Ar	0.00824046
10: c,CO2	0
11: c,H2	0
12: c,H	0
13: c,He	0
14: c,CH4	0
15: c,H2O	0

$Kn_L = 0.1$

Mapping	Value
1: z, km	108.791
2: T, K	239.146
3: r,kg/m3	1.13407E-07
4: n, #/m3	2.47379E+18
5: c,O2	0.148992
6: c,N2	0.746493
7: c,O	0.0988255
8: c,N	0
9: c,Ar	0.00559014
10: c,CO2	0
11: c,H2	0
12: c,H	0
13: c,He	0
14: c,CH4	0
15: c,H2O	0

$Kn_L = 1$

Mapping	Value
1: z, km	125.621
2: T, K	489.91
3: r,kg/m3	1.05477E-08
4: n, #/m3	2.47688E+17
5: c,O2	0.0899073
6: c,N2	0.683227
7: c,O	0.223803
8: c,N	0
9: c,Ar	0.0029503
10: c,CO2	0
11: c,H2	0
12: c,H	0
13: c,He	0.000112424
14: c,CH4	0
15: c,H2O	0

$Kn_L = 10$

Mapping	Value
1: z, km	165.952
2: T, K	760.515
3: r,kg/m3	1.0619E-09
4: n, #/m3	2.77475E+16
5: c,O2	0.0485095
6: c,N2	0.529519
7: c,O	0.419353
8: c,N	0.000419049
9: c,Ar	0.000980951
10: c,CO2	0
11: c,H2	0
12: c,H	0
13: c,He	0.0012381
14: c,CH4	0
15: c,H2O	0

$Kn_L = 100$

Mapping	Value
1: z, km	236.115
2: T, K	872.657
3: r,kg/m3	1.06834E-10
4: n, #/m3	3.28082E+15
5: c,O2	0.0179102
6: c,N2	0.2841
7: c,O	0.688856
8: c,N	0.0024
9: c,Ar	0.0002
10: c,CO2	0
11: c,H2	0
12: c,H	0.0001
13: c,He	0.00653377
14: c,CH4	0
15: c,H2O	0

$Kn_L = 1000$

Mapping	Value
1: z, km	333.666
2: T, K	890.647
3: r,kg/m3	1.04201E-11
4: n, #/m3	3.77136E+14
5: c,O2	0.00338002
6: c,N2	0.0859738
7: c,O	0.872066
8: c,N	0.00337333
9: c,Ar	0
10: c,CO2	0
11: c,H2	0
12: c,H	0.000473325
13: c,He	0.0348065
14: c,CH4	0
15: c,H2O	0

$Kn_L = 10000$

Figure 23 Atmospheric Conditions at Given Knudsen Numbers

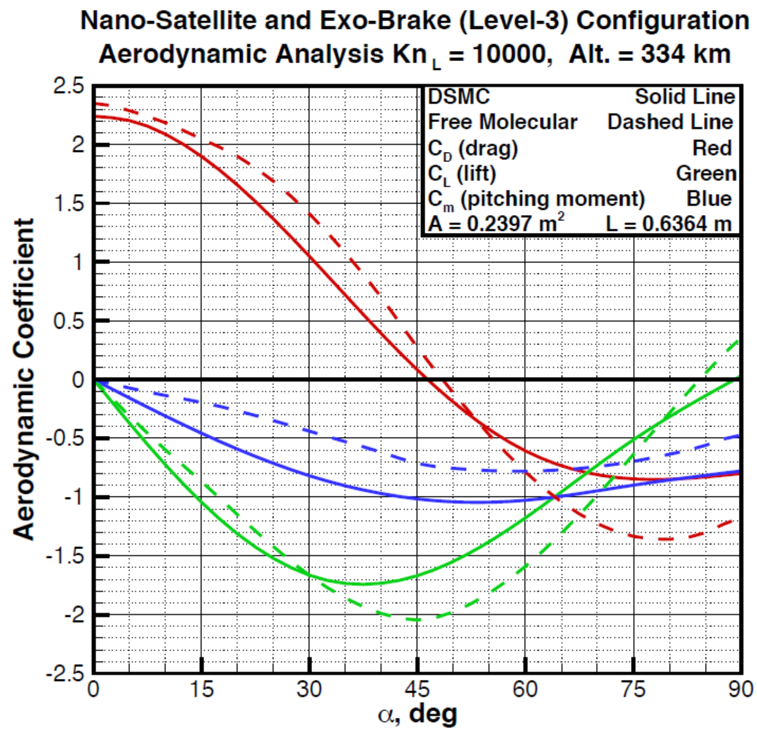


Figure 24 DAC & DACFREE Solution at 334 km

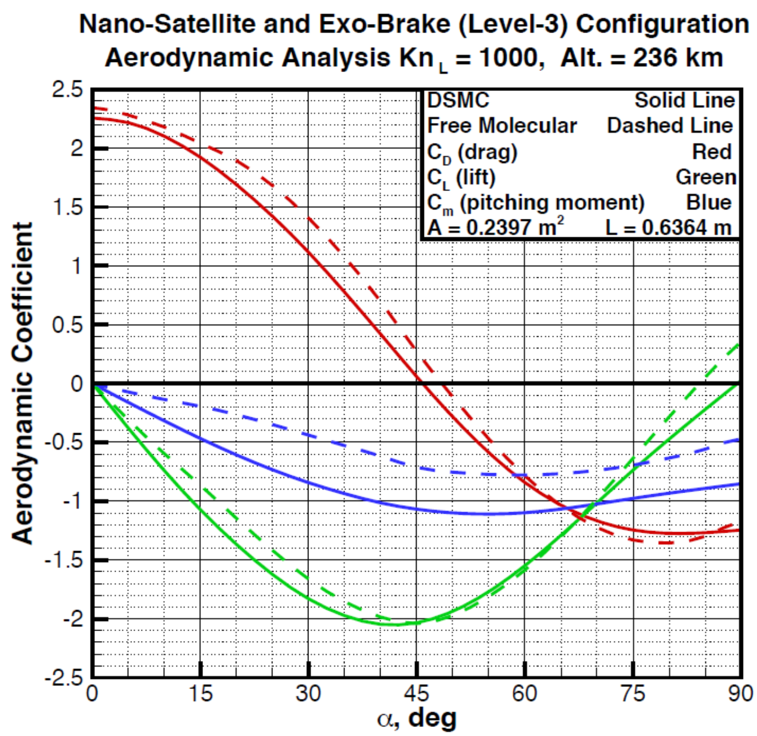


Figure 25 DAC & DACFREE Solution at 236 km

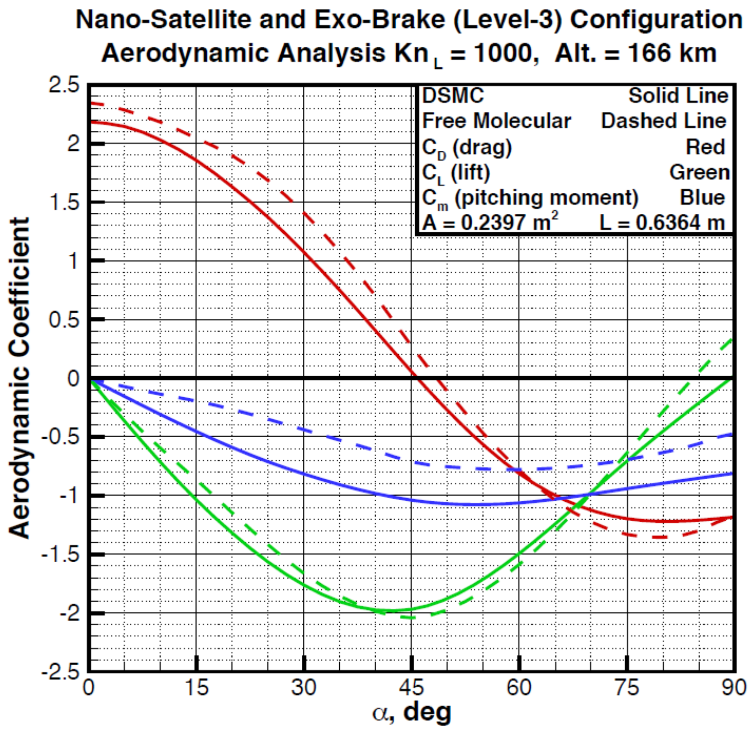


Figure 26 DAC & DACFREE Solution at 166 km

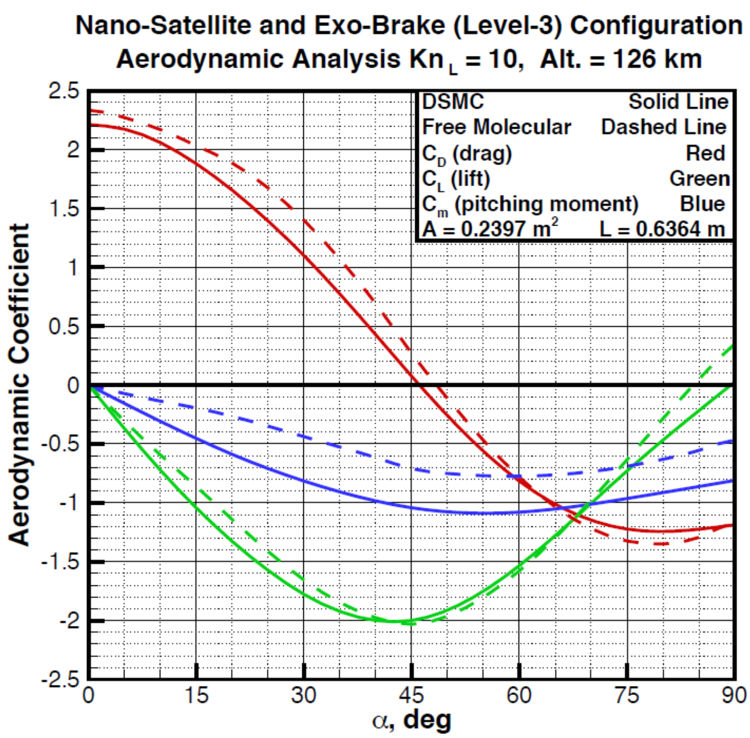


Figure 27 DAC & DACFREE Solution at 126 km

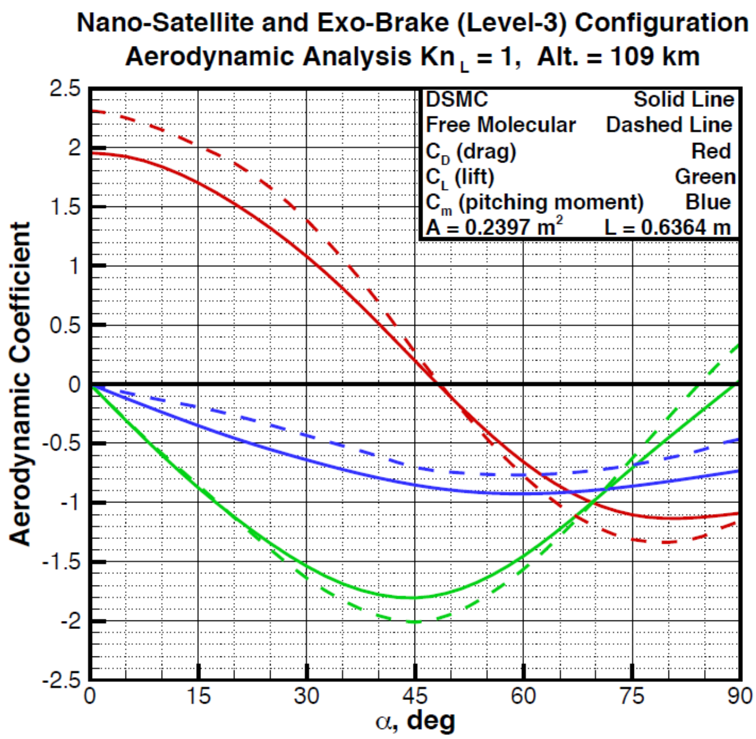


Figure 28 DAC & DACFREE Solution at 109 km

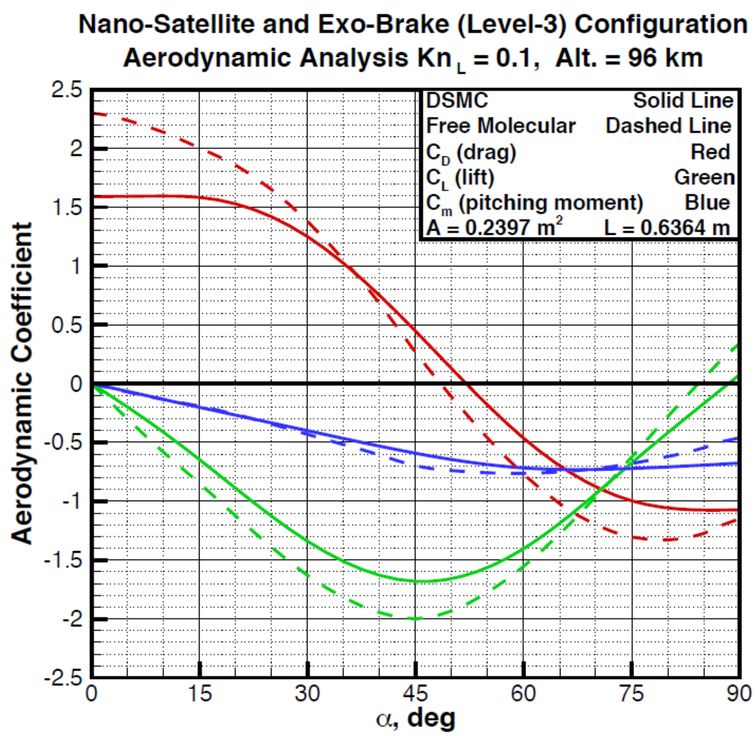


Figure 29 DAC & DACFREE Solution at 96 km

The DACFREE solution does vary much with altitude and matches the DAC values more closely at higher altitudes. The Drag coefficient at 0 degrees angle of attack is approximately 2.35 using DACFREE while the DAC values range from 2.25 at 334 km down to 1.6 at 96 km. A graph of the results for all DAC/DAFREE models at 0 degrees Angle of Attack are shown in Figure 30. Again, the simplified DACFREE code used on this complex geometry, creates shadows where the solution is not precisely calculated. The fore-body cast a shadow on the region directly behind it within the Exo-Brake.

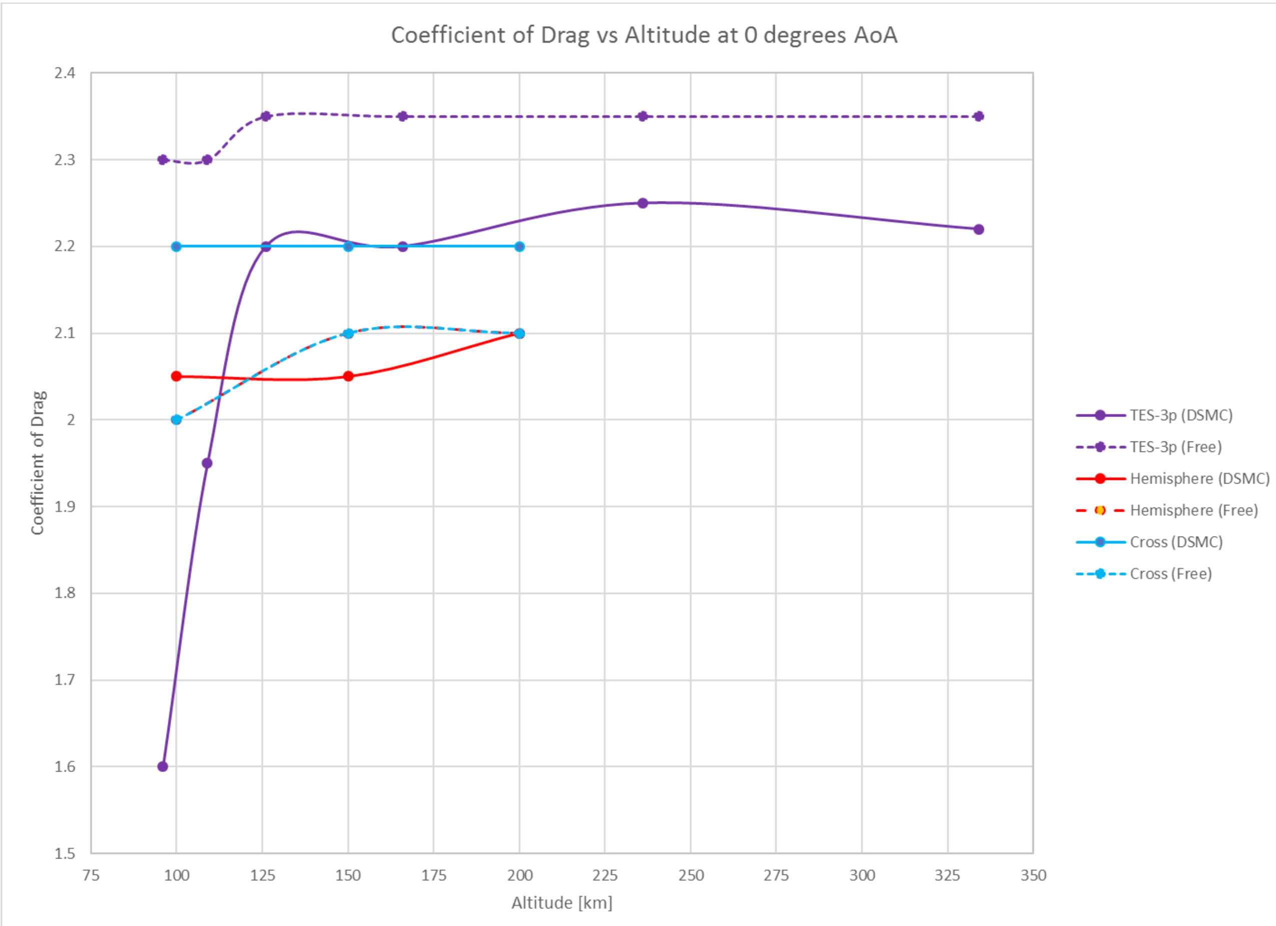


Figure 30 Coefficient of Drag versus Altitude at 0 Degrees Angle of Attack

ESI

Continued work on the 2-D solution of the simple geometries was terminated because the solutions have been found to only be accurate within the continuous flow regime. These solutions will not be shown because they cannot be compared to the free molecular flow results. A 3-D solution is not possible at this time due to increased complexity which would involve large amounts of time for both mesh creation and computation.

CBAERO

Because of the many challenges associated with mesh generation in CFD-GEOM and converting them into the mesh files needed as inputs for CBAERO, Pointwise was used to create a mesh of the entire satellite (Figure 31). Pointwise allows the user to save the mesh in a file type that is native to CBAERO.

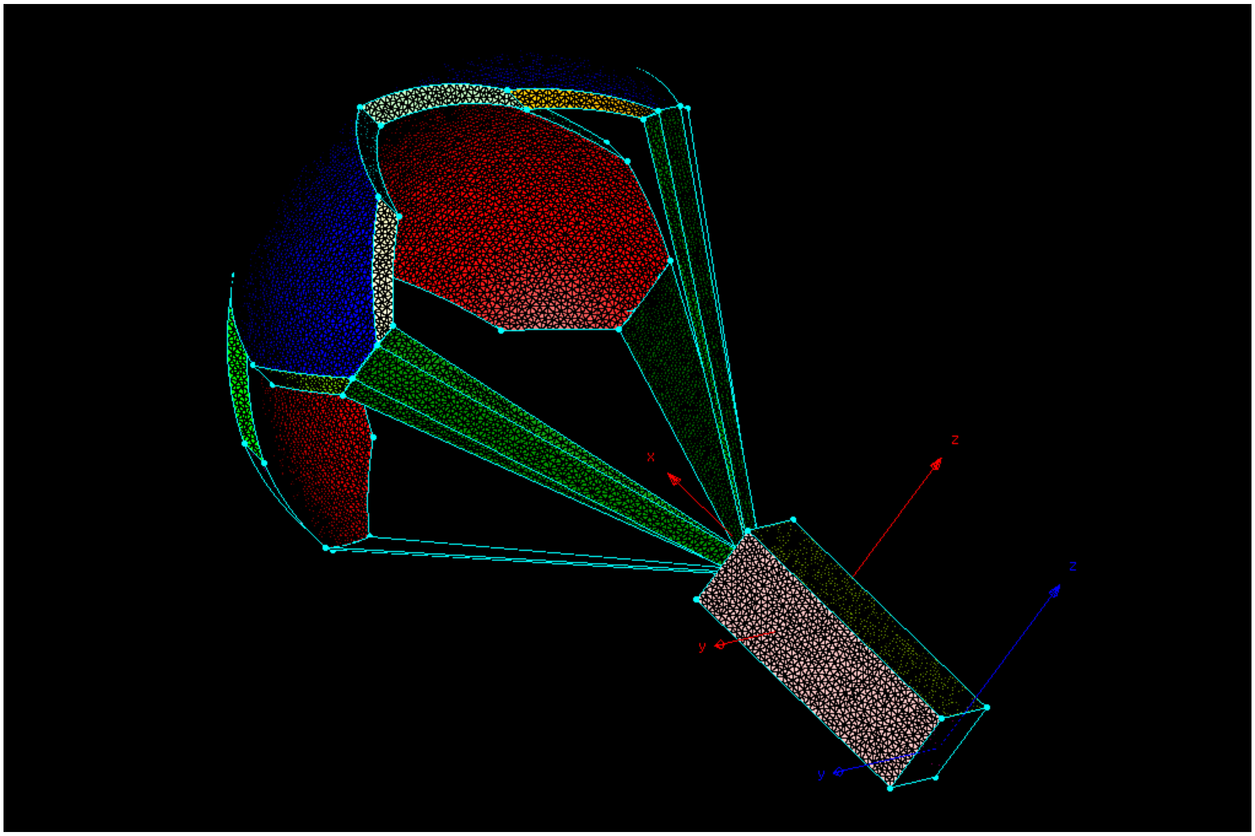


Figure 31 Full TES-3p Mesh Created in Pointwise by Ben Nikaido

Due to time constraints, only the full satellite with Exo-Brake, was analyzed using CBAERO. The inputs used within CBAREO are as follows with the results displayed below (Figure 32 to Figure 36).

1. Mach: 22.33
2. Dynamic Pressure: 5.486E-9, 1.751E-8, 7.070E-8, 5.075E-7, 1.546E-3 [pascals]
3. Altitude: 300, 250, 200, 150, 100 [km]
4. Angle of Attack: 0, 15, 30, 45, 60, 75, 90 [Degrees]
5. Modified Newtonian Method

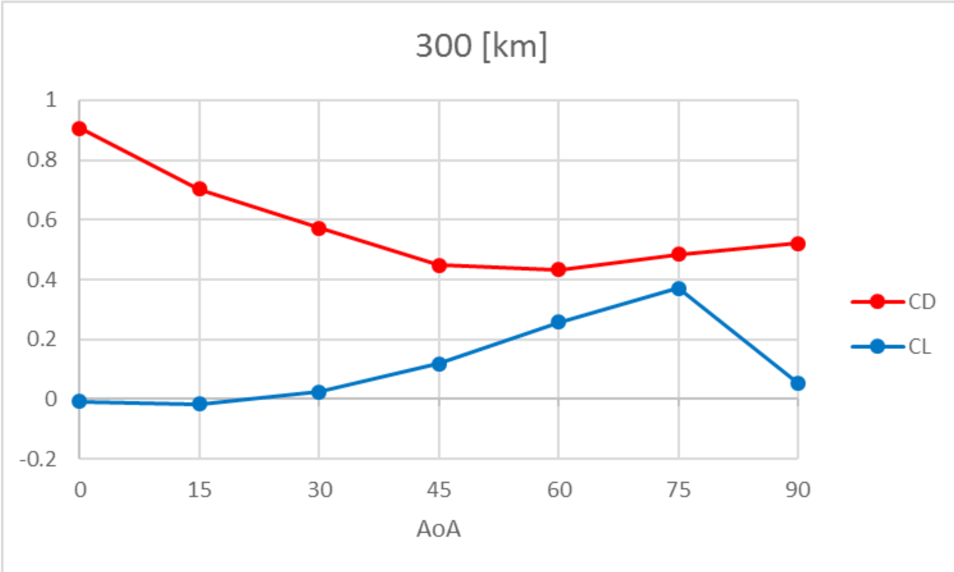


Figure 32 CBAREO Results at 300 km

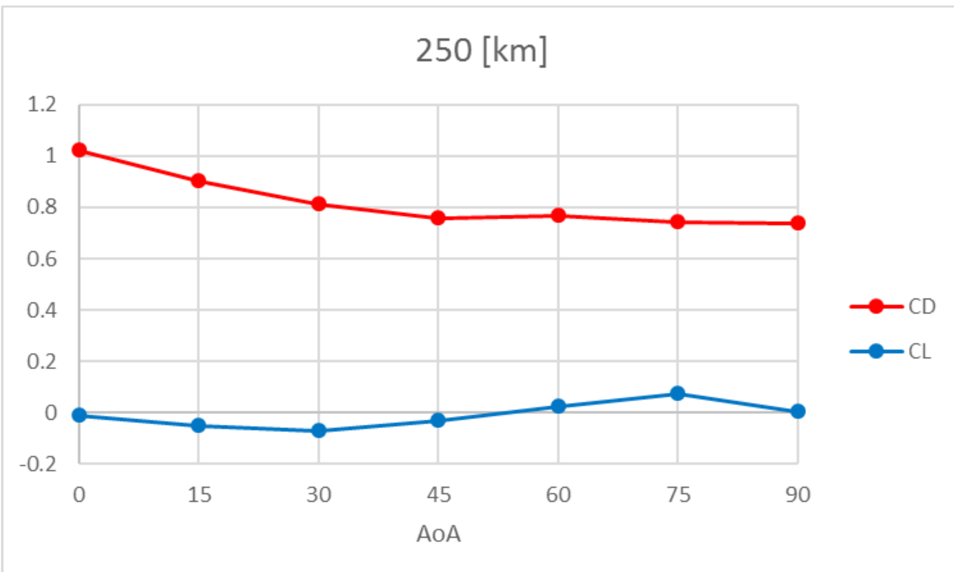


Figure 33 CBAERO Results at 250 km

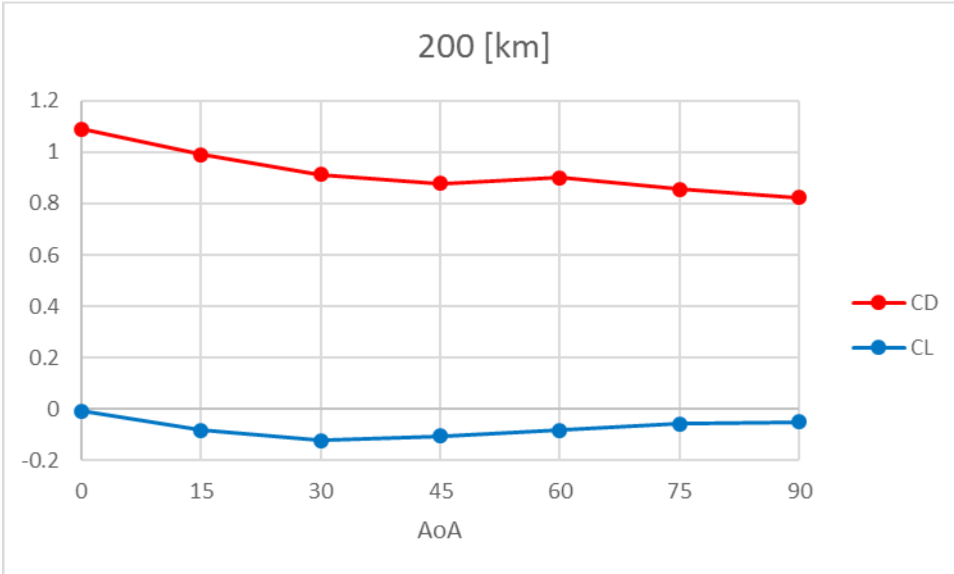


Figure 34 CBAERO Results at 200 km

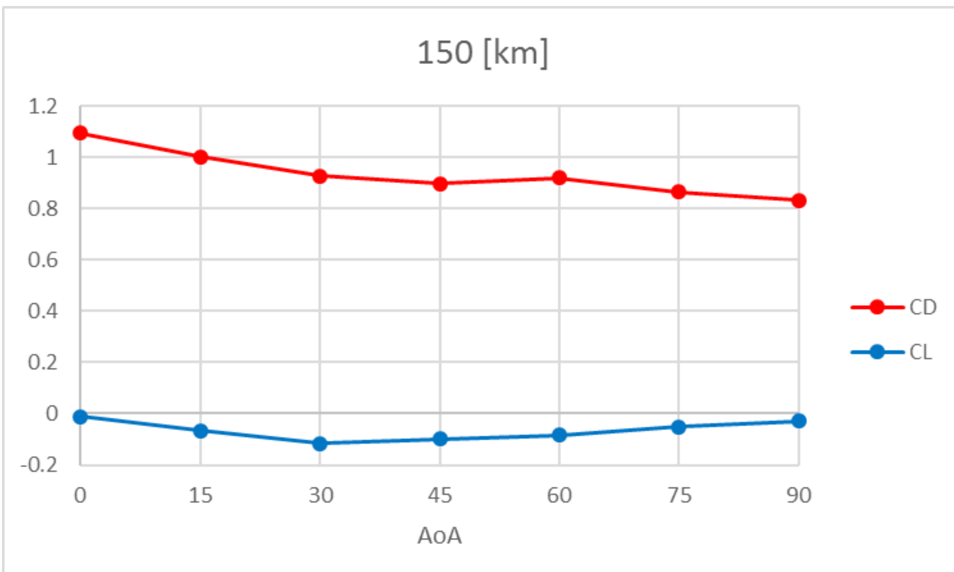


Figure 35 CBAERO Results at 150 km

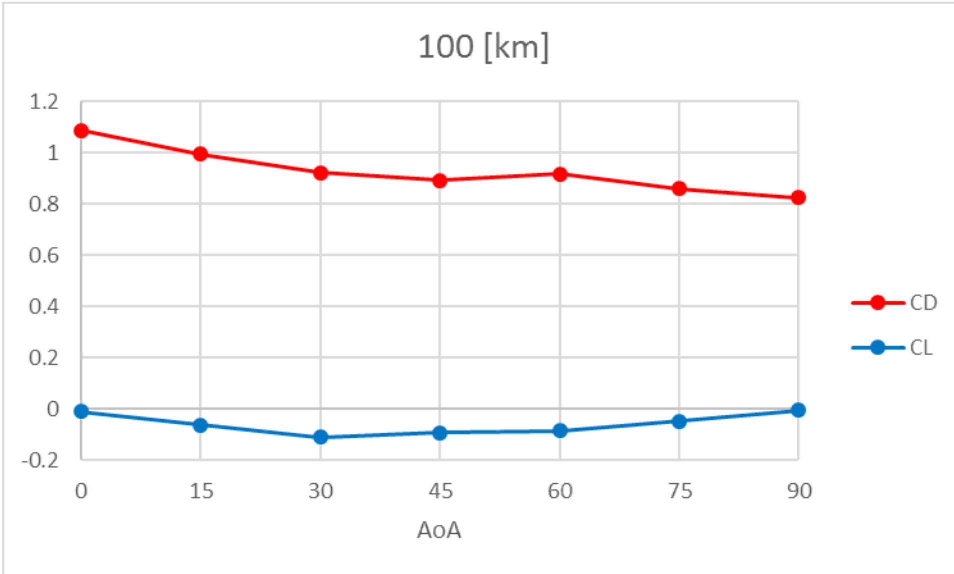


Figure 36 CBAERO Results at 100 km

The CBAERO values has a smaller range. For the coefficient of drag, the values range from 0.4 to 1.1, and the values for the coefficient of lift range from -0.2 to 0.4. These values are largely based on the drag due to pressure and neglect the drag due to friction. Friction pays less of a role in free molecular flow because of slip in the flow at the surface however if taken into consideration, friction would add to the total drag.

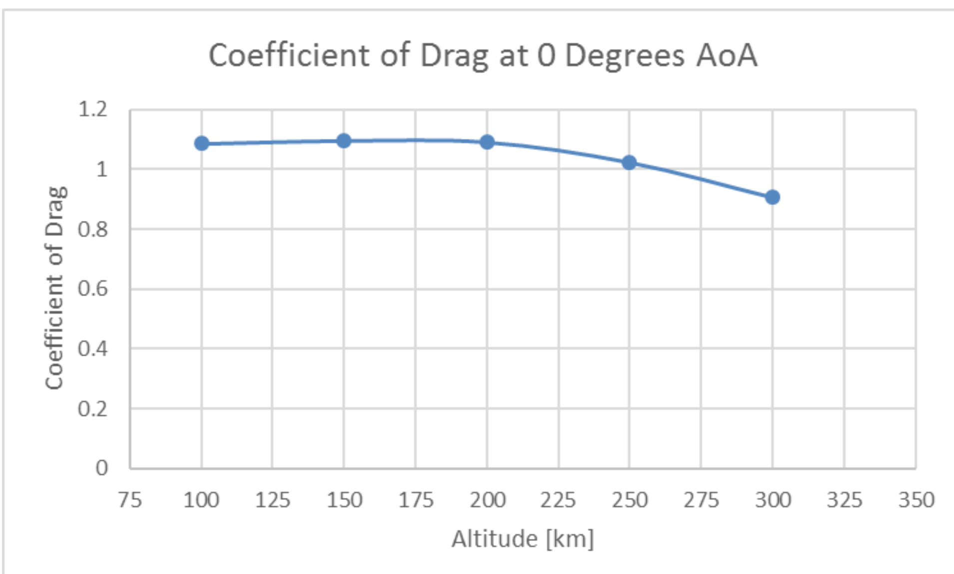


Figure 37 Coefficient of Drag versus Altitude at 0 Degrees Angle of Attack

When looking only at an angle of attack of 0 degrees while varying the altitude (Figure 37), the range for coefficient of drag is 0.9 to 1.1.

Comparison

The Direct Simulation Monte Carlo results are the highest fidelity, but also are the most difficult to compute. They require more inputs, computing power, and time. The DACFREE results are also high fidelity but don't offer the range of environments that DSMC offers. The DSMC and DACFREE values obtained are very similar above 125 km but below that the values start to vary. CBAERO offers a large range of environments but the fidelity is not high. The CBAERO code requires minimal inputs, very little computational power, and very little time, relative to the DSMC and DACFREE. The results from CBAERO are much lower than the high fidelity solvers but with more inputs and fine tuning, similar results should be obtainable. The Anchor tool in CBAERO allows results to be anchored to the code that would bound the results obtained. This would also allow CBAERO to obtain better results.

Challenges

Though the design of the TES-3p satellite is relatively simple it has some complex interfaces that made creating an air-tight volume very difficult. This created many challenges when trying to create an acceptable mesh.

The learning curve for using multiple software, proved to be too great for the time allotted to complete this project. Furthermore, acquiring these software was very time consuming and in some cases very expensive.

Conclusion

CBAERO is a great starting point for analyzing a body in free molecular flow. CBAERO can run on a normal PC and provide a solution in a matter of minutes while solvers such as DAC, need to be run on supercomputers and still takes days or weeks to return results. The power of CBAERO comes with the ability to compute results and then quickly iterate and produce better results. If a solution diverges in DAC, the results will not be known for some period of time. That time can be spent better. Once a good solution is obtained with DSMC those values can be anchored to CBAERO to fine tune the design very rapidly.