Cassini-Huygens Aerodynamics with Comparison to Flight

Derek S. Liechty

Aerothermodynamics Branch, NASA Langley Research Center, MS 408A, Hampton, VA 23681-2199

Abstract. An analysis has been performed on the aerodynamics of the Cassini-Huygens spacecraft as it passed through the atmosphere of Titan. The free stream density of Titan's atmosphere was measured by two methods. However, these methods resulted in disparate values of density, one result being 3-5 times higher than the other. In an attempt to understand the source of this discrepancy, free molecular and direct simulation Monte Carlo (DSMC) analyses were performed for two atmospheric passes. The drag coefficient was calculated using an area based on a Monte Carlo area determination program. Although the source of the discrepancy has not been determined, it has been confirmed that the original, simplified force-and-moment analysis performed by JPL produced results that were comparable to the high-fidelity DSMC analysis and that the source of the discrepancy lays elsewhere.

INTRODUCTION

Of the four NASA spacecraft that have been sent to explore Saturn, the Cassini spacecraft was the first to explore the planet's system of rings and moons from orbit. Of particular interest was Saturn's moon Titan because it is one of the few moons in the solar system with its own atmosphere. The European Space Agency's Huygens Probe entered Titan's atmosphere and landed on the surface in January 2005. Two of the Cassini spacecraft flybys of Titan have been of particular interest due to the depth to which it flew into the atmosphere. These were the Titan-A (1174 km) and Titan-5 (1027 km) flybys. The Titan-A flyby was before the Huygens Probe had been released, while the Titan-5 flyby was after the release.

As the Cassini spacecraft passed through Titan's atmosphere, two teams measured the free stream density. The first team was the Ion and Neutral Mass Spectrometer (INMS) team. The INMS was designed to measure in-situ composition and density variations with altitude of low energy positive ions and neutrals in Titan's upper atmosphere. The INMS team reported the density by two methods. The first was by reporting the density directly from the data at the specific altitude (INMS-DATA). The second method was by reporting the density from a best-fit curve through all available altitudes (INMS-FIT). Exact details as to the method of backing out the atmospheric density used by the INMS team are unknown to the author.

The other team was the Attitude and Articulation Control Subsystem (AACS) team. The AACS team used estimates of the magnitude of the Titan atmospheric torque (y- and z-axes) imparted on the spacecraft during the flybys using both telemetry (AACS-1) and estimations of the angular momentum (AACS-2). From the torque, the atmospheric density was estimated as a function of altitude by the equation:

$$\vec{T}_{Atmospheric} = \tfrac{1}{2} C_D \rho V^2 A_{projected} (\vec{c}_p - \vec{c}_m) \times (-\vec{V}_\infty) \tag{1}$$

where values for the drag coefficient (C_D) and projected area ($A_{projected}$) were estimated. Other variable definitions include the center of pressure (c_p), center of mass (c_m), and the free stream velocity (V_∞). The drag coefficient was assumed to be a constant value of 2.1. An evaluation of this value is presented later in this paper.

The resulting densities estimated by these teams were significantly different, the AACS results being 3-5 times larger than the INMS results. In an attempt to better understand the nature of this discrepancy, NASA Langley Research Center was tasked to perform free molecular and direct simulation Monte Carlo (DSMC) analyses of the Cassini-Huygens spacecraft for both the Titan-A and Titan-5 flybys. The results of these analyses and discussion are presented herein.

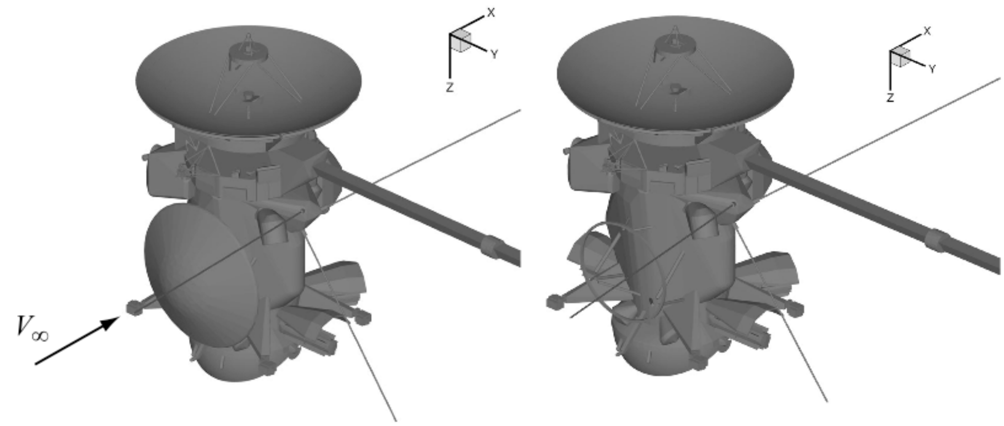
COMPUTATIONAL METHODS

The DSMC calculations were performed using DDAC, the parallel implementation of the program DAC (DSMC Analysis Code)[1,2]. In DAC, the gas molecular collisions are modeled using the variable-hard-sphere (VHS) model developed by Bird[3], and the Larsen-Borgnakke model[4] is used for internal energy exchanges. The surface geometry is represented by unstructured triangular elements that are embedded in a two-level Cartesian grid for the flow field calculations. The solution from the first level of grid cells, which are uniform in size, is used for grid refinement to create second-level cells. The grid is refined based on local conditions, thus allowing the program to meet the spatial resolution requirements without excessive global refinement. The grid cells are typically refined such that on average the second-level cells have dimensions less than the local mean free path. The local simulation parameters are set such that there are nominally 10 simulated molecules per cell, and the local time step is typically dictated by the local flow time for the problems considered.

In the simulations performed herein, the flow was allowed to reach steady state by monitoring the number of simulated molecules. When the number of simulated molecules remained approximately constant, the flow was assumed steady (usually took about 5,000 to 10,000 time steps). The simulation was then allowed to run for a sufficient number of surface collisions to occur to accumulate a reasonable number of samples.

VEHICLE GEOMETRY

The Cassini spacecraft stands more than 6.7 meters high and is more than 4 meters wide. The magnetometer instrument is mounted on an 11 meter boom that extends outward from the spacecraft. The surface geometry for the simulations was generated by using CAD geometry files, provided by the Jet Propulsion Laboratory (JPL). Pre-flight images were then used to "apply" the multi-layer insulation (MLI) to the computational model. The application of MLI is more of an art than science. It is not possible to wrap the CAD geometry exactly like the spacecraft in flight. The pre-flight images are usually few in number and do not show the entire surface of the spacecraft. It is the responsibility of the researcher to make reasonable judgments as to the placement of MLI and stay as true to the pre-flight images as possible. The program Unigraphics[5] includes a function to "wrap" selected components, which greatly facilitated the process. The final surface geometry used for the simulations can be viewed in Fig. 1. Pre-flight images of the Cassini-Huygens spacecraft can be found on the internet[6].



a) Titan-A Configuration. b) Titan-5 Configuration.

FIGURE 1. Computational geometry used (surface mesh not shown for clarity).

AREA DETERMINATION

A more accurate method of calculating the projected area of the Cassini-Huygens spacecraft was needed in order to determine the drag coefficient. As mentioned earlier, the original analysis that JPL performed used a constant value of $C_D = 2.1$. This value was chosen because both a sphere and a cylinder in free molecular flow with a large molecular speed ratio result in drag coefficients of about 2.1. One of the requirements of this investigation was to determine if this was a reasonable value to use given the densities encountered in flight and the more complicated geometry of the actual vehicle. A Monte Carlo area determination program, written by R. G. Wilmoth, was modified by the author to rotate the vehicle into the wind to get an accurate estimate of the projected area of the spacecraft in flight. This program randomly inserts points into a plane that encompasses the entire spacecraft. It then multiplies the area of the plane by the ratio of surface "hits" divided by the total number of points introduced. A total of four million points were used to estimate the projected area of the Cassini-Huygens spacecraft. The projected area of the Titan-A flyby was calculated to be 18.46 m^2, while the projected area of the Titan-5 flyby was 19.08 m^2. Although the Huygens probe was no longer attached to the Cassini spacecraft, the projected area was larger for the Titan-5 flyby. This was a result of the spacecraft orientation relative to the free stream velocity. The Huygens Probe was pointed into the wind for Titan-A, so the Cassini spacecraft masked most of its projected area. The increase in area is attributed to the rotation of the high-gain antenna, which is similar to rotating a coin. There is a much smaller area when looking at the edge, which increases as the coin is rotated.

SIMULATION DETAILS

The composition of Titan's atmosphere was assumed to be 97.28% N_2 and 2.72% CH_4 by mole using a 13-specie chemically reacting gas model. The simulations performed are summarized in Table 1. For each flyby (Titan-A and Titan-5), several free stream densities were examined. These densities correspond to the values estimated by the two teams (AACS and INMS) and the methods the respective team used to report the density (i.e., INMS-DATA vs. INMS-FIT).

TABLE 1. Simulations performed for the Cassini-Huygens spacecraft with flow conditions.

Flyby	n_∞ (1/m^3)	Velocity (u_∞, v_∞, w_∞) (m/s)	T_∞ (K)	λ_∞ (m)	T_w (K)	Surface Reflection
Titan-A (INMS-DATA)	1.0047E+15	(6060.0,8.4,-8.0)	148.62	1036.4	175/300	Specular/Diffuse
Titan-A (AACS-2)	4.5669E+15	(6060.0,8.4,-8.0)	148.62	228.0	300	Specular/Diffuse
Titan-A (AACS-1)	3.2403E+15	(6060.0,8.4,-8.0)	148.62	321.3	300	Specular/Diffuse
Titan-5 (INMS-DATA)	2.9787E+15	(6007,-752,298)	158.8	355.0	175	Diffuse
Titan-5 (INMS-FIT)	3.8919E+15	(6007,-752,298)	158.8	271.7	175	Diffuse
Titan-5 (AACS-2)	1.2393E+16	(6007,-752,298)	158.8	85.3	175	Diffuse
Titan-5 (AACS-1)	1.4785E+16	(6007,-752,298)	158.8	71.5	175	Diffuse

RESULTS

Computation of Drag Coefficient

Forces and moments are calculated by summing up the contributions of each individual surface element of the surface geometry definition after the simulation has been completed. With the knowledge of spacecraft orientation, free stream conditions, and projected area, the drag coefficient can be determined by:

$$C_a = -F_Z/(0.5\rho V^2 A_{projected}) \qquad (2)$$

$$C_n = F_X/(0.5\rho V^2 A_{projected}) \qquad (3)$$

$$C_y = F_Y/(0.5\rho V^2 A_{projected}) \qquad (4)$$

$$C_D = C_a \cos\alpha \cos\beta + C_n \sin\alpha \cos\beta - C_y \sin\beta \qquad (5)$$

where α is the angle-of-attack and β is the yaw angle.

As stated earlier, the drag coefficient that was assumed in the initial estimation of atmospheric density by the AACS team was a constant value of 2.1. The resulting drag coefficients using the updated projected area and computed aerodynamic forces are presented in Table 2 for Titan-A and Table 3 for Titan-5. The double values given in the DSMC/Diffuse column for INMS-DATA reflects two wall temperatures (175 K and 300 K). Other wall temperatures are listed in Table 1.

TABLE 2. Computed drag coefficients for Titan-A flyby.

Team/Method	DSMC		Free Molecular	
	Diffuse	Specular	Diffuse	Specular
INMS-DATA	2.110 / 2.133	2.865	2.112	2.632
INMS-FIT	-	-	-	-
AACS-1	2.129	2.861	2.110	2.632
AACS-2	2.130	2.862	2.112	2.633

TABLE 3. Computed drag coefficients for Titan-5 flyby.

Team/Method	DSMC Diffuse
INMS-DATA	2.006
INMS-FIT	2.004
AACS-1	1.992
AACS-2	1.993

From historical experience[7], the accommodation coefficient is much closer to 1.0 (diffuse) than 0.0 (specular). This being the case, the original assumption of C_D = 2.1 was very close for the Titan-A flyby. The free molecular and DSMC values of C_D were quite similar. This suggests that the Titan-A flyby was in the free molecular flow regime, as the large free stream mean free paths would suggest. The Titan-5 flyby, however, resulted in a drag coefficient of 2.0. At first glance, this appears to possibly be a Knudsen number effect, the flow field becoming transitional instead of collisionless. Upon closer inspection, however, the number density of the two Titan-A AACS estimates are very close to the two INMS estimates of the Titan-5 flyby. Therefore, the difference in drag coefficient must be due to spacecraft orientation and the change in projected area.

Comparison of Moments to AACS Data

The AACS team used moments inferred from flight data to calculate the atmospheric density, as mentioned earlier. Comparisons of the moments from the simulations performed herein to the moments inferred from flight are presented in Table 5. All of the moments are within about 15% of each other. This suggests that the method of calculation and values assumed (C_D and $A_{projected}$) in the original analysis were reasonable given the input values of the moments imparted on the spacecraft by Titan's atmosphere.

TABLE 4. Comparison of computed moments (DSMC diffuse surface reflection) and moments inferred from flight.

Flyby	Team/Method	Axis	Flight (N-m)	Simulation (N-m)
Titan-A	AACS-1	Z	-0.158	-0.134
Titan-A	AACS-2	Z	-0.103	-0.095
Titan-5	AACS-1	Y	-0.23	-0.256
Titan-5	AACS-1	Z	-0.44	-0.418
Titan-5	AACS-2	Z	-0.39	-0.35

CONCLUSION

As the Cassini-Huygens spacecraft passed through the upper atmosphere of Saturn's moon Titan, the free stream density was measured by two separate methods. The results of these measurements were dissimilar, one value being 3-5 times the other. An investigation into the nature of this discrepancy has been performed using the direct simulation Monte Carlo and free molecular techniques.

The magnitudes of the torques imparted on the Cassini-Huygens spacecraft in flight were compared to the moments resulting from free molecular and DSMC analyses. In general, these values agreed within 15%. This suggests that, if the moments inferred from flight are correct, the assumptions made in the original analysis were reasonable.

Although the root cause of the discrepancy between the two measurement methods was not determined, it was concluded that the assumptions made in the original analysis performed by the Jet Propulsion Laboratory were reasonable and the cause of the disparate values of atmospheric density lays elsewhere.

REFERENCES

1. Wilmoth, R. G., LeBeau, G. J., and Carlson, A. B., "DSMC Grid Methodologies for Computing Low-Density, Hypersonic Flows About Reusable Launch Vehicles," AIAA Paper 1996-1812, June 1996.
2. LeBeau, G. J. and Lumpkin III, F. E., "Application Highlights of the DSMC Analysis Code (DAC) Software for Simulating Rarefied Flows," *Computer Methods in Applied Mechanics and Engineering*, Vol. 191, Issues 6-7, December 7, 2001, Pages 595-609.
3. Bird, G. A., *Molecular Gas Dynamics and the Direct Simulation of Gas Flows*, Clarendon Press, Oxford, 1994.
4. Borgnakke, C. and Larsen, P. S., "Statistical Collision Model for Monte Carlo Simulation of Polyatomic Gas Mixture," *Journal of Computational Physics*, Vol. 18, Pages 405-420, 1975.
5. http://www.ugs.com/products/nx/
6. http://saturn.jpl.nasa.gov/home/index.cfm/
7. Moe, K. and Moe, M. M., "Gas-Surface Interactions and Satellite Drag Coefficients," *Planetary and Space Science*, Vol. 53, 2005, Pages 793-801.