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MARS ENTRY VEHICLE AERODYNAMIC FLIGHT MEASUREMENTS

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Abstract

Entry flight measurements of the aerodynamic coefficients from the Viking 1 and Pathfinder Mars missions have been extracted and analyzed. Both missions use a spherically blunted 70 deg. half-angle cone entry vehicle and traverse all speed regimes from free-molecule flow down to zero velocity on the planet's surface. The emphasis in this report is on the aerodynamic characteristics experienced by blunt-body vehicles as they make the transition from free-molecule flow to continuum conditions. Flight measurements of normal-to-axial force coefficient are shown for both missions. Measurements of these ratios come directly from accelerometers and do not require knowledge of the atmospheric density. To accurately simulate the aerodynamics in the hypersonic transitional flow regime, the direct simulation Monte Carlo (DSMC) method is used for most of the transitional regime and the Navier-Stokes continuum formulation is used at the less rarefied conditions. DSMC simulations are compared with flight aerodynamic coefficient ratio data in the rarefied-flow regime with good agreement. The Viking 1 flight measured drag coefficient is also presented and combined with DSMC simulations to provide a complete hypersonic to free molecule flow drag profile. Using flight acceleration measurements and code generated aerodynamics, the Pathfinder atmospheric density profile is calculated and compared to Viking 1 measured densities. Viking 1 results are slightly larger than the recent Pathfinder density data in the rarefied-flow regime, as expected due to diurnal effects, but are in excellent agreement at lower altitudes where atmospheric mixing occurs.

Introduction

Two Viking spacecraft successfully landed on Mars in 1976. Due to the tenuous Martian atmosphere, a three-tier deceleration system (aerodynamic braking, drag amplification using a parachute, and, finally, terminal descent landing rockets) was used to place the Viking science payload on the surface of the planet. During entry, both vehicles traversed all the speed regimes going from orbital velocities under near vacuum conditions, i.e., the free-molecule flow regime, through the hypersonic continuum regime, down to zero velocity on the planet's surface where the CO_2 atmospheric pressure is less than 1% of the Earth's surface pressure. The Viking aerodynamic braking phase used a spherically blunted 70 deg. half-angle cone entry vehicle. Viking 1 was designated as the "pathfinder" for the second identical entry vehicle. Data collected from the first entry was quickly processed[1] and analyzed so that knowledge gained from the first Mars entry could be used to optimize the success of the second mission. This was followed by more detailed analysis of the atmosphere[2] as well as vehicle performance[3]. Over twenty years later, on July 4, 1997, the Pathfinder mission[4] successfully placed a remotely controlled rover vehicle on Mars' surface. Pathfinder uses multiple deceleration

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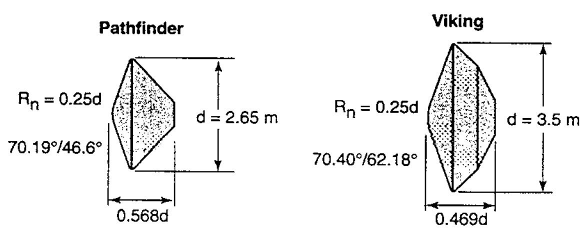
systems similar to Viking with the addition of an air bag to cushion the touchdown. Also, like the Viking mission, the first stage of deceleration uses a spherically blunted 70 deg. half-angle cone entry vehicle.

NASA has elected to pursue an aggressive Mars exploration program. The near-term future missions to Mars include plans for several direct and aerocapture transfers from the Earth-Mars trajectory, e.g. Mars Surveyor Program (MSP)-98 (a Lander mission at angle-of-attack, $\alpha \sim 0$ deg.), MSP-01 (a Lander at $\alpha \sim 11$ deg. and an Orbiter using aerocapture at $\alpha \sim 11$ deg.). MSP-98 will use a spin stabilized attitude control, similar to Pathfinder, while MSP-01 will use an active flight control scheme, similar to Viking. The planned vehicle shape for both Lander entry vehicles and the Orbiter aerocapture vehicle is a spherically blunted 70 deg. half-angle cone. Future aerobraking missions to Mars rely upon knowledge of the entry vehicle aerodynamic characteristics as it transitions from the free-molecule flow regime into the hypersonic continuum regime and knowledge of the properties of the upper atmosphere. Typically, wind-tunnel data are not available in the rarefied regime so designers rely heavily on computational results. Confidence in the computational results is greatly enhanced by comparing to flight data. Fortunately, for Mars missions, the wealth of data collected by the Viking and Pathfinder missions provides information to establish design confidence. The purpose of this paper is to present a comparison of Viking 1 flight aerodynamic extraction results with recent DSMC simulations in the rarefied-flow regime and with the flight results from the more recent Pathfinder mission. An application of the DSMC codes to calculate the Pathfinder entry vehicle aerodynamic drag is shown. A comparison of the extracted Mars upper atmospheric density for Pathfinder, using the DSMC simulation results, and the earlier Viking atmosphere results, is also included.

Mars Pathfinder and Viking Comparisons

There are many similarities to the Mars spherically blunted 70 deg. half-angle cone entry vehicles in this report, but there are some differences worth mentioning. Fig. 1 shows a scaled drawing of the Mars Pathfinder and Viking aeroshells. The included table shows some of the differences in the physical vehicles as well as trajectory differences between the two missions. For instance, the entry speed of Pathfinder is nearly twice that of Viking (7600 m/s vs. 4500 m/s) due to the direct entry on the Earth-Mars transfer trajectory, as opposed to Viking's deorbit from an existing orbit about Mars. Also, the Pathfinder entry vehicle diameter is smaller (2.65 m vs. 3.50 m) than the Viking entry vehicle. But, the differences in the mass of both vehicles yield about the same continuum ballistic coefficient (mass to drag coefficient times area ratio) of about 63.6 kg/m^2. Both vehicles have the same bluntness ratio (nose to aft radius) of 0.5, but different afterbody shapes. The hypersonic regime attitude for pathfinder is nominally 0.0 deg., using spin stabilization control methods, while Viking uses a three-axis controlled lifting entry targeted for 11.0 deg. angle-of-attack.



Pathfinder		Viking
7600	Relative velocity, m/s	4500
585.3	Entry mass, kg	980.8
5.512	Area, m^2	9.62
0.0	Angle-of-attack, deg	-11.0
Spin stabilized	Guidance & control	Three axis control

Fig. 1 Comparisons of Mars Pathfinder and Viking entry characteristics.

Trajectory and Attitude Results

The trajectories for the Viking and Pathfinder entry vehicles are reconstructed using data acquired as each vehicle transverses the CO_2 Martian atmosphere[5,6]. Both Viking and Pathfinder post-flight entry trajectory reconstruction methods use pre-entry state vectors and post-landing position fixes based upon radio tracking provided by flight operations navigation teams. These data are statistically combined with the insitu accelerometer and gyro (if available) measurements to provide the "best" estimate of the trajectory parameters actually flown, similar to the way onboard navigation processors provide position, velocity, and orientation. Direct processing of these inertial system measurements (acceleration and gyros) provide trajectory parameters independent of aerodynamics and atmosphere model assumptions.

The Viking onboard entry vehicle measurements are three-axis accelerometers and gyros, an altimeter, a mass spectrometer, stagnation pressure sensor, and other scientific instruments. Only those measurements relevant to the trajectory and aerodynamic coefficients will be discussed. Other data from Viking and more detailed results exist in the open literature[1,2,3]. The Pathfinder onboard measurements consisted of a three-axis accelerometer but no gyros. The vehicle was spin stabilized (at 2 rpm) and targeted for a ballistic entry flight path, i.e., zero deg. angle-of-attack. A low altitude altimeter (altitudes < 2000 m) and a post-landing Doppler position determination was utilized in the Pathfinder trajectory reconstruction process. To illustrate the effectiveness of the reconstruction process, Fig. 2 shows a comparison of the reconstructed trajectory (from double integration of the acceleration measurements) with redundant altimeter and landing location measurements.

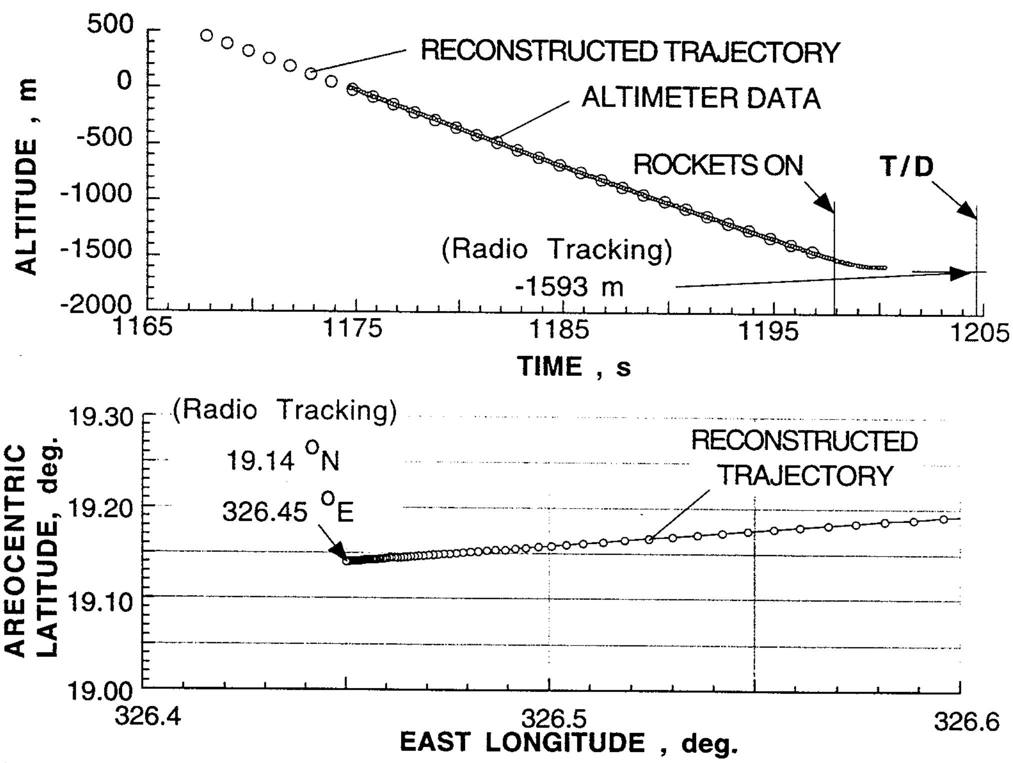


Fig. 2 Comparison of Pathfinder reconstructed trajectory with altimeter and landing location measurements.

The top graph of Fig. 2 shows a comparison of the converged trajectory parameter, altitude, as a function of time (from probe cruise stage separation) with the measured altitudes. During this entire time period, the probe is suspended from a parachute with the aeroshell heat shield discarded. There is excellent agreement between the reconstructed results and the measurements. Also included are the ignition time for the three rockets used to further slow the descent, the measured landing position obtained from radio tracking, and the time of first impact with the planet's surface. Note that altitude presented is relative to an oblate spheroid (equatorial radius = 3394.670 km and polar radius = 3376.778 km) and the probe landing location is 1593 m below this reference. The corresponding latitude and longitude ground track is given in the lower graph on Fig. 2.

The post-flight radio tracking position is also included and, again, agrees well with the landed position measurement.

A comparison of reconstructed velocity-altitude trajectories for both Pathfinder and Viking 1 missions is given in Fig. 3. Initially, both vehicles approach the planet on conics (elliptical for the Viking vehicle, and hyperbolic for Pathfinder). Thus, velocity increases as the vehicle approaches its respective periapsis. However, prior to achieving periapsis the atmosphere is encountered and abruptly lowers the velocity as kinetic energy is dissipated into heat by the atmosphere. The focus of this report is the rarefied-flow transition region from about 130 km to about 65 km where the velocity just begins to decrease, and the aerodynamic flowfield transitions from free molecule flow to the hypersonic continuum.

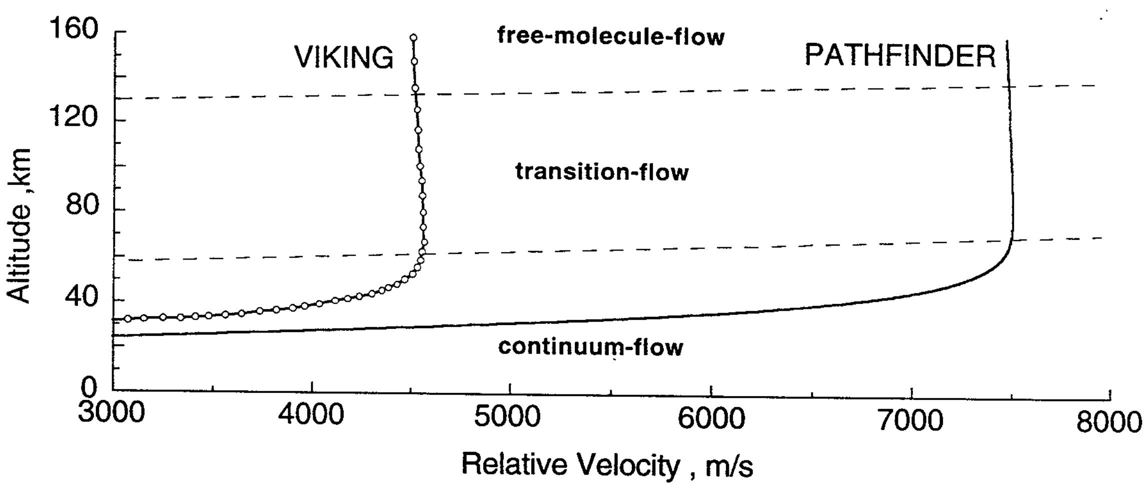


Fig. 3 Viking 1 and Pathfinder reconstructed velocity-altitude profiles.

Viking Attitude and C_N/C_A Measurements

The attitude of the Viking entry vehicle has been obtained from the gyro measurements and is shown in Fig. 4(a) as a function of altitude for Viking 1. Positive lift is generated with a negative angle-of-attack, i.e., vehicle nose down relative to the velocity vector. The Viking mission used lift to prolong the atmospheric transit time during the aerobraking phase in order to maximize the dissipation of the vehicle's kinetic energy. Above about 75 km, the on-board control system was programmed to hold a constant attitude of approximately 11 deg. At 0.05 g, which was sensed by the accelerometers, the attitude control system was programmed to switch to an attitude rate-damping mode for the remainder of the aerobraking phase. This event occurred at about 75 km, as shown in Fig. 4(a). Viking 1 trimmed hypersonically at about 10.7 deg., an angle just slightly less than the design value of 11 deg., as observed in Fig. 4(a), at altitudes from about 40 to 50 km. The attitude information shown in Fig. 4 is an important reference when interpreting the aerodynamic coefficients shown later.

The corresponding measured ratio of normal-to-axial acceleration is shown in Fig. 4(b). That is, the acceleration ratio provides the following,

$$\frac{A_n}{A_z} = \frac{C_N}{C_A} \qquad (1)$$

where the accelerometer triad is aligned with the vehicle body axes, and A_n is the root-sum-square of the two accelerometers perpendicular to the axial channel, A_z. By eliminating reliance on dynamic pressure, this ratio provides a direct measure of aerodynamic performance using only acceleration data. As seen in Fig. 4(b), Viking instrumentation provided acceleration ratio measurements in only a portion of the rarefied-flow flight regime, up to about 110 km. Beyond this altitude the signal-to-noise in the measurements is poor. Note that almost the entire set of rarefied-flow measurements were obtained at approximately 11 deg. angle-of-attack, with some small variations of about ± 0.2 degs.

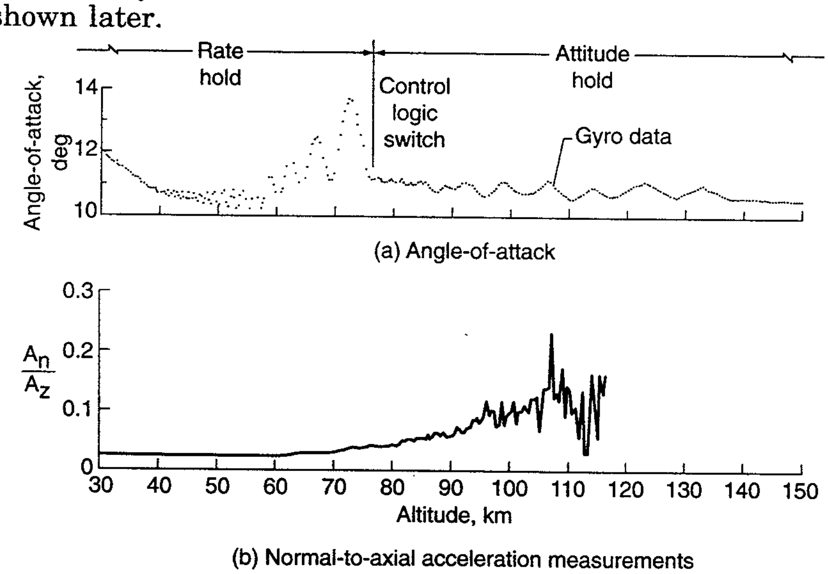


Fig. 4 Viking 1 normal-to-axial acceleration and angle-of-attack measurements.

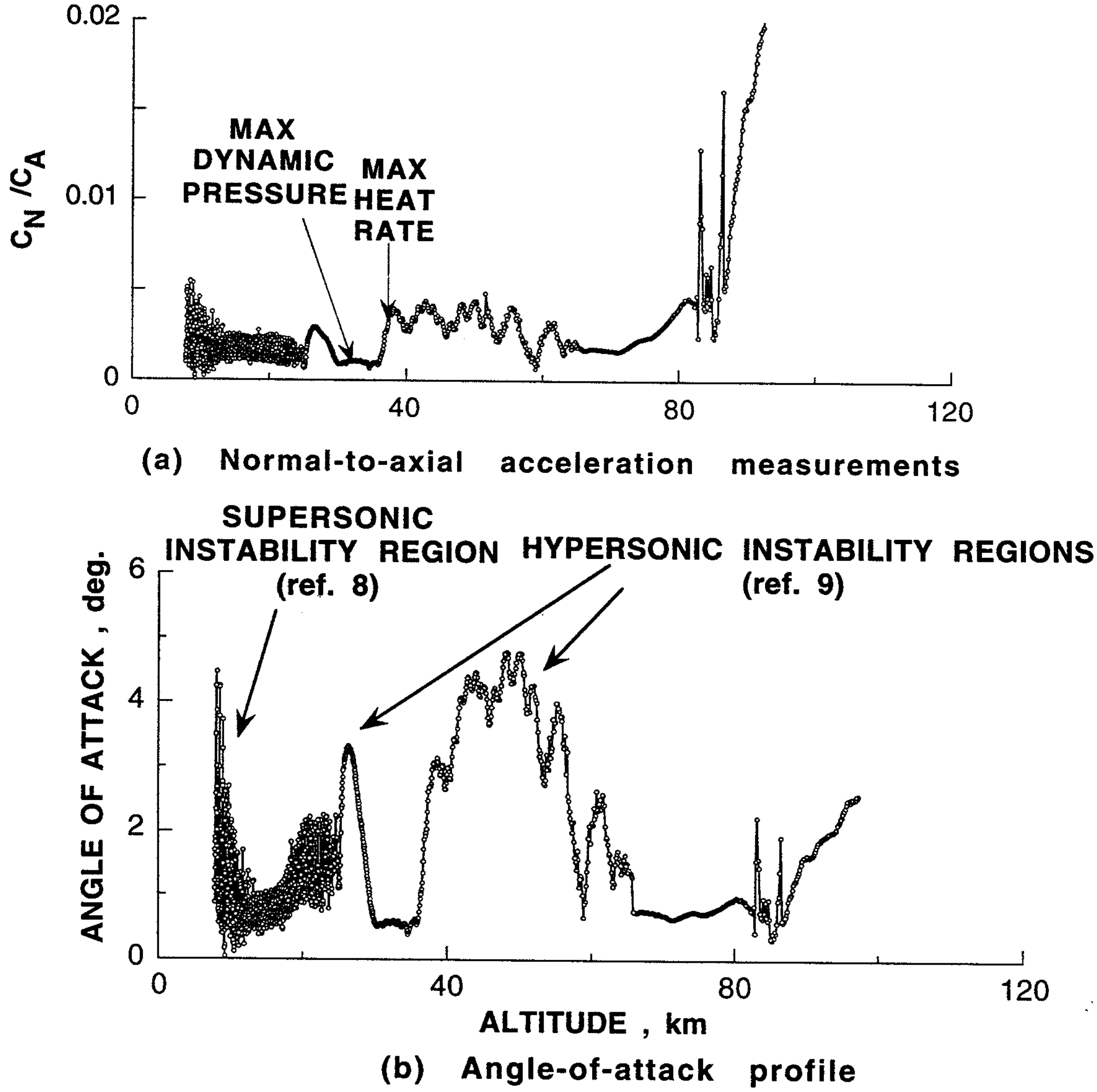


Fig. 5 Pathfinder normal-to-axial measurements and corresponding total angle-of-attack.

Pathfinder Attitude and C_N/C_A Measurements

As mentioned earlier, the Pathfinder instrument suite did not include a gyro package. However, angle-of-attack during the entry can be estimated using spacecraft accelerometer measurements and the preflight aerodynamics database[7]. This is achieved using the force coefficient ratios, C_N/C_A since this aerodynamic coefficient ratio is a function of angle-of-attack. Using the relative velocity profile from the best estimated trajectory presented earlier and the accelerometer data, the preflight aerodynamic database was interpolated to produce an estimate of angle-of-attack. This angle-of-attack, along with the corresponding normal-to-axial coefficient ratio for the entire aerobraking entry phase, is presented in Fig. 5.

For the aerobraking phase of flight, angle-of-attack is obtained using an iterative procedure starting with density obtained for the ballistic conditions. Above about 95 km, angle-of-attack is not available due to instrument resolution limitations of the normal channels. But, as altitude decreases, the A_n/A_z signal is strong enough to discern vehicle attitude. The presence of two hypersonic static instability regions and a supersonic instability region predicted in Refs. 8 and 9 is clearly evident in Fig. 5(b). The hypersonic static instability regions (centered at approximately 45 and 25 km) and the supersonic instability region (at altitudes < 10 km corresponding to Mach < 2.5) are seen in both the angle-of-attack estimates derived with the pre-flight aerodynamic database and the accelerometer measurements alone. At peak heating, the vehicle total angle-of-attack is approximately 3 degs. Maximum dynamic pressure occurs at slightly lower altitudes (33 km) where total angle-of-attack is about 0.5 degs.

Density of Mars Upper Atmosphere

The Viking flight measurements are used to generate the density encountered by the vehicle. The sources for density from flight are the mass spectrometer, the stagnation pressure sensor, and the accelerometers. The Viking mission had an open-source magnetic-sector mass spectrometer as part of its scientific complement[10]. The pressure device senses pressure by deflection of a thinly stretched diaphragm referenced to a vacuum chamber and is also part of the complement of scientific instruments. The accelerometers were used for both engineering purposes (e.g. onboard guidance and control) as well as part of the scientific complement in generating the atmospheric state properties. Figure 6 shows the density-altitude profile derived from the measurements of the mass spectrometer at higher altitudes, and the stagnation pressure sensor and accelerometers at lower altitudes.

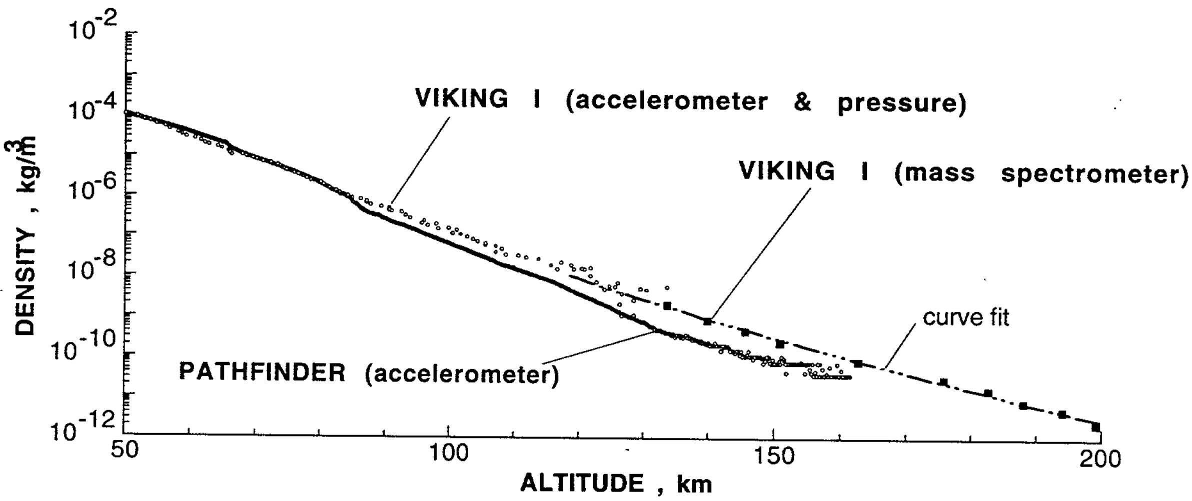


Fig. 6 Mars upper atmosphere density measurements.

Between about 110 km and 130 km, the large signal-to-noise ratio from the accelerometers and the reliability of the corrections to the open-source mass spectrometer data leave a gap between the data sets. A fit to both sets of data is used to bridge this data gap and is labeled "curve fit" on the figure. The function used for the fit and the values obtained for the function constants are,

$$\rho = 6.4 \times 10^{-8} e^{\frac{-(h-105)}{H}} \quad (2)$$

$$\text{and} \quad H = 0.02127(h-105) + 7.45$$

and h is altitude in km.

Also shown in Fig. 6 are the "engineering" density results from the recent Pathfinder mission. The atmospheric density shown is calculated independent of the trajectory parameters but, unlike Viking data, requires aerodynamic coefficient values. The density extracted from the acceleration data uses the Pathfinder aerodynamic data base (ref. 7) which includes the rarefied-flow aerodynamics discussed subsequently. The Pathfinder density data in Fig. 6 is the result of a point-by-point transformation using,

$$\rho = \frac{2A_z}{V^2 C_A \left(\frac{S}{m}\right)} \quad (3)$$

where V is the relative velocity obtained from the trajectory reconstruction process discussed previously, A_Z is the measured acceleration along the axial direction, C_A is the axial aerodynamic coefficient, and (S/m) is the probe area-to-mass ratio. The values of C_A are flight regime dependent, and since all flight regimes from free-molecule flow to subsonic flow are encountered during entry, an iterative scheme was used to obtain the proper value of this aerodynamic coefficient. This involves calculating the classical scaling parameters such as Knudsen number, Reynolds number, and Mach number using an a priori density as a starting point. These scaling quantities also involve two other atmospheric state properties, namely free-stream pressure and temperature, which are derived from density using the hydrostatic and equation-of-state relations.

The measured density profiles for Pathfinder and Viking show excellent agreement in the hypersonic regime below about 80 km. Above that altitude there are differences, with the density from Pathfinder data being consistently lower than Viking results. The landing latitudes of both missions are nearly the same (22.5 deg. N for Viking vs. 19.1 deg. N for Pathfinder). The larger values of upper atmospheric density for Viking are consistent with expected diurnal effects (i.e. Viking landing at about 4 p.m. local solar time, mid-afternoon; and Pathfinder landing at about 3 a.m. local solar time, nighttime).

Aerodynamic Results

Extracting individual coefficients from acceleration requires a knowledge of atmospheric density. For Viking this was possible during certain portions of flight, but for Pathfinder, no atmospheric measurements were attempted during the aerobraking phase of flight. When density data is not available, the most reliable aerodynamic measurements are obtained by establishing acceleration ratios since dynamic pressure cancels and the acceleration ratio is identical with the force coefficient ratio, as discussed earlier. The ratio of acceleration measurements (normal-to-axial direction) for Viking 1 as a function of altitude, along with the transformed wind axis coefficient ratio (L/D) and the corresponding angle-of-attack measurements (repeated here for reference), are presented in Fig. 7. The measurement corresponds to the hypersonic continuum regime at about 11 deg. angle of attack for altitudes less than about 70 km and the transition into the rarefied-flow regime at altitudes larger than 70 km.

Using the previously discussed information on the vehicle attitude, i.e., the density derived from mass spectrometer, pressure sensor, and acceleration measurements, along with other information (e.g., velocity), given in Ref. 3, 3-D DSMC simulations were performed for selected trajectory points[11]. The results of these calculations are shown in Figs. 7(b) and 7(c). The DMSC predictions for the rarefied-flow transition region show excellent agreement with the flight measurements. Free-molecule flow results assuming complete diffuse reflection (applicable to near orbital conditions) and modified Newtonian results for the hypersonic continuum conditions are included in both Fig. 7(b) and Fig. 7(c).

The corresponding flight measured normal-to-axial coefficients as a function of altitude for the Pathfinder entry were given earlier. A comparison of recent DSMC and Navier-Stokes simulations with the flight data are given as a function of Knudsen number (ref. length = 2.65 m) in Fig. 8.

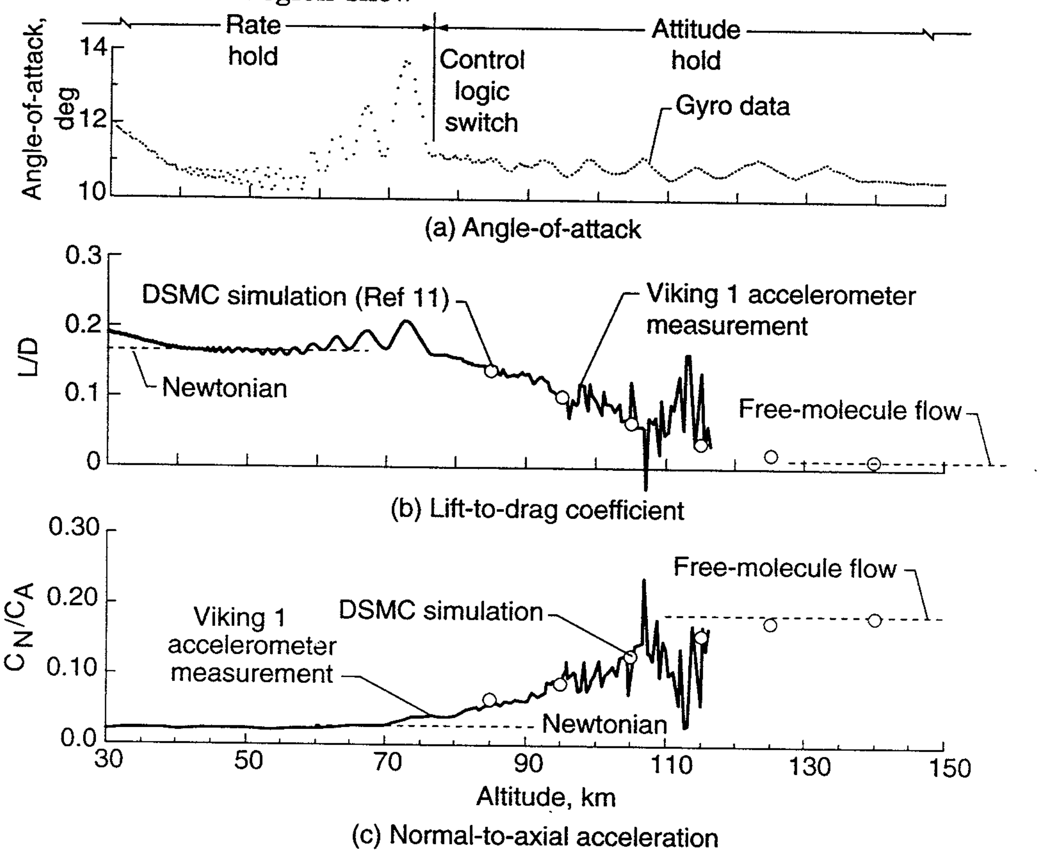


Fig. 7 Comparison of DSMC simulations with Viking 1 normal-to-axial coefficient measurements, corresponding lift-to-drag coefficients, and angle-of-attack.

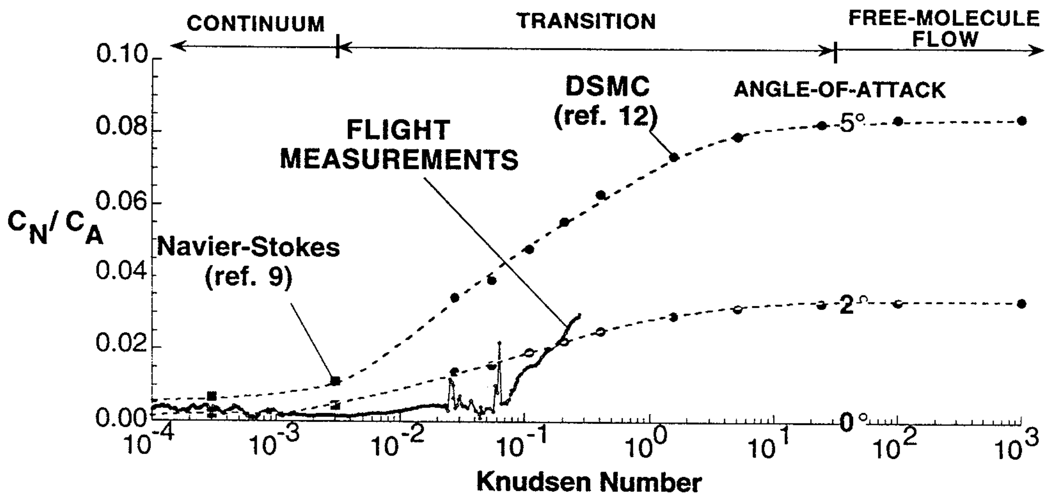


Fig. 8 Comparison of DSMC and Navier-Stokes simulations with Pathfinder flight measurements.

Shown in the rarefied-flow regime are Moss[12] 3D DSMC simulations of the Pathfinder entry at small angle-of-attack (2 and 5 degs.) and the corresponding Navier-Stokes calculations of Gnoffo, along with the flight measurements. The dotted lines are curve fits to the simulation data. Pathfinder was targeted to be at zero degs. angle-of-attack at entry and, thus, little measurement leverage is obtained by examining the acceleration ratio. However, a small segment of rarefied flow data has been accumulated. It's clear that the mission objectives of a ballistic entry were achieved, and the 2.0 rpm vehicle spin rate was adequate to overcome the aerodynamic rarefied-flow instability[12].

Previous work with the Viking 1 data reported in Ref. 3 allowed separation of the drag coefficient (C_D) from density using the stagnation pressure sensor measurements. However, this analysis was limited to the hypersonic continuum regime (altitudes less than about 70 km) due to the capability of the pressure sensor. Figure 9 shows these flight results together with the corresponding DSMC simulations for Viking 1. In addition, the corresponding free-molecule flow and modified Newtonian values are included. Figure 9 shows the aerodynamic drag of entry vehicle from free-molecule flow down into the hypersonic continuum at an angle-of-attack of about 11 deg.

The Pathfinder entry vehicle, also a spherically blunted 70 deg. half-angle cone shape, but with a slightly different afterbody, has been simulated at 0 deg. angle-of-attack with a 2-D DSMC code[13]. The Pathfinder results are also included in Fig. 9 for comparison. To make the appropriate comparison of the Pathfinder calculations on an altitude basis, the density profile measured by Viking 1 was used.

As the vehicle approaches the hypersonic continuum regime (for Viking ~70 km, corresponding to Kn ~ .001), a local minimum in C_D is achieved, which is close to the Newtonian value. At lower altitudes, C_D begins to rise slightly (~ 3%) from this minimum before becoming approximately constant. Within the continuum regime, this phenomena is due to changes in the flowfield chemistry, indicated by changes in the ratio of specific heats, γ going from about 1.4 (or 1.32 depending on the gas degrees of freedom) to about 1.1 to 1.2. As dissociation begins to dominate, the sonic line moves from being in the vicinity of the vehicle outer shoulder to a region nearer the sphere-cone juncture[9]. This sonic line shift causes a redistribution of the surface pressure, which results in a corresponding change in the C_D. This phenomena is vehicle geometry and attitude dependent and, thus, is not present for all entry vehicles (e.g., smaller half-cone angle entry vehicles), nor all angles-of-attack.

For a given altitude, both the Viking and Pathfinder simulations used the same density and also the same composition (95.37% CO_2 and 4.63% N_2 mole fractions). The Pathfinder vehicle angle-of-attack is nominally 0 deg. and, thus, it is expected that the hypersonic continuum values of C_D should be larger than the Viking vehicle at 11 deg. Notice, at about 70 km, that the Pathfinder DSMC results tend to level out at a drag coefficient that is larger than the Viking flight measured values, as expected. At the other extreme, for altitudes above 120 km, the Pathfinder free-molecule flow values differ only slightly from the Viking 1 results. It is difficult to make a direct

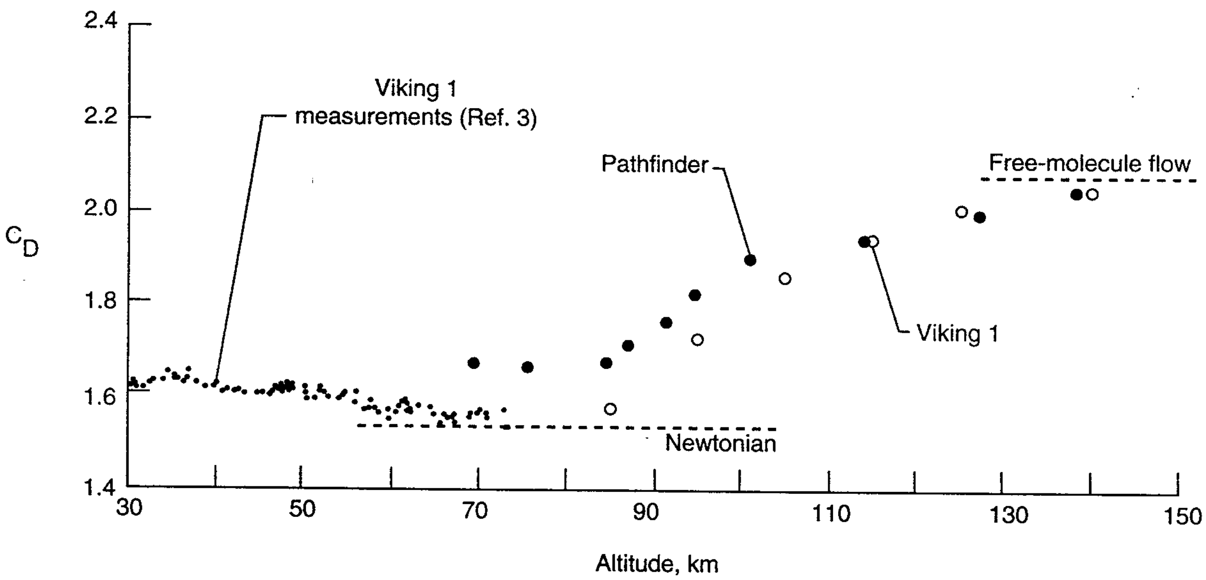


Fig. 9 Viking 1 and Pathfinder DSMC drag coefficient simulations with Viking 1 flight measurements.

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comparison between the two entry missions near the free-molecule flow regime for several reasons. First the rarefaction effect on Pathfinder is slightly larger than Viking since the Viking vehicle diameter is larger (3.50m vs. 2.65m). Also, the Pathfinder vehicle entry speed is larger than Viking entry speeds. Furthermore, the variation in C_D with angle-of-attack in the continuum is different from the variation in the free-molecule flow regime.

The success in matching the DSMC simulations with the Viking flight acceleration ratio data (Fig. 7) provides renewed confidence in aerodynamic coefficient generation procedures. Using these codes with the Pathfinder mission data establishes that mission objectives of a ballistic trajectory were achieved and the spin rate was adequate (Fig. 8). In addition, the code generated C_D (Fig. 9) provides the correct upper-atmosphere density (Fig. 6), an important piece of information for future Mars missions.

Summary

The normal-to-axial force coefficient ratio for the Viking and Pathfinder spherically blunted 70 deg. half-angle cone entry vehicles has been extracted from flight data in the transition from hypersonic continuum into free molecule flow regime. The extraction technique includes the reconstruction of the trajectory using onboard inertial navigation measurements and incorporates into the solution redundant data types, such as altimeter or radio measurements. Results from simulations of the Viking vehicle with a 3-D DSMC code are in excellent agreement with the flight data. DSMC simulations of the Pathfinder entry into Mars have been computed to the fringes of the hypersonic continuum flight regime. The drag coefficients for Pathfinder are compared to those for Viking with good qualitative agreement, taking into account the differences in the vehicles and trajectories. Using the predicted Pathfinder aerodynamics provides a flight derived upper-density profile which agrees well with the density profile extracted from the Viking 1 data, thus, providing further reinforcement that DSMC codes provide reliable aerodynamic characteristics in the rarefied-flow regimes.

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