Mars Pathfinder Entry, Descent, and Landing Reconstruction

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The primary objective of the Mars Pathfinder mission was to demonstrate an innovative, low-cost, reliable method for placing a science payload on the surface of Mars. The spacecraft performance during entry, descent, and landing is assessed. Analysis of the accelerometer and altimeter flight data obtained by the Pathfinder spacecraft during atmospheric flight is provided. Results of an effort to reconstruct the spacecraft trajectory and attitude history are presented. An estimate of the Mars atmosphere profile encountered during atmospheric flight is given.

Nomenclature

\( A_n \) = acceleration normal to the entry vehicle centerline, \( g_E \)

\( A_x, A_y, A_z \) = accelerations in the entry vehicle body-fixed directions, \( g_E \)

\( C_A \) = axial force coefficient

\( C_n \) = normal force coefficient

\( g \) = gravitational acceleration, km/s\(^2\)

\( h \) = altitude, km

\( I_{xx}, I_{yy}, I_{zz} \) = mass moments of inertia about the entry vehicle axes, kg-m\(^2\)

\( I_{xy}, I_{xz}, I_{yz} \) = mass products of inertia for body-fixed planes, kg-m\(^2\)

\( M \) = mean molecular weight, kg/kmol

\( m \) = entry vehicle mass, kg

\( p \) = ambient pressure, N/m\(^2\)

\( R \) = universal gas constant, J/(kmol-K)

\( S \) = entry vehicle frontal area, m\(^2\)

\( T \) = temperature, K

\( V \) = atmosphere-relative velocity, km/s

\( \rho \) = atmospheric density, kg/m\(^3\)

\( \omega_{\text{obs}} \) = observed vehicle roll rate, rad/s

\( \omega_z \) = roll rate about the vehicle Z axis, rad/s

Introduction

The Pathfinder spacecraft impacted the surface of the Red Planet 5 min after entering the atmosphere of Mars, then bounced and rolled to a stop, thus beginning a 3-month surface mission\(^1\) that captured the public’s attention and proved to be a monumental success for NASA. Beyond the science return and successful deployment and operation of a Mars rover, the primary purpose for the Pathfinder mission was the demonstration of a unique, low-cost method for placing science payloads on the surface of Mars. Toward this end, reconstruction of the Mars Pathfinder entry, descent, and landing (EDL) system performance from flight data is a critical legacy of this technology demonstration mission.

This paper presents the results of an effort to reconstruct the Pathfinder atmospheric entry trajectory and to assess the performance of the EDL system. In addition, a reconstruction of the Mars atmosphere profile encountered by the Pathfinder entry vehicle is presented.

EDL Sequence of Events

The Pathfinder spacecraft entered the Mars atmosphere directly from the interplanetary transfer trajectory, with an inertial velocity magnitude of 7.26 km/s. The Pathfinder EDL sequence of events is shown in Fig. 1. The cruise stage was jettisoned 30 min prior to atmospheric entry. The entry vehicle reached maximum stagnation-point heating and peak dynamic pressure during the initial 80 s of the entry phase. At 172 s past entry, the parachute was deployed, followed by the release of the heatshield 20 s later. The lander was then deployed below the backshell along a 20-m bridle. At an altitude of 1.6 km above ground level (AGL), the on-board radar altimeter acquired the ground. Altimeter data were used by the flight software to establish the timing of airbag inflation and ignition for a set of three solid rocket motors (mounted on the backshell) at an altitude of 90-m AGL. At an altitude of 21 m, the bridle was cut, and the lander fell directly to the surface, buffered at ground impact by the airbag system. Sufficient impulse remained in the solid rockets to carry the backshell and parachute to a safe distance away from the lander.

EDL Flight System Overview

With the release of the cruise stage at 30 min prior to entry, the ability to propulsively control the spacecraft was lost. The entry vehicle was spin stabilized with a roll rate of 2.0 rpm, and the vehicle spin axis was aligned so that the angle of attack with respect to the relative wind at the atmospheric interface (defined at a radius of 3522.2 km) would nominally be near zero. The entry vehicle mass was 585.3 kg, and the ballistic coefficient during hypersonic flight in the continuum regime was 63.2 kg/m\(^2\). The following sections briefly describe key components of the EDL flight system.

Aeroshell

The Pathfinder aeroshell consisted of a forebody heatshield and an aftbody backshell. The aeroshell diameter was 2.65 m, and the forebody shape was a Viking-heritage 70-deg half-angle sphere-cone with a nose radius of 0.6638 m and a shoulder radius of 0.0662 m, as seen in Fig. 2. The forebody ablative material was super lightweight ablator (SLA)-561 V, with a uniform thickness of 19.05 mm (0.75 in.). The backshell was thermally protected with the spray-on version of the SLA-561 material. The heatshield mass was 64.4 kg, and the backshell mass was 56.9 kg.
Accelerometers
Two sets of three orthogonally positioned Allied Signal QA-3000 accelerometer heads each provided three-axis acceleration measurements during entry. One set of accelerometers was part of the Atmospheric Structure Investigation/Meteorology (ASI/MET) experiment. The ASI/MET accelerometers were range switched during the entry trajectory to provide increased resolution. Dynamic ranges of 16 mg, 800 mg, and 40 g were used. The ASI/MET accelerometers were aligned parallel to the entry vehicle coordinate system axes. The second set of accelerometers was used as the primary input for the parachute deployment algorithm. This set of engineering accelerometers was oriented such that two of the sensor heads were canted at ±45 deg to the entry vehicle Z axis (the longitudinal axis) in the Y–Z plane, and the third accelerometer head was aligned with the X axis.

Parachute System
The Pathfinder parachute was a modified Viking-heritage disk-gap-band design, developed by Pioneer Aerospace. The parachute canopy was made of Dacron®, with Kevlar® suspension lines. The project requirement for maximum peak dynamic pressure at parachute deployment was 703 N/m², although parachute drop tests had indicated that dynamic pressures over 800 N/m² were within the design capability. The total parachute mass was 17.5 kg.

The stowed parachute and suspension lines were packaged within an overpack, or container, which in turn was inserted into a deployment canister. Deployment was achieved through use of a mortar assembly, which was initiated by a pyrotechnic device.

Bridle
Following heatshield release, the lander was deployed below the backshell along a 20-m bridle. The bridle deployment mechanism was based on a device that is used for emergency egress of air crews from large jet aircraft. The bridle consisted of a rate-limited Kevlar tether and metallic tape, wound on a centrifugal brake. A triple bridle was attached to the single bridle at a confluence point near the backshell. The triple bridle was connected to the backshell on the brackets that support the three solid rocket motors used during terminal descent. The mass of the bridle was 7 kg.

Radar Altimeter
The Honeywell HG8505DA radar altimeter was activated following heatshield release. The altimeter maximum range specification was 1.52 km (5000 ft). The radar altimeter operated in a first-return mode, transmitting a series of noncoherent radar pulses to the surface and clocking the time to the first received signal. Altitude data were provided with 0.3048-m (1-ft) resolution at a frequency of 50 Hz. The mass of the radar altimeter was 1.4 kg.

Rocket-Assisted Deceleration System
The rocket-assisted deceleration (RAD) system was developed by Thiokol Corporation. Three solid rocket motors, each 85 cm in length × 12.7 cm in diameter, were mounted on the backshell. The rocket motors were ignited simultaneously at a time calculated by the onboard altimeter-based RAD firing algorithm. The algorithm was designed so that the RAD system burn would bring the lander vertical velocity to zero at a nominal altitude of 13 m above the ground, with enough impulse left to carry away the backshell and...
parachute following bridle cut. The motor burn duration was 2.2 s, and each rocket produced 7938 N of thrust. The total mass of the RAD system was 30.7 kg.

Airbags

The airbag system was the key element of Pathfinder’s new approach to EDL. Designed by the Jet Propulsion Laboratory (JPL) and ILC Dover, the airbag system actually consisted of four separate interconnected airbags, each with six lobes and a gas generator. The airbag material was Vectran®️, which had a mass per unit area of 6.774 kg/m². The inflated airbag system (with the lander cushioned inside) was 5.27 m wide, 4.63 m high, and 4.80 m deep. The airbag material mass was 87.8 kg, the mass of the gas generators was 10.0 kg, and the mass of the airbag retraction motors was 6.2 kg. Inflation time of the airbags was 0.5 s, and the deflation/retraction time was between 0.5 and 1.5 h.

The airbag system was rigorously tested preflight through drop tests at Sandia National Laboratory and the NASA John H. Glenn Research Center at Lewis Field, Plum Brook Station chamber (Fig. 3). The system was designed to withstand a vertical impact velocity of 14 m/s and a horizontal impact velocity of 20 m/s. It was tested to land on 0.5-m-high rocks without failure.

Inertia Properties

The entry vehicle center-of-mass (c.m.) location and inertia properties are shown in Table 1. The c.m. location and inertia properties are expressed in the EDL coordinate system: The origin of the system is in the plane at the top of the backshell interface pads, the Z axis is directed through the nose of the heatshield, and the X and Y axes are perpendicular to the vehicle axis of symmetry. The values shown in Table 1 were measured at Kennedy Space Center 1 month prior to launch.

Trajectory Reconstruction

The Pathfinder entry trajectory has been reconstructed from several data sources. Radiometric tracking data taken during the interplanetary approach phase provide an estimate of the vehicle state at atmospheric entry. Onboard accelerometer measurements taken during EDL provide a time history of the entry vehicle body-fixed accelerations. Radar altimeter measurements during terminal descent are available for the final 1591 m of flight. One-way Doppler data have been constructed from the carrier signal transmitted by the spacecraft during atmospheric entry. Finally, a landed position fix has been determined through landmark identification and tracking of the landed spacecraft.

Entry State

The orbit determination solution obtained for the pre-entry trajectory utilized range and Doppler data collected from Feb. 4, 1997 to July 4, 1997, at 15:36 universal time, coordinated (UTC). Tracking data after 15:36 UTC was not used for entry state determination because at that time the spacecraft had switched from a coherent to a noncoherent tracking mode, which reduced the accuracy of the data. However, these noncoherent Doppler data were later utilized in conjunction with onboard accelerometer and other spacecraft-based data for trajectory reconstruction.

The results of this solution were used to update and predict the conditions at the atmospheric entry point, which was defined to occur at a radial distance of 3522.2 km. This entry state serves as the initial estimate for atmospheric entry trajectory reconstruction efforts. Table 2 gives the entry state resulting from this orbit solution.

Acceleration History

Time-ordered acceleration data showing key events during the Pathfinder entry, as measured by the ASI/MET accelerometers, are given in Figs. 4–8. Figures 4–8 are presented in time segments starting at the atmospheric entry interface and extending beyond touchdown. The accelerations are expressed in units of Earth gravitational acceleration, where 1 g has a value of 9.795 m/s² (as calibrated in the JPL test lab). Figure 4 presents the initial 40 s of the entry trajectory starting at the time corresponding to the entry interface radius of 3352.2 km. The normal acceleration (lower plot) is the root sum squared of the two accelerometers normal to the axial acceleration (top plot). Namely,

\[ A_n = \sqrt{A_x^2 + A_y^2} \]  

(1)

The axial accelerometer data in Fig. 4 show the acceleration disturbance created when the instrument detects an automatic uprange
Fig. 4 Axial and normal acceleration measurements during entry: $0 \leq \text{time} \leq 40\text{s}$.

Fig. 5 Axial and normal acceleration measurements during entry: $40 \leq \text{time} \leq 180\text{s}$.

Fig. 6 Axial and normal acceleration measurements during entry: $180 \leq \text{time} \leq 280\text{s}$.

Fig. 7 Axial and normal acceleration measurements during entry: $280 \leq \text{time} \leq 310\text{s}$.

Fig. 8 Axial and normal acceleration measurements following impact: $300 \leq \text{time} \leq 360\text{s}$.

condition. This spurious spike in the data is a measurement artifact and does not represent a change in the actual spacecraft acceleration. Similar spikes are seen at gain-switching points in Figs. 5–7 as well. The normal acceleration disturbance from 27 to 30 s is attributed to the removal of the Kapton thermal shield, which protected the probe during interplanetary cruise phase. Details of the Pathfinder spacecraft’s flight through this rarefied atmospheric regime are presented in Ref. 5.

Figure 5 presents a continuation of the accelerometer data from 40 to 180 s. The axial accelerometer range changes to its maximum value of 40 g (full scale) at about 44 s. A short time later, both the Y- and X-axis accelerometers changed to their next range level (0.8 g). The axial accelerations show the key events of 1) maximum dynamic pressure, which closely corresponds to the maximum acceleration of 15.9 g; 2) firing of the pyrotechnic device, which jettisons the parachute canister (labeled mortar fire); and 3) the 6.2-g shock induced when the parachute opens. The time of the maximum heating rate is included for completeness, and it was calculated (along with the dynamic pressure) using the trajectory and atmosphere reconstruction results discussed in the subsequent sections. As discussed later, the normal acceleration data clearly show the two static instability regions predicted prior to flight using computational fluid dynamics techniques.

Figure 6 shows a continuation of these data during the parachute phase of the mission for a time period spanning 180–280 s from
the atmospheric interface. The axial accelerometer shows the automatic downrange to its next lowest scale of 0.8 g. Also seen are the separation of the heatshield and the separation of the lander from the backshell, along the 20-m bridle. At this time, there is a corresponding frequency shift in the normal accelerations. This is accountable because the spacecraft c.m. has shifted significantly, providing an additional small but spurious centripetal input into the accelerometers (which are no longer located near the system c.m.). Figure 7, next in this sequence, shows the remaining portion of the parachute phase down to airbag impact, including the first bounce on the surface of the planet. Both the axial and normal accelerometers were commanded through flight software to go to full scale (40 g) in anticipation of landing. The signature changes of the instruments are clearly seen in Fig. 7. Shortly thereafter, the airbags are inflated, and then the RAD system is ignited. Note that a small component of the thrust appears in the normal direction. While the rockets provide the retarding force, the bridle, from which the lander is suspended, is cut, and the lander free falls to the surface and begins to bounce. The first bounce spike due to impact with the surface is indicated in Fig. 7. Shortly thereafter, the airbags are inflated, and all 14 acceleration spikes indicating ground impacts were recorded. The accelerometer measurements were stopped at about 359.3 s, but the flight system continued to bounce before coming to rest. A time-ordered listing of the major EDL events is presented in Table 3.

### Table 3 Pathfinder EDL events time-ordered listing

<table>
<thead>
<tr>
<th>Event</th>
<th>Time from entry, s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry interface (radius = 3522.2 km)</td>
<td>0</td>
</tr>
<tr>
<td>Thermal blanket removal (begin)</td>
<td>29.0</td>
</tr>
<tr>
<td>Max heat rate</td>
<td>75.0</td>
</tr>
<tr>
<td>Max dynamic pressure</td>
<td>77.9</td>
</tr>
<tr>
<td>Mortar fire</td>
<td>171.4</td>
</tr>
<tr>
<td>Parachute open</td>
<td>172.7</td>
</tr>
<tr>
<td>Heatshield separation</td>
<td>192.1</td>
</tr>
<tr>
<td>Briddle deploy (lander separation)</td>
<td>211.4</td>
</tr>
<tr>
<td>Radar ground acquisition</td>
<td>276.0</td>
</tr>
<tr>
<td>Inflated airbags (begin)</td>
<td>295.2</td>
</tr>
<tr>
<td>Rocket ignition</td>
<td>299.1</td>
</tr>
<tr>
<td>Briddle cut</td>
<td>301.3</td>
</tr>
<tr>
<td>Touchdown (first bounce)</td>
<td>305.0</td>
</tr>
<tr>
<td>Last recorded bounce</td>
<td>360.2</td>
</tr>
<tr>
<td>Last data record</td>
<td>361.1</td>
</tr>
</tbody>
</table>

Parachute Deployment Algorithm Performance

The parachute deployment algorithm design and performance during EDL is documented in Ref. 2. The parachute deployment flight software algorithm was based on accelerometer measurements and a timing system, designed to fire the parachute mortar when the vehicle dynamic pressure was within the range of 580–703 N/m², and the Mach number was within the range of 1.70–2.29. The target dynamic pressure for parachute deployment was 600 N/m². Figure 9 shows that the dynamic pressure at parachute mortar firing (171.4 s after entry) was approximately 585 N/m². The Mach number at parachute deployment was 1.8.

Radar Altimeter Data

The radar altimeter first acquired the ground at an altitude of 1591 m, slightly higher than the maximum range specification for the altimeter. Ground acquisition occurred 276 s after atmospheric entry; at this point in the EDL sequence, the parachute had been opened, the heatshield released, and the lander had been deployed along the 20-m bridle below the backshell. Figure 10 shows the complete radar altimeter data set following ground acquisition, which extends from 276 through 301 s past atmospheric interface. It is apparent from Fig. 10 that there were no dropouts, spurious measurements, or loss of data from the radar altimeter during terminal descent. From the slope of the radar data, the terminal velocity on the parachute prior to ignition of the RAD motors is estimated as 63 m/s. This is significantly higher than the preflight estimate of terminal velocity, which was 53 m/s. This discrepancy can be attributed to several potential factors: atmospheric density mismodeling, errors in the predicted parachute drag area or aerodynamic coefficients, or errors in the modeled vehicle mass. The uncertainty in the vehicle suspended mass on the parachute is small (<2 kg), and postflight reconstruction of the atmosphere indicates that the predicted density profile was accurate. Thus, it is likely that there were significant modeling errors in the parachute drag characteristics.

The RAD firing algorithm was designed to select the time for the ignition of the RAD rockets, such that the lander's descent rate would be nulled at an altitude of 13-m AGL, at which time the bridle connecting the lander to the backshell/RAD system would be cut. Figure 11 shows the radar altimeter data taken during the RAD system burn and ending at the time of bridle cut. The RAD firing algorithm and the rockets themselves performed as predicted, igniting the rockets at an altitude of 88 m and bringing the descent rate to near zero at 21-m AGL, when the bridle was cut.

Landed Position Fix

Two independent methods were used to locate the actual landing site. The first method utilized landmark identification. Horizon features such as hills, knobs, and craters are seen in the panoramic images from the lander. These features were easily identified and located on images of the surface obtained from the Viking orbiters, from which an estimate (uncertainty ~ 100 m) of the lander’s location was obtained. The second method utilized radiometric tracking from the lander in a manner not unlike the orbit determination performed during cruise. Table 4 gives the results of these two methods. The difference between the two positions is attributed to map-tie
Table 4  Landing site solutions

<table>
<thead>
<tr>
<th>Method</th>
<th>Radius, km</th>
<th>Longitude, °E</th>
<th>Areodetic latitude, °</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landmark recognition</td>
<td>N/A</td>
<td>326.45</td>
<td>19.33</td>
</tr>
<tr>
<td>Lander radiometric</td>
<td>3389.714</td>
<td>326.48</td>
<td>19.28</td>
</tr>
</tbody>
</table>

Flight Path

The Mars Pathfinder flight path during EDL has been reconstructed from the available flight data. Two different trajectory estimates, one developed using least-squares estimation techniques and the other using a sequential estimation scheme, have been computed. Both reconstructions utilized the three-axis accelerometer and radar altimeter data. A ballistic, zero-lift trajectory is assumed for the least-squares fit. The sequential estimate makes use of measurements of the received frequency of the X-band carrier signal broadcast by the spacecraft. The landing site position fix (Table 3) from postlanding radiometric tracking served as a boundary condition for the least-squares estimate and was treated as a multidimensional measurement in the sequential estimate. Finally, the entry state vector estimate (Table 1) and error covariance matrix from the navigation team was used as an initial condition for both the least-squares and sequential estimations.

The least-squares reconstruction process is shown in Fig. 12. The first step in developing this reconstruction was the calculation of an initial estimate of the position and velocity history. This was accomplished through integration of the three-degree-of-freedom kinematic equations of motion in a nonrotating, Mars-centered coordinate frame using accelerometer data and a model for the gravitational field of Mars. Subsequently, the initial conditions for the accelerometer-computed trajectory were numerically adjusted such that the resultant trajectory best fit the radar altimeter data in a least-squares sense. In addition, the entry conditions were manipulated so that the trajectory terminated at the landed position fix, as described earlier.

The sequential reconstruction process began in a manner similar to the least-squares process of Fig. 12, in that an initial estimate of the flight path was computed from accelerometer data, in this case using the best-estimated state vector at entry as the initial condition. The partial derivatives of the trajectory parameters with respect to initial condition errors and accelerometer sensor errors were also computed. This initial reference trajectory was then improved by using a linearized formulation of the discrete Kalman filter algorithm to estimate corrections using both the received frequency and altimeter data sets.

The sequential filter program produced two different estimates of the corrected flight path, along with computations of the error covariance matrix associated with each estimate. The first estimate was obtained by processing the received frequency and altimeter data from the predicted time of entry interface to the time of initial impact on the Mars surface. The second estimate was obtained by processing the same data set, but with time running backward, using the postlanding position fix and its error covariance as initial conditions. In addition to estimates of the deviations in position and velocity from the accelerometer-only trajectory, the filter algorithm also computed estimates of the errors in the measurements, including accelerometer sensor errors, altimeter errors, and drift of the spacecraft’s transmit frequency relative to the profile predicted prior to entry. The final step in the sequential reconstruction process was to compute revised estimates of the position and velocity deviations from the reference, i.e., accelerometer-computed trajectory, and sensor error parameters. Estimates derived from the forward and backward filtering of the received frequency and altimeter data were smoothed together, using the Fraser–Potter smoothing algorithm.

Figure 13 shows the altitude (measured relative to the landing site radius) history of the Pathfinder spacecraft during EDL, for the ballistic least-squares and sequential estimates. Figure 14 shows the altitude history for the two estimates during the parachute descent phase, and Fig. 15 compares the estimates during the final...
Fig. 14 Altitude during parachute descent phase and RAD firing.

Fig. 15 Altitude estimates compared with radar altimeter data.

Table 5 Key trajectory parameter comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best estimates from flight data</th>
<th>Ballistic, least-squares fit</th>
<th>Sequential estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertial flight-path angle, ( \dot{\alpha} )</td>
<td>(-14.06 \pm 0.03)</td>
<td>(-13.97)</td>
<td>(-14.05)</td>
</tr>
<tr>
<td>deg, at ( r = 3522.2 ) km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radar acquisition time</td>
<td>275.96</td>
<td>273.30</td>
<td>275.66</td>
</tr>
<tr>
<td>(time of ( h_{AGL} = 1591 ) m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Landing site</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerocentric latitude, ( \phi )</td>
<td>19.09 ( \pm ) 0.01</td>
<td>19.09</td>
<td>19.06</td>
</tr>
<tr>
<td>Longitude, ( \lambda )</td>
<td>33.52 ( \pm ) 0.01</td>
<td>33.52</td>
<td>33.43</td>
</tr>
<tr>
<td>Radius, ( R )</td>
<td>3389.71 ( \pm ) 0.02</td>
<td>3389.71</td>
<td>3389.72</td>
</tr>
</tbody>
</table>

Roll Rate

During interplanetary cruise, the Pathfinder spacecraft was rotating about its principal axis at a 2-rpm roll rate. This roll rate was to remain unchanged through cruise-stage separation and into the atmospheric flight to provide a means of stability as the dynamic pressure decreased prior to parachute deployment and to null out any lift forces during the atmospheric expansion. Expanding the scale of the data shown in Fig. 4, but including data taken prior to encountering the atmospheric interface, Fig. 17 shows an oscillation with a period of approximately 110 s in the high-altitude accelerometer data.

This motion, in which the vehicle is coming about its principal axis, is a result of the misalignment between the vehicle’s body axes (defined by the aeroshell axis of symmetry) and the principal axes (defined by the entry vehicle inertial properties). The vehicle roll rate can be derived from this motion as

\[
\omega_{obs} = \|(1 - I_{zz}/I_{xx})\|\omega_z
\]

The substitution of the Pathfinder entry vehicle moment-of-inertia ratio of 1.2727 and the observed 0.0091-Hz frequency of Fig. 14 yields a 2.000-rpm roll rate. Hence, cruise-stage separation did not significantly alter the entry vehicle spin. Whereas roll-rate data within the atmosphere were not obtained, no means of significant roll damping existed, i.e., there was little fluid slosh, a low degree of inertial coupling, and minor boundary-layer aerodynamic effects. Hence, this 2-rpm roll rate was likely maintained throughout the atmospheric entry.

Angle-of-Attack Profile

Based on the spacecraft accelerometer measurements, it is clear that the Pathfinder spacecraft did not follow a purely ballistic entry flight path. Several regions of nonzero normal acceleration are shown in the flight data presented in Fig. 5. In each of these regions, the resultant force vector was not parallel to the relative velocity vector; hence, the vehicle was at a nonzero total angle of attack. Here, total angle of attack is defined as the angle between the vehicle’s axis of symmetry and the relative velocity vector.

Total angle of attack during the entry phase prior to parachute deployment has been estimated using the spacecraft accelerometer measurements and the preflight aerodynamics database. The normal force coefficient \( C_n \) in Eq. (3) and the aerodynamic coefficient ratio \( C_n/C_A \) in Eq. (4) are each functions of total angle of attack and relative velocity. Hence, total angle of attack could be estimated with either of these relations:

\[
A_n = \frac{\rho V^2 C_n S}{2m}
\]

\[
A_n/A_c = C_n/C_A
\]

In this analysis, total angle of attack was estimated with use of Eq. (4) because no reliance on an atmospheric density prediction was required and the continuum hypersonic \( C_A \) uncertainty for a 70-deg sphere-cone at small angles of attack is low. With use of the relative velocity profile from the least-squares trajectory estimate presented in Fig. 16 and the accelerometer data (taken from Fig. 5) shown in Fig. 18a, the preflight aerodynamic database was
interpolated to produce an estimate of total angle of attack. This total angle-of-attack estimate is presented in Fig. 18b.

Note that a total angle-of-attack estimate is not obtainable in this manner for the first 20 s of the atmospheric entry, due to the resolution in the lateral accelerometer channels. However, as the density increases above $1.0 \times 10^{-6} \text{ kg/m}^3$ at an altitude of approximately 95 km, the $A_n/A_z$ signal is strong enough to discern vehicle attitude. Further detail on the higher altitude portion of the Pathfinder atmospheric entry is provided in Ref. 5.

The presence of two hypersonic static instability regions and a supersonic dynamic instability region, as predicted in Ref. 11, are clearly evident in Fig. 18b. In fact, the hypersonic static instability regions (centered at approximately 55 and 85 s) are strong enough to be evident in both Fig. 18b (the angle-of-attack estimate derived with the preflight aerodynamic database) and Fig. 18a (accelerometer data). This derived angle-of-attack estimate bears striking similarity to preflight predictions.$^{10,12}$ At the time of peak heating, the vehicle is estimated to be at a total angle of attack below 3 deg.

**Mars Atmosphere Profile**

A Mars atmosphere profile, in terms of temperature, pressure, and density, has been estimated. The atmosphere properties were derived based on the sensed accelerations, the assumed axial aerodynamic coefficients from the Pathfinder aerodynamic database, and the relative velocity obtained from the least-squares trajectory reconstruction:

$$
\rho = \frac{2A_n}{V^2C_A(S/m)} \quad (5)
$$

The values of $C_A$ are flight regime dependent, and because all flight regimes from free-molecule flow to subsonic flow are encountered...
a) Normal-to-axial acceleration measurements

b) Angle-of-attack profile

Fig. 18 Normal-to-axial accelerations and estimated angle of attack during entry phase.

Fig. 19 Estimated temperature profiles.

Fig. 20 Estimated density profiles.

during entry, an iterative scheme has been developed to obtain the proper value of this aerodynamic coefficient in the procedure. This involves calculating the classical scaling parameters such as Knudsen, Reynolds, and Mach numbers and using an a priori estimate of density as a starting point. Clearly, uncertainty in the estimate of $C_A$ translates into density uncertainty.

Once density is obtained, it can then be used to calculate pressure from the hydrostatic equation,

$$\frac{dp}{dh} = -\rho g$$

This equation is integrated from a starting value of pressure $p_0$, which is adjusted to provide a smooth variation at large altitudes. Slight errors in $\rho_0$ produce large variations in temperature because the density at these large altitudes is also a small quantity.

The remaining variable, temperature, is calculated from the ideal gas law:

$$T = (M/R)\frac{p}{\rho}$$

where $M$ is the mean molecular weight (43.2685 kg/kmol) and $R$ is the universal gas constant (8314.34 J/kmol-K). For this analysis, $M$ is assumed to have a fixed value. This will produce a small error in the temperature calculations at very high altitudes, roughly above about 120 km.

Figures 19 and 20 show a comparison of the temperature and density profiles computed from this engineering reconstruction, along with the profiles computed by the ASI/MET science team. There are minimal deviations between the two estimated temperature profiles, and the estimated density profiles are nearly identical.

Conclusions

The Pathfinder EDL sequence of events, flight path, and attitude history have been reconstructed from the available flight data. In addition, an atmosphere profile has been estimated. The flight data indicate that the Pathfinder EDL system performed as expected throughout the hypersonic entry phase. The terminal velocity on the parachute was higher than expected from preflight modeling, but was within the capabilities of the terminal descent system. Preflight
estimates of aeroshell performance, aerodynamic stability, and landing location have been confirmed. The parachute deployment and RAD firing algorithms performed flawlessly. The airbag system enabled the lander to survive an initial 16-g impact and subsequent bounces.

The technology demonstration of the Pathfinder EDL system was a success. The utilization of similar landing system technologies should be considered by future missions for which access to rugged terrain is required.

Acknowledgments

The work described in this paper was performed at the NASA Langley Research Center and at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. The authors would like to acknowledge David Gruel for providing the processed flight data on which the analyses described in this paper are based. We would also like to acknowledge Julio Magalhaes, John T. Schofield, and Al Seiff for providing an independently produced atmosphere profile, for comparison.

References


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Guest Editor