Review of the Trajectory and Atmospheric Structure Reconstruction for Mars Pathfinder

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Talk Structure

- Pathfinder's Entry, Descent, and Landing
- Measurements Used in Pathfinder's Trajectory Reconstruction
- Various Trajectory Reconstructions for Pathfinder
- Pathfinder's Aerodynamic Database
- Atmospheric Structure and Angle of Attack Reconstruction
- Conclusions
Pathfinder's Entry, Descent, and Landing
Mars Pathfinder entry, descent and landing

http://atmos.nmsu.edu/PDS/data/mpam_0001/document/images/edler_ds.tif
<table>
<thead>
<tr>
<th>Event</th>
<th>Time</th>
<th>Altitude</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruise stage separation</td>
<td>L - 35 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Entry</td>
<td>L - 5 min</td>
<td>130 km</td>
<td>7470 m/s</td>
</tr>
<tr>
<td>Parachute deployment</td>
<td>L - 134 s</td>
<td>9.4 km</td>
<td>370 m/s, 16g</td>
</tr>
<tr>
<td>Heatshield separation</td>
<td>L - 114 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lander separation</td>
<td>L - 94 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radar ground acquisition</td>
<td>L - 28.7 s</td>
<td>1.6 km</td>
<td>68 m/s</td>
</tr>
<tr>
<td>Airbag inflation</td>
<td>L - 10.1 s</td>
<td>355 m</td>
<td></td>
</tr>
<tr>
<td>Rocket ignition</td>
<td>L - 6.1 s</td>
<td>98 m</td>
<td>61.2 m/s</td>
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<tr>
<td>Bridle cut</td>
<td>L - 3.8 s</td>
<td>21.5 m</td>
<td></td>
</tr>
<tr>
<td>Landing</td>
<td>2:58 a.m.</td>
<td>0</td>
<td>14 m/s, 19g</td>
</tr>
<tr>
<td>Roll stop</td>
<td>L + 2 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deflation</td>
<td>L + 20 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airbag retracted</td>
<td>L + 74 min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Petals opened</td>
<td>L + 87 min</td>
<td></td>
<td></td>
</tr>
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</table>

http://www.sciencemag.org/cgi/content/full/278/5344/1743
Overview of MPF EDL

- Direct entry from cruise at 7 km/s and 17 deg below horizontal
- Hypersonic entry inside 2.65 m diameter aeroshell, spin stabilized at 2 rpm near zero angle of attack, no active attitude control
- At 9 km altitude and Mach 1.8, deploy Viking heritage 12.7 m diameter disk-gap-band parachute, release front heatshield, drop lander below backshell on 20m-long bridle
- Radar altimeter locks onto ground at 1.5 km altitude
- Inflate airbags in 0.5 sec at 0.3 km altitude
- Fire retrorockets at 0.1 km altitude
- Cut bridle between lander and backshell, fall to ground 20 m below
- Bounce, bounce, and bounce again
### Table 1  Mars Pathfinder and Viking entry comparison

<table>
<thead>
<tr>
<th>Entry characteristic</th>
<th>Mars Pathfinder</th>
<th>Viking</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_e, \text{inertial, km/s} )</td>
<td>7.4(^{a})</td>
<td>4.73(^{a}, 4.65(^{b})</td>
</tr>
<tr>
<td>( V_e, \text{relative, km/s} )</td>
<td>7.6</td>
<td>4.50(^{a}, 4.42(^{b})</td>
</tr>
<tr>
<td>( \gamma_{e, \text{relative}}, \text{deg} )</td>
<td>-14.8(^{a})</td>
<td>-17.63(^{b})</td>
</tr>
<tr>
<td>Entry mass, kg</td>
<td>552.0</td>
<td>980.8</td>
</tr>
<tr>
<td>( S, \text{m}^2 )</td>
<td>5.52</td>
<td>9.62</td>
</tr>
<tr>
<td>( \alpha, \text{deg} )</td>
<td>0.0</td>
<td>-11.1</td>
</tr>
<tr>
<td>( C_D )</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>Ballistic coefficient, kg/m(^2)</td>
<td>58.8</td>
<td>63.7</td>
</tr>
<tr>
<td>( L/D )</td>
<td>0.0</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Guidance and control system

- Mars Pathfinder: Spin stabilized
- Viking: Three-axis control

\(^{a}\) Measured at 125-km altitude. \(^{b}\) Measured at 243.8-km altitude.

Fig. 2  Mars Pathfinder and Viking entry profile comparison.
Spin and Attitude Control

- No gyroscopes to monitor attitude, no guidance system to change attitude - use aerodynamic behaviour to keep angle of attack near zero

- Axisymmetric spacecraft, spins about symmetry axis at a roll rate of 2 revs per minute, rate does not change much during EDL

- If it spins too slowly, then lift/side forces do not smear out in all directions and the trajectory is adversely affected

- If it spins too quickly, then attitude in inertial frame stays fixed as direction of flight path changes, so the angle of attack increases (gyroscopic stiffness)

- Spin also helps to damp non-zero angle of attack upon entry
Spencer et al. (1999) J. Spacecraft and Rockets, 36(3), 357-366
Aeroshell and heatshield

- Lander sits inside a protective aeroshell. 2.65 m diameter, during entry
- Aeroshell consists of a forebody heatshield and an aftbody backshell
- 2 cm layer of ablative material (SLA-561V) on heatshield
- Viking heritage 70-deg half-angle sphere-cone, scaled down in size
- Entry mass of 585.3 kg, reference area of 5.526 m²
- Axisymmetric about z-axis
- Centre of mass on symmetry axis
Descent and Landing

- Parachute was Viking-heritage disk-gap-band type, 12.7 m diameter, made of Dacron fabric, attached to the backshell by >20m lines
- Lander hangs 20 m below backshell on Kevlar bridle (accelerometers now away from centre of mass, angular inputs)
- 4 sets of 6 airbags around lander inflated at 300 m altitude in 0.5 sec
- 3 retrorockets, each 85 cm long and 13 cm wide, attached to backshell, generate 3 x 8000 N of thrust in 2.2 seconds between ~100 m and ~20 m altitude
- Retrorockets slow lander to zero descent speed 20 m above ground, bridle is cut, and lander falls as last thrust from retrorockets carries backshell and parachute away from lander
- The lander hits with a vertical speed of 12 m/s and a horizontal speed of 6 m/s, bounces > 15 times for > 1 minute, rolls ~ 1 km
Measurements Used in Trajectory Reconstruction
Measurements during EDL

• Known entry state (position and velocity)
• Accelerometers (aerodynamic accelerations)
• Doppler shift in Earth-received telemetry signal, gives line-of-sight speed, but transmission frequency drifts a lot during entry
• Dynamic pressure measurements after parachute opens
• Poor temperature measurements after parachute opens
• Radar altimeter below 1.5 km altitude, with 0.3 m resolution and 50 Hz sampling rate (altitude and descent speed)
• Known landed position (after ~ 1 km of bouncing)
Accelerometers (1)

- 6 identical Allied Signal QA-3000-003 single axis units, which electromagnetically restrict a test mass to a precise null position
- 2 sets of 3 accelerometers, science and engineering, each set mutually orthogonal
- z-direction science accelerometer on z-axis, 5 cm away from centre-of-mass
- x- and y-direction science accelerometers about 10 and 15 cm away, respectively, from centre-of-mass along z-axis
- Engineering accelerometers used to control EDL events such as parachute opening
- No gyroscopes
Accelerometers (2)

- Three gain states for each accelerometer of
  +/- 40 g  +/- 800 millig  +/- 16 millig
- 14 bit digitization leads to digital resolutions of
  5 millig  100 microg  2 microg
- 7 orders of magnitude dynamic range
- Noise levels of 1-2 counts
- Detected atmosphere at 160 km, density of $2 \times 10^{-11}$ kg/m$^3$
- Sampling rates on all 6 accelerometers of 32 Hz
- Gain states changed to (a) maximize sensitivity to aerodynamic accelerations or (b) monitor critical events like impact
Entry State

- Direct entry from interplanetary cruise, unlike Viking which was released from orbit
- July 4th, 1997, 1700 GMT
- Speed of 7 km/s, flight path angle of 17 deg, heading west, descent speed of 2 km/s
- 23 deg N, 340 deg E, 0300 hours local solar time (so winds are not fast and wind shear is not large, unlike MER)
- Scientists' and engineers' reconstructions publish different (and inconsistent) entry states, but their resultant trajectories are similar
- Did science reconstruction use its published entry state or not?
Various Trajectory Reconstructions
Nominal Trajectory Reconstruction

- Choose a reference frame - centred on Mars or somewhere else, inertial or non-inertial, rotating or non-rotating, Cartesian or polar coordinates, etc

- Write equations of motion, eg \( dz = v_z \, dt \), \( dv_z = (a_z + g) \, dt \), etc

- Get expression for gravity in chosen frame, since accelerometers don't measure it

- Convert acceleration measurements made in spacecraft-fixed frame at some position away from its centre of mass to the aerodynamic accelerations experienced by the centre of mass in chosen frame. Complicated, requires spacecraft orientation

- Start from entry state and integrate forward in time

- Worry about complicated motion of parachute, radar data, and consistency with known landed position
Scientists' Trajectory Reconstruction

- Mars-centred, rotating spherical coordinate system
- Gravity field up to $J_2$
- Scientists' entry state, shifted within uncertainties to reproduce known landed position (after bouncing)
- $z$-axis accelerations assumed to be directed along flight path (zero angle of attack)
- $x$- and $y$-axis accelerations not used?
- Not sure how spacecraft orientation was determined during parachute descent, possibly same zero angle of attack as above?
- Radar altimeter data not used
Engineers' Simple Trajectory Reconstruction
Spencer et al. (1999) J. Spacecraft and Rockets, 36(3), 357-366

- Mars-centred, non-rotating coordinate system
- Unspecified gravity field - spherically symmetric, $J_2$, detailed?
- Engineers' entry state used initially
- $z$-axis accelerations assumed to be directed along flight path (zero angle of attack) and no lift, so $x$- and $y$-axis accelerations neglected
- Adjust entry state within uncertainties to ensure impact at known landed position and to have best fit to radar altimeter data
- Use of radar data assumes level topography beneath flight path
Engineers' Complicated Trajectory Reconstruction

Spencer et al. (1999) J. Spacecraft and Rockets, 36(3), 357-366

- Mars-centred, non-rotating coordinate system
- Unspecified gravity field - spherically symmetric, $J_2$, detailed?
- Get initial trajectory and error covariance matrix from best entry state and z-axis accelerometer data only
- Then use a linearized Kalman filter, together with Doppler shifts in telemetry and radar altimeter data, to improve trajectory
- Repeat going backwards in time from landed position
- Combine forwards and backwards trajectories to get best trajectory
- Engineers don't say whether simple or complicated is better...
Comparison of Three Trajectories

- Basically identical during aeroshell portion of entry
- Differences in descent speed (~10 m/s) and altitude (~200 m) as a function of time after the parachute opens
- Due to accelerometer data and assumptions about parachute dynamics not providing complete and accurate picture of dynamics during parachute descent
- Also due to different uses of radar altimeter data during parachute descent
- Dynamics of lander/backshell/parachute not perfectly understood
- Predicted parachute $C_D$ was 0.5, actual $C_D$ was closer to 0.4
What about the Drag and Lift Coefficients?

- Neither drag nor lift coefficients have been used so far...
- ...have only been used indirectly to justify assuming zero angle of attack
- Were used before flight to design nominal trajectory and EDL algorithms, but not used to reconstruct trajectory after flight
- Necessary for reconstruction of angle-of-attack profile and the atmospheric structure
- If time is short, next section will be omitted!
Pathfinder's Aerodynamic Database
Generation of Aerodynamic Coefficients (1)

- Need to know forces and torques, usually parameterized and expressed as dimensionless coefficients, due to atmospheric interactions that act on Pathfinder for the environmental conditions experienced during entry.

- Also heating rates, hence study “aerothermodynamics”

- Chose a nominal atmospheric profile - composition, density, and temperature as a function of altitude.

- Estimate nominal profile of speed as a function of altitude using probable entry state and first-guess aerodynamic database (come back to here and iterate using improved aerodynamic database).

- Can express these conditions as Ma, Re, and Kn numbers.
Generation of Aerodynamic Coefficients (2)

• Select ~10 points along this nominal trajectory and note nominal atmospheric composition, density, and temperature, speed

• Do not work with, say, several possible speeds at a given atmospheric density - unless you later find that the nominal trajectory is incorrect

• For ~8 angles of attack, predict the forces, torques, and heating rates that affect Pathfinder at these points along nominal trajectory

• Express them as dimensionless coefficients

• Check that they are consistent with those assumed to derive the nominal trajectory! If not, use them to derive a new nominal trajectory and repeat until they are consistent.
How to get the coefficients

- Wind tunnel tests
  - Not done for Pathfinder's aerodynamic database, but Viking wind tunnel tests and flight data were used to validate it
- Numerical model, modelling atmosphere as collection of individual molecules, appropriate to rarefied flow at top of atmosphere with $Kn > 0.01$
- Numerical model, modelling atmosphere as a continuous fluid, appropriate to continuum flow lower in atmosphere with $Kn < 0.01$
- I'm not going to talk about aerodynamics during parachute descent
Rarefied and Transitional Flow
Moss et al. (1998) AIAA 98-0298

- $\text{Kn} > 0.01$
- Direct Simulation Monte Carlo model, G2, DAC
- Atmospheric molecules (97% by mass CO$_2$, 3% N$_2$, plus their reaction products) occasionally collide with each other, transfer energy between rotational and vibrational modes, take part in chemical reactions
- Molecules hit spacecraft, then rebound in random direction with temperature (speed) equal to spacecraft surface temperature
- This transfers momentum and energy to the spacecraft, which gets hotter and slows down
- Centre of gravity behind centre of pressure, some instabilities
Continuum Flow
Gnoffo et al. (1996) J. Spacecraft and Rockets, 33(2), 169-177

- Kn < 0.01
- Simulations use either non-viscous, perfect gas in HALIS (fast) or viscous, real gas in LAURA (slow), and most use forebody shape only
- Non-viscous - Rankine-Hugoniot bow-shock, flow tangent to spacecraft surface, constant flow enthalpy, some approximations for chemistry
- Viscous - more complicated, allows chemical reactions between atmospheric species
- Two regions of instability during entry where angle of attack will steadily increase
$C_D / C_L$ and angle of attack

- At given atmospheric composition, density, and temperature, speed, $C_D / C_L$ is a single-valued function of angle of attack.

- $C_D / C_L$ is related to the measured ratio of axial and normal accelerations.

- Given the reconstructed trajectory and a preliminary atmospheric structure reconstruction (which needs a preliminary $C_D$), can use measured $a_{\text{axial}} / a_{\text{normal}}$ to find the angle of attack along the trajectory.

- Will be derived as part of the iterative atmospheric structure reconstruction.

- Compare to predictions for spacecraft attitude during EDL.
Atmospheric Structure and Angle of Attack Reconstruction
Reconstruction of Atmospheric Density

- Scientists and engineers used same techniques, engineers used their simple trajectory, results are very similar

\[ \rho = -\frac{2m}{C_D A} \frac{a_v}{v_R^2} \]

- Pointwise formula, no integration of anything along the profile
- \( m, A \) known and \( a_v, v_R \) known from trajectory results
- Use preliminary \( \rho, T, v_R \), measured \( a_{\text{axial}}/a_{\text{normal}} \) to get angle of attack, use preliminary \( \rho, T, v_R \), angle of attack to get \( C_D \), use this \( C_D \) to get an updated density
- Iterate atmospheric structure reconstruction until preliminary and derived atmospheric properties agree
- Angle of attack profile is a product of this process
Reconstruction of Atmospheric Pressure and Temperature

- \( p = \text{integral of } -\rho g \, dz \)

- Hydrostatic equilibrium derived from vertical component of momentum conservation, neglects horizontal components and horizontal motion of Pathfinder during its descent, probably not a major problem.

- Assume isothermal at top of atmosphere, relate measured density scale height to pressure there to get a boundary condition.

- \( T = \text{mean molecular mass/} \ k_{\text{Boltzmann}} \ast p / \rho \)

- Aerodynamics during parachute phase not known well enough to allow atmospheric structure reconstruction.
Gnoffo et al. (1998) AIAA 98-2445
Consistency checks

- Do derived altitude, latitude, longitude, speed, angle of attack, density, pressure, and temperature agree with all the assumptions that went into the reconstructions?

- For example, does angle of attack get large enough to provide lift and invalidate the zero lift assumption?

- Does a simulated entry of Pathfinder into the reconstructed atmosphere reproduce the same trajectory?

- Did the nominal trajectory used for generating the aerodynamic database match the observed trajectory?

- Are deviations from preflight predictions understood?
Conclusions

- Pathfinder's trajectory reconstruction was relatively simple due to:
  - axisymmetry
  - zero angle of attack
  - z-axis accelerometer on axis of symmetry
  - lack of any forces/torques from a guidance system
  - entry into an already well-characterized atmosphere

- Measurements were insufficient to characterize the parachute descent phase accurately

- Information needed to independently test published reconstructions is (currently) easily available

- A good test case for developing your own reconstruction tools!