Review of the Trajectory and Atmospheric Structure Reconstruction for Mars Pathfinder

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Planetary Probe Atmospheric Entry and Descent Trajectory
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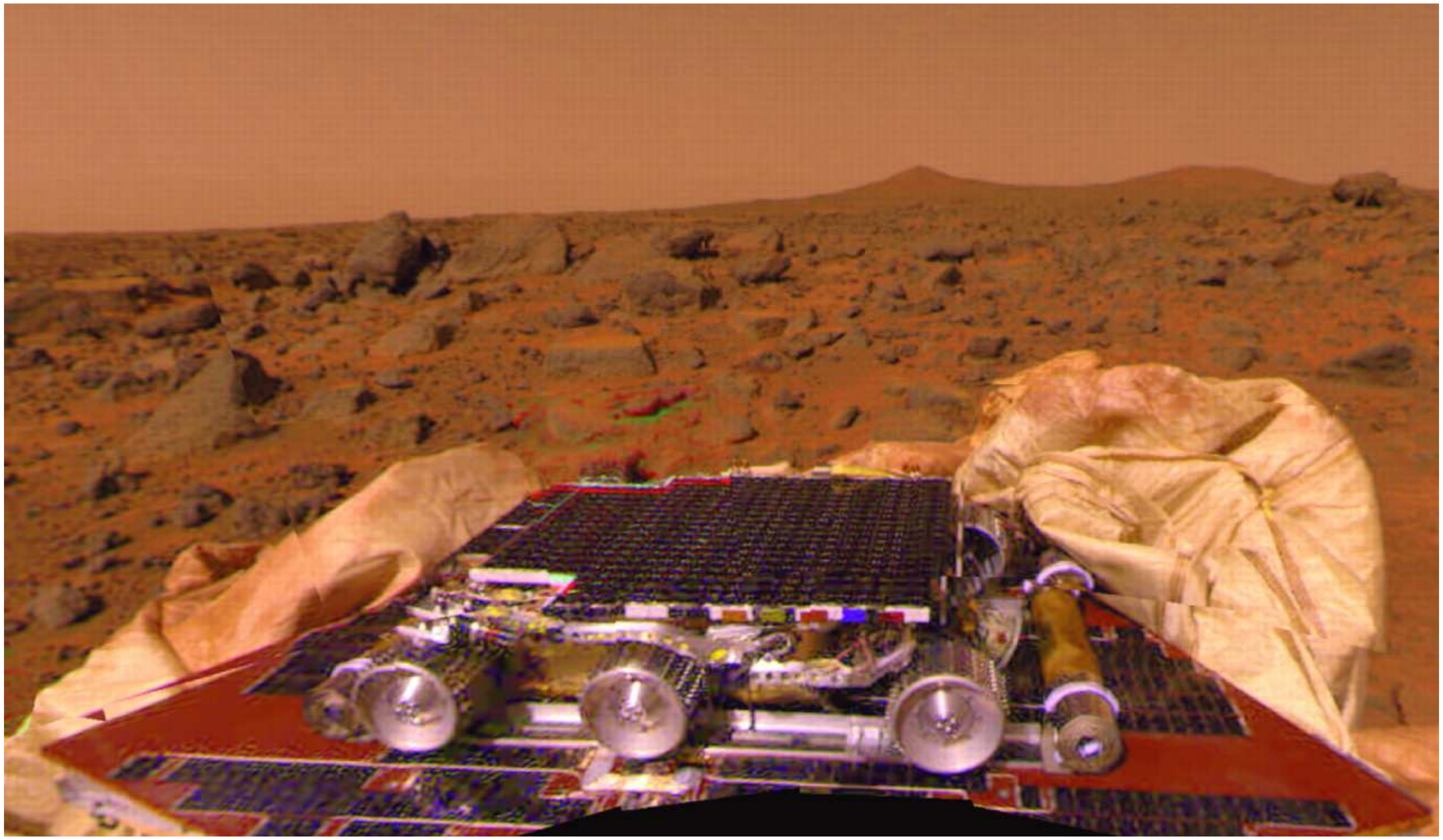
Talk Structure

- 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

http://photojournal.jpl.nasa.gov/catalog/PIA01121



http://www.sciencemag.org/cgi/content/full/278/5344/1743

http://mars.jpl.nasa.gov/MPF/nasa/figstabs/figures/

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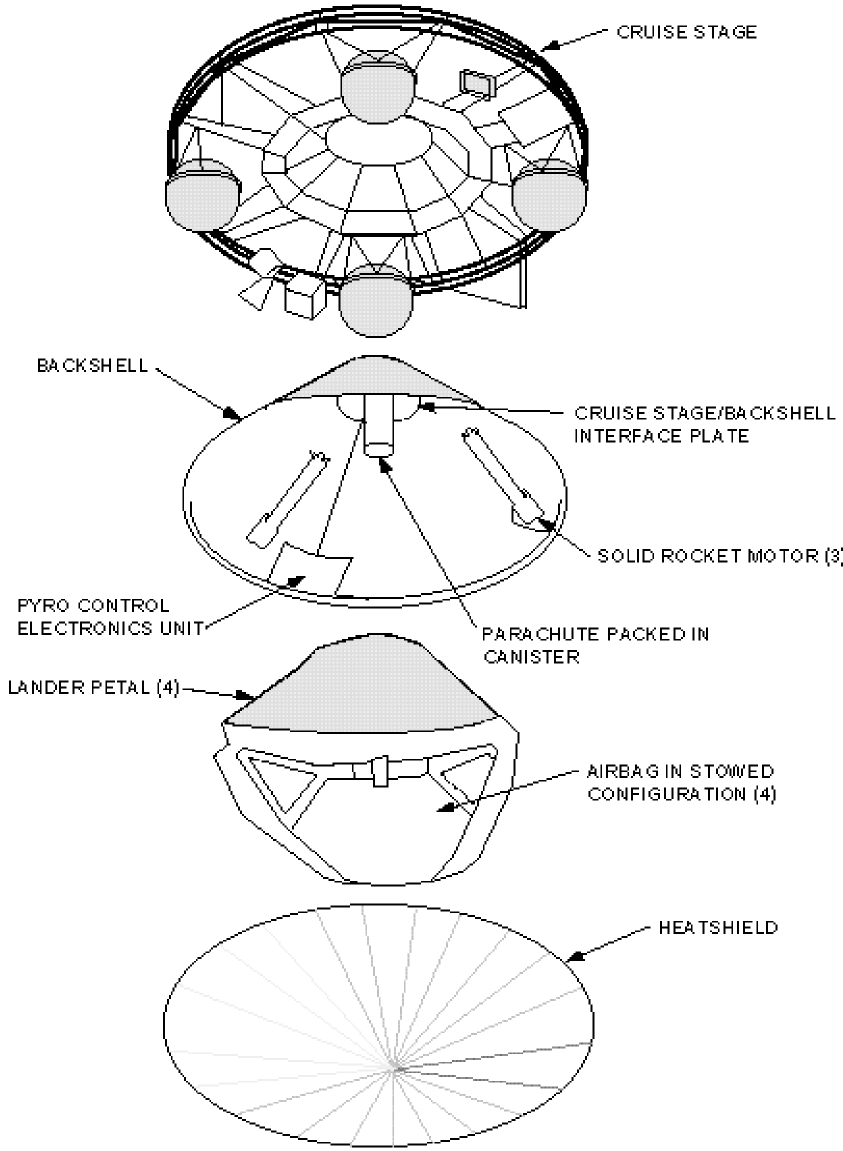
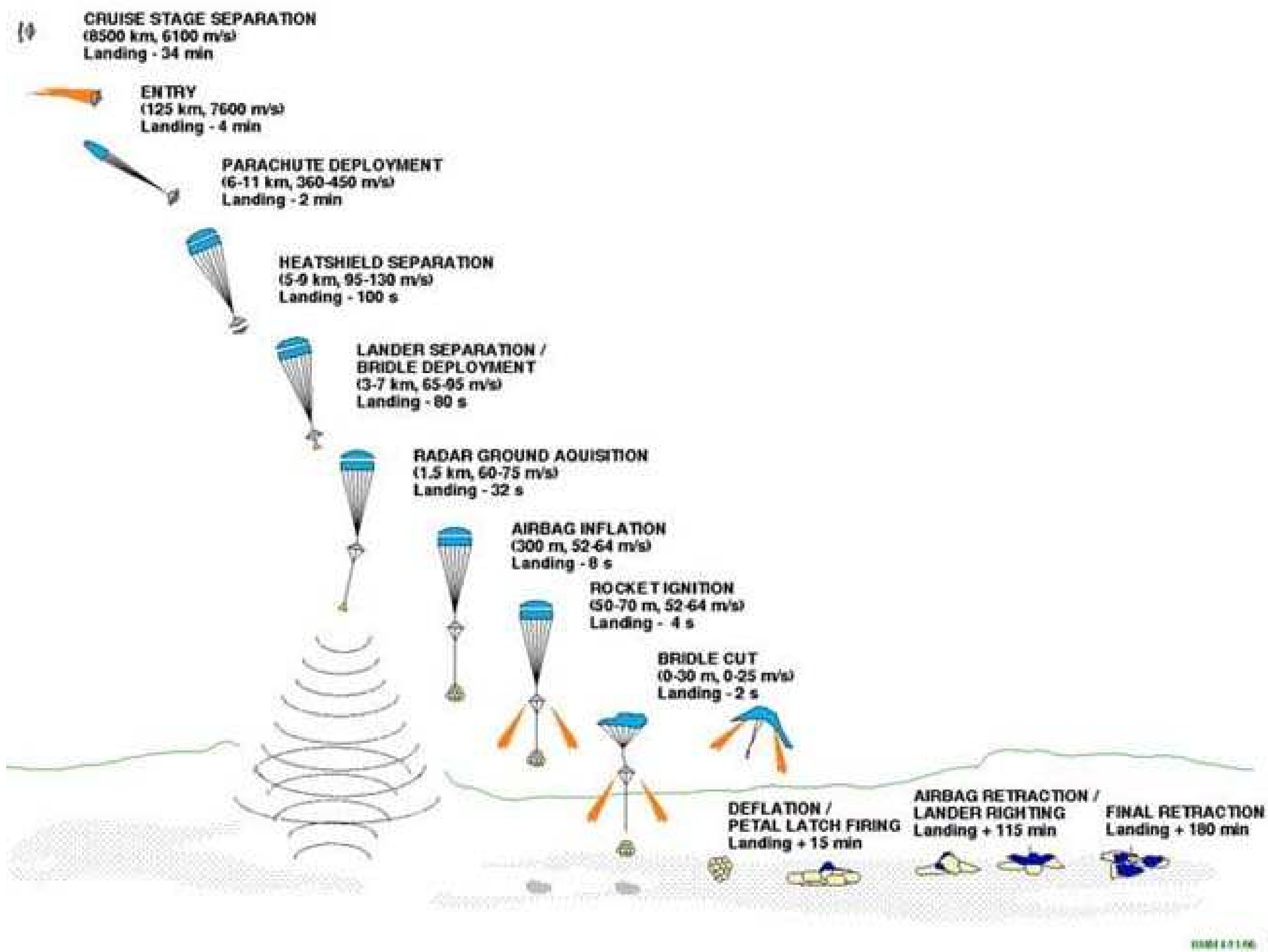


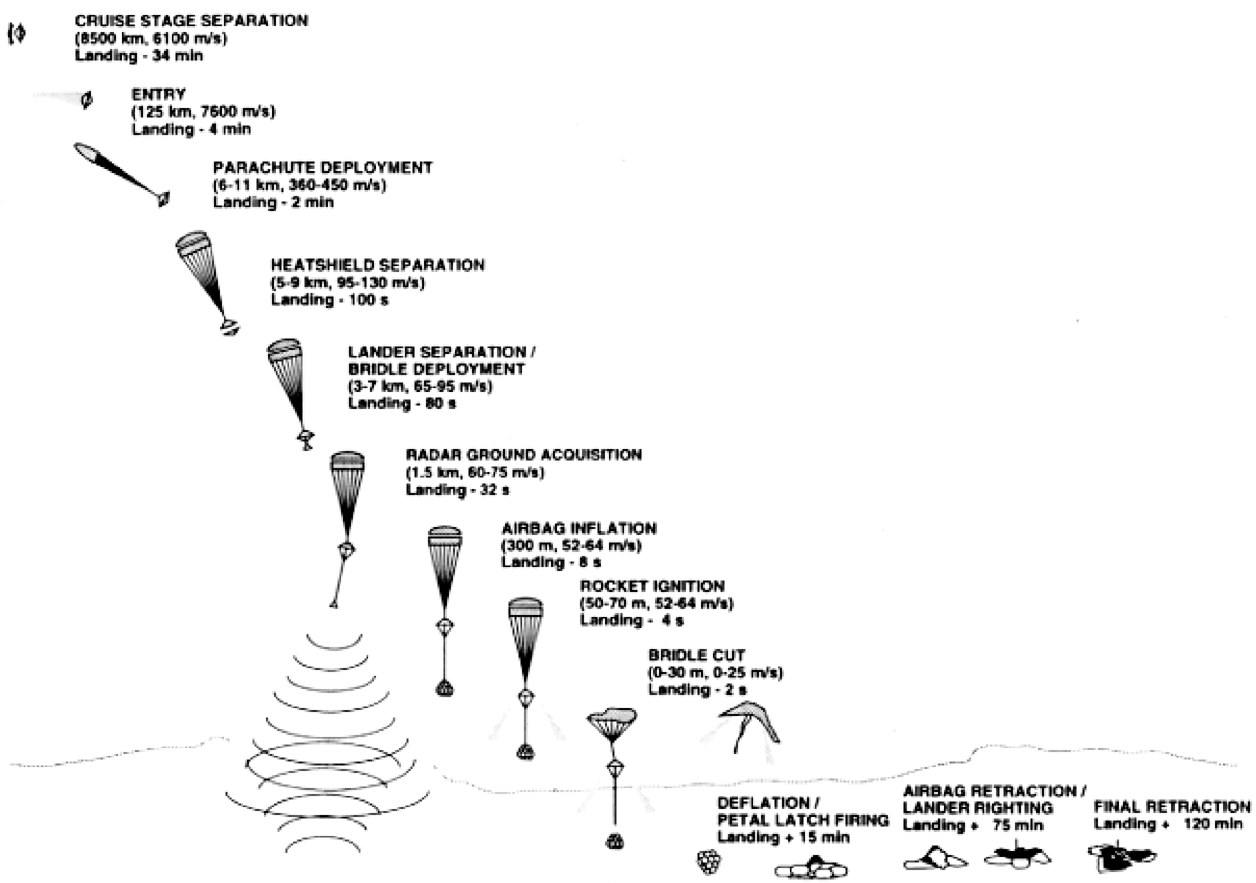
Mars Pathfinder Flight System (Exploded View)

http://atmos.nmsu.edu/PDS/data/mpam_0001/document/images/insthst2.gif

Figure 1

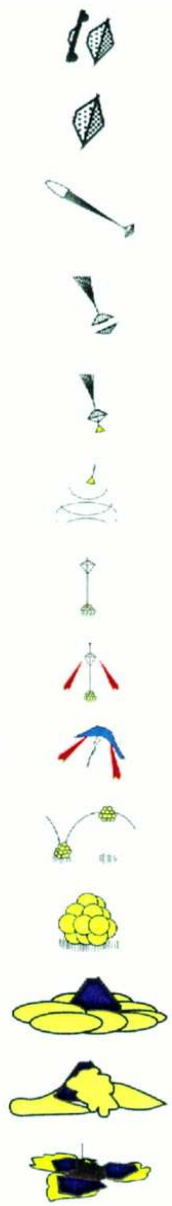


http://mars.jpl.nasa.gov/MPF/nasa/figstabs/figures/



Mars Pathfinder entry, descent and landing

http://atmos.nmsu.edu/PDS/data/mpam_0001/document/images/edler_ds.tif



Event	Time	Altitude	Velocity
Cruise stage separation	L - 35 min		
Entry	L - 5 min	130 km	7470 m/s
Parachute deployment	L - 134 s	9.4 km	370 m/s, 16*g*
Heatshield separation	L - 114 s		
Lander separation	L - 94 s		
Radar ground acquisition	L - 28.7 s	1.6 km	68 m/s
Airbag inflation	L - 10.1 s	355 m	
Rocket ignition	L - 6.1 s	98 m	61.2 m/s
Bridle cut	L - 3.8 s	21.5 m	
Landing	2:58 a.m.	0	14 m/s, 19*g*
Roll stop	L + 2 min		
Deflation	L + 20 min		
Airbag retracted	L + 74 min		
Petals opened	L + 87 min		

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

Entry characteristic	Mars Pathfinder	Viking
$V_{e,\mathrm{inertial}}$, km/s	7.4[a]	4.73[a], 4.65[b]
$V_{e,\mathrm{relative}}$, km/s	7.6 (retrograde)	4.50[a], 4.42[b] (direct)
$\gamma_{e,\mathrm{relative}}$, deg	−14.8[a]	−17.63[b]
Entry mass, kg	552.0	980.8
S, m^2	5.52	9.62
α, deg	0.0	−11.1
C_D	1.7	1.6
Ballistic coefficient, kg/m^2	58.8	63.7
L/D	0.0	0.18
Guidance and control system	Spin stabilized	Three-axis control

[a]Measured at 125-km altitude. [b]Measured at 243.8-km altitude.

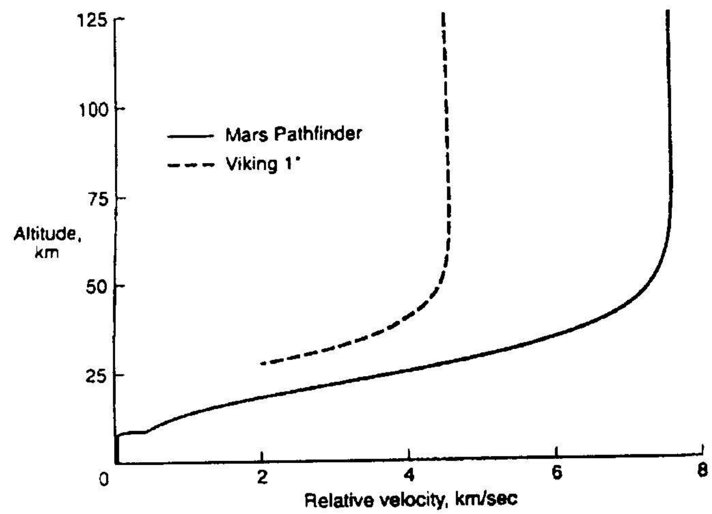
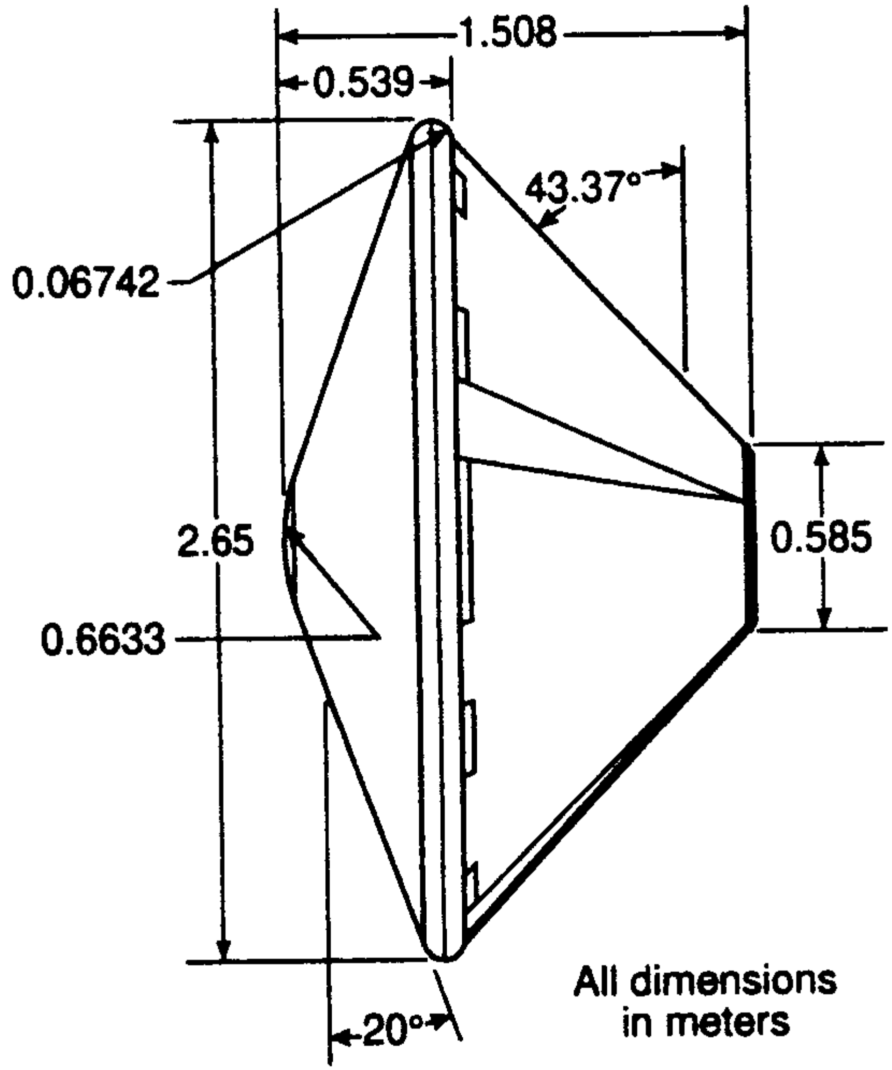


Fig. 2 Mars Pathfinder and Viking entry profile comparison.

Braun et al. (1995) J. Spacecraft and Rockets, 32(6), 993-1000

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 m^2
- Axisymmetric about z-axis
- Centre of mass on symmetry axis

http://mars.jpl.nasa.gov/MPF/rovercom/images/concept-edl.jpg

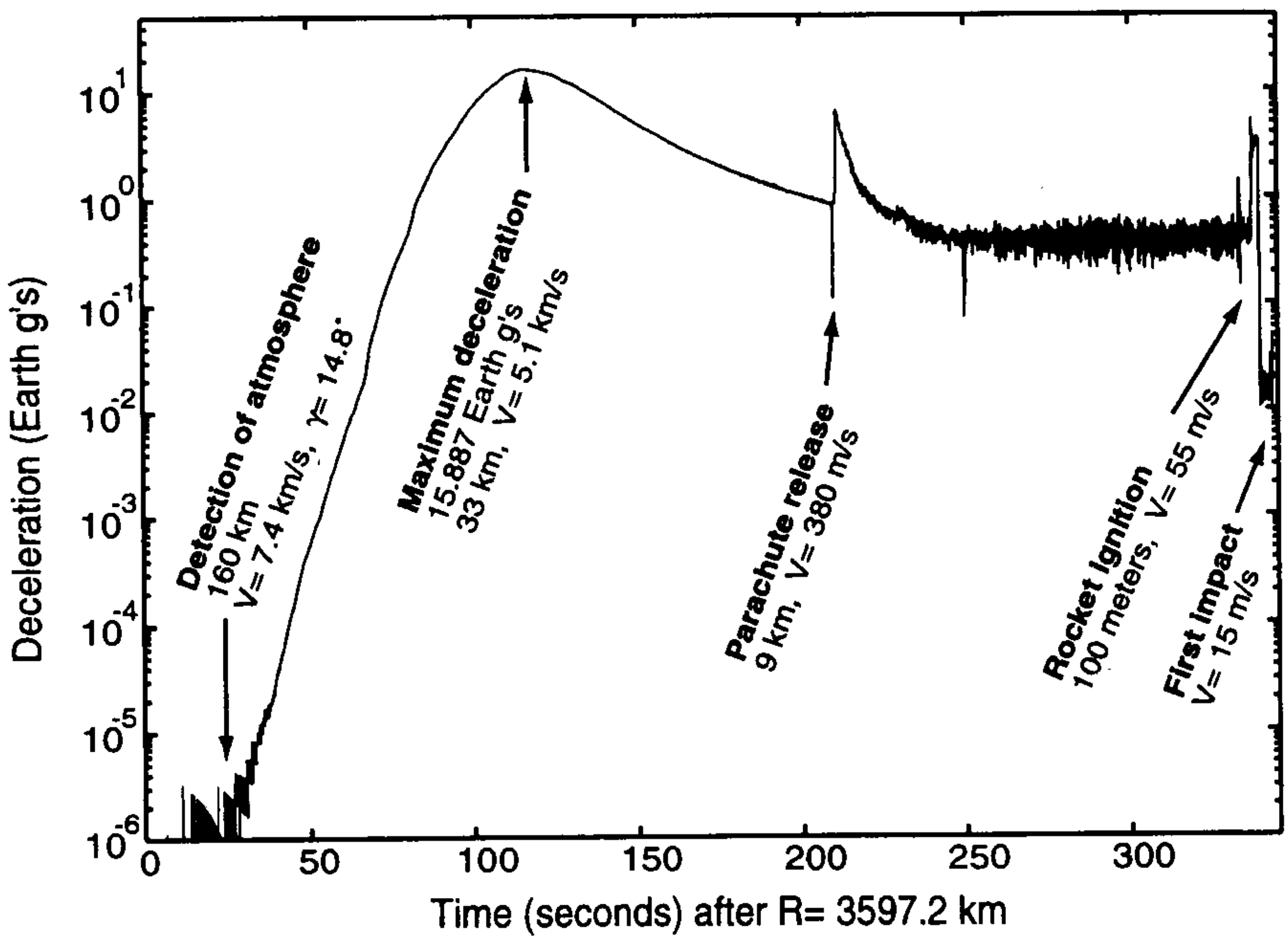
http://mars3.jpl.nasa.gov/MPF/mpf/rad.html

http://mars3.jpl.nasa.gov/MPF/mpf/mpfairbags.html

http://mars3.jpl.nasa.gov/MPF/mpf/mpfairbags.html

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

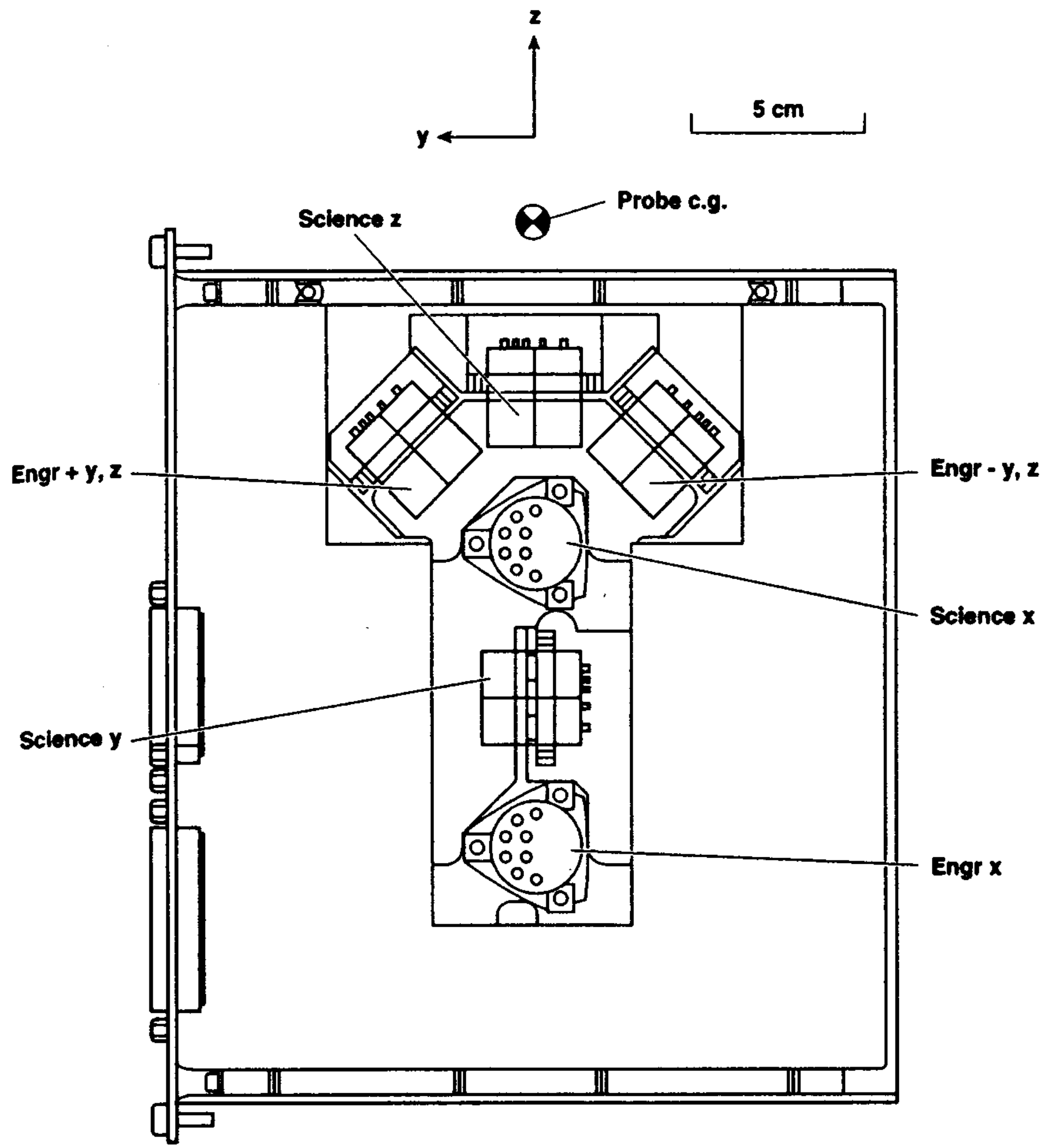


Magalhaes et al. (1999) J. Geophys. Res., 104(E4), 8943-8955

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)



Seiff et al. (1997) J. Geophys. Res., 102(E2), 4045-4056

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 $2x10^{-11}$ 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

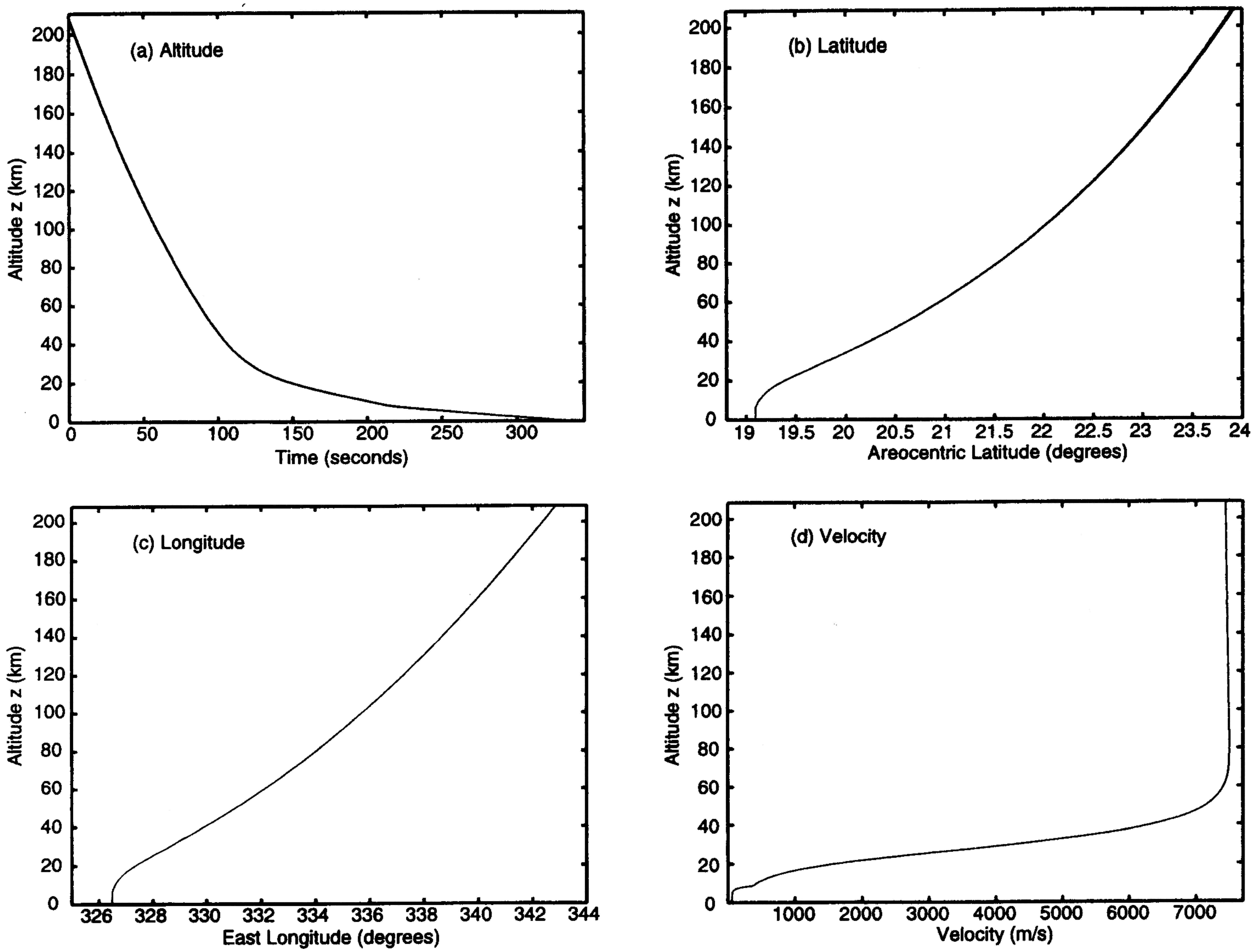
Entry State

- 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



Magalhaes et al. (1999) J. Geophys. Res., 104(E4), 8943-8955

Scientists' Trajectory Reconstruction

Magalhaes et al. (1999) J. Geophys. Res., 104(E4), 8943-8955

- 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 <u>and</u> 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

http://techreports.larc.nasa.gov/ltrs/PDF/1998/aiaa/NASA-aiaa-98-0298.pdf

- 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_{axial}/a_{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

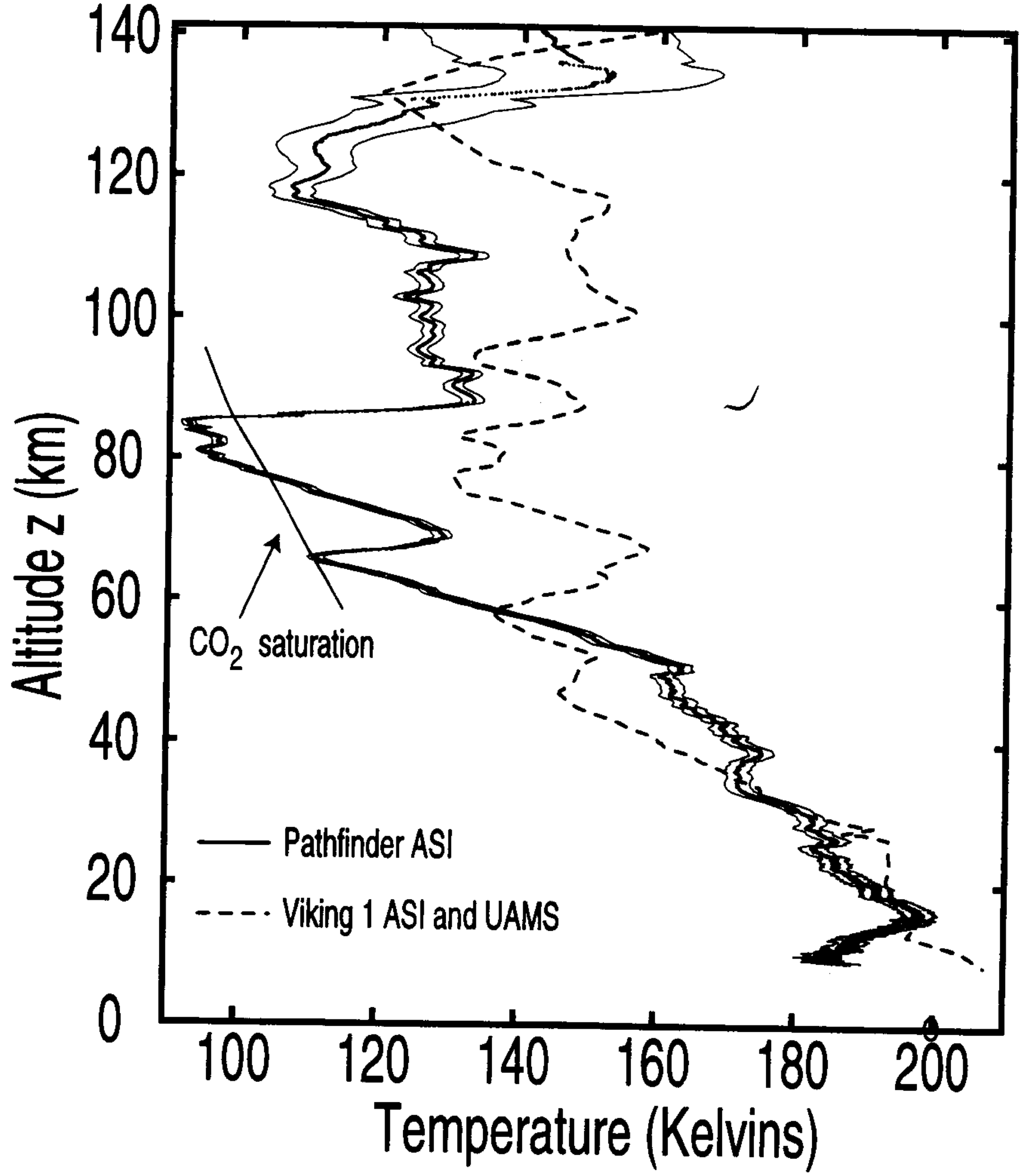
Atmospheric Structure and Angle of Attack Reconstruction

Reconstruction of Atmospheric Density

- Scientists and engineers used same techniques, engineers used their simple trajectory, results are very similar
- rho = $- 2\, m / C_D A * a_v / v_R^2$
- 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_{axial}/a_{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 = 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 = mean molecular mass/ $k_{Boltzman}$ * p / rho
- Aerodynamics during parachute phase not known well enough to allow atmospheric structure reconstruction



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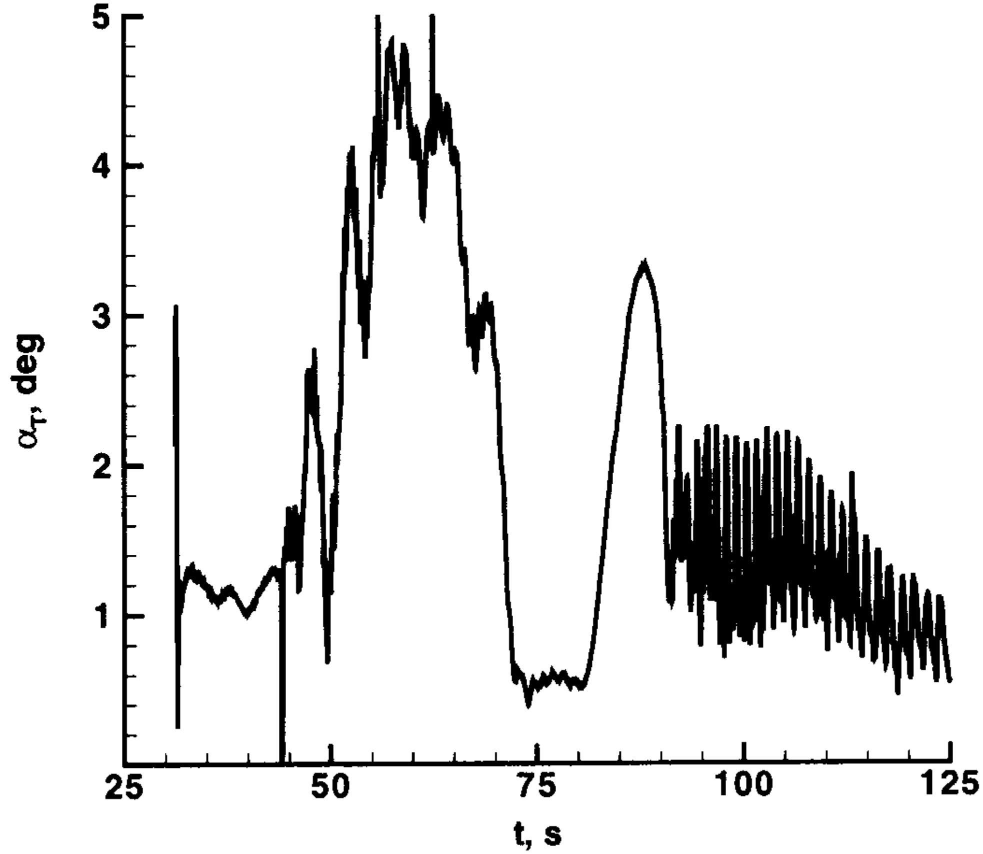

Gnoffo et al. (1998) AIAA 98-2445
http://techreports.larc.nasa.gov/ltrs/PDF/1998/aiaa/NASA-aiaa-98-2445.pdf

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!