

Mars Pathfinder EDL Trajectory and Atmosphere Reconstruction Using NewSTEP

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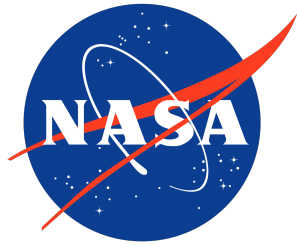
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Abstract

The entry, descent, and landing trajectory reconstruction of the Mars Pathfinder vehicle was revisited to recreate reconstruction data that was not archived properly and has been lost. Archived accelerometer data from the onboard atmospheric structure investigation experiment were integrated to generate an estimate of the capsule position and velocity. The measured accelerations were combined with a model of the capsule aerodynamics to reconstruct the atmospheric density along the trajectory. The resulting trajectory and atmosphere reconstruction was compared with plots from a previous reconstruction, for which the trajectory data was not archived, and with solutions from the archived atmospheric structure investigation data analysis. The revisited trajectory and atmosphere reconstruction compares well with the previously published results. The new reconstruction is anticipated to be used to inform future Mars mission trajectory analyses.

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Nomenclature

a_x, a_y, a_z	=	X, Y, and Z-Axis acceleration, m/s ²
C_A	=	Axial force coefficient
C_D	=	Drag force coefficient
C_L	=	Lift force coefficient
C_l	=	Rolling moment coefficient
C_m	=	Pitching moment coefficient
C_N	=	Normal force coefficient
C_n	=	Yawing moment coefficient
C_Y	=	Side force coefficient
g	=	Acceleration due to gravity, m/s ²
I_{xx}, I_{yy}, I_{zz}	=	Mass moments of inertia, kg-m ²
I_{xy}, I_{xz}, I_{yz}	=	Mass products of inertia, kg-m ²
J_2	=	Second zonal harmonic coefficient
M	=	Mean molecular weight, kg/kmol
m	=	Mass, kg
P	=	Pressure, Pa
R_e	=	Mars mean equatorial radius, m
R_p	=	Mars polar radius, m

$\mathcal{R}$	=	Universal gas constant, kg/kmol
S	=	Aerodynamic reference area, m ²
T	=	Temperature, K
$\mathcal{T}_{p2fm}$	=	Rotation matrix from Pathfinder frame to flight mechanics frame
V	=	Velocity magnitude, m/s
X, Y, Z	=	Coordinate axes in a specified frame
z	=	Geodetic altitude, m
λ	=	Nonlinear equation relating ratios of accelerations to ratios of force coefficients
μ	=	Mars gravitational parameter, m ³ /s ²
ρ	=	Atmospheric density, kg/m ³

Abbreviations

ASI/MET	=	Atmospheric Structure Investigation/Meteorology
EDL	=	Entry, Descent, and Landing
EI	=	Entry Interface
DOF	=	Degrees-of-freedom
IMU	=	Inertial Measurement Unit
LOS	=	Loss of Signal
MER	=	Mars Exploration Rover
MEX	=	Matlab Executable
MSL	=	Mars Science Laboratory
NewSTEP	=	New Statistical Trajectory Estimation Program
PDS	=	Planetary Data System
RAD	=	Rocket Assisted Deceleration

1 Introduction

The Mars Pathfinder mission was launched on December 4, 1996, and was the first successful mission to land on Mars since the Viking program in 1976 [1,2]. Pathfinder successfully landed on Mars on July 4, 1997, where it completed its surface mission over the course of a three month period. Pathfinder collected and transmitted a variety of data back to Earth over the course its mission, which has been reviewed and analyzed for several different scientific and engineering purposes. In the case of the vehicle’s Entry, Descent, and Landing (EDL) portion of its journey to the Martian surface, Pathfinder carried a set of instrumentation that was designed to collect measurements to be used to reconstruct the as-flown trajectory and atmosphere. This instrumentation package was known as the Atmospheric Structure Investigation/Meteorology (ASI/MET) experiment [3–5]. One set of sensors from this package were three-axis accelerometers that provided the primary measurements to be used in the reconstruction process.

The results of the ASI/MET EDL atmospheric reconstruction are documented in [5] and are archived on the Planetary Data System (PDS)¹. The archive contains time histories of position, density, temperature, and pressure from approximately 140 km altitude to the parachute deployment altitude at 9 km.

An engineering reconstruction of Pathfinder EDL based on the ASI/MET accelerometer data was published in [6]. This reconstruction was focused towards evaluating the Pathfinder capsule EDL flight performance and included a reconstruction of position, velocity, flight path angle, total angle of attack, dynamic pressure, and the atmospheric properties computed along the reconstructed trajectory. The findings of the reconstruction indicate that the hypersonic flight performance and aerodynamic stability were within predictions. The terminal velocity on the parachute was higher than expected but was within the system capabilities [6].

The reconstructed data products resulting from the efforts described in [6] were not properly archived and thus the reconstructed data have been lost. There remains significant interest in the EDL community for an as-flown Pathfinder trajectory for use with various systems analyses to feed into future Mars and other planetary missions. To this end, this memorandum documents the revisited reconstruction of the Mars Pathfinder as-flown entry trajectory and atmosphere based on the archived ASI/MET accelerometer data. The results are compared to the ASI/MET solution [5] and to figures from [6].

The reconstruction approach leverages NASA Langley Research Center’s tool designed specifically for solving these types of problems, known as the New Statistical Trajectory Estimation Program (NewSTEP) [7,8]. This code has been used extensively over the last two decades for solving a variety of trajectory reconstruction problems at different planetary bodies, and in particular has been applied to many Mars EDL reconstructions, including the Mars Exploration Rovers (MER) [9], Phoenix [10], Mars Science Laboratory (MSL) [11], InSight [12], and most recently to the Mars 2020 EDL reconstruction [13]. NewSTEP can be combined with a post-processing tool described in [14] for computing estimates of the atmosphere along

¹<https://pds.nasa.gov/data/mpfl-m-asimet-4-ddr-edl-v1.0/mpam.0001/document/edlddrds.htm>, accessed January 2026.

the reconstructed trajectory based on the measured accelerations and the assumed aerodynamic model of the capsule.

The remainder of this work is organized as follows. Section 2 describes the EDL concept of operations and the as-flown timeline of events along the trajectory. Pathfinder vehicle systems are summarized in Section 3. The data sources available for use in the reconstruction are described in Section 4, which includes a variety of sources, including sensors such as accelerometers, and models such as the capsule aerodynamics. Section 5 includes a summary of the reconstruction methodology and results of the trajectory and atmosphere reconstruction of the Mars Pathfinder EDL. A summary of the reconstructed conditions at certain points during the EDL trajectory is provided in Section 6. Finally, concluding remarks are given in Section 7.

2 Pathfinder EDL Concept of Operations

Prior to beginning its descent, Pathfinder prepared itself for entry. The vehicle first separated from its cruise stage approximately 30 minutes before Entry Interface (EI) while spin stabilized with a rate of 2 rpm [6]. Approximately 15 minutes before EI, accelerometers turned on and began collecting data at a frequency of 1 Hz. Shortly before EI, the accelerometers began to collect data at a higher frequency of 32 Hz. Pathfinder began its descent with a total mass of 585.3 kg and an initial entry speed of 7.26 km/s. The sequence of EDL events are shown in Fig. 1 [6].

The as-flown timeline of events along the EDL trajectory is summarized in Table 1. The EI time corresponds to 16:51:50.482 UTC on July 4, 1997, where the spacecraft was at a radial distance of 3522.2 km from the center of Mars [6]. Note that the timeline in Table 1 differs by up to 1.7 s relative to a similar table listed in [6] due to different time synchronization assumptions. Details of time synchronization are described in Section 4.2.

Table 1: EDL as-flown event timeline.

Event	Time From Entry [s]
Entry Interface	0.0
Maximum Dynamic Pressure	76.2
Mortar Fire	169.9
Parachute Deployment	171.2
Heatshield Separation	191.1
Bridle Deploy (lander separation)	210.0
Inflate Airbags (begin)	293.4
Rocket Ignition	297.7
Bridle Cut	299.8
Touchdown (first bounce)	303.8
Last Recorded Bounce	358.9
Last Data Record	359.5

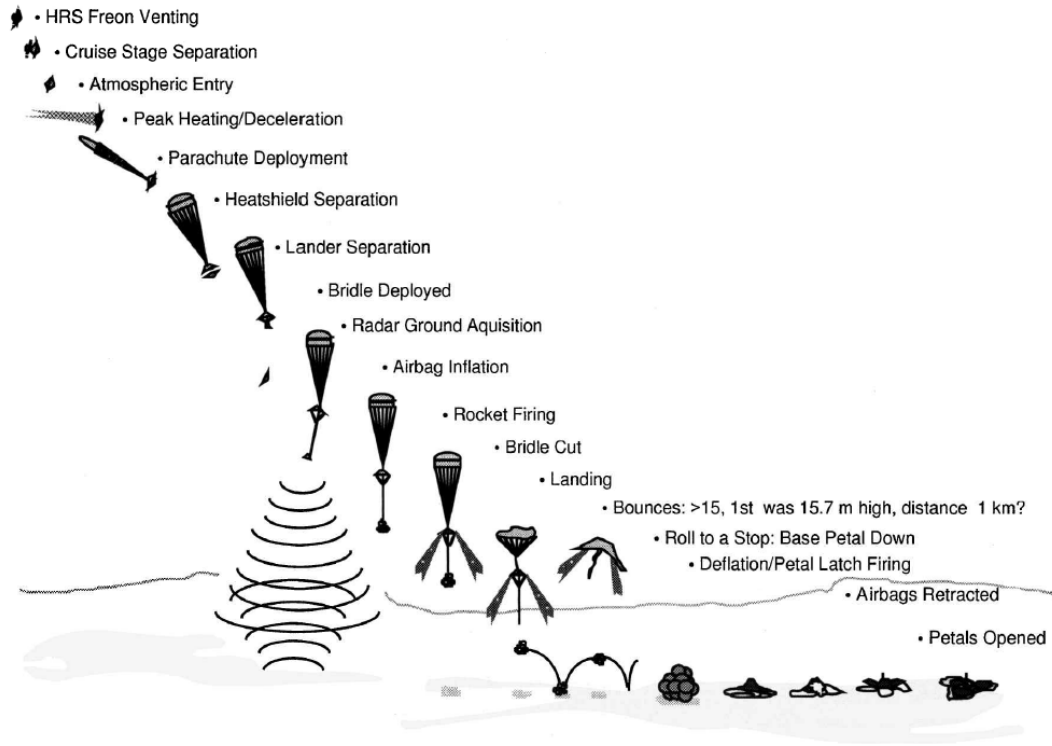


Figure 1: EDL concept of operations [6].

3 Pathfinder Vehicle and Systems

The EDL systems and mass properties that were specific to performing this Pathfinder reconstruction are described below. See [6] for additional details regarding these systems.

3.1 Aeroshell

The Pathfinder aeroshell design was a 70-degree sphere-cone shape with heritage from the previous Viking program. The aeroshell diameter was 2.65 m with a reference area of 5.51 m^2 , a nose radius of 0.6638 m, and a shoulder radius of 0.0662 m. The heatshield had a mass of 64.4 kg and the backshell mass was 56.9 kg.

3.2 Parachute and Bridle

Developed by Pioneer Aerospace, the Pathfinder parachute, which was a modified version of the Viking mission parachute, was attached to the vehicle backshell and had a total mass of 17.5 kg. The 12.5 m diameter parachute deployed during entry at approximately Mach 1.8. Additionally, the bridle that suspended the payload was attached to the vehicle backshell and had a total mass of 7 kg.

3.3 Rocket Assisted Deceleration System

Mounted to the Pathfinder backshell was the Rocket Assisted Deceleration (RAD) system, which consisted of three rocket motors. The RAD system was used to bring the vertical velocity of the vehicle to zero at 13 m above the Martian surface [6]. To accomplish this task, the rockets each produced 7938 N of thrust and the RAD system burn duration was 2.2 s [6]. While the vertical velocity of Pathfinder was briefly zero, the bridle was cut, dropping the payload to the surface. The RAD system had a mass of 30.7 kg [6].

3.4 Pathfinder Airbags

To protect the payload from impact after the bridle was cut, airbags were inflated to surround and protect the payload. There were a total of four separate airbags. The total mass of the airbag material was 87.8 kg, the gas generators had a mass of 10 kg, and the mass of the airbag retraction motors was 6.2 kg [6]. It took 0.5 s for the airbags to inflate, and between 0.5 to 1.5 h for the airbags to fully deflate and then retract [6]. The acceleration due to gravity on Mars is approximately one third of that on Earth, which increases the survivability of an object dropped on Mars because of the decreased impact when compared to a drop from the same height on Earth.

4 Data Sources

4.1 Vehicle Coordinate Axes

There are two main coordinate systems that are used throughout this report. The first of these is referred to as the Pathfinder coordinate system, and it is the reference system used for the vehicle's mechanical and flight systems. The coordinate frame, illustrated in Fig. 2, has the +Z axis oriented out the heatshield along the vehicle spin axis. The +Y axis of the Pathfinder frame is perpendicular to the +Z axis and is directed towards the star scanner assembly when the entry vehicle and cruise stage are mated [15]. The +X axis completes the right-handed system. The XY plane of the Pathfinder frame is the plane of the entry vehicle interface pads located at the top of the backshell interface plate [15, 16].

The second frame used in this report is the flight mechanics frame, which is a 90° rotation about the +Y Pathfinder frame such that the flight mechanics +X axis is oriented positive out from the heatshield along the vehicle axis of symmetry. The origin of this frame is located at the vehicle center of mass. This frame, shown in Fig. 3, follows the normal convention used in atmospheric flight vehicles where the X axis is positive out the nose of the vehicle. This frame is the primary frame used for the trajectory reconstruction. The coordinate transformation matrix from the Pathfinder frame to the flight mechanics frame is

$$\mathcal{T}_{p2fm} = \begin{bmatrix} 0 & 0 & -1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix} \quad (1)$$

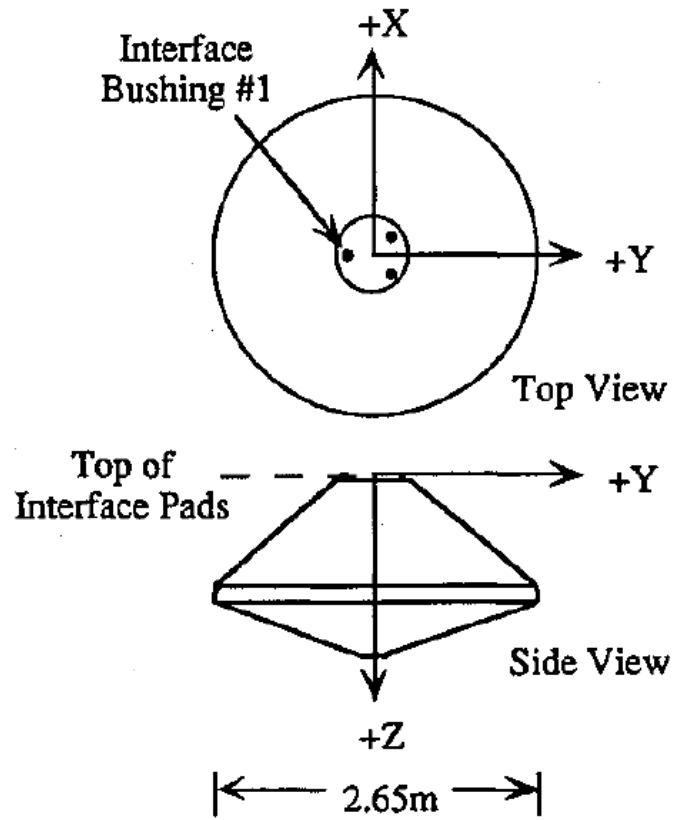


Figure 2: Mars Pathfinder frame [16].

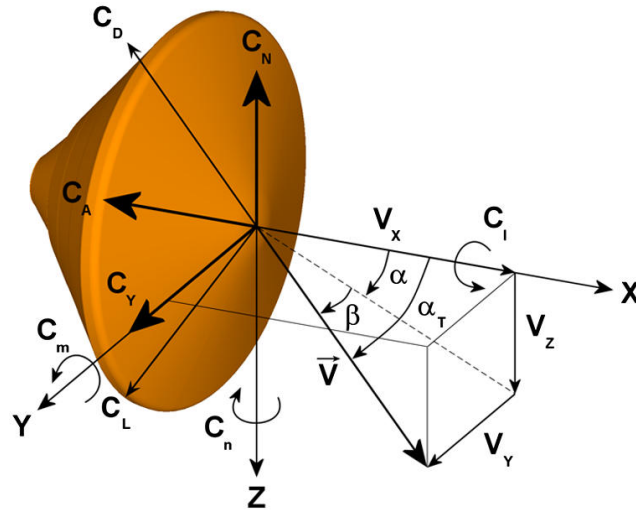


Figure 3: Flight mechanics coordinate system showing definitions of aerodynamic coefficients and aerodynamic flow angles.

The definitions of the vehicle aerodynamic coefficients and aerodynamic flow angles relative to the flight mechanics frame are illustrated in Fig. 3. This figure illustrates the directions of the force and moment coefficients relative to the axes of the flight mechanics frame and the geometry of the angle of attack, angle of sideslip, and total angle of attack relative to the body-axis atmospheric-relative velocity. Following the usual definitions, the axial and normal force coefficients (C_A and C_N) are directed along the -X and -Z axes, respectively, while the side force coefficient (C_Y) is directed long the +Y axis. The drag force coefficient (C_D) is the force coefficient directed opposite to the wind-relative velocity and the lift force coefficient is the coefficient of force directed perpendicular to the wind-relative velocity. The moment coefficients (C_l , C_m , and C_n) are defined by the direction of positive rotations about each axis of the flight mechanics frame.

4.2 Accelerometers

Pathfinder carried two sets of three Allied Signal QA-3000-003 accelerometers, each with a sample rate of 32 Hz. The first set of accelerometers were used for the ASI/MET experiment [3] and were intended as the primary set of sensor data to be used for trajectory and atmosphere reconstruction. The ASI/MET sensors were aligned with the Pathfinder coordinate axes as described in Section 4.1. The accelerometers were located within 15 mm of the vehicle centerline and within 155 mm of the vehicle center of mass [5].

The second set of accelerometers were the engineering accelerometers that were used onboard in the triggering logic to deploy the parachute during EDL on Mars [17]. These sensors were aligned differently than the ASI/MET experiment sensors. The set of engineering accelerometers had one unit installed in the +X direction in the Pathfinder coordinate frame, while the other two sensors were in the YZ plane canted at $\pm 45^\circ$ angles away from the vehicle centerline (the +Z axis) [5, 6].

The ASI/MET acceleration measurements are shown in Fig. 4. The accelerations shown here have been converted from raw counts to engineering units. Note that the calibrated sensor output is in engineering units of Earth gravitational acceleration, where $1 \text{ g} = 9.795433 \text{ m/s}^2$ [3]. The accelerometers were capable of being set to three different full scale ranges during EDL, corresponding to 0.016 g, 0.800 g, or 40.0 g, such that finer resolution data could be obtained at high altitudes [3]. The resolutions at each full scale range correspond to $2 \mu\text{g}$, $100 \mu\text{g}$, and 5 mg, respectively [3]. The switches in full scale ranges cause a fictitious spike in the recorded accelerations. These are visible in the axial acceleration at $t=25.5 \text{ s}$ as the accelerometer full scale range changes from 0.016 g to 0.800 g, and again at $t=42.5 \text{ s}$ as the acceleration full scale range changes from 0.800 g to 40.0 g. These data spikes were a by-product of the change in full scale range, and thus were edited out of the data prior to its use in the reconstruction. The ASI/MET accelerometer 3σ measurement uncertainties include 2 counts of noise [3], a 4 mg measurement bias, and a scale factor uncertainty of 80 ppm [18]. The alignment of the accelerometers relative to the Pathfinder coordinate frame was known within 0.25° [3]. Data from the engineering accelerometers were transformed into the Pathfinder coordinate frame for comparison with the ASI/MET sensor data and were found to be in agreement.

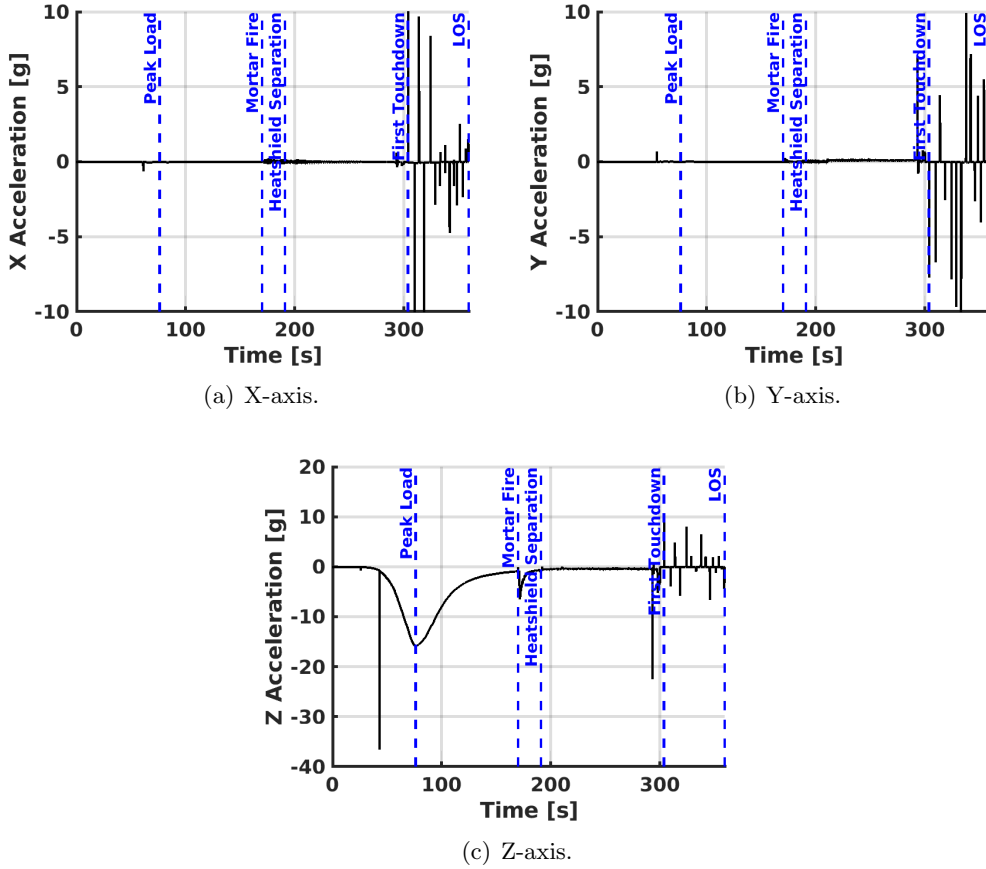


Figure 4: ASI/MET accelerometer measurements.

The time synchronization of the acceleration measurements in this work were based on the epoch times given in the archived ASI/MET data from PDS. The first recorded acceleration measurement given in the archived ASI/MET data was timestamped July 4, 1997, 16:36:50.172 UTC, which corresponds to 900.310 s or roughly 15 minutes prior to the EI time of 16:51:50.482 UTC. The acceleration measurements were recorded at a rate of 1 Hz until an elapsed time of 870.0 s before switching to the full 32 Hz sample rate for the remainder of the spacecraft's EDL. The last recorded acceleration measurement was timestamped July 4, 1997, 16:57:50.019 UTC, 1259.84375 s after the initial measurement time and 359.53375 s from the EI time. This synchronization leads to some discrepancies with the data set used in the reconstruction given in [6], which states that a total of 361.1 s of data were available from EI to the end of the recorded data. These discrepancies lead to differences in the reconstructed timeline listed in Table 1 in this work compared to the equivalent timeline given in Table 3 of [6], on the order of up to 1.7 s. Timing issues and other anomalies between the ASI/MET PDS archive and [6] were also noted in [19, 20].

4.3 Radar Altimeter

Pathfinder was equipped with a Honeywell HG8505DA radar altimeter that began searching for the Martian surface after heatshield release. The radar altimeter had a mass of 1.4 kg and a maximum range specification of 1.52 km. The altimeter provided altitude and altitude-rate measurements at a sample rate of 50 Hz. It had a resolution of 0.1 m and 0.1 m/s, respectively, with 3σ altitude and altitude rate uncertainties of 0.3 m and 1 m/s, respectively [6, 21]. The full 50 Hz data set from the radar was not archived on PDS, though a 1 Hz representation of the data was available from [21]. The measurement data are shown in Fig. 5.

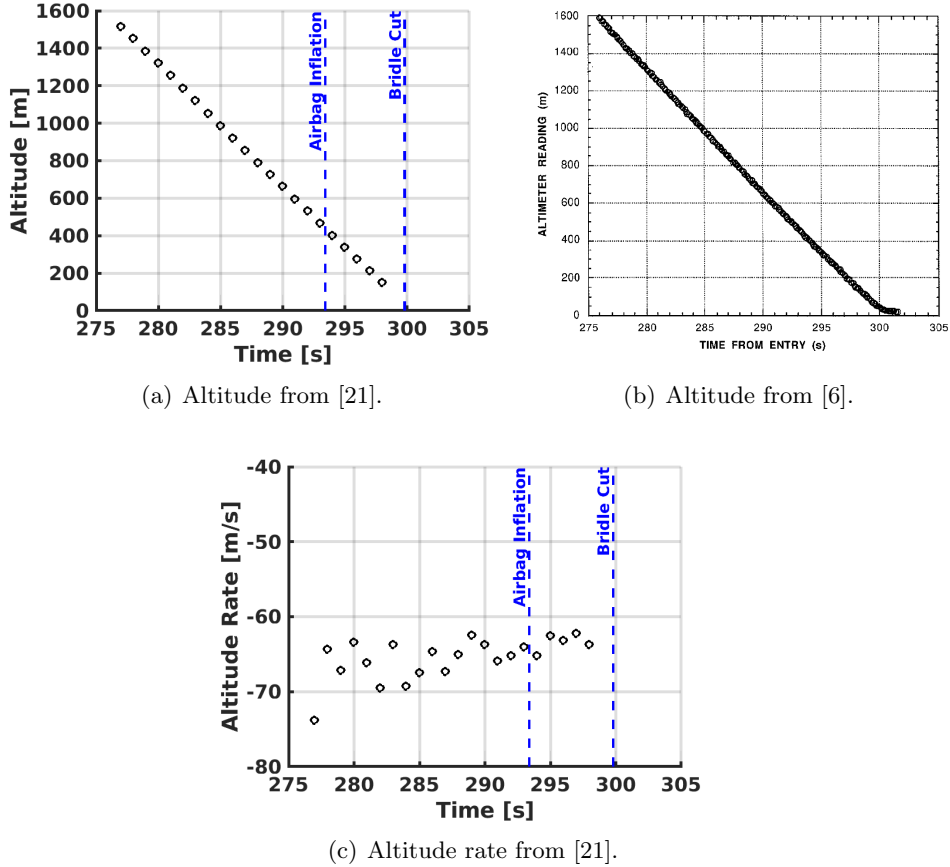


Figure 5: Altimeter measurements.

There are several discrepancies between the radar data from [21] and [6], aside from the difference in sample rate already noted. The first data point in the altitude measurements from [21] at approximately 277 s from entry is 1518 m, whereas the initial value from [6] is given as 1591 m, which is a difference of 73 m. Both measurement sources match at $t=285$ s with an altitude of roughly 1000 m. The last altitude measurement from [21] occurs at $t=298$ s at an altitude of 152 m whereas the corresponding value from the dataset in [6] is approximately 175 m, judging from Fig 5(b). The dataset from [6] continues past the rocket ignition to a time of roughly

301.5 s from EI. The differences in altitudes between the two datasets prior to rocket ignition indicate a difference in the mean descent rate under the parachutes, with [6] indicating a descent rate of 63 m/s, and the data from [21] giving a mean descent rate of 65 m/s. The cause of these discrepancies is not known, and thus the radar altimetry was not used in the reconstruction presented in this report.

4.4 Entry State

Orbit determination solutions during approach to Mars [22] were used to obtain estimates of the spacecraft position and velocity at the moment of EI, which is defined as the moment when the vehicle is at a radial distance of 3522.2 km from the center of the planet [6]. The estimated state at EI is given in Table 2. This state is used as the initial conditions for reconstruction described in this report.

Table 2: Estimated entry state from orbit determination [6].

Parameter	Estimate
Epoch	July 4, 1997, 16:51:50.482 UTC
Radius	3522.2 km
Declination	22.6303°
Longitude	337.9976°
Inertial velocity	7.2642 km/s
Inertial flight path angle	-14.0614°
Inertial flight path azimuth	253.1481°

4.5 Landing Site Coordinates

After successfully landing on the surface of Mars, the landing point of Pathfinder was determined through radiometric tracking [23]. The resulting landing site coordinates are given in Table 3.

Table 3: Estimated landing site location from radiometric tracking [6,23].

Parameter	Estimate
Radius	3389.714 km
Declination	19.07°
Longitude	326.48°

Note that Table 4 in [6] specified the angular position north from the equatorial plane as an areodetic latitude. This aerodetic angle of 19.28° [6] has been converted to a declination of 19.07° in Table 3 to be consistent with the spherical coordinates given in the orbit determination solution for the initial state.

Also note that this location specifies the final location of the lander after it had come to rest following multiple bounces as a result of the inflated airbag system.

The location of the first impact with the surface is some distance away from the final landing site location.

4.6 Mass Properties

Entry vehicle mass properties were measured at the Kennedy Space Center one month prior to launch. The mass properties provided in the Pathfinder coordinate system are listed in Table 4, from [6].

Table 4: Pathfinder mass properties [6].

Parameter	Units	Value	Uncertainty
Mass	kg	585.3	± 2
X_{CM}	m	0.000435	± 0.00013
Y_{CM}	m	0.000107	± 0.00013
Z_{CM}	m	0.79359	± 0.010
I_{xx}	kg-m ²	254	$\pm 5 \%$
I_{yy}	kg-m ²	248	$\pm 5 \%$
I_{zz}	kg-m ²	339	$\pm 5 \%$
I_{xy}	kg-m ²	3	$\pm 100 \%$
I_{xz}	kg-m ²	-433	$\pm 12 \%$
I_{yz}	kg-m ²	-62	$\pm 12 \%$

4.7 Aerodynamic Database

An aerodynamic model of the Pathfinder entry capsule has been constructed based on a combination of computational fluid dynamics simulations and experimental results [16, 24–26]. The aerodynamic database encapsulates the expected trajectory space, covering Mach ranges from EI to parachute deployment with a total angle of attack range of up to 11° . The database was implemented in a Fortran routine that computes the force and moment coefficients for the given flight conditions. The database used in this work is an updated version of that used in the reconstruction documented in [6] that contains additional data and other revisions. In this work, the Fortran database routine was implemented as a Matlab Executable (MEX) function for incorporation into the reconstruction tools. Further information on the vehicle aerodynamics can be found in [16, 24–26].

4.8 Gravity Model

A model for the planetary gravitational acceleration is required to integrate the sensed accelerations in order to produce estimates of the spacecraft position and velocity. In this work a model including the second zonal harmonic was used to provide the gravitational accelerations. The second zonal harmonic coefficient value used in this work was $J_2 = 0.001958616$ with a gravitational parameter $\mu = 42828.376383$ km³/s². The equatorial and polar radii were assumed to have values of $R_e = 3396.19$ km and $R_p = 3376.20$ km, respectively.

5 Trajectory and Atmosphere Reconstruction

5.1 Reconstruction Methods

The reconstruction approach was based on the use of the NewSTEP trajectory reconstruction software to integrate the measured accelerations to produce an estimate of the as-flown trajectory relative to the surface of the rotating planet. In a second step, the atmosphere was estimated along the reconstructed trajectory based on the measured accelerations and the nominal aerodynamic database.

NewSTEP's basic formulation of the equations of motion assumes that a complete Inertial Measurement Unit (IMU) containing accelerometers and gyroscopes is available to measure the three-axis linear accelerations and angular rates that the vehicle experiences over the course of the trajectory. These measurements are then integrated numerically to produce estimates of the vehicle position, velocity, and attitude. In the case of Pathfinder, there were just three-axis accelerometers and no gyroscopes. Thus, the trajectory integration method was formulated following the approach used for MER [9] in which the total angle of attack of the vehicle was fixed at zero such that the axial acceleration was directed along the anti-velocity vector direction. This assumption enables a three degrees-of-freedom (3-DOF) integration of the measured accelerations to produce an estimate of the vehicle position and velocity versus time, given the set of initial conditions listed in Table 2. In this work the numerical integration was carried out using a fourth-order fixed step Runge-Kutta method with a step size matching the 32 Hz data rate of the ASI/MET accelerometers. Numerical integration performed in NewSTEP using the ASI/MET accelerometer data began at EI and ended when Pathfinder made first contact with the ground.

After reconstructing the trajectory, the atmospheric conditions were computed using the approach given in [14]. The atmospheric reconstruction begins at EI and terminates at mortar fire where the Pathfinder rigid body aerodynamic model is no longer valid due to the presence of the parachute. In this approach, the density is computed from the axial acceleration and the assumed nominal axial force coefficient using the relation

$$\rho = -\frac{2ma_x}{V^2 C_A S} \quad (2)$$

Eq. (2) is complicated by the dependence of the axial force coefficient on the vehicle angle of attack. Thus, an iterative approach was implemented to simultaneously solve the system of nonlinear algebraic equations based on ratios of the axial to normal and side accelerations and the corresponding force coefficients. The equation was of the form

$$\lambda(\alpha, \beta) = \begin{Bmatrix} a_z/a_x - C_N/C_A \\ a_y/a_x + C_Y/C_A \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \quad (3)$$

Eq. (3) was solved using a Newton-secant method to compute estimates of the angles of attack and sideslip. These angles were then fed back as inputs to the axial force coefficient in Eq. (2) and the entire process was iterated until convergence at each instant in time along the trajectory before proceeding on to the next measurement point and repeating the process.

The resulting density was then integrated using the hydrostatic equation to obtain pressure versus altitude, for a given initial value of the pressure. Next, the temperature was computed from the ideal gas law, thus completing the atmosphere reconstruction. Further details on the implementation of the atmosphere reconstruction method can be found in [14].

The integration of the hydrostatic equation requires an initial value for the pressure. Initial values can be estimated from models or other observations. An iterative approach was utilized in this work following the approach given in [5]. In this approach, a first pass through the data was performed to estimate the density from the solution to Eqs. (2-3). This result yields the density as a function of altitude when combined with the reconstructed trajectory relative to the rotating planet. The density versus altitude relation can be differentiated numerically to compute the density scale height [27], which can be manipulated to solve for the temperature, given by

$$T = -\frac{Mg\rho}{\mathcal{R}} \left(\frac{d\rho}{dz} \right)^{-1} \quad (4)$$

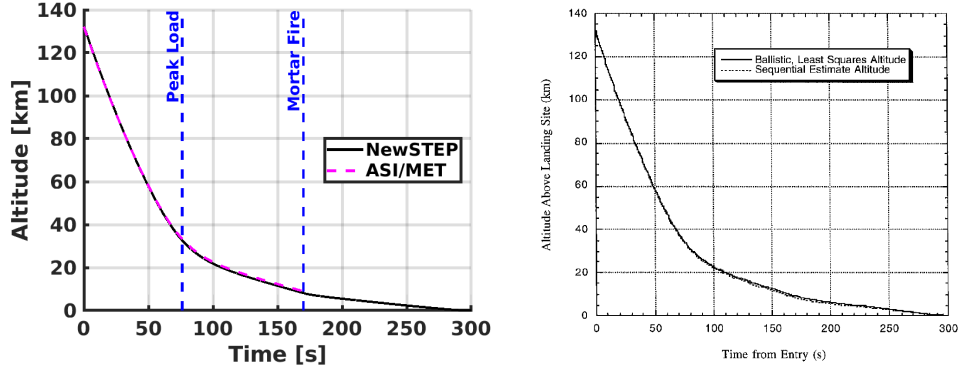
where the mean molecular weight, M , and the universal gas constant, $\mathcal{R}$, were 43.2685 kg/kmol and 8314.34 J/kmol-K respectively [6].

Thus, the temperature can be computed at the initial altitude by means of Eq. (4) and then pressure can be computed from the ideal gas law. This value of pressure was used as the initial condition for the integration of the hydrostatic equation in the second and final iteration of the atmosphere reconstruction process.

5.2 Trajectory Reconstruction Results

Results of the NewSTEP trajectory reconstruction are described in this section. Where possible, the results are compared with the solutions of the ASI/MET science team that were archived on PDS [5], and the plots of the data given in the reconstruction documented in [6].

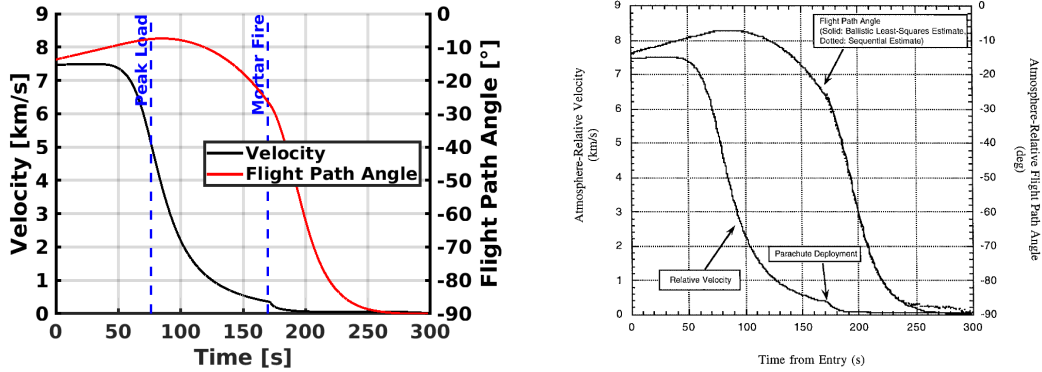
Fig. 6 shows a comparison of the reconstructed altitudes. Fig. 6(a) shows the NewSTEP reconstruction coplotted with the ASI/MET altitude reconstruction from PDS. Note that the ASI/MET reconstruction ceased at the instant of the parachute mortar fire. Also, the ASI/MET data was saved with an output rate of 4 Hz whereas the NewSTEP reconstruction was computed based on the full 32 Hz rate acceleration measurements. Fig. 6(b) shows the corresponding altitude time history obtained from the reconstruction documented in [6]. The altitude reconstruction from all three reconstructions are in agreement.



(a) NewSTEP and ASI/MET [5] reconstructed altitude. (b) Reconstructed altitude from [6].

Figure 6: Altitude comparison.

The reconstructed velocity and flight path angle time histories are shown in Fig. 7. Fig. 7(a) shows the NewSTEP reconstruction and Fig. 7(b) shows the corresponding result from the reconstruction given in [6]. Note that there are no velocity or flight path angle outputs to compare with from the ASI/MET PDS archive. The NewSTEP reconstruction of velocity and flight path angle matches with the reconstruction from [6]. The NewSTEP reconstructed velocity at mortar fire was estimated as 374.2 m/s.

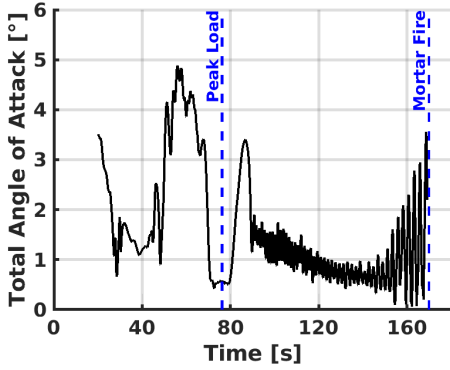


(a) NewSTEP reconstructed velocity and flight path angle. (b) Reconstructed velocity and flight path angle from [6].

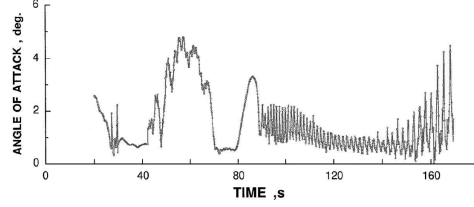
Figure 7: Velocity and flight path angle comparison.

The total angle of attack reconstructions are shown in Fig. 8. Recall that these estimates come as a by-product of the atmosphere reconstruction as the solution to Eq. (3). No estimate of the angle of attack was provided in the ASI/MET data from the PDS archive. Note that the angle of attack reconstruction begins at $t=20$ s from EI, where the signal in the axial acceleration begins to rise above the noise such that the ratios of accelerations produce reasonable values. The angle of attack

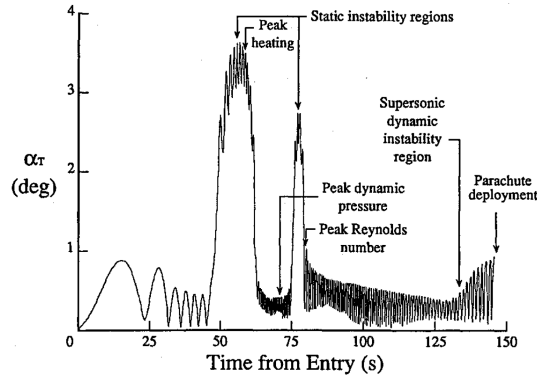
reconstruction terminates at mortar fire, as discussed in Section 5.1. The NewSTEP reconstruction generally agrees with the reconstruction given in [6]. Both reconstructions show the effect of static instability regions on either side of the peak dynamic pressure causing a growth in the amplitude of the angle of attack. These instabilities matched with predictions from the preflight aerodynamic modeling efforts. For comparison, a preflight simulation of the total angle of attack is shown in Fig. 8(c) from [16], in which the static instability regions and other points of interest are annotated. See [26] for further discussion of the prediction and validation of the hypersonic aerodynamics of the Pathfinder entry capsule. Some small differences between the reconstructions can be noted such as two spikes in the reconstruction from [6] at approximately $t = 25$ s, a jump of approximately 0.5° in the reconstruction from [6] just after $t = 40$ s that is not present in the NewSTEP reconstruction, and amplitude differences after the second static instability region. The NewSTEP reconstruction after the second static instability region is below 2° amplitude whereas the data from [6] is initially higher than 2° . These discrepancies could be due to differences in the assumed aerodynamic database used in the reconstructions.



(a) NewSTEP reconstructed total angle of attack.



(b) Reconstructed total angle of attack from [6].



(c) Preflight total angle of attack simulation from [16].

Figure 8: Total angle of attack comparison.

The reconstructed dynamic pressure is shown in Fig. 9. Fig. 9(a) shows the reconstruction from NewSTEP and Fig. 9(b) shows the corresponding reconstruction from [6]. Each case shows the reconstruction over the last 20 seconds leading up to the time of the mortar fire. The system was designed to fire the mortar within a dynamic pressure range of 580-703 Pa and a Mach number range of 1.70 to 2.29, with a target dynamic pressure of 600 Pa [6].

The Mach number time history was not plotted in [6], but the corresponding Mach reconstruction from NewSTEP is shown in Fig. 10. The reconstruction of [6] states the mortar fire condition was at a dynamic pressure of 585 Pa and a Mach number of 1.8. The NewSTEP reconstruction indicates a mortar fire condition of 576 Pa dynamic pressure at a Mach number of 1.70. The NewSTEP estimates for dynamic pressure and Mach number at mortar fire are both lower than those given in [6], but the values are still within the expected ranges relative to the target condition. Further details on the parachute trigger performance can be found in [17].

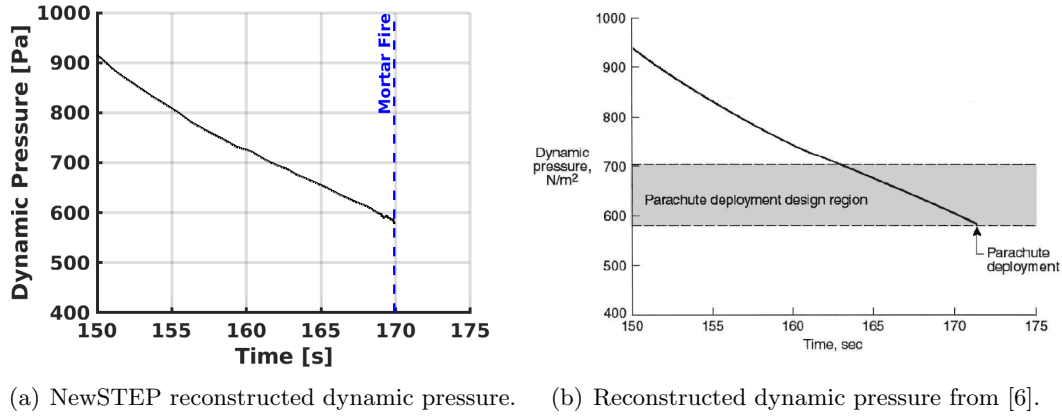


Figure 9: Dynamic pressure comparison.

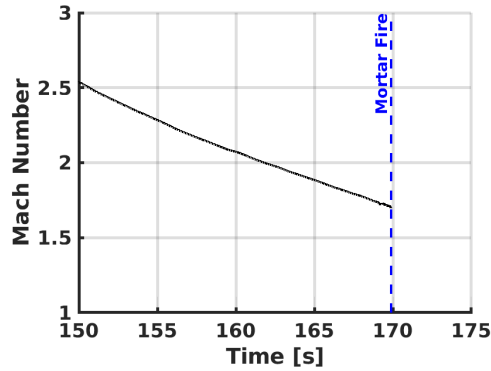


Figure 10: Mach number.

Lastly, the reconstructed declination and longitude at the time of the first contact with the ground were 19.04° and 327.68° , respectively.

5.3 Atmosphere Reconstruction Results

The results of the NewSTEP atmosphere reconstruction are compared with the ASI/MET reconstruction and the results from [6] in the following figures. The reconstructed density versus altitude is shown in Fig. 11. Fig. 11(a) shows the NewSTEP reconstruction coplotted with that of the ASI/MET reconstruction, while Fig. 11(b) shows the reconstructed density from [6]. The three reconstructions are in agreement.

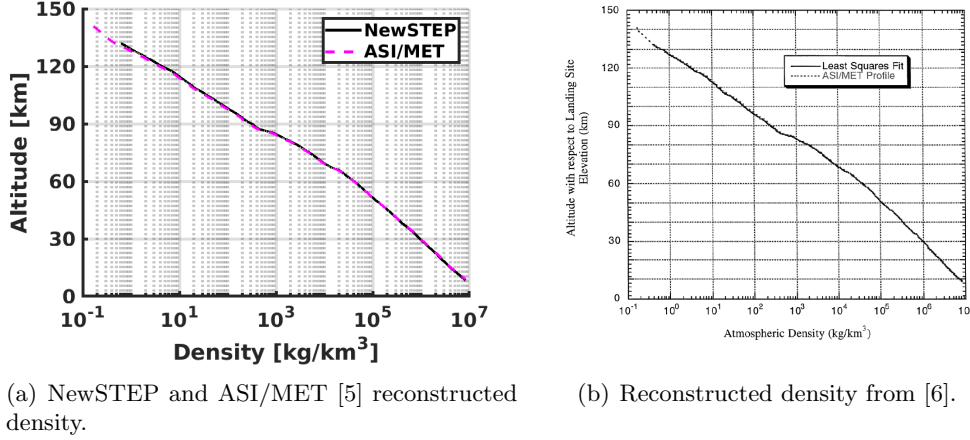


Figure 11: Density comparison.

The temperature reconstruction is compared in Fig. 12. The three reconstructions match for altitudes below approximately 120 km, with differences on the order of 5 K or less. Above 120 km, the ASI/MET reconstructed temperature is up to 45 K higher than the NewSTEP reconstruction. The reconstruction from [6] is in agreement with the NewSTEP reconstruction in this altitude range. The curve labeled as the ASI/MET profile in Fig 12(b) from [6] does not match with the ASI/MET profile found on PDS that is coplotted in Fig 12(a). The version of the ASI/MET data plotted in [6] as shown in Fig. 12(b) is presumably an early version of the scientific reconstruction since it is referenced in [6] to [4] and not to the final ASI/MET reconstruction given in [5] that is archived on PDS. Upper altitude differences in the temperature profile between the ASI/MET reconstruction [5] and the NewSTEP reconstruction are likely due to differences in the initialization of the numerical integration of the hydrostatic equation. The upper altitude profiles can be sensitive to the initialization assumptions for the integration of the hydrostatic equation, as noted in [5]. The sensitivity is negligible at lower altitudes. This sensitivity is the likely cause of the differences in the upper altitude reconstruction as the lower reconstructions match lower in the profile below roughly 120 km.

Lastly, the pressure reconstruction is shown in Fig. 13. Note that the pressure reconstruction was not shown in [6], therefore Fig. 13 shows just the comparison of the NewSTEP reconstruction to the corresponding reconstruction given in the ASI/MET PDS archive [5]. The two reconstructions are a close match.

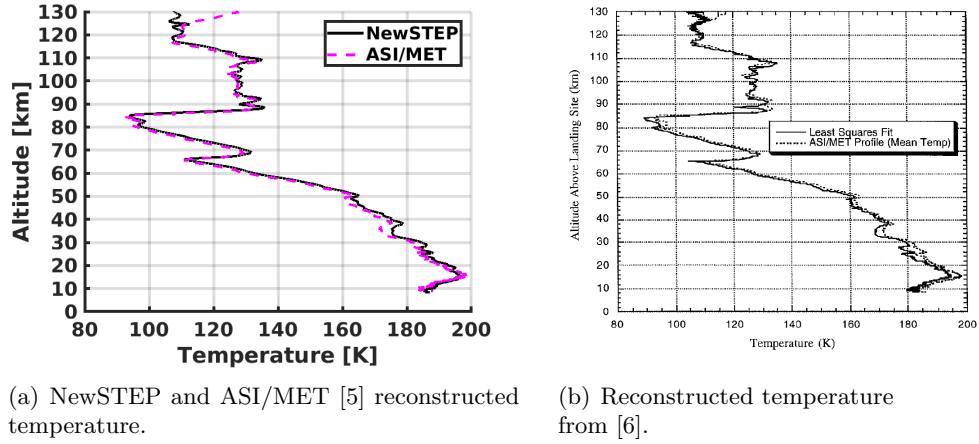


Figure 12: Temperature comparison.

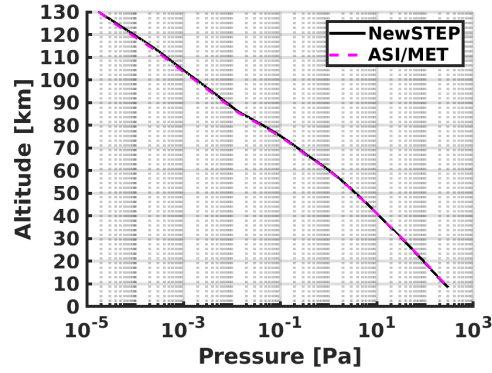


Figure 13: Pressure comparison.

6 Trajectory Conditions

A summary of the trajectory conditions at several events during EDL from the reconstruction described in this report is provided in Table 5.

Table 5: Trajectory conditions during EDL.

Event	Time from EI s	Mach Number	Dynamic Pressure Pa	Ground-Relative Velocity m/s	Areodetic Altitude km	Flight Path Angle °	Total Angle of Attack °
Entry Interface	0.00	N/A	0.0	7478.63	128.99	-13.65	N/A
Mach 30	66.87	30.00	6984.46	6347.23	36.81	-7.98	3.29
Mach 25	74.75	25.00	9496.30	5290.65	30.59	-7.55	0.55
Peak Deceleration	76.20	23.84	9607.67	5066.34	29.61	-7.50	0.56
Mach 20	80.93	20.00	9155.78	4347.30	26.73	-7.378	1.11
Mach 15	88.76	15.00	7624.78	3282.67	22.93	-7.36	2.36
Mach 10	99.75	10.00	5048.32	2194.26	19.04	-7.81	1.09
Mach 5	121.36	5.00	2112.14	1116.24	13.87	-10.37	0.76
Mortar Fire	169.90	1.70	576.14	374.19	5.30	-26.52	1.66

7 Conclusions

The Mars Pathfinder entry, descent, and landing trajectory and atmosphere reconstruction was revisited to further analyze accelerometer data for use in future Mars and other planetary missions. A new reconstruction was generated based on data from the accelerometers that were part of the atmospheric structure investigation science package carried onboard Pathfinder. The trajectory and atmosphere reconstruction results were a match to previous reconstructions developed for 1) engineering validation of trajectory predictions, and 2) scientific analysis as part of the atmospheric structure investigation experiment. The results of this reconstruction are expected to be useful for providing a historical record of the Mars Pathfinder as-flown trajectory and atmosphere that can be fed forward into future missions.

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