Re-Examination of Mars Pathfinder Parachute Drag Coefficient Estimate

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Motivation:

The Mars Exploration Rover (MER) mission utilizes the Mars Pathfinder (MPF) parachute design. The MPF parachute drag coefficient (C_D) is a driver for the MER entry, descent, and landing (EDL) design. As a result, a good estimate of the performance of the MPF parachute at Mars is required.

Examination of previous estimates of the MPF parachute C_D revealed a few inconsistencies in the assumptions utilized in those analyses. For example, the MPF parachute C_D calculation was performed at an altitude of 150 m (after airbag inflation). However, analysis utilized non-inflated airbag Lander C_D and reference area values in governing equations. Additionally, the atmospheric temperature assumption neglected the thermal inversion layer near the surface. This assumption would lead to an over prediction of the atmospheric density, and produces an underestimate of the parachute C_D. Due to the inconsistencies identified in the previous analyses, another investigation was initiated to determine the best possible estimate for the MPF parachute C_D as exhibited on Mars. This report summarizes the methodology utilized in the re-examination of the MPF parachute C_D estimate.

Approach:

All parameters required for calculation of the parachute C_D are re-examined: MPF altimeter flight data, atmospheric properties, Backshell and Lander C_D values, parachute area, and total vehicle volume. Values for parameters are updated where appropriate. Specifically, outlined is the rationale for the improvement in the estimates for the value of the terminal velocity and atmospheric properties, which are the largest contributors to the parachute C_D estimate. Note, conservative assumptions are utilized where appropriate.

In addition, this investigation employs the use of a Monte Carlo technique instead of the previous analyses' point calculation estimates. As a result, dispersions in all the parameters can be accounted for in the analysis. In so doing, a statistical range on the MPF parachute C_D can be defined. With this approach, a more rigorous methodology is employed which provides for a better MPF parachute C_D estimate than previous efforts.

Atmospheric Density

Accurate density estimation is necessary for determining the parachute C_D, since the two parameters are coupled. However, neither density, pressure, nor temperature were measured during the MPF parachute descent.

Density can be derived through temperature and pressure measurements. Accurate MPF temperature and pressure measurements are available at the surface (altitude of 1 m). However, measurements are required above the surface near terminal velocity conditions. Therefore, surface pressure and temperature must be extrapolated to the altitude where C_D is derived. Pressure can be extrapolated accurately, however, temperature must be derived from models or other measurements. The original MPF parachute C_D estimate was performed at an altitude of 150 m. The corresponding density was calculated by extrapolating the pressure and temperature which were measured at 1 m.

The original MPF parachute C_D value (calculated at 150 m) was underestimated because temperature was underestimated. The narrow nighttime surface temperature inversion layer was neglected. The temperature increases rapidly with altitude from the surface over the lower few hundred meters. However, considerable uncertainty exists for extrapolating the temperature from the surface to higher altitudes due to the uncertainty in the width of the temperature inversion layer.

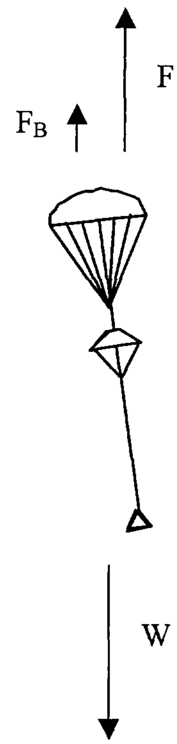
Therefore, current atmospheric property estimates are supplemented by Mars Global Surveyor (MGS) radio-occultation data. See appendix at end of attached set of charts for a detailed description on the rationale. Current best estimate of MPF parachute C_D is performed at an altitude of 1 km. The temperature at 1 km is taken from profiles derived from MGS radio-occultation measurements. High vertical resolution profiles from the surface to 30 km are obtained near the Pathfinder season, local time, and location, but for the next Mars year. The profiles show a maximum temperature of 220 K at 1 km with little day-to-day variation. This estimate is based on the assumption that year-to-year temperature variability at 1 km is small.

The year-to-year temperature variability at 1 km is well within +/-9 K (3-σ) error assumed. Multi-year radio-occultation measurements are not available for the MPF conditions. However, MGS TES data show little year-year variability in mean 0-10 km temperature at other seasons. Multi-year TES coverage of the MPF season are not yet available, although, Viking and MPF Landers demonstrate that surface pressure varies little from year-to-year.

The assumptions outlined in this investigation regarding the atmospheric properties were independently reviewed by Dr. Richard Zurek of the Jet Propulsion Laboratory. His assessment is that the assumptions described are very reasonable and that the approach taken is consistent with known modeling constraints and uncertainties. Overall, the approach developed is the best that can be constructed with the available data to define the atmospheric properties during the MPF parachute descent.

Terminal Velocity

At the terminal velocity condition, the sum of the vehicle drag force (F_D) and the buoyancy force (F_B) equal the weight of the vehicle (W)



$$W = mg$$
$$F_B = \rho \, g \, Vol$$

$$F_D = \frac{1}{2} \rho \, v^2 \left(C_{D_{Par}} A_{Par} + C_{D_{B/S}} A_{B/S} + C_{D_{B/S}} A_{B/S}\right)$$

where

m = suspended mass,
ρ = atmospheric density,
v = terminal velocity,
$C_{D_{B/S}}$ = Backshell drag coefficient,
$C_{D_{Lan}}$ = Lander drag coefficient,
$C_{D_{Par}}$ = Parachute drag coefficient,

g = graviatational acceleration
Vol = total vehicle volume

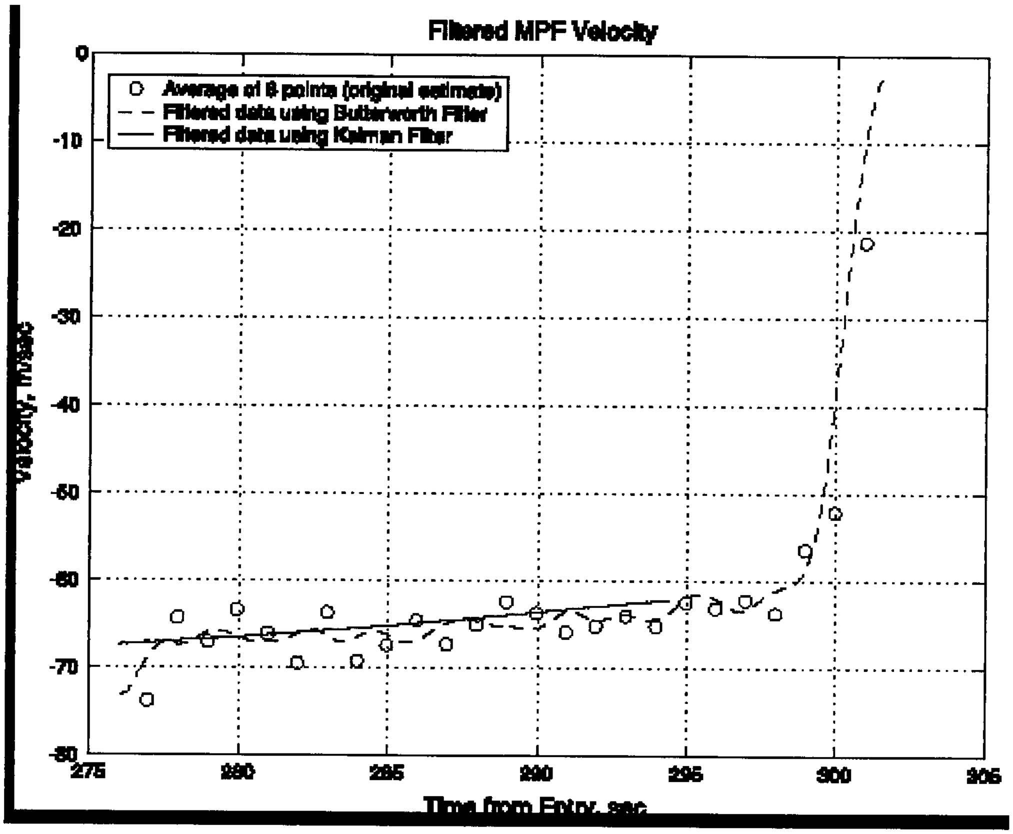
$A_{B/S}$ = Backshell reference area
A_{Lan} = Lander reference area
A_{Par} = Parachute reference area

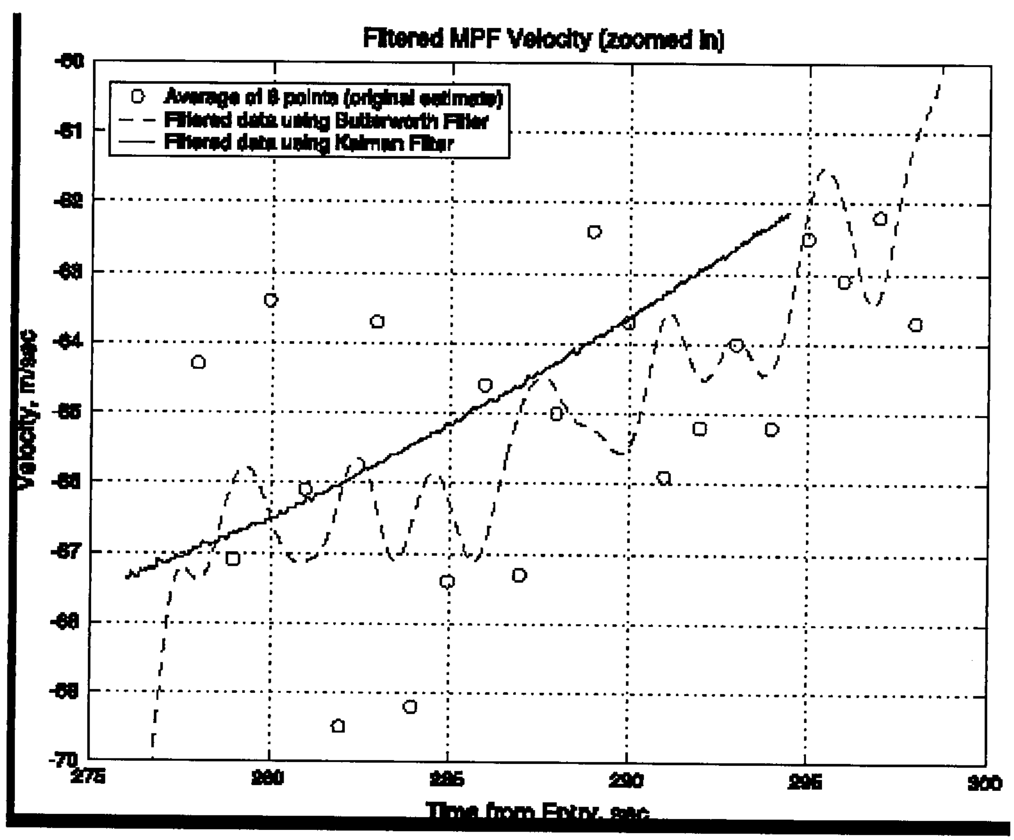
Then

$$\rho g Vol + \frac{1}{2} \rho v^2 \left(C_{D_{Par}} A_{Par} + C_{D_{B/S}} A_{B/S} + C_{D_{Lan}} A_{Lan}\right) = mg$$

Note, the velocity and density are the largest contributors for determining $C_{D_{Par}}$. Hence, an accurate estimate for both parameters is necessary.

The MPF altimeter flight data was re-examined using higher order filtering techniques beyond that performed in the previous analyses. The previous analyses employed a simple averaging technique (averaging every 8 points of the flight data). The current investigation performs two independent filtering techniques in an effort to smooth the MPF altimeter flight data to obtain a more accurate determination of the terminal velocity. A Butterworth filter and a more sophisticated Kalman filter were utilized on the flight data.





The Kalman filter (actually a backward-in-time filter plus a forward-in-time smoother, as explained below) was designed to process data simultaneously from the MPF 3-axis accelerometer and the radar altimeter. Nine parameters were estimated in the filter. These were: height above the ground, horizontal distance from the touchdown point, vertical and horizontal speed relative to the ground, vertical and horizontal non-conservative (i.e. drag) acceleration components and the time derivatives of these accelerations, and the angle between the MPF lander base petal and the vertical direction.

The filter was first run backwards in time over the accelerometer and radar data set, from a point in time just before the MPF retrorockets fired, to the time of the first radar measurement, a time span of approximately 20 seconds. The filter state vector was initialized by integrating the accelerometer data backwards in time, assuming a constant gravitational acceleration of 3.7165 m/s^2. The backward-in-time sequence of events included the initial impact with the ground, the free-fall of the lander through the air, the severing of the MPF bridle connecting the lander with backshell and parachute, and the firing of the retrorockets. A large covariance was used for the backward-in-time filter pass.

Subsequently, the forward-in-time filter was initialized with the state vector of the backward-in-time filter, taken at the first radar measurement time. The state vector histories vs. time of the forward and backward filters were averaged to produce the smoothed estimated state. The measurement residuals computed with the smoothed state had essentially zero bias, and RMS values of 1.47 meters for the altimeter measurements, and approximately 0.05 Earth g's per axis for the accelerometer measurements. One component of the smoothed estimated state, the vertical velocity, is shown in the plots

The two different filtering techniques show a good agreement in the mean value for the terminal velocity, and reduce the scatter in the estimate. In addition, as a by-product of the Kalman filtering technique, a statistical estimate on the uncertainty in the terminal velocity is obtained. This uncertainty estimate can be directly used in the Monte Carlo approach for specifying a dispersion on the terminal velocity.

Other Parameters

The MPF parachute area (of the flight unit) was a quantity that was not explicitly measured. Unfortunately, there was no requirement to control the actual MPF canopy area. As a result, its exact value is unknown. Since the parachute area is a quantity that directly affects the value of the parachute C_D, an accurate knowledge is required to calculate the value of the MPF parachute C_D.

To improve the knowledge of the MPF canopy area, Pioneer Aerospace measured the area of existing MPF Qualification Parachutes. The flight and qualification parachutes were manufactured at the same time from the same lot of material. Hence, the final dimensions should be similar. From these measurements, a mean value of the MPF parachute area and its variation were determined. This variation in parachute area was taken into account as part of the Monte Carlo methodology in determining the range on the MPF parachute C_D value.

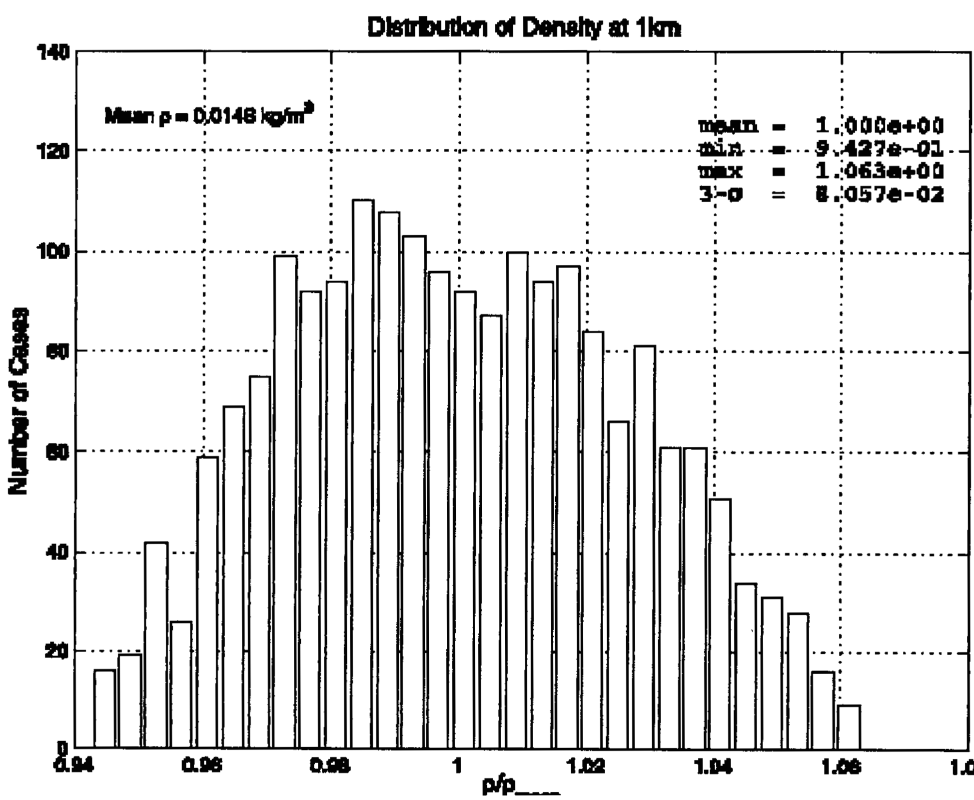
The values for the Backshell C_D and Lander C_D were also updated based on wind tunnel tests. The tests improved the knowledge in the C_D values of both configurations from that utilized in previous analyses.

Results:

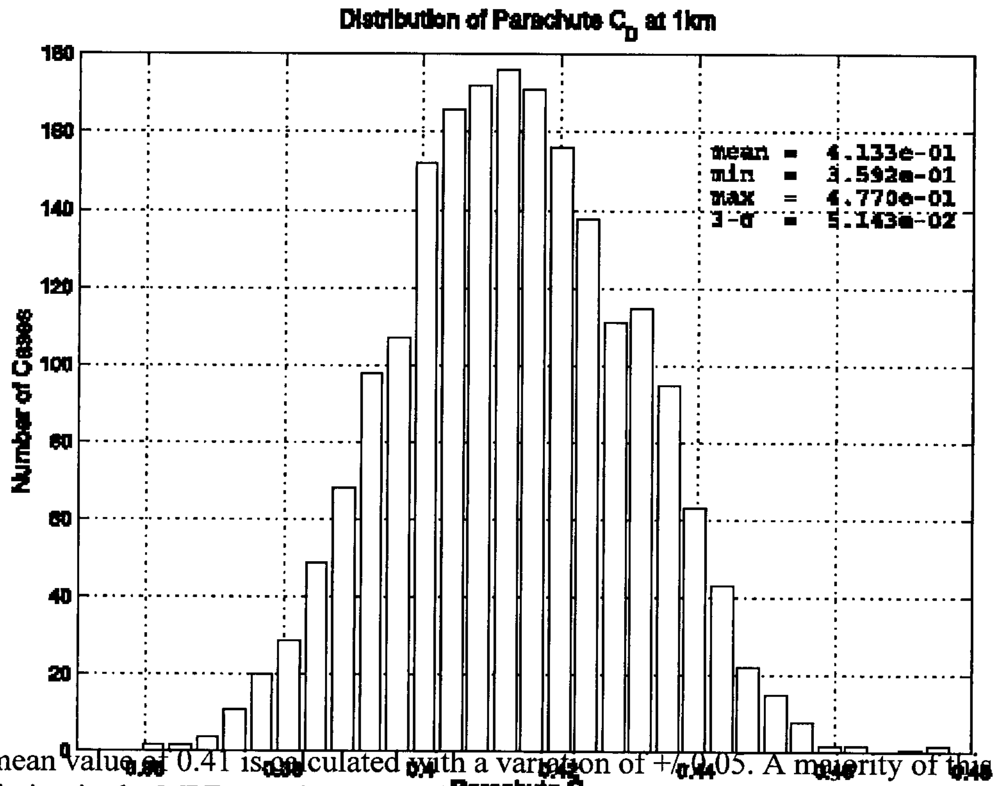
Based on the re-examination of all the parameters described, the MPF parachute C_D value is determined via a Monte Carlo analysis. The list of parameters included in the analysis are given below, along with their mean value and dispersion range:

Parameter	Mean	Distribution	Dispersion Range
m, kg	520.9	-	-
g, m/s^2	3.7245	-	-
Backshell area, m^2	5.39	-	-
Lander area, m^2	1.76	-	-
Parachute area, m^2	127.6	Gaussian	+/-5% (3-σ)
Vol, m^3	135	uniform	+/-20%
$C_{D_{B/S}}$	1.33	uniform	+/-5%
$C_{D_{La}}$	1.072	uniform	+/-5%
Temperature, K	221	uniform	+/-9
Surface Pressure, mbar	6.76	uniform	+/-0.15
v, m/s	65.5	Gaussian	+/-1.8 (3- σ)

The distribution in atmospheric density is shown below, where a variation of approximately +/- 6% is observed about the mean.



The resulting distribution in the MPF parachute C_D value is as follows:



A mean value of 0.41 is calculated with a variation of +/-0.05. A majority of this variation in the MPF parachute C_D value is due to the variation in the atmospheric density. The minimum value obtained for the MPF parachute C_D is 0.36. Note, in obtaining this revised prediction, conservative assumptions were utilized where appropriate.

Conclusions:

Based on the assumptions presented and re-examination of all the parameters (additional filtering of MPF radar altimeter data, revised atmospheric property estimates, and updated parachute area and Backshell and Lander C_D values), a revised mean MPF parachute C_D value of 0.41 is obtained with a proposed range of 0.36-0.46. A majority of this variation in the MPF parachute C_D value is due to the variation in the atmospheric density. In obtaining this revised prediction, conservative assumptions were utilized where appropriate.

The largest contributor to uncertainty in the MPF parachute C_D is uncertainty in density and the terminal velocity. Re-examination of the radar altimeter flight data allows for a better estimate on the terminal velocity and its uncertainty. In addition, re-examination of the atmospheric properties, supplemented by additional data, allows for a better estimate on the density and its uncertainty. Furthermore, the use of the Monte Carlo technique statistically allows for incorporation of uncertainties on all the parameters to better assess the variation on the MPF parachute C_D value. Consequently, with the refined, more consistent assumptions outlined in this investigation, the present calculation of the MPF parachute C_D value is an improvement over previous estimates.

After review of the assumptions of the present analysis, Dave Spencer of the Jet Propulsion Laboratory, who calculated the original estimate of the MPF parachute C_D value, endorses that the current estimate is an improvement beyond his previous prediction. Hence, due to the more rigorous and more thorough effort of the present investigation, the range in the value for the MPF parachute C_D defined by the present investigation is more appropriate than previous estimates.

Appendix: Density Estimation Procedure

In order to revise the Pathfinder C_D calculation for descent on the parachute, it is necessary to find the accurate density of the atmosphere at some level near the surface, where the Pathfinder Lander is falling at close to its terminal velocity. Density can be obtained from direct measurements, or can be inferred from measurements of pressure and temperature using Eqn (1) below.

The atmospheric density profile was derived from Pathfinder accelerometer measurements down to an altitude of just below 9 km, where the parachute deployed. Accurate measurements of surface pressure and temperature at 1 m were made immediately after landing, and at the same local time on subsequent days at the landing site. Unfortunately, no high quality temperature and pressure measurements were taken during parachute descent.

In our original approach, we attempted to calculate density at 300 m (altitude prior to airbag inflation) by extrapolating temperature and pressure from the known conditions at the surface. Pressure can be extrapolated fairly accurately using the hydrostatic equation (Eqn (2) & (3) below). To extrapolate temperature, we used results from the 1-D boundary layer model, calculated by Jim Murphy for Pathfinder conditions (Murphy, Personal Communication), and shifted by a few degrees to agree with the 201.5 K Pathfinder measurement at 1 m.

Models show that for the Pathfinder landing conditions (Ls = 143°, LTST = 03:00, Lat = 19.5° N, Lon = 33.5° W), atmospheric temperature should increase from a minimum at the surface to a maximum at roughly 1 km, before falling with increasing altitude. Dr. Richard Zurek pointed out that there was considerable uncertainty in the width of the inversion layer below 1 km, so that our temperature extrapolation to 300 m might be subject to significant error.

MGS obtained radio occultation temperature profiles near the Pathfinder season, local time, and location, but for the following Mars year. These profiles have a vertical resolution of 0.5-1.0 km, are accurate in the lower atmosphere, but do not extend completely to the surface. Four profiles supplied by David Hinson, selected within the bin Ls = 139.9°-141.4°, LTST = 04:11, Lat = 16.5°-20.9° N, Lon = 26.6°-42.8° W, are consistent with each other to a few K below 10 km and show near surface temperature peaks of 220 K near 1 km altitude.

The MGS radio-occultation data suggested a new approach. Densities calculated near 1 km (the atmospheric temperature peak) are less sensitive to vertical gradients, and can be based on reliable radio-occultation temperature measurements. The recommended density calculation is summarized below:

1. Derive $\rho(z)$ from P(z) and T(z) at 1 km, using Eqn (1) below.
2. Based on the occultation data, T(z) = 221 K +/- 3K (1-σ) at 1 km.
3. P(z) at 1 km is derived from Eqns (2) & (3) below.

Given: Ps = 6.76 +/- 0.05 mbar (1- σ) from Pathfinder (Eqn (2)).
T = 215 K in Eqn (3).

Note: T is the mean temperature from 0-1 km, which is probably weighted more towards the 1 km than the 1 m temperature because the surface temperature inversion is significantly narrower than 1 km. The consequences of this are not very significant in the pressure calculation.

From the ideal gas law, the density at altitude z km in the Martian atmosphere is given by the expression:

$$\rho(z) = [P(z)/P0] * [T0/T(z)] * [M/Vm] \quad (1)$$

where:
$\rho(z)$ is the density at altitude z in gm/cm^3
P(z) is the pressure at altitude z in mbars
T(z) is the temperature at altitude z in Kelvin
P0 = 1013.24 mbar (Standard Pressure)
T0 = 273.15 K (Standard Temperature)
M = 43.5 gm (Mean atmospheric molar weight)
Vm = 2.241e+4 cm^3 (Molar volume at STP)

Given P(z) and T(z) we can calculate density from Eqn (1).

T(z) at the level of interest must be specified. Provided z < 2 km, P(z) can be extrapolated from the surface using the expression:

$$P(z) = Ps * Exp(-z/H) \quad (2)$$

where:
Ps is Surface Pressure
H is the mean atmospheric pressure scale height in km

H is approximated by the expression:

$$H = RT/(Mg) \qquad (3)$$

where:

$R = 8.314$ J/K/Mole (The gas constant)
T = Mean temperature from 0-z km (need not be very accurate)
$M = 43.5$ gm (Mean molar weight as in Eqn (1))
$g = 3.717\ m/s^2$ (Acceleration due to gravity at surface)