EVALUATION OF THE MARS PATHFINDER PARACHUTE DRAG COEFFICIENT

Amanda M. Verges[1], Robert D. Braun[2]

[1] *Undergraduate Student, Georgia Institute of Technology, School of Aerospace Engineering, Atlanta, GA 30332-0150 USA, Email: averges@gatech.edu*

[2] *David and Andrew Lewis Professor of Space Technology, Georgia Institute of Technology, School of Aerospace Engineering, Atlanta, GA 30332-0150 USA, Email: robert.braun@aerospace.gatech.edu*

ABSTRACT

Flight reconstruction of the successful landing of the Mars Pathfinder (MPF) mission was performed after landing. During development of the Mars Exploration Rover mission, the MPF parachute drag coefficient was re-examined. Using radar altimeter data, it was determined that the MPF parachute drag coefficient was 0.4133 (based on the parachute's nominal area), with a 3-sigma uncertainty of 0.0514. This study assumed a quasi-steady state terminal descent, neglecting the effect of the parachute's continued deceleration. In the present study, the MPF parachute drag coefficient is evaluated using the same radar altimeter data but taking into account the fact that the MPF parachute continued to decelerate during its terminal descent. This deceleration is also evaluated from the radar altimeter data. The present investigation yields a drag coefficient of 0.4419, with a 3-sigma uncertainty of 0.0549. Taking into account the acceleration effect increases the reconstructed value of the drag coefficient by approximately 7 percent. The difference in drag coefficients determined from the two reconstructions is relatively large because the deceleration being experienced by the system at this time is approximately 0.240 m/s^2, a relatively significant value in comparison to the acceleration of gravity on Mars (3.7245 m/s^2).

NOMENCLATURE

$A_{B/S}$	backshell area
A_{Lan}	lander area
A_{Par}	parachute nominal area
$C_{D_{B/S}}$	backshell drag coefficient
$C_{D_{Lan}}$	lander drag coefficient
$C_{D_{Par}}$	parachute drag coefficient
F_B	buoyancy force
F_D	drag force
g	gravitational acceleration
h	height
m	mass of the system
ρ	atmospheric density
t	time
v	velocity
Vol	lander volume
W	weight

1. INTRODUCTION

Parachute drag coefficient is a key parameter in the performance of an entry, descent, and landing system and must be accurately understood in order to appropriately design and analyze such a system. Despite the successful landings of previous missions on Mars, it remains difficult to determine the drag coefficient of a Mars parachute because the exact operating conditions cannot be matched in tests on the Earth. Also, it is difficult to separate estimation of atmospheric density from parachute drag coefficient in reconstruction of Mars flight data.

Reconstruction of the Mars Pathfinder entry, descent and landing system performance was performed in [1]. A detailed reconstruction of the Mars Pathfinder parachute drag coefficient was performed in [2]. The Reference [2] reconstruction included the assumption of quasi-steady state motion ($\frac{dv}{dt}$ =0).

In the present study, the deceleration term is estimated and a more accurate value of the Mars Pathfinder parachute drag coefficient is determined. This study includes a re-assessment of the [2] reconstruction, a reconstruction that does not assume quasi-steady state motion, a comparison between these two approaches, and a comparison with estimates of the Mars Pathfinder parachute drag coefficient obtained through wind-tunnel testing and drop testing.

2. ANALYSIS

The Reference [2] analysis of the Mars Pathfinder (MPF) parachute drag coefficient ($C_{D_{Par}}$) was recreated in order to assess the assumptions made and to provide a baseline for the present analysis.

2.1 Quasi-Steady State Equation of Motion

In the $C_{D_{Par}}$ reconstruction performed at NASA Langley Research Center and Jet Propulsion Lab [2], the equation of motion given in Eq. 1 was evaluated at the terminal descent condition (Fig. 1) at 1000 m above the surface. At the terminal descent condition, the sum of the vehicle drag force and the buoyancy force were assumed to be equal to the weight of the vehicle (i.e., the acceleration term given in Eq. 2 was assumed to be zero). Additional implicit assumptions in the [2] analysis include vertical descent and flight of a non-gliding parachute.

$$F_D + F_B - W = m\frac{d^2h}{dt^2} = 0 \quad (1)$$

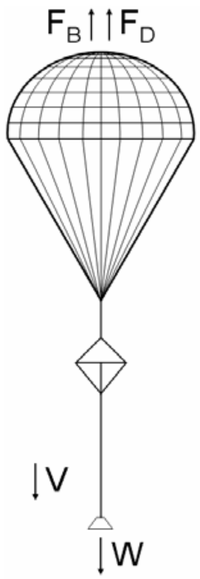

Fig. 1. Terminal descent configuration

$$a = -\frac{dv}{dt} = \frac{d^2h}{dt^2}$$
$$v = -\frac{dh}{dt} \quad (2)$$

The terms in Eq. 1 are further defined for the drag force (Eq. 3), the buoyancy force (Eq. 4), and the vehicle weight (Eq. 5).

$$F_D = \frac{1}{2}\rho v^2 (C_{D_{Par}} A_{Par} + C_{D_{B/S}} A_{B/S} + C_{D_{Lan}} A_{Lan}) \quad (3)$$

$$F_B = \rho g Vol \quad (4)$$

$$W = mg \quad (5)$$

Rearrangement of Eq. 1 and substitution from Eqs. 3-5 yields an equation for $C_{D_{Par}}$ as shown in Eq. 6 under assumption of quasi-steady state motion.

$$C_{D_{Par}} = \frac{2(mg - \rho g Vol)}{(\rho v^2 A_{Par})} - \frac{C_{D_{B/S}} A_{B/S} + C_{D_{Lan}} A_{Lan}}{A_{Par}} \quad (6)$$

2.2 Input Variables

To solve Eq. 6, knowledge of numerous vehicle and environmental parameters must be estimated. Some of these parameter were measured for the MPF system and are known precisely; whereas, others can only be estimated and considerably uncertainty remains. As such, a deterministic reconstruction of the MPF drag coefficient can not be obtained; however, a statistical distribution of the reconstructed MPF drag coefficient can be estimated. The best estimate of these parameters and their uncertainty is described in [2], and will not be repeated herein. In this investigation, the same best estimate and uncertainty in these parameters is assumed. The parameters, mean values, distribution type, and uncertainty range are listed in Table 1 for completeness.

Table 1. The input variables for the $C_{D_{Par}}$

Parameter	Mean	Distribution	Uncertainty Range
m, kg	520.9	--	--
g, m/s^2	3.7245	--	--
$A_{B/S}$, m^2	5.39	--	--
A_{Lan}, m^2	1.76	--	--
A_{Par}, m^2	127.6	Gaussian	5% (3-σ)
Vol, m^3	135	Uniform	20%
$C_{DB/S}$	1.33	Uniform	5%
C_{DLan}	1.072	Uniform	5%
Temp., K	221	Uniform	9
S. Press., mbar	6.76	Uniform	0.15
v, m/s	65.5	Gaussian	1.8 (3-σ)

2.3 Quasi-Steady State Estimation of MPF Drag Coefficient

Using the specified distributions for each parameter, a Monte Carlo analysis of 1000 random samples was conducted to determine the mean and standard deviation of $C_{D_{Par}}$. This Monte Carlo analysis agrees quite well with [2] result, as shown in Table 2. The distribution of $C_{D_{Par}}$ values for the Monte Carlo analysis is shown in Figure 2.

Table 2. The Statistical $C_{D_{Par}}$ Values for [2] and Current Quasi-Steady State Monte Carlo Analyses

Value	Original Quasi-Steady State Estimate	Present Quasi-Steady State Estimate	% Difference
Mean	0.4133	0.4108	0.61
3-σ	0.0514	0.0515	0.18

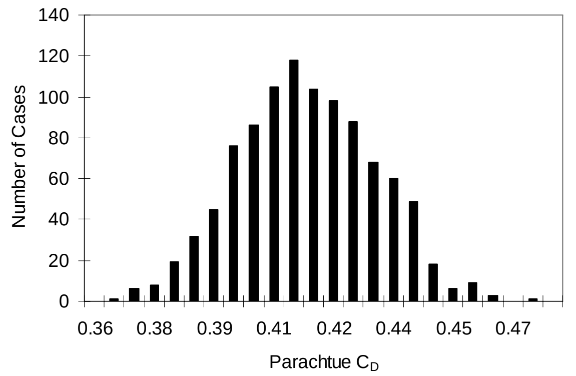

Fig. 2. Distribution of Reconstructed MPF $C_{D_{Par}}$ Values Assuming Quasi-Steady State Terminal Descent

2.4. Acceleration Term

Reference [2] assumed equilibrium of forces during terminal descent. However, due to the thin atmosphere of Mars, this assumption may not be sufficiently accurate. In order to assess the impact of the acceleration term on the $C_{D_{Par}}$, Eq. 1 is solved without the quasi-steady state terminal velocity assumption, as shown in Eq. 7.

$$F_D + F_B - W = m\frac{d^2h}{dt^2} \neq 0 \qquad (7)$$

From Eq. 7, it follows that $C_{D_{Par}}$ may be estimated, including the acceleration term, as shown in Eq. 8.

$$C_{D_{Par}} = \frac{2(m\frac{d^2h}{dt^2} + mg - \rho g Vol)}{(\rho v^2 A_{Par})} - \frac{C_{D_{B/S}} A_{B/S} + C_{D_{Lan}} A_{Lan}}{A_{Par}} \qquad (8)$$

The MPF radar altimeter data, taken at a sampling rate of 8 Hz, was analyzed to find the acceleration (Fig. 3). The data was analyzed for ±5 seconds around the 1000 m altitude point (284.83 s), since this is the altitude used in the density calculations of [2].

Although the assumption of zero acceleration appears to fit the altimeter data at first glance, a closer look at the data shows that the altitude-time profile is not linear in shape, i.e., this data has a non-zero second derivative (acceleration term).

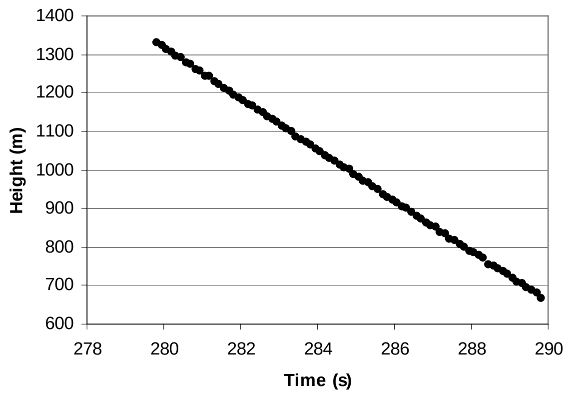

Fig. 3. MPF altimeter data: height as a function of time

The height data was fit with three polynomials: a quadratic fit (Eq. 9), a cubic fit (Eq. 10), and a fourth order fit (Eq. 11).

$$h = 0.11994t^2 - 134.42t + 29553 \qquad (9)$$

$$h = 0.00793393t^3 - 6.65954017t^2 + 1796t - 153749 \qquad (10)$$

$$h = 0.00793393t^3 - 6.65954017t^2 + 1796t - 153749 \qquad (11)$$

Differentiating the equation for h(t) twice, and evaluating it at 284.83 s (1000.7 m), results in the following accelerations: 0.23988 m/s^2 (quadratic) and 0.23985 m/s^2 (cubic and fourth order). Each of these curve fits yield essentially the same acceleration: 0.240 m/s^2. This is the value that is used in the refined evaluation of the drag coefficient.

2.5 Estimation of MPF Drag Coefficient Including the Acceleration Term

The acceleration term was included in the 1000-case Monte Carlo analysis and compared to the quasi-steady state estimation with respect to mean and standard deviation values (Table 4). The distribution of $C_{D_{Par}}$ values for this Monte Carlo analysis is shown in Figure 4.

Table 4. The Effects of Including the Non-Zero Acceleration Term on Estimation of the MPF Parachute C_D

Value	Quasi-Steady State Estimate	Non-Zero Acceleration Estimate	% Diff.
Mean	0.4108	0.4419	7.04
3-σ	0.0515	0.0549	6.12

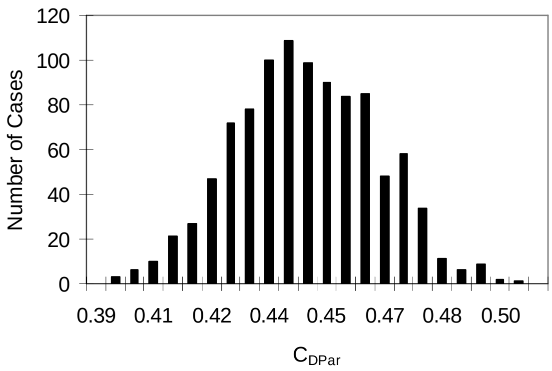

Fig. 4. Distribution of Reconstructed MPF $C_{D_{Par}}$ Including the Acceleration Term.

Inclusion of the acceleration term increases the mean $C_{D_{Par}}$ by approximately 7% over the quasi-steady state estimation. This demonstrates the importance of including this term in reconstruction of $C_{D_{Par}}$ for EDL analysis.

It is of historical interest to note that a $C_{D_{Par}}$ of 0.5 was used in all Mars Pathfinder pre-flight and operations engineering analysis [3]. While this value is statistically possible, it is unlikely that such a high drag coefficient was achieved by the MPF flight system in flight on Mars.

3. COMPARISON WITH PREVIOUS DATA

The best estimate of $C_{D_{Par}}$ from this investigation was also compared to estimates derived by other techniques (Table 5). In the Earth-based aerial drop-test reconstruction performed by Witkowski [4], $C_{D_{Par}}$ was calculated to be 0.43. Note that in an Earth drop test, the system descends slower than it would on Mars due mainly to atmospheric density differences between the two planets. This makes the acceleration term smaller so the effect of the acceleration term on the $C_{D_{Par}}$ reconstruction is small. As a result, one would expect a drag coefficient derived from this test to be bounded by the two Mars reconstruction estimates calculated in the present investigation (between the estimate which assumes quasi-steady state motion and the estimate which includes the non-zero acceleration term). It should be noted that the accuracy of the drop test instrumentation, atmospheric motion and fabric permeability differences could also affect this drag coefficient comparison. Given this uncertainty, the results from the present reconstruction and the aerial drop test can be viewed as a consistent data set.

In wind tunnel tests of sub-scale disk-gap band parachutes [5], a mean $C_{D_{Par}}$ of 0.405 was estimated at the relevant Mach number to that achieved by the MPF system at 1000 m. While matching Mach number, corrections to the wind-tunnel data were applied due to the higher dynamic and absolute pressure environment experienced in the tunnel relative to that reconstructed for the MPF EDL. The mean reconstructed value calculated in the present analysis, that includes the acceleration term (0.442), is within the uncertainty range estimated by the wind-tunnel testing. Given the wind tunnel model scale, and uncertainty in fabric permeability effects, differences between the wind tunnel tests and the flight system are not surprising. In fact, the results from the present reconstruction and the wind tunnel test can be viewed as a consistent data set.

Table 5. $C_{D_{Par}}$ estimate with acceleration compared to previous results

	C_{DPar}	% Difference
Estimate with Non-Zero Acceleration	0.4419 ± 0.024	---
Aerial Drop Test	0.43	2.69
Wind Tunnel Test	0.405 ± 0.023	8.35

To summarize, based on consideration of multiple estimates of the Mars Pathfinder parachute drag coefficient, it is felt that the present reconstruction, inclusive of the acceleration term, provides the best estimate of the Mars Pathfinder parachute flight system drag coefficient as 0.442 ± 5.49% (3-σ).

4. REFERENCES

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