Statistical Entry, Descent and Landing Performance Reconstruction of the Mars Phoenix Lander

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OVERVIEW

The Phoenix Lander successfully landed on the surface of Mars on May 25, 2008. During entry, descent and landing (EDL), the vehicle had instruments on-board that took sensed acceleration, angular rates and altimeter measurements. The inertial measurements were used to create a deterministic estimate of the flight trajectory at that time.[1,2] This study, however, will demonstrate a statistically-based methodology to reconstruct the trajectory and other EDL performance information while utilizing all of the observations from the on-board sensors. Additionally, the methodology not only reconstructs the EDL parameters, but also the uncertainties in the estimate.

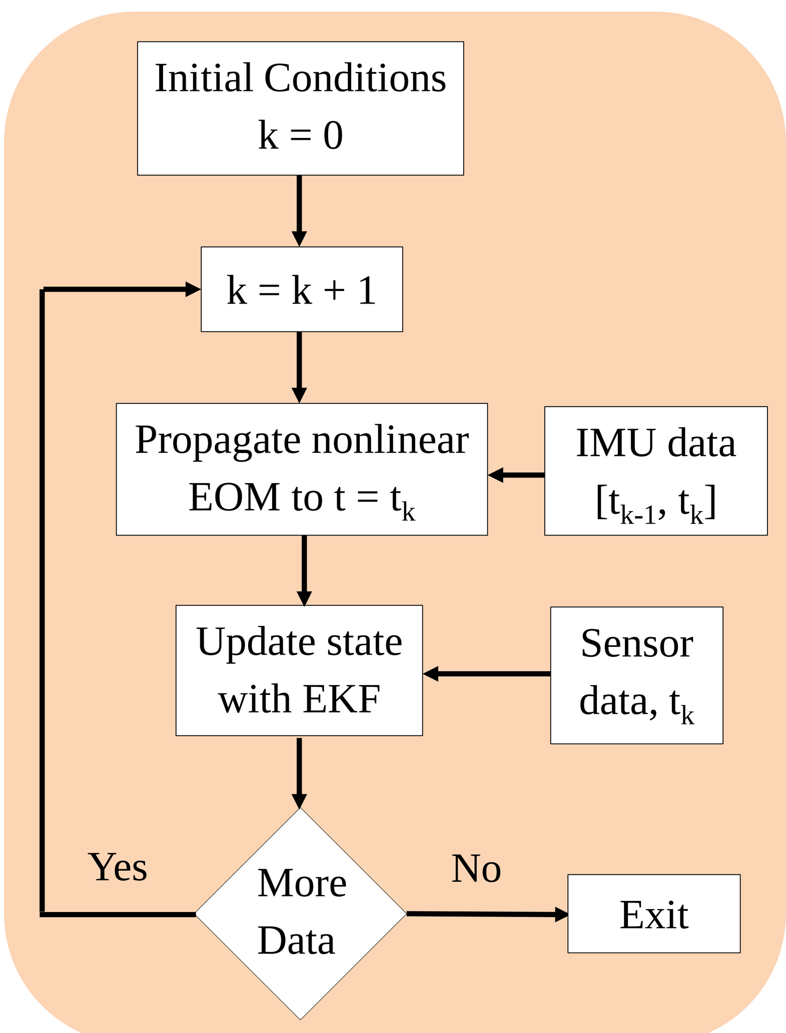
METHODOLOGY

The process of analyzing Phoenix's EDL dataset consisted of three estimation steps

1. Estimation of the flight trajectory
2. Atmosphere reconstruction
3. Parachute performance analysis

Statistical estimation process

The statistical process used is an Extended Kalman filter (EKF) and it processes signals from the sensors to update the estimate of the state vector of interest. For EDL trajectory reconstruction, the state variables are position, velocity and attitude states.



This state estimate is affected by the uncertainty in the process (in this case this includes the uncertainty in the IMU data) and sensor data.

Direction of data processing

The data from the on-board sensors can be processed in two directions:

1. Forward run: Atmospheric entry to the ground
2. Backward run: Ground up to the top of the atmosphere

The forward pass starts its estimate from an initial state and covariance that is usually provided by means independent of the trajectory reconstruction process. Also, the forward run is conducted in a chronological manner. The backwards run has the advantage of starting at a smaller uncertainty value as it begins from the end of the forward estimate. For this reconstruction, both methods were used and a Fraser-Potter smoothing algorithm is used to reconcile the two estimates.

Entry states and uncertainties[2, 3]

State	Values	3σ Uncertainty
Radius (km)	3522	0.0075
Declination (deg)	69.36	0.001
Longitude (deg)	197.7	0.002
Inertial velocity (km/s)	5.6	0.000439
Flight path angle (deg)	-13.01	0.0003
Azimuth angle (deg)	77.7	0.007

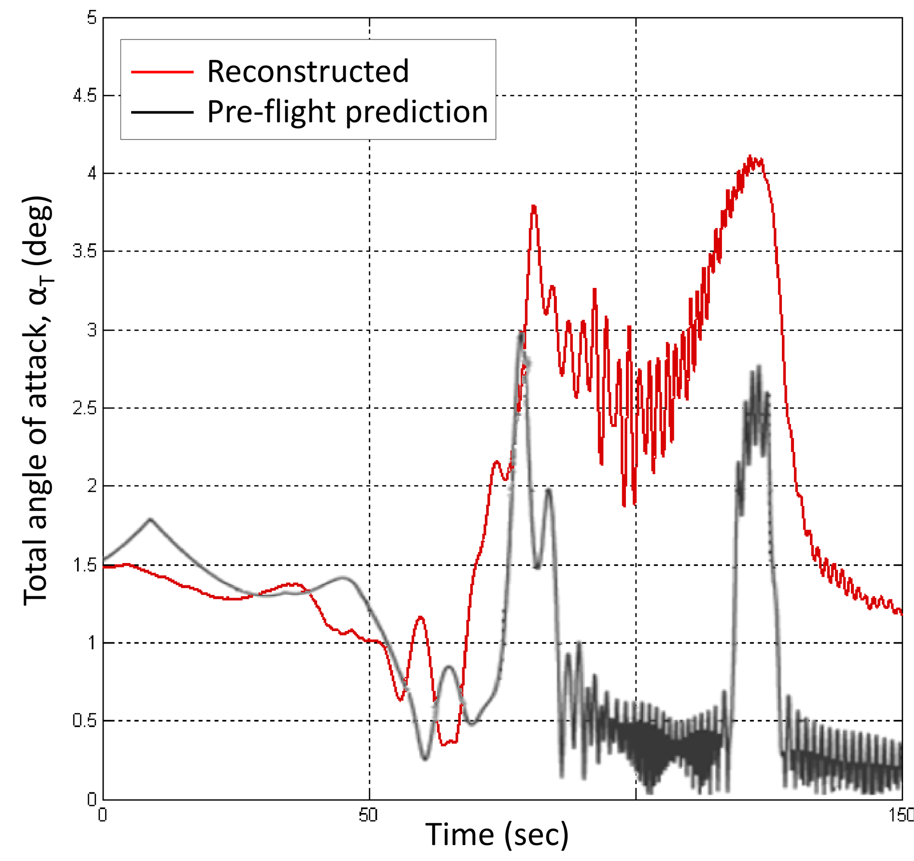
TRAJECTORY RECONSTRUCTION

Events timeline and other metrics

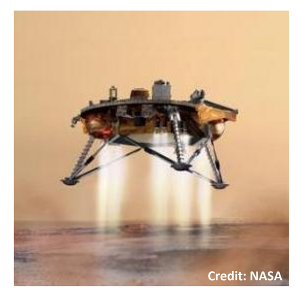
Metric	Pre-Flight[1]	Desai et al.[1]	EKF	EKF Uncer. 3σ
Peak Deceleration (g)	9.3	8.5	8.52	
Parachute deployment time from entry (sec)	219.9	227.8	227.9	
Height at parachute deployment (AGL km)	12.7	13.3	13.1	0.714
Relative velocity (m/s)	368.3	387.6	395.6	12.4
Height at heatshield jettison (AGL km)	11.1	11.6	10.9	0.84
Height at lander leg deployment (AGL km)	10.2	10.9	10.6	0.842
Lander separation time from entry (sec)	392.3	404.9	405	
Height at lander separation (AGL m)	982	925	951	64
Height at pitch-up (AGL m)	952	897	859	63.6
Height at gravity turn (AGL m)	806	720	748	62.7
Height at constant velocity start (AGL m)	51.9	52.1	52.5	6.16
Landing time from entry (sec)	436.2	446.1	446	
Relative velocity (m/s)	2.16	2.38	2.96	9.17

Note: AGL = above ground level

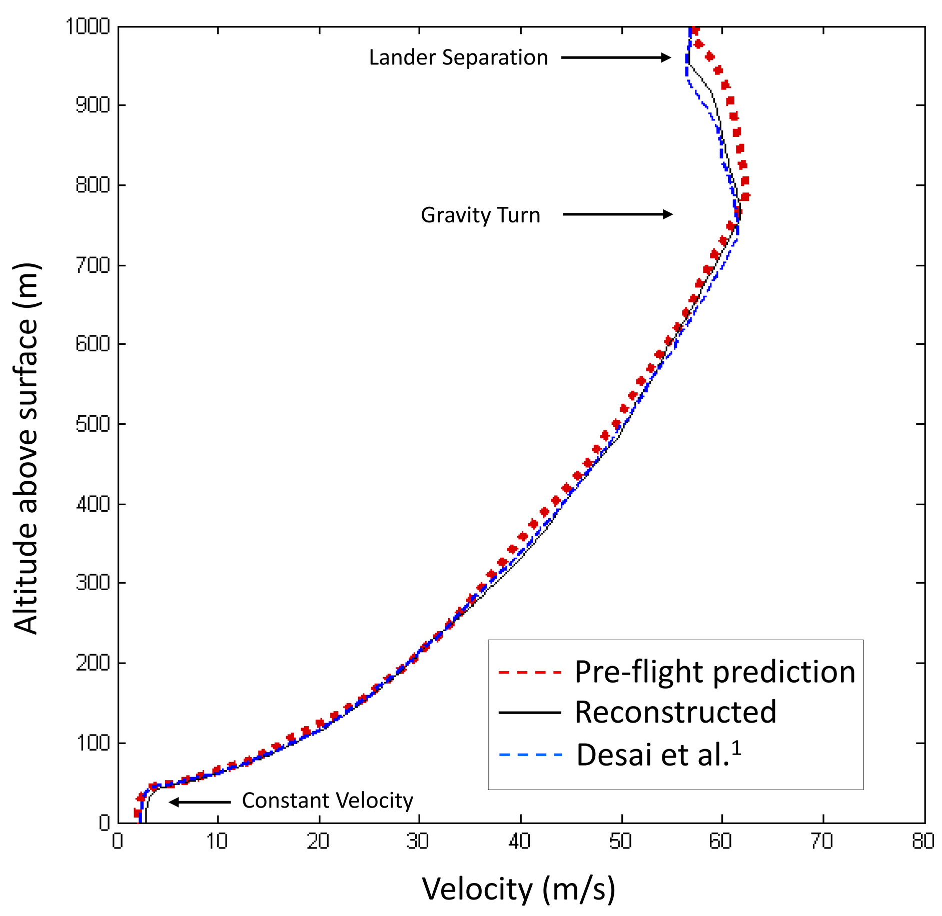
The discrepancy between the reconstructed trajectory and pre-flight prediction can be explained by a higher than expected total angle of attack of the vehicle in the hypersonic regime.

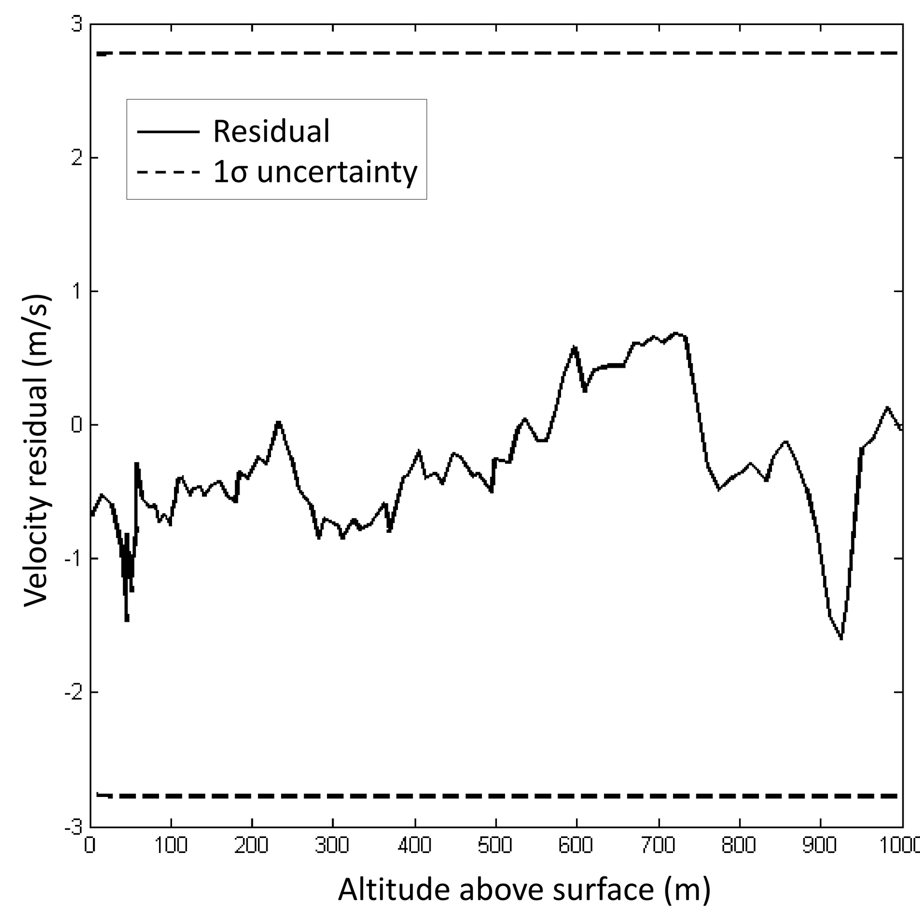


Terminal descent and landing



The EKF-based reconstruction gave the final landing site for the vehicle at 68.9° N ± 1.23x10-5 deg. (1σ) and 234.2° E ± 5.08x10-5 deg. (1σ).

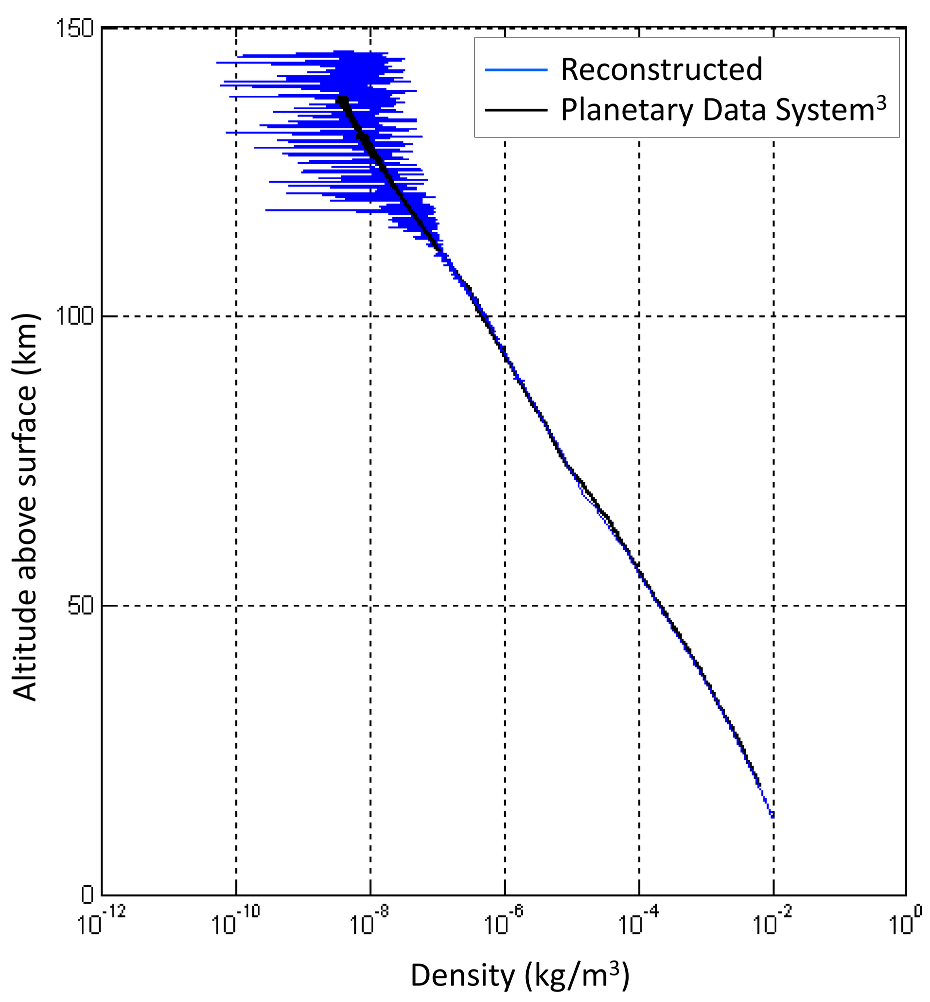


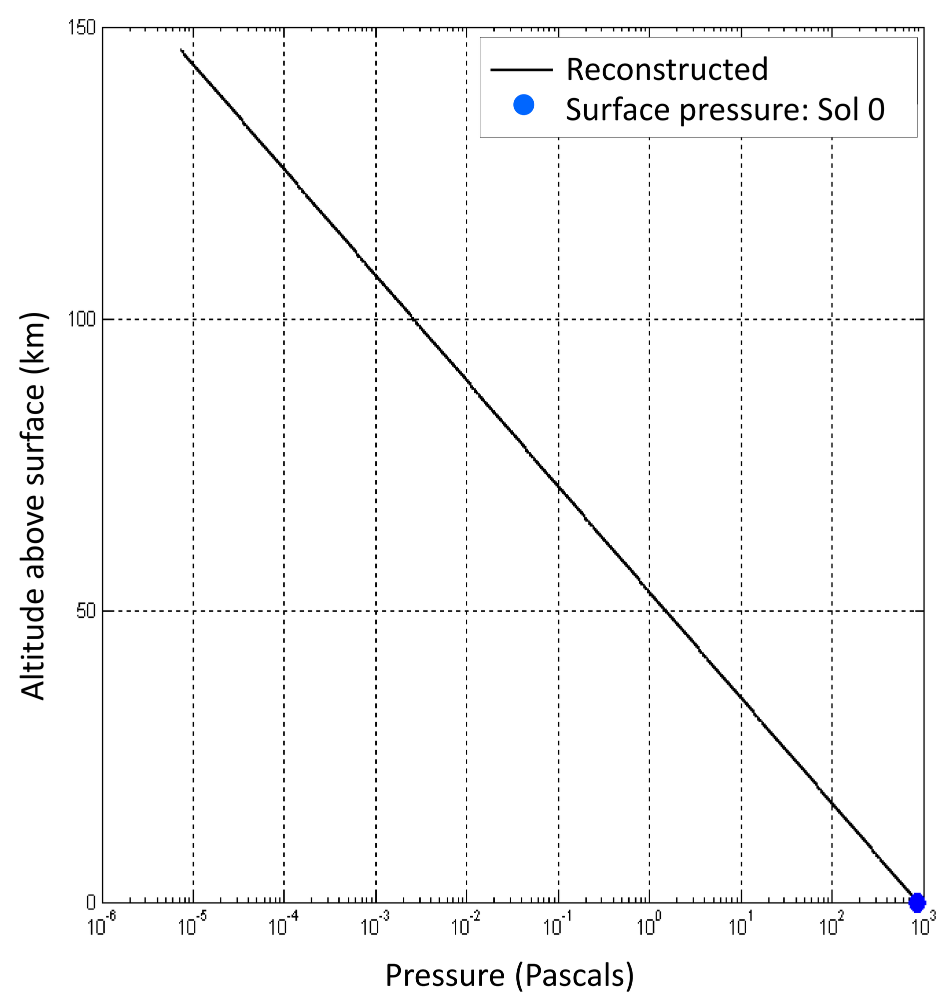


ATMOSPHERE RECONSTRUCTION

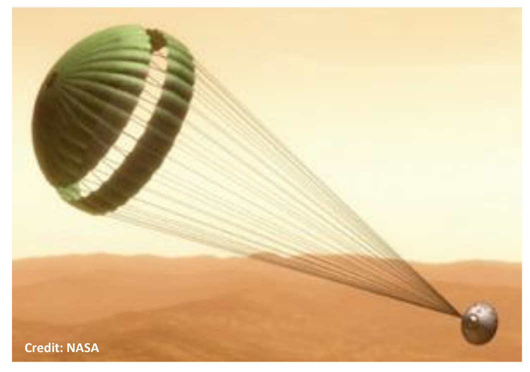
The freestream density, pressure and temperature, have been reconstructed for Phoenix. Acceleration measurements in the axial direction (a_x) are used to estimate density (ρ_∞) by having knowledge of the axial force coefficient (C_A) of the vehicle and an estimate of the vehicle's freestream velocity (V_∞). However, uncertainties in the aerodynamics cannot be separated from atmospheric uncertainties, as one assumes a perfect knowledge of the aerodynamic characteristics. Pressure is reconstructed using the hydrostatic equation. Surface atmospheric measurements taken by Phoenix's meteorological equipment shortly after landing is used for the reconstruction of freestream pressure (P_∞). The equation has to be integrated from a reference pressure value. Using an arbitrary low value of pressure at the top of the atmosphere can lead to a bias error. Thus, the surface pressure measurement serves as the integration constant. The temperature, if needed, can be estimated by the perfect gas law.

$$\rho_\infty = \frac{2ma_x}{C_A V_\infty^2 S} \qquad \frac{dP_\infty}{dh} = -\rho_\infty g$$





PARACHUTE PERFORMANCE



The vehicle drag coefficient (C_D) after parachute deployment and before lander separation is a combination of the parachute drag (C_{D0}) and drag from the entry body (C_{Dbody}). The drag coefficient reference area (S) during parachute deployment is based on the parachute reference length of 11.8 m, while the reference area for the lander/aeroshell body (S_{body}) changes with if the heatshield is attached to the lander or not.

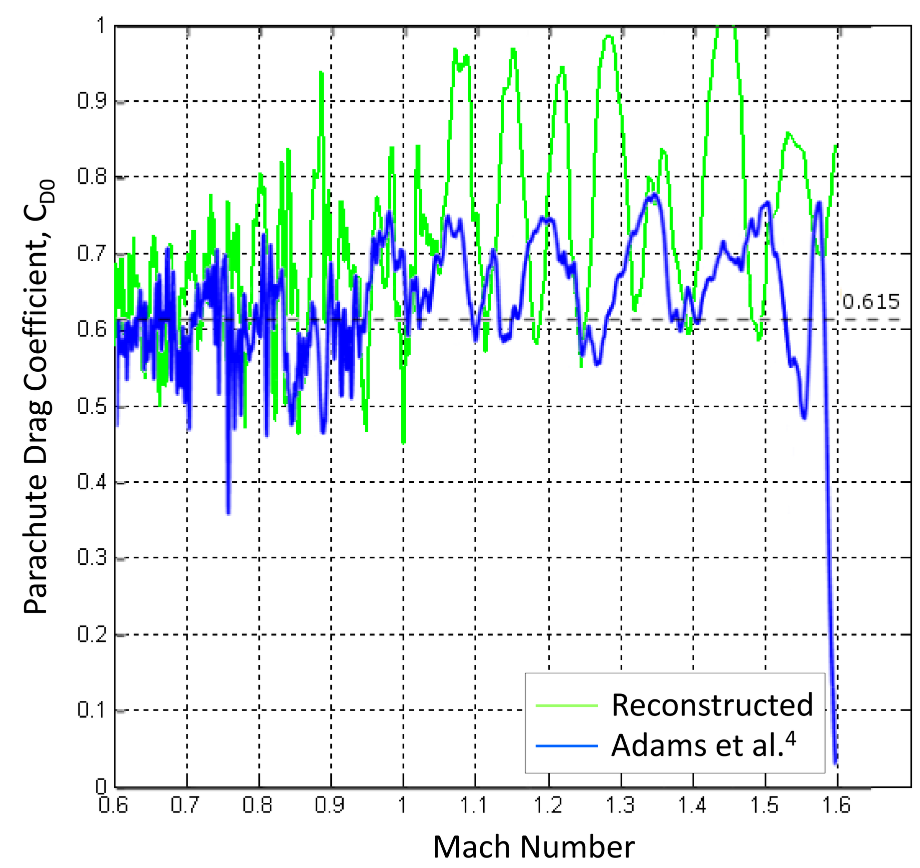
$$C_{D0} = \frac{C_D S - C_{Dbody} S_{body}}{S}$$

The sensed acceleration measurements is used to find C_D using the definition of the drag coefficient, but there exists some ambiguity about what value to use for freestream density. Two approaches are:

1. Exponential atmospheric based regression
2. Set of differential equations based on the hydrostatic equation and the perfect gas law

$$\dot{P}_\infty = \rho_\infty g w \qquad \dot{\rho}_\infty = \frac{\rho_\infty^2 g w}{P_\infty}$$

With the drag coefficient definition, there are three equations for three unknowns (C_D, ρ_∞ and P_∞). This approach is used here.



CONCLUSIONS

A statistically based methodology to reconstruct the trajectory, atmosphere and aerodynamic characteristics of a Mars EDL vehicle is presented and the process is demonstrated using the Phoenix lander dataset. Results compared well with independent efforts in the literature, but had the added benefit of quantifying the uncertainties of these estimates. The reconstruction methodology shows promise and can be matured to reconstruct EDL system performance for future missions and potentially enhance current system design tools.

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