STATISTICAL ENTRY, DESCENT AND LANDING PERFORMANCE RECONSTRUCTION OF THE MARS PHOENIX LANDER

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ABSTRACT

The Phoenix Lander successfully landed on the surface of Mars on May 25, 2008. During the entry, descent and landing (EDL), the vehicle had instruments on-board that took sensed acceleration, angular rates and altimeter measurements. In this study, methodology used to reconstruct the trajectory and other EDL performance information using a statistical filter to process the observations from the sensors is demonstrated. A statistical filter estimates parameters simultaneously with the uncertainty in the estimates. The results presented here will include Phoenix's event timeline, trajectory information, time-of-flight atmosphere and aerodynamic coefficients of an EDL subsystem as well as the uncertainty in the estimated states.

1. INTRODUCTION

Phoenix became the first successful powered lander on the surface of the Mars since the original Viking missions from the 1970s. The entry, descent and landing (EDL) system safely delivered the lander to the surface and the vehicle then safely operated in the Martian Northern hemisphere from June to November 2008. However, the final landing site for the vehicle was about 22 km away from its final pre-flight landing site [1]. Thus, an analysis of the flight data was necessary to understand the cause for the discrepancy. Additionally, post-flight reconstruction of the flight data is useful to glean other important information about the vehicle and its subsystem performance. Such information can improve the design of future missions by improving the fidelity of current design tools.

Although Phoenix's trajectory has been reconstructed in the past [1, 2], this reconstruction differs from past efforts due to the current use of stochastic estimation techniques to blend the different EDL data types. Previous studies have generally integrated the data from the accelerometer and gyroscope to estimate the vehicle's velocity and position. Such reconstruction efforts have been deterministic in nature and have not utilized the knowledge of the entry state uncertainties and uncertainty in the measurement data within the reconstruction algorithm. The estimation algorithm used in this study will utilize an Extended Kalman filter (EKF), which is adept at reconstructing states and their uncertainties from measurements. The stochastic nature of the reconstruction uses the inherent uncertainty in the measurement sensor data and propagates these values to quantify the uncertainties associated with the estimated trajectory parameters. The results of this reconstruction can thus provide a statistically based range of parameters to describe the flight trajectory.

Moreover, this study will analyze factors that affect the performance of the vehicle, such as the atmospheric parameters observed by the vehicle. Freestream density, pressure and temperature are reconstructed from the EKF results. These parameters then are compared with results in the literature [3]. Such reconstructions can mature current atmospheric modeling tools by providing verification cases and uncertainty data. Additionally, performance analysis can be conducted for Phoenix's subsystems from the results of the trajectory and atmosphere reconstruction. This analysis will demonstrate this capability by analyzing aerodynamic coefficients for the supersonic, disk-gap band parachute, especially during the parachute deployment phase. The flight dynamics during this phase is highly oscillatory and there is some uncertainty in the aerodynamic coefficients for this regime. The reconstructed parameters are compared with data from literature [4].

2. METHODOLOGY

The methodology for analyzing Phoenix's EDL dataset consists of three types of estimation procedures. First, a statistical filter, in this case EKF, is used to process simultaneously all sensor data to create an estimate of the vehicle's trajectory from entry to touchdown. Next, the atmospheric parameters, such as density and pressure, are estimated from the reconstructed trajectory and knowledge of the aerodynamic database. Finally, the aerodynamic performance of an EDL subsystem, specifically the disk-gap-band parachute, is reconstructed.

2.1 Statistical filtering and trajectory estimation

EKF is a statistical procedure that processes signals from sensors to update the estimate of the state vector of interest. Moreover, the filter assumes that the measurements and the state variables can be described as a Gaussian distribution. In the case of EDL performance reconstruction, the state variables are trajectory variables in the form of position, velocity and attitude states. The measurements in the Phoenix EDL dataset consist of inertial measurement unit (IMU) data from accelerometer and gyroscope and information from the on-board radar altimeter. Fig. 1 describes the process.

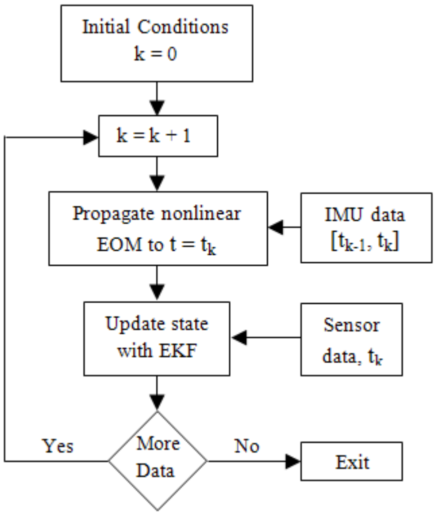

Fig. 1. Flow diagram of the statistical EDL parameter reconstruction process.

The EKF propagates the state variable simultaneously with the state uncertainty. This state estimate is affected by the uncertainty in the process (which consists of the uncertainty in the IMU data) and the uncertainty in the sensor data. The reader can find a detailed description of how the EKF was applied to an EDL dataset in Dutta et al. [5].

Additionally, it should be noted that the filter can process the sensor measurements from atmospheric entry down to the ground (forward run) or from the ground up to the top of the atmosphere (backward run). The forward pass starts its estimate from an initial state and covariance is usually provided by means independent of the EDL trajectory reconstruction process. Usually, this independent means consists of the final orbital determination and navigation result of the spacecraft prior to atmospheric entry. In addition, the forward run is conducted in a chronological manner in the order the events actually occurred. 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 are used and a Fraser-Potter smoothing algorithm is used to reconcile the two estimates.

In addition, other statistical estimation techniques can improve the estimate of the uncertainties. Previous studies have shown that the EKF is able to estimate the state variables reasonably well, but the estimate of the uncertainties can be improved using higher order filters such as the Unscented Kalman filter (UKF) or second order Kalman filters (SOKF) [6]. The estimation algorithm shown in Fig. 1 would have to be modified to use the higher order filters. The current analysis will be extended in the future to utilize the capabilities of filters like the UKF and SOKF.

2.2 Atmospheric reconstruction

Atmospheric parameters, such as freestream density, pressure and temperature, can be reconstructed for Phoenix's EDL trajectory. The dataset used in the atmospheric reconstruction is the sensed acceleration measurements in the axial direction (a_x). Freestream density (ρ_∞) is estimated from this dataset by having knowledge of the aerodynamic characteristics of the vehicle and an estimate of the vehicle's freestream velocity (V_∞). The axial force coefficient (C_A) then is used to calculate the freestream density as seen in Eq. 1. However, uncertainties in the aerodynamics cannot be separated from the atmospheric uncertainties, since one usually assumes a perfect knowledge of the aerodynamic characteristics to use Eq. 1. This shortcoming can be overcome when static pressure data from the aeroshell can be blended with other EDL sensor data during reconstruction. See Dutta et al. [5] for a description of such atmosphere reconstruction. On-board pressure data was not available for Phoenix; thus, atmosphere estimation is restricted to using Eq. 1.

$$\rho_\infty = \frac{2ma_x}{C_A V_\infty^2 S} \qquad (1)$$

However, the upcoming Mars Science Laboratory mission will have pressure measurement instruments on its aeroshell that will allow direct measurement of the freestream pressure [7]; thus, atmospheric parameters can be reconstructed without the assumption of perfect knowledge of the aerodynamics.

As described later in the results section, the density reconstruction using knowledge from the aerodynamic database is normally done for the flight regime before parachute deployment. There is usually more uncertainty in the aerodynamic parameters once the vehicle has deployed a parachute. Thus, the density after parachute deployment is estimated using some form of an exponential atmosphere expression where the constants are set using either the surface measurements or a regression fit of the reconstructed density prior to the parachute deployment.

Additionally, Phoenix made atmospheric measurements shortly after it landed using meteorological station equipment on-board the lander [8]. Although these measurements do not exactly correspond with the timeline of the EDL events and measurements, these independent density, temperature and pressure measurements can be used to compare the estimated atmospheric values at the surface.

Moreover, the independent atmospheric measurements are crucial for the reconstruction of freestream pressure (P_∞) and temperature (T_∞). Pressure is reconstructed using the hydrostatic equation as shown in Eq. 2. However, 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 [9]. Thus, a surface pressure measurement (e.g. from the lander's meteorological station shortly after landing) can serve as the integration constant. The temperature, if needed, can then be reconstructed using the perfect gas law. For the temperature calculations, the gas constant can be held constant without affecting the results tremendously as seen in Withers et al. [9]. Note that the hydrostatic equation and perfect gas law is valid in the continuum region of the atmosphere that might not be applicable for high altitudes, especially for Mars where the atmosphere is thin.

$$\frac{dP_\infty}{dh} = -\rho_\infty g \tag{2}$$

2.3 Parachute performance analysis

The drag coefficient for the vehicle (C_D) after parachute deployment and before lander separation is a combination of the drag from the parachute (traditionally referred as C_{D0}) and drag from the entry body itself (C_{Dbody}). Prior to heatshield jettison, the drag from the body can be safely assumed to be the drag value coefficient from the aerodynamic database (such as the one provided in [10]). However, after the heatshield jettison, the drag from the body is not the same as the values from the aerodynamic database that assumes that the body has the geometry of a 70-degree spherecone. Nevertheless, Blanchard [2] provides a drag coefficient value of 1.1 for the body after leg deployment and prior to lander separation.

It can be argued that C_{Dbody} can also be made part of the estimation process along with C_{D0} so that one would not have to deal with the ambiguity of what value to use for the body drag coefficient. However, note that there is only one set of sensor measurements (in this case the sensed acceleration) that is being used to estimate the drag coefficient. One set of measurements cannot estimate two unknown drag coefficients simultaneously. This is similar to the estimation process for density using Eq. 1, where the aerodynamic coefficient was assumed to be known. Since there is more uncertainty in the value of the parachute drag coefficient and C_{D0} has a larger influence on the overall vehicle dynamics than C_{Dbody} while the parachute is deployed, C_{Dbody} is assumed to be known in order to estimate the value for C_{D0}.

The reference area for the drag coefficient (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 depending on the fact if the heatshield is attached to the lander or not. Blanchard provides a summary of the reference lengths and areas [2]. Based on the above description, the drag coefficient of the parachute can be calculated as shown in Eq. 3.

$$C_{D0} = \frac{C_D S - C_{Dbody} S_{body}}{S} \tag{3}$$

In Eq. 3, the vehicle drag coefficient is calculated from the sensed acceleration measurements and the definition of the drag coefficient. Within the definition of the drag coefficient expression, there exists some ambiguity about what value to use for the freestream density. Freestream density cannot be calculated in this region using simply Eq. 1 since the axial force coefficient is unknown. One could use an exponential atmospheric relation (as described in the previous section).

Additionally, since one can get a good estimate of the density (and hence pressure) just prior to parachute deployment or on the Martian surface (through independent measurements), a set of differential equations in time (Eqs. 4) is used to estimate values for freestream density and pressure as a function of time. Eqs. 4 combined with the drag coefficient definition yield three equations for three unknowns (C_D, ρ_∞ and P_∞). Eqs. 4 is integrated in time using values from the trajectory reconstruction. Next, the vehicle drag coefficient is calculated at each time step using the propagated freestream density from Eq. 4b, the sensed acceleration from the IMU measurements and the freestream velocity from the trajectory reconstruction. Finally, C_D, ρ_∞ and P_∞ is used with Eq. 3 to solve for C_{D0}. Dutta et al. [5] shows the derivation of Eqs. 4 in which g is the local gravitational acceleration and w is the downward velocity.

$$\dot{P}_\infty = \rho_\infty g w \tag{4a}$$

$$\dot{\rho}_\infty = \frac{\rho_\infty^2 g w}{P_\infty} \tag{4b}$$

3. RESULTS

Phoenix telemetry data was provided to the authors by NASA. The IMU data was provided in the form of ΔV and Δθ in three axes as a function of time. Since the reconstruction algorithm described earlier requires acceleration and angular rate information, numerical methods were used to convert ΔV and Δθ. Blanchard describes the process in detail [2]. It should be noted that unlike Blanchard, no filtering methods were applied to smooth the IMU data. Since the EKF itself is a filter, the algorithm can handle the numerical noise associated with the conversion process internally.

The initial conditions and the uncertainties for the trajectory state variables are shown in Table 1. These values are found from the final prediction of the spacecraft's navigation and orbit determination process before atmospheric entry [2, 3].

Table 1. Initial states and uncertainties [2, 3] and process and measurement noise.

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)	5.600	0.000439
Flight path angle (deg)	-13.01	0.0003
Azimuth angle (deg)	77.70	0.007
Acceleration noise (mm/s^2)	-	8.10
Angular rate noise (μrad/s)	-	135
Radar altimeter (m)	-	3.00

Table 1 also contains process noise and measurement uncertainty information. The values for these quantities is derived from information in Taylor et al. [3], which describes the IMU sensors and their calibration data, and Skulsky et al. [11], which describes the performance of the on-board radar. Typically, the process noise is a parameter that is tuned based on the problem in question and the propagation time step size used in the reconstruction. However, in this case, the propagation equations were found to be highly sensitive to variations in the IMU measurements. Any other variations in the process were at a lower order of magnitude when compared to the IMU noise level. Thus, IMU uncertainties were assumed to be the actual values for the process noise.

3.1 Trajectory reconstruction

The EKF tool generated an estimate of the flight trajectory, which included Phoenix's position, velocity and attitude from atmospheric entry to touchdown. Table 2 shows the reconstructed values of some key parameters for Phoenix's trajectory, such as the timeline of major events, the EKF propagated uncertainties, pre-flight predictions and the EDL reconstruction conducted by Desai et al. [1].

Table 2. Events timeline and other metrics for Phoenix.

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	0.840
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	405.0	
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 the start of constant velocity (AGL m)	51.9	52.1	52.5	6.16
Landing time from entry (sec)	436.2	446.1	446.0	
Relative velocity (m/s)	2.16	2.38	2.96	9.17

Note: AGL = above ground level

Table 2 shows that the values for the Desai et al. reconstruction and the EKF reconstruction are close to each other, although the EFK reconstruction has the added benefit of quantifying the uncertainty bounds for the estimated properties. The reconstructed events appear to have occurred somewhat later than the pre-flight predictions. For example, the estimated height of parachute deployment was approximately 400 m higher than the pre-flight mean. Past reconstructions explain this discrepancy by a higher-than-expected total angle of attack of the vehicle in the hypersonic regime of flight [1]. NASA reconstruction efforts attribute this situation to an under-prediction of the aerodynamic coefficients in the hypersonic phase or a center-of-gravity shift in the radial direction leading to a trajectory with higher lift [12].

Phoenix was designed to fly a ballistic trajectory, thus even a small offset in the radial direction could have led to a larger angle of attack for trim and a higher lift force than expected. Desai et al. notes that the largest discrepancy between the pre-flight and reconstructed aerodynamics occurred between 75 to 125 seconds [1]. The EFK trajectory estimation shows that the freestream velocity (V_∞) for this period was between 4 and 5.5 km/s. Fig. 2 displays the reconstructed total angle of attack from the EKF reconstruction and includes the pre-flight prediction from Desai et al.[1]. The EKF-based reconstruction does indeed seem to corroborate the NASA explanation for the deviation from pre-flight predictions.

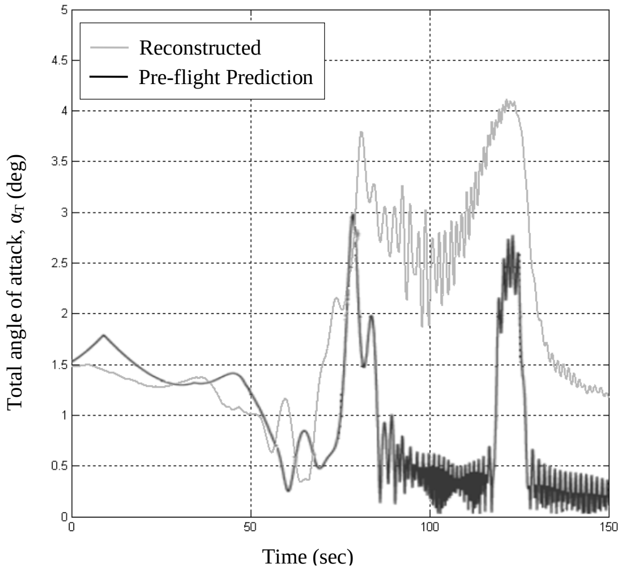

Fig. 2. Total angle of attack reconstruction.

The trim angle of attack appears to be around 2.5 degrees from 75 to 125 seconds, while the pre-flight prediction for this region was about 0.5 degrees. Assuming modified Newtonian aerodynamics and using the aeroshell geometry described in Edquist et al. [10], a radial offset of around 4-5 mm can lead to the approximate change in trim angle seen in Fig. 2. Results from Edquist et al. [10] would support that conclusion, although recall that the estimate for the radial offset provided here is based purely on first-order methods, whereas higher fidelity tools, such as computational fluid dynamics, can improve the estimate of the offset.

Fig. 3 compares the EKF flight reconstruction of the terminal descent portion of the EDL with literature and pre-flight predictions [1]. Key timeline elements such as lander separation, gravity turn and constant velocity landing are present in the figure. The EKF reconstruction agrees well with the literature results. In fact, Fig. 4 shows the residual between the EKF reconstructed velocity and the Desai et al. reconstruction and the difference is within the estimated 1σ uncertainty. Additionally, it should be noted that the velocity uncertainty does change from initial conditions; however, the filter processes so much sensor data from the top of the atmosphere to the terminal descent sequence that the velocity uncertainty does not change significantly in this section of the trajectory.

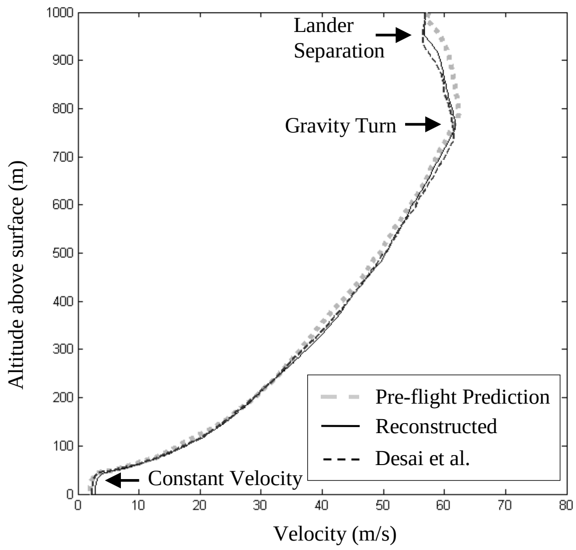

Fig. 3. Altitude versus ground relative velocity.

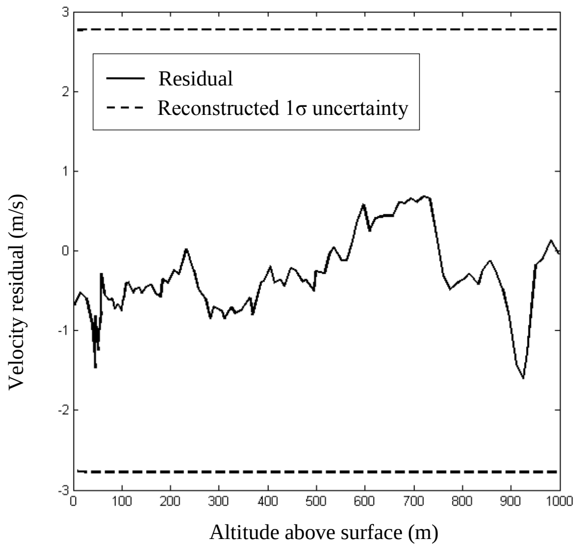

Fig. 4. Residual velocity compared to literature.

The EKF-based reconstruction gives the final landing site for the vehicle at 68.9° N ± 1.23×10^{-5} deg. (1σ) and 234.2° E ± 5.08×10^{-5} deg. (1σ). The estimated trajectory parameters correspond well with figures published in the literature from deterministic reconstructions [1, 2], but the EKF-based reconstruction also quantifies the uncertainty in these values. Additionally, the EKF reconstruction methodology is able to simultaneously incorporate different types of vehicle sensor data (in this case IMU with radar altimeter) to create a coherent estimate of the trajectory. Since the true trajectory of the vehicle is unknown, incorporating information from all available sensors rather than relying on only one or two data types can improve one's best estimate of the trajectory.

3.2 Atmosphere reconstruction

Atmospheric parameters, such as density, can be reconstructed from IMU data, knowledge of the aerodynamic database and the estimated velocity history. Edquist et al. [10] provides the aerodynamic database for the flight regime prior to parachute deployment. Fig. 5 shows the reconstructed density profile from the EKF estimated states and the results from an independent atmospheric reconstruction done as part of the Planetary Data System (PDS) program at NASA [3]. The results only go down to parachute deployment.

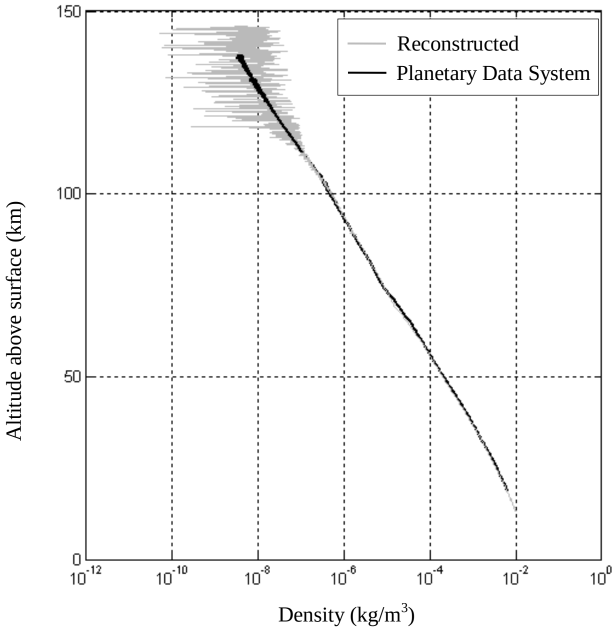

Fig. 5. Density reconstruction.

The fluctuations in the reconstructed density at higher altitudes are due to the large noise in the sensed acceleration data during the early part of entry. This noise can be smoothed by using a moving average filter as seen in Withers and Catling [3]. However, for altitudes under 100 km, the density estimated by the EKF closely matches the PDS solution even without using the moving average filter. This is especially interesting since the PDS solution was done deterministically [3, 9], and used an aerodynamic database that did not have as many data points as the database from Edquist et al. [10]. It appears that the density reconstruction for Phoenix's trajectory is not as sensitive to the aerodynamic database information; thus, the assumption of perfect knowledge of aerodynamics seems more reasonable since the aerodynamic uncertainty does not seem to affect adversely the atmospheric estimate.

Fig. 6 shows the reconstructed pressure using the hydrostatic equation (Eq. 2). The surface pressure measurement that Phoenix's meteorological station took shortly after landing is also shown in Fig. 6. Since the integration process is a smoothing procedure, it is not surprising that the fluctuations seen in the density reconstruction have been removed.

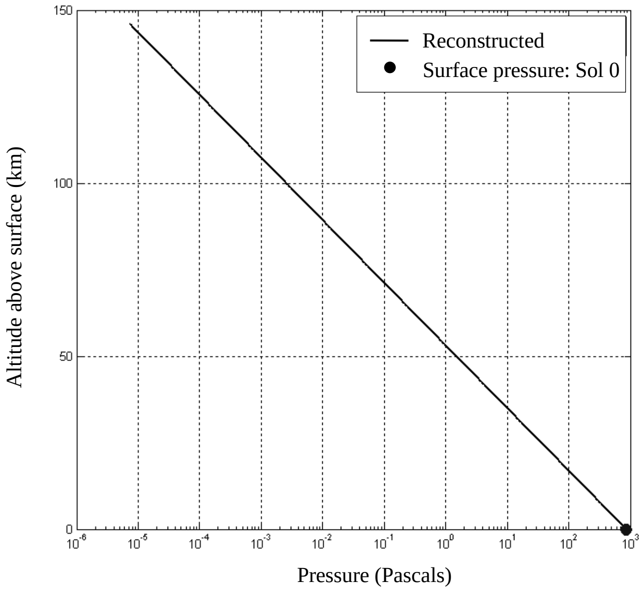

Fig. 6. Pressure reconstruction.

It is again worth noting that the reconstruction in Fig. 6 was done using the hydrostatic equation, which assumes continuum atmosphere, which may not be valid at high altitudes.

3.3 Parachute performance reconstruction

Fig. 7 shows the drag coefficient for the parachute together with the parachute reconstruction conducted by Adams et al. [4]. Also depicted is the C_{D0} of 0.615 that was found from a parachute drop test on Earth [4].

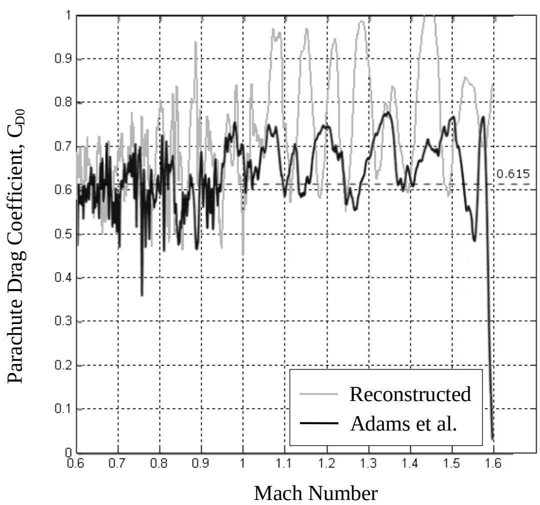

Fig. 7. Parachute drag coefficient reconstruction.

The reconstructed values from Adams et al. and the current study do not exactly match as shown in Fig. 7. However, the discrepancy can be attributed to the different reconstruction techniques used for both processes. Adams et al. used the trajectory reconstructed from deterministic algorithms similar to Desai et al.'s work, whereas this study's results were heavily influenced by the uncertainty in the process and measurements by the EKF. Since the reconstructed trajectory parameters appear often in the calculation of C_{D0} in the form of the freestream velocity, density and the total angle of attack, it is not surprising that the values of the two reconstructions do not match exactly. Nevertheless, both figures show a similar trend and are close to the C_{D0} of 0.615 predicted from terrestrial drop tests [4]. The EKF-based reconstruction has the advantage of incorporating the process and measurement uncertainty in the estimation methodology. Thus, the reconstructed parameters also have their uncertainties quantified from the actual flight data itself. However, the deterministically based reconstruction would need an additional Monte Carlo analysis to quantify the uncertainties in the aerodynamics.

4. CONCLUSIONS

A statistically based methodology to reconstruct the trajectory, atmosphere and aerodynamic characteristics of a Mars EDL vehicle is shown and the process is demonstrated using the Phoenix lander dataset. Results are compared with figures in the literature, and overall the statistical method provides similar results to these independent efforts with the added benefit of statistically quantifying the uncertainties of these estimates. The specific results provided in this paper includes Phoenix's event timeline, reconstructed terminal descent trajectory, freestream density, pressure, and the estimated drag coefficient of the supersonic parachute.

The reconstruction methodology demonstrated here shows promise and can be used reconstruct EDL system performance for future missions and potentially enhance current system design tools. However, a few improvements to the reconstruction methodology are noted in this study. The methodology can be improved for atmospheric and aerodynamic coefficient reconstruction if direct measurement of the freestream pressure can be made. Then the aerodynamic uncertainty can be separated from the atmospheric uncertainty. This type of data will available from the Mars Science Laboratory dataset. Additionally, a statistical estimator that is of a higher order than the EKF can improve the quantification of the state variable uncertainty.

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