STUDY OF SOME PLANETARY ATMOSPHERES FEATURES BY PROBE ENTRY AND DESCENT SIMULATIONS

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ABSTRACT

Characterization of planetary atmospheres is analyzed by its effects in the entry and descent trajectories of probes. Emphasis is on the most important variables that characterize atmospheres e.g. density profile with altitude. Probe trajectories are numerically determined with ENTRAP, a developing multi-purpose computational tool for entry and descent trajectory simulations capable of taking into account many features and perturbations. Real data from Mars Pathfinder mission is used. The goal is to be able to determine more accurately the atmosphere structure by observing real trajectories and what changes are to expect in probe descent trajectories if atmospheres have different properties than the ones assumed initially.

1. INTRODUCTION

Prediction and reconstruction of entry and descent trajectories of probes in planetary atmospheres is a difficult and important task as the success of a mission can depend on the correct assessment of the real conditions that probes will run into. Trajectory prediction and reconstruction have to rely on approximations that are often based on assumed knowledge of the eventual answers it tries to attain [1]. It is very important to check consistency of results and desirable to have diversity of reconstruction tools with eventually different approaches to cope with all the assumptions and phenomena involved.

ENTRAP — ENtry TRajectories in Atmospheres of Planets, is a developing software tool for precise orbit prediction and entry and descent trajectory prediction and reconstruction, capable of taking into account all kind of parameters [2]. Once it is fully developed it will be easily applied to all kind of trajectory determination in different planets and situations, allowing changes in assumptions and running all kind of tests effortlessly. Presently ENTRAP is already in a working state although the desired flexibility and ease of use is still not achieved.

One of the aspects determining probe real trajectory is the atmospheric structure especially the density profile with altitude. Usually, an iterated procedure is used during the trajectory reconstruction from initial conditions of probe entry and previous knowledge of the atmospheric and aerodynamic properties to obtain all the atmospheric and aerodynamic information at the time of the event including the density profile.

Planetary atmosphere models can be constructed in a similar way of what is done for our planet. In the case of Earth much information is available and there are very sophisticated and complete density models [3]. For other solar system planets and satellites information is scarce and simpler models are used as a reflection of our lack of knowledge. They should however be adequate to model probe trajectories since uncertainty in other important parameters such as angle of attack or drag coefficient C_D is relatively high and more precise values can only be obtained during the trajectory reconstruction process.

When predicting an entry and descent trajectory not only an adequate atmosphere model should be considered but also how the probe will behave if atmosphere conditions are different than previously assumed since these are not in general well known. This kind of study can possibly estimate the limits of possible variations induced on the trajectory by the atmosphere local conditions and applied in mission design to foreseen undesirable situations.

In this work Mars Pathfinder (MPF) is used to assess the influence of the atmosphere density profiles used in studying probe entry and descent trajectories. From MPF data simple density profile models are derived. A comparison of simulated MPF trajectories using these models and some variations of them is performed to evaluate the dependency of some trajectory parameters regarding the atmospheric density profile with altitude. Inducing known changes in the atmosphere model parameters allow studying its effect on the simulated trajectories of

Table 1. Mars Pathfinder entry characteristics from Spencer et al. *(1999).*

Entry characteristic	Mars Pathfinder
V_e, inertial, km/s	7.264
V_e, relative, km/s	7.479 (retrograde)
Radial distance, km	3522.2
Inertial flight path angle	-14.06
Entry mass, kg	585.3
S, m^2	5.526
Angle of attack α, deg	0^a
C_D	1.7^b
L/D	0^a
Guidance and control system	Spin stabilized

[a]Nominal.
[b]Nominal, for continuum flow.

probes towards a better understanding of by what extent those changes affect probe descent. This work also contributes to further test and develop our reconstruction tool with a real example.

Mars Pathfinder is a good test case for developing reconstruction tools [1] and conduct this kind of study since all information needed is available and much work has been developed that can be used for comparison (see section 2).

2. SIMULATING PATHFINDER'S ENTRY AND DESCENT

2.1. different Trajectory Reconstructions and Initial Conditions

Pathfinder entered the Martian atmosphere directly from interplanetary transfer. Direct entry led to a high entry speed. During Pathfinder's entry, descent and landing (EDL) the angle of attack between its symmetry axis and the direction of its velocity relative to the atmosphere was near-zero. The spinning about its symmetry axis was designed to be fast enough that the lift and side forces, occurring if the angle of attack was not precisely zero, were averaged to near-zero by the continuous changing direction. At 9 km altitude a parachute opened and shortly afterwards the front heatshield was released. Latter on the airbags were inflated, retrorockets fired and the lander eventually bounced on the ground more than 15 times and for longer than 1 minute, stopping $\sim$1 km away from the impact site. A more complete description of Pathfinder's EDL can be found in [1].

Various Pathfinder trajectory reconstructions can be found in literature. The work developed by the Pathfinder scientists [4] including the accelerometer measurements and the reconstruction trajectory together with the derived atmosphere properties can be found on the Planetary Data System (PDS) which is available online [5]. An independent reconstruction by the pathfinder engineers [6, 7] was based on accelerometer, altimeter and ground-based measurements generated two more reconstructed trajectories. Both efforts used different initial conditions (i.e. different initial altitude). The reconstructed trajectories are basically identical before parachute opening. Following this event there are some differences that can be attributed to incomplete understanding of Pathfinder's aerodynamics after parachute opening [1]. MPF data was latter analyzed and used as test case in work related to the Huygens probe [8] and Beagle 2 [9] analysis tools. In this work the MPF trajectory is only simulated until parachute opening, avoiding the region where uncertainties are significative and would imply difficulty in comparing results. Table 1 summarizes the MPF entry characteristics and initial conditions considered in our work as provided by Spencer *et al.* [6, 7].

2.2. Aerodynamic Coefficients, Atmospheric Structure and Angle of Attack

Aerodynamics characteristics are necessary to design Pathfinder's trajectory and EDL control algorithms. Qualitative reasoning was used to justify the nominal zero angle of attack. To predict forces, torques and heating rates for a given atmosphere structure and probe speed, attitude aerothermodynamics studies are developed to construct an aerodynamic database in an iteration process with the nominal trajectory. If there is a suggestion during an eventual trajectory reconstruction that conditions are different than expected, additional simulations can be needed to provide relevant aerodynamic characteristics.

The ratio of the drag coefficient C_D to the lift coefficient C_L can be related to the measured ratio of axial and normal accelerations and it is proportional to the angle of attack for a given speed and atmospheric structure. The atmospheric density ρ is related to drag by

$$\rho = -\frac{2m}{C_D A} \times \frac{a_t}{v_R^2} \qquad (1)$$

where m is the probe mass, that changes along the trajectory due to the heat shield ablation, A is the probe reference area, C_D is the appropriate drag coefficient for the angle of attack and atmospheric density, temperature and composition at each instant, a_t is the acceleration along the flight path and v_R is the relative speed to the atmosphere. Atmospheric pressure is related to atmospheric density by the equation of hydrostatic equilibrium and atmospheric temperature can be obtained from the equation of state for a known atmospheric composition. An iterative procedure is then used to reconstruct the trajectory and the real atmospheric structure, and to determine the C_D and angle of attack along the EDL trajectory.

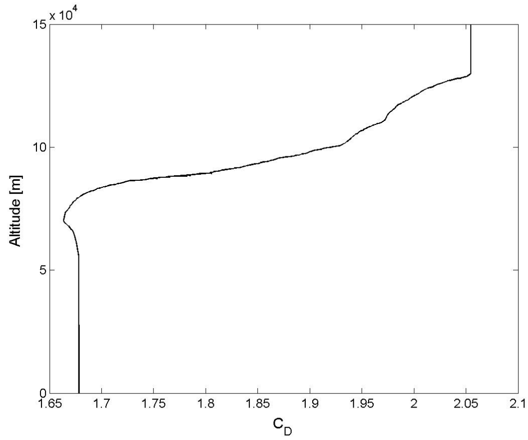

Figure 1. Considered C_D variation with altitude estimated from reconstructed values.

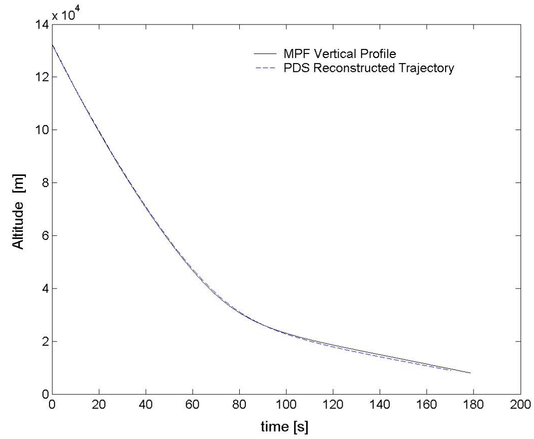

Figure 2. Comparison of the altitude profiles computed by ENTRAP *with the reconstructed from PDS. Altitude profiles are calculated with respect to the radius of the MPF landing site of 3389.72 km [11] (in [7] the altitude is given with respect to the Mars reference ellipsoid.)*

In this work the iterative process was not applied. The reconstructed PDS atmospheric density profile with altitude was adopted and the drag coefficient variation (Fig. 1) was accounted using an approximation of the values determined for the MPF reconstructed trajectory of [8] that used the aerodynamic database from [10]. The C_D values were used as reference values but when the atmospheric density profile is changed they should also vary, which was not considered. This is not a major effect although for precise calculations it should be taken into account. Lift and side forces were not considered, following the design idea that spacecraft's spin would averaged them to near-zero (see discussion of results).

2.3. Reference Atmospheric Density Profile

With all relevant parameters taken from reconstruction efforts, from the aerodynamic coefficients to atmospheric structure, it should be possible to immediately obtain a good approximation of the reconstructed trajectory without any iteration. Results should only be limited by the additional approximation of zero angle of attack. This was used to test our reconstruction tool. Comparison of the MPF vertical profile computed by ENTRAP with the reconstructed from PDS is shown in Fig. 2. They are in good agreement, with altitude residuals of less than 1 km justifying the zero angle of attack approximation. Differences are of the same order of magnitude of the found between other reconstruction efforts [8, 9] and seems to confirm the suggestion that reasonable results can be obtain using only simple aerodynamic information.

The MPF density profile with altitude from PDS was used as reference for comparison and a base to construct simple density profile models and simulating different atmospheric conditions to assess its influence in the trajectory.

3. ATMOSPHERIC DENSITY PROFILE VARIATIONS

As already indicated some variations in the atmospheric density profiles will be considered without changing the determined variation with altitude of the drag coefficient and without considering any lift. Some experimental simulations performed with different values of these parameters (not shown) suggest that differences in the results are less important than variations in density and those found between independent reconstructed trajectories. This confirms the presumption that the drag coefficient changes slowly (logarithmically) with atmospheric density [1]. Thus, MPF trajectories simulated in different atmospheric density profiles used the same determined parameters of the reference trajectory — the one obtained with the reference atmospheric density profile from PDS.

3.1. Case I: Simple Density Profile Models

To assess the influence of considering simple models for the atmospheric density profile two different models were developed: from the MPF vertical profile of the atmospheric density (the reference model) a simple exponential (one layer) and a three-layer exponential density profiles are obtained. In each layer of a model density ρ is determined by

$$\rho = \rho_{0i} e^{-\frac{h-h_i}{H_i}} \tag{2}$$

where ρ_{0i}, h_i and H_i are respectively density at the base of the layer, altitude of the base and the layer scale height. The exponential model is obtained from a simple exponential regression and similarly for the three-layer model but considering three different exponential regressions in different segments adjusted in the best way. Boundaries between layers in the three

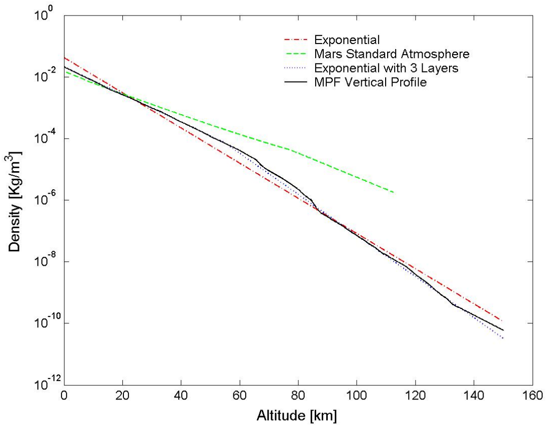

Figure 3. Comparison of simple models with the MPF profile of density with altitude (Case I).

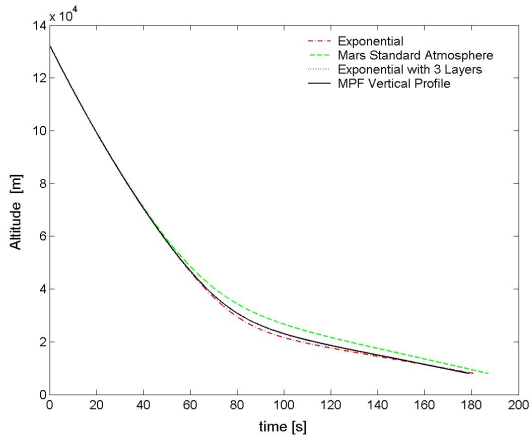

Figure 4. Comparison of altitude profiles for simple density profile models (Case I).

layer model are at about 20 km and 54 km altitude. A third model was considered for comparison: the Mars Standard Atmosphere (that can be found for example in http://www.grc.nasa.gov/WWW/K-12/airplane/atmosmre.html) extrapolated to much higher altitudes. Density profiles with altitude are shown in Fig. 3.

Altitude profiles for all the considered density profiles can be compared in Fig. 4. It can be seen that the three-layer exponential model is very close to the MPF profile while differences to others are significant although not large. This behavior is more pronounced in relative speed with altitude (Fig. 5) and in acceleration with altitude (Fig. 6). Aerodynamic heating (not shown) varies in a similar way as acceleration with altitude as expected. Differences in latitude and especially in longitude (also not shown) are also noticeable.

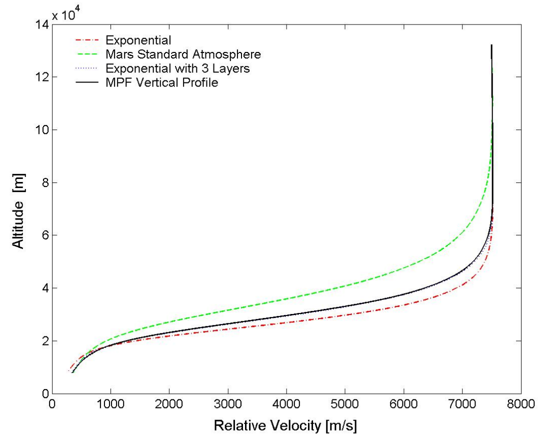

Figure 5. Comparison of relative speed with altitude for simple density profile models (Case I).

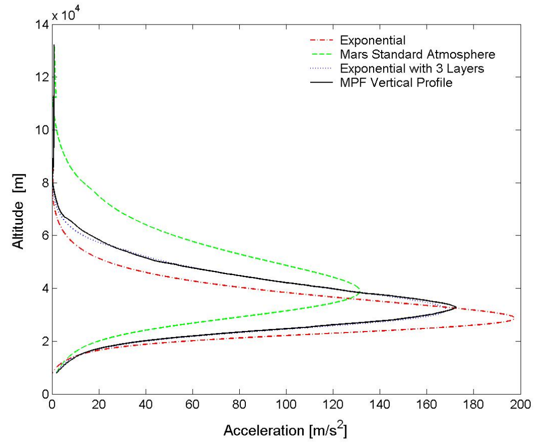

Figure 6. Comparison of acceleration with altitude for simple density profile models (Case I).

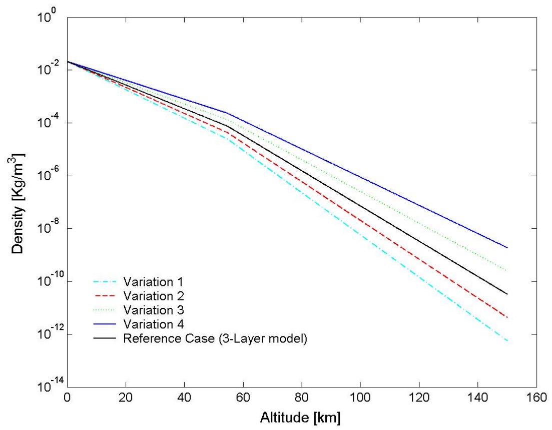

Figure 7. Case II: Comparison of the effect of varying the scale height by ±10% and ±20% in a three-layer density profile model. Variations 1 to 4 corresponds to increasing values of the scale heights.

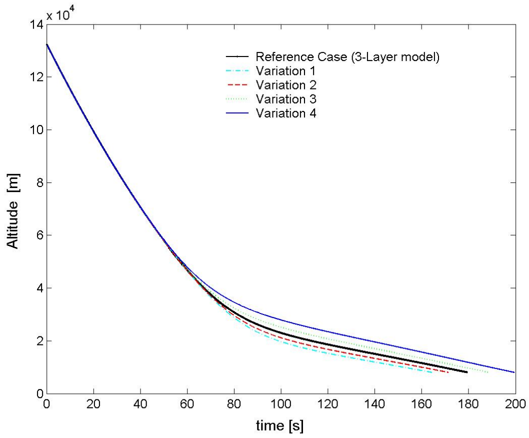

Figure 8. Comparison of altitude profiles for Case II.

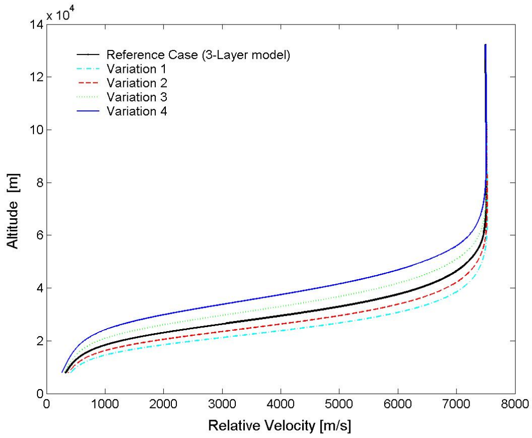

Figure 9. Comparison of relative speed with altitude for Case II.

3.2. Case II: Density Profile Model Variations

In the second set of simulations the goal was to emulate the solar cycle expansion and retraction effect in the atmosphere. The three-layer density profile model was used as reference and for simplicity the solar cycle effect was simulated by varying all scale heights H_i of the reference model in Eq. 2 by $\pm 10\%$ and $\pm 20\%$ (Fig. 7). Variations 1 to 4 of case II corresponds to increasing values of the scale heights.

As in Case I, differences in the altitude profiles (Fig. 8) are not too large but are significant and they are more compelling when relative speed and acceleration with altitude are observed (Fig. 9 and Fig. 10).

3.3. Discussion of Results

The three layer exponential model presents very small differences to the MPF profile from PDS. This is reflected

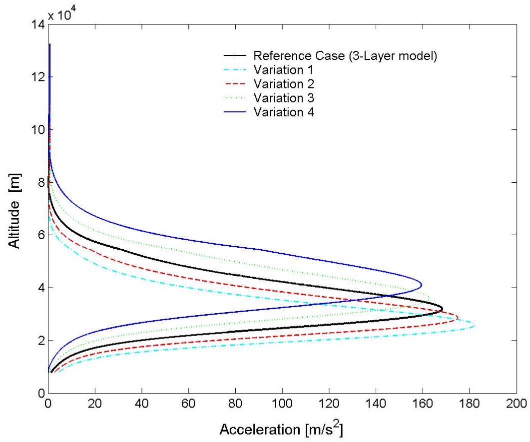

Figure 10. Comparison of acceleration with altitude for Case II.

in similar values for problem parameters such as acceleration and relative speed. Use of the three layer profile to model the atmospheric density profile seems to be acceptable but a precise evaluation should take into account the variation in the aerodynamic coefficients. The other models considered in Case I are not acceptable since they present huge differences in the evaluated parameters.

Although the induced variations in the scale heights in Case II were considerable, implying large variations in the evaluated parameters, results present a regularity that seems to indicate a smooth dependency on scale height.

The no lift approximation should not be a problem within the approximations used to determine the drag coefficient. It can have a positive side of separating different problems and simplifying the analysis. Since the MPF was spin stabilized, small differences found between the PDS reconstructed trajectory and the determined by ENTRAP seem to be consistent with the possible ones being originated from small lift components induced by probe spin and not exactly zero angle of attack. This question should be further examined.

4. CONCLUSIONS AND FUTURE WORK

The three layer model for the density profile with altitude is adequate for trajectory simulations. Differences obtained are of the same order of magnitude of differences between independent reconstruction efforts (even when using relatively limited aerodynamic information). This result reinforces similar results from [9].

Density profile variations have important consequences in some of the problem parameters such as maximum acceleration; landing site can be also affected although probably less. Variations of the problem parameters with changing density profile seem to be smooth which should probably be expected because of the slow variation of some aerodynamic parameters with density.

The work developed was advantageous to confirm validation of the ENTRAP trajectory simulation tool.

This is a work in progress. Much more results can be easily obtained, from different density profiles to changing aerodynamic coefficients. One technical limitation highlighted during this work was the impossibility of applying the iterative process during simulations. This question should be addressed in the future.

Future work should point to assess dependency on the aerodynamic information and the related uncertainty. Wind can possibly have important consequences in the trajectory and to address this question more studies regarding the relations between lift, angle of attack and other aerodynamic information should be developed.

ACKNOWLEDGMENTS

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