All Recent Mars Landers Have Landed Downrange – Are Mars Atmosphere Models Mis-Predicting Density?

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Introduction: All recent Mars landers (Mars Pathfinder, the two Mars Exploration Rovers Spirit and Opportunity, and the Mars Phoenix Lander) have landed further downrange than their pre-entry predictions. Mars Pathfinder landed 27 km downrange of its prediction [1], Spirit and Opportunity landed 13.4 km and 14.9 km, respectively, downrange from their predictions [2], and Phoenix landed 21 km downrange from its prediction [3]. Reconstruction of their entries revealed a lower density profile than the best a priori atmospheric model predictions. Do these results suggest that there is a systemic issue in present Mars atmosphere models that predict a higher density than observed on landing day?

Spirit Landing: The landing location for Spirit was 13.4 km downrange of the prediction as shown in Fig. 1. The navigation errors upon Mars arrival were very small [2]. As such, the entry interface conditions were not responsible for this downrange landing. Consequently, experiencing a lower density during the entry was the underlying cause. The reconstructed density profile that Spirit experienced is shown in Fig. 2, which is plotted as a fraction of the pre-entry baseline prediction that was used for all the entry, descent, and landing (EDL) design analyses. The reconstructed density is observed to be less dense throughout the descent reaching a maximum reduction of 15% at 21 km. This lower density corresponded to approximately a 1-σ low profile relative to the dispersions predicted. Nearly all the deceleration during the entry occurs within 10-50 km. As such, prediction of density within this altitude band is most critical for entry flight dynamics analyses and design (e.g., aerodynamic and aerothermodynamic predictions, landing location, etc.).

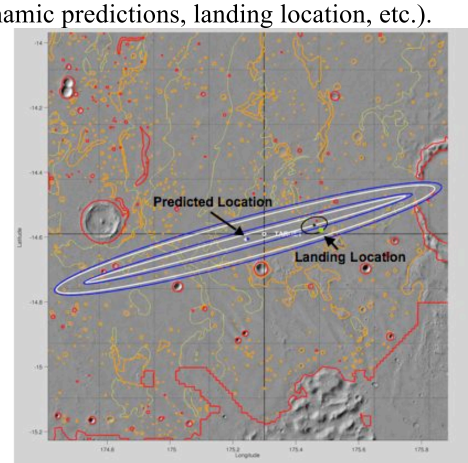

Figure 1. Spirit Landing Location.

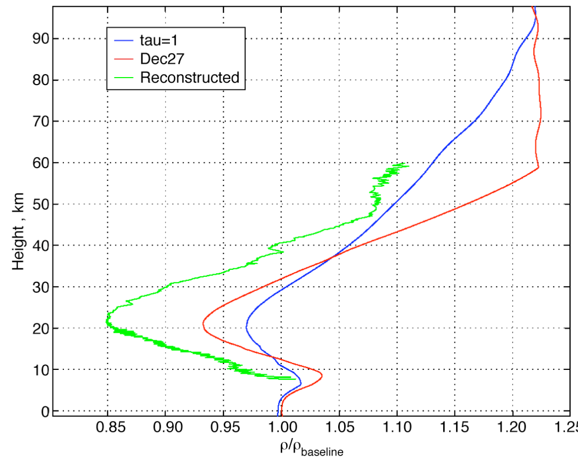

Figure 2. Reconstructed Density for the Spirit Entry.

Also shown in Fig. 2 are two other density profiles: 1) a Tau=1 profile which was a predicted "high dust content" atmosphere representing a worst case density profile scenario, and 2) a profile generated using temperature measurements on December 27 from the Thermal Emission Spectrometer instrument on Mars Global Surveyor few days prior to landing. As seen, both a representative worst case profile prediction and one using updated temperature measurements still produced a more dense profile than what was actually experienced. Although, both were closer to the reconstructed profile than the baseline prediction and both did capture the overall density structure. The corresponding reconstructed temperature profile is shown in Fig. 3.

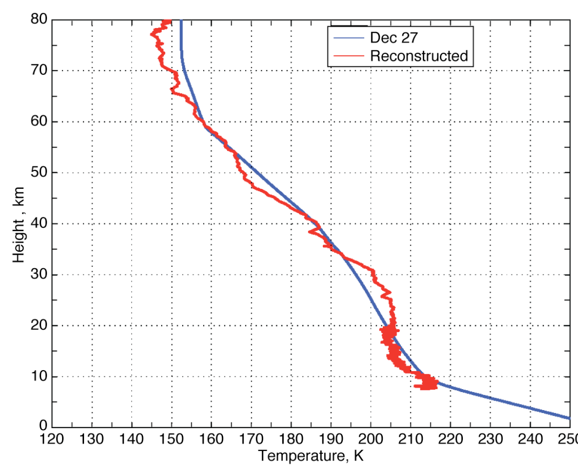

Figure 3. Reconstructed Temperature for the Spirit Entry.

Opportunity Landing: The landing location for Opportunity was 14.9 km downrange of the prediction as shown in Fig. 4. Again, the navigation errors upon Mars arrival were very small [2]; hence, the entry interface conditions were not responsible for this downrange landing. Consequently, experiencing a lower density during the entry was the underlying cause. The reconstructed density profile that Opportunity experienced is shown in Fig. 5, which is plotted as a fraction of the pre-entry baseline prediction that was used for all the EDL design analyses. Again, the reconstructed density is observed to be less dense throughout most of the descent reaching a maximum reduction of 17% at 18 km. This lower density corresponded to approximately a 1-σ low profile relative to the dispersions predicted.

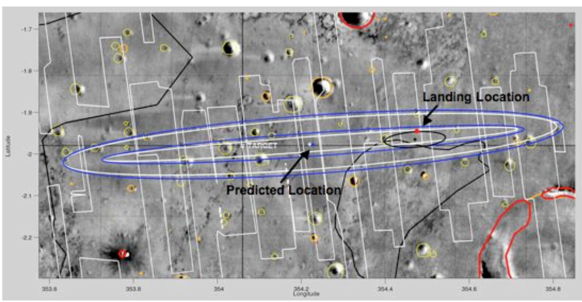

Figure 4. Opportunity Landing Location.

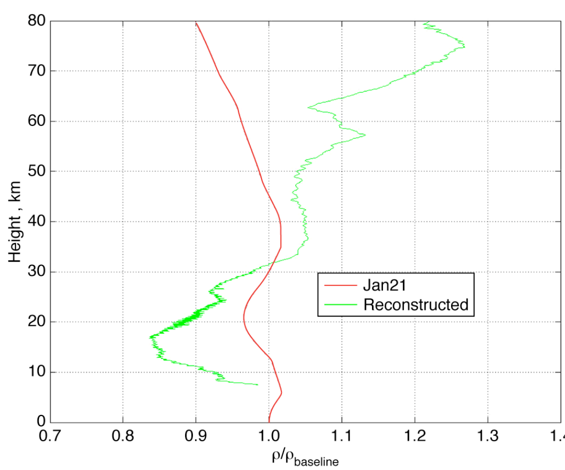

Figure 5. Reconstructed Density for the Opportunity Entry.

Also shown in Fig. 5 is a profile generated using temperature measurements on January 21 from TES on few days prior to landing. As seen, again using updated temperature measurements a few days prior to entry still produced a more dense profile than what was actually experienced. Although again, it was closer to the reconstructed profile than the baseline prediction and it did capture the overall density structure. The corresponding reconstructed temperature profile the for Opportunity entry is shown in Fig. 6.

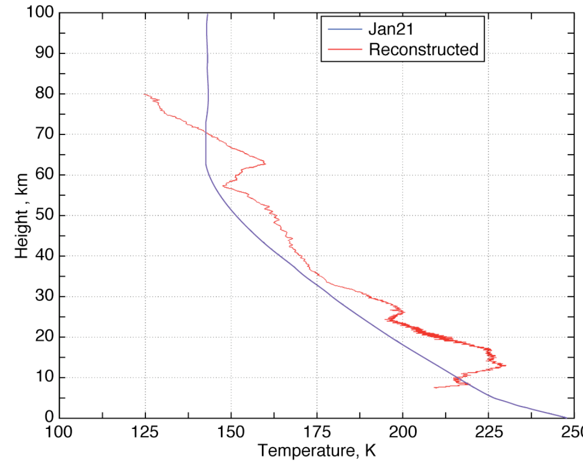

Figure 6. Reconstructed Temperature for the Opportunity Entry.

Phoenix Landing: The landing location for Phoenix was 21 km downrange of the prediction as shown in Fig. 7. Again, the navigation errors upon Mars arrival were very small [3]; hence, the entry interface conditions were not responsible for this downrange landing. However, for Phoenix, experiencing a lower density during the entry was also not the underlying cause for the downrange landing location. Unlike for Pathfinder, Spirit, and Opportunity, Phoenix was not a spinning entry. Hence, any lift present during the entry would not average out to zero. Consequently, Phoenix's downrange landing location was due primarily to it flying a lifting trajectory [3]. However, the density experienced by Phoenix during its entry was again lower.

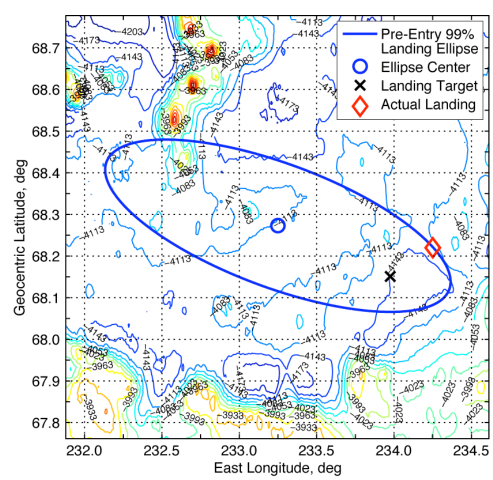

Figure 7. Phoenix Landing Location.

The reconstructed density profile for Phoenix is shown in Fig. 8, which is plotted as a fraction of the pre-entry baseline prediction that was used for all the EDL design analyses. Again, the reconstructed density is observed to be less dense throughout the descent reaching a maximum reduction of 8% at 28 km. This lower density corresponded to approximately a 1.5-σ low profile relative to the dispersions predicted. This lower density alone produces a landing location that is 4.2 km further downrange.

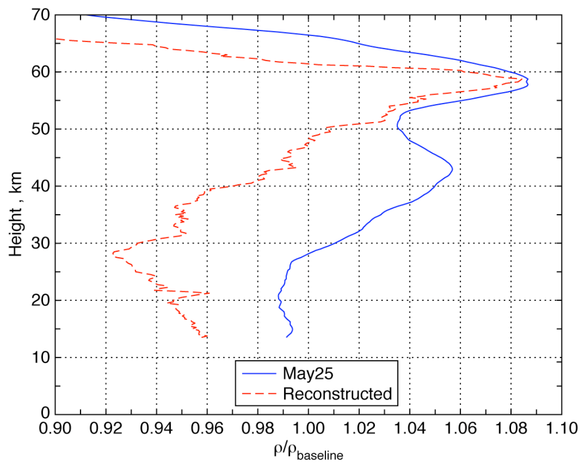

Figure 5. Reconstructed Density for the Phoenix Entry.

Also shown in Fig. 8 is a profile generated using temperature measurements on entry day May 25 from the Mars Climate Sounder [4] instrument on Mars Reconnaissance Orbiter. As seen, using updated temperature measurements still produced a more dense profile than what was actually experienced. The corresponding temperature profile has not been reconstructed as of yet.

Summary: Although, the lower densities experienced by these recent missions were within the dispersions expected, does the fact that every one of these entries encountered a lower atmospheric density profile than predicted indicate a random chance occurrence or is there a systemic bias in current Mars atmospheric models? As such, a question is posed to the atmospheric community to consider if the current Mars modeling assumptions are appropriate or is there underlying modeling issues that need to be reexamined or revaluated. Additionally, although, the entire density profile is necessary for entry, descent, and landing design, nearly all the deceleration during the entry occurs between 10-50 km. As such, prediction of density within this altitude band is most critical for entry flight dynamics analyses and design.

References: [1] Braun, R. D., Spencer, D. A., Kallemeyn, P. H., and Vaughan, R. M., "Mars Pathfinder Atmospheric Entry Navigation Operations," *Journal of Spacecraft and Rockets*, Vol. 36, No. 3, May-June 1999, pp. 348-356. [2] Desai, P. N. and Knocke, P. C., "Mars Exploration Rovers Entry, Descent, and Landing Trajectory Analysis," *Journal of Astronautical Sciences*, Vol. 55, No. 3, July-Sept 2007, pp. 311-323. [3] Desai, P. N., Prince, J. L., Queen, E. M., and Grover, M. R., "Entry, Descent, and Landing Performance of the Mars Phoenix Lander" AIAA Paper 2008-7346, Proceedings of AIAA Guidance, Navigation, and Control Conference, Honolulu, HI, August 2008. [4] McCleese, D. J., Schofield, J. T., Taylor, F. W., Calcutt, S. B., Foote, M. C., Kass, D. M., Leovy, C. B., Paige, D. A., Read, P. L., Zurek, R. W., "Mars Climate Sounder: An investigation of thermal and water vapor structure, dust and condensate distributions in the atmosphere, and energy balance of the polar regions," *Journal of Geophysical Research*, Vol. 112(E5), DOI: 10.1029/2006JE002790, 2007.