MESOSCALE ATMOSPHERE MODEL IMPLEMENTATION INTO MARS SCIENCE LABORATORY PERFORMANCE SIMULATIONS

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Introduction: Previous recent entries at Mars, like Pathfinder, Mars Exploration Rovers (MER) and Phoenix, were ballistic and therefore had smaller downrange distances between entry and touchdown compared to the Mars Science Laboratory (MSL) guided entry. See Figure 1. Consequently "hand-crafted" vertical profiles of the atmosphere at the landing site, tailored for the expected conditions on the day of entry by individuals, were sufficient for the trajectory simulations used to design the earlier missions.

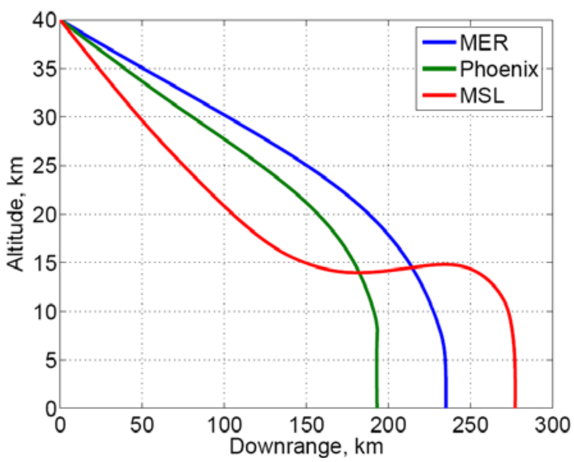

Figure 1. *Comparison of entry trajectory downrange versus altitude for MER, MSL and the Phoenix Lander normalized at an altitude of 40 km.*

MSL, however, faces several different challenges that require alternative methods for atmosphere modeling. The first challenge is that the increase in range covered during the entry as compared to the ballistic missions does not allow the use of a single vertical density and wind profile for accurate entry simulations. Second, the MSL guided entry has much higher sensitivities with respect to timeline and altitude margins than previous lander missions. The guided entry allows for landing within 10 km of a target so many of the proposed landing sites are located in landscapes that offer much more challenging local atmosphere effects near critical events like parachute deploy than has been experienced in previous missions. Additionally, much of the entry sequence relies on sensed triggers that are also highly sensitive to atmospheric conditions.

Monte Carlo trajectory simulations are relied on heavily to characterize entry, descent and landing (EDL) margins (e.g. propellant, timeline, altitude, etc.) by accounting for all known uncertainties. Uncertainties that are typically modeled include aerodynamics, mass properties, reaction control system thruster performance, parachute drag, and initial delivery and knowledge states and attitude errors. However one of the largest uncertainties at Mars is the highly variable and sparsely sampled atmosphere. In order to meet the demands of the MSL EDL design, the engineers evaluating the entry performance of the vehicle have teamed with atmospheric scientists to develop models of density and wind profiles at all potential MSL landing sites. These scientists develop models at all spatial scales from very large scale global circulation to regional or mesoscale models to small scale Large Eddie Simulations.

This paper describes the implementation of mesoscale atmosphere models through the use of the engineering Mars Global Reference Atmosphere Model (MarsGRAM)[1] interface in MSL EDL performance simulations. MarsGRAM contains density and wind perturbation models that can be easily tuned to match desired characteristics. The mesoscale models selected for MSL are briefly described as is the process for reducing the large amounts of mesoscale data into a MarsGRAM similar format such that the MarsGRAM perturbation models can be used. Finally a discussion of the results of the mesoscale model implementation and the EDL design implications of those results are provided.

Mesoscale Implementation: The standard atmosphere model in the MSL Program to Optimize Simulated Trajectories[2] (POST2) entry and descent 6DOF simulation is MarsGRAM 2005. It is fully integrated into the structure of the simulation code and design engineers are familiar with the mathematical models it uses to apply atmospheric perturbations. For this reason, the existing MarsGRAM structures and functionality were retained and utilized to simplify the implementation of the mesoscale model data. POST2 also has the capability to read in multidimensional tables of atmosphere data. It is the combination of these features that allows for ease of the mesoscale data implementation.

The MarsGRAM mean density is a function of latitude (ϕ), longitude (θ), altitude (h), Julian Date of entry, and local time from entry (t) and is based on information from the NASA Ames Mars Global Circulation Model (GCM) in the altitudes of interest for MSL. The perturbed portion, also a function of ϕ, θ and h, includes a random part (R(t)), the one sigma density perturbation (σ_{GCM}) and a perturbation scale factor (*rpscale*). The MarsGRAM equation for density is shown in Equation 1.

$$\rho(\phi,\theta,h,t) = \mu_{GCM}(\phi,\theta,h,t) + R(t)*\sigma_{GCM}(\phi,\theta,h,t)*rpscale \qquad (1)$$

In the nominal case, *rpscale* is equal to one. POST2 was modified to allow the MarsGRAM variables of μ_{GCM}, σ_{GCM} and *rpscale* to be provided as tables instead of single values. Therefore, Equation 1 becomes

$$\rho(\phi,\theta,h,t) = \mu(table) + R(t)*\sigma_{MGCM}(table)*rpscale(table) \qquad (2)$$

Replacing the MarsGRAM mean and sigma values with the mesoscale mean and sigma tables yield Equation 3.

$$\rho(\phi,\theta,h,t) = \mu_{Meso\_\rho}(\phi,\theta,h,t) + R(t)*\sigma_{Meso\_\rho}(\phi,\theta,h,t) \qquad (3)$$

Where the perturbation scale factor, *rpscale*, is defined as

$$rpscale(table) = \frac{\sigma_{Meso\_\rho}(\phi,\theta,h,t)}{\sigma_{MGCM}(\phi,\theta,h,t)} \qquad (4)$$

The equations for the horizontal and vertical winds are similar, though vertical winds are not considered at this time. This method provides the flexibility for EDL design engineers to tune models and test the robustness of the entire system to atmosphere variations using POST2 simulations.

At the time of the release of this paper, two mesoscale models were evaluated and incorporated into the performance simulation for MSL. The models include: 1) Mars Mesoscale Model 5 (MMM5)[3] developed at Oregon State University and 2) Mars Regional Atmospheric Modeling System (MRAMS)[4] developed at the Southwest Research Institute. Preliminary analysis of the two models suggested that MMM5 and MRAMS produced comparable results.

Entry trajectories at all of the potential landing sites identified at the time of the release of this paper (See Table 1) have been simulated using both the standard MarsGRAM atmosphere as well as the two mesoscale models, MMM5 and MRAMS. To simplify the large quantities of mesoscale data to be read into the EDL performance simulation it was decided that the initial evaluation of the landing sites would consider only vertical profiles along the entry trajectory. Because the trajectory slows as it approaches the ground, more vertical profiles should be selected near the landing site. For example, consider the nominal ground track at the Nili Fossae Trough site based on the MarsGRAM atmosphere. See Figure 2. Vertical profile locations were selected at the latitude and longitude of entry 1 km apart for 10 km on each side of the landing site to account for dispersed cases. Vertical profiles are 4 km apart to ~100 km uptrack and 10 km apart beyond. Vertical profile resolution includes samples every 10 meters from the surface to 1 km, every 100 meters from 1 km to 10 km and every 500 meters from 10 km above the surface to the top of the mesoscale model (~40 km).

Table 1. Potential MSL Landing sites

MSL LANDING SITES			
NAME	**LOCATION**	**ELEVATION**	**TARGET**
Nili Fossae Trough	21.00°N, 74.45°E	-608 m	Noachian Phyllosilicates
Holden Crater Fan	26.37°S, 325.10°E	-1940 m	Fluvial Layers, Phyllosilicates
Mawrth Vallis Site 1 Site 2 Site 3 Site 4	 24.65°N, 340.09°E 24.01N, 341.03°E 23.19°N, 342.41°E 24.86°N, 339.42°E	 -3093 m -2246 m -2187 m -3359 m	Noachian Layered Phyllosilicates
Eberswalde Crater	23.86°S, 326.73°E	-1450 m	Delta
Miyamoto	3.34°S, 352.26°E	-1807 m	Phyllosilicates, Sulfates?
S Meridiani	3.05°S, 354.61°E	-1589 m	Sulfates, Phyllosilicates
Gale Crater	4.49°S, 137.42°E	-4451 m	Layered Sulfates, Phyllosilicates,

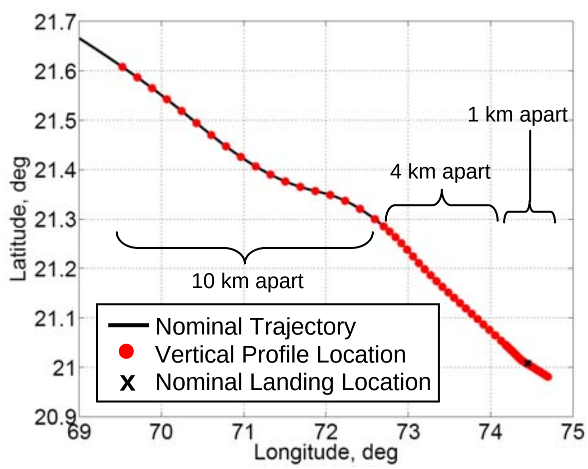

Figure 2. *Latitude and Longitude of the nominal MSL trajectory using MarsGRAM atmosphere at Nili Fossae Trough site. Red dots denote locations for vertical profiles along the trajectory. Black x denotes nominal landing location.*

The mesoscale models were then queried at each of the vertical and horizontal points. The means and standard deviations of the temperature, pressure, density, and winds were calculated over 5 hours surrounding the expected entry local solar time for five to 20 sols around the expected entry date. The means and standard deviations were converted to a POST2 tabular format. The standard deviations were then used to calculate the MarsGRAM scale factors (i.e. *rpscale* and *rwscale*) as shown in Equation 4. Finally, the MSL EDL performance simulation was executed using, as the atmosphere model, a multi dimensional (e.g. function of longitude and altitude) linear interpolation between the vertical profiles of mesoscale tabular data. It should be noted that pressure and density were linearly extrapolated in natural log space above the maximum altitude of the mesoscale models (~40 km). Temperature was held constant above the top of the mesoscale model where as the winds and wind perturbation scale factors (*rwscale*) were set to 0 m/s and the density perturbation scale factor (*rpscale*) was set to one.

Figure 3 shows the MarsGRAM nominal Nili Fossae Trough altitude profile versus longitude plotted over the MRAMS mean density vertical profiles. The topography at the site is also plotted in the figure. Despite the variable terrain just before arrival in the vicinity of Nili Fossae, the highly dense atmosphere is not encountered until the spacecraft is directly above the landing site.

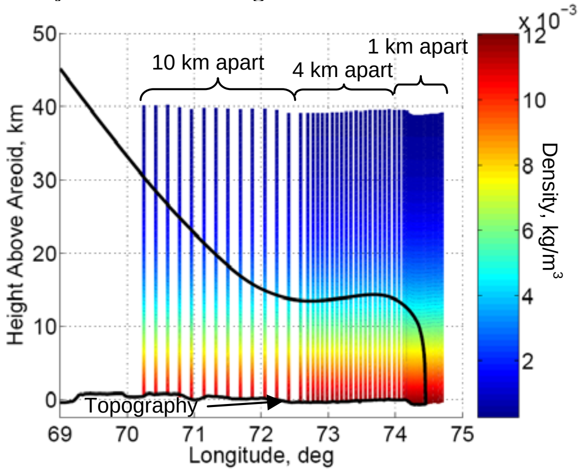

Figure 3. *Altitude versus longitude for the nominal MSL trajectory using MarsGRAM atmosphere at Nili Fossae Trough site plotted over mean MRAMS queried vertical density profiles.*

Results: Once the tables of mesoscale data were generated and incorporated into the performance simulation, the MarsGRAM perturbation process was applied to the mesoscale standard deviation to produce atmosphere perturbations in the Monte Carlos simulations for MMM5 and MRAMS. The Monte Carlo simulations used for this analysis consisted of 2000 POST2 dispersed trajectories. Output parameters such as parachute deploy opening loads and touch down footprints allow EDL design engineers to assess the impact of the various atmosphere models on the overall EDL system level performance when all other dispersions remain unchanged.

Figure 4 shows a histogram of the altitude at parachute deploy for the three atmosphere models at the Nili Fossae Trough. The MarsGRAM simulation has a 25 m/s engineering wind in addition to the perturbed winds to test the robustness of the system. Therefore, it is expected that, for most parameters of interest, the mesoscale results should remain bounded by the MarsGRAM results. The mesoscale results are also based on a smaller dataset which have smaller dispersions and are likely to be less conservative than MarsGRAM.

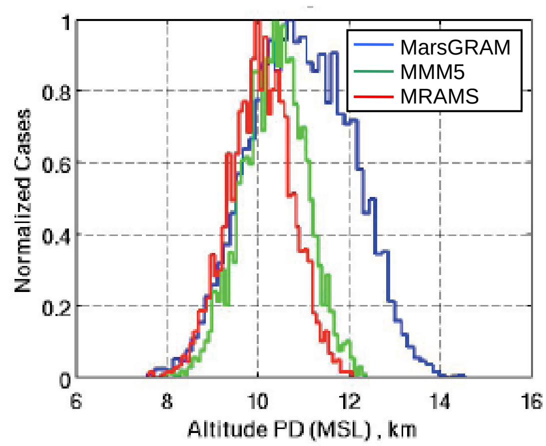

Figure 4. *Histogram of the altitude at parachute deploy for 2000 perturbed MSL entry trajectories from each atmosphere.*

In fact for almost all of the performance metrics considered for MSL, the mesoscale models are bounded by MarsGRAM. One notable exception is the parachute opening loads shown in Figure 5. For MRAMS the mean opening loads are almost 10% higher than MarsGRAM values. The reason for this is the mesoscale Mach numbers at parachute deploy are lower than nearly a third of MarsGRAM values where as the dynamic pressures remain about the same. See Figure 6.

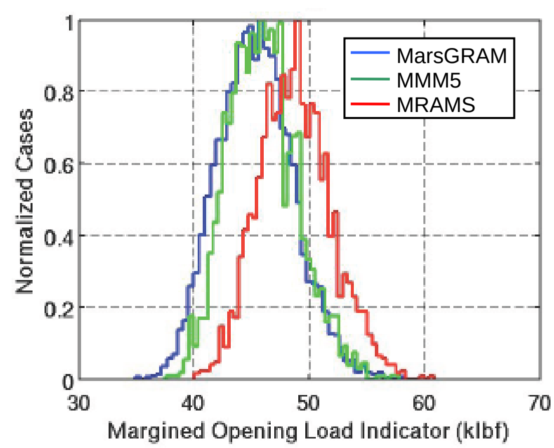

Figure 5. *Histogram of the parachute opening loads for 2000 perturbed MSL entry trajectories from each atmosphere.*

Another metric for comparing the three atmosphere models is the final touchdown location relative to the target. A footprint of the results is shown in Figure 7. Figure 7 shows that by touchdown, both MRAMS and MMM5 produce similar results and that those results are completely contained within the MarsGRAM tail wind results.

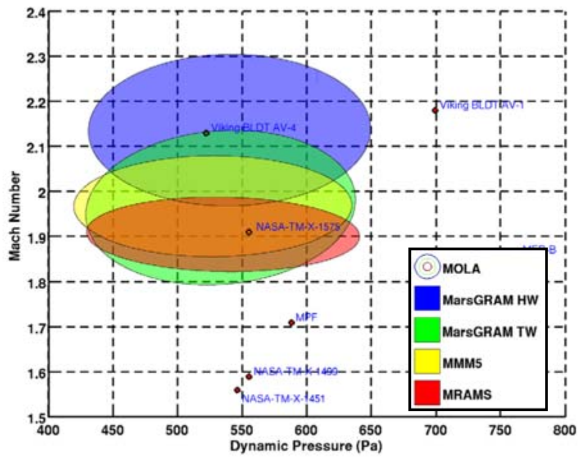

Figure 6. *Mach number versus dynamic pressure at parachute deploy for 2000 perturbed MSL entry trajectories from each atmosphere model. For clarity the MarsGRAM results are divided into headwind and tail wind ellipses.*

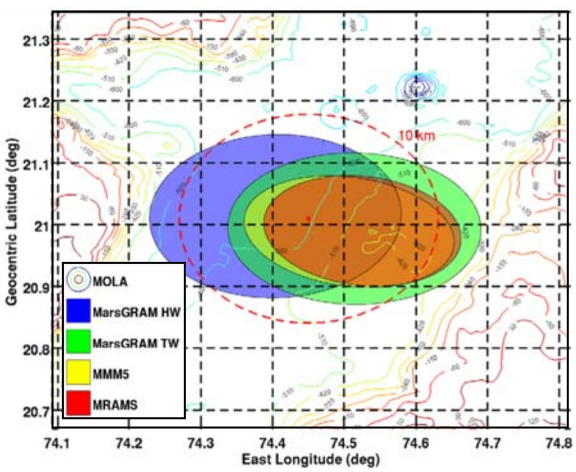

Figure 7. *Nili Fossae touchdown footprint. Latitude versus longitude at rover touchdown for 2000 perturbed MSL entry trajectories from each atmosphere model.*

It should also be noted that, in an effort to ensure that the characteristics of a self-consistent atmosphere in both time and space were not compromised in the averaging process, a three dimensional analysis was also performed. This analysis confirmed that the two dimensional and three dimensional methods gave nearly identical results. Therefore, it was concluded that the two dimensional method, which greatly simplified the model implementation, will be sufficient for the initial landing site evaluation.

Additionally, the comparison of the model landing site footprints at other candidate landing sites produce results similar to that shown for Nili Fossae.

Conclusion: A method has been developed that allows for the MSL-specific atmospheric density and wind profiles to be combined with the engineering perturbation model of MarsGRAM. This capability is being used in the evaluation of potential MSL landing sites. Results to date show that MarsGRAM, without this new capability, produce results that encompass the MSL-specific atmosphere results. The most significant exception is parachute loads, where using the MSL-specific atmospheres produce higher loads. Current plans are to continue to use both the standard MarsGRAM and MSL-specific density and wind characteristics for EDL analysis and landing site evaluations.

Due to the lack of observed data to fully validate models of the atmosphere at Mars, EDL design engineers are forced to use engineering models. To ensure system robustness for unknown unknowns, the engineers must currently identify very conservative bounding cases. However, the availability of atmosphere models based on large quantities of observed, real time data, along with highly accurate initial conditions, might enable more of Mars to be explored with lower risk.

References:

[1]Justus, C. G., Johnson, D. L., “Mars Global Reference Atmosphere Model, 2001 Version (Mars-GRAM 2001): Users Guide”, *NASA/TM-2001-210961. 2001.*

[2]Striepe, S. A., et al., “Program to Optimize Simulated Trajectories (POST II) – Utilization Manual, Volume II, Version 1.16.G,” *NASA Langley Research Center, Jan.. 2004.*

[3]Tyler, D. Barnes, J. R., Haberle, R. M., “Simulation of surface meteorology at the Pathfinder and VL1 sites using a Mars mesoscale model” *Journal of Geophysical Research, Vol. 107, No E4. 2002*

[4]Rafkin, S. C. R., Haberle, R. M., Michaels, T. I., “The Mars Regional Atmospheric Modeling System: Model Description and Selected Simulations” *Icarus Vol. 151 pp. 228-256. 2001.*