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Atmospheric risk assessment for the Mars Science Laboratory entry, descent, and landing system

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Atmospheric Risk Assessment for the Mars Science Laboratory Entry, Descent, and Landing System

Allen Chen, Ashwin Vasavada
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr. Pasadena, CA 91109
818-354-9952, 818-393-0248
allen.chen@jpl.nasa.gov, ashwin.r.vasavada@jpl.nasa.gov

Alicia Cianciolo
NASA Langley Research Center
816-662-1247
alicia.m.dwyercianciolo@nasa.gov

Jeff Barnes, Dan Tyler
College of Oceanic and Atmosphere Sciences, Oregon State University
541-737-5685
barnes@coas.oregonstate.edu, dtyler@coas.oregonstate.edu

Scot Rafkin
Department of Space Studies, Southwest Research Institute
720-240-0116
rafkin@boulder.swri.edu

David Hinson
SETI Institute
650-810-0217
dhinson@seti.org

Stephen Lewis
Open University
+44 (0)1908 655803
s.r.lewis@open.ac.uk

Abstract—In 2012, the Mars Science Laboratory (MSL) mission will pioneer the next generation of robotic Entry, Descent, and Landing (EDL) systems, by delivering the largest and most capable rover to date to the surface of Mars.¹² As with previous Mars landers, atmospheric conditions during entry, descent, and landing directly impact the performance of MSL’s EDL system. While the vehicle’s novel guided entry system allows it to “fly out” a range of atmospheric uncertainties, its trajectory through the atmosphere creates a variety of atmospheric sensitivities not present on previous Mars entry systems and landers. Given the mission’s stringent landing capability requirements, understanding the atmosphere state and spacecraft sensitivities takes on heightened importance.

MSL’s guided entry trajectory differs significantly from recent Mars landers and includes events that generate different atmospheric sensitivities than past missions. The existence of these sensitivities and general advancement in the state of Mars atmospheric knowledge has led the MSL

team to employ new atmosphere modeling techniques in addition to past practices.

A joint EDL engineering and Mars atmosphere science and modeling team has been created to identify the key system sensitivities, gather available atmospheric data sets, develop relevant atmosphere models, and formulate methods to integrate atmosphere information into EDL performance assessments. The team consists of EDL engineers, project science staff, and Mars atmospheric scientists from a variety of institutions.

This paper provides an overview of the system performance sensitivities that have driven the atmosphere modeling approach, discusses the atmosphere data sets and models employed by the team as a result of the identified sensitivities, and introduces the tools used to translate atmospheric knowledge into quantitative EDL performance assessments.

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² IEEEAC paper#1153, Version 3, Updated 2010:01:23

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1. INTRODUCTION

The MSL mission will continue the search for past or present habitable environments on Mars by delivering a 900+ kg rover with a highly capable and complex suite of scientific instruments to Mars in mid 2012. A major factor in achieving mission science goals is the capability to reach the best landing region as determined from orbital data sets.

Accordingly, MSL EDL requirements reflect the desire to broaden access to Mars relative to past missions. The EDL system is designed to have the capability of landing within 12.5 km of a given target, which may be chosen at elevations up to 1 km above the Mars Orbiter Laser Altimeter (MOLA) areoid, and anywhere within ± 30 latitude. For comparison, the Mars Exploration Rover mission delivered a 173-kg rover to an elevation of -1.44 km below the MOLA areoid with an along-track landing uncertainty of approximately 60 km. Landing sites were restricted to 15° latitude bands near the equator. An additional challenge for MSL is that the landing site will be chosen just before launch, requiring the design of an EDL system that maintains broad capability.

As a result of the large landed mass and stringent requirements, the MSL EDL architecture contains a number of notable departures from past missions. Of particular note are the introductions of guided entry and navigated velocity based event triggers, where the event is sensitive to true Mach. Previous publications have documented the MSL EDL architecture and its development [1, 2]. Event trigger logic through the EDL sequence have also been documented in detail [3].

As with previous Mars landers, atmospheric conditions during entry, descent, and landing directly impact the performance of MSL's EDL system. To understand and address atmosphere interaction issues, a joint engineering and science team dubbed the "Council of Atmospheres" was created and tasked with assessing atmospheric EDL risk associated with candidate landing sites.

Unlike previous landers, MSL's guided entry system allows it to "fly out" many atmospheric uncertainties; however,

because the guided entry trajectory through the atmosphere differs significantly from ballistic entries, the system has some different atmospheric sensitivities than previous systems. Additionally, event sensitivity to Mach number and time during parachute descent introduce other atmosphere interactions to investigate. Key atmospheric sensitivities are identified and discussed in Section 2.

Identifying key atmospheric sensitivities has allowed the team to focus on understanding certain aspects of the Martian atmosphere. While operating with a very limited data set, with only a few in situ atmospheric measurement sets available, the team has assembled a number of state of the art tools to address the sensitivities identified for the range of landing sites considered throughout the MSL landing site selection process. The data and tools have been used to both qualitatively and quantitatively assess the atmospheric conditions at potential landing sites. Global modeling, necessary to have the global coverage in place required for a rapid assessment of a site and to obtain the large-scale atmosphere background state, and mesoscale modeling, necessary for detailed resolution of topographic and other surface features, are used hand in hand to yield a flexible atmosphere assessment approach. As the number of potential landing sites is reduced, the team has increased the investigation detail for the remaining sites and focused on quantifying uncertainties in knowledge of the state of the atmosphere. An overview of the primary data sets and atmosphere modeling tools employed by the team is presented in Section 3.

To transfer knowledge of EDL sensitivities and atmosphere state into quantifiable performance at candidate landing sites, the team developed a new process for integrating atmosphere model data and observational data into existing performance simulation tools. The process developed utilizes existing tools where possible, provides the team the ability to select the level of detailed atmosphere information to include and adds the ability to approximate atmosphere uncertainties. The process and an assessment of its strengths and weaknesses are discussed in Section 4.

Finally, plans for additional work and conclusions are presented in Sections 5 and 6.

2. EDL SYSTEM ATMOSPHERIC SENSITIVITIES

Identifying key EDL system atmospheric sensitivities enables focus on certain atmospheric phenomena. It also allows the team to limit work and resources spent on atmosphere features that do not meaningfully affect performance.

To find potential performance sensitivities, the team inspected the approximate trajectory of the vehicle through the atmosphere, looked at the vehicle's closed loop response

to certain conditions, and analyzed certain key spacecraft events with strong aerodynamic influences. Hypothetical system response cases were derived from situations experienced on other missions (not restricted to Mars landers) and were not initially restricted by atmosphere phenomena seen to date.

As with previous Mars landers, the MSL EDL system is highly dependent on atmospheric drag, both during entry and parachute descent, to slow the vehicle for a safe landing. Consequently, EDL performance is most strongly tied to atmospheric density and density structure.

Unlike previous ballistic entries such as Mars Pathfinder (MPF), Mars Exploration Rovers (MER), and Phoenix, MSL's guided entry results in an increase in the downrange flown at low altitudes as shown in Figure 1. MSL spends a significant fraction of the downrange distance flown at or near level flight at approximately 10-15 km MOLA.

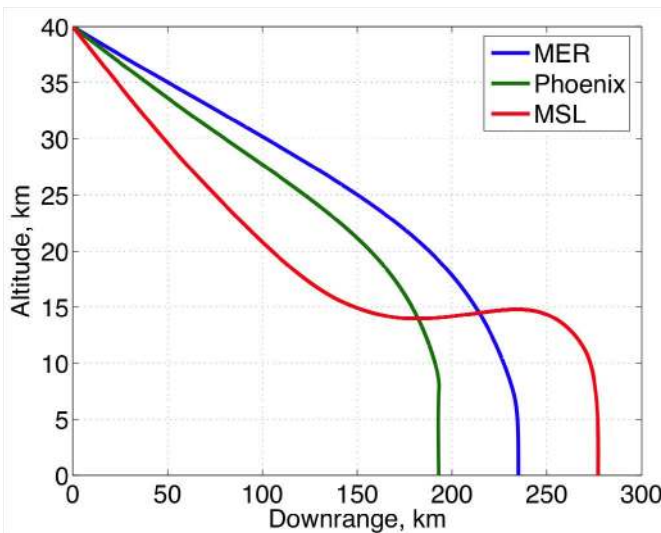


Figure 1 - Comparison of entry trajectory downrange versus altitude for MER, Phoenix, and MSL

The increase in downrange flown compared to ballistic missions suggests that the past practice of modeling atmospheric conditions using vertical profiles may mask regional variations and introduce risk to MSL. Because of the long flight time spent at 10-15 km, MSL's altitude and timeline performance are very sensitive to density conditions in this altitude region.

Like previous missions, the bulk density of the atmosphere strongly affects MSL's altitude performance because of the reliance on atmospheric drag to dissipate kinetic energy. Typically, a 10% atmosphere density reduction at altitudes below 30 km above the MOLA areoid (and especially between 10-15 km above the MOLA areoid) results in a 1 km loss of landing elevation capability. Thus, ability to

accurately predict the bulk atmosphere density is critical to determining MSL's EDL performance.

Unlike MPF, MER, and Phoenix, MSL's guided entry has a closed loop response to the atmosphere encountered. Typically, if the vehicle experiences less drag than desired, it will attempt to fly lower to seek greater atmospheric density and the accompanying increase in drag. If the vehicle experiences higher drag than desired, it will fly higher to seek lower atmospheric density. As a result, the system is sensitive not only to bulk atmospheric density, but also any density variability, e.g., in which the vehicle experiences pockets of density increases or decreases at a given altitude.

At Earth during entry, the space shuttle has experienced what have come to be known as "potholes in the sky" or regions of the atmosphere where the density changes suddenly. Since MSL's guided entry is sensitive to this type of density structure, the team performed studies to understand what type of structures significantly impact performance and where in the trajectory the system is most sensitive. Thus, the team could understand the magnitude of the threat and identify for the atmospheric scientists what features of interest should be checked for at the candidate landing sites. Density "potholes" and "speed bumps" of varying density magnitudes and spatial widths were explored in a previous publication [4]. As a result of this work, regions of interest uptrack of candidate landing sites have been examined for terrain-locked density structures.

As MSL approaches the supersonic parachute deploy event, guided entry's ability to control downrange is very limited. As a result, the vehicle is open loop in controlling downrange flown with only the capability to adjust heading slightly. The open loop nature of this "heading alignment" phase of guided entry presents additional atmospheric sensitivities. Any density or wind differences from the expected conditions will translate directly into elevation and precision performance variations. Lower than expected densities will reduce elevation performance and can also cause the vehicle to fly past the desired landing site. Higher than expected densities will increase elevation performance, but may cause landing short of the site. Vertical steady state winds will affect elevation performance depending on the duration of exposure. Similarly, horizontal steady state winds different than those expected will reduce precision performance and can also affect elevation performance by changing the effective drag on the entry capsule.

Wind conditions at the parachute deploy and heatshield separation events also present key performance sensitivities. Both events are sensitive to Mach number: parachute inflation and drag performance depend on Mach; heatshield separation safety is impacted by Mach due to reduced parachute drag near Mach 1. Winds directly impact the true Mach experienced at the events. Since MSL utilizes inertially propagated navigated velocity triggers for both

parachute deploy and heatshield separation and lacks the ability to sense instantaneous wind speeds, variations in winds from the expected condition increase the spread and distribution of Mach at the events. The ability of wind to spread Mach is evident in Figure 2 and Figure 3 below. Imposing a 25 m/s steady state horizontal wind uncertainty of uniformly varying azimuth, as shown in Figure 3, significantly spreads the Mach number at parachute deploy when compared to the nominal case, shown in Figure 2.

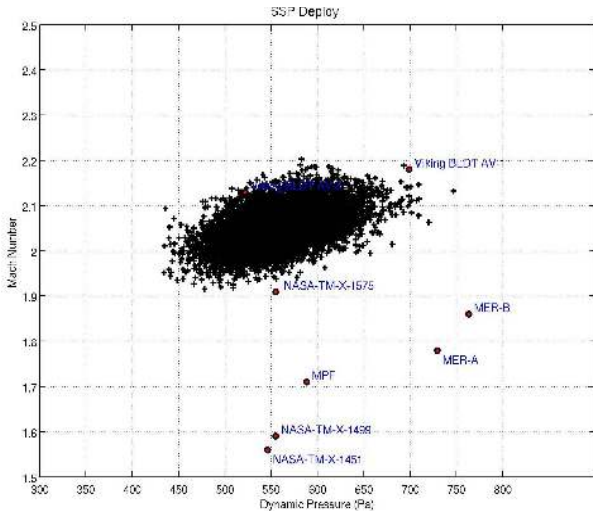


Figure 2 - Mach vs. Dynamic Pressure at Parachute Deploy with Nominal Winds

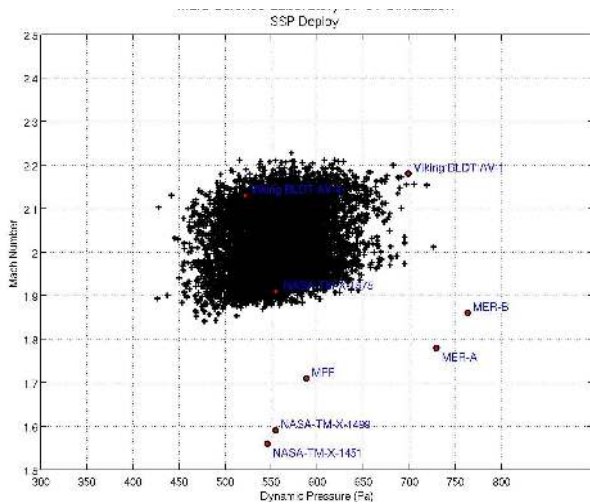


Figure 3 - Mach vs. Dynamic Pressure at Parachute Deploy with 25 m/s Steady State Winds of Uncertain Direction Superimposed on Nominal Winds

As with previous missions, wind deviations from the expected winds experienced during the parachute descent phase add additional landing precision error. Steady state wind differences from the expected winds cause position drift on the parachute. The vehicle has no ability to combat the wind drift while on the parachute and lacks sufficient

propellant to correct for any drift during powered descent. Thus, an understanding of steady state winds during parachute descent is essential in assessing landing precision, especially for lower elevation sites where the time on parachute is large.

In summary, major MSL system performance sensitivities include bulk density, local density variation, winds especially at parachute deploy, etc. Armed with the identified sensitivities, candidate landing sites, and spatial regions of interest, the team searched for applicable atmosphere data sets and models to compare potential landing sites and educate EDL performance assessments.

3. ATMOSPHERE MODELING APPROACH AND RELEVANT DATA SETS

Mars atmospheric observations, and therefore understanding and predictability, are very limited, especially at the spatial scales of interest for MSL. Additionally, the limited data sets make it difficult to directly capture the full range of atmospheric uncertainties that the EDL system must accommodate. To address the identified sensitivities, the EDL engineering/atmospheric science team has assembled an array of complementary data sets and models to characterize the atmospheric features of interest.

As noted in section 2, bulk atmospheric density, especially along the flight path where the vehicle flies horizontally, strongly affects EDL performance. Mars' axial tilt and orbital eccentricity create a significant and seasonally repeatable pressure cycle where up to 25% of the mass of the atmosphere is trapped in the winter carbon dioxide polar ice cap, with southern winter being longer and more extreme than northern. As a result, the density of the atmosphere also varies significantly with season. Capturing these bulk density changes and predicting the density for the MSL landing season is critical to assessing EDL risk.

To characterize the seasonal pressure cycle, two primary data types exist: surface pressure measurements from previous landers and radio science occultation measurements via orbiters. Viking 1 (VL1), Viking 2, MPF, and Phoenix carried instrumentation to measure surface pressure. Several orbiters, most notably Mars Global Surveyor (MGS) [5], have performed occultation observations across a range of latitudes and longitudes. Given the sparse spatial and temporal sampling of these data sets, they are used primarily as "truth points" for numerical models that explicitly simulate the CO₂ cycle.

Given its accurate instrumentation and long surface lifetime, VL1 provides the best measurements of the annual pressure cycle, though the measurements include contributions from CO₂ condensation/sublimation, planetary-scale thermal patterns and circulations, and topographic effects specific to its landing site. To predict surface pressures at other places

and elevations, global circulation models (GCMs) and certain atmospheric assumptions must be used. The breadth of available radio science measurements allows some degree of validation of the VL1 extrapolated measurements. A comparison of VL1 surface pressures and MGS radio science results as a function of solar longitude is presented in Figure 4 and shows fairly good agreement.

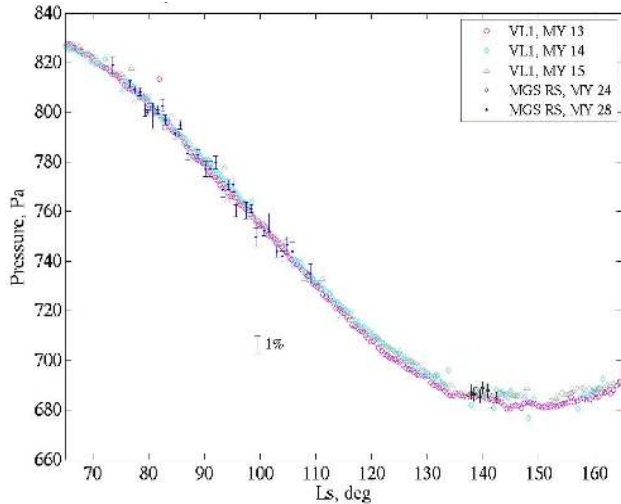


Figure 4 - Comparison of Pressures from Viking Lander 1 and Mars Global Surveyor Radio Science Measurements

The use of GCMs, validated against the VL1 pressure measurements, enables accounting for surface pressure variations with local time, latitude, and longitude that arise from thermal tides, geostrophic balance of the mean zonal winds, baroclinic eddies, stationary waves, and topographic effects. Thus, to address the EDL system’s bulk density sensitivity, the team is extrapolating VL1 data with models and validating the model results with radio science. This approach has been demonstrated with good agreement for the Phoenix landing site as shown in Figure 5.

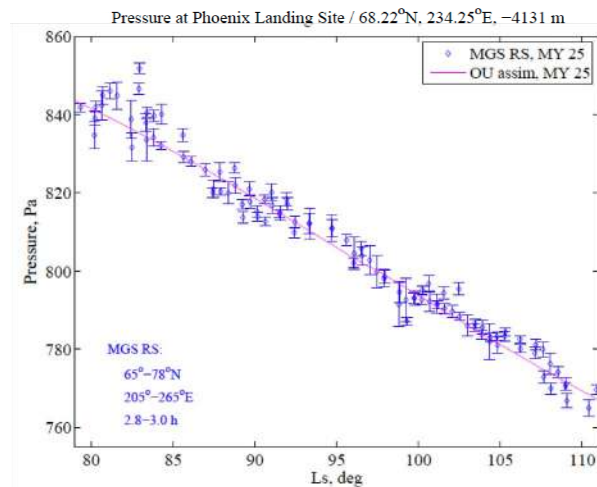


Figure 5 - Comparison of Model Predicted Phoenix Landing Site Surface Pressure vs. MGS Radio Science Surface Pressure Measurements

When compared to actual measurements taken by the Phoenix lander during its surface mission, model predicted pressures were typically accurate to approximately 1%. The team primarily uses the Open University Mars GCM for its surface pressure predictions because of the extent of its validation and its assimilation of multi-year, daily orbital measurements of atmospheric temperatures [6]. Additionally, TES assimilation in the OU GCM also allows investigation of the same period in two or three different Mars years to assess interannual variability.

As noted in section 2, MSL’s EDL sensitivities extend beyond bulk atmospheric density and include sensitivities to density structures. Atmospheric scientists have identified topography around the incoming trajectory and landing site as a likely cause of density structures that may be seen. Because of MSL’s small landing ellipse, candidate landing sites have much more topography and relief than the “big and flat” landing sites considered for previous missions. As a result, the sites are likely to strong topographically forced density and wind structures.

To capture atmospheric effects of the topography, the atmosphere must be modeled at higher resolution (e.g., down to 1 km horizontally) than used by GCMs. Consequently, the team has utilized state of the art mesoscale (regional) models to reach the necessary resolution to investigate landing site atmosphere dynamic conditions including topographic effects, diurnal forcing, stationary waves, and potential regional weather. Model developers for both the Mars Regional Atmospheric Modeling System (MRAMS), developed by Southwest Research Institute [7], and the Mars MM5 (MMM5) model, developed by Oregon State University [8], are part of the Council of Atmospheres assessing atmospheric flight risk. While both use the NASA Ames GCM for global boundary

conditions, the mesoscale calculations are independent in terms of model architecture and coding.

With the incoming trajectory azimuth to the landing site and landing season specified by mission designers, mesoscale modelers laid out increasing resolution model grids along the trajectory to capture the periods of interest as identified by EDL engineers. An example of the MRAMS mesoscale grids for a candidate landing site are shown in Figure 6. Note the bias towards the West as the vehicle's trajectory moves from West to East.

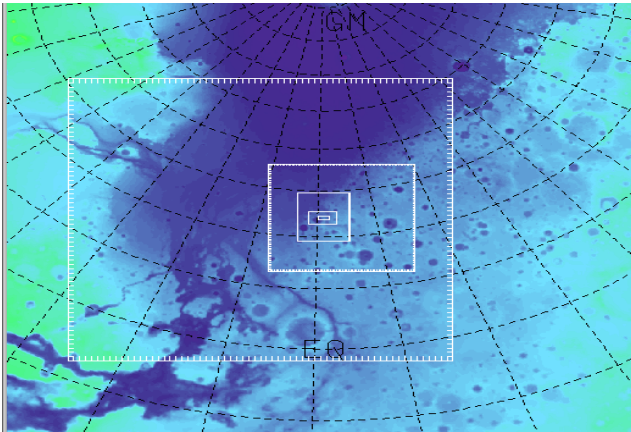


Figure 6 - MRAMS Mesoscale Grids for Candidate Landing Site

Given the state of the art nature of the mesoscale models, significant effort has been devoted to validating the atmosphere model results against observational data. Unfortunately, the atmosphere data sets are limited in size and resolution. Data from the MGS's Thermal Emission Spectrometer (TES) and Mars Reconnaissance Orbiter's Mars Climate Sounder (MCS) instruments have been compared to model output. As a result of these comparisons, small changes to the models and model parameters have been made to better match model output to observations.

As discussed in section 2, wind can also impact EDL performance. As with density structure, local topography and dynamics strongly influence wind. The resolution need to accurately model the winds necessitates the use of much higher resolution models than GCMs. Once again, mesoscale tools are appropriate. Both the MRAMS and MMM5 model have been used to generate predicted wind fields at the various candidate landing sites. An example of the wind fields predicted is shown in Figure 7.

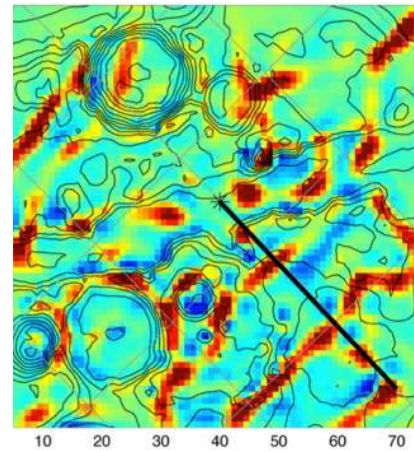


Figure 7 - Vertical Wind Fields As Modeled by MMM5 for Candidate Landing Site

Unfortunately, unlike density structure, no applicable wind data sets exist with which to validate the model outputs. Surface wind measurements from the Viking landers do not yield much insight into winds aloft and no orbiting instruments have had the capability to measure winds. Fortunately, winds aloft are primarily planetary scale circulations (e.g., similar to Hadley cells and jet streams on Earth), so there is confidence that Mars GCMs, that have evolved from Earth weather models, will result in accurate predictions of the average state over the lower part of the atmosphere (0-40 km), which is of most importance to MSL landing.

To attempt the capture the true uncertainty in possible wind and density conditions at the site, the team has attempted to use model output variability as a proxy for uncertainty. Many steps have been taken to increase the model variability to span the uncertainty in atmosphere conditions. Model conditions for candidate landing sites are sampled over a range of sols around the expected arrival date to capture seasonal variability and capture modeled weather patterns that pass through the landing site region. Additionally, on each sol, model data from several hours around the expected landing time are sampled to capture thermal tides and diurnal variability. Finally, using two different mesoscale models, each with different modeling approaches and parameter choices, extends output variability. The use of the two mesoscale models in concert with the Open University TES-assimilated GCM for validation also provides a system of checks for the model results. If a particular atmospheric feature is identified in one model and not the others, the team can investigate.

Having addressed the nominal range of atmosphere conditions via the tools discussed above, the team has also investigated the atmospheric effects of less likely events such as dust storms. Dust storms typically affect atmospheric density structure and winds, though their effects and likelihood are site dependent.

To assess the likelihood of dust events at the candidate landing sites and characterize those events, the team has used and continues to use data from MRO's Mars Color Imager (MARCI) instrument. [9] A survey of images from MARCI during MSL landing season was performed. Dust events near the candidate landing sites were identified and the size, opacity, and frequency of the events were recorded, as shown in Figure 8 and Figure 9.

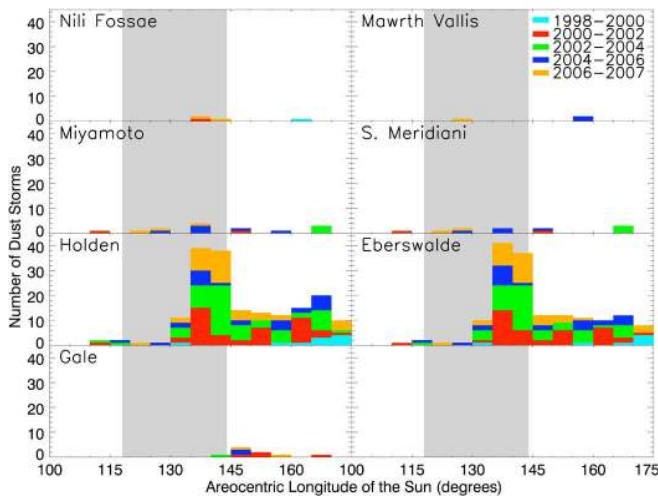


Figure 8 - Dust Storm Frequency at Candidate Landing Sites

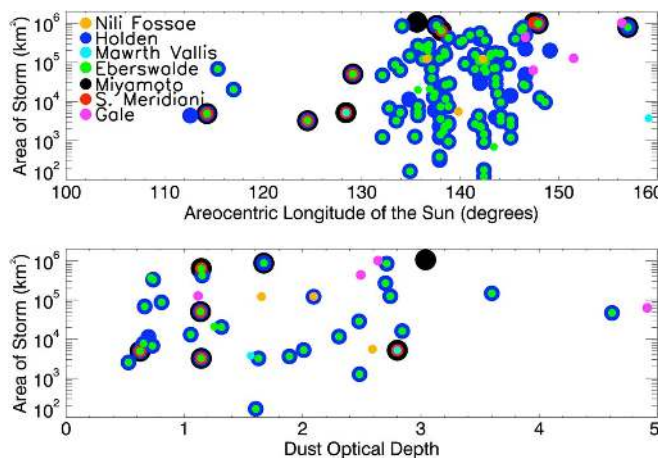


Figure 9 - Areal Extent of Dust Storms at Candidate Landing Sites

Armed with a measure of the statistical likelihood of dust events at the sites, the modeling community was engaged to help understand the effects on density and wind structure of the dust events characterized in MSL's landing season. The MARCI observational data set along with TES profiles helped modelers initialize dust effect characterization runs by allowing them to artificially introduce an appropriate amount of dust at the observed altitudes. The atmospheric dynamics introduced by the dust could then be characterized as the mesoscale models progressed. As a result, the density and wind conditions caused by dust events can be quantified. An example of the atmospheric effects of a

modeled dust event at a candidate landing site is shown in Figure 10.

Using MSL's sensitivities as a starting point, atmospheric scientists and modelers have developed the ability to characterize the range of potential atmospheric conditions of interest at the candidate landing sites. To fully assess the resultant atmospheric flight risk, the atmosphere information needs to be integrated into flight dynamics simulations to capture the end-to-end performance effects.

4. INTEGRATING ATMOSPHERE INFORMATION IN PERFORMANCE ASSESSMENTS

Because Mars relevant flight tests are virtually impossible for the MSL EDL system, characterization of EDL performance and margins is heavily dependent on Monte Carlo trajectory simulations. These simulations contain vehicle models, such as mass properties and thruster models, as well as environmental interaction models such as aerodynamics and radar/terrain models [10]. Clearly, the atmosphere is another necessary model to include.

As discussed in section 2, MSL's trajectory suggests that the past practice of using a single vertical atmosphere profile over the landing site for an entire trajectory simulation is unconservative. The mesoscale models discussed in section 3 enable sampling of different parts of the atmosphere (latitude, longitude, and altitude). Thus, the modeled atmosphere along the trajectory of the vehicle could be sampled and used.

The mesoscale model output contains information for thousands of latitude/longitude points, altitudes/pressure levels and model run times. As a result, porting all of the model output into performance simulations is prohibitive logistically, especially for Monte Carlo simulations where thousands of trajectory cases are run. If each trajectory used a full model output snapshot, runtimes and disk space limitations would present extreme challenges. To combat these problems, the team has developed a methodology that utilizes the engineering Mars Global Reference Atmosphere Model (MarsGRAM, [11]) to statistically transfer mesoscale model outputs into EDL performance simulations.

Prior to the use of mesoscale models for site-specific investigations, the MSL EDL team relied exclusively on MarsGRAM to provide approximate atmosphere conditions and uncertainties for performance simulations. As a result, EDL performance simulations already have clearly defined interfaces with MarsGRAM and its use has been extensively tested for compatibility with the performance simulations. Thus, utilizing MarsGRAM to ingest mesoscale model output data reuse a tool very familiar to the simulation developers and operators; this proved to be distinct advantage over developing new model data integration

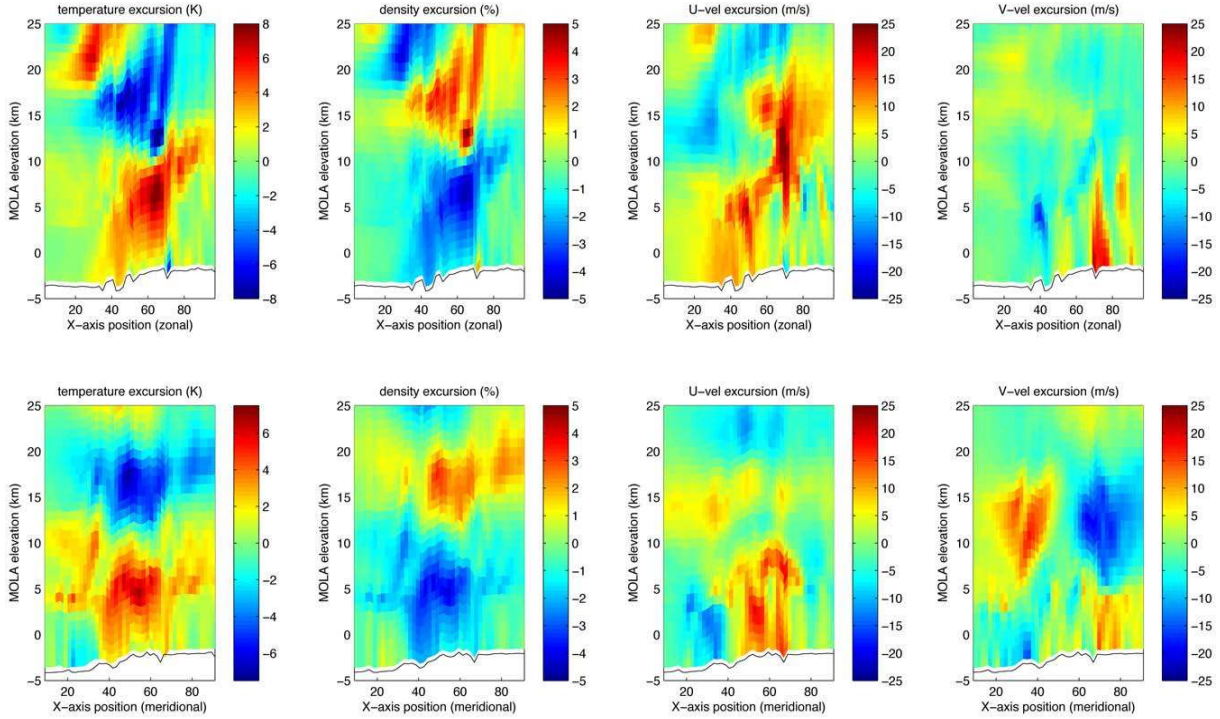


Figure 10 - Atmospheric Effects of a Dust Event as Modeled in MMM5

techniques. An overview of the technique developed is presented below; for more details, see reference [12].

Using the standard MarsGRAM atmosphere output, approximate entry trajectories can be determined. For the simplest mesoscale integration approach, vertical profiles from the mesoscale model output are sampled along the approximate entry trajectory. This greatly reduces the large quantities of mesoscale data to be ingested by the performance simulations. Because the vehicle's trajectory slows as it approaches the landing site, more vertical profiles are selected, thus leveraging the mesoscale model's high resolution and passing the high resolution information into the performance simulations. Typically, in the immediate 10 km around the landing site, mesoscale based vertical atmosphere profiles are sampled at 1 km spacings. From 10 km – 100 km from the landing site, spacing increases to ~4 km. At greater than 100 km from the landing site, profiles are 10 km apart. This sampling is shown graphically along the vehicle's trajectory in Figure 11 and Figure 12.

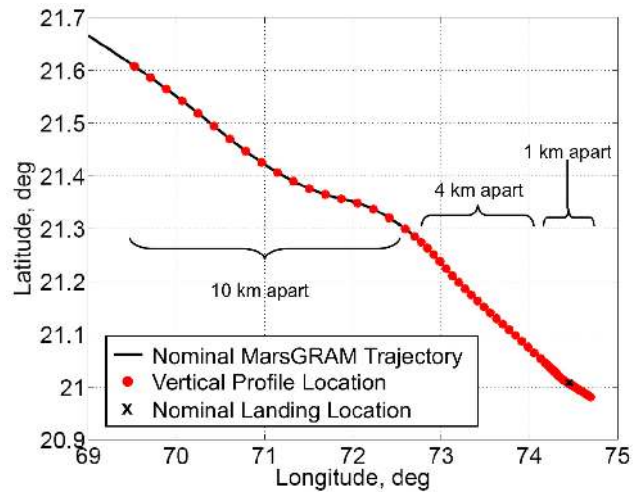


Figure 11 - Mesoscale Sampling Points Along Vehicle Trajectory

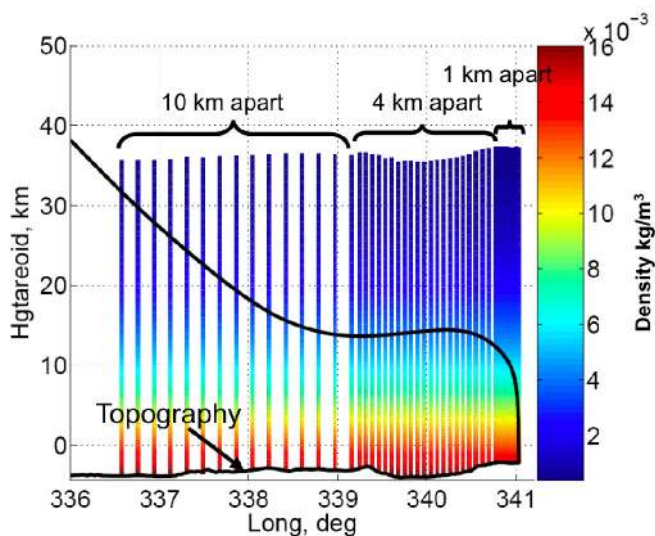


Figure 12 - Mesoscale Model Output Vertical Profile Sampling Along Vehicle Trajectory

For every available altitude in a mesoscale vertical profile, 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 10 – 20 sols around the expected entry date and placed in a multidimensional table. The standard deviations were then used to calculate the required scale factors for MarsGRAM use. As a result, the mesoscale data are captured statistically with the use of MarsGRAM and can be passed easily to the performance simulation.

Another advantage of the MarsGRAM mesoscale integration approach is the ability to use MarsGRAM scale factors to expand statistical atmosphere variations as desired to create performance stress cases. The nominal MarsGRAM approach captures the variations present in the mesoscale model raw output; increasing the resulting scale factors increases the statistical spread introduced in the performance simulations. Thus, the magnitude of density and wind perturbations can be artificially inflated to assess performance against more difficult atmosphere conditions.

To ensure that the statistical approach to capturing the mesoscale atmosphere information does not overly dilute time-consistent “real” atmosphere structures, a case-consistent modeling approach has also been developed. Instead of attempting to span the bounds of the mesoscale atmosphere data sets, the case consistent method selects a snapshot of data from the model at a particular run time sol and local time. It then captures vertical profiles not only along the nominal trajectory, but also at other latitude and longitude points alongside the nominal trajectory as shown in Figure 13. This ensures that as the vehicle moves in latitude and longitude away from the nominal trajectory that other atmosphere data points are sampled, potentially capturing terrain locked atmosphere structures.

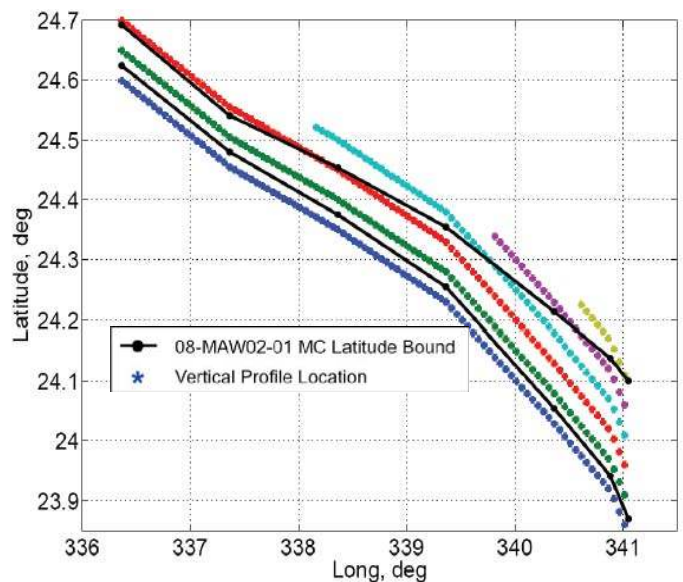


Figure 13 - Vertical Profiles Collected for Case Consistent Atmosphere Integration Approach

Using the atmosphere tables created from model output snapshot, the EDL performance simulations can be executed and the closed loop response of the vehicle to time-consistent atmosphere structures can be investigated. The case consistent approach is logistically more complicated with many more tables to build and manipulate. Also, it does not attempt to span the complete mesoscale output variability space or allow for easy construction of stress cases. Typically, the case-consistent results fall well with the performance envelope swept out by the MarsGRAM statistical approach. However, judicious use or spot-checking using the case consistent method helps to ensure that no adverse controller responses occur when the system is presented with “real” atmosphere structures as modeled in the mesoscale tools.

With the ability to insert atmosphere information into the Monte Carlo performance simulations, the full EDL performance can be interrogated. As mentioned previously, this includes analyzing the telemetry for individual cases. Additionally, key performance parameters such as parachute deploy conditions, propellant usage, and touchdown footprints statistics can be constructed from the simulation results as shown in the example in Figure 14.

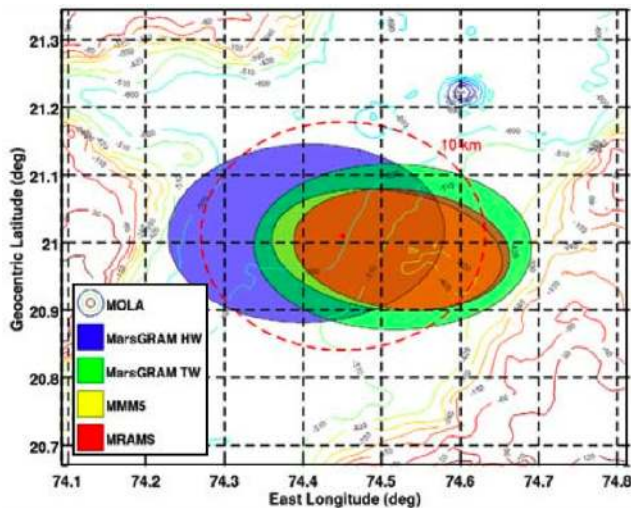


Figure 14 - Monte Carlo Touchdown Footprints for Different Atmosphere Model Sources

Monte Carlo simulation results are a primary tool in assessing EDL risk at each landing site candidate. Thus, the ability to run these simulations with good characterizations of the atmosphere is critical.

5. FUTURE PLANS

The delay of MSL's launch from the 2009 to the 2011 opportunity has required some minor rework of the atmosphere modeling and EDL risk assessment plan. Because of slight differences in the launch/arrival opportunities, the 2012 arrival is slightly later in the Martian year than the 2010 arrival would have been. As a result, the atmospheric science and modeling efforts have been refocused towards investigating the later arrival season. Mesoscale models have been rerun to target the new arrival dates. The results feed detailed EDL performance simulations that are in progress.

The launch delay does afford the team more time to improve our atmosphere modeling approaches, tools, and integration plans. This includes finalizing the surface pressure normalization procedure and incorporating data from MCS observations as post-processing methods improve. Additionally, the launch delay allows another Mars year of atmosphere observations, including another look at the projected landing season. Also, as investigations of candidate landing site become more detailed, Large Eddy Simulations (LES) will be used to better characterize wind structure at or near the landing site.

6. CONCLUSIONS

Atmospheric flight risk assessment is an essential part of the overall landing site EDL risk assessment for MSL. To address this risk, members of the EDL team and atmospheric science community have teamed up to

characterize the atmosphere and understand the performance ramifications for each candidate landing site. These efforts will enable selection of a landing site based partially on quantified atmospheric risk to safe landing.

Key system performance atmospheric sensitivities have been identified and used to guide the atmosphere characterization and modeling approach. Relevant data sets have been assembled and used to enhance state of the art modeling tools and methods in response to the system sensitivities identified. Finally, processes have been developed to integrate atmosphere information into EDL performance simulations to enable investigation of the effects of the atmosphere on the system's performance.

Over the next few years, the atmospheric risk assessment process and tools will continued to be honed in support of landing site selection in early 2011 and eventual operations and landing in the fall of 2012.

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BIOGRAPHY



Allen Chen is a systems engineer in the Entry, Descent, and Landing Systems and Advanced Technologies group at the Jet Propulsion Laboratory (JPL). On the MSL team, he is the EDL Flight Dynamics lead, co-leads the “Council of Atmospheres” team, and is the EDL Operations Planning lead. He has been a member of the MSL EDL Systems Engineering Team and the MSL Flight System Systems Engineering Team since his arrival at JPL in 2002. He holds a S.B. and S.M. in Aeronautics and Astronautics from the Massachusetts Institute of Technology and an M.B.A. from the University of California, Los Angeles.



Ashwin Vasavada is a Research Scientist in the Geophysics and Planetary Geoscience Group at JPL. He is the MSL Deputy Project Scientist and co-leads the “Council of Atmospheres” team. Additionally, he is a Co-Investigator on the Lunar Reconnaissance Orbiter Diviner Radiometer and serves on the Committee on Public Affairs of the American Geophysical Union. Previously, he has been the W. W. Rubey Faculty Fellow at the University of California, Los Angeles and an AAAS Science and Technology Policy Fellow for the United States Congress. He holds a B.S. in Geophysics and Space Physics from the University of California, Los Angeles and a Ph.D. in Planetary Science from the California Institute of Technology.



Alicia Cianciolo is an aerospace engineer at the NASA Langley Research Center. Her work primarily focuses on the flight mechanics of mission, specifically the ascent and entry, descent, and landing of various planetary missions. Her work has included flight operation for Mars Odyssey aerobraking and independent validation and verification for the EDL phase of the Mars Exploration Rovers mission. She has also been involved with work on the Mars Reconnaissance Orbiter and Mars Sample Return mission as well as Mars Scout proposals and advanced studies for defining technology requirements for next generation missions to Mars. She has a bachelor’s degree

in physics from Creighton University and a master's degree in mechanical engineering from the George Washington University.



Jeff Barnes has been involved in Mars atmospheric studies since the Viking Mission in 1977. He is an expert in atmospheric dynamics, circulation modeling, and the analysis of spacecraft data. He was a member of the Mars Pathfinder Atmospheric

Structure/Meteorology Team and a member of the Science Advisory Team that designed this instrument package. He was a Participating Scientist on the PMIRR Team for both Mars Global Surveyor and the Mars Climate Orbiter. He previously participated in the atmospheric modeling effort for the Phoenix EDL and site selection. He holds a B.S. in Physics from Iowa State University, an M.S. in Planetary Science from the California Institute of Technology, and a Ph.D. in Atmospheric Science from the University of Washington. He is a Professor of Atmospheric Sciences in the College of Oceanic and Atmospheric Sciences at Oregon State University.



Dan Tyler is a faculty research assistant at Oregon State University. He developed the OSU Mars MM5 (OSU MMM5) as part of his doctoral work at OSU under the guidance of Dr. Jeffrey R. Barnes. He is responsible for configuring and running this model as

part of the MSL EDL studies. As a post-doc at OSU he developed the OSU Mars Large Eddy Simulation (LES) model. He was a collaborator with the Phoenix team, providing mesoscale and LES model results that were used by the EDL engineering team. Dan has a strong interest in the Martian water cycle, especially as related to the North Polar Residual Cap, and is currently developing and using the OSU MMM5 in this research. He earned a BS in Mathematics from Ft. Lewis College and an MS in Meteorology from San Jose State University. It was at San Jose State in 1993 where he connected with the Mars atmospheric science community while working under Dr. R. M. Haberle. In between periods of earning degrees he has taught high school Mathematics and Physics for a total of seven years. For recreation, he has been flying hang gliders for 23 years and is currently earning his private pilot certificate.



Scot Rafkin has a strong background in Earth systems science, planetary atmosphere dynamics, cloud microphysics, and numerical modeling. He participated in and provided numerical model data for the entry, descent, and landing atmospheric hazard assessment for the Mars Exploration Rovers, Phoenix and

MSL. He is currently the Project Scientist for the Radiation Assessment Detector instrument on the Mars Science Laboratory. Dr. Rafkin has authored or co-authored over 30 journal articles and authored dozens of conference proceedings on a variety of meteorological topics for Earth and Mars, including weather forecasting and numerical weather prediction



David Hinson is a Principal Investigator at the SETI Institute. He is an expert on radio occultation sounding of planetary atmospheres, and he has participated in radio occultation experiments conducted throughout the solar system by Voyagers 1 and 2, Galileo, Magellan, and Mars Global Surveyor. He is currently a

member of the Radio Science Teams on Mars Express and New Horizons. His most recent research focuses on the weather and climate of Mars. He has authored or co-authored more than 50 journal articles.



Stephen Lewis is an Academic Fellow in the Department of Physics and Astronomy at the Open University, UK, where his research includes the application of a range of numerical models of planetary atmospheres to the study of dynamical processes and to the analysis of spacecraft observations by

data assimilation. As well as Mars, his interests include the atmospheres of Giant Planets, Venus, the Earth's paleoclimate and the atmospheres of extra-solar planets. He is a Co-Investigator on the Mars Reconnaissance Orbiter, Mars Climate Sounder instrument. Before joining the Open University, he was a University Lecturer in Atmospheric, Oceanic and Planetary Physics at the University of Oxford, a Fellow of Wolfson College, and a College Lecturer in Physics at Trinity College, Oxford. He holds an M.A. in Natural Sciences from the University of Cambridge and a D.Phil. in Atmospheric Physics from the University of Oxford.

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