Atmospheric Modeling Challenges and Measurement Requirements for Mars Entry, Descent and Landing

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Introduction: Successful aerobraking, aerocapture, and entry, descent, and landing (EDL) at Mars requires knowledge of the nominal atmospheric density as well as mesoscale and local weather conditions. Whether aerobraking at altitudes of the order 100 km, aerocapturing at 30-50 km, or performing an EDL sequence where maximum aerodynamic loads occur near 40 km followed by terminal descent to the surface, latitudinal, seasonal, diurnal atmosphere variations, and in the case of terminal descent and landing, near surface winds must all be considered to determine the nominal flight environments. Currently, uncertainties in the nominal atmospheric density associated with the engineering models[1, 2] used for aerobraking, aerocapture, and EDL mission design across these altitude bands range from 25 to 200%. Furthermore, unmodeled, short temporal and spatial scale variations can have a significant affect on the success of the mission.

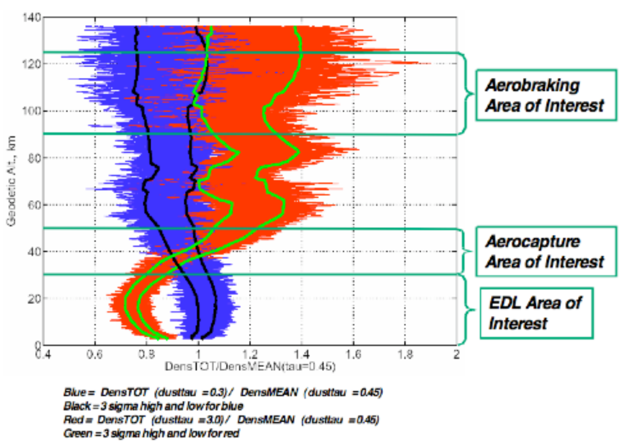

Figure 1. *Density Variability as Predicted by Mars Gram 2005*

The three Mars aerobraking orbiters (MGS, Odyssey, and MRO) have made between them approximately 2000 atmospheric passes and have provided significant data to refine the high altitude, upper atmospheric models used for aerobraking. The success of these missions and the atmospheric knowledge gained has made aerobraking at Mars a mature operational mode. The knowledge gained, which is now included in future aerobraking mission designs, includes the observation that at 100 km, density profiles have frequently doubled in 20 km of purely down track (constant altitude) motion.[3] Though smaller in relative amplitude, similar waves have been identified in the middle atmosphere during the six successful NASA EDL missions, Viking I & II, Mars Pathfinder (MPF), MER Spirit and Opportunity, and Phoenix. Several EDL missions encountered unexpectedly high winds in the lower 10 km and perhaps even clear air turbulence. Future missions with requirements for precision landing will be particularly difficult with high wind uncertainties. Wind speed impacts EDL in multiple ways, including guidance algorithm design, event trigger tuning, parachute opening loads, parachute deploy Mach number, and range to target. In order to ensure robust system level designs for successful missions, the current approach is to absorb these large uncertainties and variations using safety margins between 25 and 100 per cent, which typically translates to large increases in system mass. In addition this uncertainty may preclude the consideration of many scientifically significant landing sites. Because these large uncertainties in atmosphere models directly increase mission risk, reduce payload margins and limit potential landing sites, adequate knowledge of atmosphere properties is as fundamental to mission success, in as much as the knowledge of the strength of aluminum alloys or the space radiation environment.

The Mars atmosphere has two characteristics that significantly increase aeroassisted orbit insertion including aerobraking and aerocapture, and EDL risk. First, the atmosphere responds rapidly and dramatically to regional and global dust storms which can cause large density and wind variations throughout the entire atmosphere to 100 km and higher within a few days. Improving the physical models in general circulation models (GCMs) will be required to address this issue. Second, topographically forced winds can be greater than 10 m/s and can produce landing errors of over a kilometer during the EDL parachute phase. There is essentially no validation data for the mesoscale models (MM), which area used to generate these predictions. Atmospheric measurements to date have suffered either from lack of vertical resolution, spatial coverage (latitude and longitude) or temporal coverage (seasonal and diurnal). A global measurement campaign will be needed to improve the physics of both the GCMs and MMs.

NASA has obtained limited atmospheric data to confirm the atmospheric models at lower altitudes used in the design and evaluation of EDL and aerocapture at Mars. The six successful landers each provided accelerometer data during their respective EDL phases, which has been used to infer localized density and wind characteristics. The 2009 Mars Science Laboratory (MSL) mission has incorporated an EDL instrument suite on the entry aeroshell which includes the Mars Entry Atmospheric Data System (MEADS). This will provide a direct measurement of the atmospheric density profile during the entire entry phase though the parachute deployment. The Viking landers, MPF, and Phoenix have each provided some localized ground level data on pressure, temperature, and winds. The TES, THEMIS, and MCS instruments have provided low resolution temperature and dust characteristics, but the data gathered is insufficient to reduce the uncertainty in the density models, and provides no data to improve the wind models. This uncertainty in density and wind profiles has had significant impact on the mission design, spacecraft design and capability, mission risk, and landing site selection for the current MSL development efforts. As the landed missions evolve from MSL to larger robotic and ultimately human scale missions, it is imperative that the models of the Mars atmosphere including wind profiles be improved upon.

The quest for improved knowledge of the Martian atmosphere must be considered not only as a scientific endeavor, but also one of improving the aerocapture and EDL engineering model capabilities, and ultimately system level robustness for future large robotic and human scale missions. Doing this permits trades studies on committing resources for improving atmosphere models versus mission considerations such as payload, robustness of the control system, survivability of the aeroshell, precision of landing, landing latitude, etc. In other words, a holistic system approach is required that includes the atmosphere as one part of the engineered system. Such an approach focuses on developing technologies and a knowledge base that reduces mission cost and risk while increasing mission success. To provide the databases to perform such holistic trade studies, conceptual studies should be performed to understand the cost/benefit and requirements for future Mars atmospheric exploration missions, to define the instrument suites and data collection strategies (e.g. orbital, entry, surface), to identify missions of opportunity for complementary measurements, and to define requirements for scientific missions to Mars. This paper will describe in detail the current state of Mars atmospheric models and knowledge utilized for EDL engineering mission designs, and highlight requirements and opportunities for the Mars engineering and atmospheric science communities to work together to enhance and improve Mars Atmospheric modeling efforts

References:

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