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Atmospheric studies from the Mars Science Laboratory Entry, Descent and Landing atmospheric structure reconstruction

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ABSTRACT

The Mars Science Laboratory (MSL) entered the martian atmosphere on Aug. 6, 2012 landing in Gale crater (4.6°S, 137.4°E) in the local mid-afternoon. Aerodynamic accelerations were measured during descent and atmospheric density, pressure and temperature profiles have been calculated from this data. Using an averaging technique developed for the NASA Phoenix Mars mission, the profiles are extended to 134.1 km, twice that of the engineering reconstruction. Large-scale temperature oscillations in the MSL temperature profile are suggestive of thermal tides. Comparing the MSL temperature profile with measured Mars Climate Sounder temperature profiles and Mars Climate Database model output highlights the presence of diurnal tides. Derived vertical wavelengths for the diurnal migrating tide are larger than predicted from idealized tidal theory, indicating an added presence of nonmigrating diurnal tides. Sub-CO_2 condensation mesospheric temperatures, very similar to the Pathfinder temperature profile, allude to the possibility of CO_2 clouds. This is however not supported by recent observations and models.

1. Introduction

The Curiosity rover, the centerpiece of the Mars Science Laboratory (MSL) mission, successfully landed on Mars on August 6, 2012 at 05:18 UTC. Landing occurred on Ls = 150.7°, MY 31 in the local afternoon (15:03 Local Mean Solar Time (LMST), 15:36 Local True Solar Time (LTST)) at a radius of 3391.13 km for the landing site in Gale Crater (4.6°S, 137.4°E, ~4.5 km below the MOLA aeroid) (Withers, 2012; Way et al., 2013; Karlgaard et al., 2014; Kornfeld et al., 2014).

MSL's entry into the atmosphere of Mars was unprecedented in many ways: largest entry mass, largest aeroshell, smallest landing ellipse, and largest lift-to-drag ratio (Dyakonov et al., 2007). Consequently, its entry system is distinctly new, rather than a simple scaling-up from the designs of past landers. During its hypersonic entry phase, the MSL entry vehicle flew at a non-zero angle of attack and had a much larger lift-to-drag ratio than any lander since Viking. Pathfinder, Spirit, Opportunity, and Phoenix all flew at near-zero angles of attack with negligible lift (Dyakonov et al., 2007; Karlgaard et al., 2014). For MSL, the direction of its lift vector was not fixed. Instead, it was actively adjusted during entry by a reaction control system in order to achieve the desired trajectory (Karlgaard et al., 2014). As a result, MSL was the first Mars lander since Viking to experience a substantial period of near-horizontal flight towards the end of its hypersonic entry phase.

Data from the Entry, Descent, and Landing (EDL) of the MSL spacecraft have been used to obtain a profile of martian atmospheric density, pressure, and temperature from 134.1 km to 12.1 km above the surface with excellent sub-km vertical resolution.

The thermal structure of the martian atmosphere is sensitive to radiative forcing from suspended dust and to diabatic heating associated with atmospheric dynamics (Zurek et al., 1992). It is also perturbed by a wide variety of waves and tides. Although a single profile of atmospheric temperature seems trivial by comparison to the vast number of Mars Global Surveyor Thermal Emission Spectrometer and Mars Reconnaissance Orbiter (MRO) Mars Climate Sounder (MCS) profiles, the unsurpassed vertical range and resolution of entry profiles continues to make them scientifically valuable at Mars. Their "whole atmosphere sampling" of thermal structure, their surface-to-thermosphere sampling of atmospheric tides, and their ability to characterize small-scale gravity waves are all useful contributions to Mars science.

Section 2 describes how an atmospheric profile was obtained from entry data, Section 3 reports the findings of scientific analysis

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of that atmospheric profile, and Section 4 presents the conclusions of this work.

2. Trajectory and atmospheric structure reconstruction

2.1. Trajectory reconstruction

The MSL spacecraft carried an inertial measurement unit (IMU) that measured the 3-axis linear acceleration and 3-axis angular velocity at 200 Hz throughout the entire period of atmospheric flight (popularly known as the seven minutes of terror). Integrating these measurements forward in time from an initial entry state at the top of the atmosphere yields a time series of spacecraft position and velocity. This task was performed by the project engineers and the reconstructed trajectory is reported and discussed in Karlgaard et al. (2014) and Dutta and Braun (2014). This reconstructed trajectory, which is available as a SPICE kernel (http://naif.jpl.nasa.gov/pub/naif/MSL/kernels/spk/msl_edl_v01.bsp), is shown in Fig. 1. Note that all heights in this paper should be interpreted as radial distance above the landing site, whose radial distance from the center of mass of Mars is 3391.1 km (Dutta and Braun, 2014). Note also that all times in this paper are referenced to the time when data was first collected at Spacecraft Clock Time 397501174.997338s (Dutta and Braun, 2014; Karlgaard et al., 2014). With these conventions, atmospheric entry (defined as a radial distance of 3522.2 km) occurred at a time of 540 s and a height of 131.1 km, whereas parachute deployment occurred at a time of 799 s and a height of 12.1 km. The period of horizontal flight at about 18.4 km height, between 640 s and 720 s, is a striking feature of the trajectory, during which MSL flew 105.3 km horizontally.

2.2. Information required for atmospheric reconstruction

In addition to the trajectory information, an atmospheric reconstruction requires the measured aerodynamic accelerations. As spacecraft accelerations are proprietary information, systems engineer Allen Chen (JPL) supplied us with time series of the 3-axis linear accelerations experienced at the spacecraft's center of mass in the Descent Stage frame, spacecraft position and velocity in the J2000 frame, and the quaternion matrix linking the J2000 and Descent Stage frames. J2000 is an inertial reference frame fixed with respect to the positions of the vernal equinox and the Earth's equator at epoch J2000 (http://naif.jpl.nasa.gov/pub/naif/toolkit_docs/Tutorials/pdf/individual_docs/17_frames_and_coordinate_systems.pdf). The Descent Stage frame is a non-inertial reference frame, fixed with respect to the Curiosity rover inside the MSL entry vehicle (http://naif.jpl.nasa.gov/pub/naif/MSL/kernels/fk/msl.tf). These 200 Hz acceleration data were used in the work reported here.

The final reconstruction results are most useful in a Mars-centric spherical coordinate system rotating with the planet, as per previous reconstruction efforts (Magalhães et al., 1999; Withers and Smith, 2006; Withers and Catling, 2010). Accordingly, we calculated time series of latitude, longitude and radial distance from the center of mass of Mars from the J2000 trajectory using SPICE routines and kernels.

The atmospheric reconstruction requires knowledge of two additional quantities which can be calculated from the available information: the speed of the spacecraft relative to the atmosphere (v_{rel}) and the (total) angle of attack (α). By assuming that the atmosphere of the planet is rotating with the same angular velocity as the interior of the planet, v_{rel} is calculated by subtracting the rotational speed of the planet at the appropriate latitude and radial distance from the spacecraft velocity relative to the center of mass of the planet. The total angle of attack is simply the angle between the vector v_{rel} and the spacecraft symmetry axis, which is fixed in the Descent Stage frame.

2.3. Enhanced aerodynamic accelerations

For atmospheric reconstruction the most important component is the axial acceleration, which is shown in Fig. 2. Instrument digitization and noise render the measured accelerations unusable for reconstruction prior to 570 s, equivalent to a height

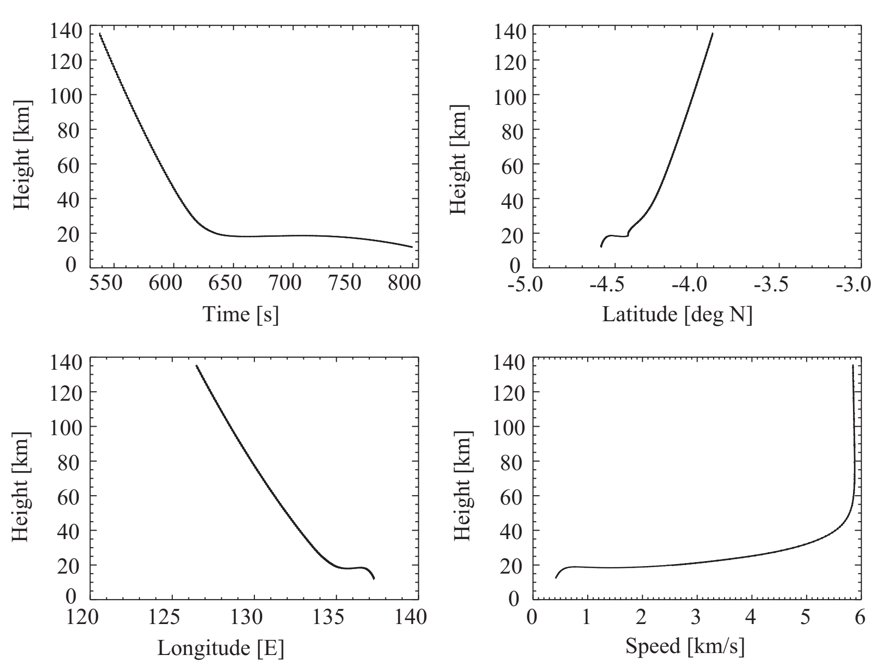

Fig. 1. MSL entry trajectory (time, latitude and longitude) and spacecraft speed as a function of height above the landing site from atmospheric entry to parachute deployment. The horizontal flight period is clearly visible just below 20 km height.