Mars Exploration Rovers Entry, Descent, and Landing Navigation

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Darren Baird (Lead),
Tim McElrath, Michael Watkins, Louis D'Amario, Joseph Guinn, Brian Portock, Eric Graat, Geoffrey Wawrzyniak, Philip Knocke
Jet Propulsion Laboratory, California Institute of Technology,
Pasadena, CA 91109-8099

Extended Abstract

During the final approach and Entry, Descent and Landing (EDL) of both Mars Exploration Rovers (MER), one-way Doppler were monitored to detect, in real-time, the following events:

1) transition from the cruise stage Medium Gain Antenna (MGA) to the cruise stage Low Gain Antenna (LGA)
2) turn-to-entry attitude
3) venting of the Heat Rejection System (HRS)
4) cruise stage separation
5) atmospheric deceleration
6) parachute deploy, which was only detectable by the loss of lock on the carrier.

In addition, an attempt was made to ascertain, in near real-time, the relative density of the atmosphere with respect to the nominal predicted density.

Detection of each event was complicated by several factors, including oscillator instability, acceleration, temperature changes caused by cycling of the HRS thermal valve, pressure effects, and Allen variance. These factors resulted in signatures that could not be modeled predictively. Nonetheless, an understanding of the expected Doppler signatures and the distinct Doppler pattern caused by each event enabled the Navigation team to detect each event without difficulty.

Residual Dispersion Analyses

The successful detection of each event was based on comparing one-way Doppler data during each event to one-way Doppler residuals obtained from analyses that modeled variations in entry flight path angles. All the events, except for HRS venting, were modeled in a simulated reference trajectory with a nominal flight path angle. By passing the reference trajectory through simulated truth trajectories that modeled nominal, ± 1-σ, ± 2-σ, and ± 3-σ flight path angles, a range of residual dispersions that the Navigation team could expect to observe during EDL was determined.

Real-time Detection of Events

The transition from two-way Doppler to one-way Doppler was one of the easiest events to detect in real-time. In addition to the obvious change in data type, a large bias in the Doppler display was expected due to limitations of the one-way Doppler display.

In an ideal world, the turn-to-entry attitude would have been easily discernable due to the increasing amplitude of the spin signature as a result of the increasing Earth aspect angle. In flight, the signature caused by the oscillator instability and the cycling of the HRS thermal valve made it difficult to detect a change in amplitude. However, a special feature of the one-way Doppler display was used to compute the amplitude of the spin signature over short time periods, which allowed the Navigators to determine a rough estimate of the Earth aspect angle at arbitrary times during the turn.

The signature caused by HRS venting could not be modeled predictively, but the 6-minute oscillations disappeared as a result of HRS venting, providing Navigation with an indirect means of detecting this event.

Cruise stage separation was characterized by a short data outage due to the time required for the backshell LGA to become visible to Earth and additional time for the Deep Space Network (DSN) to lock onto the carrier. Because HRS venting occurred 15 minutes prior to cruise stage separation, no large oscillations were apparent that could mask the expected Doppler shift due to the ΔV imparted on the entry vehicle.

During the ~4.1 minutes from entry until parachute deploy, atmospheric deceleration was characterized by a -138 kHz Doppler shift for MER-A and a -120 kHz Doppler shift for MER-B. This event was unmistakable, and the large ΔV dominated the second-order effects caused by oscillator instability, acceleration, temperature effects, pressure effects, and Allen variance on the small deep space transponder.

A loss of lock on the carrier by the Block-V receiver at the DSN was expected at and indicative of parachute deploy. By determining that loss of lock occurred between the nominal predicted parachute deploy time and the latest time that the backup timer would have deployed the parachute, it was possible to conclude with reasonable confidence that parachute deploy occurred.

Determination of Relative Atmospheric Density

A near real-time determination of the atmospheric density was attempted by comparing the observables from differenced one-way Doppler, also known as interferometric narrowband spacecraft Doppler, to predicted observables computed from trajectories that modeled positive 3-σ and negative 3-σ atmospheric column densities. For MER-A, the variation in density from entry until parachute deploy made it difficult to determine the average atmospheric density relative to the predicted nominal density. For MER-B, the Navigation team determined, in near real-time, that the average atmospheric density was less than the predicted nominal density by approximately 1.5-σ.

Summary

For both MER-A and MER-B, the Navigation team successfully detected the transition from the cruise stage Medium Gain Antenna to the cruise stage Low Gain Antenna, the turn-to-entry attitude, venting of the Heat Rejection System, cruise stage separation, atmospheric deceleration, and parachute deploy in real-time using only one-way Doppler. For MER-A, the average atmospheric density was difficult to determine using only Doppler data, but for MER-B the Navigation team was able to assess, in near-real time, that the average atmospheric density was less than expected.

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Condensed Abstract

During final approach and Entry, Descent, and Landing (EDL), the Mars Exploration Rovers (MER) Navigation team was tasked with detecting, in real-time, the following events for MER-A and MER-B: transition from the cruise stage Medium Gain Antenna to the cruise stage Low Gain Antenna, turn-to-entry attitude, venting of the Heat Rejection System, cruise stage separation, atmospheric deceleration, and parachute deploy. In addition, an attempt was made to ascertain, in near real-time, the relative average density of the atmosphere with respect to the nominal predicted density. This paper describes the analyses and processes required for the successful detection of these events. It also provides a comparison of the results from the pre-arrival analyses to the Doppler data seen during final approach and EDL on both spacecraft.