Mars Exploration Rover Cruise Orbit Determination

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Extended Abstract

After 3 years of development the first Mars Exploration Rover (MER) mission known as MER-A began with the lift-off of its first spacecraft containing the rover Spirit. Just under one month later the second Mars Exploration Rover mission, known as MER-B launched carrying the rover Opportunity into orbit on its way to Mars. Immediately after each spacecraft separated from the launch vehicle third stage and started sending a signal to Earth, the MER navigation team began work to determine each orbit toward Mars. The primary goal of the navigation team was to accurately deliver each spacecraft to the desired landing site. In order to deliver the spacecraft to the correct landing site the navigation team needed to determine the orbit of the spacecraft very accurately using radiometric tracking data and predict the atmospheric entry conditions. This is the process of orbit determination or OD and is only one part of the overall navigation process, which also includes maneuver design and landing site targeting. This paper will describe the results of the orbit determination process for each mission, MER-A and MER-B, during their cruise phase to Mars ending with there final approach to Mars atmospheric entry.

Launch Orbit Determination

The purpose of OD directly after launch is to aide the Deep Space Network (DSN) in acquiring the initial signals from the spacecraft after it separates from the launch vehicle. The initial acquisition of signal is generally based on the launch vehicles predicted trajectory. The navigation team does receive state estimates from the launch vehicle's telemetry at multiple points during the launch trajectory. This data is analyzed and can be used to aide the DSN in acquiring the signal. Even if the initial spacecraft signal is acquired nominally, the angular position of the spacecraft needs to be determined to ±0.032 deg (the 34 m –3 db half-cone beamwidth) or the launch vehicle injection errors would grow to the point that next the DSN complex attempting to acquire the signal may be unsuccessful, causing a mission failure. The primary job of the OD analysts on the navigation team after launch is to update the spacecraft trajectory based on angle, Doppler, and range data to guarantee signal acquisition at the second DSN station rise.

In the case of MER-A and MER-B launches, no action was taken based on the launch vehicle telemetry data. The DSN successfully acquired the signal from each spacecraft within minutes of the predicted time. At the time of signal acquisition angle data and one-way Doppler data was collected. After the operations team established a two-way coherent uplink with the spacecraft, two-way Doppler began being collected. Finally after the spacecraft was deemed to be in a healthy state two-way ranging was established and began being collected from the spacecraft. Using this data and trajectory models, the angular position of MER-A and MER-B were determined such that the 2nd station acquisition went smoothly.

Cruise Orbit Determination

The primary purpose of cruise orbit determination is to reconstruct the spacecraft trajectory in the past and predict it forward to Mars. This needs to be done to an accurate enough level to perform trajectory correction maneuvers (TCM) that correct injection bias, launch vehicle injection error as well as subsequent TCM execution errors. The secondary purpose of cruise orbit determination is to improve the trajectory modeling such that we can accurately target the Mars atmospheric interface point during the approach phase.

There are three TCMs that fall in the cruise phase. The first TCM (known as TCM-A1 for MER-A and TCM-B1 for MER-B) primarily removes the launch vehicle injection bias and launch vehicle injection errors. The launch vehicle injection bias is used to insure that the launch vehicle third stage is not injected into a Mars impacting trajectory. TCM-A2 and TCM-B2 mainly clean up from TCM-1 execution errors. Similarly TCM-A3 and TCM-B3 correct OD and execution errors from TCM-2.

There were two major model verification activities during the cruise phase, an attitude change ΔV calibration and a spacecraft solar radiation pressure analysis. Shortly after launch we performed a calibration of the turns to measure that the amount of residual ΔV imparted to the trajectory from using spacecraft thrusters to perform the turn. The spacecraft has to perform turns every so often (about 1per month) to keep the communication antenna pointing at Earth and the solar arrays point close to the Sun. The turns are done with a set of balanced thrusters on the spacecraft but with miss-alignments and center of mass uncertainty the turns could impart ΔV. Prior to launch this ΔV was predicted to be as much as 3 mm/sec, which was high enough to make it the most significant error source in the pre-launch OD analysis. The calibration showed the actual ΔV per turn to be much less which contributed to a reduction in the OD uncertainty prior to each maneuver. The MER-A residual turn ΔV was estimated from the calibration to be approximately 0.05 mm/sec per axis for a 10-degree turn. The corresponding MER-B estimate was slightly larger reaching 0.1 mm/sec for the out of trajectory plane component.

The solar radiation pressure model was the second major model that was verified during the cruise phase. Our model consisted of 3 components representing the spacecraft. The model included a cylindrical component which combined a cylindrical spacecraft feature called the HRS panels surrounding the cruise stage with the cylindrical like shape of the heat shield at the point where the heat shield mates with the backshell. The second and largest component model was a flat plate model, which represented the top of the cruise stage including the solar arrays and launch vehicle adaptor plate. The third component that needed to be modeled was the conical backshell that was partially shaded by the cruise stage. Our software did not support a specific cone model nonetheless the shading on the backshell by the cruise stage. A look up table model was used which modeled the solar radiation of the backshell as a function of solar aspect angle to calculate the amount of sun light incident on a cone the same dimensions as the backshell. The navigation team used information about the component physical properties to estimate the reflectivity coefficients of each component. The team also used information about the thermal properties of the spacecraft in order to take into account any re-radiation effects from the spacecraft. The diffuse reflectivity coefficient on the cruise stage flat plate component was increased due to re-radiation of heat out the cruise stage, which was absorbed by other components such as the backshell. This amount of re-radiation was also accounted for as a function of solar aspect angle. This model was verified during the cruse phase and was performing very well. No significant adjustments were made.

The cruise OD analysis went very well using the models described above. The OD knowledge prior to each of the cruise TCMs was significantly smaller than the amount of correction made by the maneuvers. The results for MER-A are shown in B-plane coordinates below. The OD and TCMs performed so well for MER-B that TCM-B3 was canceled.

Approach Orbit Determination

The primary goal of approach orbit determination was to refine the models such that the spacecraft could be delivered to the atmospheric interface (Mars radius of 3522.2 km) with an entry flight path angle (FPA) of –11.5 deg ±0.12 deg (3σ) for MER-A and ±0.14 deg (3σ) for MER-B. The data types used in the approach phase consisted of two-way Doppler, two-way range, and delta-differenced one-way range (ΔDOR). ΔDOR is an interferometric measurement based on a one-way tone from the spacecraft and transmissions from quasars, which when received by two DSN complexes are differenced. ΔDOR is a measure of the angular position of the spacecraft in the plane of sky relative to the known position of a quasar. For the MER spacecraft this measurement was good to 4.5 nrad in the plane of sky, which translates to just under 1 km at Mars. ΔDOR along with the Doppler and range data is very powerful for OD. During the approach phase both spacecraft held continuous DSN coverage for Doppler and range data and collected as much as 2 ΔDOR measurements per day.

Three TCMs (TCM-4, TCM-5, TCM-6) were planned during the approach phase for both spacecraft. TCM-4 at entry minus 8 days was used to clean up OD and execution errors that were propagated from TCM-3 and to precisely target the entry conditions. The purpose of TCM-5 at entry minus 2 days was to further refine the targeting after TCM-4 with the latest OD knowledge to meet the entry interface FPA requirements. TCM-6 at entry – 4 hours was only planned for use in case there was a major error in the OD that was realized as the spacecraft reached deep enough into the Mars gravity well. For both MER-A and MER-B the OD and TCM-4 performed well enough to cancel TCM-5.

Following TCM-4 the estimated entry points for both MER-A and MER-B were well within the required delivery ellipse. In the time between TCM-4 and TCM-5 the OD solution were extremely stable such that at the time of the scheduled TCM-5 decision meeting the MER-A FPA results were -11.486 deg ±0.028 deg (3σ) well with the ±0.12 deg prediction. The MER-B FPA results were –11.464 deg ±0.035 deg (3σ) well with the ±0.14 deg prediction. Sine both spacecraft were well within the desired FPA corridor at the TCM-5 decision point and the uncertainties were well better than predicted, the decisions were made to cancel those maneuvers.

TCM-6 was scheduled to only be executed in the case where there was a gross OD modeling error which was realized late in the trajectory, within 1 day of entry as the gravity of Mars took hold of the spacecraft and dominated the dynamics. The OD solutions were very stable in the time between the TCM-5 decision and the TCM-6 decision. The MER-A entry flight path angle estimate only varied by 0.005 deg from the TCM-A5 decision value during the time from the TCM-A5 decision to the TCM-A6 decision. The MER-B FPA estimate only varied 0.001 deg from the TCM-B5 decision value. Again both spacecraft were well within the FPA corridor, no gross OD modeling error existed and therefore no TCM-6 maneuver was executed on either spacecraft.

Another use of the OD solutions was to refine the parameters used in the spacecraft entry, descent, and landing (EDL) software. The algorithms used in the EDL software to decide when to deploy the parachute depended on the estimated time of entry, the entry FPA, and the entry FPA dispersion. The operations team scheduled multiple times to update the EDL parameters during the approach phase. Mainly the parameter updates were scheduled after TCMs so that as soon as the trajectory was changed due to a TCM the EDL parameters were updated to reflect that change. As TCM-5 and TCM-6 were canceled the EDL parameter updates remained and the decision of whether or not to update the spacecraft's parameters was made after new parameters were calculated based on the latest OD solution. The OD solutions were stable enough so that no EDL parameter updates were made based on changes in entry state estimates. All the updates were due to either refinement in the atmosphere model or in the EDL system modeling.

Summary

After seven months of travel and 4 trajectory correction maneuvers on MER-A and only 3 trajectory correction maneuvers on MER-B, the MER navigation team delivered each spacecraft safely to there corresponding atmospheric interface points to within 0.006 deg ±0.010 deg (3σ) for MER-A and 0.03 ±0.021 deg (3σ) for MER-B. Along the way the OD uncertainty results were well within pre-launch predicted values, which allowed the team to identify a DSN station location error, estimated for solar plasma effects on the data, and refine the spacecraft dynamic models. All of this effort paid off ten fold on January 3 and January 24, 2004 when the Spirit and Opportunity spacecraft safely landed on the surface of Mars only ~10 km and ~12 km down-track of the target respectively.

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Condensed Abstract

The Mars Exploration Rover project consisted of two missions (MER-A and MER-B) that launched spacecraft on June 10, 2003 and July 8, 2003 respectively. The spacecraft arrived at Mars approximately seven months later on January 4, 2004 and January 24, 2004. These spacecraft needed to be precisely navigated to a Mars atmospheric entry flight path angle of –11.5 deg ±0.12 deg (3σ) for MER-A and ±0.14 deg (3σ) for MER-B in order to satisfy the landing site delivery requirements. The orbit determination task of the navigation team needed to accurately determine the trajectory of the spacecraft, predict the trajectory to Mars atmospheric entry and account for all possible errors sources so that the each spacecraft could be correctly targeted using 5 trajectory corrections along the way. This paper describes the analysis which allowed the first spacecraft, MER-A to be targeted using only 4 trajectory correction maneuvers to an entry flight path angle of –11.494 deg ±0.010 deg (3σ) and the second spacecraft (MER-B) to be targeted using only 3 trajectory correction maneuvers to an entry flight path angle of -11.470 ±0.021 deg (3σ).