MARS SCIENCE LABORATORY NAVIGATION RESULTS

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Abstract: *The Mars Science Laboratory (MSL), carrying the Curiosity rover to Mars, was launched on November 26, 2011, from Cape Canaveral, Florida. The target for MSL was selected to be Gale Crater, near the equator of Mars, with an arrival date in early August 2012. The two main interplanetary navigation tasks for the mission were to deliver the spacecraft to an entry interface point that would allow the rover to safely reach the landing area, and to tell the spacecraft where it entered the atmosphere of Mars, so it could guide itself accurately to close proximity of the landing target. MSL used entry guidance as it slowed down from the entry speed to a speed low enough to allow for a successful parachute deployment, and this guidance allowed shrinking the landing ellipse to a 99% conservative estimate of 7 by 20 kilometers. Since there is no global positioning system in Mars, achieving this accuracy was predicated on flying a trajectory that closely matched the reference trajectory used to design the guidance algorithm, and on initializing the guidance system with an accurate Mars-relative entry state that could be used as the starting point to integrate the inertial measurement unit data during entry and descent. The pre-launch entry flight path angle (EFPA) delivery requirement was ±0.20°, but after launch a smaller threshold of ±0.05° was used as the criteria for late trajectory correction maneuver (TCM) decisions. The pre-launch requirement for entry state knowledge was 2.8 kilometers in position error and 2 meters per second in velocity error, but also smaller thresholds were defined after launch to evaluate entry state update opportunities. The biggest challenge for the navigation team was to accurately predict the trajectory of the spacecraft, so the estimates of the entry conditions could be stable, and late trajectory correction maneuvers or entry parameter updates could be waved off. As a matter of fact, the prediction accuracy was such that the last TCM performed was a small burn executed eight days before landing, and the entry state that was calculated just 36 hours after that TCM, and that was uploaded to the spacecraft the same day, did not need to be updated. The final EFPA was 0.013° shallower than the -15.5° target, and the on-board entry state was just 200 meters in position and 0.11 meters per second in velocity from the post-landing reconstructed entry state. Overall the entry delivery and knowledge requirements were fulfilled with a margin of more than 90% with respect to the pre-launch thresholds. This excellent accuracy contributed to a very successful and accurate entry, descent, and landing, and surface mission.*

Keywords: *Mars, navigation.*

1. Introduction

The Mars Science Laboratory, carrying the Curiosity rover, was launched on November 26, 2011, from Cape Canaveral, for an August 6, 2012 landing on Gale Crater. The Curiosity rover is the heaviest vehicle ever landed on Mars, and it was delivered to its surface using an innovative entry, descent, and landing (EDL) system [1]. The challenge for the navigation team was to deliver the spacecraft to the right atmospheric entry interface point, and to tell it where it was as it reached this point, so it could safely and accurately guide itself to the proximity of the selected landing target. The landing target coordinates were chosen based on the best estimate of the performance of all the components contributing to the landing dispersion. The target needed to be as close as possible to the area that the scientist wanted to explore, while at the same time ensuring that the vehicle would successfully land with a high confidence level. Descent, landing, and surface mobility hazards had to be assessed around the proposed landing zone and a number of landing targets were evaluated using the criteria previously outlined.

One of the innovations of MSL with respect to previous Mars landers was the use of guided lifting during the main deceleration phase of EDL. This allowed for a significant reduction in the size of the landing ellipse, and also prompted a change in the relationship between entry delivery errors and landing position errors. Unlike previous missions, the location of the landing ellipse did not depend directly on where the vehicle entered the atmosphere of Mars, but on how well was that entry point known by the spacecraft. Guidance allowed for a reduction in the landing ellipse from the 10 by 80 kilometers ellipses of the MER rovers [2], to just 7 by 20 kilometers. In a first approximation, and assuming that the atmospheric delivery was done with sufficient accuracy, that ellipse size was not affected by navigation delivery errors. Entry knowledge errors affected the ellipse size in two ways. The uncertainty of the exact entry point would contribute to the ellipse size, but since it was combined with other error contributors, such as initial attitude error or atmospheric conditions, at the expected performance levels it did not have a significant contribution to the ellipse size. On the other hand, a known entry delivery error, if not communicated to the spacecraft, would shift the predicted ellipse by a known amount.

The challenge for the MSL navigation team was to accurately predict the trajectory of the spacecraft over the last few weeks up to entry. For the last 45 days, Doppler and range data was collected almost continuously, and for the last 28 days, Delta Differenced One-way Range (DDOR) sessions were performed twice a day, at the overlaps between the Madrid and Goldstone, and Goldstone and Canberra Deep Space Network (DSN) complexes; the forces acting on the spacecraft, gravitational and non-gravitational, were assessed and accurately modeled; the latest ephemeris of Mars relative to the Earth were used; and tracking of the Mars orbiters was used to verify the level of accuracy of the MSL trajectory relative to Mars.

2. Mission Overview

The primary objective of the MSL Project was to land a sophisticated, mobile, analytical laboratory at or near a target of high scientific value in the surface of Mars, in order to assess the area as a potential habitat for life, past or present [3]. MSL used an advanced EDL system that allowed for an increased landed mass over the previously used airbag or retrorocket systems, and much higher surface delivery accuracy, while minimizing landing dispersions to be able to use a smaller landing zone close to terrain of high scientific interest. This required a more accurate delivery of the spacecraft to the entry interface, and a late update of the spacecraft state at entry, which was used to initialize the descent guidance system.

After several down selections of the launch/arrival period [4], the MSL project decided on a 24-day launch period, starting on November 25, 2011, with a Type 1 Earth-Mars trajectory, and a fixed arrival date of August 6, 2012. This launch/arrival combination provided dual Mars orbiter EDL relay coverage without requiring large changes in the orbital nodes of the orbiters.

In the about eight months from launch to arrival, a total of six maneuver opportunities were scheduled to remove the injection bias, and to target to the entry aim point for the final landing site. From many landing sites proposed by scientists, a final set of four possible sites were chosen on May of 2010, ranging in longitude from -45°E to 137°E, and in latitude from 27°S to 24°N. Gale Crater at about 137.42°E and 4.49°S was finally selected on July 2011. The mission design and navigation team had to provide targets to the launch vehicle provider that would allow for retargeting to any of the four landing sites. A central landing site was used to generate the targets, and analyses were performed to ensure that all sites could then be reached within the available cruise propellant [5].

The mission started with the Cruise phase, right after launch, followed by the approach phase, starting 45 days before entry, which ended with the EDL event. The MSL EDL system built on the heritage from Apollo, Viking, and MER, among others. The lifted guidance algorithm used during the main deceleration phase was based on the algorithm used for Apollo reentry. Lift was used by Viking to prolong deceleration, and the 21.5 m disk-gap parachute used by MSL is an extrapolation of the 16.5m parachute used by Viking. The MSL cruise stage design is basically a scaled-up version of the one used on Mars Pathfinder and MER, while the transition for approach to entry is based on MER. An innovative component of the MSL landing system was the Sky Crane maneuver. Mars Pathfinder and MER used solid rocket motors in the backshell to reduce the terminal velocity and, in the case of MER, to minimize the lateral velocity component before impact. MSL used a descent stage separate from the backshell that lowered the rover down to the surface using tethers. This allowed for a much softer landing, removing the need for airbags, and allowing the rover to land on its own wheels.

Once the rover landed, it started the surface phase of the mission, which is planned to last at least one Martian year (687 days). The rover carries a total of 10 advanced instruments designed to assess whether Mars ever had an environment capable of supporting life. It is powered by a radioisotope thermal generator, and can communicate with Earth either directly using low and high gain X-band antennas, or through a Mars orbiting spacecraft using an UHF antenna. The rover can traverse about 40 meters per day and up to a total 10 to 20 kilometers during the primary mission, reaching up to the lower slopes of Mount Sharp.

3. MSL Spacecraft Configuration

3.1. Stages and Components

Figure 1 displays a breakdown of the MSL flight system and Figure 2 shows a detailed view of the spacecraft in the cruise configuration. The MSL flight system consists of four major elements: cruise stage, aeroshell (heat shield and back shell), descent stage, and rover. The aero shell encloses the descent stage and rover. The total mass of the flight system right after separation from the launch vehicle was about 3,840 kg, of which 540 kg corresponded to the cruise stage, 70 kg of those being cruise propellant; about 1,020 kg for the aeroshell; 145 kg of cruise balance masses; 168 kg of entry balance masses; 1,070 kg for the descent stage, including 400 kg of propellant; and 900 kg for the rover. The total mass of the entry vehicle after separating from the descent stage and releasing the cruise balance masses was about 3150 kg.

The design of the MSL cruise flight system is an extrapolation of the Mars Pathfinder and MER cruise spacecraft design, with a wider diameter and a reshaped backshell to accommodate the much larger descent stage and rover. From separation from the launch vehicle to minutes before entering the atmosphere of Mars, MSL was spin stabilized with a spin rate of about 2 rpm. The cruise stage included solar panels; the cruise propulsion system, with two propellant tanks and two thruster clusters; the heat rejection system; the attitude control system, with a star scanner and sun sensors; and the medium gain antenna for late cruise X-band communication. The antenna was oriented towards the –Z axis of the spacecraft, as were the solar panels. The cruise stage separated from the entry stage ten minutes prior to entry.

The backshell, together with the heatshield, enclosed the descent stage and the rover during cruise. The parachute cone of the backshell carried not only the parachute, but also two X-band low gain antennas, one in the –Z direction for early cruise communication with Earth, and one tilted for communication with Earth during EDL. The cone was also covered with a UHF wraparound antenna for communications with the relay orbiters during EDL. The backshell carried two sets of balance masses: the two cruise balance masses that when removed created a center of mass offset with respect to the –Z axis, in order to generate lift during the guided phase of EDL, and six entry balance masses that were ejected to realign the center of mass before parachute deploy. The heatshield for MSL was instrumented in order to collect engineering data during EDL, and to be able to more accurately reconstruct the EDL conditions.

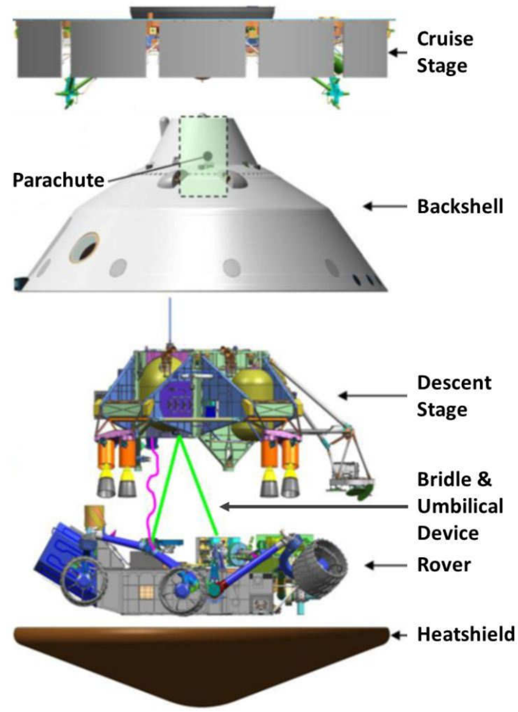

Figure 1. Main components of the MSL flight system

The descent stage carried eight reaction control thrusters, used after cruise stage separation; eight main landing engines, used after heatshield and backshell separation; and three propellant tanks that fed them. The stage also carried the inertial measurement unit (IMU) used for guided entry; the Terminal descent sensor (TDS), a system with six independent radar beams used to determine the position of the spacecraft relative to the ground; a small deep space transponder (SDST); and the travelling-wave tube amplifier (TWTA) used for cruise communications.

The rover was released from the descent stage using three bridles and an umbilical device. The rover carried an SDST and a solid state power amplifier (SSPA), which could have been used as a backup for X-band communications during cruise. The rover carried batteries that were also used during cruise. These batteries were fully charged using the solar array days before EDL.

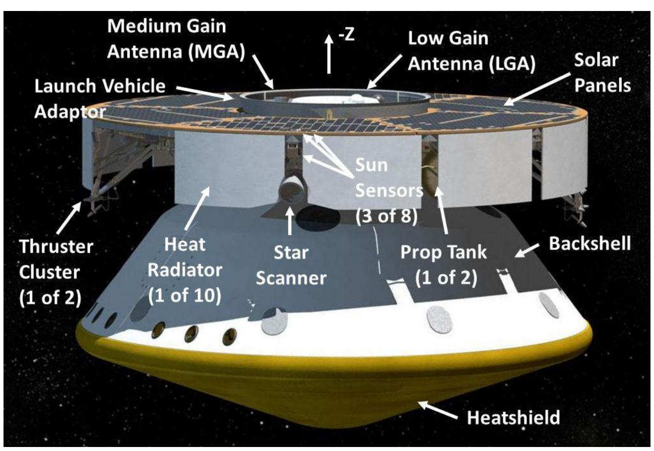

Figure 2. MSL configuration during cruise

3.2. Cruise Propulsion System

The MSL cruise propulsion system was similar to that of MER: two clusters of four thrusters each in opposite sides of the solar panel, and two propellant tanks. The cruise propellant system was used to perform trajectory and attitude control maneuvers from separation form the launch vehicle upper stage to the ejection of the cruise stage. Each tank contained 36kg of hydrazine at launch. The thrusters produced about 4.35 N of thrust each at the start of the mission, and about 3.09 N for the last maneuver that was executed, TCM-4. Each thruster cluster had four thrusters canted 40° with respect to the imaginary line joining both clusters. There was one thruster in each cluster canted towards –Z, and one towards +Z, while the other two thrusters in each cluster where canted towards each of the lateral directions. Maneuvers were performed using both clusters, but could have been performed, if necessary, just using one cluster. Using both clusters allowed for balanced attitude maneuvers, and reduced the attitude perturbation and execution error for translational maneuvers.

The maneuver execution modes that were available were four, two for attitude maneuvers and two for trajectory maneuvers. To change the direction of the spin axis, pairs of thrusters along the Z axis were fired in turns to create a torque perpendicular to the Z axis. To increase or decrease the spin rate, a matching pair of lateral thrusters would be fired to generate a torque of the appropriate sign along the Z axis. For trajectory maneuvers the two available execution modes were called axial and lateral. In the axial mode the thrusters in either the +Z or –Z direction would be fired simultaneously, creating thrust along the Z axis. In the lateral mode the four thrusters from each cluster were fired for up to 5 seconds, out of the 30 second spin period, when they traversed the appropriate clock angle range. One of the axial thrusters in each cluster had to be fired for shorter times in order to ensure that the combined thrust vector passed thought the center of mass of the spacecraft and no net torque was created. Lateral burns were more efficient in terms of propellant usage, but axial burns could be executed faster. To achieve a particular change in velocity (ΔV), the spacecraft could be rotated and then an axial or a lateral burn could be performed at that attitude, or the spacecraft could stay at its current attitude and a vector mode maneuver, combining an axial and a lateral burn, could be performed.

Attitude maneuvers were performed in closed loop, using the Sun sensor or the IMU to assess the change in attitude. Trajectory maneuvers were performed in open loop: the total firing time would be computed on the ground and commanded to the spacecraft. Small thruster alignment errors, variations in thrust level thruster to thruster, and plume impingement effects made the attitude maneuvers not perfectly balanced in translation, and created attitude disturbances and execution errors during trajectory maneuvers.

3.3. Cruise Telecommunications System

The MSL telecommunications system [6] can use X-band for direct to Earth (DTE) communications during all mission phases. During EDL and surface, it can also use a UHF system to communicate with the Mars orbiters. During cruise the X-band telecommunication system was used to track the spacecraft. The system operated through one of two antennas, one low gain antenna used during early cruise, and a medium gain antenna used during late cruise and approach. The nominal cruise telecom configuration was to use the descent stage Group III SDST and the TWTA, while the identical rover SDST and the SSPA could be used as a backup but, due to the lower power of the SSPA compared with the TWTA, at lower signal levels and data rates. The SDST provides the capability to coherently transpond the received carrier phase, to sample the uplink ranging channel and to modulate it into the downlink signal, and to modulate differential one-way ranging (DOR) tones into the downlink signal.

4. Key Navigation Requirements

The following lists the most significant high-level requirements levied on the MSL Navigation function, and how the requirements were fulfilled during operations.

4.1. Planetary Protection

1. The probability of Mars impact by the launch vehicle upper stage shall be less than 1.0×10^{-4}.
2. The probability of non-nominal impact of Mars due to failure during the cruise and approach phases shall not exceed 1.0 x 10-2.

The launch vehicle upper stage impact requirement was fulfilled by biasing the injection aimpoint off the desired entry aimpoint to the atmosphere of Mars. The target for TCM-1 was also constrained to ensure that the second requirement was fulfilled. By the time of the TCM-2 design, it was possible to target directly to the entry point and still fulfill the requirement [7].

4.2. TCM ΔV and Propellant

1. The maneuver design shall ensure a 99% probability of successful targeting to the atmospheric entry point with respect to available propellant.
2. The maneuver design shall ensure that the TCM propellant budget is sufficient with 90% probability for TCM-1 delayed until launch plus 30 days.

Pre-launch maneuver analysis was performed to ensure that any of the possible landing sites could be reached for any possible launch/arrival combination using the available propellant. The very precise launch vehicle injection provided ample propellant margin. Because of concerns about the propulsion system, and to work on other early cruise issues, TCM-1 was postponed from its pre-launch location, launch plus 15 days. A lateral calibration maneuver was executed on December 22 (launch plus 26 days), and TCM-1 on January 11 (launch plus 46 days). During cruise, 21.2 kg of propellant were used for trajectory correction maneuvers, and 7.3 kg for attitude maneuvers, with 43.5 kg left in the tanks at the time of cruise stage separation.

4.3. Atmospheric Entry Delivery and Knowledge Accuracy

1. The entry vehicle shall be delivered to the specified atmospheric entry conditions with an inertial entry flight path angle error of less than or equal to 0.20 degrees.
2. The EDL guidance system shall be initialized with an entry state with an accuracy of 2.8 km in position and 2.0 meters per second in velocity.
3. The navigation system shall support performing the final update of the entry state vector not later than entry minus 2 hours.

Based on a post-landing cruise trajectory estimation using all the data and calibrations up to entry, the actual EFPA was 0.013° shallower than the -15.5° target, and the on-board entry state was just 200 meters in position and 0.11 meters per second in velocity off from the post-landing reconstructed entry state. That state was calculated and uploaded to the spacecraft six days before entry and did not need to be updated.

5. Navigation System

The MSL navigation system was composed of three major parts: trajectory modeling and determination, trajectory control maneuver design and analysis, and EDL and relay trajectory analysis. Navigation functions during cruise included the following:

1. Estimate the spacecraft trajectory based on radiometric tracking data: Doppler, range, and Delta Difference One-way Range (ΔDOR) measurements.
2. Generate spacecraft ephemerides and ancillary trajectory data products for the DSN and the mission operations teams.

3. Perform EDL trajectory analysis to determine the desired atmospheric entry aimpoint and to evaluate landing dispersions.
4. Determine the desired ΔV vector for TCMs and verify the maneuver implementation generated by the spacecraft team.
5. Provide real-time tracking data residual monitoring during TCMs, EDL, and other dynamic events.
6. Reconstruct TCM ΔVs using pre- and post-TCM tracking data.
7. Perform EDL trajectory analysis to provide inputs for uplink of EDL parameter updates.

The reminder of this section describes the data, models, and processes used for navigation analysis.

5.1. Tracking Data Types

The tracking data types that were used for MSL orbit determination were: two-way coherent Doppler, two-way coherent sequential range, and ΔDOR. MSL did not have an oscillator stable enough to provide useable 1-way Doppler data. The data was collected by the 34-m and 70-m antennas of the Deep Space Network at Canberra, Australia; Goldstone, California; and Madrid, Spain. Doppler data provided a high resolution, high accuracy measurement of the line of sight velocity of the spacecraft with respect to the ground antennas, at a level of about 0.1 mm/s for 300-second compression time. Range provided an accurate measurement of the line-of-sight distance to the spacecraft, with an accuracy of about one meter. ΔDOR provided a measurement of the plane-of-sky angle error with respect to nearby quasars, with accuracies at the 40 ps level for one session, or around 400 m at the Mars arrival distance during final approach. This combination of data types resulted on typical position error covariance ellipsoids that looked like a pancake, very narrow in the line-of-sight direction, and wider in the plane-of-sky directions. Increased bandwidth between JPL and the DSN complexes allowed for fast delivery of ΔDOR data, with a total turnaround time from collection to delivery to the Navigation team of less than three hours possible when personnel was on-site.

Like other previous Mars missions, excluding the MRO approach optical navigation experiment, MSL flew to Mars using data collected at Earth. MSL did not have any means to track Mars, either optically or radiometrically, before arriving at its atmosphere.

For some of the MSL Goldstone-Canberra ΔDOR sessions, once a week for the final two months prior to Mars arrival, data from Mars Odyssey and Mars Reconnaissance Orbiter were also collected. ΔDORs were generated for the orbiters and for MSL, and double-differenced carrier phase measurements, of increased resolution, were created between MSL and the orbiters. The MSL navigation team processed range and ΔDOR data for the NASA Mars orbiters, using the reconstructed Mars-relative trajectories provided by their respective navigation teams and the latest Mars ephemeris, in order to assess how well the Mars ephemeris was predicting the position of Mars. The double-differenced phase measurements were similarly processed to assess the plane of sky error of MSL relative to Mars.

The Deep Space Network provided media, troposphere and ionosphere, and Earth orientation calibrations to be used when processing the tracking data.

5.1. DSN Tracking Schedule

The DSN tracking schedule used for pre-launch navigation analysis is listed in Table 1. The number of tracking passes during early and mid-cruise was not driven by navigation requirements, but by operational considerations. During operations the number of passes was actually higher, in order to accommodate spacecraft checkout activities and software uploads. Overall, the DSN performance was excellent. A total of 79 ΔDOR sessions were successfully executed, including 10 multi-spacecraft collections. Just a few of the ΔDOR sessions were not successful due to tracking equipment problems. The effect of this was most noticeable when only one ΔDOR session per week was being performed. Losing that session meant not having data from one of the baselines for almost a month.

Table 1: MSL tracking plan

<table>
<tr><th>Start</th><th>End</th><th>Doppler/Range Passes</th><th>ΔDOR Sessions</th></tr>
<tr><td>Launch</td><td>L + 30d</td><td>Continuous</td><td>None</td></tr>
<tr><td>L + 30d</td><td>E – 67d</td><td rowspan="2">5 per week</td><td>1 per week</td></tr>
<tr><td>E – 67d</td><td>E – 45d</td><td rowspan="2">2 per week</td></tr>
<tr><td>E – 45d</td><td>E – 28d</td><td rowspan="2">Continuous</td></tr>
<tr><td>E – 28d</td><td>Entry</td><td>2 per day</td></tr>
</table>

5.3. Trajectory Modeling

A key contributor to good navigation performance is being able to accurately predict the trajectory of the spacecraft relative to its target. The ephemeris of Mars is periodically updated using the latest range and ΔDOR measurements to the Mars orbiters. MSL used two releases of to the planetary ephemeris during operations: DE424, generated two months before launch; and DE425, generated three months before arrival. The update in the position of Mars at the time of MSL arrival between these two ephemerides was small, just tens of meters, and the actual error of the ephemeris was probably not more than one or two hundred meters, at the error level of the ΔDOR data used to generate them.

A spacecraft trajectory is affected by gravitational and non-gravitational forces. The gravitational forces are known with high accuracy, consistent with the accuracy of the planetary ephemerides. The main non-gravitational forces acting on MSL during cruise were: outgassing during the first few weeks after launch, thrusting for trajectory correction maneuvers, solar and thermal radiation pressure, and the effect of the slight unbalance of the thruster pairs during attitude maneuvers.

TCMs were calibrated using tracking data, and the results of these calibrations were provided to the propulsion and ACS teams, so they could better predict thruster performance in future maneuvers.

A pre-launch solar and thermal radiation pressure model was constructed using spacecraft dimensions, surface properties, and data from the thermal team. This model was then fitted using Sun colatitude Fourier series in order to generate a simpler parameterization of the combined effect. Experience with previous missions showed that estimating reflectivity parameters sometimes produced non-physical values. The new model was tested using MER data, and allowed for a similar fit using a much smaller number of parameters.

The residual translational ΔV from attitude turns was assessed during the ACSNAV calibration by using a series of especially designed turns that allowed observing all components of the resulting ΔV.

5.4. Orbit Determination

The orbit determination filter performed a weighted least-squares minimization of the tracking data residuals and the a-priori parameter constraints. Two key considerations in the MSL orbit determination strategy [8] were:

1. To accurately assess the uncertainty of the parameters that were being either estimated and constrained, or considered.
2. To properly weight the tracking data, so the final fit would be consistent with the expected accuracy of the data, and the covariance estimates would be accurate.

In order to realize the highest possible accuracy in the Doppler data and since MSL was a spin-stabilized spacecraft, the spin effects on the data had to be accurately modeled and removed. Since the X-band signals used by MSL are circularly polarized, the spinning of the spacecraft introduces a bias in the Doppler proportional to the spin rate. In addition, since the tracking antennas are not located along the spin axis, a signal with the same period as the spin period is added to the center-of-mass Doppler. The MSL navigation team used the antenna coordinates with respect to the center of mass and the periodic Doppler signature to estimate what was the rotational state of the spacecraft. Then the estimated rotational state was used to calculate and remove the periodic signature and the bias from the Doppler and range, producing measurements relative to the center of mass. This process was performed using small Doppler compression times, 1 to 5 seconds, and after the data was corrected the Doppler measurements were compressed to 300 seconds for use by the orbit determination filter. The data were accurate enough that the antenna phase center change with clock angle was observable, and using several passes of data it was possible to estimate the full attitude and the antenna arm with respect to the spin axis.

The MSL filter configuration allowed for the estimation of interplanetary medium charged particle delays. During early cruise a few solar coronal mass ejections produced significant biases and an increase in the noise of the tracking data, but post-landed analysis showed that the overall effect of these delays could have been neglected with a very small impact on the quality of the resulting trajectories.

A number of data arcs were used during operations, with the start of the data arc advanced in order to remove earlier data and reduce the amount of time required to generate an acceptable orbit determination solution. For some of the orbit determination data cut offs and arcs several filter configuration strategies were evaluated to assess what the effect of changing the baseline assumptions was on the estimated solution and its covariance.

5.5. Trajectory Control

The targets provided to the launch vehicle for MSL injection into an Earth to Mars trajectory did not directly aim for the Gale crater atmospheric entry point. The aimpoint was moved away from Mars so the probability of the launch vehicle upper stage hitting Mars was low, and the time of closest approach (TCA) was selected so the highest cost of retargeting to any of the down-selected landing sites was minimized.

Table 2 shows the pre-launch maneuver plan, and the actual dates for the TCMs executed during cruise operations. TCM-1 and TCM-2 were optimized jointly in order to minimize total propellant, and to fulfill planetary protection requirements, but TCM-2 was re-optimized after TCM-1 was executed, to also correct for TCM-1 delivery errors and to directly target the atmospheric entry target. According to pre-launch analysis which used conservative assumptions, TCM-5 should have been the last maneuver needed to fulfill the delivery requirement. Good trajectory prediction and maneuver execution performance allowed for TCM-5 to be cancelled. TCM-6 was a contingency opportunity to correct unexpected gross delivery errors that may have compromised the capability of the EDL system and it was not needed.

Table 2: TCM schedule

TCM	Pre-launch planned date	Actual execution date	Description
Lateral Calibration	not planned	Dec. 22, L + 26d	Test of the cruise propulsion system
TCM-1	L + 15d	Jan. 11, L + 46d	Remove injection bias and error, target to the selected landing site.
TCM-2	L + 120d	Mar. 26, L + 121d	
TCM-3	E – 60d	Jun. 26, E – 40d	Correct TCM-2 delivery errors
TCM-4	E – 8d	Jul 28, E – 8d	Correct TCM-3 delivery errors
TCM-5	E – 2d	Waved off	Correct TCM-4 delivery errors
TCM-5X	E – 1d	Not needed	Backup TCM-5 opportunity
TCM-6	E – 9h	Waved off	Contingency opportunity to correct non-survivable delivery errors

The orbit determination data cut off (DCO) was seven days before the maneuver execution time for TCM-1, -2, and -3; 13 hours for TCM-4 and -5; and 5 hours for TCM-6. The execution time for TCM-6 was a compromise between the need to observe the trajectory error before the TCM DCO, as the spacecraft was pulled by Mars, and of being able to reconstruct the trajectory after the maneuver, in order to initialize the EDL guidance system.

TCM design was performed using an open-loop simulation of the EDL trajectory, and it was targeted to the landing site, but moved North by 8 kilometers at the entry point in order to avoid re-contact of the cruise stage with the entry stage.

The decisions to execute or not TCM-5 and TCM-6 were based on cross-track and entry flight path angle thresholds. For TCM-5 the thresholds were set so the delivery envelop was within the many Monte Carlo simulations that were performed during development. For TCM-6 the thresholds were wider, and were set to ensure that the EDL system would have enough margins to land successfully.

Since the launch vehicle injection was very accurate and, consequently, the cruise propellant margin was ample, all TCMs were executed at the current cruise attitude and pre-TCM turns were not necessary. TCM-1, -2, and -3 were executed in no-turn vector mode, with an axial and a lateral burn executed in sequence, while TCM-4 was executed with just a lateral burn. TCM power and telecom constraints, while evaluated during TCM design, never played a role for maneuver implementation.

5.6. Entry, Descent and Landing Analysis

The navigation team collaborated with the EDL engineering team in order to perform EDL simulations, analyze EDL performance, and evaluate changes in the EDL system, its configuration, and its initialization [9]. The orbit determination team generated entry state files, containing typically 8,001 delivery and knowledge states, which were used to perform EDL Monte Carlo simulations. One of the results of each Monte Carlo was the landing points file, which listed the achieved landing point for every knowledge/delivery pair of states. This file was processed together with a landing hazards file in order to arrive to an estimate of the landing success probability.

One very significant difference between MSL and previous Mars lander missions was the fact that MSL used entry guidance. For previous missions the landing point location was directly correlated with the point at which the spacecraft entered the atmosphere of Mars. That was not the case for MSL. The vehicle was told at what point it was entering the Marian atmosphere, and what the landing target was, so it could guide itself to it using bank angle modulation during its pre-parachute hypersonic flight. This meant that, as long as the delivery was done within the range of entry conditions that the guidance could compensate for and assuming perfect knowledge, the center of the landing ellipse was not affected by the actual entry point. That is why TCM decisions were based on entry flight path angle and cross-track thresholds, and not on the location of the landing ellipse with and without TCM. In addition, the size of the delivery ellipse was dominated by factors not controlled by navigation, such as atmospheric density fluctuations, winds, attitude initialization, and EDL system guidance performance. The effect of the expected knowledge errors was much smaller than that some of those other factors listed. Errors in the predicted entry state sent to the spacecraft would directly map to the ground, but, again those were expected to be small and did not affect significantly the overall landing success rate. The difference between the state currently in the spacecraft and the latest available predict was evaluated during the entry parameter update opportunities, but the differences were always found to be small when compared with the expected uncertainty of the estimate, and did not make a significant difference on the ground.

5.7. Orbiter Relay Support

The navigation team produced EDL relay targets that were used by the currently operationally Mars orbiters, NASA’s Mars Odyssey and Mars Reconnaissance Orbiter (MRO), and ESA’s Mars Express, to design orbit change strategies that would ensure that the orbiter would be able to receive the UHF signal from MSL during EDL [10]. It was not necessary to request the orbiters to change their orbital planes, but the location within the orbit needed to change so each of the orbiters will come closer to MSL during EDL. The targets were adjusted as the location and time of MSL entry was refined, and the telecom performance was evaluated to assess whether additional changes to the orbiter trajectories were warranted. The team also generated surface trajectory predicts and products to assist with surface mission planning, and continues to do so during the surface phase of the mission.

6. Navigation Results

6.1. Launch and First Station Acquisition

Pre-launch the project planned and tested a strategy to de-orbit the spacecraft for the hypothetical case in which the launch vehicle was not able to boost it out of Earth orbit. In order to minimize the probability of the nuclear fuel pellets rupturing, it was planned to de-orbit the spacecraft using the descent stage RCS thrusters over a depopulated area of the Pacific Ocean. Fortunately, this was not needed for MSL, but the orbit determination and trajectory modeling processes and tools prepared for this contingency were used to support the Phobos-Grunt recovery effort, which was finally not successful.

MSL was very accurately launched in an Atlas V 541 from the Cape Canaveral Air Force Station (CCAFS) Space Launch Complex 41 on November 26, 2011, at 15:02:00 UTC, on the first launch opportunity of the second day of its launch period, as the launch had to be delayed one day to replace one of the flight termination batteries of the launch vehicle. The navigation team prepared spacecraft mode transition commands for every launch opportunity of every launch day of the launch period. As the launch and separation times changed from opportunity to opportunity, the mode timers needed to change to ensure that the spacecraft was in the proper configuration to enable a prompt initial station acquisition after separation.

Initial acquisition by the Deep Space Network station in Canberra occurred at 15:52:29. Since the spacecraft was so close to the station, the signal was stronger than what could be received by the 34m antennas, they were configured to receive at the opposite polarization to reduce the received signal level. This allowed reflected multipath to mix with the directly received signal and greatly increased the Doppler noise. In addition the angle measuring system at DSS-34, equipped with an acquisition aid antenna, did not work properly and did not produce usable angle measurements. Despite all this, and helped by the excellent injection performance, the navigation team was able to prepare pointing predicts for subsequent passes, for which the proper cross polarization was used, and acquisition and tracking afterwards were nominal. The calculated injection error was less than 0.5 sigma of the pre-launch injection accuracy estimate. That meant than the cost to correct the injection error was small, when combined with the removal of the injection bias and the landing site retargeting.

Launching early on the launch period allowed for the Mars orbiters to stay at their nominal LMST node. Preliminary EDL relay targets were sent to the orbiter teams a few days after launch.

6.2. Early Cruise

The injection was so accurate that the execution of the first trajectory correction maneuver (TCM) could be postponed, and this allowed for the cruise team to have time to investigate some unexpected issues with the spacecraft computer. The anomaly was discovered the first time the start scanner was used, and forced the star scanner to be switched off until the issue was resolved. Navigation provided the Attitude Control team with Earth angle estimates based on the Doppler spin signature, and these values were combined with the Sun sensor data to produce spacecraft attitude estimates in absence of star scanner data. These estimates were used for the early turns.

Out-gassing accelerations were evident during the first few weeks of cruise, and small stochastic accelerations had to be estimated in order to get a good fit of the tracking data. By mid-December the level of the out-gassing acceleration was small enough that it could be neglected.

Due to concerns about the propellant valves, the project decided to perform a lateral calibration maneuver before TCM-1 in order to assess the health of the cruise propulsion system. The maneuver, two lateral burn segments with a combined ΔV of 0.555 m/s, was executed on December 22, 2011, resulting on an underburn of just 1.7%, with a misspointing of less than 0.5°, a very good performance considering that this was MSL’s first translational maneuver. TCM-1 was then executed on January 11, 2012, with an axial burn of 1.585 m/s and a lateral burn of 5.611 m/s. TCM-1 was designed to reduce the B-plane miss distance from 47,513 km to 4,956 km, and the TCA from 14 hours 50 minutes to 34 minutes. The total TCM-1 maneuver execution error was small, +2.3% in magnitude, and 0.52° in pointing. Both the lateral calibration maneuver and TCM-1 were executed using ground calculated attitudes based on Doppler and Sun sensor data.

On January 25, 2012, an ACS/Navigation calibration was performed in order to assess the residual translational ΔV resulting from spacecraft turns. The activity consisted of a first turn away from the Earth line, to an Earth angle of about 40°, and then of two sets of four turns, each

set consisting of turns of about 4.5°, away and towards the Earth line, and around the Earth line and back. The estimated translational ΔV from the calibration was small, less than 0.03 mm/s per degree, with a repeatability of about 0.002 mm/s per degree, or about 0.02 mm/s for a typical late approach turn. These estimates were used to calculate the a priori ΔV values for future turns, and corrections to those ΔVs were estimated with a constraint of 0.005 mm/s per degree.
Towards the end of January the Sun started to be more active, and on January 27 an X-class coronal mass ejection was unleashed in the Earth's direction. The effect on the range and Doppler residuals of the increased density of charged particles between the Earth and MSL was clearly observable, and the orbit determination filter was changed in order to estimate charged particle delays, so this would not affect the trajectory estimate.

6.3. Mid Cruise

Post TCM-1 orbit determination was fairly stable. On February 28, 2012, the spacecraft was commanded to switch from using the low gain antenna to use the medium gain antenna, with an observed decrease in tracking data noise, both due to increased received power and reduced antenna pattern effects.
As the distance to the Sun changed rapidly, as did the angle between the spin axis and the Sun direction (Figure 3), it was obvious that the ΔDOR fit was getting worst, and that turn ΔV estimates were not consistent with the ACS/NAV calibration values. Early in cruise a solar radiation pressure model with a total of 12 parameters was used. This model provided a very good fit of the pre-launch solar and thermal acceleration calculations, and was able to fit MER-B data very well for its whole cruise. One of the differences between the MER and MSL missions is that MSL was equipped with a Multi-Mission Radioisotope Thermal Generator (MMRTG), which produced heat and electricity for the rover. The thermal output of the generator was about 2 kW, which amounted to 5-10% of the solar power received by the spacecraft. That energy was

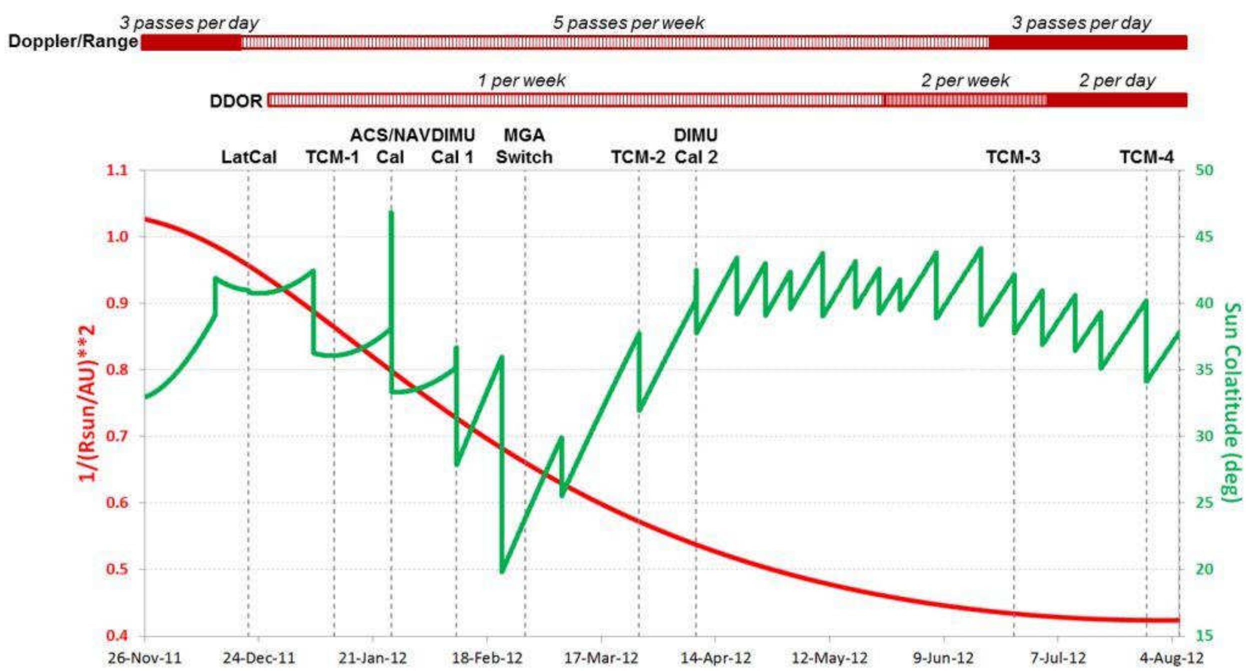

Figure 3: Inverse of the square of the distance to the Sun and Sun colatitude as a function of time

dissipated during cruise mostly through the radiators of the heat rejection system, but some of it was also being radiated through the backshell. Since the acceleration due to solar radiation pressure was being scaled with the inverse of the square of the distance to the Sun, the contribution of the MMRTG was not being properly modeled. The solar and thermal model was changed to have just three bias parameters for solar effects, one per axis, and a weekly stochastic acceleration along the Z axis of the spacecraft to fit changes due to solar panel utilization, component temperature, and MMRTG heat radiation. After this update, the ΔDOR fit was as expected, turn ΔV estimates stayed at their predicted levels, and future data pass-troughs improved significantly.

Pre-launch planning had assumed a combined TCM-1, -2, & -3 optimization to reduce the probability of non-nominal impact with Mars. Once TCM-1 was executed, it was not necessary anymore to bias TCM-2 away from the entry target, so TCM-2 was aimed for the Gale atmospheric entry interface point. TCM-2 was executed on March 26, 2012, and consisted of an axial burn of 0.195 m/s followed by a lateral burn of 0.726 m/s, with a total B-plane change of 5,002 km and the TCA shifted later by 21 minutes and 30 seconds. The maneuver was executed with almost zero magnitude error and a 0.4° pointing error.

Soon after TCM-2 execution, mission management requested to delay TCM-3 in order to load and upgrade the flight software and to perform instrument checkouts. There was no negative impact of doing it, so TCM-3 was postponed by 19 days, to June 26, 2012.

During this time two calibrations of the descent stage inertial measurement units (DIMU) were performed. These calibrations were important in order to estimate the biases in the measured acceleration and turn angle, so the EDL guidance system could use the DIMU data to find its way to the landing site. The DIMU calibrations consisted of sets of fairly big turns. After the second calibration was completed, it was noticed that the observed turn ΔVs were significantly smaller than the values predicted during the ACS/NAV calibration. Subsequent turns exhibited a similar trend, with decreasing line-of-sight Doppler offsets. Ultimately, it was decided to estimate an overall turn ΔV scale factor as a weekly stochastic, and increase the turn ΔV uncertainty by a factor of two.

In May 2012, the solar system dynamics group released the final planetary ephemerides update for MSL, DE425. The changes with respect to the ephemerides previously used, DE424, were small, about 25 meters at the time of MSL arrival to Mars. The navigation team incorporated the update and started using the Earth-Mars covariance recommended for the new set, corresponding to a predicted arrival uncertainty of about 100 m in right ascension, 150 m in declination, and 10 m in range.

6.4 Late Cruise

The successful use of the entry state by the entry guidance algorithm to find its way to the landing site relies not only on the accuracy of the state, but also on the accuracy of the spacecraft timing system. An error of 1 second when timing the initial state would map into an error of about 6 km in position. While the correlation of on-board time with ground time is something that has been done successfully in many missions by transmitting timing packets, it was desired to verify that this correlation was being done properly for MSL. The method that was used was to compare the attitude state estimates, in particular the clock angle, between the on-board attitude estimate that used the Sun sensor, and the method used to remove the Doppler signature. High rate ACS telemetry was collected over a period of almost eight hours, and was used to generate a time-tagged attitude file. This attitude file, with different offsets in the time tags, was used by navigation to model the spin signature. The time offset that produced the smallest residuals was just about -0.015 s, well within the timing accuracy needed for a safe landing.

The successful execution and analysis of calibrations and verification activities during cruise allowed for a reconsideration of the size of the landing ellipse. Pre-launch planning had used an ellipse size of 20 by 25 km, but Monte Carlo simulations using the latest assumptions produced an ellipse size of 7 by 20 km. Since Gale Crater was a go-to landing site, where the rover did not land on the region of highest scientific interest, but was expected to drive to a location outside the landing ellipse, there was an opportunity to reduce the length and duration of the surface drive by moving the landing target closer to the area preferred by the science team. Different landing targets were evaluated, and the final landing targets coordinates were selected by choosing a point as close as possible to the science area that did not significantly decrease the total probability of success integrated over the landing ellipse, for a number of plausible ellipse sizes based on optimistic, baseline, and conservative assumptions. The resulting landing target was about 6.5 km south and 1.3 km west from the original landing target. The adjustment in the lading target changed the B-plane and TCA targets. Those new targets were used for the TCM-3 design.

TCM-3 was executed on June 26, 2012, as a no-turn vector mode maneuver with an axial burn of 27.7 mm/s and a lateral burn of 25.6 mm/s. One week later, after two ΔDOR sessions were collected for each DSN baseline, the execution estimate had a magnitude error of 1.1%, and a pointing error of 2.4°. The error, while within the requirements, was proportionally higher than for previous maneuvers for two reasons: it was a much smaller maneuver, and it required a +Z axial burn, while TCM-1 and -2 had had –Z axial burns. The consequence was that the resulting entry flight path angle was predicted to be outside of the 0.2° corridor, and a TCM-4 would be needed.

Orbit determination following TCM-3 was very stable, with the line-of-sight residual pass-through for the aforementioned solution being within ±10m after three weeks of prediction (Figure 4). The period between TCM-3 and TCM-4 was similar in Sun-spacecraft distance and solar angle to the period between TCM-4 and entry, so this period was used to refine the solar

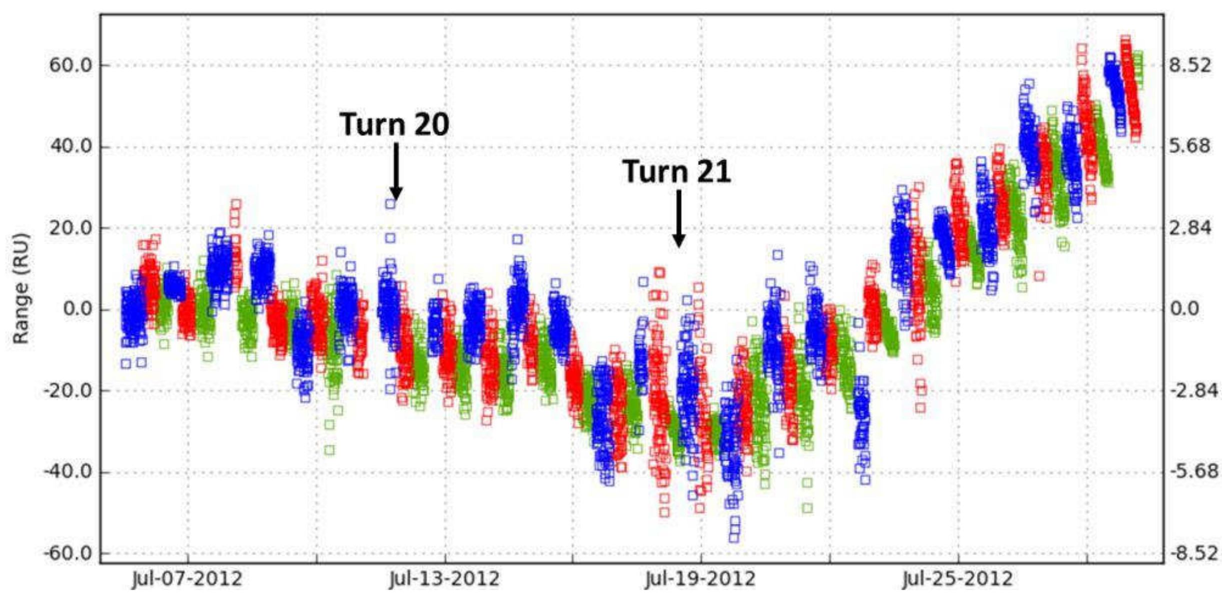

Figure 4: Range pass-through residuals up to TCM-4

and thermal radiation pressure model that would be used for the final approach.

ΔDOR and range data for the orbiters continued to be processed to confirm the accuracy of the Mars ephemeris, and spacecraft-to-spacecraft phase VLBI measurements were taken and processed to assess the quality of the MSL trajectory with respect to Mars (Figures 5-7)

Two weeks before Mars arrival, and in preparation for TCM-4 design, the navigation team started to receive and use daily media and Earth orientation parameter calibrations.

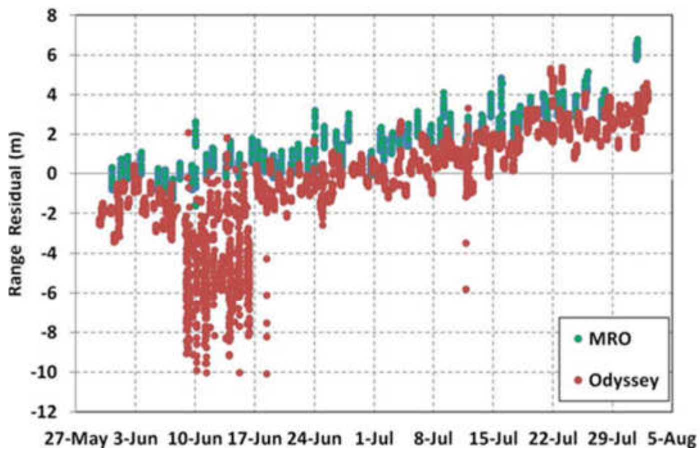

Figure 5: Orbiter range residual with DE425

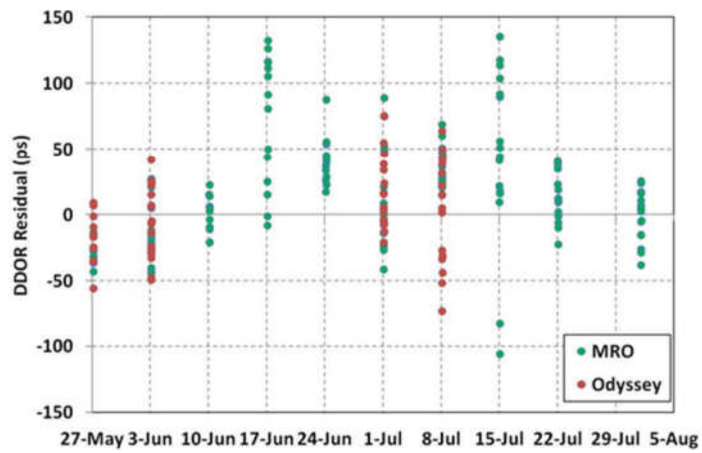

Figure 6: Orbiter ΔDOR residual with DE425

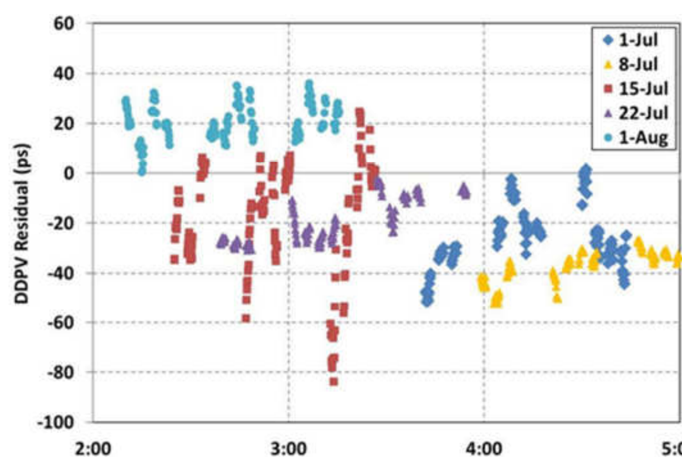

Figure 7: MSL – MRO phase VLBI double differenced residual

6.5 Final Approach

TCM-4 was executed on July 28, 2012, as an 11 mm/s lateral-only maneuver, followed by the last turn before Mars arrival. The lateral-only maneuver mode could not fully correct for entry time or entry flight path angle, but it resulted on just one third of the size of the vector mode implementation, was assumed to be more accurate, and the expected entry time and flight path angle misses were not big enough to be of concern. The line of sight Doppler error during the maneuver was +4.6%.

35 hours after TCM-4 was executed, six and a half days before entry, and after just one ΔDOR session from each DSN baseline, an orbit determination solution was obtained to calculate the first entry state that would be uploaded into the spacecraft, EPU1. There would be another three opportunities to update the entry state and additional opportunities if another maneuver was required.

Several days after TCM-4, the navigation team generated a Doppler-based attitude solution using data from multiple passes after that maneuver and obtained an attitude solution that was 0.023° from the attitude calculated by ACS using star scanner data, well within the requirements for attitude initialization before EDL.

At the TCM-5 decision point, the orbit determination solution was still well within the decision box, so the maneuver implementation was cancelled. When the entry parameter updates for the data cut offs at entry minus 33, 14, and 6 hours were evaluated, the orbit solutions had not moved significantly, either in the B-plane or when propagated to the ground using EPU1, and the updates of the on-board state were all cancelled. By the time of the last update, the line-of-sight residuals with respect to the EPU1 solution were just two meters off. TCM-6 was also waved off. After processing all of the two-way data before entry, the latest estimate of the entry state was just 200 m away from the EPU1 state. During these last few days, the trajectory prediction was so stable that the solution sometimes moved away when ΔDORs without updated media calibrations were added, only to move back when the calibrations were received (Figures 9 & 10).

One-way Doppler data were used to confirm atmospheric entry and parachute deploy, but were lost approximately five minutes after entry when the spacecraft was occulted behind Mars as it descended on its parachute. Real-time UHF telemetry relayed by Odyssey confirmed a successful landing, with the first images from the hazard detection cameras being received just minutes afterwards.

6.6 Rover Position Determination

MSL was imaged by MRO as it hung on the parachute and the MSL Mars Descent Imager (MARDI) took pictures of the surface as it descended, allowing for a prompt determination of the actual landing site. Curiosity landed about 2.4 km east for the target, and 400 m north. As soon as two-way DSN Doppler was

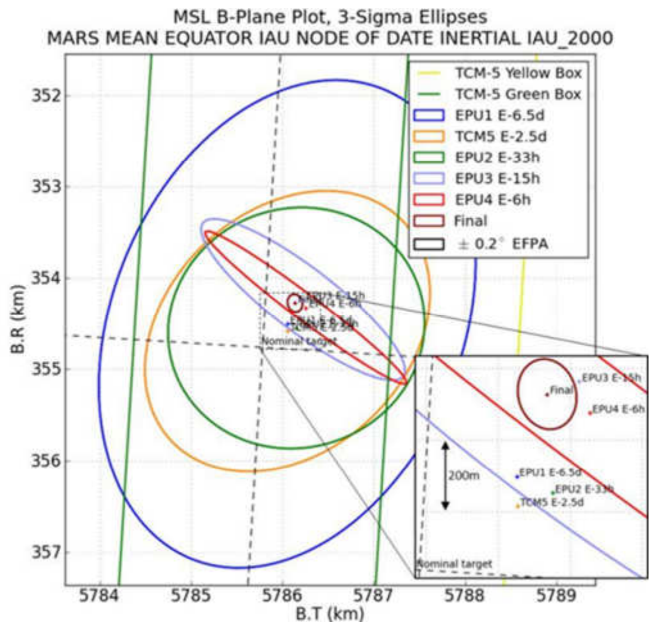

Figure 8: B-plane ellipses for EPU and TCM-5 DCOs

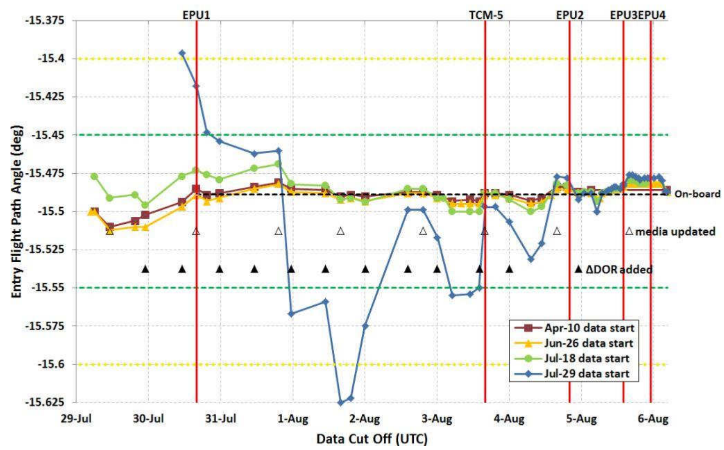

Figure 9: Evolution of EFPA estimates after TCM-4

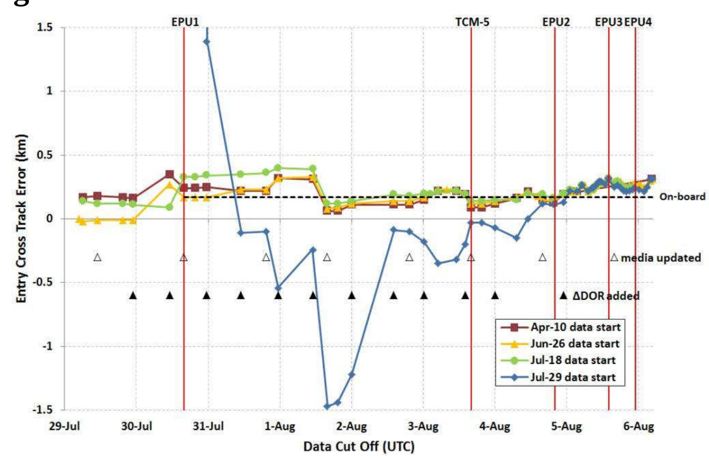

Figure 10: Evolution of cross track error estimates after TCM-4

collected, the navigation team also produced radiometric estimates of the rover position. The final radiometric estimate, using all the DSN data before the rover started moving, was 76 meters north from the MARDI estimate, with a latitude uncertainty of 62 meters, one sigma. The radiometric solution would have benefited from 2-way UHF Doppler but since the location was already well determined with MARDI data, no UHF Doppler data were collected.

7. Conclusion

The MSL interplanetary navigation system fulfilled all the requirements leveled on it by a considerable margin. Not only that, but navigation by-products were used to perform ground-based attitude determination, and to verify the spacecraft time correlation. It seemed that everything that could go well did go well. The launch vehicle injection was spot on; the inputs used by the navigation team – tracking data, media calibrations, Earth orientation, planetary ephemerides – were highly accurate; maneuver execution errors were much smaller than the required values; the spacecraft was clean; the propulsion system was well balanced. But it was not just the inputs used by the navigation team; it also was the tracking data processing strategies, dynamic models, and estimation assumptions devised by the team. There was a conscious effort not to overfit data in order to get the best possible prediction; the number of estimated parameters was pared down; and models were chosen to improve observability and prediction performance. This excellent navigation performance allowed the project to concentrate resources on resolving anomalies, decreased the level of stress during final approach, and contributed to the also excellent performance of the EDL system and to a successful landing and surface mission.

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