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MARS SCIENCE LABORATORY INTERPLANETARY NAVIGATION PERFORMANCE

Tomas J. Martin-Mur,[*] Gerhard Kruizinga,[†] and Mau Wong[‡]

The Mars Science Laboratory spacecraft, carrying the Curiosity rover to Mars, hit the top of the Martian atmosphere just 200 meters from where it had been predicted more than six days earlier, and 2.6 million kilometers away. This unexpected level of accuracy was achieved by a combination of factors including: spacecraft performance, tracking data processing, dynamical modeling choices, and navigation filter setup. This paper will describe our best understanding of what were the factors that contributed to this excellent interplanetary trajectory prediction performance. The accurate interplanetary navigation contributed to the very precise landing performance, and to the overall success of the mission.

INTRODUCTION

The Mars Science Laboratory (MSL) – carrying the Curiosity rover – was launched on November 26, 2011, from Cape Canaveral, and landed on the Gale Crater on August 6, 2012. The Curiosity rover is the heaviest vehicle ever landed on Mars[1], and it was delivered to its surface using an innovative entry, descent, and landing (EDL) system[2]. The challenge for the MSL 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 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, including navigation errors. The target needed to be as close as possible to the area that the scientists 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 those criteria[3].

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. It 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, as long as the delivery error could be corrected, but on how well was that entry point known by the spacecraft.

[*] MSL Navigation Team Chief, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology~~JPL~~, 4800 Oak Grove Drive, Pasadena, CA 91109.
[†] MSL Orbit Determination Lead, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology~~JPL~~, 4800 Oak Grove Drive, Pasadena, CA 91109.
[‡‡] MSL Maneuver Design Lead, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology~~JPL~~, 4800 Oak Grove Drive, Pasadena, CA 91109..

Guidance allowed for a reduction in the landing ellipse from the 80 by 10 kilometers ellipses of the MER rovers[4], to just about 20 by 7 kilometers. In a first approximation, and assuming that the atmospheric delivery was done with sufficient accuracy, that ellipse size was not significantly affected by navigation delivery errors. Entry knowledge errors affected the landing ellipse 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 uncertainties, at the expected performance levels it did not contribute significantly to ellipse size. In contrast, an entry delivery shift, 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, in order to decide what trajectory correction maneuvers (TCM) to perform, and to be able to predict the entry state of the spacecraft. The project had planned for a number of TCM and entry parameter update (EPU) opportunities over the last days before landing, based on the predicted performance of the navigation system, but eventually only one final TCM and one parameter update were used, indicating that the actual navigation performance had been much better than what was predicted in the pre-launch analysis.

KEY NAVIGATION REQUIREMENTS

The MSL navigation function had to comply with a number of requirements concerning launch opportunities, planetary protection, trajectory correction maneuvers and propellant usage, and EDL communications coverage[5], but the requirements that will be discussed in the following will only be those concerning the 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 at entry minus 2 hours.

PRE-LAUNCH ANALYSIS

Pre-launch analysis was performed to verify that the requirements stated above could be fulfilled for any of the possible landing sites and launch-arrival periods that were being considered by the project[6]. For this analysis two sets of results were computed: one, named baseline, using the stated requirements and conservative performance assumptions for the factors affecting the navigation function, and another, named no-margin, using the best estimate of what those factors would be during operations. For example, the cruise propulsion system had stated requirements of what the TCM execution accuracy should be, but it used the same components as those used by MER. The baseline analysis used those stated TCM requirements in order to assess the TCM executing accuracy, while the no-margin analysis used values based on the actual performance seen for the MER spacecraft.

The baseline results were used to plan the schedule of TCM and parameter update opportunities, since there was no guarantee that the very good performance seen in the MER spacecraft and other previous missions would be repeated. The plan for the final approach was to have trajectory correction maneuver opportunities at entry minus 8 days (TCM-4), entry minus two days (TCM-5), and entry minus nine hours (TCM-6); and entry parameter upload opportunities with data cut-offs at entry minus six and a half days (EPU1), entry minus 33 hours (EPU2), entry minus 15 hours (EPU3), and entry minus 6 hours (EPU4).

Pre-launch analysis, exemplified in Table 1, showed that under no-margin assumptions TCM-4 would be the last maneuver needed to fulfill delivery requirements, with TCM-5 needed in some cases under baseline assumptions, and TCM-6 being just a contingency opportunity to correct gross navigation or planetary ephemeris errors. The analysis also showed that knowledge requirements could be fulfilled in most cases with a parameter update as early as EPU2.

Table 1. Pre-Launch Navigation Analysis Example.

Case	1125-0806-M		1125-0806-G		1125-0806-H	
Launch Date	25-NOV-2011		25-NOV-2011		25-NOV-2011	
Arrival Date	06-AUG-2012		06-AUG-2012		06-AUG-2012	
Landing Site Name	Mawrth Vallis		Gale Crater		Holden Crater Fan	
Epoch of the Data Arc	E-44.9 days		E-45.5 days		E-45.0 days	
Entry Flight Path Angle	- 15.50 deg		- 15.50 deg		- 15.50 deg	
Entry Flight Path Angle Requirement (3σ)	0.2 deg		0.2 deg		0.2 deg	
Entry Position Knowledge Requirement (3σ)	2.8 km		2.8 km		2.8 km	
Entry Velocity Knowledge Requirement (3σ)	2.0 m/sec		2.0 m/sec		2.0 m/sec	
B-plane Angle	- 26.25 deg		3.96 deg		27.20 deg	
dB/d(EFPA)	27.9 km/deg		27.9 km/deg		27.9 km/deg	
	Baseline	No-Margin	Baseline	No-Margin	Baseline	No-Margin
TCM-4 Delivery:						
Data Cutoff Epoch	E-8.4 days	E-8.4 days	E-9.0 days	E-9.0 days	E-8.5 days	E-8.5 days
Apriori TCM-4 Execution Error (3σ)	7.68 mm/sec	5.92 mm/sec	7.84 mm/sec	6.12 mm/sec	8.33 mm/sec	6.74 mm/sec
Semi-major Axis (3σ)	6.66 km	4.48 km	7.19 km	4.89 km	7.04 km	5.01 km
Semi-minor Axis (3σ)	6.12 km	4.34 km	6.62 km	4.77 km	6.55 km	4.91 km
Ellipse Orientation Angle	159.4 deg	156.7 deg	161.6 deg	160.8 deg	161.0 deg	161.5 deg
Linearized Flight Time (3σ)	1.62 sec	1.14 sec	1.75 sec	1.26 sec	1.74 sec	1.30 sec
Entry Time (3σ)	4.17 sec	2.87 sec	4.51 sec	3.16 sec	4.40 sec	3.26 sec
B Magnitude (3σ)	6.66 km	4.48 km	7.11 km	4.87 km	6.79 km	4.96 km
$d(3\sigma_{EFPA})/d(EFPA)$	0.015 deg/deg	0.010 deg/deg	0.016 deg/deg	0.011 deg/deg	0.015 deg/deg	0.011 deg/deg
Entry Flight Path Angle (3σ)	± 0.24 deg	± 0.16 deg	± 0.25 deg	± 0.17 deg	± 0.24 deg	± 0.18 deg
TCM-5 Delivery:						
Data Cutoff Epoch	E-2.5 days	E-2.5 days	E-2.5 days	E-2.5 days	E-2.5 days	E-2.5 days
Apriori TCM-5 Execution Error (3σ)	5.74 mm/sec	3.00 mm/sec	5.76 mm/sec	3.02 mm/sec	5.76 mm/sec	3.02 mm/sec
Semi-major Axis (3σ)	2.97 km	1.79 km	3.10 km	1.72 km	3.01 km	1.81 km
Semi-minor Axis (3σ)	2.20 km	1.35 km	2.27 km	1.30 km	2.22 km	1.37 km
Ellipse Orientation Angle	149.4 deg	137.3 deg	149.0 deg	147.9 deg	149.3 deg	136.4 deg
Linearized Flight Time (3σ)	0.49 sec	0.29 sec	0.50 sec	0.27 sec	0.50 sec	0.29 sec
Entry Time (3σ)	1.51 sec	0.86 sec	1.51 sec	0.83 sec	1.42 sec	0.83 sec
B Magnitude (3σ)	2.97 km	1.76 km	2.86 km	1.58 km	2.47 km	1.42 km
$d(3\sigma_{EFPA})/d(EFPA)$	0.007 deg/deg	0.004 deg/deg	0.006 deg/deg	0.004 deg/deg	0.006 deg/deg	0.003 deg/deg
Entry Flight Path Angle (3σ)	± 0.11 deg	± 0.06 deg	± 0.10 deg	± 0.06 deg	± 0.09 deg	± 0.05 deg
Entry Knowledge Without TCM-5 (3σ)						
Position @ E-33h	2.32 km	1.44 km	2.63 km	1.67 km	2.80 km	1.82 km
Velocity @ E-33h	1.32 m/sec	0.82 m/sec	1.56 m/sec	1.01 m/sec	1.71 m/sec	1.13 m/sec
Position @ E-6h	1.16 km	0.81 km	1.58 km	1.08 km	1.79 km	1.22 km
Velocity @ E-6h	0.78 m/sec	0.54 m/sec	1.08 m/sec	0.74 m/sec	1.23 m/sec	0.84 m/sec
Entry Knowledge With TCM-5 (3σ)						
Position @ E-33h	2.49 km	1.54 km	2.82 km	1.78 km	3.04 km	1.94 km
Velocity @ E-33h	1.41 m/sec	0.88 m/sec	1.68 m/sec	1.07 m/sec	1.87 m/sec	1.20 m/sec
Position @ E-6h	1.24 km	0.84 km	1.67 km	1.11 km	1.90 km	1.26 km
Velocity @ E-6h	0.83 m/sec	0.56 m/sec	1.14 m/sec	0.76 m/sec	1.31 m/sec	0.86 m/sec

Baseline results were used to generate the entry state dispersions used for EDL Monte Carlo analysis. Those dispersions in delivery and knowledge assumed the execution of TCM-5 and an EPU4 parameter update.

OPERATIONAL SETUP AND CALIBRATIONS

Once the spacecraft was launched, the navigation team started using baseline assumptions to model the uncertainty of the factors affecting the navigation solution. As maneuvers were executed and solar and a thermal radiation pressure model for the spacecraft was estimated and refined, the assumptions were tightened to reflect what was actually observed in the spacecraft. The following sections describe the different factors affecting the navigation solution, and how the assumptions changed during operations.

Orbit Determination Filter Setup and Assumptions

Table 2 lists the different error sources contributing to the orbit determination and prediction accuracy, and how they were modeled during pre-launch analysis and during final approach operations. The values used for MER are also listed for comparison.

Table 2. Orbit Determination Assumptions, 1-Sigma.

Error Source	MER Final Approach Operations	MSL Pre-launch Baseline	MSL Pre-launch No-margin	MSL Final Approach Operations	Comments
2-way Doppler measurement weight	Weight by pass ≥ 0.05 mm/s	0.1 mm/s	0.05 mm/s	Weight by pass ≥ 0.044 mm/s	After removing the spin signature 3.36 x RMS (60 sec) of residuals
Range measure-ment weight	Weight by pass ≥ 0.14 m	3 m	3 m	Weight by pass ≥ 1 m	
Range biases	2/- m estimated	2/- m estimated	1/- m estimated	1/2 m estimated	Per pass / per station
ΔDOR measure-ment weight	60 ps	60 ps	40 ps	35,ps	Equivalent per ses-sion
Station locations errors	Full 2003 cov. considered	Full 2003 cov. considered	Full 2003 cov. considered	Full 2003 cov. considered	
Quasar location errors	2 nrad considered	1 nrad considered	1 nrad considered	1 nrad considered	
Pole X. Y errors	1-4 cm estimated stochastic	1-4 cm estimated stochastic	1 cm estimated stochastic	1 cm considered	
UT1 errors	1.7 – 9 cm estimated stochastic	1.7 – 15 cm estimated stochastic	1.7 – 7.5 cm estimated stochastic	1.7 cm considered	
Ionosphere day/night calibra-tion errors	6.1/1.7 cm estimated stochastic	6.1/1.7 cm estimated stochastic	6.1/1.7 cm estimated stochastic	6.1/1.7 cm considered	X-band units, x6 when no actuals
Troposphere wet/dry calibration errors	1/1 cm estimated stochastic	1/1 cm estimated stochastic	1/1 cm estimated stochastic	1/1 cm considered	Zenith values, x2 when no actuals
Mars-Earth ephemeris errors	9-136-442 m considered	8-169-294 m considered	4-85-147 m considered	13-90-156 m considered	Radial, transversal, normal
Turn residual translational ΔV	0.05 – 0.1 mm/s estimated	1 mm/s estimated	0.1 mm/s estimated	0.03 mm/s estimated	Per axis
Late TCM execu-tion errors	1.67% estimated	1.67% + 1.33 mm/s estimated	1.67% + 0.67 mm/s estimated	1.67% + 1.33 mm/s estimated	
Solar & thermal radiation pressure model errors	10% estimated bias & stochastic	5%/1% estimated bias & stochastic	2%/1% estimated bias & stochastic	2%/1% estimated bias & stochastic	Specular/diffuse coefficients for MER, in-plane/ out-of-plane for MSL

Measurement Weighting and Range Biases

Range and Doppler measurement weights and range bias uncertainties were assigned based on the performance seen on previous missions, and the actual tracking performance observed for MSL. The contribution of changes in the range and Doppler values, in any case, had a very small effect on the combined navigation accuracy[6], since it was dominated by the plane-of-sky uncertainty, which is better resolved with delta difference one-way range (ΔDOR) data. The range and Doppler data was weighted by pass, scaling the Doppler post-fit residual root mean square (rms) to take into account solar plasma noise effects.

The navigation team used the ΔDOR measurement weights recommended by the ΔDOR team for each observing session, down to 60 picoseconds for a successful three data point session. Post-fit ΔDOR residuals rms were about 38 ps, with the mean residual for some sessions sometimes above this value, see Figure 1. Based on the observed navigation performance, it seems that the level of ΔDOR weighting was correct. A tighter weight would have made the solution move in order to fit mean ΔDOR error, and a looser weight would have resulted in bigger predicted uncertainty.

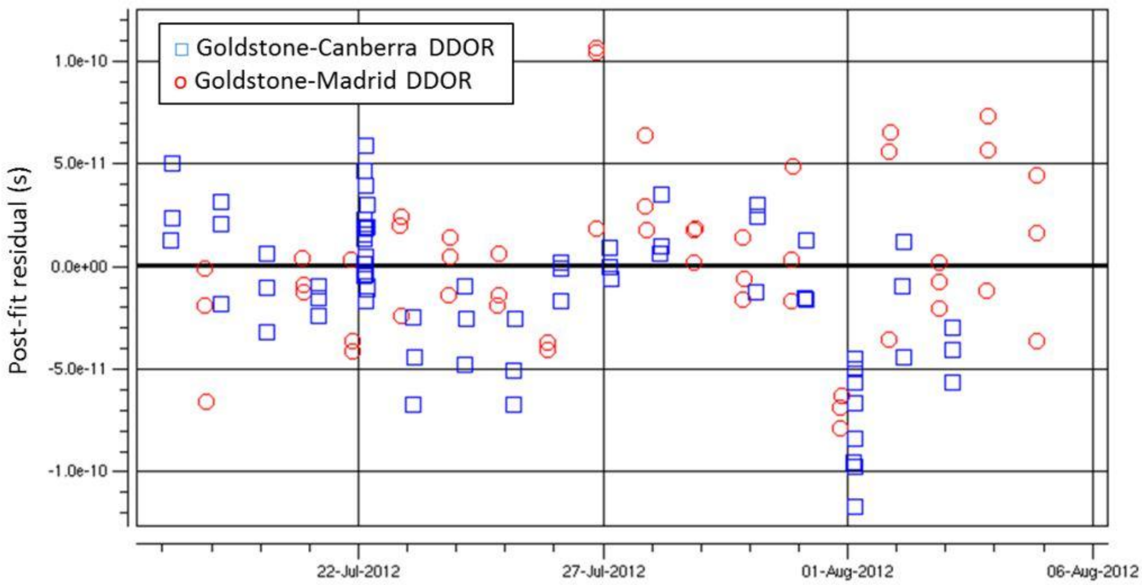

Figure 1. ΔDOR Post-Fit Residuals for the Final Approach.

Quasars

The position uncertainty of all the quasars used for referencing in differential one-way ranging was assumed to be the same, 1 nanoradian in right ascension and declination. This value, while a significant improvement with respect to what was used for MER, may have been a conservative estimate of the quasar position error, but it was used in order to protect against possible changes in quasar positions that have occasionally been observed in the past. The actual quasars that were used did not suffer of any position shift, so their position errors were probably much smaller, perhaps in the order of 0.5 nrad. In addition, the same quasar catalog that was used for MSL navigation was also used for the determination of the Mars ephemeris, and over the course of the several years of ΔDOR tracking performed in support of Mars ephemeris estimation a number of the same quasars have been used for both Mars and MSL ephemeris estimation, producing a correlation between the quasar errors and ephemeris errors that was not modeled in the MSL navigation filter. This correlation would have had the effect of reducing the error of the MSL trajectory relative to Mars, since a possible quasar position error would have shifted both trajectories in a similar way.

Media

The MSL pre-launch analysis, and the operational setup for MER, estimated troposphere and ionosphere calibration corrections as stochastic parameters during both the DSN tracking sessions. These estimates, while reducing the size of the post-fit residuals, did not estimated meaningful media corrections, just fitted the mean measurement noise of the period of the stochastic batch. The MSL navigation advisory group recommended considering these effects instead. When that was implemented in the MSL navigation setup, the same a priori uncertainties used to estimate the media parameters stochastically were used to consider them, but a smaller uncertainty should have been used since the consider effect is equivalent to a constant error over the filtering arc, and the mean effect of a stochastically varying error would be smaller than the uncertainty of a single batch. Also in this case, since the same system and models that were used for the generation of media calibration for spacecraft navigation were also used for the determination of station and quasar locations and planetary ephemeris, there was also a correlation effect that was not taken into account. In addition, while the MSL mission was launch close to the peak of the solar cycle, it was a fairly mild peak, and solar activity after peaking out during early cruise, remained low during the final approach.

Taking into account all these effects, a more realistic estimate of the mean tropospheric error, when considered, was probably a quarter of what was used during operations, and it was about half in the case of the ionospheric error.

Maneuver Execution Results

The TCMs executed before TCM-4 had components with sizes between 27.7 mm/s and 5.61 m/s. TCM-4 was expected to be an even smaller maneuver, so the fixed maneuver execution errors would dominate the total execution uncertainty. Execution errors for previous maneuvers had been estimated up to a maximum of 2.3% in magnitude and 2.4° in pointing, with the largest pointing error happening for TCM-3, the smallest maneuver. TCM-4, the last maneuver to be performed, had a magnitude error of -5.7%, outside to the 3-sigma of the proportional error assumption but, since the maneuver delta-V was just 11 mm/s, it was small when compared with the fixed error assumption[7]. This relatively good TCM-4 performance meant that no further maneuvers needed to be executed. Based on the observed TCM execution performance it seems that the fixed error assumption may have been conservative, but the post-maneuver orbit determination solution, once ΔDORs from both baselines were collected, was fairly insensitive to loose TCM execution assumptions, and it would not have been performed as well if tighter maneuver execution assumptions had been used.

Post-landing navigation analysis showed that the maneuver execution errors were commensurate with the orbit prediction errors. For each maneuver, the error in achieving the desired target due to the execution error was similar in magnitude to the error due to the trajectory modeling prediction uncertainty.

ACS/NAV Calibration and Turn ΔV Analysis

The thruster combinations used for spacecraft spin rate and spin axis orientation changes were, by design, balanced, but small errors in thruster alignment or performance could produce a net change in translational velocity (ΔV). Pre-launch analysis was based in the GNC requirements and the performance observed for MER. ACS/NAV calibration and turn ΔV. A significant effort was made during development to devise an ACS/NAV calibration schema that would provide the most accurate turn ΔV estimates. A kinematic spin removal strategy was implementing to model and remove rotation and nutation effects, and so to be able to get the full accuracy of the data even right after propulsive events, and the frame for the ΔV estimation and modeling was carefully selected to get the most repeatable results[8].

Actual flight results for the ACS/NAV calibration were better than those used during the MER operations, and allowed for the use of an uncertainty smaller than that used for pre-launch no-margin analysis. This performance was confirmed during subsequent turns and significantly reduced the effect of turn ΔV uncertainty on the overall navigation performance.

Solar and Thermal Radiation Pressure

One of the biggest uncertainties affecting navigation performance was the solar and thermal radiation pressure effect on the trajectory. The Mars Science Laboratory had multiple types of surfaces exposed to the Sun: solar panels, the launch adaptor, the parachute cone, antennas, radiators, and sensors, and some of them were shadowed by each other as a function of the location of the Sun with respect to the spin axis of the spacecraft. Surface reflective properties were obtained for the main elements of the spacecraft, and a thermal analysis was made to understand the mean temperature of each element, but this also varied with the changing Sun angle and distance to the Sun, shown in Figure 2. A conscious decision was made not to try to estimate the individual surface properties, as it had been done in most of previous missions, but to estimate the overall acceleration as a function of the solar angle. Since the spacecraft was spinning, only the average effect over one or multiple spin periods was important.

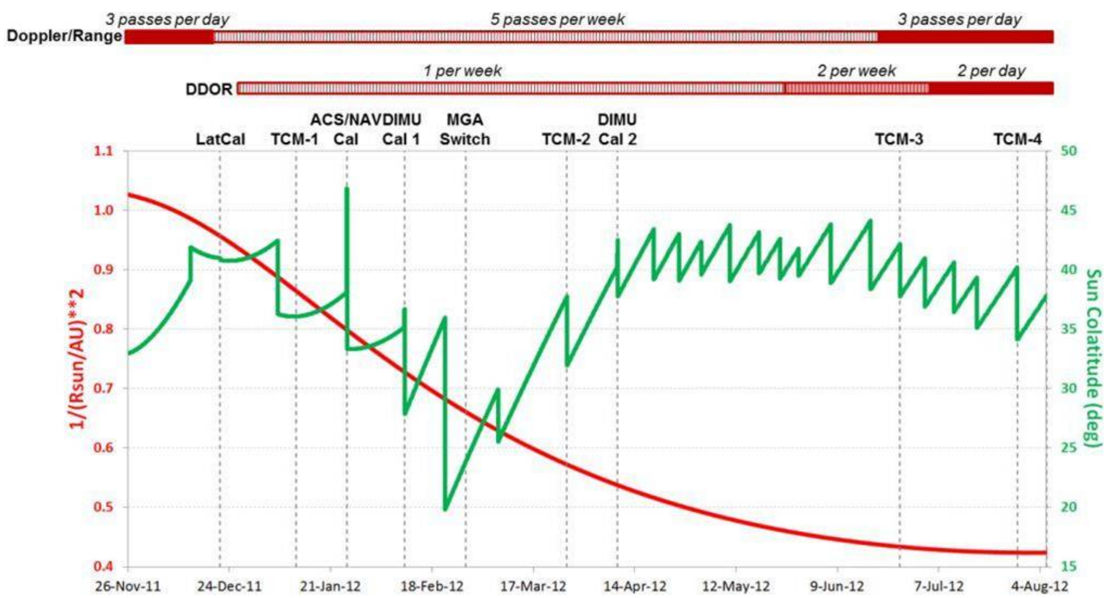

Figure 2. Tracking Schedule, Cruise Events, and Solar Angle and Distance.

A pre-launch radiation pressure model was obtained based on surface properties and thermal analysis, but it was used just to estimate initial values for coefficients of a truncated Fourier expansion on the solar angle. A significant difference with respect to the MER mission was that MSL carried a radioisotope thermal generator that produced a stable level of heat throughout cruise. This, and the fact that the temperatures of the different components changed with the distance to the Sun, required adding an empirical stochastic acceleration term along the spin axis that was not modulated with the distance to the Sun[8]. During operations the navigation team estimated the radiation pressure parameters based on tracking data. The set of coefficients that were estimated changed during cruise, and by the final approach a very small set was used that produced excellent trajectory prediction performance.

Planetary Ephemeris Updates

Pre-launch analysis used the planetary ephemeris uncertainty provided by JPL's Solar System Dynamics group. This uncertainty assumed monthly range and ΔDOR tracking of Mars orbiting spacecraft up to three months before entry. Two planetary ephemeris sets were generated specifically for the MSL project, one called DE-424, generated two months before launch, and one called DE425, generated three months before entry. The change between the two, since they shared most of the data used to create them, was much smaller than the uncertainty estimated at entry, just tens of meters. These ephemerides benefited from ΔDOR tracking of the Mars orbiters for more than two Earth-Mars synodic periods.

As mentioned before, the Mars-Earth ephemeris uncertainty estimated for DE425 and used by MSL did not take into account the effect of using some error sources that were common to both the planetary and spacecraft ephemeris, such as the quasar and DSN station coordinates, or media calibration models. That made the navigation uncertainty estimate somewhat conservative.

FINAL APPROACH RESULTS

Once the radiation pressure model had been simplified and improved using the estimates obtained during mid-cruise, the late cruise trajectory prediction performance was excellent. Figure 3 shows the range data residuals that were obtained when processing three weeks of data, up to TCM-4, using the solution obtained one week after TCM-3. The data displayed was not used in the solution, so this meant that the line-of-sight position of the spacecraft was predicted to better that ten meters after three weeks of prediction, a remarkable feat anywhere in the solar system. This performance could be obtained even in the presence of two turns, indicating that the turn ΔV estimates were also very precise. This kind of performance gave us a high confidence that, in absence of unexpected events or gross TCM-4 execution errors, the trajectory estimates should be very stable.

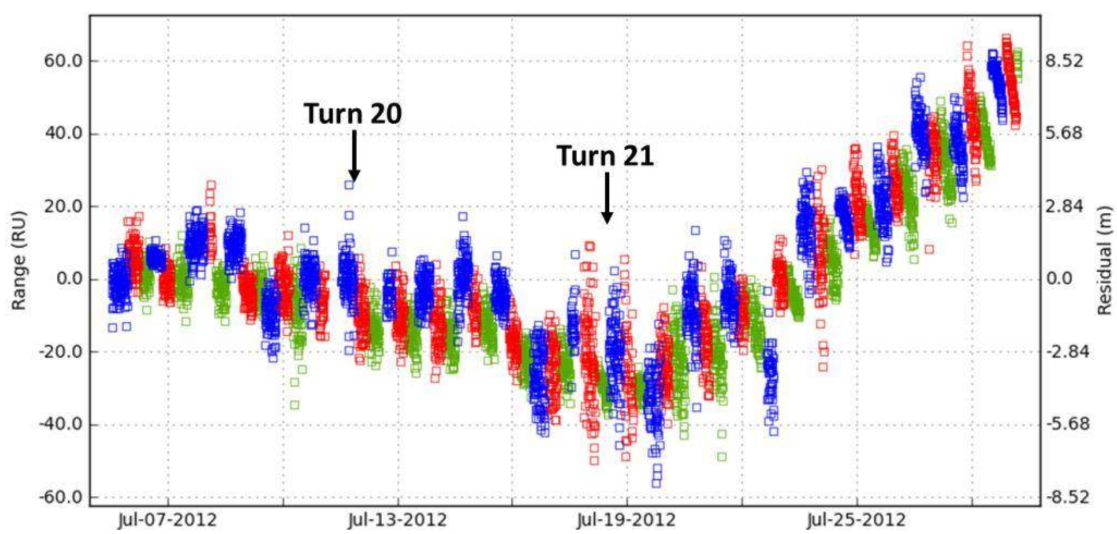

Figure 3. Range Data Pass-thru Residuals for Three Weeks When Using a Solution Obtained One Week after TCM-3

Figure 4 shows the evolution of the trajectory solution in the B-plane after TCM-4 as a function of the data cut off, when using all the best available calibrations, and at steps of 1 hour. The operational solutions evolved in a similar way. The dots represent the best estimate of the solution, while the ellipses represent the 3-sigma uncertainty level associated with each solution. It is evident that the variation seen in the solution estimates is considerably smaller than what should be expected based on the associated uncertainties.

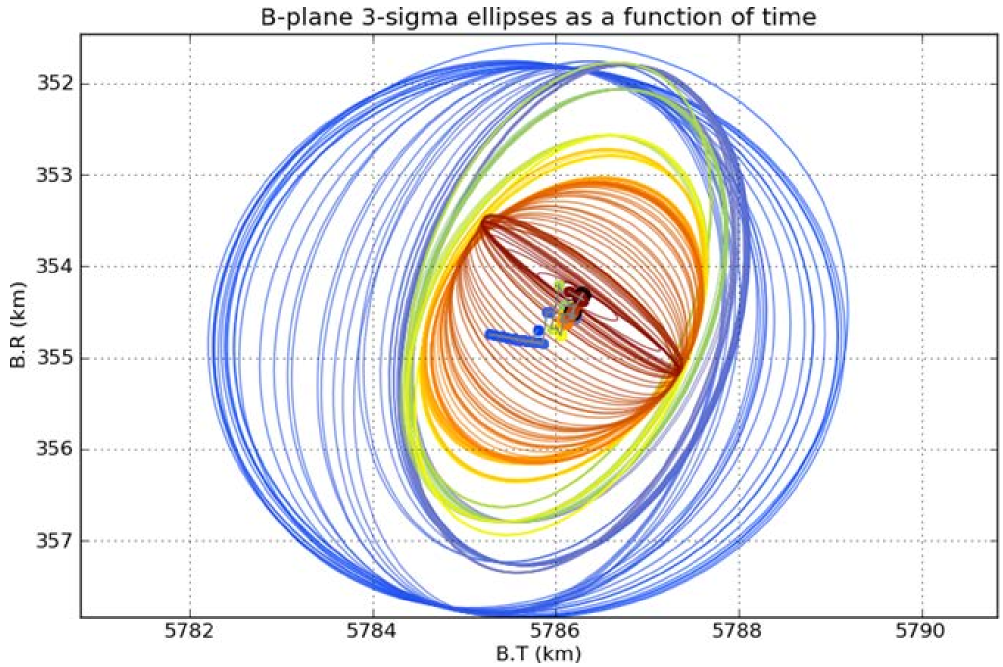

Figure 4. Evolution of the Trajectory Solution and 3-sigma Uncertainty from TCM-4 Execution to Entry

Figures 5 and 6 show the evolution of the two B-plane coordinates, as well as the data cut offs (DCO) for the first entry parameter generation (EPU1) and for the TCM-5 maneuver opportunity. Changes in B·T were mostly aligned with changes in entry flight path angle and longitude, while changes in B·R represented mostly changes in entry latitude.

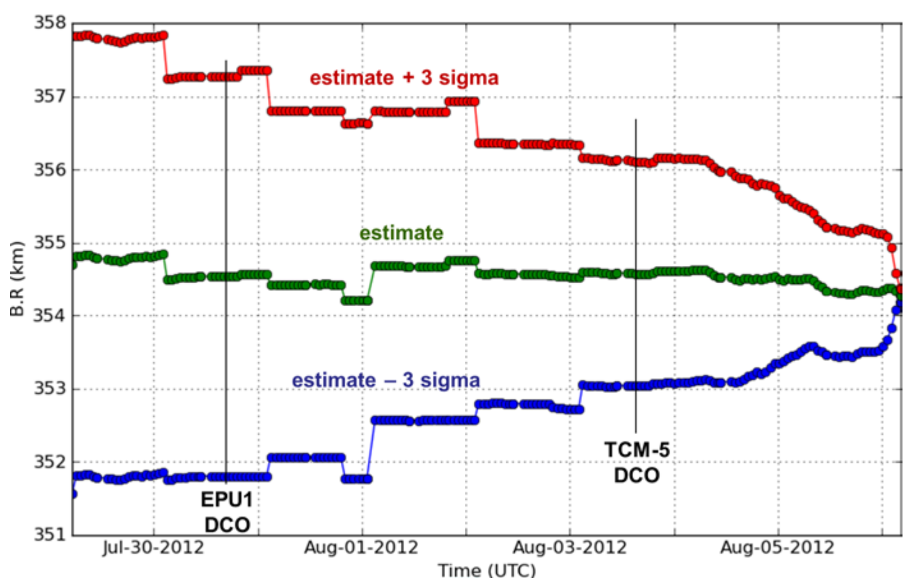

Figure 5. Evolution of the B·R Coordinate Estimate During the Final Approach

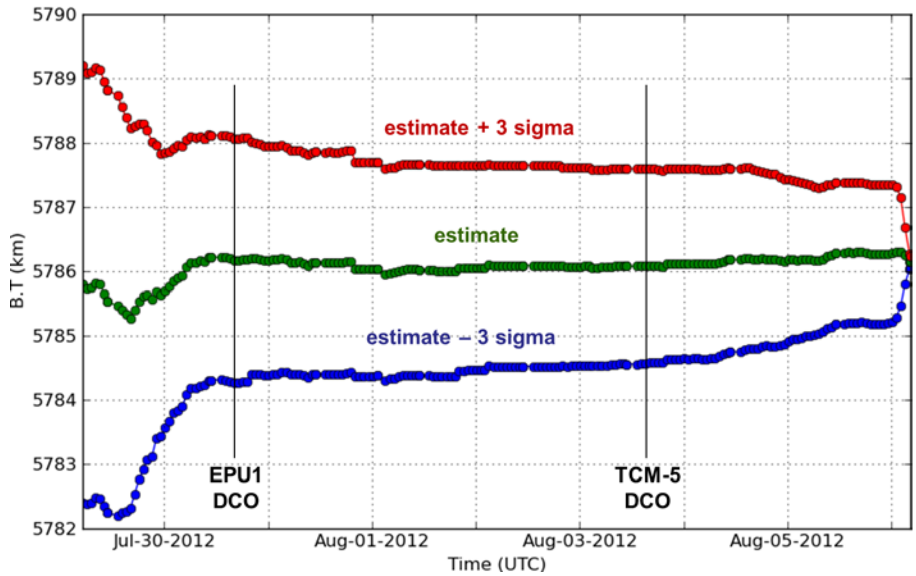

Figure 6. . Evolution of the B·T Coordinate Estimate During the Final Approach

The effect of adding ΔDOR sessions to the solution is more obvious in Figure 5, as they make both best estimate of B·R jump and its uncertainty to decrease. The effect of the errors and uncertainty of the planetary ephemeris can be seen in the last 48 hours of the estimates, when the uncertainties, first gradually and for the last few hours rapidly, contract. The initial uncertainty level is dominated by the TCM-4 maneuver execution uncertainty, but since the execution was fairly accurate, the uncertainty decreased as more tracking data was added without significantly changing the actual estimates.

The relatively accurate execution of TCM-4, and the excellent trajectory prediction performance allowed for the cancellation of the TCM-5 and TCM-6 maneuvers, and of the EPU2, EPU3, and EPU4 entry parameter updates. 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 onboard 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.

Post-landing analysis, using all the data up to entry and the final calibrations, showed that the actual entry state was just 200 m in position and 0.11 meters per second in velocity away from that onboard the spacecraft, with the entry flight path angle just being 0.013° shallower than the -15.5° requirement.

REASSESSMENT OF THE FINAL APPROACH COVARIANCE

The evolution of the solution between the execution of TCM-4 and the TCM-5 DCO could be divided into two segments: one first segment of about three days in which the TCM-4 maneuver execution error is being resolved, with the uncertainty decreasing steadily, and a second segment of about two and a half days with fairly constant uncertainty.

For the first segment, the initial covariance is dominated by the maneuver execution uncertainty. Operational experience prior to TCM-4 seemed to indicate that the actually maneuver execution performance was somewhat better than the pre-launch requirements, but since the magnitude of the maneuvers executed so far was larger than that for TCM-4, it was not possible to determine whether the proportional errors or the fixed errors were dominant. The navigation team generated solution uncertainties based on different TCM-4 maneuver execution error levels, and it was clear that TCM-5 would not be needed if TCM-4 was executed with accuracy proportional to that seen for previous maneuvers. The line-of-sight error observed during the execution of TCM-4 was larger than that seen for previous maneuvers, so it there was no compelling reason to reduce the TCM-4 maneuver uncertainty assumptions after it was executed. As a matter of fact, later analysis showed that had we used a smaller maneuver execution uncertainty, the solution may have moved more and we may have had a worse entry state estimate for EPU1. EPU1 was generated using just one ΔDOR session from each of the DSN baselines, but that, combined with a not-too-constrained TCM-4, was enough to fairly accurately determine TCM-4. This, together with the good trajectory prediction performance using the final radiation pressure model, produced an entry state estimate that was very close to truth.

For the second segment, the uncertainty of the solution up to the TCM-5 DCO seems bigger than what it should have been, when one sees the changes in the estimate up to entry. There is always the possibility of dumb luck but, given the consistency of the solution between EPU1 and entry, it seems to be more than just luck that we got the solution right at EPU1. Some of our uncertainty assumptions were probably too conservative, and a more realistic estimate of the solution uncertainty should have been smaller.

There were some indications during cruise that our navigation performance was better than what our covariance analysis indicated. One was the performance of range residual using predicted trajectories, as shown previously. Another was the evaluation of tracking data residuals for the Mars orbiters[5]. The orbiters were tracked regularly by the DSN, producing range and Doppler data, and weekly ΔDOR sessions were performed during which both MSL and the orbiters were tracked. The MSL navigation team processed the orbiter range and ΔDOR observations using orbiter reconstructed trajectories, produced using just Doppler data and relative to Mars, together with the DE425 Mars ephemeris, and using the MSL measurement modeling setup. Range residuals so obtained were below 10 meters, while mean residuals for ΔDOR sessions were in the few-hundred-meter level for the plane-of-sky position coordinates. Phase referencing VLBI sessions were also performed between MSL and MRO, and the residuals for those were also at the same few-hundred-meter level[5].

As it has been described in previous sections, post-landing scrubbing of the covariance assumptions found some candidates for the conservatism in the navigation uncertainty estimates. Media uncertainties were too conservatives when the errors were being considered, because the effect was the same as assuming a constant error. Ionospheric calibration errors were not as big as expected, even at the top of the solar cycle, since this was a fairly mild cycle and the Sun was not very active during the final approach. Quasar position uncertainties were at an appropriate level when the choice of the particular quasars that would be used was not known, and to protect against quasar position shifts observed in some quasars but, after the fact, they were conservative given the performance of the actual quasars that were used in operations. In addition, while we used absolute error estimates for each of our error sources, those estimates included the errors from some of the same sources that we were modeling. Quasar and DSN station coordinate errors affected both the planetary ephemeris solution and the MSL trajectory solution, but the resulting ephemeris errors may have been correlated, reducing the error of the MSL relative to Mars.

CONCLUSION

The MSL navigation team, and the other teams supporting it, accurately navigated MSL to Mars, possibly at the limit of what is possible with current calibration and tracking measurement errors. The main contributors to this excellent performance were the hard work and dedication of everybody involved, the high accuracy of the DSN radiometric and calibration data, the careful modeling of the spacecraft attitude and its radiation pressure forces, and the conscious choice to optimize the navigation filter in order to improve the trajectory prediction performance, by drastically reducing the set of parameters being estimated and by properly weighting the tracking measurements, without trying to over fit noisy data.

Looking back at the MSL navigation error assumptions used during development and operations, the only clearly conservative assumptions that were used were the tropospheric calibration uncertainties and neglecting the correlation between planetary ephemeris and quasar and DSN station coordinate errors, but changing these assumptions would not have made a significant difference when comparing the operational results with the no-margin results. During operations the B-plane uncertainties were still dominated by maneuver execution error assumptions and without a dedicated calibration campaign for small TCMs – operationally time consuming and risky – it may not have been possible to shrink those assumptions. TCM execution performance was adequate early in the mission, since the effect of maneuver execution errors was comparable to the effect of trajectory prediction errors, and more accurate execution would only have made a difference for planning TCM and parameter update opportunities during final approach. In addition, landing ellipse size was also not dominated by interplanetary navigation errors, but by attitude initialization and atmospheric mismodeling errors. Nevertheless, the excellent interplanetary navigation performance made possible to free up time during the final approach for other more pressing activities, and helped to ensure a successful EDL and an accurate delivery to desired landing target inside the Gale Crater.

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