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2011 MARS SCIENCE LABORATORY TRAJECTORY RECONSTRUCTION AND PERFORMANCE FROM LAUNCH THROUGH LANDING

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The Mars Science Laboratory (MSL) mission successfully launched on an Atlas V 541 Expendable Evolved Launch Vehicle (EELV) from the Eastern Test Range (ETR) at Cape Canaveral Air Force Station (CCAFS) in Florida at 15:02:00 UTC on November 26th, 2011. At 15:52:06 UTC, six minutes after the MSL spacecraft separated from the Centaur upper stage, the spacecraft transmitter was turned on and in less than 20 s spacecraft carrier lock was achieved at the Universal Space Network (USN) Dongara tracking station located in Western Australia. MSL, carrying the most sophisticated rover ever sent to Mars, entered the Martian atmosphere at 05:10:46 SpaceCraft Event Time (SCET) UTC, and landed inside Gale Crater at 05:17:57 SCET UTC on August 6th, 2012. Confirmation of nominal landing was received at the Deep Space Network (DSN) Canberra tracking station via the Mars Odyssey relay spacecraft at 05:31:45 Earth Received Time (ERT) UTC. This paper summarizes in detail the actual vs. predicted trajectory performance in terms of launch vehicle events, launch vehicle injection performance, actual DSN/USN spacecraft lockup, trajectory correction maneuver performance, Entry, Descent, and Landing events, and overall trajectory and geometry characteristics.

INTRODUCTION

The primary objective of the Mars Science Laboratory rover, also known as Curiosity, is to assess if the landing region ever had the conditions necessary to support microbial life in the past or even in the present[1]. Due to the massive weight of the spacecraft at launch of 3,841 kg, coupled with the small cruise propellant allocation of 70 kg to maximize the payload mass to be delivered to Mars, a nominal injection imparted by the launch vehicle, small maneuver execution errors, and good orbit determination solutions were critical to precisely deliver the MSL spacecraft to the correct Mars atmospheric Entry Interface Point (EIP). The excellent trans-Mars injection, maneuver performance, and orbit determination accuracy resulted in ample cruise propellant margins at Mars arrival. MSL navigation and Entry, Descent, and Landing (EDL) performance were outstanding. After flying more than 550 million km, MSL hit the EIP only ~700 m away from the target EIP inside a ~2.5 km x ~11.5 km window, and just ~200 m from the state that was uploaded to the spacecraft six days before landing. During the ~431 s descent, good attitude initialization, exceptional performance by the on-board entry guidance system, and atmospheric uncertainties and winds within the expected levels, resulted on the successful and extremely precise landing of Curiosity only ~2.4 km away from the intended target.

LAUNCH PERIOD

The MSL launch period consisted of 24 consecutive days extending from November 25 through December 18, 2011. The open of the launch period was mostly driven by atmosphere-relative entry speeds at Mars whereas the close of the launch period was constrained by the Atlas V 541 launch performance capability. UHF EDL communications via the Mars Reconnaissance Orbiter (MRO) and Mars Odyssey

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bounded the arrival date space. X-band Direct-To-Earth (DTE) communications were also an important factor on the design of the launch/arrival strategy. The arrival date on August 6, 2012 (UTC) was maintained constant for all launch days and the actual entry time only varied ~15 min across the launch period. This strategy provided excellent UHF relay communications support during EDL via both MRO and Mars Odyssey with no Local Mean Solar Time (LMST) node change required by the orbiter assets. X-band DTE 8 kbps tones were available through entry plus ~5 minutes when Mars occulted the spacecraft as seen from the Earth. Figure 1 shows the MSL launch/arrival strategy.

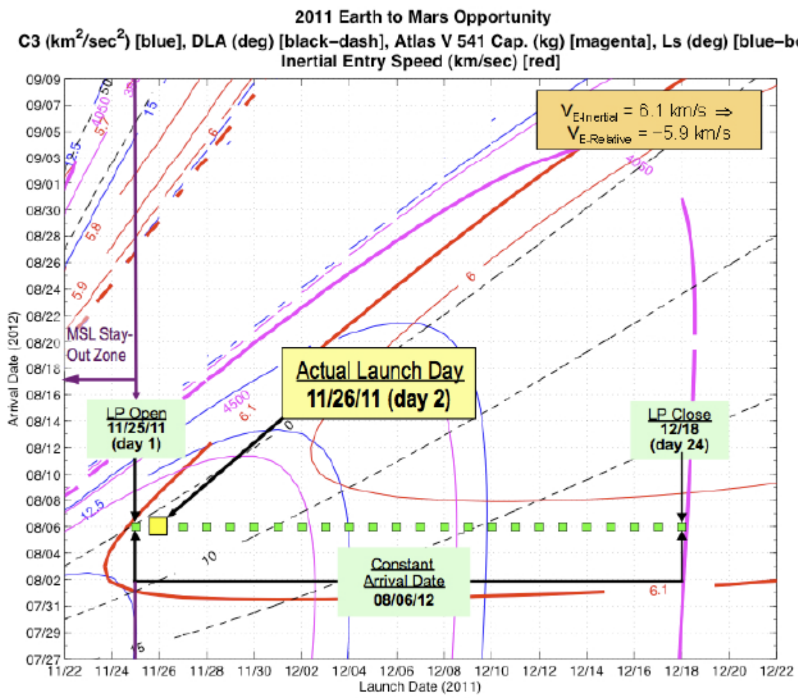

Figure 1. MSL Launch/Arrival Strategy

LAUNCH WINDOW AND LIFTOFF TIMES

The duration of the launch window was primarily determined by the variable Declination of the Launch Asymptote (DLA), the LC-41 launch site latitude of 28.42 deg, a fixed launch azimuth of 97 deg, launch vehicle ascent trajectory capabilities, and available launch vehicle performance for which the launch vehicle could liftoff and deliver the spacecraft to the specified targets. The available propellant for the trans-Mars injection burn by the Centaur upper stage was limited by propellant reserves to account for lower than expected launch vehicle performance, launch vehicle weight uncertainties, and environmental variation effects. For MSL, the Mission Required Margin (MRM) propellant reserved was 222 kg and the Launch Vehicle Contingency (LVC) expendable propellant allocated was 113 kg.

For the MSL mission, launch opportunities occurred every five minutes on the whole minute, and on the last possible integer-minute opportunity. The Right ascension of the Launch Asymptote (RLA) determined the actual liftoff time. The launch windows satisfied the requirement associated with a payload containing radioisotope materials for which a launch shall occur during civil twilight and Centaur mandatory telemetry coverage constraints[2].

Launch vehicle rollout for a launch attempt on November 25, 2011 was delayed one day to allow time for the team to replace a flight termination system battery. MSL successfully launched on November 26, 2011 at 15:02 UTC (10:02 EST) which corresponded to the launch window open time on launch day 2. Table 1 and Figure 2 provide the final launch times and launch windows for each day in the launch period.[3] Note that launch windows for days 1-17 were calculated assuming a spacecraft mass of 4,000 kg; for days 18-24, a mass of 3,940 kg was assumed.

Table 1. Launch Windows and Launch Times

Launch Date (2011)	Launch Day	Number of Launch Opp.	Launch Window Duration (hh:mm)	Coordinated Universal Time (UTC)			Eastern Standard Time (EST)			Pacific Standard Time (PST)		
				Open	Optimal	Close	Open	Optimal	Close	Open	Optimal	Close
11/25	1	22	1:43	15:25	16:15	17:08	10:25	11:15	12:08	7:25	8:15	9:08
11/26	2	22	1:43	15:02	15:52	16:45	10:02	10:52	11:45	7:02	7:52	8:45
11/27	3	22	1:43	14:41	15:31	16:24	9:41	10:31	11:24	6:41	7:31	8:24
11/28	4	21	1:40	14:19	15:14	15:59	9:19	10:14	10:59	6:19	7:14	7:59
11/29	5	21	1:40	14:03	14:58	15:43	9:03	9:58	10:43	6:03	6:58	7:43
11/30	6	22	1:45	13:48	14:43	15:33	8:48	9:43	10:33	5:48	6:43	7:33
12/01	7	23	1:48	13:35	14:30	15:23	8:35	9:30	10:23	5:35	6:30	7:23
12/02	8	23	1:48	13:22	14:17	15:10	8:22	9:17	10:10	5:22	6:17	7:10
12/03	9	23	1:48	13:11	14:06	14:59	8:11	9:06	9:59	5:11	6:06	6:59
12/04	10	23	1:48	13:00	13:55	14:48	8:00	8:55	9:48	5:00	5:55	6:48
12/05	11	23	1:47	12:50	13:45	14:37	7:50	8:45	9:37	4:50	5:45	6:37
12/06	12	23	1:47	12:40	13:35	14:27	7:40	8:35	9:27	4:40	5:35	6:27
12/07	13	22	1:45	12:31	13:26	14:16	7:31	8:26	9:16	4:31	5:26	6:16
12/08	14	22	1:45	12:23	13:18	14:08	7:23	8:18	9:08	4:23	5:18	6:08
12/09	15	22	1:42	12:15	13:10	13:57	7:15	8:10	8:57	4:15	5:10	5:57
12/10	16	21	1:37	12:12	13:02	13:49	7:12	8:02	8:49	4:12	5:02	5:49
12/11	17	20	1:35	12:05	12:55	13:40	7:05	7:55	8:40	4:05	4:55	5:40
12/12	18	20	1:35	12:03	12:53	13:38	7:03	7:53	8:38	4:03	4:53	5:38
12/13	19	20	1:34	11:47	12:37	13:21	6:47	7:37	8:21	3:47	4:37	5:21
12/14	20	19	1:27	11:46	12:31	13:13	6:46	7:31	8:13	3:46	4:31	5:13
12/15	21	17	1:18	11:45	12:25	13:03	6:45	7:25	8:03	3:45	4:25	5:03
12/16	22	15	1:10	11:43	12:18	12:53	6:43	7:18	7:53	3:43	4:18	4:53
12/17	23	13	1:00	11:42	12:12	12:42	6:42	7:12	7:42	3:42	4:12	4:42
12/18	24	10	0:44	11:46	12:06	12:30	6:46	7:06	7:30	3:46	4:06	4:30

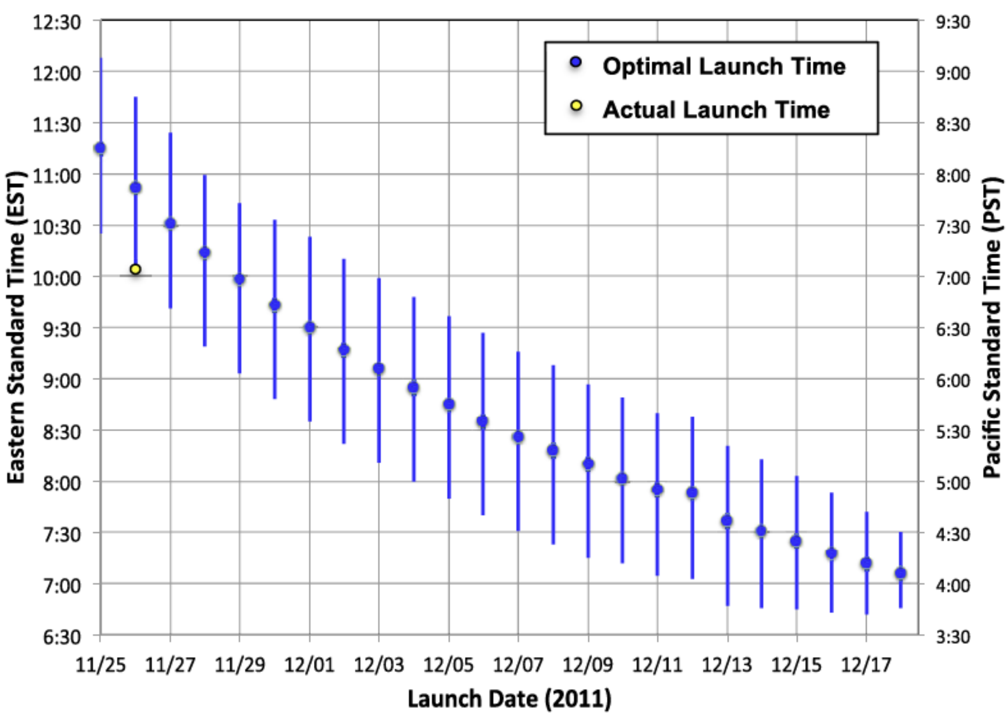

Figure 2. Launch Windows and Launch Times

LAUNCH VEHICLE EVENTS

The mission utilized a standard Atlas V ascent profile. On the ground, the booster engine system was ignited and at a fixed time from Go-Inertial, the four Solid Rocket Boosters (SRBs) were also ignited. Liftoff occurred shortly thereafter. At approximately 90 sec, the SRBs burned out and were jettisoned at the 1 min, 52 sec mark into the flight. At this point, only the Common Core Booster (CCB) and its RD-180 engine powered the vehicle. CCB ascent and Centaur separation were nominal. After a nearly seven minute burn, the Centaur put the spacecraft into the desired 165 x 265 km, 28.9 deg inclination parking orbit. During the ~20 min coasting period, MSL sent telemetry indicating that the Cruise stage was power-positive. A second burn of the Centaur RL-10 engine injected the spacecraft into the interplanetary transfer trajectory. Spacecraft separation took place 223 s after this second injection burn once the Centaur spun up MSL to ~ 2 RPM and maneuvered into the spacecraft separation attitude. Launch event time variability for a given launch opportunity was important to ensure initial acquisition of the spacecraft. The average 3-sigma dispersion for the spacecraft separation time event across all launch days was ±21.04 s. The flight performance of the launch vehicle was outstanding and the MSL spacecraft separated only ~3.3 s later than the nominal time. Table 2 shows the expected vs. the actual even time from Go-Inertial command to spacecraft separation.

Table 2. Planned vs. Actual Launch Vehicle Time Events

Event	Flight Times From/To T-Zero			Delta (sec)
	Expected Time (sec)	Actual Time (sec)	Actual Time (hh:mm:ss.ss)	
G-Inertial	-7.960	-7.960		0.000
T-Zero	0.000	0.000	00:00.000	0.000
SRM Ignition	0.800	0.800	00:00.800	0.000
SRB 1 & 2 Jettison	112.500	112.545	01:52.545	0.045
SRB 3 & 4 Jettison	114.000	114.045	01:54.045	0.045
Payload Fairijng Jetisson	204.900	204.967	03:24.967	0.067
BECO	261.500	261.439	04:21.439	-0.061
CCB Stage Separation	267.500	267.445	04:27.445	-0.055
MES1	277.400	277.439	04:37.439	0.039
MECO1	689.500	688.759	11:28.759	-0.741
BURN 1 Duration	412.100	411.320	N/A	-0.780
MES2	1943.800	1943.019	0:32:23.019	-0.781
MECO2	2422.600	2425.899	0:40:25.899	3.299
BURN 2 Duration	478.800	482.880	N/A	4.080
Spacecraft Separation	2645.600	2648.899	0:44:08.899	3.299

LAUNCH INJECTION ACCURACY

The MSL launch targets (C3, DLA, and RLA) at the Targeting Interface Point (TIP) were generated using open-loop entry trajectories targeted to a latitude and longitude corresponding to the approximate midpoints of the range of latitudes and longitudes for the final candidate landing sites. This fictitious landing site was referred to as the "central landing site" with an areocentric latitude of 0 deg and an East longitude of 45 deg (IAU 2000). The targets were delivered to ULA in the form of launch polynomials with the independent variable being the time in minutes measured from the optimal launch time. The launch targets also satisfied two planetary protection requirements: (1) The probability of impact of Mars by the launch vehicle shall not exceed 10^{-4}, and (2) the probability of non-nominal impact of Mars due to failure during the cruise and approach phases which shall not exceed 1.0×10^{-2}. This was achieved by biasing the injection aimpoint and using Trajectory Correction Maneuvers (TCMs) during cruise to remove the injection bias. Due to an outstanding injection imparted by the Centaur, and small maneuver execution and orbit determination errors, a combined TCM-1/TCM-2 optimization strategy was able to remove all the injection biasing.

The launch energy (C3) increased from ~11.8 km^2/s^2 at the open of the launch period to the maximum value of 20.1 km^2/s^2 at the close of the launch period. The declination of the launch asymptote (DLA) ranged from a minimum value of ~ -1.1 deg at the launch window open on launch day 1 to a maximum value of ~17.0 deg on launch window close on day 24. Table 3 shows the target conditions for the open, middle, and close of the launch window for each launch day.[2,4] The targets assumed a spacecraft mass of 4,000 kg for days 1-17, and a spacecraft mass of 3,940 kg for days 18-24. Note that the targets were specified at the Target Interface Point (TIP), which was defined at 300 s after spacecraft separation.

Table 3. MSL Launch Targets

Launch Day	Launch Date (2011)	Arrival Date (2012)	Launch Targets (EME2000 Coordinates at TIP)								
			C3 (km^2/s^2)			DLA (deg)			RLA (deg)		
			Launch Window Open	Launch Window Optimal	Launch Window Close	Launch Window Open	Launch Window Optimal	Launch Window Close	Launch Window Open	Launch Window Optimal	Launch Window Close
1	11/25	08/06	10.784	10.778	10.767	-1.090	-0.944	-0.763	126.571	126.578	126.594
2	11/26	08/06	10.721	10.720	10.717	1.670	1.787	1.933	126.611	126.609	126.615
3	11/27	08/06	10.775	10.778	10.780	3.883	3.978	4.099	126.513	126.506	126.506
4	11/28	08/06	10.908	10.915	10.919	5.684	5.770	5.855	126.330	126.317	126.313
5	11/29	08/06	11.101	11.109	11.116	7.189	7.261	7.333	126.093	126.078	126.071
6	11/30	08/06	11.339	11.348	11.358	8.458	8.520	8.588	125.825	125.808	125.799
7	12/01	08/06	11.614	11.625	11.636	9.542	9.595	9.658	125.541	125.524	125.513
8	12/02	08/06	11.920	11.932	11.945	10.477	10.523	10.578	125.253	125.235	125.224
9	12/03	08/06	12.255	12.268	12.281	11.292	11.332	11.380	124.967	124.949	124.938
10	12/04	08/06	12.616	12.630	12.644	12.007	12.043	12.085	124.689	124.671	124.660
11	12/05	08/06	13.000	13.015	13.029	12.639	12.671	12.708	124.423	124.406	124.394
12	12/06	08/06	13.408	13.423	13.438	13.201	13.229	13.262	124.171	124.155	124.144
13	12/07	08/06	13.837	13.853	13.868	13.702	13.728	13.756	123.936	123.920	123.910
14	12/08	08/06	14.289	14.306	14.321	14.151	14.173	14.199	123.722	123.707	123.697
15	12/09	08/06	14.763	14.780	14.796	14.552	14.572	14.594	123.530	123.516	123.508
16	12/10	08/06	15.262	15.279	15.295	14.908	14.924	14.943	123.371	123.359	123.353
17	12/11	08/06	15.790	15.808	15.824	15.198	15.211	15.226	123.277	123.270	123.268
18	12/12	08/06	16.382	16.403	16.425	15.153	15.123	15.091	123.423	123.433	123.450
19	12/13	08/06	16.772	16.793	16.813	15.901	15.923	15.947	122.173	122.189	122.204
20	12/14	08/06	17.409	17.426	17.444	16.194	16.205	16.218	122.375	122.370	122.368
21	12/15	08/06	18.036	18.052	18.068	16.423	16.432	16.442	122.335	122.329	122.324
22	12/16	08/06	18.685	18.699	18.714	16.637	16.644	16.653	122.262	122.256	122.252
23	12/17	08/06	19.361	19.374	19.387	16.835	16.841	16.848	122.188	122.183	122.180
24	12/18	08/06	20.071	20.080	20.091	17.020	17.023	17.028	122.123	122.121	122.118

Historically, planetary missions have used a variety of methods to assess injection accuracy. A commonly used method would simply compare the actual C3, DLA, and RLA errors to the individual maximum allowable values or tolerances. Other methods would evaluate the magnitude of the post-launch ΔV to target to the desired atmospheric entry aimpoint or to target back to the desired biased injection point, and compare them to the maximum allowable values. These methods are typically appropriate for orbiter missions that carry large propellant margins or spacecraft that use planetary flybys or large Deep Space Maneuvers (DSM), which can offset a significant amount of the injection error. MSL carried only ~73 kg of cruise propellant, which translated into potentially small cruise propellant margins; hence, large cruise ΔV to correct injection errors could have been catastrophic. In order to account for the effects of injection errors on cruise propellant usage, an error ellipsoid probability method was developed. This method included the effects of injection errors mapped to the Mars B-plane by accounting for corrections of C3, DLA, and RLA errors and worst case cruise propellant usage at the 99.0% probability level (3.36σ for a 3-dimensional distribution). This method was dependent on the Injection Covariance Matrices (ICMs), accounted for effects of injection errors on Mars impact probability in order to satisfy planetary protection requirements, and was simple to implement. For MSL, the post-launch ΔV to target the to desired atmospheric entry point method was not acceptable since this method did not account for the effects of injection errors on planetary protection requirements. The post-launch ΔV to target the biased injection aimpoint method did account for the effects of injection errors on planetary protection requirements; however, this method was complicated to implement since it required tables of biased injection aimpoints and maximum allowable ΔV values as a function of launch date and time. Figure 3 illustrates the C3, DLA, and RLA error method. Figure 4 shows the injection error ellipsoid probability method.

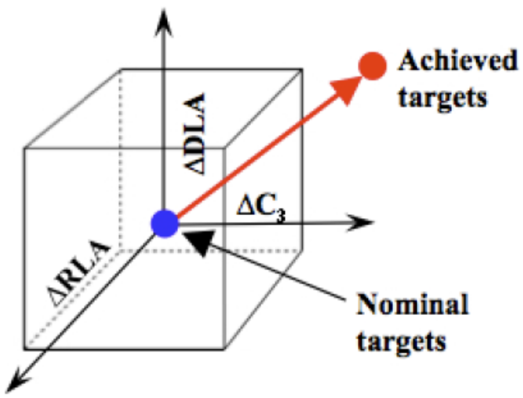

Figure 3. C3, DLA, RLA Error Method

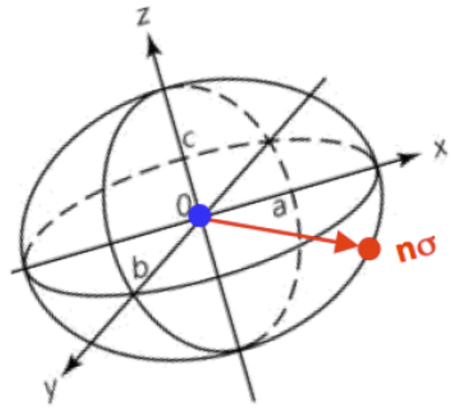

Figure 4. Ellipsoid Probability Method

Table 4 shows the injection accuracy results in terms of C3, DLA, and RLA at TIP in EME2000 coordinates, the 1σ uncertainties based on the MSL Navigation Team orbit determination solution, expected 1σ dispersions, and the sigma levels of the errors with respect to the expected 1σ dispersions. The expected dispersions were derived from the ICM for a launch on November 26, 2011 at the optimal minus 45 min launch (T-Zero = 15:07:00 UTC).[5]

Table 4. Injection Accuracy Assessment

Parameter	Achieved	Target	Error	OD Uncertainty (1σ)	Expected Dispersion (1σ)	Error σ Level
TIP Epoch	11/26/2011 15:51:09.02					
C_3 (km^2/s^2)	10.7193	10.7209	-0.0016	3.48E-07	±0.0105	-0.15σ
DLA* (deg)	1.6678	1.6698	-0.0020	1.75E-05	±0.0246	-0.08σ
RLA* (deg)	126.6165	126.6105	0.0060	1.13E-05	±0.0222	0.27σ
*EME2000 coordinate system.						

With respect to the principal axis injection error ellipsoid defined by the ICM corresponding to the actual launch time, the injection errors corresponded to a 0.23σ (0.30% probability error), which easily satisfied the 3.36σ injection accuracy requirement (99.0% probability error).

MARS B-PLANE PARAMETERS

The injection errors propagated to the Mars B-plane in terms of B•R, B•T, and Time of Closest Approach (TCA) are shown in Table 5. The targets were obtained by propagating the TIP state included in the Near Earth Trajectory Space (NETS) files provided by the launch vehicle provider to the Mars B-plane. The achieved values and 1σ uncertainties were based on the MSL Navigation Team orbit determination solution. The expected 1σ dispersions were derived from the ICM for a launch on November 26, 2011 at the optimal minus 45 min launch (T-Zero = 15:07:00 UTC) propagated to the Mars B-plane. The B•R, B•T parameters are expressed in the Mars Mean Equator and Equinox of Epoch.[5]

Table 5. Injection Errors Mapped to the Mars B-Plane

Parameter	Achieved	Target	Error	OD Uncertainty (1σ)	Expected Dispersion (1σ)	Error σ Level
B.R* (km)	-60843.6	-54996.3	-5847.3	104.4	41768.8	-0.14σ
B.T* (km)	6898.6	12435.8	-5537.2	77.4	27379.6	-0.20σ
TCA** (6-Aug-2011, hh:mm:ss, UTC)	22:29:44.0	21:33:36.5	00:56:07.5	00:00:58.9	06:33:40.5	0.14σ
*Mars Mean Equator and Equinox of Epoch coordinate system. **TCA = Time of Closest Approach.						

SEPARATION ACCURACY ASSESSMENT

The spacecraft separation attitude and angular rates targets were fixed across the launch period. This separation was defined as the instant of loss of contact between the spacecraft and the separation system hardware on the Centaur upper stage. Table 6 shows the spacecraft separation requirements. Note that the spacecraft separation attitude error included nutation effects and spacecraft wobble effects that could manifest after spacecraft separation but prior to any spacecraft propulsive maneuvers.

Table 6. Spacecraft Separation Requirements

Parameter	Value
Pointing Attitude of the $-Z_{SC}$ axis (Centaur $-X_B$ axis) in the EME2000 coordinate system	Declination = 12.00 deg Right Ascension = 243.50 deg
SC Separation Attitude Error (measured from the SC Z axis)	8.0 degree half-cone (99% probability)
SC Separation Angular Rates (right-hand rule about SC axes)	+Zsc = 15.0 +/- 3.0 deg/s (2.5 RPM +/- 0.5 RPM)

Table 7 shows the separation accuracy results in terms of the right ascension and declination of the spacecraft –Z-axis in EME2000 coordinates, and spacecraft spin rate (positive about the +Z axis). The estimated values were based on post-separation spacecraft telemetry.[5]

Table 7. Separation Accuracy Assessment

Parameter	Estimated	Desired	Error	Estimate Uncertainty	Required Accuracy
Spacecraft Separation Epoch	26-Nov-2011 15:46:09.02				
-Z Axis Right Ascension[1] (deg)	243.564	243.500	0.064	–	–
-Z Axis Declination[1] (deg)	12.216	12.000	0.216	–	–
Total Attitude Error (deg)	–	–	0.225	±0.5	±8.0
Spin Rate[2] (deg/s)	15.021	15.000	0.021	±0.015	±3.0
[1]EME2000 coordinate system. [2]Positive about +Z axis.					

The achieved separation conditions in terms of spacecraft attitude and spin rate following separation from the Centaur upper stage were very close to the desired values; hence, satisfying the separation accuracy requirements. The trans-Mars injection and Spacecraft separation provided by the Centaur was outstanding and set a new standard on launch vehicle performance.

DSN INITIAL ACQUISITION

Spacecraft telemetry was available from launch through spacecraft separation via interleaving with the launch vehicle telemetry and transmitted to the ground through the Tracking Data Relay System (TDRS). Upon completion of the second Centaur injection burn and following a wait time of 223.0 s, pyrotechnic actuators and push-off springs on the launch vehicle released the spacecraft with a separation velocity of 0.27 m/s, and a pointing attitude and angular rates discussed in the previous section. Spacecraft separation was one of the most critical events of the mission since it marked the first time the spacecraft communicated directly to the Deep Space Network antennas via its low-gain antenna. This was achieved by turning on the spacecraft's Travelling Wave Tube Amplifier (TWTA), which powered the transmitter. Due to possible interference with the Centaur telecommunications systems, a 1-min wait time was introduced via a cruise mode timer onboard the spacecraft. This ensured the MSL spacecraft had separated a sufficient distance from the Centaur prior to the initial data transmission. Once the cruise mode timer expired, spacecraft cruise configuration tables were executed and transition from launch mode to cruise mode was completed two minutes after spacecraft separation from the Centaur. At this point, the TWTA was powered on and based on pre-launch testing, the spacecraft was expected to transmit ~4 min later following a TWTA warm up period.[1,4] Figure 5 shows the nominal MSL ground track, main launch vehicle events, and initial ground station rise/set times. During actual flight, both Canberra stations (DSS-34 and DSS-45) and the USN Dongara station acquired the MSL downlink signal within 20 sec after the MSL spacecraft started transmitting. The three stations reported carrier in-lock times within ~3 s from each other and the signal reached the stations ~5 s earlier than their reported lock times. The stations achieved solid telemetry lock less than 30 s after carrier lock.[6] The first No-Op (No Operation function) command was radiated one hour after initial acquisition. Table 8 shows the expected and the actual carrier/telemetry lock times. Rise times and spacecraft transmitter times are also shown for reference. Minor intermittent frame gaps from receiver saturation and wide fluctuations in the Symbol Signal-to-Noise Ratio (SSNR) due to a rotating spacecraft combined with its low gain antenna patter were observed; however, modifications in the received bandwidth configuration were made in order to compensate for this problem. There were no frame gaps after the initial Canberra pass and DSN performance was completely nominal. The initial acquisition telemetry confirmed that the spacecraft had achieved a thermally stable, positive energy balance, and commandable configuration.

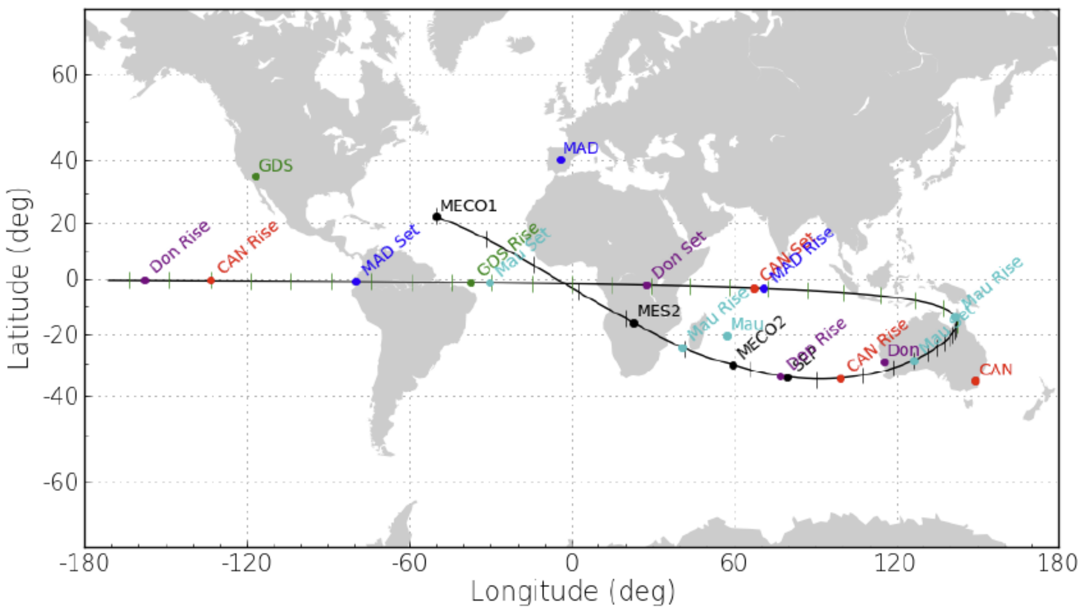

Figure 5. Launch Trajectory Ground Track – 11/26/2012 (launch window open: 15:02 UTC)

Table 8. DSN/USN Rise Times and Carrier/Telemetry Lock Times

Event	DNS/USN Initial Acquisition Times				
	Expected Time from S/C Transmitter ON (sec)	Expected Time (UTC, hh:mm:ss)	Actual Time from S/C Transmitter ON (sec)	Actual Time (UTC, hh:mm:ss)	Delta (sec)
Dongara Rise	-0:06:27	15:45:39	N/A	N/A	N/A
Canberra (DSS-34) Rise	-0:01:17	15:50:49	N/A	N/A	N/A
Spacecraft Transmitter ON	-	15:52:06	-	15:52:09	~3
Dongara Carrier Lock	N/A	N/A	0:00:16	15:52:25	N/A
Canberra (DSS-45) Carrier Lock	TXR_ON+10 sec	15:52:19	0:00:18	15:52:27	~7
Canberra (DSS-34) Carrier Lock	TXR_ON+10 sec	15:52:19	0:00:19	15:52:28	~8
Canberra (DSS-45) Telemetry Lock	CarrierLock+20sec	15:52:47	0:00:43	15:52:52	~5
Canberra (DSS-34) Telemetry Lock	CarrierLock+20sec	15:52:48	0:00:51	15:53:00	~12

INTERPLANETARY CRUISE AND MARS APPROACH

The Cruise phase began with the first commanding of the spacecraft (No-Op) following initial acquisition on November 26th, 2011 and ended on June 21st, 2012 when the spacecraft was 45 days from entry into the Martian atmosphere. The Approach phase immediately followed the Cruise phase and ended when the spacecraft reached the Mars atmospheric entry interface point, 3522.2 km from the center of Mars. During cruise, major spacecraft activities included Trajectory Correction Maneuvers (TCMs) to correct launch vehicle injection errors, remove injection bias and target to the desired landing site; engineering and instrument checkouts; spacecraft attitude corrections to maintain power and telecommunications; and navigation activities for determining and correcting the spacecraft flight path.[1] The propulsion system on the cruise stage was used to maintain the spin rate, perform attitude maintenance maneuvers, and execute TCMs. The Approach phase was mainly focused on preparations for EDL to ensure the spacecraft was delivered accurately to the required entry point and all the EDL sequence parameters were loaded correctly onboard the vehicle. Eight ~5 N thrusters were mounted in two thruster clusters diametrically opposed and located in a plane normal to the Z-axis such that there were coupled thruster pairs allowing both axial and lateral maneuvers.[7] Figure 6 shows the MSL Cruise Configuration.

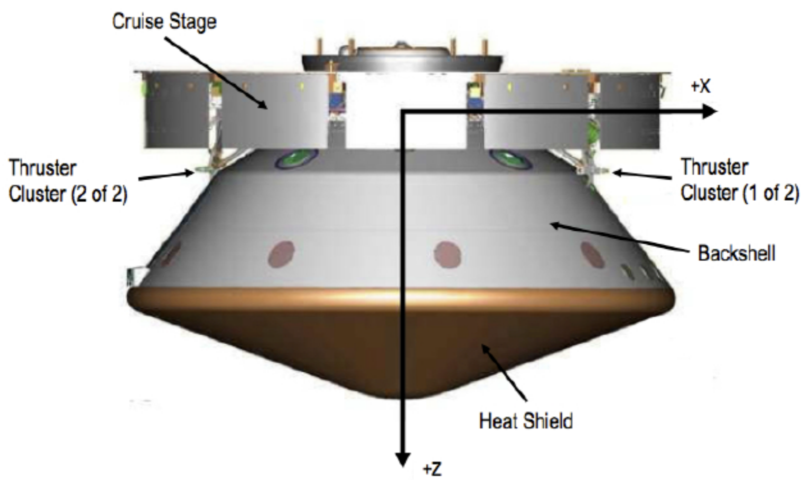

Figure 6. MSL Cruise Configuration

Two of the thrusters in each cluster ("axial" thrusters) were canted 40 deg towards the +Z and –Z directions. The other two thrusters in each cluster were canted 40 deg away from the line connecting to the two thruster clusters in a plane normal to the Z-axis. Two 19-in diameter tanks were loaded with at least 70 kg of hydrazine propellant (actual propellant load was 73.8 kg). Axial burns were accomplished by firing pairs of axial thrusters continuously for a determined period of time. Lateral burns imparted a ΔV approximately normal to the Z-axis by firing all four thrusters in each cluster for 5 s at the appropriate orientation during each spacecraft revolution, resulting in two 5 s lateral pulses per revolution with one of the axial thrusters firing during a smaller interval in order to ensure that the thrust vector went through the center of mass of the spacecraft. The average Isp values for axial and lateral TCMs were 212.4 s and 221.8 s respectively. These values include blowdown effects and are adjusted to account for thruster plume impingement losses of 6% for axial burns and 1% for lateral burns. During interplanetary cruise, up to six TCMs (and a backup TCM) were planned. Figure 7 shows the MSL interplanetary trajectory and planned TCM slots. The first three TCMs occurred during the Cruise phase and the final three were planned to be executed during the Approach phase. Due to excellent orbit determination and good maneuver execution performance, TCM-5 and TCM-6 were not required and hence canceled. TCM-1, TCM-2, and TCM-3 were chained optimized in order to minimize total cruise propellant. During pre-launch activities, TCM-1 was planned to correct injection errors and all or part of the injection biasing to satisfy the non-nominal impact probability requirement; TCM-2 was designed to correct TCM-1 execution errors and move the biasing aimpoint closer to the desired entry point; and TCM-3 was scheduled to correct TCM-2 execution errors and to target to the desired atmospheric point. During flight and following TCM-1 execution, TCM-2 was re-optimized to correct both TCM-1 execution errors and target to the landing site. TCM-3 and TCM-4 were implemented to correct TCM-2 and TCM-3 maneuver execution errors.[8,9]

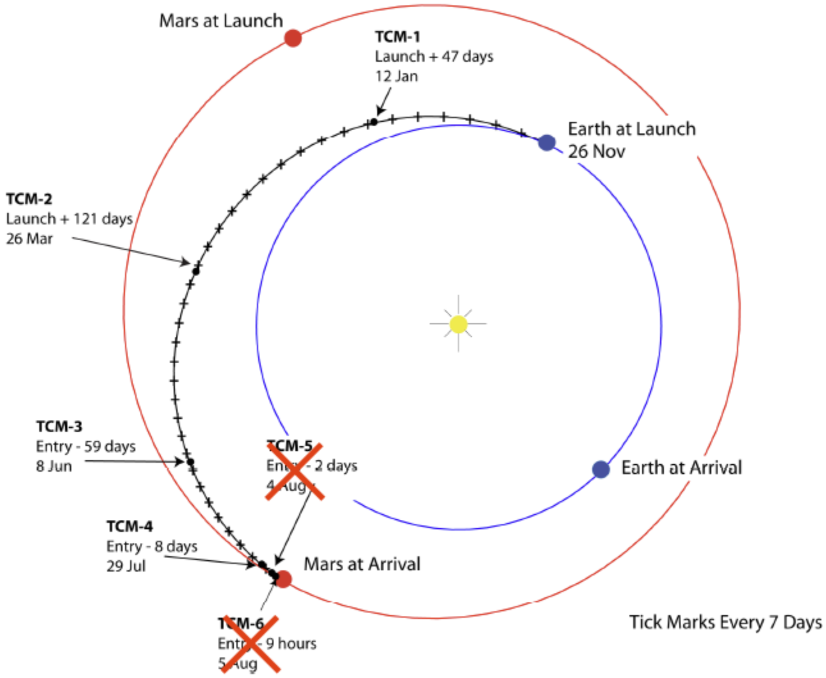

Figure 7. MSL Interplanetary Trajectory

TRAJECTORY CORRECTION MANEUVER PERFORMANCE

Due to the small cruise propellant allocation, good orbit determination solutions and small maneuver execution errors were critical for a precise delivery of the vehicle at the desired atmospheric entry point. Prior to launch, 99% propellant mass estimates were computed across the launch window for each launch day to ensure MSL would have enough cruise propellant to remove launch vehicle errors, aimpoint biasing, and retarget to the desired EIP.[4] Figure 8 shows the 99% propellant mas and propellant margin across the launch period.

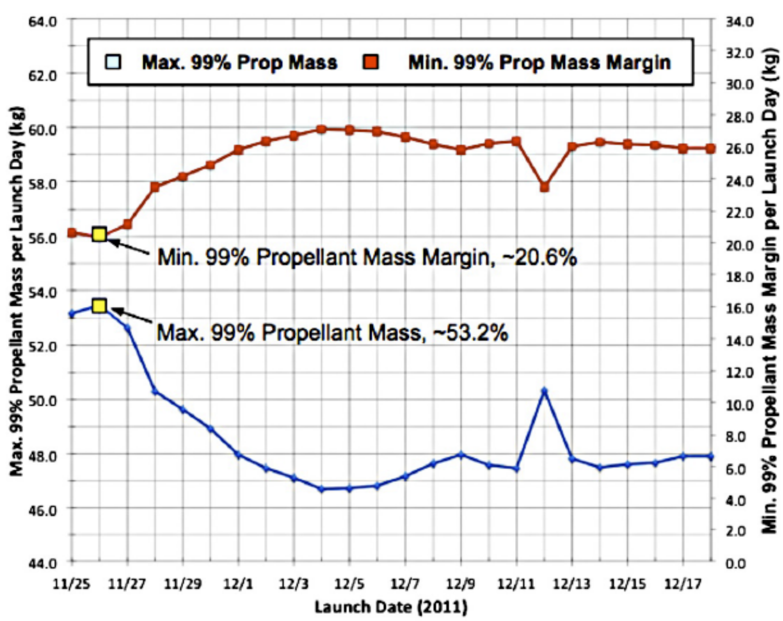

Figure 8. 99% Propellant Mass and Mass Margins

The total implemented ΔV for TCM-1 through TCM-4 was ~6.27 m/s and the corresponding resulting ΔV was ~6.40 m/s. The estimated TCM propellant used was ~20.4 kg. Maneuver execution errors were very small and the largest magnitude error (~5.7%) corresponded to the smallest TCM of ~10 cm/s. Pointing errors were less than 2.5 deg. The actual maneuver execution time for TCM-1 was delayed from the planned launch plus 15 days to launch plus 46 days. This was enabled by the extremely accurate trans-Mars injection burn, which permitted delaying TCM-1 several weeks without significant impact to the cruise propellant margin. TCM-3 was also delayed in order to load an upgrade the flight software and perform an additional instrument checkout. Table 9 shows the pre-launch and actual maneuver dates, planned and estimated ΔVs, estimated TCM propellant usage and ΔV magnitude and pointing errors.[10]

Table 9. TCM Maneuver Performance

Segment	Pre-Launch Date (UTC)	Actual Date (UTC)	Planned ΔV (m/s)	Estimated ΔV (m/s)	Estimated TCM Propellant Usage (kg)	Magnitude Error (%)	Pointing Error (deg)
TCM-1	12/11/11	1/11/12	5.5071	5.6350	18.032	2.323	0.618
TCM-2	3/25/12	3/26/12	0.7116	0.7119	2.227	0.038	0.388
TCM-3	6/7/12	6/26/12	0.0414	0.0418	0.138	1.029	2.462
TCM-4	7/29/12	7/29/12	0.0111	0.0104	0.026	-5.702	1.750
TCM-5	8/4/12	Cancelled	-	-	-	-	-
TCM-5X	8/5/12	N/A	-	-	-	-	-
TCM-6	8/5/12	Cancelled	-	-	-	-	-
		TOTAL	6.2712	6.3991	20.423		

CRUISE MAINTENANCE ACTIVITY PERFORMANCE

During cruise and approach, several spacecraft activities that required usage of the cruise propulsion stage were performed. These activities included spacecraft spin down from the spin rate following Centaur separation to the nominal spin rate of 2 RPM, Attitude Control System (ACS) maintenance turns to maintain good –Z-axis off-Sun and off-Earth angles for the vehicle to remain at a safe attitude for both power and communications, ACS calibrations in order to assess residual translation ΔV resulting from spacecraft turns, and calibration of the Descent stage Inertial Measurement Unit (DIMU). Table 10 shows the total cruise propellant mass used during cruise activities.

Table 10. Cruise Propellant Mass Utilization

Date	Event	Total Spacecraft Wet Mass (kg)	Propellant Mass Used (kg)	Propellant Mass Available (kg)	Propellant Mass Available (%)
11/26/11	**T-Zero**	3840.5	-	73.8	100.0%
11/26/11	Separation	3838.7	1.78	72.0	97.6%
11/28/11 - 01/06/12	Spindown, ACS Turn #1,#2, and Lat Cal	3837.1	1.63	70.4	95.4%
01/11/12	**TCM-1**	3819.0	18.03	52.3	70.9%
01/25/12 - 03/07/12	ACS Cals, ACS Turns #3-6, DIMU Cal #1	3815.7	3.33	49.0	66.4%
03/26/12	**TCM-2**	3813.5	2.23	46.8	63.4%
03/26/12 - 06/18/12	ACS Turns #7-17, DIMU Cal #2	3811.6	1.90	44.9	60.8%
06/26/12	**TCM-3**	3811.4	0.14	44.7	60.6%
06/26/12 - 07/18/12	ACS Turns #18-21	3811.2	0.19	44.6	60.4%
07/29/12	**TCM-4**	3811.2	0.03	44.5	60.3%
07/29/12	ACS Turn #22	3811.2	0.07	44.5	60.3%
		TOTAL CRUISE PROPELLANT USED	29.33		

ATMOSPHERIC ENTRY DELIVERY AND KNOWLEDGE ACCURACY

The 3-sigma atmospheric entry delivery requirement stated that "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". Based on a post-landing trajectory reconstruction using all the data and calibrations leading up to atmospheric entry, the actual Entry Flight Path Angle (EFPA) was well within the 3-sigma requirement being estimated as 0.013 deg shallower than the -15.5 deg EFPA target. The knowledge accuracy requirement was specified as "the EDL guidance system shall be initialized with an entry state with an accuracy of 2.8 km in position and 2.0 meter per second in velocity" with a "final update of the entry state vector not later than entry minus 2 hours". The entry state calculated just 36 hours after TCM-4 (six days prior to atmospheric entry) and that was uploaded to the spacecraft on the same day was off by 0.2 km in position and 0.11 meters per second in velocity from the post-landing reconstructed entry state. Figure 9 shows the location of the entry target, the estimated entry point prior to TCM-4 execution, the estimated entry point based on a Data Cut-Off (DCO) at Entry – 20 min, and the coordinates of the on-board entry state. The difference between the OD used to generate the on-board state at Entry minus six and a half days and any subsequent ODs was in the order of ~500 m or less; hence, a second entry state vector update was not needed. The distance between the EIP of the TCM-4 target and the actual EIP based on OD230 was ~699 m. The distance between the EIP of the TCM-4 target and the EPU-1 location (onboard state) was ~489 m. Of most importance was the range between the actual EIP location and the EPU-1 location which was only of ~242 m. The locations of these points on the B-Plane are shown in Table 11.[8,9]

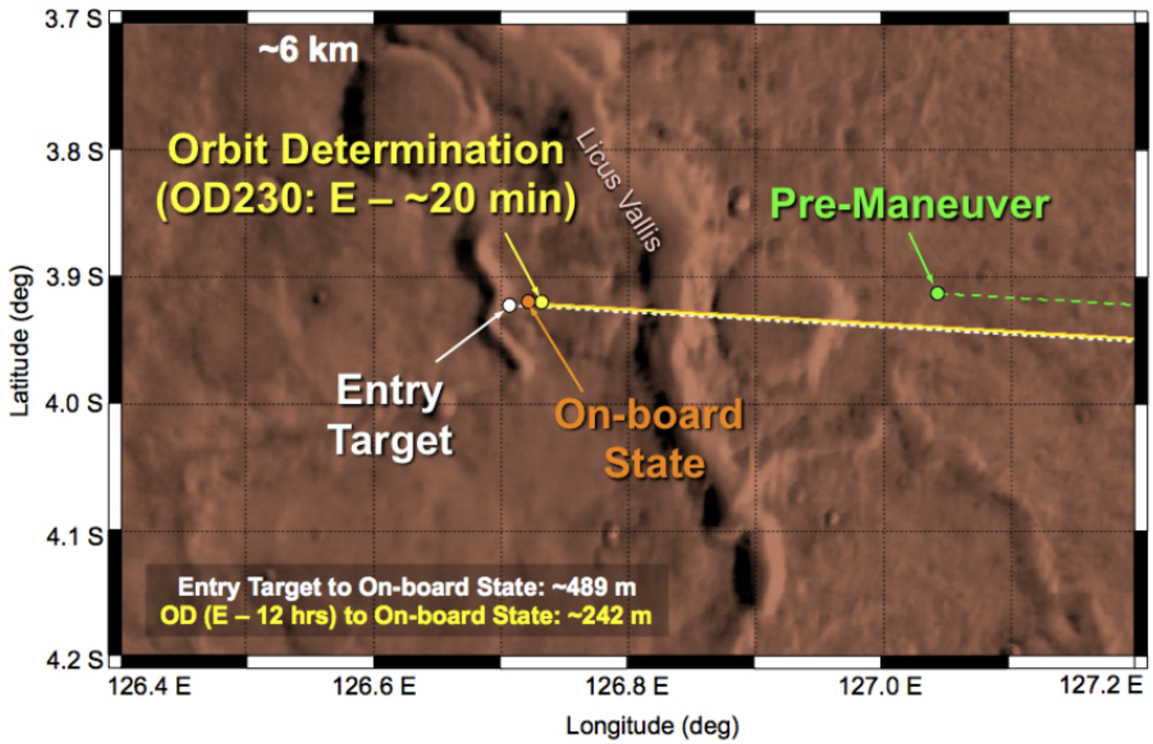

Figure 9. On-Board State Vs. Entry Target and OD at E – 12 hrs

Table 11. B-Plane locations for TCM-4 Target, EPU-1, and OD230

Point	B·R	B·T	DCO
TCM-4 target	354.78694	5785.65433	28-JUL-2012 16:00:00 UTC
EPU-1 location	354.50276	5786.05250	30-JUL-2012 15:57:30 UTC
od230 location	354.27242	5786.12788	06-AUG-2012 04:22:32 UTC

EDL ATTITUDE INITIALIZATION

The attitude knowledge requirement for EDL attitude initialization was 4.35 mrad (~0.25 deg), 3-sigma, per axis with a goal of achieving 0.1 deg. A comparison of the onboard ACS data to the long-arc despin at the vehicle's final pre-entry attitude showed that the error in the estimated negative-H vector (i.e., the "spin axis") was about 0.023 deg. Including the noise floor of the data, the error in spin phase amounted to 0.03 deg. There was no formal requirement for control of the attitude at EDL beyond the 2 deg cruise requirement for pointing control as long as the EDL Nav Filter knew the 3-axis attitude to 0.25 deg. Preliminary EDL reconstruction analysis indicated an attitude initialization error of less than 0.03 deg, or one order of magnitude less than the requirement.

ARRIVAL GEOMETRY

MRO, Mars Odyssey, and Mars Express executed a series of on-orbit phasing maneuvers after the launch of MSL to achieve an optimal geometry at the time of atmospheric Entry. MRO served as the primary EDL coverage asset and recorded the telemetry data stream in open loop. Mars Odyssey captured the telemetry in unreliable mode and via its bent pipe capabilities, retransmitted the data back to Earth, providing near real-time (minus the one-way light time delay) monitoring of the spacecraft health during EDL. Mars Express provided canister, carrier only recording. Figure 10 illustrates a close-up of the arrival geometry.

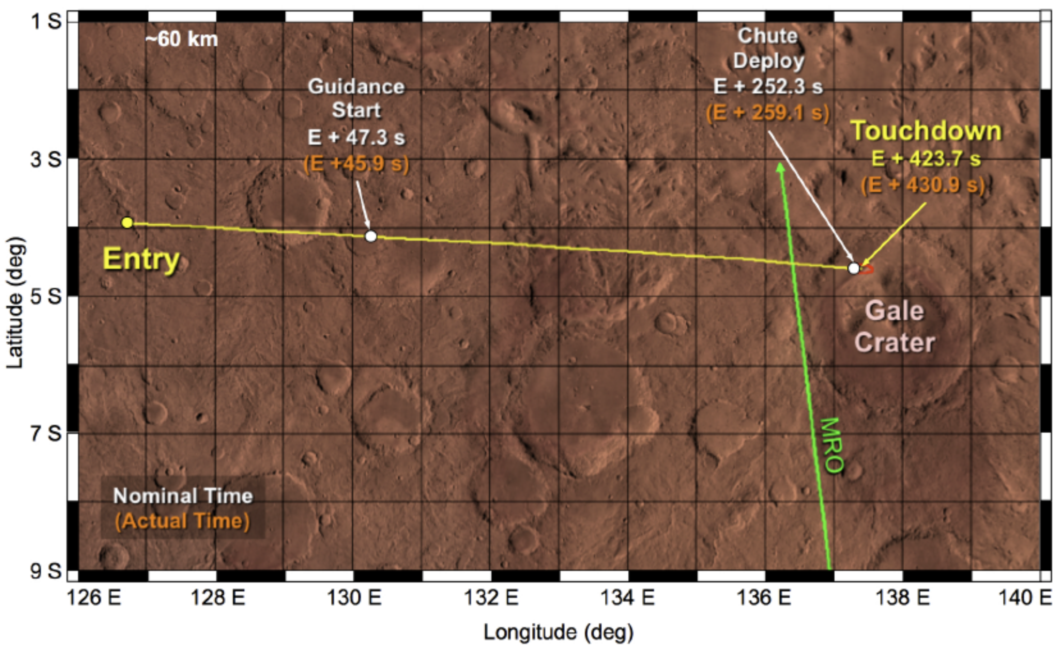

Figure 10. Arrival Geometry Close-up

In order to accomplish a successful EDL communications event, the MSL Navigation team and the orbiters' Navigation teams continuously exchanged trajectory predicts which were evaluated to adjust the requested orbiter positioning as necessary. These targets were specified in the EDL Relay Target Files (ERTF), which in the case of MRO and Odyssey took the form of the latitude, and LMST to be achieved at the MSL Entry epoch. For Mars Express, the ERTFs specified the target latitude and longitude at the MSL Entry epoch. The final phasing targets delivered at Entry minus 56 days were provided in ERTF #8A. Subsequent ERTF deliveries did not levy any requirements and were used for reference purposes only in order to track the evolution of the targets and trajectory predicts. The orbiter teams were expected to achieve their EDL relay targets within ± 30 s (MRO), and ± 60 s (Odyssey). Mars Express EDL comm support was on a best effort basis with a goal of achieving the target within ± 60 s. Table 12 summarizes the timing error to achieve the requested target latitude at the time of MSL entry per ERTF cycle. Although, ERTF #8A specified the final phasing targets, during each ERTF cycle new targets were generated to compare them with the ones specified on ERTF #8A. Note that Mars Odyssey entered safe mode during one of the planned on-orbit phasing maneuvers which caused an early violation of the phasing requirements. This phasing error of ~125 s was later corrected after successfully executing an additional phasing maneuver. Note that the three orbiters satisfied the phasing requirements with significant margin.[11]

Table 12. Time to Target Latitude Crossing from Entry Minus 56 Days

		Time to Target Latitude Crossing (s)																	
		ERTF Response																	
		ERTF 8A			ERTF 9			ERTF 10			ERTF 11			ERTF 12			ERTF 13		
		MRO	ODY	MEX	MRO	ODY	MEX	MRO	ODY	MEX	MRO	ODY	MEX	MRO	ODY	MEX	MRO	ODY	MEX
ERTF Request	ERTF 8A	0.0	-124.5	34.7	0.0	-124.5	34.7	9.8	-25.1	39.8	9.0	-25.0	41.5	9.0	-25.0	41.5	**9.0**	**-25.0**	**41.5**
	ERTF 9	-	-	-	-5.2	-124.4	34.8	-	-	-	-	-	-	-	-	-	-	-	-
	ERTF 10	-	-	-	-	-	-	19.0	-24.3	41.4	-	-	-	-	-	-	-	-	-
	ERTF 11	-	-	-	-	-	-	-	-	-	18.7	-24.4	43.1	-	-	-	-	-	-
	ERTF 12	-	-	-	-	-	-	-	-	-	-	-	-	18.9	-24.3	43.1	-	-	-
	ERTF 13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18.9	-24.3	43.0

EDL TRAJECTORY PERFORMANCE

The performance of the EDL vehicle was outstanding. The pre-launch landing uncertainty was between -40 s and +60 s but the actual EDL events times occurred within 7 s from the predicted EDL event times based on the latest orbit determination solution (OD230).[12] This landing time uncertainty remained the same as it was primarily a function of altitude at parachute deploy and parachute aerodynamics. The Navigation orbit determination was updated as the vehicle approached Mars but that only shifted the mean time of landing and not the actual landing uncertainty. Table 13 shows the predicted/nominal EDL event timeline and the actual values.

Table 13. Predicted Vs. Actual EDL Event Timeline

EDL Event Timeline										
	Predicted (based on OD230 Mean)^				Actual†					
Event Name	Time from Entry (s)	Time from Landing (s)	Altitude AGL (m)	Mars Relative Velocity (m/s)	Time from Entry (s)	Time from Landing (s)	Altitude AGL (m)	Mars Relative Velocity (m/s)	Spacecraft Event Time (08/06/2012, UTC)	Earth Received Time (08/05/2012, PDT)
Entry Interface Point	0.0	423.7	125,169.2	5,845.31	0.0	430.9	124,993.7	5,845.39	5:10:46	22:24:34
Guidance Start	47.3	376.4	56,384.4	5,863.19	45.9	385.0	58,042.2	5,863.60	5:11:32	22:25:20
Heading Alignment	136.4	287.3	14,487.9	1,098.97	135.6	295.2	15,160.2	1,098.50	5:13:02	22:26:50
Begin SUFR	235.7	188.0	13,925.0	454.56	239.9	191.0	14,796.9	454.60	5:14:46	22:28:34
End SUFR	249.4	174.3	12,597.0*	418.87*	253.9	177.0	12,933.6	419.61	5:15:00	22:28:48
Parachute Deploy	252.3	171.4	11,848.1	405.99	259.1	171.7	12,146.8	406.35	5:15:05	22:28:53
Heat Shield Separation	273.9	149.8	9,670.2	144.25	278.9	152.0	9,996.7	146.04	5:15:25	22:29:13
Earth Occultation	305.9	117.8	-	-	305.9	125.0	-	-	5:15:52	22:29:40
TDS Data Start	308.2	115.6	6,813.3	94.04	297.1	133.7	8,355.1	101.69	5:15:43	22:29:31
Backshell Separation	370.8	52.9	1,662.8	77.42	375.9	54.9	1,670.8	78.89	5:17:02	22:30:50
Rover Separation	408.1	15.6	20.7	0.75	412.9	18.0	21.6	0.74	5:17:39	22:31:27
Touchdown	423.7	0.0	9.0	0.75	430.9	0.0	9.4	0.60	5:17:57	22:31:45

^ Predicted altitude and velocity measured with respect to the wet vehicle center of gravity.
* Indicates value interpolated from nominal trajectory.
† Events are measured with respect to the descent stage IMU.

In order to calculate the predicted event timeline, a Monte Carlo was run in POST[13] and the mean data was calculated to determine the time, altitude, and velocity for most of the events. Some of the events were tracked differently in the Monte Carlo and are noted on the table. For these data, a mean from the Monte Carlo could not be extracted, so the data were interpolated from the nominal trajectory run in the Monte Carlo.

Spacecraft data were interpreted to provide the actual times, altitudes, and velocities. The spacecraft directly reported out the time that the events, such as pyro firings for heatshield separation, occurred. The spacecraft also stored all of the sensor data, such as from the IMU and TDS, onboard. These data were retransmitted to Earth within weeks after landing. A best estimated trajectory of the spacecraft state, including altitudes and velocities, were calculated on the ground through this data along with knowledge of the entry and landing locations. Figure 11 shows the actual event times in graphical form.

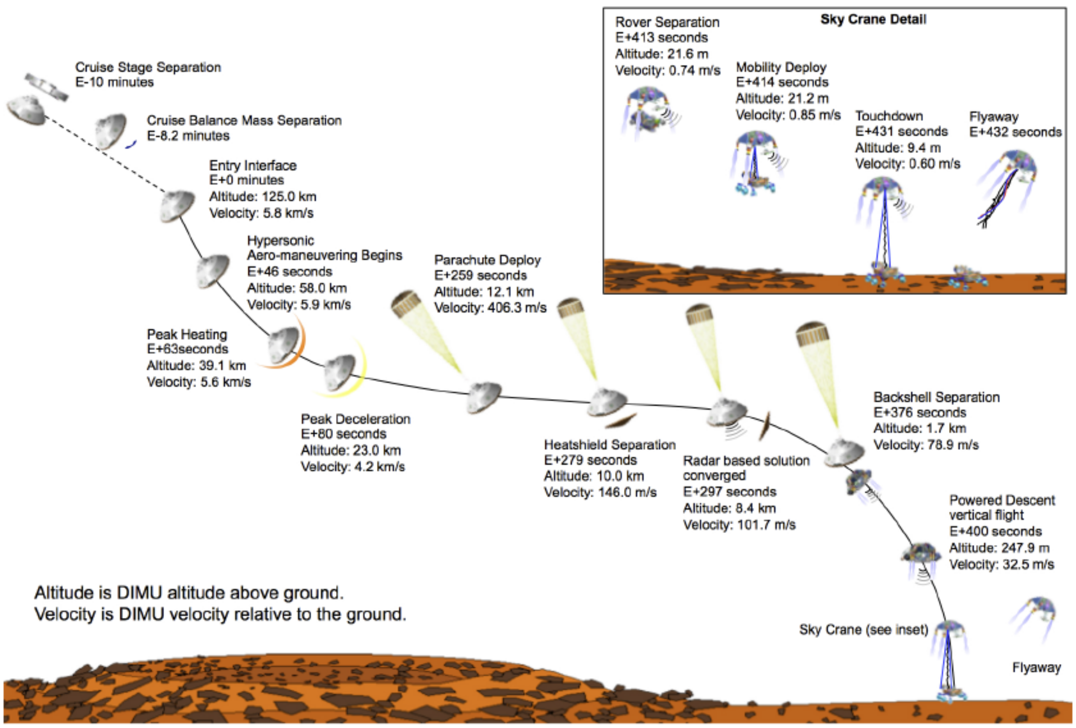

Figure 11. EDL Event Timeline (Actuals)

LANDING ACCURACY

The original MSL landing ellipse of about 21 km (13 mi) by 12 km (7.5 mi) was already significantly smaller than the landing ellipse for any previous Mars mission. This key characteristic of MSL was enabled by the usage of entry guidance. EDL analysis continued after the launch of MSL and the initial attitude error of 0.25 deg was reduced to 0.1 deg which resulted in confidence in landing within an even smaller area, about 21 km (13 mi) by 7 km (4.3 mi). By using the smaller ellipse, the MSL Project elected to move the center of the target closer to the mountain in order to reduce by half the traversing distance to the foothills of Gale crater where geological layers of high scientific interest exist. Table 14 shows the areocentric location of the target site and the achieved landing location.

Table 14. Target Vs. Achieved Landing Location

Landing Location	Areocentric Latitude (deg)	Longitude (deg)	Radius (m)
Target	-4.5965	137.4019	3391.134
Actual (Bradbury Landing)	-4.5895	137.4417	3391.133

Figure 12 compares the actual landing location with the Monte Carlo predictions based on OD230, as well as the 1σ (39.35%-tile), 2σ (86.47%-tile), and the 3σ (98.89%-tile) probability ellipses. The observed landing distance of 0.7473σ (23.747%) to the OD230 Monte Carlo predictions amounted to a separation between the target landing site and the achieved target site of ~2.4 km.[13]

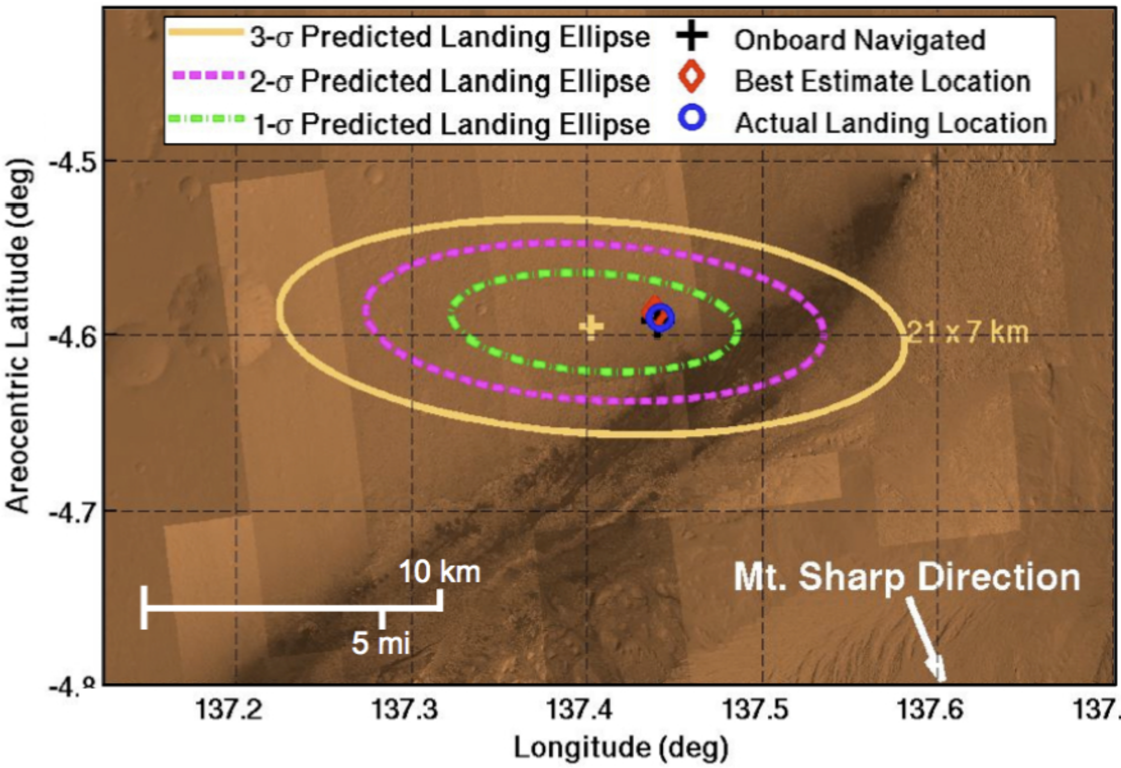

Figure 12. Actual Landing Location and Monte Carlo Predictions from OD229

CONCLUSION

Performance of the MSL spacecraft and all associated assets and resources required to carry out its mission was outstanding which ultimately led to a successful landing inside Gale Crater only ~2.4 km away from the intended target. Launch vehicle injection errors were ~0.23σ, DSN initial acquisition took place within seconds of the expected lock times, trajectory correction maneuver execution errors were less than 5% which coupled with excellent orbit determination solutions and performance of cruise activities resulted in more than 60% of the cruise propellant available after the last ACS turn prior to EDL. All relay assets, namely, MRO, ODY, and Mars Express, successfully executed phasing maneuvers to position themselves in an optimal geometry in order to receive MSL signal during EDL. The DSN also successfully acquired MSL's signal via the Direct-To-Earth X-band tones until the spacecraft became occulted by Mars as seen from the Earth, and downlinked both the near real-time data stream from Odyssey and MRO's open loop recording. The MSL's UHF Direct-To-Earth carrier signal was also received as expected at the Parkes Observatory while the spacecraft was in view. Following a 550 million km trip, MSL hit the Entry Interface Point (EIP) only ~699 m away from the optimal EIP inside a ~2.5 km x ~11.5 km window. The Curiosity rover was successfully delivered ~431 s later inside its ~21 km x ~7 km 3σ landing dispersion ellipse, with only a 0.75σ delivery error or ~2.38 km away from the intended target. The outstanding performance of every aspect of the MSL vehicle, orbiter relays, and ground assets, arguably set a new standard in robotic exploration of the Solar System.

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