2011 Mars Science Laboratory Mission Design Overview

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ABSTRACT

Scheduled to launch in the fall of 2011 with arrival at Mars occurring in the summer of 2012, NASA's Mars Science Laboratory will explore and assess whether Mars ever had conditions capable of supporting microbial life. In order to achieve its science objectives, the Mars Science Laboratory will be equipped with the most advanced suite of instruments ever sent to the surface of the Red Planet. Delivering the next mobile science laboratory safely to the surface of Mars has various key challenges derived from a strict set of requirements which include launch vehicle performance, spacecraft mass, communications coverage during Entry, Descent, and Landing, atmosphere-relative entry speeds, latitude accessibility, and dust storm season avoidance among others. The Mars Science Laboratory launch/arrival strategy selected after careful review satisfies all these mission requirements.

INTRODUCTION

The primary objective of the Mars Science Laboratory Mission is to place a mobile science laboratory on the surface of Mars to assess the biological potential of the landing site, characterize the geology of the landing region, investigate planetary processes that influence habitability, and characterize the broad spectrum of surface radiation. Observations of Mars geology, advanced micro-imagery, spectrometry, radiation environment assessment, and study of surface environments will also be conducted.

The mission will be launched from the Eastern Test Range at Cape Canaveral Air Force Station (CCAFS) in Florida during the 2011 Earth to Mars opportunity, with launch dates ranging from mid-October through mid-December 2011, and arrival dates at Mars between early August and mid-September 2012.

The main elements of the MSL Project consist of a single flight system including payloads and a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), a launch vehicle, and the mission system/ground data system. The flight system consists of an Earth-Mars cruise spacecraft, an atmospheric Entry, Descent, and Landing (EDL) system, and a mobile science rover. An expanded view of the MSL flight system is shown in Figure 1. The MSL rover carries an integrated instrument package composed of a suite of 10 science instruments that span the areas of remote sensing (Mastcam and ChemCam), in-situ (MAHLI and APXS), analytical (CheMin and SAM), and environmental (RAD, MARDI, DAN, and REMS). Figure 2 shows the location of the different instruments on the MSL rover. The primary data return paths during EDL are via an X-band direct-to-Earth communications link through the Deep Space Network (DSN) and an Ultra High Frequency (UHF) link to existing Mars network orbiting assets, which include Mars Reconnaissance Orbiter (MRO) and Mars Odyssey (ODY) (Ferdowsi B., 2007).

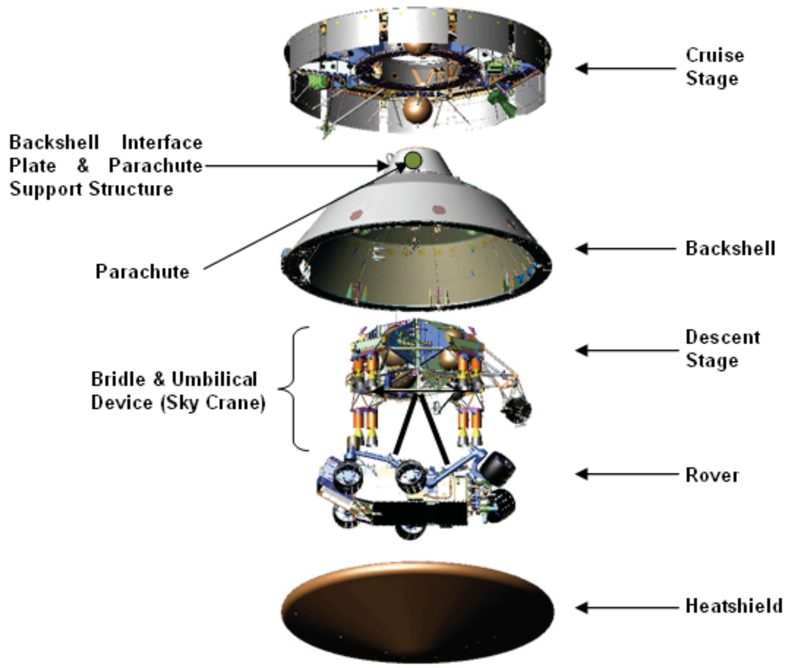


Figure 1. MSL Flight System Expanded View

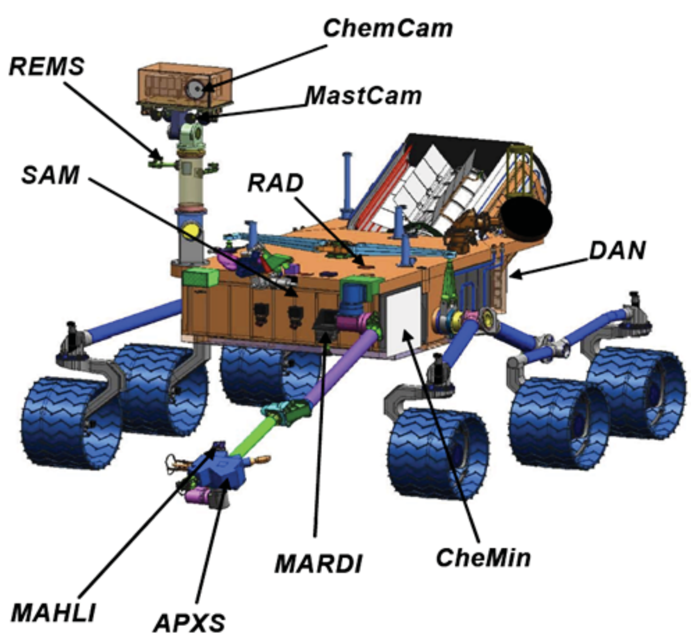


Figure 2. Instrument Mountings on MSL Rover

LAUNCH PHASE

Overview

NASA will launch the MSL mission during the 2011 Earth to Mars opportunity. The launch vehicle is an Evolved Expendable Launch Vehicle (EELV) Atlas V 541 (5-m fairing with 4 strap-on solid rocket boosters) consisting of a liquid oxygen / kerosene Common Core Booster (CCB) first stage and a liquid oxygen / liquid hydrogen Centaur upper stage. The launch phase begins when the spacecraft transfers to internal power on the launch pad and ends when the spacecraft has achieved a thermally stable, positive energy balance and commandable configuration and has successfully played back the launch phase telemetry. After the initial ascent phase and following Main Engine Cutoff 1 (MECO1) of the Centaur upper state, the 165 km x 271 km, 29.0 deg inclination parking orbit is established. For launch days with high launch declinations (DLA), utilizing a 35.6 deg inclination parking orbit is being considered. After the necessary coasting time in order to achieve the required departure geometry, the second Centaur burn injects the spacecraft onto the interplanetary transfer trajectory.

Launch/Arrival Strategy Requirements

The selected MSL launch period meets the following high-level mission requirements, except where noted:

- A minimum of 20 consecutive launch days in the 2011 Earth to Mars opportunity.
- Full Entry, Descent and Landing (EDL) communications coverage (from atmospheric entry, defined to occur at a radius of 3522.2 km, through landing plus 1 min) via Direct-To-Earth (DTE) using an X-band link and via Mars Reconnaissance Orbiter (MRO) and Mars Odyssey (ODY) using an UHF link.
    - DTE coverage is not available for all landing sites.
    - Simultaneous UHF coverage via Mars Odyssey (ODY) is desired for redundancy but is not possible for all launch days for some landing sites.
    - EDL communications drop-outs are expected to occur between landing – 60 s and landing – 20 s due to parachute and powered descent dynamics.
    - Since having simultaneous EDL coverage via MRO, ODY and DTE is not always possible, the goal is to at least maintain EDL coverage via two of these assets for redundancy purposes.
- Accessibility to a range of latitudes that encompass the current candidate landing sites, i.e. from 25°N to 27°S.
- Atmosphere-relative entry speeds between 5.3 km/s and 5.9 km/s.
- Launch during daylight (requirement due to launching a payload with an MMRTG on board).
- Time from launch to eclipse exit or separation (whichever is later) is less than 101.5 minutes, which is driven by rover battery capability for depletion to 45% State-Of-Charge (SOC).

In addition, the following constraints must also satisfied:

- $C_3 < 20.1$ km^2/s^2 which corresponds to a maximum spacecraft injected mass of 4050 kg on an Atlas V 541.
- Longitude of the Sun at arrival, Ls < 170 deg.
- DTE EDL coverage from separation to entry.
- MRO/ODY antenna angles (defined as the angle between the MSL anti-velocity vector and the direction to MRO/ODY) < 135 deg during the EDL phase.
- DTE antenna angles (defined as the angle between the MSL anti-velocity vector and the direction to Earth) < 75 deg during the EDL phase.
- Elevation of MRO/ODY/DTE at landing plus one min > 10 deg.

Several assumptions that mostly affected the feasibility of EDL coverage were also taken into account in order to determine the launch/arrival strategy:

- MRO's Local Mean Solar Time (LMST) node is nominally at 3:00 PM (ascending) and can be moved to provide EDL coverage to MSL.
- ODY's LMST node is nominally at 3:45 PM (descending) and can be moved to provide EDL coverage to MSL.
- Nominal Atmospheric Entry Flight Path Angle (EFPA) = - 15.5 deg (inertial)

The following guidelines were used as criteria for the optimization of the launch/arrival strategy:

- Provide as many launch days as possible.
- Enable EDL coverage via Mars Odyssey.
    - In the few cases in which enough flexibility exists so that all mission constraints are satisfied and various solutions exist, EDL coverage via Mars Odyssey may be taken into account in the launch period selection, but may not compromise EDL coverage via MRO.
- Maintain MRO/ODY LMST nodes as close as possible to their nominal values.
    - Available MRO LMST nodes range between 3:00 PM and 1:45 PM (LMST nodes at 1:30 PM may also be possible but have not been fully analyzed by the MRO flight team).
    - Available ODY LMST nodes range between 3:45 PM and 3:00 PM.
- Keep antenna angles as low as possible to enable higher telecom margins during EDL
- Arrive at Mars with Ls values as low as possible.
- Minimize required number of target sets.
    - A target set is required when mission constraints cannot be satisfied simultaneously for all landing sites using the same launch/arrival dates. All target sets share the same launch days but may have different arrival dates.
- Keep arrival dates constant when possible.

- Simplifies planning for surface mission operations.

Other important Navigation, Maneuver and Orbit Determination (OD) requirements related to planetary protection, TCM ΔV and propellant requirements, and atmospheric entry delivery/knowledge accuracies were satisfied but are not discussed in detail herein.

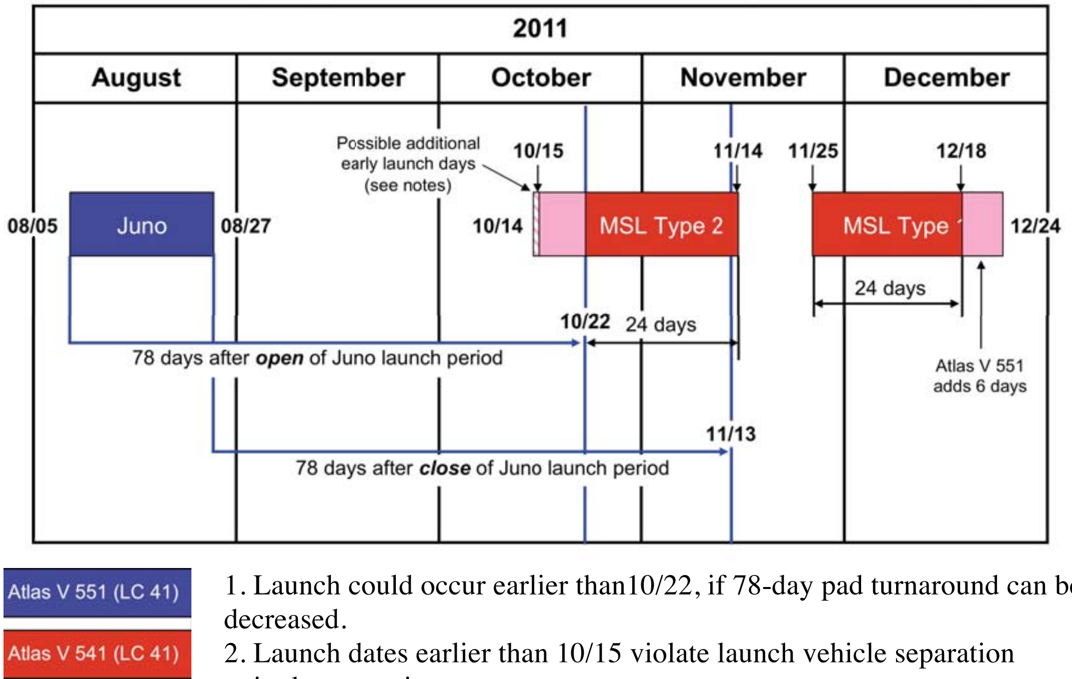
Launch Period

The 2011 MSL launch period consists of two launch periods of 24 consecutive launch days each. The first 24-day launch period is located in the Type 2 region of trajectories from Earth to Mars, and the second 24-day launch period is located in the Type 1 region. Type 1 trajectories have, by definition, transfer angles between Earth and Mars of less than 180 deg. Type 2 trajectories have transfer angles greater than 180 deg but less than 360 deg.

The Type 2 launch period extends from October 22 through November 14, 2011 and consists of three different target sets. These target sets are required in order to provide both MRO and DTE EDL coverage across the full latitude range (25°N to 27°S). Arrival dates extend from August 27 through September 12, 2012. EDL communications coverage via Mars Odyssey (ODY) is, in general, not possible except for certain launch days and latitude bands.

The Type 1 launch period extends from November 25 through December 18, 2011 and has a single target set with both MRO and ODY EDL coverage. DTE coverage is, in general, not possible except for a few launch days and mostly at Northerly latitudes. Arrival dates extend from August 6 through August 20, 2012. The Type 1 launch period is required due to a potential launch pad conflict with NASA's Juno mission to Jupiter during the Type 2 launch period.

The Juno launch period extends from August 5 through August 27, 2011, and because both Juno and MSL use the same Atlas V launch pad, a 78-day separation between launches is required to refurbish the launch pad and complete pre-launch activities prior to the launch of MSL. Hence, October 22, 2011 is the first possible MSL launch day, if Juno were to launch on the first day of its launch period (August 5, 2011). Figure 3 shows the MSL and Juno launch periods. Based on the first available launch day, the launch/arrival strategy optimization process was originally focused on the Type 2 region which has lower entry speeds (< 5.6 km/s) than its Type 1 counterpart. The launch/arrival trade space in the Type 2 region is initially bounded by October 22, 2011 and by launch vehicle performance at the end of the launch period. Launch vehicle performance is significantly degraded starting on day 17 due to high DLAs (>29.0 deg); the DLA reaches its maximum value of 36.2 deg on day 24. Whereas launch vehicle performance is a key driver in the launch period selection, the launch/arrival trade space in the Type 2 region was mostly constrained by the requirement to have simultaneous EDL coverage using both the MRO and DTE links.



1. Launch could occur earlier than10/22, if 78-day pad turnaround can be decreased.
2. Launch dates earlier than 10/15 violate launch vehicle separation attitude constraints.
3. Earliest launch date included in Target Spec is 10/14.

Figure 3. MSL and Juno Launch Periods

A couple of more days could have been added at the end of the launch period but they would have required launching with even higher DLA values which feature high inclination parking orbits that would fly over populated areas on Southern regions of Africa. Even if a waiver had been granted and launching with these DLAs would have provided the necessary injected mass, arrival dates for some of the landing sites would have had Ls values greater than 170 deg which was not acceptable.

Another important criterion that was used to select the arrival dates was to keep the MRO LMST node as close as possible to its nominal value (3:00 PM). In addition, earlier arrival dates were preferred since they typically feature lower MRO antenna values while preserving DTE EDL coverage.

The Type 1 launch period became available once it was determined that atmosphere-relative entry speeds as high as 5.9 km/s (corresponding to inertial entry speeds ~ 6.1 km/s) would be acceptable. In the Type 1 region, both MRO and DTE EDL coverage is not possible across all latitudes; however, simultaneous MRO and ODY coverage is available. In the Type 1 region, the launch/arrival trade space is bounded by atmosphere-relative entry speed at the beginning of the launch period and by launch vehicle performance at the end of the launch period.

Arrival dates initially follow the entry speed contour, since DTE coverage is better for later arrival dates, and then stay within the region that has simultaneous MRO and DTE coverage for both Northerly and Equatorial sites, since no arrival dates can provide both MRO and DTE EDL coverage to Southerly sites. The first unconflicted launch day for both Type 2 and Type 1 launch periods is November 14, 2011, which is day 24 of the Type 2 launch period. The Type 1 launch period is not contingent on Juno's launch since November 25, 2011 (day 1) is more than 78 days after the close of Juno's launch period. It is likely that Juno will launch early in its launch period, and consequently MSL has a high probability of launching in the Type 2 launch period. Figure 4 shows the Type 2 launch period with its three target sets referred to as TS1, which covers 25°N to 20°N, TS2, which covers 20°N to 5°N, and TS3, which covers 5°N to 27°S, as well as the Type 1 launch period with its single target set, which covers 25°N to 27°S. Figure 5 shows the location of the current candidate landing sites (Abilleira F., 2009). Note that currently, no candidate landing sites fall within the range of latitudes covered in TS2; however, this target set was included in case a new landing site located within the latitude bounds of TS2 was added at a later time. To allow analysis of TS2, a fictitious site located at 10°N was included in the design process.

Serious discussions took place to decide if the Type 1 launch period was robust enough to become MSL's sole launch period and eliminate the Type 2 launch period. Having DTE was considered critical in order to reconstruct a potential flight anomaly during EDL in case MRO and/or ODY were not available; therefore, although the Type 2 launch period is contingent on Juno's launch, it was decided to carry both the Type 2 and Type 1 launch periods since a very high probability exists for MSL to launch in the more desirable Type 2 region.

The MSL launch strategy will provide for a finite-duration launch window (nominally two hours) in order to more easily accommodate and deal with minor spacecraft and/or launch vehicle hardware problems, range and short-term weather violations at the launch pad, and launch holds caused by potential collisions with objects in Earth orbit.

Launch Vehicle Targeting

The Earth-relative target conditions are specified by the injection energy per unit mass (C_3, or hyperbolic excess velocity squared, $C_3 = V_\infty^2$), the declination of the launch asymptote (DLA), and the right ascension of the launch asymptote (RLA) at the targeting interface point (TIP), defined as 5 min after spacecraft separation from the Centaur on a given launch date. Separation occurs 223 s after the second Main Engine Cutoff (MECO2). These target conditions represent the conditions of the osculating departure hyperbola at TIP expressed in an Earth-centered, inertial, Earth Mean Equator and Equinox of Epoch J2000 (EME2000) coordinate system (D'Amario L., 2008).

The injected spacecraft mass allocation is 4050 kg, corresponding to a maximum C_3 of ~20.1 km^2/s^2. The maximum required C_3 is 11.2 km^2/s^2 for the Type 2 launch period (day 1) and 19.9 km^2/s^2 for the Type 1 launch period (day 24). The launch window on any given day has duration of up to 2 hours (except for a few launch days at the end of each launch period for which the launch windows are less than 2 hours).

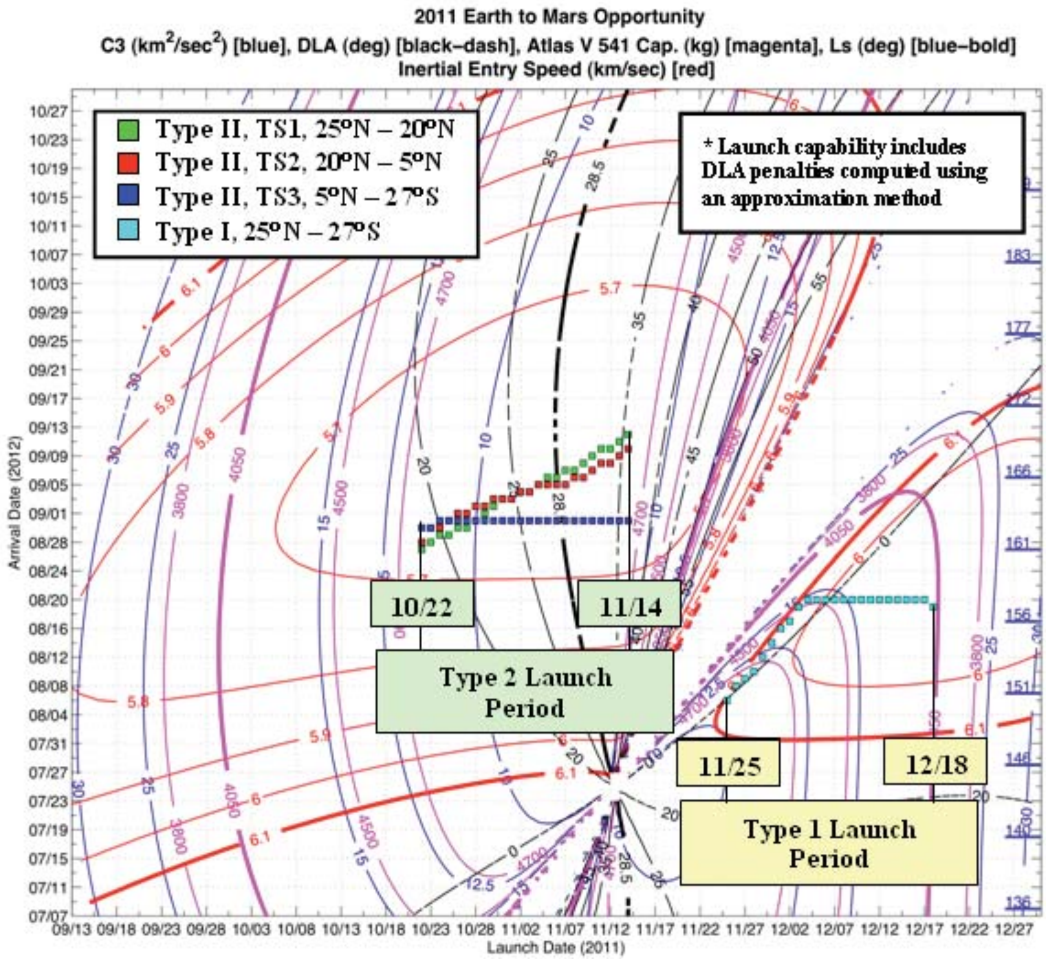


Figure 4. MSL Launch/Arrival Strategy

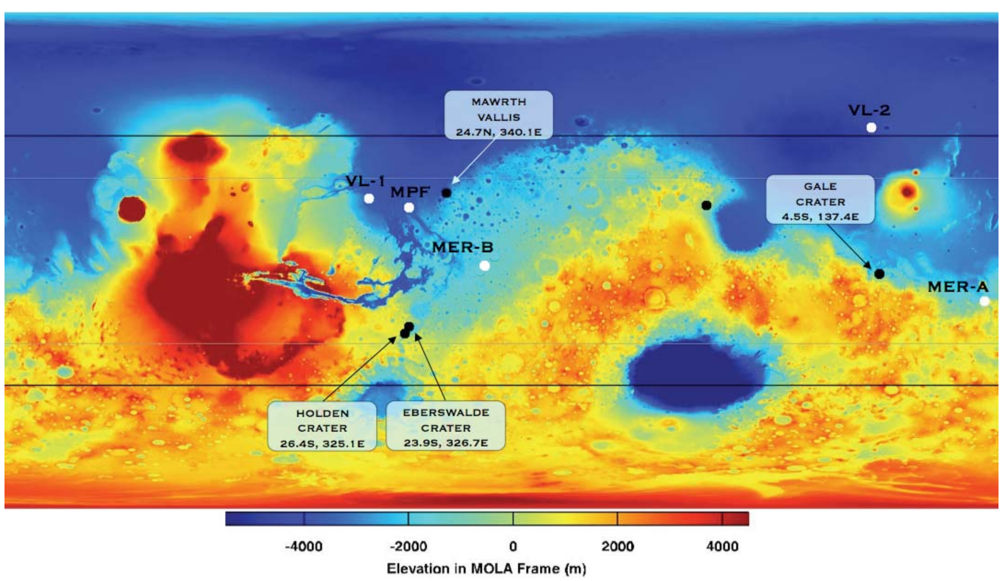


Figure 5. MSL Candidate Landing Sites

Daily excess launch vehicle performance determines the duration of the daily launch window. The launch vehicle targets correspond to numerically integrated trajectories which are biased away from Mars in order to satisfy planetary protection requirements for the Centaur upper stage. Trajectory correction maneuvers (TCM) executed during cruise will be used to remove this biasing, correct for launch vehicle dispersions, and target the selected landing site. The launch targets for both the Type 2 and Type 1 launch periods are shown on Table 1 and Table 2 respectively (D'Amario L., 2009).

Launch Trajectory Characteristics

To satisfy launch approval requirements when carrying an MMRTG, all launches must occur during daylight, which is defined to start at the beginning of morning civil twilight and end at the end of evening civil twilight. Morning civil twilight is defined to begin when the geometric center of the Sun is 6° below the horizon prior to sunrise; likewise, evening civil twilight is defined to end when the geometric center of the Sun is 6° below the horizon after sunset. Figure 6 and Figure 7 show the launch times for both Type 2 and Type 1 launch periods, respectively. Since the launch targets across target sets for the Type 2 launch period are very similar, the actual launch times corresponding to the three different target sets occur at approximately the same local times.

The maximum allowable time from launch to eclipse exit or spacecraft separation (whichever is later) is driven by the battery capacity on board of the flight system. The Type 2 launch period has eclipses that amount to a maximum of 84 minutes from launch to eclipse exit. The Type 1 launch period has no eclipses except for the launch window close on day 1 (Nov 25, 2011) and the maximum time from launch to separation is 52 minutes. Since both of these maximum times are less than 101.5 min for 45% SOC of the battery (see Launch/Arrival Strategy Requirements section), a Centaur attitude turn is not necessary to provide power input from illumination of solar arrays during the on-orbit coast; nevertheless, for other reasons, such as to increase the number of launch attempts per day, or in support of the On-Orbit Contingency Plan (OOCP)[1], a Centaur attitude turn may still be implemented. Figure 8 and Figure 9 show the times from launch to eclipse exit for the Type 2 and Type 1 launch periods respectively. Note that although the geometric characteristics vary from day to day, the times from launch to eclipse exit are very similar for the three target sets in the Type 2 launch period.

Following separation of the spacecraft from the Centaur, the spacecraft transmitter is turned on. The earliest possible receipt of the spacecraft signal at the Deep Space Network (DSN) occurs no earlier than the time of separation plus 1 min for the time lag in turning on the spacecraft transmitter plus 4 minutes for the time required to power up the spacecraft transmitter. Initial acquisition will be accomplished with the

[1] The On-Orbit Contingency Plan (OOCP) is a procedure designed to safely deorbit the flight system in case the Centaur upper stage is not able to execute the Trans-Mars injection maneuver from the nominal parking orbit.

34-m DSN antenna by an acquisition aid which will locate the spacecraft to aid in accurately pointing the antenna. Figure 10 and Figure 11 show the time of earliest signal receipt for both Type 2 and Type 1 launch periods. For the Type 2 launch period, times of earliest signal receipt for Target Set 3, which includes 3 out of the current 4 candidate landing sites, were used. For the cases in which no DSN station is in view when the spacecraft could be transmitting, USN stations at Dongara, Australia and South Point, Hawaii could provide some tracking due to their favorable location with respect to the ascent trajectory.

Table 1. Type 2 Launch Period Characteristics

		TS 1 (25°N - 20°N) MRO 2:00 PM			TS 2 (20°N - 5°N) MRO 1:45 PM			TS 3 (5°N - 27°S) MRO 1:45 PM			Atmosphere-Relative Entry Speed (km/s)				
Launch Day	Launch Date†	Arrival Date	C_3 (km^2/s^2)	DLA (deg)	Arrival Date	C_3 (km^2/s^2)	DLA (deg)	Arrival Date	C_3 (km^2/s^2)	DLA (deg)	Mawrth Site 2	TS2 Site	Gale Crater	Eberswalde Crater	Holden Crater
1	10/22/2011	08/27/2012	11.210	19.259	08/27/2012	11.210	19.259	08/30/2012	11.232	19.489	5.488	5.456	5.436	5.446	5.449
2	10/23/2011	08/27/2012	10.955	19.533	08/30/2012	10.974	19.765	08/30/2012	10.974	19.765	5.488	5.448	5.436	5.445	5.448
3	10/24/2011	08/29/2012	10.716	20.035	08/30/2012	10.726	20.149	08/31/2012	10.737	20.258	5.484	5.448	5.431	5.441	5.444
4	10/25/2011	08/29/2012	10.481	20.473	08/31/2012	10.500	20.698	08/31/2012	10.500	20.698	5.484	5.444	5.431	5.439	5.443
5	10/26/2011	08/30/2012	10.269	21.065	09/01/2012	10.289	21.279	08/31/2012	10.278	21.175	5.480	5.440	5.430	5.439	5.442
6	10/27/2011	08/30/2012	10.065	21.573	09/01/2012	10.084	21.788	08/31/2012	10.074	21.684	5.480	5.440	5.430	5.438	5.441
7	10/28/2011	08/31/2012	9.888	22.220	09/02/2012	9.908	22.422	08/31/2012	9.888	22.220	5.476	5.436	5.429	5.437	5.441
8	10/29/2011	09/01/2012	9.742	22.874	09/02/2012	9.753	22.971	08/31/2012	9.733	22.770	5.473	5.436	5.429	5.437	5.440
9	10/30/2011	09/02/2012	9.601	23.553	09/03/2012	9.612	23.643	08/31/2012	9.583	23.353	5.471	5.433	5.428	5.436	5.440
10	10/31/2011	09/03/2012	9.477	24.245	09/03/2012	9.477	24.245	08/31/2012	9.451	23.960	5.468	5.433	5.428	5.436	5.439
11	11/01/2011	09/03/2012	9.360	24.869	09/03/2012	9.360	24.869	08/31/2012	9.336	24.590	5.469	5.433	5.428	5.435	5.439
12	11/02/2011	09/04/2012	9.267	25.593	09/04/2012	9.267	25.593	08/31/2012	9.238	25.244	5.467	5.430	5.428	5.435	5.439
13	11/03/2011	09/04/2012	9.180	26.260	09/04/2012	9.180	26.260	08/31/2012	9.155	25.925	5.467	5.430	5.428	5.435	5.438
14	11/04/2011	09/05/2012	9.115	27.015	09/05/2012	9.115	27.015	08/31/2012	9.087	26.633	5.466	5.428	5.429	5.435	5.438
15	11/05/2011	09/06/2012	9.063	27.779	09/05/2012	9.057	27.726	08/31/2012	9.035	27.370	5.465	5.429	5.429	5.435	5.438
16	11/06/2011	09/06/2012	9.025	28.496	09/05/2012	9.019	28.451	08/31/2012	9.001	28.131	5.466	5.429	5.429	5.435	5.439
17	11/07/2011	09/07/2012	8.998	29.280	09/05/2012	8.989	29.208	08/31/2012	8.978	28.926	5.465	5.430	5.430	5.436	5.439
18	11/08/2011	09/07/2012	8.980	30.073	09/06/2012	8.976	30.047	08/31/2012	8.971	29.767	5.467	5.428	5.431	5.436	5.439
19	11/09/2011	09/08/2012	8.984	30.919	09/06/2012	8.976	30.889	08/31/2012	8.981	30.669	5.467	5.429	5.432	5.437	5.440
20	11/10/2011	09/09/2012	8.996	31.782	09/07/2012	8.995	31.785	08/31/2012	9.009	31.630	5.468	5.429	5.433	5.438	5.441
21	11/11/2011	09/10/2012	9.018	32.668	09/08/2012	9.021	32.706	08/31/2012	9.055	32.656	5.470	5.429	5.435	5.439	5.442
22	11/12/2011	09/10/2012	9.058	33.600	09/08/2012	9.066	33.670	08/31/2012	9.143	33.774	5.472	5.431	5.437	5.440	5.443
23	11/13/2011	09/11/2012	9.099	34.485	09/09/2012	9.112	34.594	08/31/2012	9.214	34.925	5.475	5.432	5.439	5.442	5.445
24	11/14/2011	09/12/2012	9.171	35.421	09/10/2012	9.192	35.572	08/31/2012	9.347	36.201	5.479	5.434	5.442	5.445	5.448
		MAX	11.210	35.421		11.210	35.572		11.232	36.201	5.488	5.456	5.442	5.446	5.449
		MIN	8.980	19.259		8.976	19.259		8.971	19.489	5.465	5.428	5.428	5.435	5.438

Table 2. Type 1 Launch Period Characteristics

		25°N - 27°S MRO 2:30 PM			Atmosphere-Relative Entry Speed (km/s)			
Launch Day	Launch Date†	Arrival Date	C_3 (km^2/s^2)	DLA (deg)	Mawrth Site 2	Gale Crater	Eberswalde Crater	Holden Crater
1	11/25/2011	08/06/2012	10.773	-0.908	5.881	5.862	5.879	5.884
2	11/26/2011	08/08/2012	11.348	-3.227	5.881	5.862	5.881	5.886
3	11/27/2011	08/09/2012	11.559	-2.689	5.866	5.847	5.866	5.871
4	11/28/2011	08/10/2012	11.795	-2.173	5.852	5.833	5.852	5.857
5	11/29/2011	08/12/2012	12.434	-4.041	5.854	5.835	5.856	5.862
6	11/30/2011	08/14/2012	13.139	-5.828	5.860	5.842	5.866	5.871
7	12/01/2011	08/16/2012	13.908	-7.539	5.872	5.854	5.879	5.885
8	12/02/2011	08/17/2012	14.131	-6.668	5.856	5.837	5.863	5.868
9	12/03/2011	08/19/2012	14.942	-8.204	5.870	5.852	5.880	5.885
10	12/04/2011	08/20/2012	15.174	-7.300	5.855	5.836	5.864	5.870
11	12/05/2011	08/20/2012	14.966	-4.396	5.816	5.797	5.822	5.828
12	12/06/2011	08/20/2012	14.938	-1.936	5.787	5.767	5.791	5.797
13	12/07/2011	08/20/2012	15.035	0.159	5.765	5.745	5.767	5.772
14	12/08/2011	08/20/2012	15.230	1.958	5.748	5.727	5.749	5.754
15	12/09/2011	08/20/2012	15.499	3.507	5.735	5.714	5.734	5.739
16	12/10/2011	08/20/2012	15.829	4.841	5.724	5.703	5.723	5.728
17	12/11/2011	08/20/2012	16.210	5.960	5.716	5.694	5.714	5.718
18	12/12/2011	08/20/2012	16.624	6.813	5.711	5.688	5.707	5.711
19	12/13/2011	08/20/2012	17.030	7.931	5.706	5.683	5.701	5.706
20	12/14/2011	08/20/2012	17.528	8.951	5.702	5.679	5.697	5.701
21	12/15/2011	08/20/2012	18.066	9.740	5.700	5.676	5.693	5.698
22	12/16/2011	08/20/2012	18.636	10.428	5.699	5.674	5.691	5.696
23	12/17/2011	08/20/2012	19.238	11.046	5.698	5.674	5.690	5.694
24	12/18/2011	08/20/2012	19.876	11.604	5.698	5.673	5.689	5.694
		MAX	19.876	11.604	5.881	5.862	5.881	5.886
		MIN	10.773	-8.204	5.698	5.673	5.689	5.694

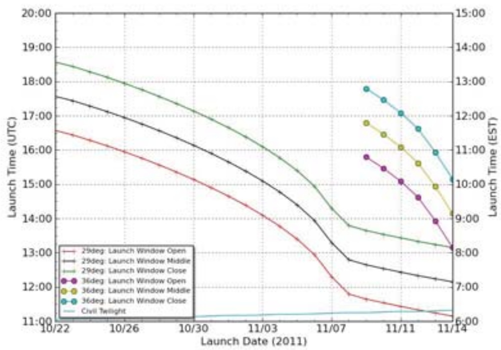


Figure 6. Launch Times Type 2, TS3

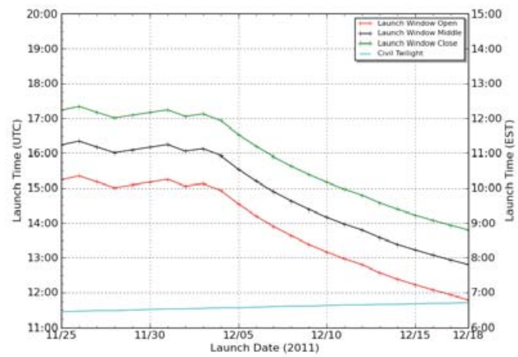


Figure 7. Launch Times Type 1

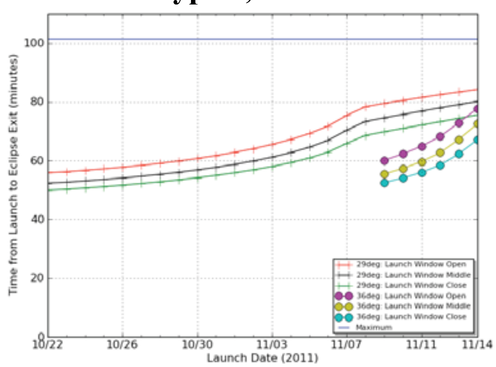


Figure 8. Launch to Eclipse Exit Type 2, TS3

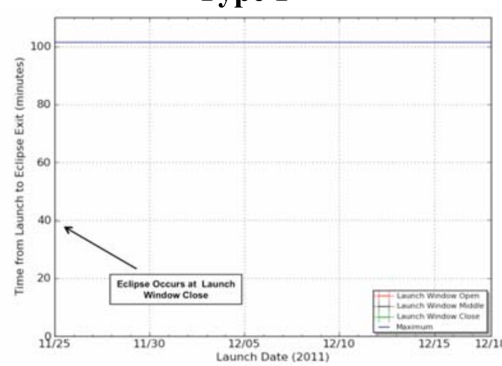


Figure 9. Launch to Eclipse Exit Type 1

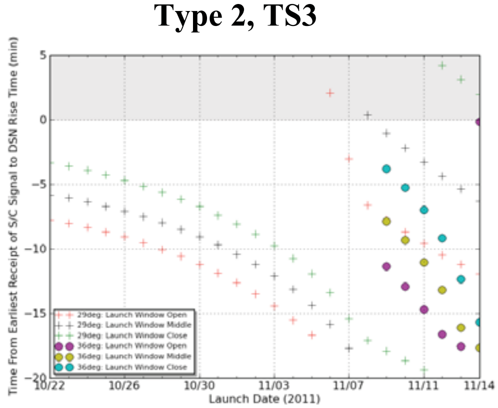


Figure 10. Time of Earliest Signal Receipt - Type 2, TS3

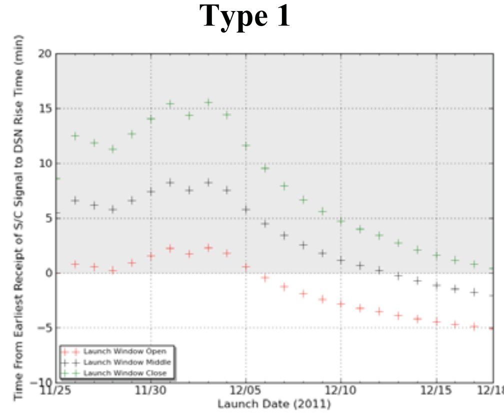


Figure 11. Time of Earliest Signal Receipt - Type 1

INTERPLANETARY CRUISE PHASE

Overview

The interplanetary cruise phase starts after the end of the launch phase once playback of the launch telemetry has been completed and extends until the approach phase begins, 45 days prior to atmospheric entry. The cruise and approach phases span a duration of ~300 days for the Type 2 launch period and ~250 days for the Type 1 launch period. The Earth range at arrival is between 1.78 and 1.86 AU for the Type 2 launch period and between 1.66 and 1.74 AU for the Type 1 launch period. The Sun range at arrival is between 1.49 and 1.51 AU for the Type 2 launch period and 1.52 and 1.54 AU for the Type 1 launch period. Primary activities during interplanetary cruise include Trajectory Correction Maneuvers (TCMs) to target the selected landing site, spacecraft and payload checkout and calibration, daily monitoring of spacecraft subsystems, and periodic attitude adjustments for power and telecommunications. The interplanetary transfer trajectories for the open of the Type 2 launch period (Oct 22, 2011) and for the open of the Type 1 launch period (Nov 25, 2011) are shown in Figure 12 and Figure 13 respectively.

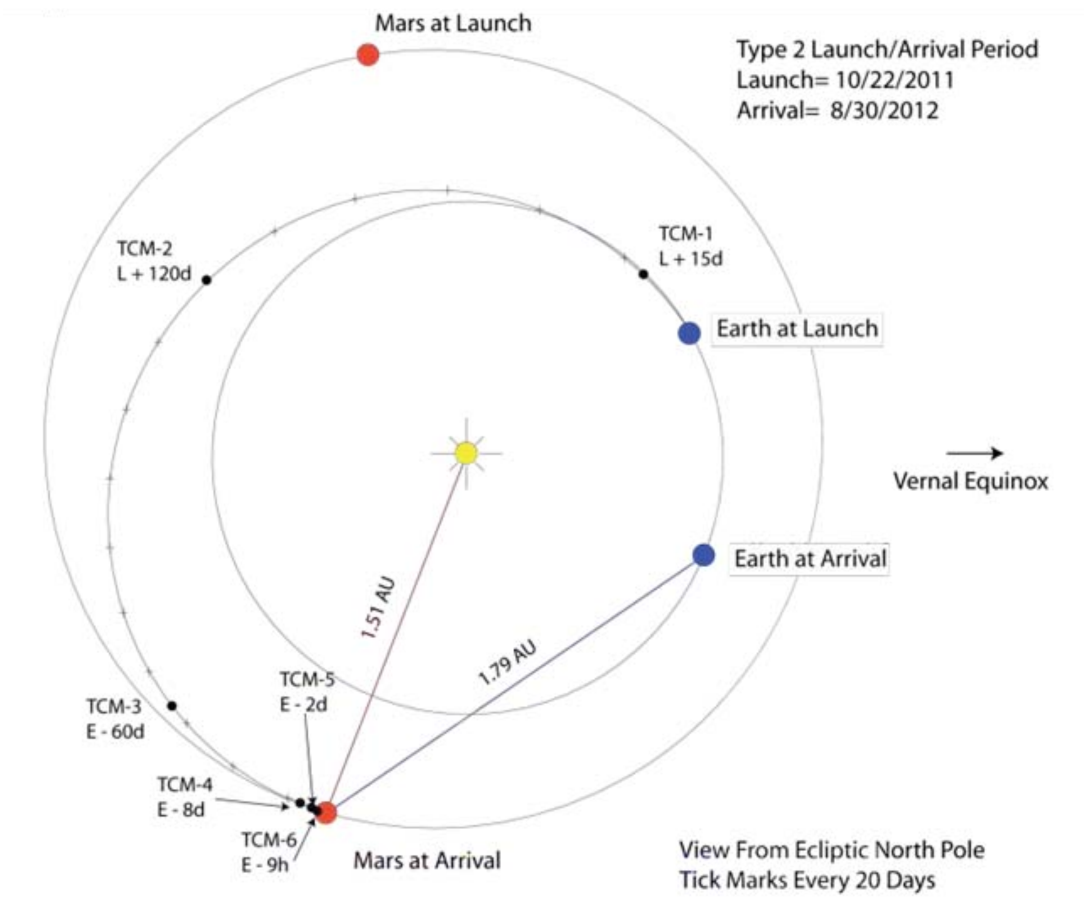


Figure 12. Interplanetary Trajectory for Open of Type 2 Launch Period (Oct 22, 2011)

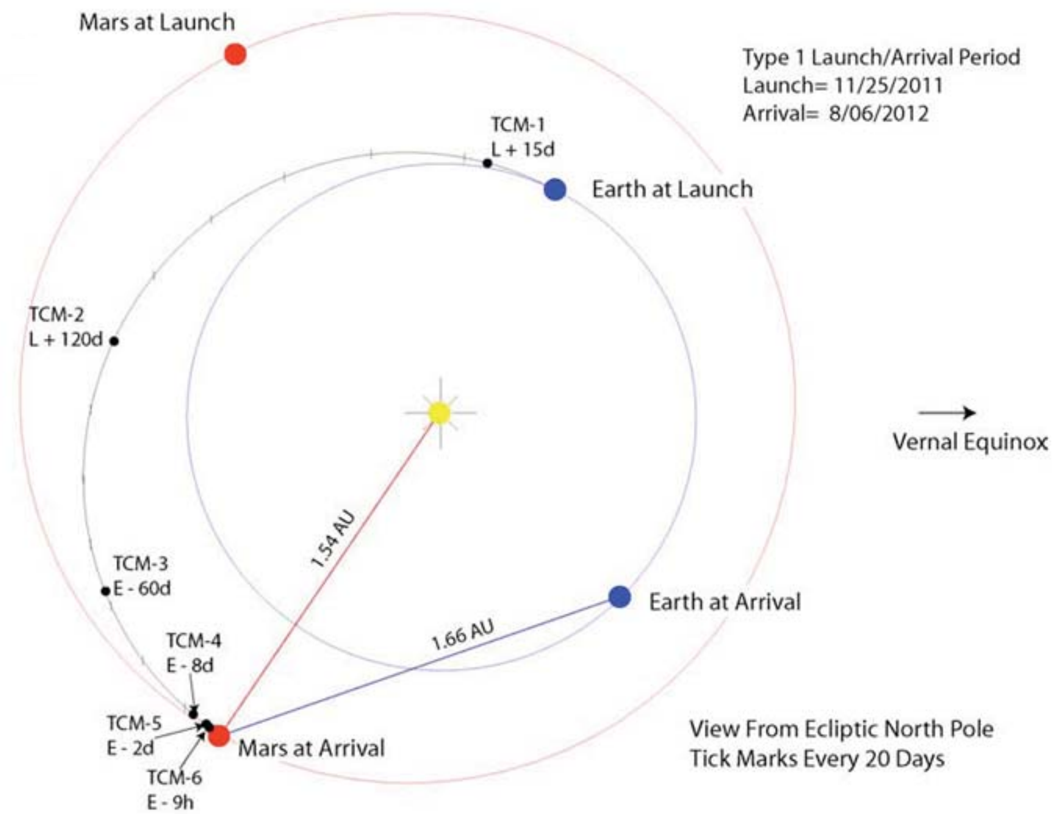


Figure 13. Interplanetary Trajectory for Open of Type 1 Launch Period (Nov 25, 2011)

Cruise Trajectory Design

During interplanetary cruise, the spacecraft is spin-stabilized at 2 rpm. Up to six TCMs are planned to control the trajectory and adjust the atmospheric entry aimpoint, where the atmospheric entry interface point is defined to be at a Mars radius of 3522.2 km. The first three TCMs occur during the cruise phase and the last three occur during the approach phase. This TCM profile is shown in Table 3. Note that TCM-5X and TCM-6 are contingency maneuvers.

The launch vehicle injects the spacecraft on an interplanetary trajectory targeted to an aimpoint that is biased away from Mars for planetary protection in order to achieve a probability less than 10^{-4} of the Centaur upper stage impacting Mars. In addition, planetary protection requires that the probability of an anomalous impact of the MSL spacecraft with Mars must be less than 10^{-2}. This is referred to as the non-nominal impact probability requirement. In order to satisfy the non-nominal impact probability requirement, the aimpoints for TCM-1 and TCM-2 must be biased away from Mars in order to reduce the time when a spacecraft failure would result in a non-nominal impact. Thus, TCM-3 is the first maneuver to target to the desired Mars atmospheric entry aimpoint. In addition, periodic attitude maintenance turns are performed to maintain adequate power and telecom margins, and checkouts and calibrations of various spacecraft systems are carried out (Martin-Mur T., 2009).

The cruise stage has two clusters of 4 thrusters each (8 total) used for attitude/spin control and TCMs with an Isp = 212.4 s (axial) and 221.8 s (lateral). These values include plume impingement and blow-down effects. Figure 14 shows the MSL cruise stage configuration.

Table 3. TCM Profile

TCM	Maneuver Time	Description
TCM-1	Launch + 15 days	Correct injection errors; remove part of injection bias required for planetary protection
TCM-2	Launch + 120 days	Correct TCM-1 errors; remove part of the injection bias required for planetary protection
TCM-3	Entry - 60 days	Correct TCM-2 errors; target to desired atmospheric entry aimpoint
TCM-4	Entry - 8 days	Correct TCM-3 errors
TCM-5	Entry - 2 days	Correct TCM-4 errors
TCM-5X	Entry - 1 day	Contingency maneuver for failure to execute TCM-5
TCM-6	Entry - 9 hrs	Contingency maneuver: final opportunity to correct entry aimpoint

TCMs can be performed at cruise attitude without turning the spacecraft, or the spacecraft can turn to a specified attitude to execute the maneuver. Performing the maneuver without changing the spacecraft attitude corresponds to a vector mode implementation, so called because the desired ΔV is accomplished by a combination of axial and lateral burns such that the vector sum of those components produces the desired ΔV.

If the maneuver is performed with a spacecraft turn, either a vector mode implementation can be used, or the desired ΔV can be accomplished with a purely axial or lateral burn. Because MSL is a spinning spacecraft, lateral burns are accomplished by firing all four thrusters in each thruster cluster once per spacecraft revolution. Axial burns are accomplished by firing the –Z or +Z thrusters in both thruster clusters continuously.

Because of the potentially large propellant cost of performing TCM-1 in vector mode, this TCM can be executed in either vector-mode or turn/burn mode if the desired ΔV is within the Earth- and Sun- angle constraints. Other alternatives include executing a limited turn, followed by a vector mode. The remaining TCMs are performed in vector mode to eliminate the need to turn the spacecraft, thus precluding trajectory perturbations that would result from the turn. TCMs 1, 2, and 3 utilize "Auto-TCM" behavior which is a flight software logic that executes a TCM given the attitude(s), burn type(s), ΔV(s), duration(s), and number of retries. "Auto-TCM" has a "critical" mode which allows recovery from a fault and attempts to resume execution of the TCM and "non-critical" mode which simply terminates the TCM in the event of a fault and awaits action from the flight team.

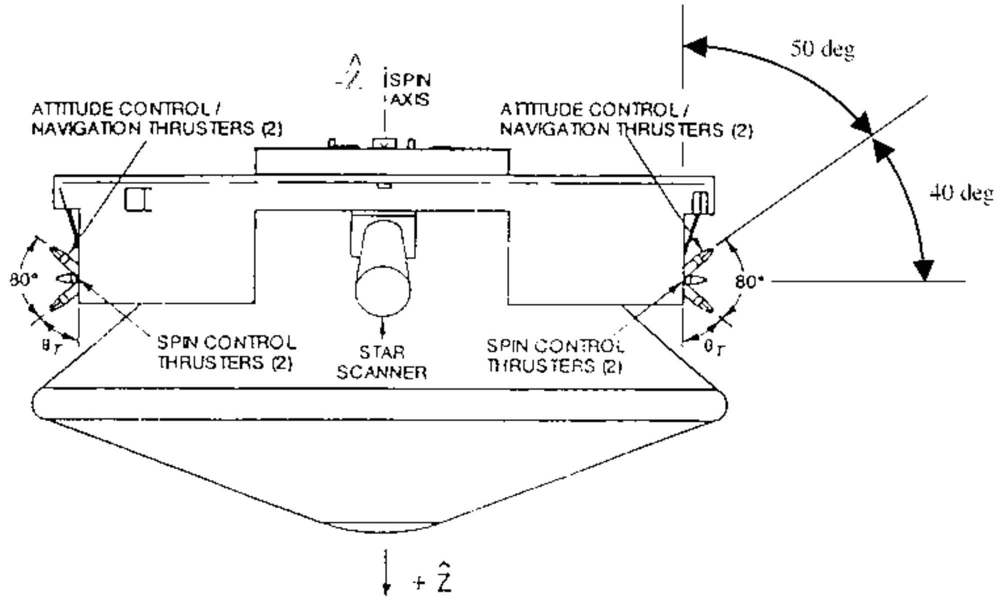


Figure 14. Cruise Stage Configuration

APPROACH PHASE

Overview

The final 45 days prior to arrival at Mars are referred to as the approach phase. This mission phase is focused on preparations for Entry, Descent, and Landing (EDL) to ensure an accurate delivery to the required entry aimpoint and that all EDL sequence parameters are properly loaded on the spacecraft. Also, during this phase all activities that could compromise the spacecraft trajectory are minimized, and significant increases in DSN coverage and navigation tracking data are used to improve the accuracy of trajectory solutions for TCMs 4, 5, 5X, and 6. Preparations for EDL, which include repeatedly initializing the onboard EDL flight software with the latest estimate of the atmospheric entry state vector, also occur during this phase.

Approach Design & Geometry

The final navigation delivery accuracy at the atmospheric entry interface point is a function of the targeted landing site and the arrival date (determined by the launch date). The performance of the telecommunications system just prior to, during, and after EDL is mainly driven by the geometry of the trajectory relative to Earth, as well as MRO and ODY. Table 4 and Table 5 show key characteristics of the MSL arrival trajectories for the open, middle, and close of the Type 2 and Type 1 launch periods respectively. The approach phase includes execution of TCM-4 (if needed) and ends at the instant the spacecraft behavior transitions from Pre-EDL (PEDL) to EDL, nominally at entry – 15 minutes.

Table 4. – Arrival Characteristics - Type 2 Launch period

Launch Day	Launch Date	Landing Site	Arrival Date	Arrival V-Infinity (km/sec)	Approach Declination MMEQE (deg)	Inertial Entry Velocity (km/sec)	Atm-Relative Entry Velocity (km/sec)	Earth Range (AU)	Sun Range (AU)	Ls (deg)	Landing Time LTST (hh:mm)
1	22-Oct-2011	Mawrth	28-Aug-2012	2.7967	-16.9731	5.6693	5.4879	1.784	1.507	162.2	15:21
		TS2 Site	28-Aug-2012	2.8017	-16.9608	5.6717	5.4561	1.783	1.508	162.1	14:47
		Gale	29-Aug-2012	2.7888	-16.9952	5.6654	5.4364	1.792	1.505	163.1	14:20
		Eberswalde	30-Aug-2012	2.7831	-17.0183	5.6626	5.4456	1.794	1.505	163.3	14:02
		Holden	30-Aug-2012	2.7828	-17.0161	5.6624	5.4493	1.794	1.505	163.3	14:01
12	02-Nov-2011	Mawrth	04-Sep-2012	2.7293	-20.1452	5.6363	5.4668	1.820	1.498	166.1	15:21
		TS2 Site	04-Sep-2012	2.7337	-20.1469	5.6384	5.4303	1.819	1.498	166.0	14:41
		Gale	30-Aug-2012	2.7632	-19.8777	5.6528	5.4282	1.797	1.504	163.6	14:32
		Eberswalde	31-Aug-2012	2.7568	-19.9388	5.6497	5.4351	1.800	1.503	163.9	14:09
		Holden	31-Aug-2012	2.7564	-19.9378	5.6495	5.4385	1.800	1.503	163.9	14:07
24 (i = 29.0°)	14-Nov-2011	Mawrth	12-Sep-2012	2.7035	-25.8962	5.6239	5.4789	1.860	1.487	170.5	15:21
		TS2 Site	10-Sep-2012	2.7081	-26.0694	5.6261	5.4342	1.850	1.490	169.3	14:36
		Gale	30-Aug-2012	2.7669	-26.3281	5.6546	5.4424	1.797	1.504	163.6	14:42
		Eberswalde	31-Aug-2012	2.7605	-26.2680	5.6515	5.4448	1.800	1.503	163.9	14:08
		Holden	31-Aug-2012	2.7602	-26.2551	5.6513	5.4477	1.800	1.503	163.9	14:05
24 (i = 35.6°)	14-Nov-2011	Mawrth	12-Sep-2012	2.7037	-25.9637	5.6240	5.4793	1.860	1.487	170.5	15:21
		TS2 Site	10-Sep-2012	2.7083	-26.1341	5.6262	5.4345	1.850	1.490	169.3	14:36
		Gale	30-Aug-2012	2.7672	-26.4251	5.6548	5.4427	1.797	1.504	163.6	14:42
		Eberswalde	31-Aug-2012	2.7608	-26.3702	5.6516	5.4451	1.800	1.503	163.9	14:08
		Holden	31-Aug-2012	2.7605	-26.3573	5.6515	5.4480	1.800	1.503	163.9	14:05

Table 5. – Arrival Characteristics - Type 1 Launch period

Launch Day	Launch Date	Landing Site	Arrival Date	Arrival V-Infinity (km/sec)	Approach Declination MMEQE (deg)	Inertial Entry Velocity (km/sec)	Atm-Relative Entry Velocity (km/sec)	Earth Range (AU)	Sun Range (AU)	Ls (deg)	Landing Time LTST (hh:mm)
1	25-Nov-2011	Mawrth	06-Aug-2012	3.5854	-2.1972	6.0971	5.8818	1.662	1.536	150.9	15:47
		Gale	06-Aug-2012	3.5942	-2.4097	6.1023	5.8629	1.659	1.536	150.7	15:35
		Eberswalde	06-Aug-2012	3.5857	-2.0876	6.0973	5.8789	1.662	1.535	151.0	15:39
		Holden	06-Aug-2012	3.5854	-2.0825	6.0971	5.8836	1.662	1.535	151.0	15:40
12	06-Dec-2011	Mawrth	21-Aug-2012	3.4272	2.6706	6.0054	5.7871	1.745	1.517	158.4	14:50
		Gale	20-Aug-2012	3.4292	2.4814	6.0066	5.7678	1.742	1.517	158.2	14:48
		Eberswalde	21-Aug-2012	3.4278	2.7884	6.0058	5.7913	1.745	1.517	158.4	15:00
		Holden	21-Aug-2012	3.4276	2.7926	6.0056	5.7966	1.745	1.517	158.4	15:03
24	18-Dec-2011	Mawrth	21-Aug-2012	3.2543	-6.0130	5.9085	5.6987	1.745	1.517	158.4	15:01
		Gale	20-Aug-2012	3.2613	-6.1012	5.9123	5.6738	1.742	1.517	158.2	14:39
		Eberswalde	21-Aug-2012	3.2549	-5.9129	5.9088	5.6894	1.745	1.517	158.4	14:38
		Holden	21-Aug-2012	3.2546	-5.9090	5.9086	5.6939	1.745	1.517	158.4	14:39

Approach Navigation

The radiometric data types that are used for MSL orbit determination during this phase are two-way coherent Doppler, two-way ranging, and ΔDOR measurements generated by the DSN X-band tracking system.

TCM Delivery and Entry Knowledge Accuracies

In order to limit atmospheric entry dispersions to within the capabilities of the entry guidance system and to ensure flight system safety during EDL, the entry flight path angle (EFPA) delivery error must be less than ± 0.2 deg with respect to the targeted entry flight path angle, and the entry state vector knowledge error at Entry – 9 minutes (based on a navigation data cutoff at Entry – 6 hrs) must be less than 2.8 km in position and 2.0 m/s in velocity and the entry flight path angle (EFPA) delivery error must be less than ± 0.2 deg relative to the targeted entry flight path angle (all values quoted above are 3σ).

ENTRY, DESCENT, AND LANDING PHASE

EDL Communications Coverage

The selected launch periods satisfy the requirement of maintaining full EDL communications from entry to landing + 1 min via two assets (see launch period section for more details). It is assumed that EDL communications are available when the asset (orbiter or Earth) has a direct line of sight to MSL (i.e., MSL is not being occulted by Mars as seen by the asset) and the antenna angle is within the antenna angle constraints. The antenna angle is defined as the angle between the atmosphere-relative anti-velocity vector and the line of sight to the asset. The antenna actually points along the -Z-axis, which is not necessarily oriented in the direction of the anti-velocity vector. However, comparisons of antenna angles measured with respect to the anti-velocity vector with those measured with respect to the -Z axis from 6DOF simulations indicate that, for preliminary analysis, using the atmosphere-relative anti-velocity vector is a valid approximation. Additionally, it is required that the elevation angle at the time of landing and landing plus 1 min must be > 10 deg – i.e. the asset must be 10 deg or higher above the horizon between the time of landing and landing plus 1 min.

For any launch date and landing site, there is a range of relay orbiter LMST nodes that would place the orbit in the correct geometry in order to support EDL communications. The launch period design process evaluated the nominal nodes for both MRO (3:00 PM, ascending) and ODY (3:45 PM, descending) to verify that the orbiters would have a EDL communications coverage across all latitude bands for all launch days. When this goal could not be met, the latest LMST node (closest to the nominal) that would provide EDL coverage was determined. Keeping the LMST node of the orbiters as close as possible to their nominal values decreases the propellant usage of the orbiters, thereby potentially increasing their lifetimes and decreasing the impact on the orbiters' science return. Table 6 and Table 7 show the latest required MRO or ODY node for both the Type 2 and Type 1 launch periods respectively.

Table 6. MRO/ODY LMST Node Required for Full EDL Coverage, Type2

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="10">Type 2 Launch Period
Latest MRO/ODY LMST Node</th></tr>
<tr><th colspan="2">Mawrth Vallis Site 2 (24.01°N)</th><th colspan="2">TS2Site (10.00°N)</th><th colspan="2">Gale Crater (4.49°S)</th><th colspan="2">Eberswalde Crater (23.86°S)</th><th colspan="2">Holden Crater (26.37°S)</th></tr>
<tr><th>Launch Day</th><th>Launch Date</th><th>MRO</th><th>ODY</th><th>MRO</th><th>ODY</th><th>MRO</th><th>ODY</th><th>MRO</th><th>ODY</th><th>MRO</th><th>ODY</th></tr>
<tr><td>1</td><td>10/22/2011</td><td rowspan="14">2:15 PM</td><td rowspan="24">3:45 PM</td><td rowspan="6">2:00 PM</td><td rowspan="8">3:15 PM</td><td rowspan="24">1:45 PM</td><td>3:00 PM^</td><td rowspan="2">2:00 PM</td><td rowspan="24">3:00 PM^</td><td rowspan="2">2:00 PM</td><td rowspan="24">3:00 PM^</td></tr>
<tr><td>2</td><td>10/23/2011</td><td>3:00 PM^^</td></tr>
<tr><td>3</td><td>10/24/2011</td><td rowspan="2">3:00 PM^</td><td rowspan="18">1:45 PM</td><td rowspan="18">1:45 PM</td></tr>
<tr><td>4</td><td>10/25/2011</td></tr>
<tr><td>5</td><td>10/26/2011</td><td rowspan="13">3:00 PM</td></tr>
<tr><td>6</td><td>10/27/2011</td></tr>
<tr><td>7</td><td>10/28/2011</td><td rowspan="14">1:45 PM</td></tr>
<tr><td>8</td><td>10/29/2011</td></tr>
<tr><td>9</td><td>10/30/2011</td><td>3:00 PM</td></tr>
<tr><td>10</td><td>10/31/2011</td><td rowspan="4">3:15 PM</td></tr>
<tr><td>11</td><td>11/01/2011</td></tr>
<tr><td>12</td><td>11/02/2011</td></tr>
<tr><td>13</td><td>11/03/2011</td></tr>
<tr><td>14</td><td>11/04/2011</td><td>3:00 PM</td></tr>
<tr><td>15</td><td>11/05/2011</td><td rowspan="10">2:00 PM</td><td rowspan="6">3:15 PM</td></tr>
<tr><td>16</td><td>11/06/2011</td></tr>
<tr><td>17</td><td>11/07/2011</td></tr>
<tr><td>18</td><td>11/08/2011</td><td rowspan="7">3:15 PM</td></tr>
<tr><td>19</td><td>11/09/2011</td></tr>
<tr><td>20</td><td>11/10/2011</td></tr>
<tr><td>21</td><td>11/11/2011</td><td>1:45 PM*</td><td>3:00 PM</td><td rowspan="3">1:45 PM**</td><td rowspan="3">1:45 PM**</td></tr>
<tr><td>22</td><td>11/12/2011</td><td>1:45 PM**</td><td>3:15 PM</td></tr>
<tr><td>23</td><td>11/13/2011</td><td rowspan="2">1:45 PM*</td><td rowspan="2">3:00 PM</td></tr>
<tr><td>24</td><td>11/14/2011</td><td>1:45 PM*</td><td>1:45 PM*</td></tr>
</table>

* Full EDL coverage not available at this node; coverage starts no later than ~30 s after entry.
** Mean anomaly range is less than MRO's phasing control, i.e. < 3.2 deg.
^ Full EDL coverage not available at this node; coverage starts no later than ~90 s before landing.
^^ Mean anomaly range is less than ODY's phasing control, i.e. < 3.2 deg.

Preliminary analysis shows that the most effective way for the orbiters to achieve the required LMST node is to execute a maneuver to change the orbit inclination that would start a nodal drift. Once the target LMST node has been achieved, another maneuver would be executed in order to stop the nodal drift. The more time that is allowed for the node to drift, the less propellant is required. Currently, a final decision on the selected landing site is scheduled for June 2011. However, the launch day is the latest opportunity to select the landing site; hence, the orbiter's nodal drift will not be started until after MSL launches. In some instances and depending on the location of the landing site, an opportunity to retarget a new landing site may be available at the time of TCM-1. This opportunity is heavily dependent on the longitude of the landing site, since changes in longitude correspond to changes in arrival time, and arrival time changes are very costly in terms of ΔV. In addition to the required LMST node, a range of mean anomalies at MSL entry for MRO and/or ODY must exist such that all the EDL coverage constraints mentioned earlier are satisfied. This range of mean anomalies defines the orbital phasings from which MRO or ODY could provide full EDL coverage. The committed phasing control for both MRO and ODY is ±30 s or ~±1.6 deg. Given this known uncertainty on the orbital phasing control of the orbiters, a valid mean anomaly range must not be less than 3.2 deg.

Figure 15 and Figure 16 show the arrival geometries for day 1 of the Type 2 launch period targeted to Mawrth Vallis Site 2 and for day 1 of the Type 1 launch period targeted to Holden Crater. These figures illustrate the incoming trajectories relative to MRO and ODY, as well as the direction of the Earth and the Sun at the time of atmospheric entry interface (Abilleira F., 2008).

Table 7. MRO/ODY LMST Node Required for Full EDL Coverage, Type1

<table>
<tr><th></th><th></th><th colspan="8">Type 1 Launch Period
Latest MRO/ODY LMST Node</th></tr>
<tr><th></th><th></th><th colspan="2">Mawrth
Vallis Site 2
(24.01°N)</th><th colspan="2">Gale
Crater
(4.49°S)</th><th colspan="2">Eberswalde
Crater
(23.86°S)</th><th colspan="2">Holden
Crater
(26.37°S)</th></tr>
<tr><th>Launch Day</th><th>Launch Date</th><th>MRO</th><th>ODY</th><th>MRO</th><th>ODY</th><th>MRO</th><th>ODY</th><th>MRO</th><th>ODY</th></tr>
<tr><td>1</td><td>11/25/2011</td><td rowspan="7">3:00 PM</td><td rowspan="6">3:45 PM</td><td rowspan="15">3:00 PM</td><td rowspan="4">3:45 PM</td><td rowspan="20">3:00 PM</td><td>3:45 PM</td><td rowspan="22">3:00 PM</td><td>3:45 PM</td></tr>
<tr><td>2</td><td>11/26/2011</td><td rowspan="3">3:30 PM</td><td rowspan="3">3:30 PM</td></tr>
<tr><td>3</td><td>11/27/2011</td></tr>
<tr><td>4</td><td>11/28/2011</td></tr>
<tr><td>5</td><td>11/29/2011</td><td>3:30 PM</td><td rowspan="2">3:15 PM</td><td rowspan="2">3:15 PM</td></tr>
<tr><td>6</td><td>11/30/2011</td><td>3:15 PM</td></tr>
<tr><td>7</td><td>12/01/2011</td><td rowspan="2">3:30 PM</td><td rowspan="2">3:00 PM</td><td rowspan="2">3:00 PM</td><td rowspan="2">3:00 PM</td></tr>
<tr><td>8</td><td>12/02/2011</td><td rowspan="13">2:45 PM</td></tr>
<tr><td>9</td><td>12/03/2011</td><td>3:15 PM</td><td rowspan="2">3:00 PM^^</td><td>3:00 PM^^</td><td>3:00 PM^^</td></tr>
<tr><td>10</td><td>12/04/2011</td><td>3:00 PM</td><td rowspan="2">3:00 PM^</td><td rowspan="2">3:00 PM^</td></tr>
<tr><td>11</td><td>12/05/2011</td><td rowspan="2">3:15 PM</td><td rowspan="14">3:00 PM</td></tr>
<tr><td>12</td><td>12/06/2011</td><td rowspan="13">3:00 PM^^</td><td rowspan="13">3:00 PM^^</td></tr>
<tr><td>13</td><td>12/07/2011</td><td rowspan="12">3:30 PM</td></tr>
<tr><td>14</td><td>12/08/2011</td></tr>
<tr><td>15</td><td>12/09/2011</td></tr>
<tr><td>16</td><td>12/10/2011</td><td rowspan="7">2:45 PM</td></tr>
<tr><td>17</td><td>12/11/2011</td></tr>
<tr><td>18</td><td>12/12/2011</td></tr>
<tr><td>19</td><td>12/13/2011</td></tr>
<tr><td>20</td><td>12/14/2011</td></tr>
<tr><td>21</td><td>12/15/2011</td><td rowspan="4">2:30 PM</td><td rowspan="4">2:45 PM</td></tr>
<tr><td>22</td><td>12/16/2011</td></tr>
<tr><td>23</td><td>12/17/2011</td><td rowspan="2">2:30 PM</td><td rowspan="2">2:45 PM</td></tr>
<tr><td>24</td><td>12/18/2011</td></tr>
</table>

^ Full EDL coverage not available at this node; coverage starts no later than ~30 s after entry.
^^ Mean anomaly range is less than ODY's phasing control, i.e. < 3.2 deg.

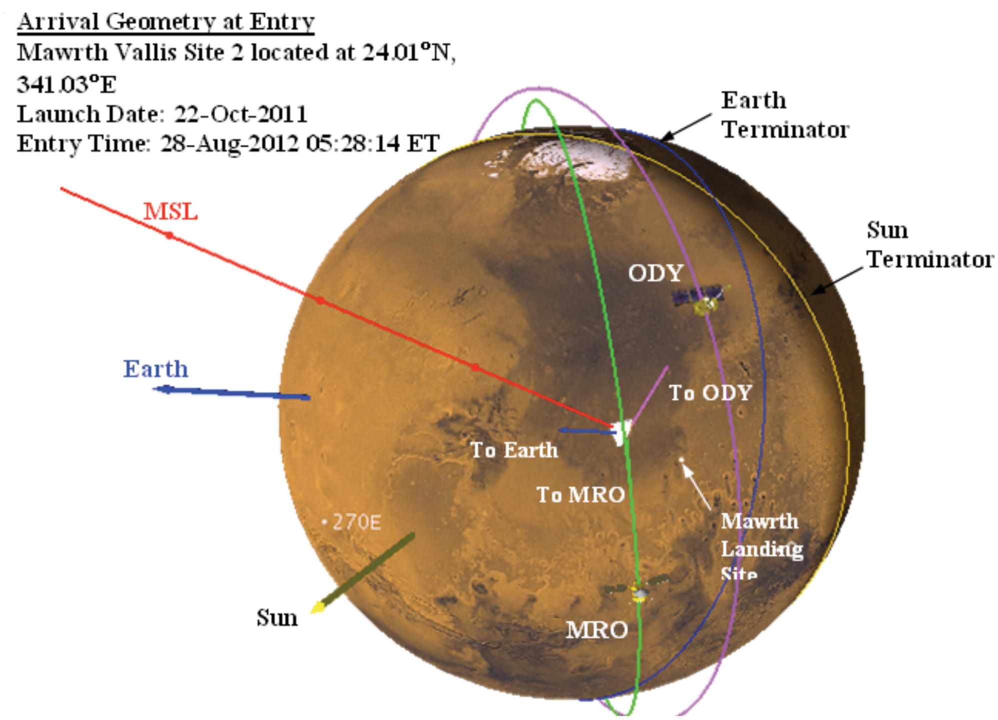


Figure 15. EDL Coverage Geometry Targeted to Mawrth for Day 1 (22-Oct-2011) of Type 2 Launch Period

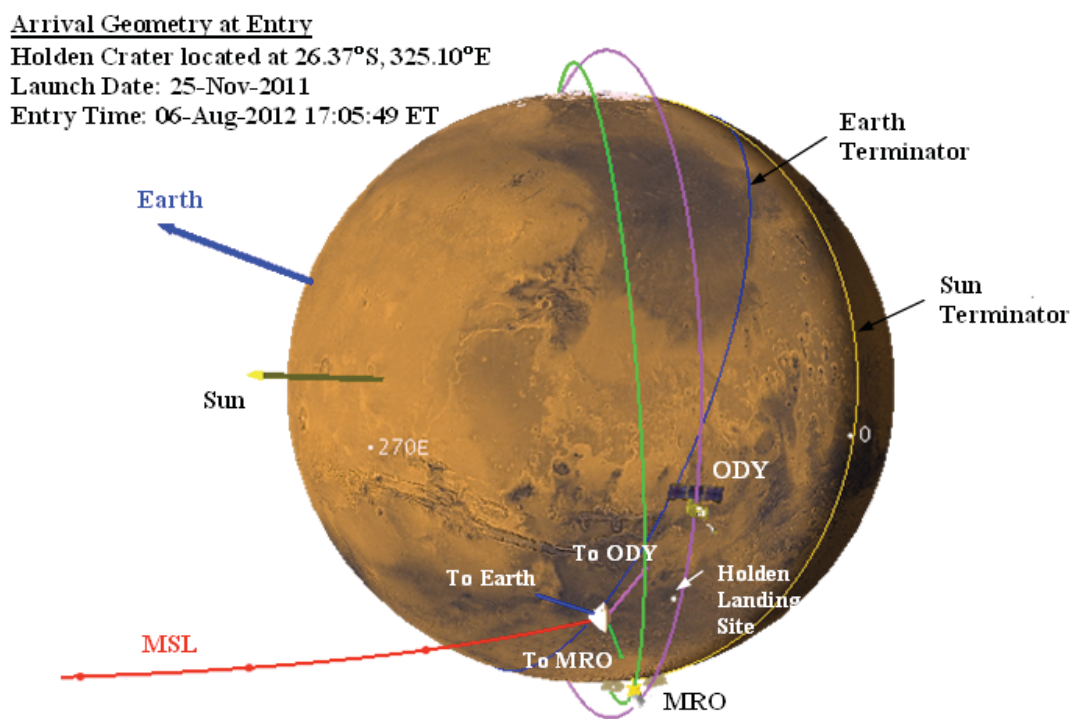


Figure 16. EDL Coverage Geometry Targeted to Holden for Day 1 (25-Nov-2011) of Type 1 Launch Period

Entry, Descent, and Landing Timeline

The Entry, Descent and Landing (EDL) phase follows the Pre-EDL phase and is defined to begin when the spacecraft reaches the atmospheric entry interface point at a Mars radius of 3522.2 km and ends after the flyaway event and all flight system components have reached zero kinetic energy. Figure 17 shows the vehicle orientation at Entry interface. Figures 18 through 20 illustrate the different events occurring during the EDL phase (Prakash R., 2008).

Final Approach - EDL Initialization

During final approach, the final TCMs are executed (if needed), and the EDL parameter and navigation updates are uploaded to the flight system. Final approach starts 5 days before entry with issuance and uplink from the ground of the "Do PEDL" command to set up the vehicle for EDL during a quiet time. TCM-5 is scheduled to occur at Entry – 2 days, with a contingency TCM-5X at Entry - 1 day in the event that TCM-5 cannot be performed. A final contingency TCM opportunity (TCM-6) is at Entry – 9 hrs. Final EDL parameter and navigation update opportunities occur at Entry -1 day and at Entry - 2 hrs.

EDL Start

The Pre-EDL phase comprises the EDL Start and the Exo-Atmospheric segments. The EDL Start segment starts with issuance of the "Do EDL" command 15 minutes before entry. This command requires one of the updates from PEDL for proper EDL initialization. During this phase, the Heat Rejection System (HRS) venting occurs at 3.5 min before cruise stage separation which occurs 10 min before atmospheric entry. Cruise stage separation marks the end of the EDL Start segment.

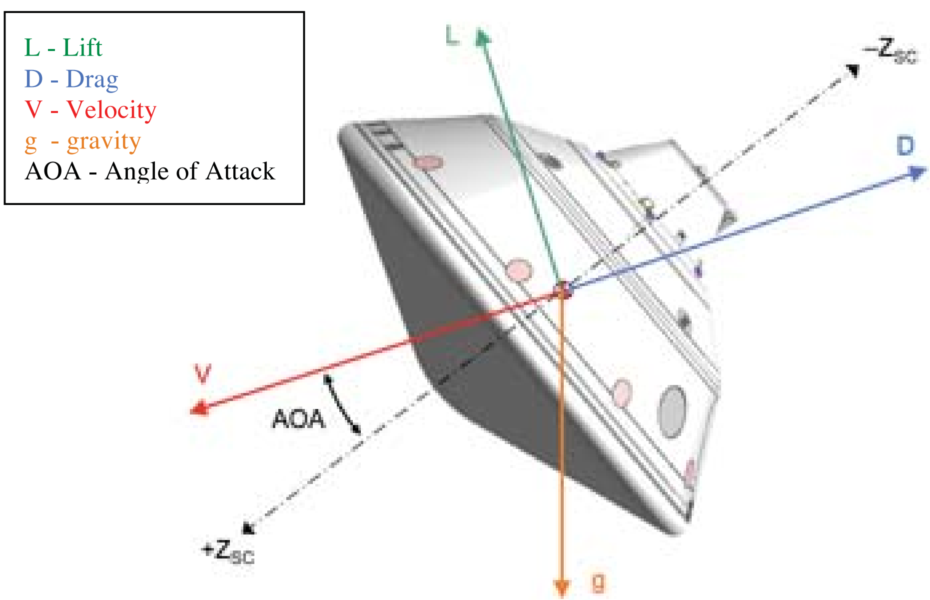


Figure 17. Vehicle Orientation at Entry Interface

Exo-Atmospheric

Once the cruise stage has been mechanically separated from the entry vehicle, the MSL EDL Instrumentation (MEDLI) suite located on the heatshield is enabled. At 9 min before entry, the Guidance, Navigation, and Control (GN&C) system is enabled. Once enabled, the GN&C system despins, detumbles and turns the vehicle to the desired entry attitude. At this point in time, two 75-kg Cruise Balance Masses (CBMs) are separated in order to move the center of mass of the vehicle away from the centerline. This produces a nominal lift-to-drag ratio of 0.24 at Mach 24 and induces an angle of attack (~16 deg) that creates aerodynamic lift. Figure 18 shows the Final Approach and Pre-EDL Phases.

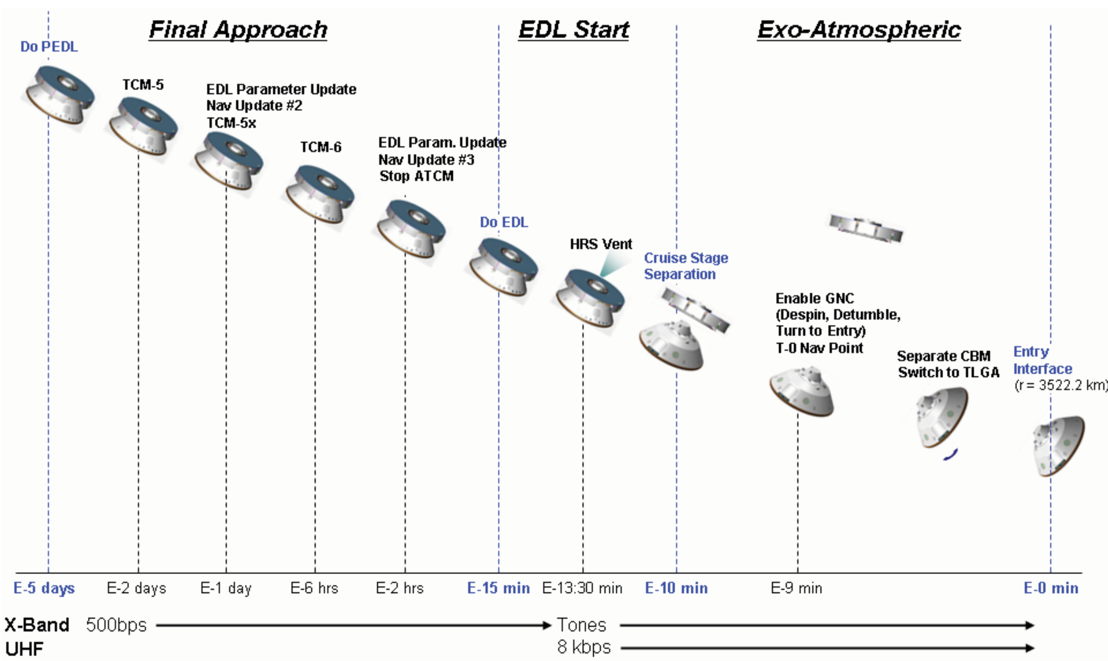


Figure 18. Final Approach and Pre-EDL Phases

Entry

Once the flight vehicle reaches entry interface, the entry segment starts and the Reaction Control System (RCS) is pressurized. The RCS propulsion system is required to provide control authority during bank reversals. Right after the entry guidance system becomes active, the guided entry phase starts and guidance starts modulating the lift vector by rotating the entry vehicle to achieve the necessary downrange and cross range control and to counteract aerodynamic and atmospheric dispersions. Once entry guidance is completed, a Straighten Up and Fly Right (SUFR) maneuver is executed which jettisons six 25-kg ejectable balance mass devices (EBMDs) to re-align the center of mass to pre-entry conditions (no lift). This maneuver occurs at approximately Entry + 230 s. These masses are ejected in 2-second intervals to minimize potential attitude disturbances. In addition to the SUFR maneuver, the vehicle is rotated by doing a 180 roll (+X up is 0 bank angle, full lift up) so the Terminal Descent Sensor (TDS) points towards the ground (in the +Z direction). During this phase peak aeroheating (entry plus 85 s) and peak deceleration (Entry + 96 s) are experienced.

Parachute Descent

Once flight conditions are within the supersonic parachute deploy regime, parachute deploy occurs (Entry + 245 s) at between Mach 1.8 and Mach 2.2). Due to a possible oscillatory behavior of the capsule suspended underneath a parachute, an active wrist mode damping mechanism using the RCS thrusters will activate. This wrist mode ensures a safe heatshield separation, good TDS surface acquisition, and a safe backshell separation. This wrist mode management begins about 10 s after parachute deploy. Once the vehicle is decelerated to subsonic conditions, heatshield jettison occurs (between Mach 0.5 and Mach 0.8 at Entry + 274 s) which exposes the powered descent vehicle and allows for TDS to begin taking ground altitude and velocity measurements. Once altitude solutions are obtained, surface relative navigation begins. Just before backshell separation (at an altitude between 1500 and 2000 m above ground level), each of the 8 Mars Landing Engines (MLEs) are set to 1% throttle to begin the propellant flow to the MLEs. Figure 19 illustrates the Entry and Parachute Descent Phases.

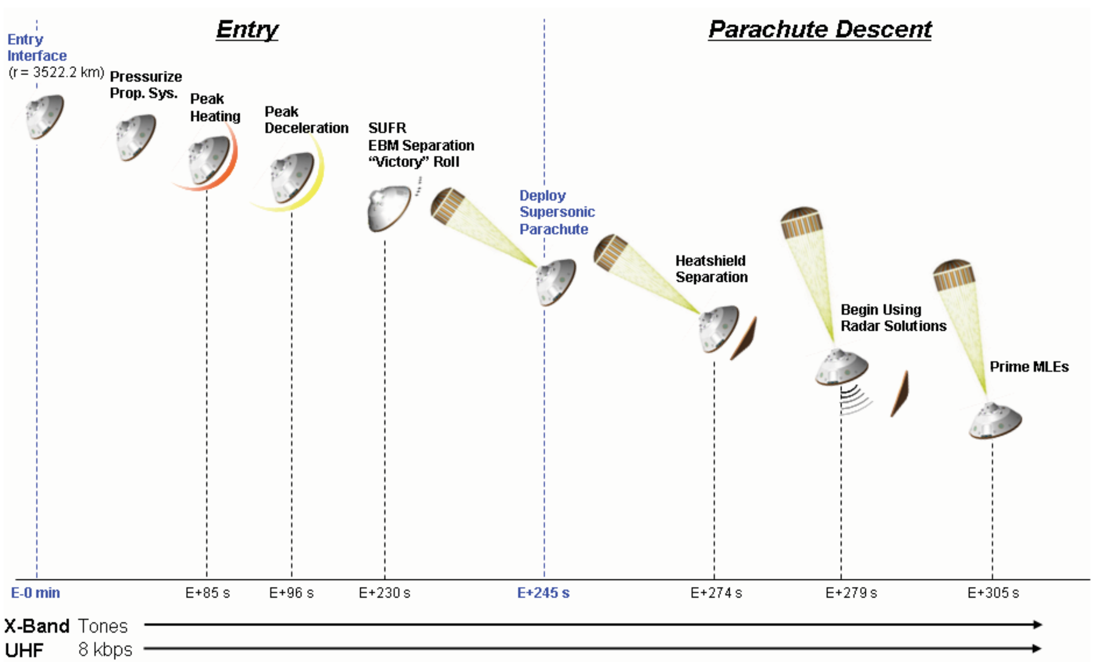


Figure 19. Entry and Parachute Descent Phases

Powered descent

Powered descent begins right after backshell separation and is responsible for delivering the spacecraft to the Sky Crane condition (18.6-m altitude, 0.75 m/s vertical descent velocity, 0 m/s horizontal velocity) and for diverting the spacecraft away from the initial trajectory to avoid potentially landing at the same location as the backshell and parachute. For one second, the powered descent vehicle (PDV) freefalls (except for drag effects and 1% engine throttle) in order to allow for sufficient separation to avoid any potential recontact with the backshell and then throttles to

20%. The freefall vertical speed is ~120 m/s. The following 2.2 s remove any residual attitude rates from the backshell separation event. Then, the PDV follows a 3-D polynomial trajectory computed at backshell separation that zeroes out the horizontal velocity component and reduces the vertical velocity component to 20 m/s. The end point of this trajectory is about 100 m above the surface. Figure 20 illustrates the Powered Flight Phase.

Due to potential errors in altitude knowledge at backshell separation, a period of constant vertical velocity is implemented. This approach accounts for scenarios in which the altitude at backshell separation is up to 50 m different than the nominal 100-m altitude. This phase is termed as the Constant Velocity Accordion. For the case in which the surface is 50 m closer than initially calculated, the Constant Velocity Accordion is zero. Similarly, for the case in which the surface is 50 m lower than expected, the PDV will need to traverse 100 m to reach an altitude of 50 m above surface which marks the beginning of the Constant Deceleration phase.

The Constant Deceleration phase brings the PDV from 20 m/s to 0.75 m/s. This is achieved by throttling the engines at 90%. This phase ends at 21 m above the surface. At this point, more than half of the initial 400 kg of fuel has been consumed; hence, in order to maintain thrust equal to weight, the MLEs are throttled back to 20-25%. The MLEs are more efficient at 50% throttle; therefore, half of the MLEs are throttled back to near shutdown conditions (1% throttle) whereas the remaining four MLEs throttle at ~50%.

Sky crane and Flyaway

At an altitude of 18.6 m, the GNC mode issues a rover separation command which lowers the rover from the descent stage on a triple bridle until the bridles are fully extended to a length of 7.5 m while the descent stage maintains a constant vertical velocity of 0.75 m/s As the rover is lowered by the Sky Crane, the rover is simultaneously being deployed. Seven seconds after rover separation from the descent stage, the bridle is fully deployed at which point the motion stops. After a couple of seconds to allow the descent stage to remove any disturbances the system is ready for touchdown.

The constant velocity is maintained until rover touchdown is detected via persistence of bridle offloading. After touchdown, the rover weight is supported by the surface, the bridle offloaded, and the commanded vertical thrust reduced to half. This commanded thrust will persist after touchdown and is used to declare touchdown via a touchdown logic algorithm that is enabled 9 seconds after rover separation.

Once touchdown is confirmed, the descent stage stops vertical motion and hovers to cut the triple bridles. Two of the MLE engines are brought to 100% while the other two engines are at slightly less than 100%, causing the descent stage to pitch about the descent stage Y-axis to 45°. Once the turn duration is complete, all four engines are brought to 100% with the controller making adjustments for maintaining zero attitude rates. Constant thrust is applied for enough time to ensure that the descent stage touches the surface at least 150 m from the rover's position. The rover is designed to land on rover length slopes of up to 15 deg with vertical and horizontal velocities up to 0.85 m/s and 0.5 m/s respectively. This system has many advantages over other traditional systems, including lower touchdown velocities, lower impact loads, and no egress phase.

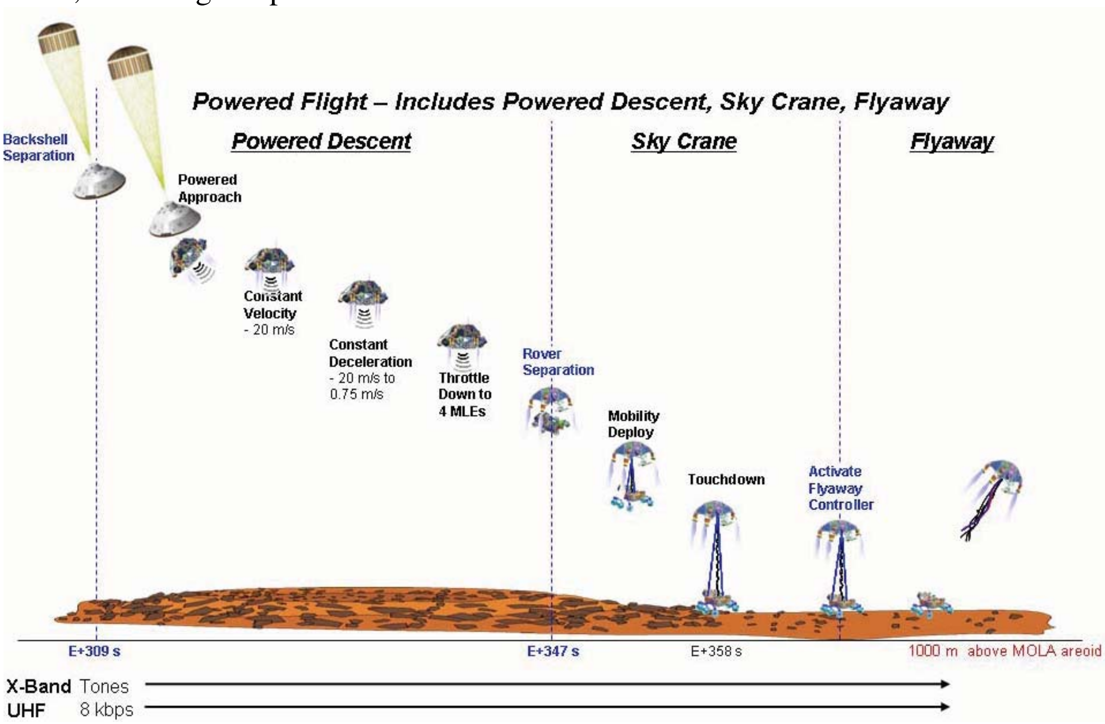


Figure 20. Powered Flight Phase

CONCLUSIONS

After the recent successes of Mars Pathfinder (1997) and the Mars Exploration Rovers (2004), NASA is planning on delivering to Mars a much larger rover known as the Mars Science Laboratory (MSL) as the next logical step in Mars exploration. This paper has summarized the launch/arrival strategies and presented results to demonstrate that all MSL mission design requirements are satisfied. This strategy consists of two 24-day launch periods that provide EDL communications coverage via a UHF link to MRO and either UHF link to ODY or X-band DTE link for landing latitudes between 25°N and 27°S. In order for the orbiters to provide EDL coverage, their orbit LMST nodes will need to be moved as a function of launch day and landing site. Five trajectory correction maneuvers (TCMs) are planned in order to satisfy atmospheric entry delivery and knowledge requirements. The EDL system described herein significantly improves current delivery capabilities in terms of mass delivered and landing accuracy.

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