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Mars Science Laboratory Cruise Propulsion Maneuvering Operations

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Abstract

Mars Science Laboratory "Curiosity" is NASA's most recent mission to Mars, launched in November 2011, and landed in August 2012. It is a subcompact car-sized nuclear powered rover designed for a long duration mission, with an extensive suite of science instruments. Entry, descent and landing used a unique "skycrane" concept. This report describes the propulsive maneuvering operations during cruise from Earth to Mars, to control attitudes and to target the vehicle for entry. The propulsion subsystem, mission operations, and flight performance are discussed. All trajectory control maneuvers were well within accuracy requirements, and all turns and spin corrections were nominal.

I. Mission Description

Mars Science Laboratory (MSL) is NASA's most recent mission to Mars, launched in November 2011 and landed in August 2012 (Figure 1). The rover named "Curiosity" is comparable in size to a subcompact car. Electrical power is derived from a multi-mission radioisotope thermoelectric generator (MMRTG), which charges a battery that can provide sufficient power at night and during the winter season. Its primary goal is to assess whether Mars ever had an environment that may have been able to support life. To this end, a robust suite of scientific instruments is carried. Extended mission duration and long-range mobility are planned (Figure 2).

Figure 1 Gale crater panorama on Mars. *Image credit: NASA/JPL-Caltech/MSSS*

Figure 2. Curiosity rover in testing. *Image credit: NASA/JPL-Caltech*

MSL was launched on an Atlas V launch vehicle on November 26th, 2011, near the beginning of the launch window. Figure 3 shows the spacecraft configuration during interplanetary cruise. The large aeroshell below encloses the folded-up rover. The cruise stage above is the portion that conducts the flight to Mars. Around its perimeter are large radiators to reject heat pumped by fluid loops from the MMRTG. One of the two cruise propellant tanks is visible behind the radiator near the center. The small cruise stage thrusters are not visible in this view.

Figure 3. Cruise configuration in testing. *Image credit: NASA/JPL-Caltech*

After launch, the spin rate was slightly reduced from that initially delivered by the launch vehicle upon separation. During cruise, the spacecraft was spin-stabilized. Subsequently, a small lateral maneuver was performed to calibrate the center of mass model.

A heliocentric view of a typical interplanetary trajectory is shown in Figure 4. After launch, between 4 to 6 trajectory control maneuvers (TCM) were planned to target the Mars entry window. The first maneuver removed the launch injection bias intended to prevent the "dirty" upper stage from impacting Mars. Subsequent maneuvers corrected the trajectory to target the required Mars entry window. The last two maneuvers were contingencies that should not be necessary if previous maneuvers executed nominally.

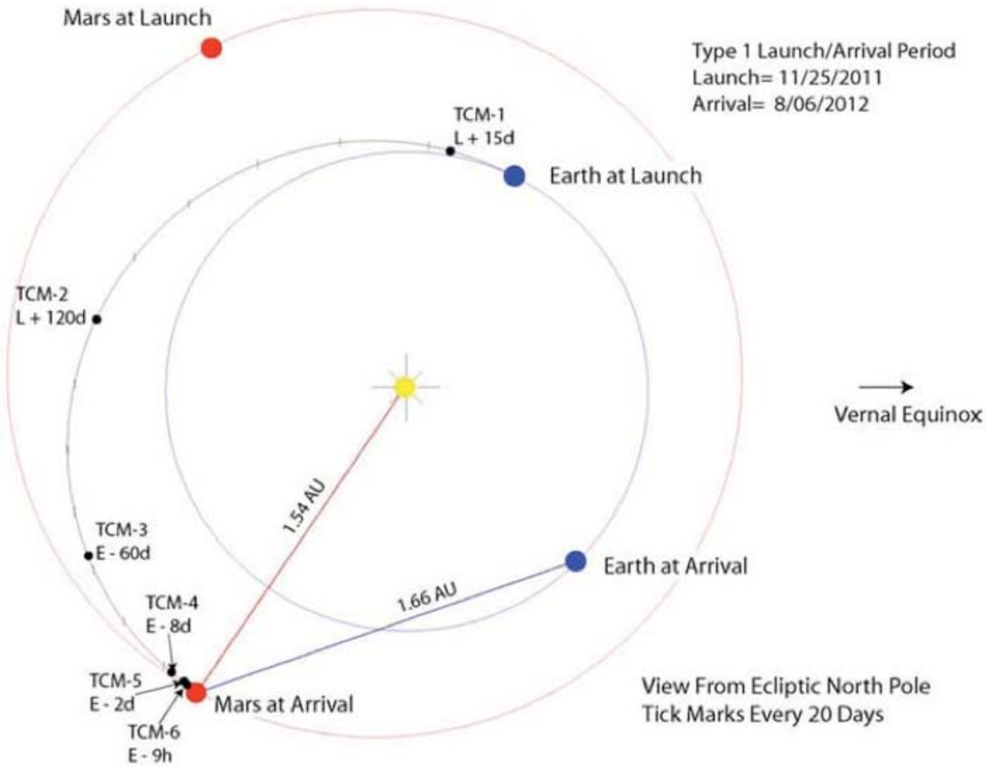

Figure 4 Cruise mission design, sample [1]

Approximately 40 turns were performed. The sun angle was maintained in a desired range for thermal and solar panel power considerations. The Earth angle was maintained within required limits for telecommunications, particularly when the narrower angle medium gain antenna was in use. In addition, several turns, some very large, were performed to calibrate attitude control system (ACS) sensors.

Transition from space flight to a landed configuration, called "entry, descent and landing," (EDL) was probably the most complex and demanding phase of the mission. First, the cruise stage that flies the vehicle through space from Earth to Mars separated from the aeroshell. The aeroshell entered the Mars atmosphere and decelerated. Lower in the atmosphere, a parachute deployed to further slow the vehicle. Then the heat shield separated, allowing the Mars surface to be seen by sensors, and the propulsion system to be started. The descent stage separated from the upper backshell, and descended under rocket power. Precision guidance was used to achieve safe insertion into potentially rough terrain. The rover was lowered from the descent stage on a bridle. The descent stage hovered over the planet surface, suspending the rover in a unique "skycrane" scheme. After rover touchdown on the surface, the bridle was cut, and the descent stage flew off for disposal a safe distance away. [2], [3] On August 5th, 2012 (Pacific time), the rover touched down successfully on the surface of Mars.

This report describes the maneuvering operations during cruise from Earth to Mars, an aspect of the mission less glamorous than EDL or rover operations, but no less essential. These maneuvers were accomplished using the cruise stage propulsion system.

II. Propulsion Subsystem

The cruise stage propulsion was a simple, monopropellant, blow-down system based on successful flight heritage of Mars Pathfinder (MPF) and Mars Exploration Rover (MER).[4] The entire subsystem was designed and assembled at JPL. A schematic is shown in Figure 5. There were two spherical, titanium alloy-wall propellant tanks, with an elastomeric diaphragm positive-expulsion device. Helium was utilized as the pressurant gas. The tank exit ports were manifolded and fed into the Propellant Distribution Module (PDM). Integral to the PDM plate was a propellant filter, redundant pressure transducers, and latch valves separating each thruster cluster branch. Each thruster cluster incorporated four small Rocket Engine Assemblies (REAs).

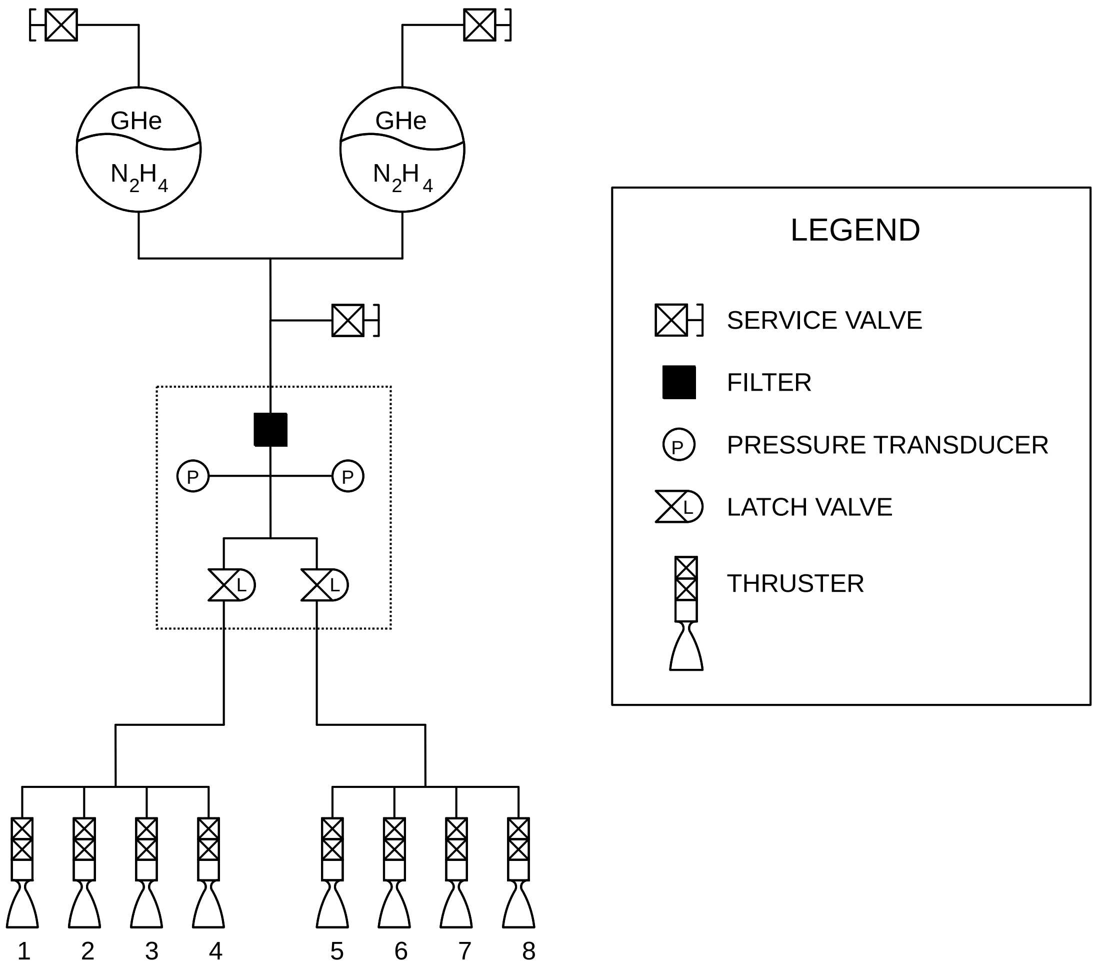

Figure 5. Cruise propulsion schematic

The REAs were canted at an angle, and installed as shown in Figure 6. In this way, the spin-stabilized spacecraft could be controlled using only two clusters of four thrusters, with redundancy. Thruster units were individually selected and placed to minimize net thrust differences during turning maneuvers.

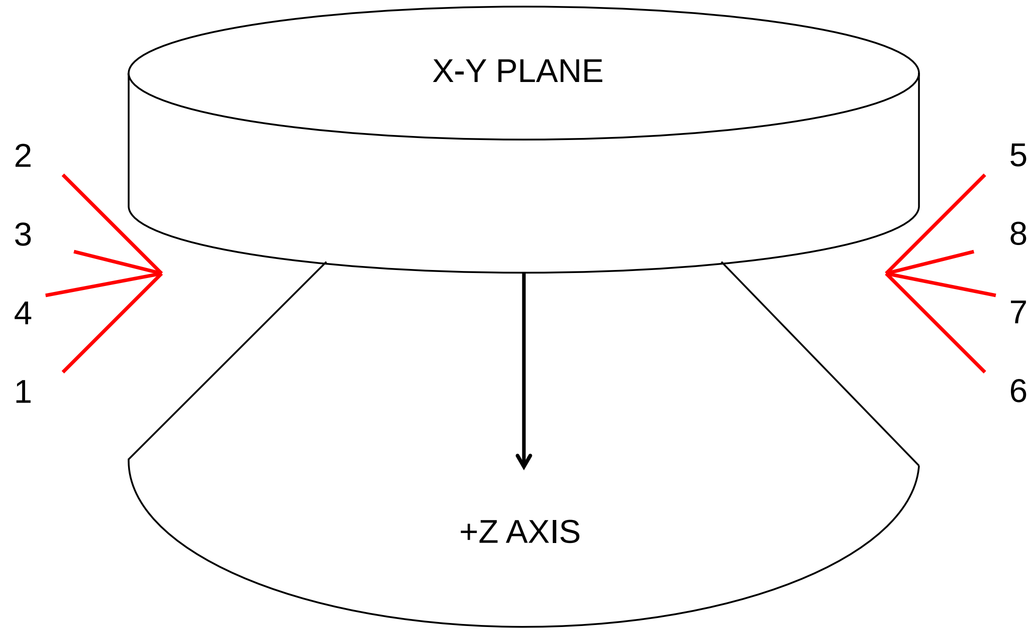

Figure 6. Cruise thruster layout

Axial maneuvers in the +Z direction were performed by firing thrusters 2 and 5 continuously. -Z maneuvers used thrusters 1 and 6. For lateral maneuvers, all 4 thrusters on a cluster were fired in a pulse mode when they are pointed in the appropriate orientation, then the other 4 thrusters were fired when they spun into the same orientation. Pulse durations were adjusted to assure the net force vector goes through the center of mass. Therefore, "lateral" maneuvers were not truly in the X-Y plane, but were slightly inclined from it. In addition, a "vector" TCM could be made with both axial and lateral components to effect the desired delta-V vector.

Turns and nutation control were performed by pulsing coupled thruster pairs 1 and 5, or 2 and 6 when they spun into the appropriate orientation, thereby imparting little or no net delta-V to the spacecraft. The spinning spacecraft had a significant angular momentum vector magnitude, so changing the vector direction with a turn required a substantial amount of propellant. Spin increases and decreases were accomplished firing thruster pairs 4 and 8, or 3 and 7, respectively.

The subsystem was single fault tolerant to most credible failures. With dual thruster valves, leakage or fail open would not result in catastrophic propellant release or loss of control. In case of a thruster or latch valve failure, the mission could still be flown with a single thruster cluster, with the caveat that there may be excess delta-V from non-coupled firings, and looser attitude control to deal with. All heaters were redundant, with fault protection logic implemented to swap autonomously to the redundant heater in case an anomaly was detected. Pressure transducers were also redundant.

Thermal control for thruster valves, the PDM plate, and tanks were provided using primary and redundant mechanical thermostats. Each thruster had redundant catalyst bed heaters, which were simply turned on and off by command. The propellant lines were separated into zones containing redundant heaters, utilizing software control. Thermal control of the propellant lines, with an extended geometry, exposed to space, with variable solar radiation influx, and nearby hardware at different temperatures, proved to be a challenge. [5] [6]

One aspect of the subsystem that diverged from MER heritage was its interface to non-MER heritage dual string avionics. Because of interface limitations, each side of the avionics could read only one pressure transducer, and only 4 out of the 8 thruster valve and catbed temperatures. REA temperature sensors were "cross-wired" so that each avionics side could read thruster valves on one cluster, and catbeds on the other cluster.

III. Propulsion Operations

A wide range of processes and infrastructure were used to conduct cruise propulsion mission operations.

A. Ground Data Systems

The ground data system used on MSL was a new system, using modern computing methods as compared to the legacy system.[7] One notable benefit was that users can quickly and fairly easily define complex displays. However, as a new system, there was a learning curve for users that required a substantial investment of time, and numerous bugs were discovered during the course of operations that had to be corrected or worked around. Project information was stored in a number of different websites, based on wiki and other platforms.

Two main programs were used to conduct propulsion analyses. PROP was a program in the ground software that calculated the performances of the cruise stage thrusters when the thrusters operate in steady state or pulse mode for delta-V maneuvers. PROP was a modification of the program of the same name used during MPF and MER mission operations to compute the performances of the thrusters. MTANK was a program in the ground software that calculated propellant tank properties as functions of tank pressure, tank temperature, propellant mass remaining, pressurant mass, etc. It had three modes of operation: calculate all properties of a single tank containing hydrazine propellant and helium pressurant, calculate the propellant mass remaining in the propulsion system from the measured tank pressure, and predict the tank pressure at a future time. MTANK was a generalized and upgraded version of the TANK program used during MER mission operations for the same purposes.

In addition, a spreadsheet was used to track and trend propulsion parameters, calculate the thruster model propellant consumption, generate status reports and automatically create plots.

B. Uplink

Routine propulsion operations tasks associated with command uplink included the following.

Thrust predictions were made for TCMs. Performance was predicted using PROP based on estimated propellant use between time of prediction and the maneuver, and predicted tank temperatures just before the maneuver. The primary variable affecting thrust is the predicted tank pressure at the time of maneuver. Thrust factors were adjusted based on pre-launch analysis, and on previous TCM performance as determined from maneuver reconstruction. The thrust predictions were delivered to Attitude Control Subsystem (ACS) personnel, who designed the maneuver and generated command sequences to implement it.

Command sequences to be sent to the spacecraft were reviewed. Sequences containing commands that affect propulsion were individually reviewed. Integrated modeled products, containing all planned commands in chronological order, were reviewed for an overall view of planned activities, and to see if any other commands might affect propulsion. Testbed runs of planned propulsion activities were reviewed to verify proper expected operation. For more routine activities, results of software simulations, which run much more quickly, were reviewed.

Less frequently, propulsion personnel also generated command sequences. These included propulsion propulsion subsystem checkouts , and contingency commanding. Software simulation or testbed runs were made to validate the sequences, as appropriate.

C. Downlink

Routine propulsion operations tasks associated with telemetry downlink included the following.

Subsystem health and status were monitored. In real-time operations, console display pages showed telemetry data in schematic, tabulated and time history plot presentations. Red alarms were warnings which would indicate anomalous states and readings. Yellow alarms were warnings that indicate states that should not persist long term, or readings that are approaching red alarm limits. Checklists gave the expected readings of telemetry channels, and conditions under which an activity may be performed or a contingency should be executed.

Propellant quantity on the cruise stage was tracked. In the "tank" model, propellant quantity was calculated based on tank pressure and temperatures. After some initial hydrazine usage, this was considered the most accurate indication of propellant quantity. However, there was too much noise for it to be an accurately measure change in propellant quantity for each maneuver. In the "thruster" model, propellant usage was calculated based on telemetered thruster on-times and feed pressure. This was considered the most accurate measure of propellant consumed during a maneuver. However, inaccuracies in the flowrate model accumulate over time, and the estimate of propellant remaining may be inaccurate. Propellant usage for maneuvers was calculated based on thruster on-times and feed pressure. In addition, there was an on-board calculation similar to the thruster model. However, resets or swaps of the on-board computers can alter the value of propellant quantity, and it sometimes needed to be updated with uplinked values from the ground.

Thruster performance during TCMs was reconstructed. The actual tank pressure, temperatures and thruster on-times during the maneuver were obtained from telemetry. The actual maneuver delta-V magnitudes for the axial and/or lateral components were obtained from orbit determination by navigation personnel. The PROP tool was then run, using those actual conditions. The thrust factors and polytropic coefficient were adjusted until the actual delta-Vs and temperature change profile are obtained. Those parameters gave an indication of thruster performance and tank blowdown characteristics. They were also used in performance prediction of subsequent maneuvers, to help improve their accuracy.

IV. Flight Performance

Even before launch, thermal control of the propulsion system presented a challenge. On the one hand, the vehicle required aggressive air cooling to reject heat generated by the MMRTG. On the other hand, the propulsion system needed to be kept warm enough to remain within hardware qualified limits as well as to preclude freezing of hydrazine with margin. This required subsystem heaters to be kept strategically on, drawing a significant amount of power from the umbilical and batteries. [8]

After initial acquisition, it was found that cruise thruster valve temperatures were slowly but steadily increasing, exceeding the maximum allowable non-firing limit. Therefore, one catbed heater string was turned off, after which the temperatures decreased and leveled off, but still above the limit. Upon a closer look, it was determined this behavior was in fact not dissimilar to MER heritage. On MER, catbed heaters were nominally off, and one string was turned on a time period prior to the maneuver to warm up the catbeds prior to thruster firing, and was turned off after firing; however, while the heater was on, thruster valve temperatures were actually steadily increasing. Unfortunately, pre-launch testing and analyses did not replicate the flight conditions or heater-on durations, so this behavior was not anticipated. Therefore, it was decided to operate the catbed heaters like MER, keeping them off except as needed for burns. However, some autonomous fault protection responses could fire thrusters without a warm-up period. This would result in a cold start which is a limited consumable, or a frozen start which could cause hardware damage. As solar distance increased, catbed temperature with the heater off decreased which increases risk of frozen start, but valve temperature with the heater on also decreased. Therefore, at a prudent point, one catbed heater string was turned on and left on, for the benefit of planned maneuvers and potential autonomous firings. In addition, allowable maximum temperatures of the valves were increased to be more representative of actual hardware capability.[9]

Because of a combination of the valve temperature concerns above, known challenges of cruise propulsion line temperature management with flow, and some perceived residual risk of valve functionality, an 'envelope expansion' of propulsion system usage was performed. First, propellant drop to wet the lines between latch valves to thrusters gave a preliminary assessment of the effects of moving propellant. Spindown exercised a short continuous burn of two spin thrusters. The first turn performed a short pulse set on the turn thrusters. Lateral calibration was two short sets of pulses an all thrusters. Finally, the TCM-1 was a long continuous burn on two of the axial thrusters, followed by extended pulse sets on all thrusters. This was expected to be the largest burn of the entire mission, but the valve soakback temperatures were well below maximum allowable limits.

REA thermal management was complicated by the fact that a given avionics string could only read thruster valve temperatures on one cluster, and catbed temperatures on the other. Therefore, for a given thruster, valve temperatures had to be inferred from catbed temperatures, and vice versa. Further complicating matters was the fact that the thermal environment of the two TCAs are somewhat different. During brief periods of time, the other avionics string was activated to confirm the correlation, but this configuration was not maintained for extended periods due to implications for fault protection logic.

Results of propellant quantity tracking are shown in Figure 7. As can be seen, the tank model and the on-board telemetry thruster model agreed extremely well. The ground based thruster model actually slightly overpredicted propellant consumption, but as mentioned, thruster models are not expected to be an accurate measure of propellant quantity. At the end of cruise, there was a significant quantity of propellant remaining. This was because propellant budgeting is based on statistically extreme cases and to cover contingency scenarios. In reality, the launch vehicle injection was accurate, and the TCMs were accurate, and no significant maneuvering anomalies occurred.

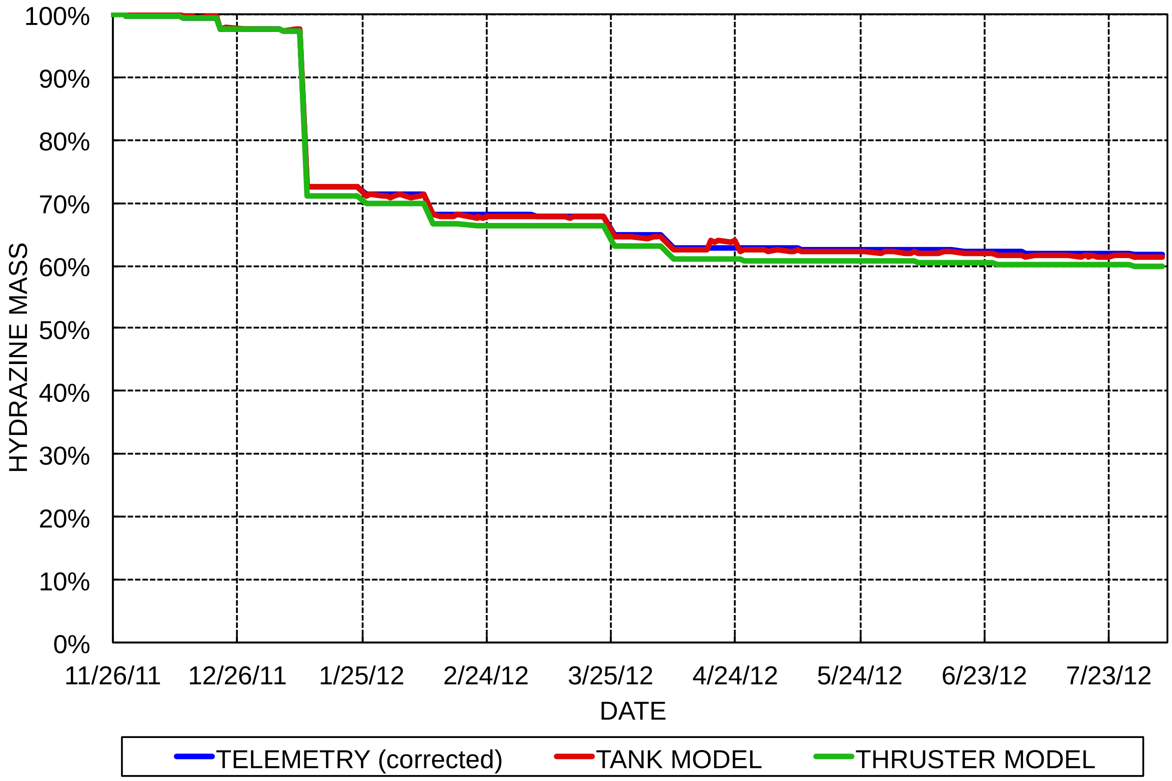

Figure 7. Cruise stage hydrazine quantity history

A total of 4 TCMs were performed. The first one, TCM-1, was by far the largest. The second one, TCM-2, was a moderate size maneuver and the first to target the Mars entry point. The final TCM-4 established a trajectory within the required Mars entry window, and very close to the ideal target. All maneuvers were well within accuracy requirements. After an initial maneuver component of a particular type, subsequent maneuver components of that type were considered calibrated, and were planned to a smaller uncertainty. TCMs and their performance are summarized below. Reconstructed performance of a maneuver was used to tune performance parameters for and improve accuracy of subsequent maneuvers. Thruster performance was the percent difference from ground test data. Plume impingement analyses predicted a certain amount of thrust loss, and the actual loss appears to be less than was predicted. Also, the baseline ground test thrust data are actually calculated from chamber pressures and other parameters, and may have some built-in inaccuracy. Note that TCM-3 and TCM-4 were small maneuvers, so a higher degree of maneuver execution and thruster performance inaccuracies are to be expected, for various reasons.

Table 1 Trajectory control maneuver summary

MANEUVER	TYPE	MANEUVER ACCURACY			THRUSTER PERFORMANCE		
		+Z	-Z	LATERAL	+Z	-Z	LATERAL
Lateral calibration	lateral						-2.5%
TCM-1	-Z vector		4.2%	2.2%		-2.8%	-1.5%
TCM-2	-Z vector		1.3%	-0.1%		-1.1%	-1.6%
TCM-3	+Z vector	4.7%		-2.0%	-1.1%		-0.8%
TCM-4	lateral			-5.9%			-4.6%

Approximately 40 turns were performed, both to maintain the desired attitude with respect to the Sun and Earth, as well as to calibrate ACS sensors. Because turns required moving the large magnitude angular momentum vector of a heavy spinning spacecraft, they expended substantial amounts of hydrazine. All turns were analyzed to infer actual thrust performance vs. ground test performance, though the presence of interleaved additional thruster firings to correct nutation during turns complicated this effort. A simple model was developed to compare the actual angular momentum change of the spacecraft during turns (based on spacecraft moment of inertia about the z-axis, change in attitude, etc.) to that predicted based on thrust and on-time. In this way, a percentage error in delivered vs. expected thrust could be calculated. Figure 8 depicts the turn thruster percentage error as a function of executed turn angle, from turn angles as low as 3 degrees up to values near 51 degrees. Obvious nutation pulses not centered on spacecraft half-revolutions at the end of turns were removed from the analysis. As expected, smaller turns show a greater degree of underperformance vs. larger turns, since nutation correction during turns is a larger percentage of the error for smaller turns. The equivalent plot in Ref. 4 had errors as large as 35%, so MSL results are much more favorable, which is consistent with MSL being a much heavier spacecraft with smaller nutation. Even though agreement with ground test is not as good as for TCM performance and spin thruster performance, these data still show a consistent pattern and nominal turn thruster performance during flight, very likely within the noise level of the analysis. If plume effects were excluded, all data points in the plot would increase around 4%, bringing large turns especially within familiar levels (4 to 5 % underperformance). Compared to spin thruster modeling, this problem is not as "clean" and one dimensional, so larger errors are anticipated, particularly given the difficulty in removing mid-turn nutation pulses. Overall, very good in-flight performance of the turn thrusters was demonstrated.

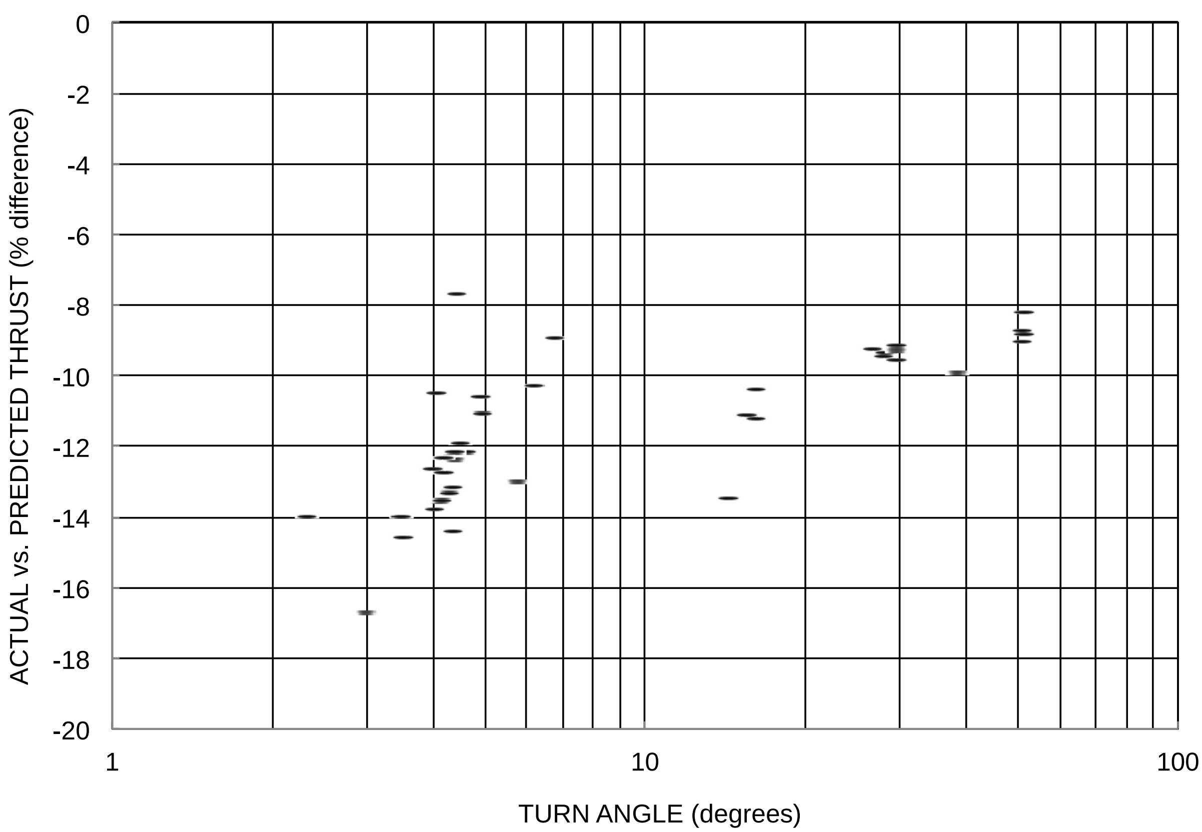

Figure 8. Turn thruster performance

The cruise stage spin thrusters were used to correct spacecraft spin rate, although only infrequently. Initial spindown fired thrusters 3 & 7 for about 30 seconds each, reducing the spacecraft spin rate from 2.50 to about 2.04 rpm. The only other negative spin rate correction in the mission occurred during ACS Turn #1, firing thrusters 3 & 7 for less than one second each. Thrusters 4 & 8, the spin-up thrusters, were only used to increase the spacecraft spin rate on one day of the mission, just after four lateral segments during TCM-1. A simple model was developed to compare the actual angular momentum change of the spacecraft during spin correction events (based on spacecraft moment of inertia about the z-axis, change in spin rate, etc.) to that predicted based on thrust and on-time. In this way, a percentage error in delivered vs. expected thrust could be calculated. Figure 9 depicts the spin thruster percentage error as a function of per thruster on time, for all of the events mentioned above. Note a consistent underperformance of about 4% for the spindown thrusters 3 & 7 vs. ground models, compared to an overperformance of 2.5 to 4.5% for the spin-up thrusters 4 & 8. This agreement with ground test is excellent, very likely within the noise level of the analysis. This demonstrates very good in-flight performance of the spin thrusters.

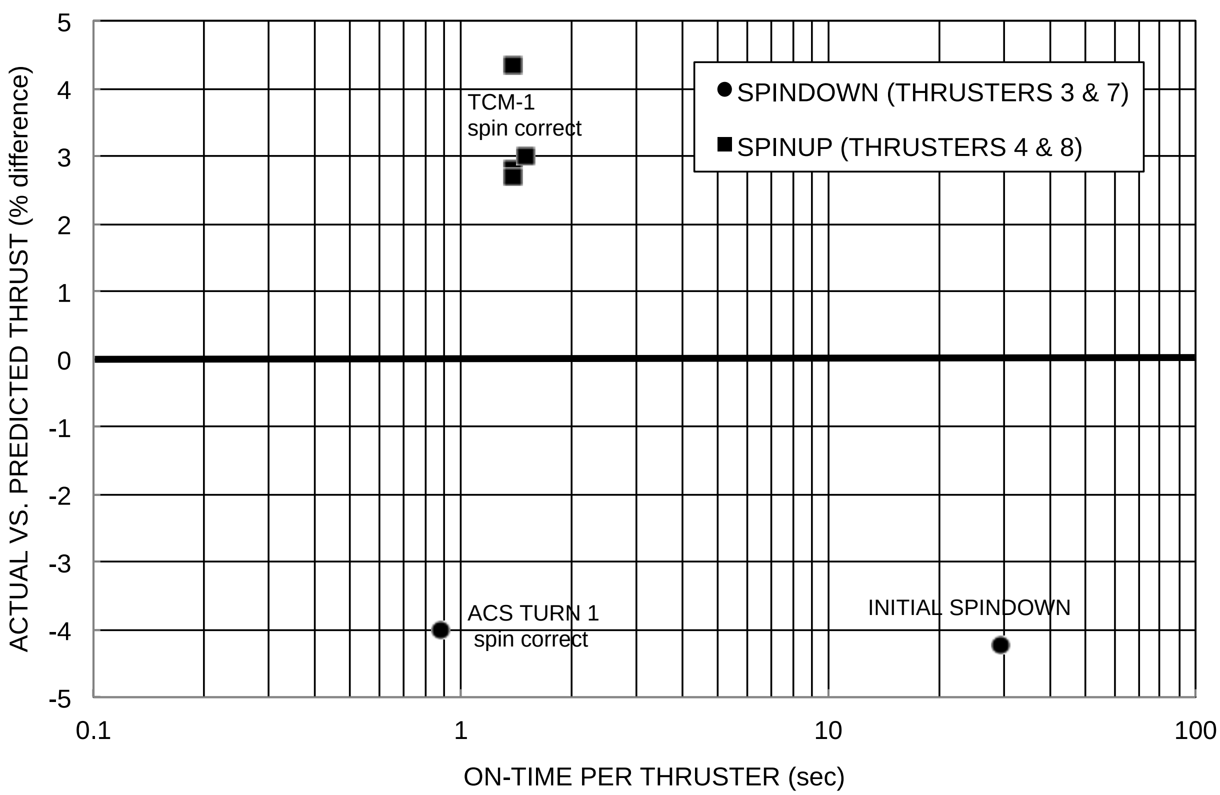

Figure 9. Spin thruster performance

Thermal management of cruise propellant lines was known to be a challenge, as previously mentioned. No single set of thermal control parameters could assure an acceptable range of temperatures throughout cruise. Therefore, thermal engineers updated the control parameters on a number of occasions during cruise. These included control setpoints, fault protection trip levels, and default heater duty cycles.

V. Concluding Remarks

MSL launched in November 2011 and landed on Mars in August 2012. During the intervening cruise between Earth and Mars, propulsive maneuvers were conducted to control attitudes and to target the vehicle for entry.

- The cruise propulsion subsystem and mission design were based on established heritage of MPF and MER
- Four trajectory control maneuvers were performed, and all were well within accuracy requirements.
- A number of turns and spin corrections were made with the spinning spacecraft, and the thruster performance was nominal.
- To maintain acceptable temperatures on the propulsion subsystem, operational changes were implemented on several occasions.
- Ground processes and infrastructure used to conduct mission operations included many updated and modernized systems.
- At Mars entry, the trajectory was well within the required bounds, leading up to a successful landing.

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14. ABSTRACT
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